Levee Breach Analysis for King County Rivers

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KING COUNTY FLOOD CONTROL DISTRICT

King County

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Executive Summary

This levee breach analysis was initiated by the King County Flood Control District to provide a review of currently available information to characterize the potential for levee breaches and the resultant risk to people and infrastructure. The analysis summarizes what is known about the physical character of containment levee systems and adjacent existing land uses and identifies potential risks and consequences should a breach occur. The analysis also identifies data gaps and provides recommendations for obtaining additional information and conducting further investigations as needed to increase understanding of the potential for levee breaches. Planning level cost estimates were developed for use in considering the level of effort that may be needed to obtain site data and conduct technical analyses currently not available but necessary to further the understanding of the potential for breaches along certain lengths of containment levee systems. This study only looks at publicly owned or operated flood protection facilities and does not include an assessment of potential flood hazards in reaches with natural river banks or those protected by privately installed flood protection armoring.

Six containment levee systems were evaluated, as follows:

- Lower Tolt River from River Mile (RM) 2.2 (Holberg levee) to the confluence with the Snoqualmie River
- Lower Raging River from RM 1.5 (328th Way SE) to the confluence with the Snoqualmie River
- South Fork Snoqualmie River from RM 5.4 (McConky and Holstein Ext. Levees) to RM 2.1 (Snoqualmie Valley Trail Crossing)
- Lower Cedar River from RM 1.3 to Lake Washington
- Lower Green River from RM 30.9 (Lone’s Addition levee) to RM 11.0 (Black River pump station)
- Town of Skykomish Left Bank Levee RM 15.85 to RM 16.42

For each of these systems the report includes the following:

- Compilation and synthesis of existing information about levee condition and potential for levee breaches along each studied levee system;
- Characterization of levee containment systems and adjacent land uses protected by each system; and
- Recommendations for additional data collection and analysis to address critical gaps in information that would be needed to improve the understanding of the susceptibility of these areas to levee breaches and the corresponding potential impacts.

A general finding of this analysis was that the available information on levee breach potential is not adequate to identify specific locations where breaches are most likely to occur. Table 23 in the body of this report lists critical data gaps for each of the systems studied. Extensive geotechnical explorations including borings and seepage analyses have been conducted on only two of the levee systems, the Green and Cedar River systems, and to a lesser extent on the South Fork Snoqualmie levee system. The other levee systems on the Tolt, Raging, and South Fork Skykomish Rivers have not had much geotechnical work at all done on them.

Topographic data and land-use information is adequate for all of the levee systems to characterize consequences in the event of a levee breach. This characterization, however, requires breach modeling and inundation mapping which has not been comprehensively completed for any of the levee systems.

Recent and detailed two dimensional (2D) hydraulic models are available for the Cedar and Tolt levee systems and these could be used to evaluate levee breach inundations. Less detailed one dimensional (1D) and 1D/2D hydraulic models are available for the Green and South Fork Snoqualmie levees. On the Green River, a limited number of levee breach simulations have been performed. No levee breach modeling has been performed for the South Fork (SF) Snoqualmie River. Hydraulic modeling for the Raging and South Fork Skykomish River levees is outdated and not useful for levee analyses. However, King County is planning to develop new modeling for the SF Skykomish in 2019.

For each of the levee systems studied additional information is required to characterize levee breach risks and prioritize risk reduction projects. The following tasks are generally needed for each of the systems:

- Hydrologic Analysis and Hydraulic Modeling: Use new or existing hydraulic models to identify locations of potential levee overtopping and to characterize in-channel hydraulic characteristics as needed for levee breach evaluations.
- Evaluate Levee Breach Potential: Synthesize levee geometry (height, width, side slopes, etc.), hydrologic properties (ramping rates, flow durations, peak water levels), and geotechnical data to develop levee probability of failure curves.
- Characterize Risks Due to Levee Breach: Use the hydraulic modeling and levee breach potential data to identify the highest risk levees.
- Prioritize locations for remedial actions.
- Develop emergency action plan for any potential breach locations found to be at high risk of failure.

The estimated costs for the recommended additional data collection and studies are summarized in Table E-1. A more detailed breakdown of costs is provided in Subsection 8.4 of this report.

Table E-1: Summary of Estimated Costs for Recommended Additional Data Collection and Studies

Containment Levee System	Recommended Additional Data Collection or Study	Cost Range	
Lower Tolt River Levee System	Sub-total	$732,000	$875,000
Lower Raging River Levee System	Sub-total	$555,000	$660,000
SF Snoqualmie River Levee System	Sub-total	$604,000	$768,000
Lower Cedar River Levee System	Sub-total	$163,000	$255,000
Lower Green River Levee System	Sub-total	$788,000	$1,725,000
SF Skykomish River Levee System	Sub-total	$120,000	$149,000
	Grand Total (rounded)	$3,000,000	$4,400,000

Notwithstanding the lack of data to characterize levee breach risks and prioritize remedial actions, this analysis did not identify any levees at imminent risk of failure due to breaching. As part of King County's River and Floodplain Management program, technical staff regularly inspect each of the levee systems every two years or more frequently and dispatch flood patrols to make observations of flood protection facilities during and after flood events. Problems identified during these regular or post-flood

inspections are prioritized for remediation. Actions may include recurring site inspections, implementation of a repair project or the development of a larger-scale capital improvement project. This level of inspection and remediation helps to reduce the potential for levee breaches by correcting obvious deficiencies, although the potential for levee breaching due to geotechnical deficiencies cannot be assessed by visual inspection alone. Historically, none of the levees included in this study have breached with the exception of a section of the lower Tolt Hwy to RR Bridge left bank levee in 2009. That breach was the result of flood waters overtopping the levee; this mode of failure is thought to be the greatest potential cause of breaches for all of the levees in this study.

1 Introduction

1.1 Purpose

In natural, unmodified river systems floods spread widely across the rivers' floodplain. To reduce the extent of flooding and its impact on people and property, levees have been built on many rivers to contain the spread of flood waters. As significant weather events, such as those of Oroville Dam and the hurricanes Harvey, Irma, and Maria have shown, even robust flood protection facilities, such as levees, are vulnerable to breaching. To understand the potential for levee breaching of containment levee systems along King County rivers, this analysis was initiated by the King County Flood Control District (FCD) to provide an initial characterization of the potential for levee breaches based upon a review of currently available information. The analysis includes the identification of data gaps and provides recommendations for obtaining additional information and conducting further investigations that would be needed to increase understanding of the potential for levee breaches. Information about the physical character of containment levee systems is considered along with information about adjacent existing land uses that receive flood protection. Together, this information provides an indication of the potential risks and consequences should a breach occur. This analysis recognizes the County's long term goal to improve flood protection systems and provides recommendations for building on currently available information to reduce risks related to levee breaching.

Funding for this Levee Breach Analysis was authorized by the FCD as part of the King County FCD Resolution 2017-07. As the service provider to the FCD, the King County Water and Land Resources Division (WLRD) through the River and Floodplain Management Section (RFMS) retained consulting services from Watershed Science and Engineering (WSE) to complete this analysis. This report provides an independent assessment on the current state of knowledge related to containment levees in King County. Included with the recommended list of further data collection and analyses to address the gaps in information identified through the assessment are planning level estimates for the costs and resources.

1.2 Background and Objective

The primary purpose of containment levees along a river is to reduce the frequency and extent of flood hazards landward of the levee by preventing floodwaters from flowing into the floodplain. However, although containment levees can reduce the extent of a flood hazard area, some hazard remains; with the degree of hazard reduction contingent on the integrity of the levee to withstand the magnitude and duration of the flood event. Levee breaches, as a result of overtopping, piping, seepage, slumping, toe scour or other failure mechanisms can take away the protection offered by levees and can actually worsen the severity of flood hazards as the speed with which an area floods after a levee breach may be substantially faster than natural flooding from a river into its floodplain. Considering the potential risks to people and properties protected by containment levees, the intent of this analysis is to evaluate and summarize current information regarding the potential for levee breaches along King County containment levees, characterize potential risks to people and property, and identify actions that can be taken to reduce those risks.

1.3 Study Area

The current study evaluates six containment levee systems in King County (see Figure 1):

- Lower Tolt River from River Mile (RM) 2.2 (Holberg levee) to the confluence with the Snoqualmie River
- Lower Raging River from RM 1.5 (328th Way SE) to the confluence with the Snoqualmie River
- South Fork Snoqualmie River from RM 5.4 (McConky and Holstein Ext. Levees) to RM 2.1 (Snoqualmie Valley Trail Crossing)
- Lower Cedar River from RM 1.3 to Lake Washington
- Lower Green River from RM 30.9 (Lone's Addition levee) to RM 11.0 (Black River pump station)
- Town of Skykomish Left Bank Levee RM 15.85 to RM 16.42

The levee containment systems are shown in Figures 2 through 7. The levees in these reaches are publicly owned or managed facilities. Information about the systems, including the length, bank, and number of levees included are summarized in Table 1. Collectively these levee systems provide flood protection to portions of the following incorporated areas: Carnation, North Bend, Auburn, Kent, Renton, Tukwila, Skykomish, and the unincorporated community of Fall City.

Table 1: King County Containment Levee Systems

Containment Levee System	Length of Levees (miles)	River Bank	Number of Publicly-Owned Levees
Lower Tolt River	4.27	Left and Right	11
Lower Raging River	2.85	Left and Right	4
South Fork Snoqualmie River	6.25	Left and Right	11
Lower Cedar River	2.38	Left and Right	2
Lower Green River	17.01	Left and Right	41
South Fork Skykomish River	0.57	Left	1

1.4 Approach/Methods

Determining where levee breaches may occur is an inexact science at best. Data on the geometry (height, width, side slopes, etc.) and physical properties (material composition, compaction, moisture content, etc.) is a necessary but not sufficient prerequisite for estimating breach potential. Additional information including the hydrologic and hydraulic conditions in the river, quantity of debris carried in the flow, potential for scour, groundwater conditions, and seepage potential are also required. The first step in this levee breach analysis is to identify whether adequate data are available for each of the leveed areas and if not, what types of data should be collected and analyzed.

WSE reviewed available data and information related to the levees listed above and prepared this report that includes the following:

- Compilation and synthesis of existing information about levee condition and potential for levee breaches along each studied levee system;

- Characterization of levee containment systems and adjacent land uses protected by each system; and
- Recommendations for additional data collection and analysis to address critical gaps in information that would be needed to improve the understanding of the susceptibility of these areas to levee breaches and the corresponding potential impacts.

The information reviewed by WSE included relevant studies and other data identified or provided by King County. WSE met with RFMS staff knowledgeable about each of the levee systems and described the focus and objectives of this study. Documents and data identified by those individuals were then collected, reviewed, and summarized for purposes of this analysis. For the summary of existing information and levee characterization, where multiple data sets were available, such as multiple iterations of hydraulic modeling, the most recent data set was considered to best reflect current conditions.

A second, and equally important, aspect of this study is understanding the extent to which the risks due to potential levee breaches has been characterized. Even well-constructed levees can be breached, for example by overtopping during a flood in excess of the design condition, and a breach could endanger people and property thought to be safeguarded by the levee. For each of the containment levees listed above the report includes a discussion of the known information about risks related to levee breaching. This provides a means for prioritizing future data collection and levee evaluation efforts.

1.5 General Overview of Levees

1.5.1 Functions

Levees can serve various functions including protecting areas from flooding (containment levee systems or ring levees), redirecting river hydraulic forces (training levees or spur levees), or providing for multiple benefits such as flood reduction, floodplain habitat restoration, and natural channel migration within setback levees. The current analysis focuses on containment levees and specifically levees providing flood protection to developed areas (homes and businesses) with significant potential for damages in the event of a levee breach. Containment levees act to isolate areas of the floodplain from the river channel, thereby reducing flood hazards in these areas under most conditions. Containment levees must tie in to high ground (either natural high ground or constructed features such as roadways or bridge fills) at the upstream and downstream ends of the levee to ensure flood waters cannot circumvent the levee. In most cases containment levees also include armoring (rock or emplaced wood) along the riverward side of the levee, preventing high velocity flows from eroding into the levee prism.

Most of the levees in this study, and many other levees in King County, were originally constructed to protect agricultural land or small communities in the floodplain from recurrent flooding. Construction techniques typically included dredging material from the river and piling it in berms along the banks and then sometimes covering the riverward side of these berms with rock riprap. Often the original levees were only constructed to an elevation high enough to contain flooding from smaller floods, for example a 5- to 10-year flood or less. Over time these levees may have been raised to provide higher levels of flood protection (sometimes up to the 100-year flood or greater) and extended to tie in to high ground and form containment levees.

1.5.2 Risks

As noted above, containment levees provide protection to floodplain areas by isolating these areas from flood waters that would otherwise overtop the riverbank and flow into the floodplain. This has the effect of reducing the flooded area behind the levee which increases flood water levels in the river, potentially increasing flood risks in the event of a levee breach. Increased flood water levels may also impact properties upriver that are not protected by the containment levee. Furthermore if not properly designed and constructed, river flows could end run the levee system upstream of the protected area, flooding areas landward of the levee. Finally, as mentioned previously, areas protected by levees are subject to rapid and potentially catastrophic flooding in the event of a levee breach. Thus levees must be appropriately designed, properly constructed and adequately maintained to reduce the potential for levee failures due to breaching.

As described above, most of the containment levees in this study were originally constructed as low agricultural levees which were turned in to containment levees as development occurred and land-uses in the floodplain changed. Some of these levees may have been improved; raised and/or strengthened to provide greater stability or to contain larger floods. However, in most cases there is little documentation on the original construction methods and materials, and limited detail on the improvements. As such the potential for levee breaches due to structural failure (seepage, piping, sloughing, etc.) is difficult to predict. In addition, land use in areas protected by these levees has often shifted from agriculture to residential or commercial, thus increasing the potential risk due to consequences of a levee breach.

King County WLRD inspects over 500 flood protection facilities (levees and revetments) on a two-year cycle, with some inspections occurring annually or more frequently, and after significant flood events. As inspections occur, and damages to facilities are identified, repair and maintenance actions are prioritized and implemented. However, it is often not apparent during a visual post-flood inspection if levees are structurally deficient due to geotechnical conditions (saturation, soil erosion, etc.) or if hydraulic conditions during a subsequent flood event could cause the levee to breach. Also, intermittent inspections may not identify changes in river bed levels, due to sediment aggradation or degradation, which can significantly alter the potential for levee breaching due to overtopping or scour. Because rivers are dynamic, and conditions can change rapidly, understanding the potential consequences of levee failures and having procedures in place to guide emergency actions is prudent for even the most robust levees to minimize consequences of a levee breach.

1.5.3 Levee Certification and FEMA Accreditation

Levee certification confirms that a levee meets Federal requirements to be recognized on FEMA flood insurance rate maps, such that levee design, construction, maintenance and operations are adequate to reduce the risk of flooding from a flood with a 1 percent chance of exceedance in any given year (commonly called a 100-year flood). Certification requires evidence that the levee meets all of the requirements of Section 65.10 of the Code of Federal Regulations (CFR) including criteria related to freeboard, closures, embankment protection, embankment and foundation stability, settlement, interior drainage, operational plans, and maintenance plans. Evidence for certification requires a signed statement by a licensed professional engineer or certification by a Federal agency responsible for levee design stating that the levee is designed and constructed“in accordance with sound engineering

practices to provide protection from the base flood"; this certification "does not constitute a warranty or guarantee of performance." (44 CFR 65.2)If a levee is certified, the Federal Emergency Management Agency (FEMA) may "accredit," or recognize, the levee on FEMA's FEMA accreditation requires containment of the 1-percent chance flood (100-year flood), plus sufficient freeboard (typically three feet). Flood Insurance Rate Maps (FIRMs) although FEMA levee accreditation does not warrant or guarantee facility performance. None of the levees included in this study are currently fully accredited by FEMA. The lower Cedar River Levee and a portion of the lower Green River right bank levee in Kent are provisionally accredited meaning that a community has committed to providing FEMA with all data necessary to certify the levee within a specific timeframe, and FEMA is therefore treating these levees as accredited for purposes of the FIRMs. The City of Renton is currently preparing data to certify the lower Cedar River levee and the City of Tukwila is working to certify the portion of the Green River levee on the left (west) bank of the Green River downstream of RM 16.7 (i.e. the Tukwila 205 levee); however, the majority of this levee has been determined to not be certifiable. The City of Kent has provided FEMA with levee certification reports for several levees along the right (east) bank of the Green River within the containment levee system. Levees currently being evaluated for certification are highlighted on Figures 5 and 6.

1.5.4 Rehabilitation and Inspection Program (PL 84-99)

The Rehabilitation and Inspection Program, promulgated through Public Law 84-99, is managed by the U.S. Army Corps of Engineers (USACE) and is intended to help local jurisdictions repair levees damaged by flood events by providing an 80:20 Federal to local cost share for local levees and 100 percent cost share for federal levees for levee repairs. The Rehabilitation and Inspection Program can implement flood damage repair projects on a levee regardless of whether the damage occurred as a result of a federally declared flood disaster or not. Participation in the program is voluntary on the part of the local jurisdiction. Levees are eligible for consideration in this program regardless of whether they meet Federal levee certification standards. Accreditation of a levee by FEMA can affect the 100-year floodplain shown on the FEMA Flood Insurance Rate Maps, but does not affect the ability of the local jurisdictions to seek federal assistance to repair levees through the USACE Rehabilitation and Inspection Program (RIP).

To qualify for the RIP, levees are initially inspected by the USACE and the local sponsor to determine whether they meet minimum structural and inspectability standards established by the USACE. If a levee meets these standards, it is considered "active" and is eligible for assistance if it is subsequently damaged and if the benefit-cost ratio of the needed repair is favorable. Levees which do not meet the minimum standards during the initial inspection are considered ineligible, and may become active if deficiencies are corrected. Correcting these deficiencies is the responsibility of the local jurisdiction.

Once enrolled in the RIP, levees are re-inspected annually for Federal levees and every other year for non-federal levees to identify potential damages and determine whether minimum standards are still being met. During these inspections, outstanding maintenance needs are noted and the status of each levee is conveyed by the USACE to the local jurisdiction via an inspection report. Levees with significant deficiencies may be put on probation, such as those along the South Fork Snoqualmie River, but remain active in the RIP and may be eligible for flood damage repair funding depending upon the next inspection. If the documented deficiencies have not been corrected by the next inspection, the levee is considered inactive and ineligible for assistance through the program. At any time, the local jurisdiction

may correct deficiencies, request re-inspection, and seek restoration of the flood protection facility to active status.

King County currently has approximately 35 miles of levees that could be considered for inclusion in the Rehabilitation and Inspection Program; however, due to many with levee deficiencies, only the Lower Green River levees and Lower Cedar federal levee are active in the program. While the County annually removes most of the non-native vegetation from its levees for access and inspection purposes, the alteration of native vegetation is limited to the removal of hazardous trees and minor damage inherent in the control of invasive species. An Interim Green River System-wide Improvement Framework was accepted by the USACE in 2017, thus all Lower Green River levees are currently eligible.

Table 2 below summarizes the status of levee segments within the six containment levee systems with regard to the USACE Rehabilitation and Inspection Program.

Table 2: PL 84-99 Status of levee segments within King County Containment Levee Systems as of September 2018

USACE Levee Segment Name	Segment Length (miles)	Ratings [b]	Status
Cedar River			
Cedar River Section 205 Left Bank Levee	1.23	M	Eligible[a]
Cedar River Section 205 Right Bank Levee	1.15	M	Eligible[a]
Green River			
Tukwila 205 (Federal)	4.1786	M	Eligible[a]
Desimone-Briscoe School	2.2024	M	Eligible[a]
Boeing	0.8453	M	Eligible[a]
Lower Russell Road – Holiday Kennel	0.9427	U	Eligible[a]
Upper Russell Road – Somes-Dolan	1.0287	M	Eligible[a]
Kent Shops – Narita	0.9325	M	Eligible[a]
Meyers Golf	0.76	M	Eligible[a]
Signature Point (County Road No. 8)	1.0795	M	Eligible[a]
Horseshoe Bend (Federal)	1.8452	M	Eligible[a]
Reddington	0.9043	A	Eligible
Galli	0.2315	M	Eligible[a]
Dykstra	1.0514	M	Eligible[a]

Eligible [a] = Eligibility status of levee segments in the USACE PL 84-99 program. The Lower Russell levee is eligible due to the Green River SWIF, even though its rating is unacceptable.

Ratings [b] = Reflects latest USACE inspection ratings. A= Acceptable, M= Minimally acceptable, U= unacceptable

1.5.5 King County Flood Protection Facility Inspections

The containment levee systems included in this analysis are comprised of one or more individual levee segments that are included in the County’s flood protection river facility inventory (RFI). Individual

levees in the inventory are generally named for current or past landowners or the river mile location of the facility. King County RFMS regularly inspects these levees as well as all other flood protection facilities in the inventory. Those inspections are completed on a two-year cycle, and in some instances annually, such as those levees in the PL84-99 program, and up to 4 times per year for Federal Levees, or in cases of known existing but non-emergency flood damage. Facility inspections are intended to identify issues with the levees such as slumps, cracks, fissures, seeps, boils, or other potential failure mechanisms. Problems identified during the regular levee inspections are recommended for remedial action as appropriate. Significant improvements are implemented through a Capital Improvement Program (CIP).

In addition to regular facility inspections, WLRD staff inspect levees during and immediately after major flood events as part of the King County Flood Warning Center (FWC) operations. As part of the FWC, flood patrol teams are dispatched to a river when Phase 3 flow conditions or above are expected to occur (see FWC operation description in following section). Flood patrols inspect facilities and document their observations, specifically looking for concerns regarding the facility's integrity or presence of flood damages. Flood patrol objectives are to: inspect King County's flood and erosion control facilities during high flow events to provide early detection of potentially hazardous situations, respond to citizen inquiries concerning potential flood and erosion hazards, provide the FWC with information on field conditions, monitor emergency repair sites until the Basin Technical Lead, Emergency Project Manager or King County Roads crew lead arrives, and inspect flood control facilities after major earthquakes.

1.5.6 Flood Warning Program

King County operates a flood warning program to warn residents and agencies of impending flooding on major rivers, so they can take action and prepare themselves before serious flooding occurs. In most locations, the flood warning system provides at least 2 hours lead time before floodwaters reach damaging levels. The County works closely with the National Weather Service to obtain forecast information. Close coordination also occurs with the Office of Emergency Management, Roads, and other County agencies to obtain up-to-date information about problems sites, road closures, evacuations and other emergency services. Coordination also occurs with the USACE and Seattle Public Utilities regarding dam operations.

When high water conditions are imminent, the County activates its FWC. County staff at the FWC monitor gages on a 24-hour basis, so that actions can be taken depending on river conditions. Personnel at the FWC are also available to answer questions and help interpret gage readings during a flood event. Operation of the FWC is based on a four-phase warning system. The phases indicate the severity of flooding and guide the County's response. Flood phases are issued independently for six major rivers in the County. The thresholds for each phase are based on river gages which measure the flow and/or stage (depth) of the rivers in various locations. Phase 1 is an internal alert to King County staff. Phase 2 indicates minor flooding in some areas. Phase 3 indicates moderate flooding in some areas. Phase 4 indicates major flooding.

At Phase 1, County personnel are put on alert and preparations are made to open the Flood Warning Center. When a Phase 2 threshold is reached, the FWC is opened. Staff at the FWC monitor river gages and flood conditions around the clock and are available to respond to calls from the public. When a Phase 3 threshold is reached, flood patrols are dispatched to observe flood conditions at King County

facilities. FWC staff coordinate with affected local jurisdictions when the flood phase is 2 or higher. At Phase 2, 3 and 4 automated flood alerts are sent to anyone who has registered.

Flood phases for the rivers included in the levee breach analysis are shown in Table 3.

Table 3: Flood Warning Phases for Rivers with Containment Levee Systems

Flood Phase	Tolt River (Near Carnation)	Snoqualmie (Sum of Forks)	Cedar River (Near Landsburg)	Green River (Near Auburn)	S.F. Skykomish (In Skykomish)
1	2,500 cfs	6,000 cfs	1,800 cfs	5,000 cfs	6,000 cfs
2	3,500 cfs	12,000 cfs	2,800 cfs	7,000 cfs	10,000 cfs
3	5,000 cfs	20,000 cfs	4,200 cfs	9,000 cfs	18,000 cfs
4	8,500 cfs	38,000 cfs	5,000 cfs	12,000 cfs	27,000 cfs

1.5.7 Effects of Dams

Three of the levee systems included in this analysis are located along rivers that have dams upstream of the containment levee system: the Tolt River, the Cedar River, and the Green River. Howard A. Hanson Dam on the Green River provides significant flood control capabilities and is operated by the USACE in a manner to restrict downstream flows at Auburn to no greater than 12,000 cfs for events up to and including a 140-year flood. At this flow rate water levels along the Green River containment levee have been found to provide at least 2 feet of freeboard to the top of the levees. Masonry Dam on the Cedar River is operated by Seattle Public Utilities (SPU). Masonry Dam is operated primarily to provide water supply storage but it also provides a limited amount of flood control storage. Historical flows on the Cedar River reflect operations at Masonry Dam and the downstream containment levee in the lower Cedar River have been designed to accommodate flows up to and including the regulated condition 100-year flow. SPU also operates Tolt Dam on the South Fork Tolt River. The Tolt Dam does not provide any dedicated flood control storage but the reservoir does provide incidental flood storage, meaning that at times the reservoir is drawn down for water supply operations and it captures some portion of floods. Historical flow data for the Tolt River from 1964 onward includes the effects of incidental flood storage at the South Fork Tolt Reservoir. In a recent study completed for the King County Office of Emergency Management and the FCD, the Emergency Action Plans and readiness of dam owners to react to structural failures at these and other dams in King County were reviewed (Tetra Tech, 2017).

2 Lower Tolt River levees from RM 2.2 (Holberg levee) to the confluence with the Snoqualmie River

2.1 Available Information

2.1.1 Survey/topography

Available topographic data for the Lower Tolt River levees includes LiDAR or aerial photogrammetric mapping for various dates including 2003, 2004, 2005, 2009, 2010, 2011, 2013, and 2014. These data provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach, or for measurement and characterization of the levee itself (height, top width, side slope, etc.). River channel cross sections are also available for the containment levee reach for various dates including the most recent comprehensive channel surveys in 2011. Bathymetric survey of the river channel from RM 0.0 to RM 2.6 was also conducted in 2017.

In addition to the channel cross sections described above, King County RFMS regularly monitors sediment accumulations within the Tolt River levee reach by resurveying approximately 30 cross sections every two to three years. Many of these cross sections include the riverward side and top of the levee but they typically do not include the landward side of the levee.

2.1.2 Geotechnical and Geomorphic Assessments

As part of the research conducted for this report, no geotechnical investigations or soil boring reports pertinent to levee prisms have been identified for the lower Tolt River levees.

The County recently completed a Channel Migration Zone (CMZ) and Mapping Study for the Tolt River (King County 2017). That study includes information about the geomorphic context of the leveed reach including the fact that it is on an alluvial fan where sediment deposition naturally occurs. Ongoing sedimentation in the levee reach is being monitored by King County RFMS. As part of the 2017 CMZ, historical information about channel locations and conditions of the existing flood protection facilities was summarized. Also, a 2018 independent review of the CMZ mapping was completed for the area near the Holberg Levee (Booth 2018). Currently, a feasibility study of the Holberg Levee area is underway and will include specific geotechnical and geomorphic analyses to develop necessary repairs to the Holberg Levee and the adjoining Frew Upper Levee.

2.1.3 Hydrogeologic/Seepage analysis

As part of the research conducted for this report, no hydrogeologic or seepage studies have been identified for the lower Tolt River levees.

2.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS operates several streamflow gaging stations in the Tolt River basin. The gage closest to the leveed reach can be used to provide hydrologic data needed for evaluation of the levee system. Relevant information related to this gage is summarized in Table 4.

Table 4: USGS Streamflow Gages on the Tolt River Mainstem, North, and South Forks.

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)	Elevation (NGVD 29)	Period of Record
Tolt River near Carnation	12148500	81.4	348	1929, 1931 and 1938 to 2010

As described previously SPU operates a water supply dam and reservoir on the South Fork Tolt River. Flows in the South Fork and downstream in the mainstem Tolt River are affected by operations at the dam. During the summer season water held in storage at the dam is released as needed to supply SPU customers and to augment instream flows. When the reservoir is drawn down it provides incidental flood control storage that can capture runoff from flood events and act to reduce downstream flows. If high flows continue for a sustained period of time, the incidental storage at the reservoir fills and the reservoir goes into spill, at which point outflow from the reservoir is essentially equal to inflow and downstream flood flows are thereafter unaffected by the dam.

Significant hydrologic analysis for the Tolt River basin was completed as part the Draft Tolt River Capital Investment Strategy (*CIS*) (King County 2017a). This work included flood frequency analysis for the USGS gage as summarized in Table 5. Also shown in Table 5 are the computed flood frequency quantiles used in the most recent FEMA Flood Insurance Study for the Tolt River (FEMA 2017). Differences between these two are the result of different periods of record and different methodologies used in the analysis.

Flow duration and ramping rate analyses have not previously been completed for the containment levee reach. However, data available from the CIS would make this a fairly routine task. An analysis relating flood flows on the lower Tolt River to coincident flows on the Snoqualmie River was completed in 2017 as part of the County's Lower Frew Levee Setback feasibility project (WSE 2017). That analysis is informative for understanding the effect of Snoqualmie River flows on water levels in the lower Tolt River.

Table 5: Annual Peak Discharge Flood Frequency Estimates for Regulated Discharges at USGS Gage 12148500 Tolt River near Carnation.

Percent Chance Exceedance	Return Period (years)	Discharges Computed for CIS (cfs)	FEMA Published Discharges (cfs)
0.2	500	21,000	23,800
0.5	200	18,400	
1.0	100	16,400	18,800
2.0	50	14,600	16,700
5.0	20	12,100	
10.0	10	10,300	11,900
20.0	5	8,400	
50.0	2	5,700	

2.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling was completed in 1995 for the most recent FEMA floodplain study of the Tolt River (FEMA 2017). The FEMA modeling used a steady state HEC-2 one-dimensional (1D) hydraulic model. Other data used in the FEMA study included channel cross section surveys taken at the time of the study and the estimated flow quantiles shown in Table 5. The FEMA analysis modeled conditions with and without the containment levees, as these are not accredited by FEMA, and mapped the composite (highest water level at all locations) among these conditions.

A RiverFlow2D hydraulic model was created for the lower six miles of the Tolt River as part of the CIS (King County, 2017a). The model used topographic and bathymetric data from 2011 LiDAR, and channel surveys from 2011 to define the river channel, existing levees, and floodplain. The 2D model provides a robust tool for evaluating existing conditions along the river and within the adjacent floodplain. The model was used in the CIS to estimate the level of containment provided by each levee segment (i.e. the discharge and recurrence interval at which water just begins to overtop each segment). The CIS includes figures summarizing this information. The CIS analysis assumed that the Snoqualmie River remained constant at a two-year flood throughout the Tolt River hydrograph, a simplifying assumption that will be addressed in an upcoming detailed levee level of service analysis which the County plans to begin in the winter of 2018. As part of this Tolt River Level of Service Study, the RiverFlow2D hydraulic model will be updated to include the most recent LiDAR and channel bathymetry data.

The RiverFlow2D model was also used in the CIS to identify locations along the levee system that are subject to high velocities on the top and backside of the levee during levee overtopping. These locations would be at significantly greater risk of an overtopping breach failure than locations that do not overtop or experience only minimal overtopping flows and velocities. Levee breach modeling has not been conducted but the 2D model would provide a useful tool for that work.

2.1.6 Inundation and Breach Progression Mapping

Breach inundation modeling and mapping and breach progression analysis have not been conducted for the Lower Tolt River levees although the 2D model developed for the CIS could be used for this purpose.

Shannon and Wilson 1993 analysis showed flow paths related to a potential failure of the Holberg levee; however, the 1994 repair of Holberg intended to address this condition.

2.1.7 Recent CIP Projects

Significant capital improvements have been implemented by King County in the Tolt River levee reach. Most notable is the Lower Tolt River Floodplain Restoration Project near Tolt MacDonald Park. This setback levee, built in 2009, is set back from the right (north) bank of the river between the mouth and SR203, approximately a one-half mile reach. The existing levee was set back within the park helping return the river corridor to its natural floodplain character and improving fish habitat. Other levee repair work by King County along the Tolt River containment levee system is summarized in Table 6.

Table 6: King County River Facility Inventory Repair History for Lower Tolt River Levee System

Facility Name	Facility Type	River Bank	River Mile[1] Downstream	River Mile[1] Upstream	Repairs listed by year		
Lower Tolt River RB	Levee	Right	0.00	0.60			
Tolt Campground	Levee	Right	0.00	0.00			
Tolt River Levee LB	Levee	Left	0.08	0.56	1976	1981	1991
Tolt River Levee RB	Levee	Right	0.46	0.57	1976	1991	
Frew	Levee	Right	0.57	1.13	1980		
Hwy to RR Bridge	Levee	Left	0.57	1.12			
Pond Berm	Levee	Right	0.63	0.68			
Remlinger	Levee	Left	1.13	1.43	1977	1998	2018
Frew Upper	Levee	Right	1.14	1.66			
Swiftwater Berm	Levee	Right	1.20	1.33			
Girl Scout Camp	Levee	Left	1.43	1.99	1976	2018	

Note: [1]River mile identifiers refer to upstream and downstream ends of the levee segment, not necessarily the location of the repair.

The 2009 repair of the Hwy to RR Bridge facility was an emergency repair of approximately 500 linear feet of levee that breached during the January 2009 flood event between RM 0.85 and RM 0.95.

As part of the FCD's six-year CIP plan, RFMS staff will conduct feasibility assessments and develop designs to improve the Lower Tolt River levees. As noted above, RFMS is currently conducting a feasibility study of the Holberg levee, a segment of the right (north) bank levee near the upstream limit of the containment levee reach.

2.1.8 PL84-99 Status

Currently there are no sections of the lower Tolt River Levee System included in the PL 84-99 program because they do not meet USACE requirements for inclusion in the program.

2.2 Site Visit/Inspections/Pertinent Observations

RFMS staff have observation-based knowledge of the Lower Tolt River levees as a result of regular visual inspections at low water conditions as well as during floods. General observations based on the most recent annual inspections conducted by RFMS staff on July 31, 2018 regarding the Tolt River levees are summarized below:

- *Lower Tolt River RB*: Could not observe riverward face of levee due to heavy vegetation. Trail on top of levee is in good shape and no cracks or potholes were observed.
- *Tolt River Levee RB*: Sparse face rock observed under SR 203 Bridge. Difficult to see face rock due to vegetation and sediment.
- *Frew*: Generally good condition. However, two damage locations were observed where the river impinges on the levee. Both damage locations are approximately 150 feet in length and both are

scheduled for repair in 2018. Observed mostly from same bank. No access to facility in places due to heavy vegetation.

- *Swiftwater Berm*: Earthen berm. No riprap observed on riverward face. No settlement or erosion was observed.
- *Frew Upper*: No damages observed along facility. Downstream of RM 1.4, sporadic rip rap observed on face and sediment and vegetation prevent observation. Upstream of RM 1.4, face rock is 1-2' diameter and is continuous. Upstream of City of Carnation boundary, the riverward slope is covered in blackberry and partially covered by gravel bar deposits.
- *Holberg*: Flow – Downstream 500 feet of levee is covered with sediment; cannot see toe because gravel bar has grown up on the face of the levee. The 1994 repair site is intact with no damages noted. Toe scour and displacement of toe rock was observed immediately upstream of 1994 repair site where river directly impinges on levee. Inspection not conducted upstream of where river impinges on levee due to lack of easement.
- *Tolt River Levee LB*: Inspection conducted from opposite bank in downstream direction. Upstream 300 feet is over steepened and undercut and some face rock displaced into river channel. At approximately RM 0.3 all rock is missing and bank is undercut. No evidence of toe rock or rock on face. No apparent facility at downstream end near confluence.
- *Highway to RR Bridge*: Levee was breached and heavily damaged during the 2009 flood. An emergency repair was completed immediately after the flood event. Although no other damage locations were observed during the 2018 inspection, this levee remains one of the most vulnerable levees in the system.
- *Remlinger*: Generally good condition. However, in the vicinity of RM 1.2, the riverward bank of the facility is over steepened (1:1 to 1.25:1 slope) and a deep side channel has developed along toe. There is the concern that if the main river were to shift into the side channel, this could cause further erosion of the facility. This location at RM 1.2 was flagged as a location to be monitored during the 2018/2019 flood season.
- *Girl Scout Camp*: Generally good condition except at one location where the river impinges directly on the levee, resulting in toe scour and undermining of toe rock. This site will be repaired in 2018. Additionally, upper bank slumps observed at two locations immediately downstream of the proposed 2018 repair location.

2.3 Data Gaps

Based on review of available studies, and reports, and discussions with RFMS staff, the following data gaps have been identified

- Levee composition and construction data
- Geotechnical (structural stability) assessment
- Groundwater and seepage assessment
- Breach modeling for overtopping or seepage failures
- Breach flood progression mapping

In addition to the above data gaps it is recommended that the County reevaluate the need for each levee segment as in some areas it may be possible to setback or remove existing levees to improve both

flood protection and habitat. For example, one of the most vulnerable levee segments in the containment system is the Left Bank Highway to RR Bridge levee. The County has purchased all but two parcels immediately landward of the levee. If the remaining two parcels can be acquired and the structures removed, the County could evaluate constructing a replacement levee setback to NE 32nd Street.

2.4 Levee and Channel Characterization (Physical Properties)

The channel surveys and topographic data (LiDAR) available for the study reach allow the levee geometric properties to be characterized (height, top width, side slopes); however this work has not yet been done. The composition and quality of construction of the levee is generally unknown and thus this information cannot be used to predict specific locations particularly susceptible to breaching. However it is believed that the lower Tolt River levees were originally constructed between 1939 and 1941 to protect rural agricultural lands from frequent flooding and they were generally fairly low and structural stability was likely not a major consideration in the design. At that time, techniques used to construct these levees generally consisted of dredging material from the river channel, placing this material into berms on the river banks with minimal compaction and then facing the riverward side of the berms with rock riprap, sometimes without any toe rock. Since then portions of these agricultural levees may have been raised and widened but the lower Tolt River levees have not been comprehensively rebuilt to today's engineering standards. As such the potential for levee breaches due to seepage, boils, sloughing, or overtopping is considerably higher than for engineered levees. One section of levee, the Holberg levee along the right bank between approximately RM 1.7 and RM 1.8, was reconstructed in 1994 to meet current engineering standards and is high enough to contain the 100-year flood; the potential for failure of this facility is therefore lower than other levees on the Tolt River.

2.5 Land-Use

Land-use landward of the lower Tolt River levees includes forest, wetlands, roads, residential and commercial structures, a school, ball fields, a park, and agricultural (including structures and farmland). The areas nearest to the levees are generally forested (including forested wetlands) or agricultural fields with a few farm structures. Remlinger Farms, a large agricultural business, is situated near the left bank levee at approximately RM 1.1 – 1.4. Another agricultural property is located downstream of SR-203 near the left bank levee from about RM 0.3 to 0.5.

There are several residential structures near the levee on the right bank (north side) of the river at approximately RM 1.8 and also near RM 2.0. Other residential structures are located near the left bank levee between RM 0.5 and RM 1.1.

2.6 Hazards

Hazards associated with the lower Tolt River levees were characterized in the Lower Tolt River Flood Hazard and Risk Assessment (WSE, 2017). Note however that that analysis did not consider flood hazards resulting from potential levee breaches. Hazards within the containment levee reach were summarized in the Flood Hazard and Risk Assessment as follows:

- ***Snoqualmie River to SR-203 (RM 0.0 to 0.6) -*** The left bank levee in this reach is susceptible to failure by overtopping and/or lateral erosion; therefore, this area is considered a high hazard.

The levee that once existed along the right bank of the river was removed and/or breached as part of a floodplain restoration project in 2009. A setback levee was constructed as part of that restoration project. Under the current river alignment, it is assumed that the setback levee is not at risk of failure.

- ***SR-203 Bridge to Trail Bridge (RM 0.6 to 1.1) -*** Both the right and left bank levees in this reach are susceptible to failure by overtopping and/or lateral erosion, and levee failure hazard is high on both sides of the river.
- ***Trail Bridge (RM 1.1) to RM 1.8 -*** Both the right and left bank levees in this reach are susceptible to failure by overtopping and/or lateral erosion. Within this reach, the highest potential for overtopping levee failure is just upstream from the trail bridge along the Frew Upper Levee. At that location the levee is relatively low and will overtop at approximately a 25-year flood. The upstream portion of this reach on the right bank includes the Holberg levee, a large facility that would not be overtopped by the 100-year flood. The probability of a levee failure at the Holberg levee is therefore lower than downstream at the Frew Upper Levee. The Stillwater berm, set back from the right bank in this reach generally contains the 100-year flood; however, it could be overtopped by larger floods. The Remlinger levee along the left bank will overtop at roughly the 25-year event and thus has an increased potential to breach at flows above that level. The Left Bank Trail Bridge levee is higher than the 100-year flood and is flanked landward by a wide area of high ground, but it may be susceptible to channel erosion. The Girl Scout Camp levee on the left bank is generally higher than the 100-year flood but is susceptible to failure by lateral erosion and could be overtopped by a larger flood.
- ***RM 1.8 to 2.4 -*** The upstream half of the Holberg facility is a rock revetment, not an elevated levee. The revetment does not meet current design standards and erosion damage to the revetment could allow the river to migrate and increase flood hazards downstream.

2.7 Risks

The Lower Tolt River Flood Hazard and Risk Assessment identified potential structures at risk due to levee breaches (WSE, 2017). A total of 50 structures are potentially at risk including 20 residences, 7 commercial structures, and 23 outbuildings. Flood risks due to levee failures within the reaches described above were characterized in the 2017 report as follows:

- ***Snoqualmie River to SR-203 (RM 0.0 to 0.6) -*** The left bank levee (Tolt River Levee LB) is susceptible to failure by overtopping and/or lateral erosion, although at this time the river is not impinging on the levee; Infrastructure that would be impacted by a failure includes NE Tolt Hill Road and the WDFW boat launch as well as several private structures. The right bank setback levee (Tolt River Levee RB) is not at risk of failure and therefore infrastructure and buildings landward of the levee are not at risk.
- ***SR-203 Bridge to Trail Bridge (RM 0.6 to 1.1) -*** Both the right and left bank levees in this reach are susceptible to failure by overtopping and/or lateral erosion. The river is impinging on sections of both levees which increases the possibility of failure by lateral erosion. If the left bank levee (Highway to Trail Bridge) fails two residential structures could be damaged (the

County has purchased and demolished all but these two) and NE 32nd Street could be damaged and closed for an extended period if the damage is severe. If the right bank levee (Lower Frew) fails SR-203 could be damaged, which could impact the mobility of emergency responders and access to the City of Carnation. .

- ***Trail Bridge (RM 1.1) to RM 1.8 -*** Both the right and left bank levees in this reach are susceptible to failure by overtopping and/or lateral erosion. The river is generally flowing parallel to and not impinging on the left bank Remlinger Levee. Most structures landward of the levee are on high ground and therefore risk is low. The downstream portion of the Remlinger levee is lower and the most likely to be overtopped during a major flood. There are no significant structures landward of this segment of levee except for a miniature railroad amusement ride. Upstream from the Remlinger Levee is the Girl Scout Camp levee. The river is impinging directly into the levee near its mid-point. If the levee fails a field used by the camp for parking cars along with a simple picnic shelter or two could be damaged.

  Along the right bank, the Frew Upper Levee is relatively low and will overtop during large floods. It is also being impinged on by the river. There are no structures immediately landward of the levee, only undeveloped floodplain forest. There is a development approximately 250 feet north of the levee, but it is on an elevated terrace and therefore risks are low. Upstream from the Frew Upper Levee is the Holberg Levee. The downstream half of this structure provides 100-year flood protection. Several homes occupy low ground landward of the levee. If this levee ever breached, these homes would be at significant risk.

- ***RM 1.8 to 2.4 -*** The upstream half of the Holberg facility is a rock revetment that prevents lateral erosion. If it fails and the river migrates it could reach and damage up to five residential structures located near the top of the bank.

3 Lower Raging River levees from RM 1.5 (328th Way SE) to the confluence with the Snoqualmie River

3.1 Available Information

3.1.1 Survey/topography

Available topographic data for the Lower Raging River levees includes LiDAR for various dates including 2011 and 2014. These data would provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach, or for measurement and characterization of the levee (height, top width, side slope, etc.).

River channel cross sections for the leveed reach were surveyed in 1993 for the Raging River Flood Insurance Study (FEMA, 2017). More recent bathymetric survey of the Raging River near its confluence with the Snoqualmie River are available for 2004, 2011, and 2015. King County collected channel survey in 2015 for the lower Raging River (RM 0.03 – RM 1.46). These surveys and LiDAR data would support the development of a terrain surface as needed for detailed hydraulic modeling.

3.1.2 Geotechnical and Geomorphic Assessments

As part of the research conducted for this report, no geotechnical investigations or soil boring reports pertinent to levee prisms have been identified for the Raging River levees.

Geology and geomorphology of the Raging River was documented by Shannon and Wilson (1991). King County is currently preparing an updated Channel Migration Zone (CMZ) and Mapping Study for the Raging River. That study will include information about the geomorphic context of the leveed reach including the fact that ongoing sedimentation in the levee reach is being monitored. As part of the CMZ study, historical information about channel locations and conditions of the existing flood protection facilities will also be summarized.

3.1.3 Hydrogeologic/Seepage analysis

As part of the research conducted for this report, no hydrogeologic or seepage studies have been found for the Raging River levees.

3.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS operates a streamflow gaging station on the Raging River near Fall City (USGS 12145500). The gage is located near SE 68th Street, approximately 1.3 miles upstream of the containment levee reach. Relevant information for this gage is summarized in Table 7. Flood frequency analysis for the Raging River was completed by Harper Houf Righellis for the 1993 Flood Insurance Study (FEMA, 2017). Results of that analysis for the gage site and for the leveed reach are summarized in Table 8. Neither flow duration nor ramping rate analyses have been completed for the leveed reach, but the USGS data for gage 12145500 could be used to complete these analyses fairly easily.

Table 7: USGS Streamflow Gages on the South Fork Snoqualmie River Mainstem.

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)	Elevation (NGVD 29)	Period of Record
Raging River near Fall City, WA	12145500	30.6	250.00	1946 to Present

Table 8: Annual Peak Discharge Flood Frequency Estimates for Raging River near Fall City.

Percent Chance Exceedance	Return Period (years)	FEMA Published Discharges (cfs)	
		At Gage 12145500	At Mouth (leveed Reach)
0.2	500	9,840	10,465
1.0	100	6,970	7,413
2.0	50	5,910	6,286
10.0	10	3,790	4,031

3.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling for the Raging River was completed in 1993 for the most recent FEMA floodplain mapping study of this river. The FEMA modeling and mapping considered conditions with and without the levees in place but did not evaluate conditions during a realistic levee breach scenario. The hydraulic modeling is outdated and would not be expected to match current conditions given sedimentation and other changes along the leveed reach. A version of this model was modified to include surveyed cross-sections from 2015 to assess the hydraulic impacts of gravel removal in the lower Raging River.

3.1.6 Inundation and Breach Progression Mapping

Hydraulic modeling for the 1993 FEMA FIS was done using a steady state hydraulic model, meaning that time varying conditions were not considered. With a steady state model scenarios such as breach development or progression of a flood wave across the floodplain could not be evaluated. A different type of hydraulic modeling would be needed to evaluate levee breaches and progression of floodplain inundation in the event of a breach. The available topographic data would support the development of a two dimensional (2D) hydraulic model but additional channel bathymetric surveys might be required.

3.1.7 Recent CIP Projects

Levee repair work by King County along the Raging River containment levee system from the County RFI is summarized in Table 9.

Table 9: King County River Facility Inventory Repair History for lower Raging River Levees

Facility Name	Facility Type	River Bank	River Mile[1] Downstream	River Mile[1] Upstream	Repairs listed by year		
Mouth to Bridge LB	Levee	Left	0.02	0.49	1987	2012	
Mouth to Bridge RB	Levee	Right	0.05	0.52	1984	1987	2018
Bridge to Bridge LB	Levee	Left	0.50	1.46	1987		
Bridge to Bridge RB	Levee	Right	0.51	1.46	1983	1987	

Note: [1]River mile identifiers refer to upstream and downstream ends of the levee segment, not necessarily the location of the repair.

3.1.8 PL84-99 Status

The Raging River levees are not currently "Active" in the PL 84-99 program because they do not meet USACE requirements for inclusion in the program.

3.2 Site Visit/Inspections/Pertinent Observations

RFMS staff have observation-based knowledge of the Raging River levees as a result of regular visual inspections at low water conditions as well as during floods. RFMS and WSE staff conducted a one day field reconnaissance of the Raging River and South Fork Snoqualmie River levees on July 5, 2018. No significant issues were identified with the levees during the field reconnaissance but it was apparent that the levee along the left bank of the river, particularly from Preston-Fall City Road downstream, was important for the protection of residential properties to the north of the river. The levee in this reach appeared to be relatively narrow. Some pertinent observations along the levee system by RFMS staff are as follows:

- RM 0.0 RB – small slope failure with fine granular material
- RM 0.4 RB – slight erosion 1 – 2 feet above toe
- RM 0.4 to 0.5 RB –slope failure due to oversteepened face
- RM 1.3 RB – bank failure, possible due to tree fall or erosion, no toe rock

3.3 Data Gaps

Based on review of available studies, and reports, and discussions with RFMS staff, the following data gaps have been identified

- Evaluation of levee materials and construction (geotechnical evaluation)
- Hydraulic evaluation to estimate overtopping frequency and duration characteristics
- Breach modeling for overtopping or seepage failures
- Breach flood progression mapping

3.4 Levee and Channel Characterization (Physical Properties)

The composition and quality of construction of the Raging River levees is generally unknown and thus this information cannot be used to identify specific locations that might be particularly susceptible to breaching. It is believed that the Raging River levees were originally constructed between 1939 and 1941 to protect rural residential and agricultural lands from frequent flooding. The Raging River levees were raised and reinforced in the 1960s (S&W, 1991). Construction techniques at that time generally consisted of dredging material from the river channel, placing this material into berms on the river banks with minimal compaction and then facing the riverward side of the berms with rock riprap, sometimes without any toe rock. Although there have been various levee maintenance and repair projects along the Raging River, the levees have not been comprehensively rebuilt to today's engineering standards. As such the potential for levee breaches due to seepage, boils, sloughing, or overtopping is higher than for engineered levees.

3.5 Land-Use

The leveed reach of the Raging River runs through the unincorporated community of Fall City. Land use along the left (north) side of the river is primarily residential, including low to moderate density single family residential properties and a mobile home park, plus several commercial properties including a King County Roads maintenance facility, restaurants, and other businesses. Land-use along the right bank is primarily rural residential upstream of Preston-Fall City Road and a golf course and associated structures downstream of that road.

3.6 Hazards

Identifying locations of potential levee breaches along the lower Raging River is problematic because of the lack of necessary data. The most recent hydraulic modeling available for this reach was performed in 1993 and since that time there have been significant changes to the river channel due to human activity (for example bridge construction) and sediment deposition. Without accurate hydraulic modeling it is not possible to characterize the likelihood of levee overtopping and the potential for overtopping induced breaches. It is also not possible to evaluate the potential for toe scour which might lead to a levee breach. Furthermore, because there is little information available on the materials and construction techniques used in building the levees it is not possible to predict locations for potential seepage or sloughing induced breaches. Because the original construction of the Raging River levees was not based on today’s engineering standards, and the levees have not been comprehensively reconstructed, it is assumed that the risk of levee breaches in this system is higher than in other, more recently constructed or repaired systems.

3.7 Risks

Overtopping or seepage related breaching of the lower Raging River levees could result in flooding of numerous structures, especially landward of the left (north) bank of the river. Although breach progression modeling and mapping has not been conducted the general topography of the area indicates that a wide swath of land could be inundated in the event of a levee breach. To the south of the river the risk is lower for several reasons including: 1) the levee appears to be broader and thus more structurally significant along this bank, 2) land-use on the right bank is generally less dense, and 3) areas along the right bank downstream of Preston Fall City Road are subject to somewhat regular flooding due to the Snoqualmie River and as such the flood hazard is somewhat common.

4 South Fork Snoqualmie River levees from RM 5.4 (McConky and Holstein Ext. Levees) to RM 2.1 (Snoqualmie Trail Crossing)

4.1 Available Information

4.1.1 Survey/topography

Available topographic data for the South Fork Snoqualmie levees includes LiDAR for various dates including 2003, 2009, 2010, 2013, and 2016. These data provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach, or for measurement and characterization of the levee itself (height, top width, side slope, etc.). River channel cross sections are also available periodically for the levee reach from 1992/1995 through 2014.

4.1.2 Geotechnical and Geomorphic Assessments

Limited geotechnical analysis was completed as part of the South Fork Snoqualmie Levee Characterization project (Levee Characterization project) (Tetra Tech, 2014). Key findings are summarized in that report, including levee conditions, levee stability, and levee problem evaluation. Subsurface soil and groundwater conditions were evaluated by reviewing previous subsurface explorations and by drilling six supplemental borings. Levee and subsurface material is highly permeable and seepage below and through the levees is widespread.

Field evaluation determined a number of priority problems areas of the containment levee including areas of observed piping and seepage, erosion and slope instability, depressions and toe erosion, areas of levee penetrations (pipe or culverts), and locations where the levee is located on the outside of a river bend and more prone to scour. Potential problem areas are tabulated in the report and rated on relative potential for levee failure (Tetra Tech, 2014). Analysis of seepage and slope stability were completed based on the seven highest rated problem areas, or “critical” levee sections. Three sections were analyzed for scour and stability of the scoured slope. The Draft King County South Fork Snoqualmie River Corridor Plan Technical Evaluation Report (Tetra Tech, 2015) presents potential tools and planning approaches to address hazards identified in the 2014 characterization report.

Geology and geomorphology of the area is documented by Bethel (2004) and King County (2011). The leveed reach is located on an alluvial fan and experiences sediment deposition. The levee, along with five road and trail crossings within the reach currently constrain channel movement.

4.1.3 Hydrogeologic/Seepage analysis

Geotechnical and Hydrogeological analysis was completed as part of the Levee Characterization project (Tetra Tech 2014). Geotechnical analysis determined adequate factors of safety against piping failure for the levee system based on analysis at critical sections.

4.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS operates several streamflow gaging stations on the South Fork Snoqualmie River including the South Fork Snoqualmie River at North Bend (USGS gage 12143600). Relevant information for this gage is summarized in Table 10. The South Fork Snoqualmie River at North bend gage is located within the leveed reach and peak flows may be affected by levee overtopping upstream.

Table 10: USGS Streamflow Gage on the South Fork Snoqualmie River Mainstem.

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)	Elevation (NGVD 29)	Period of Record
South Fork Snoqualmie River at North Bend	12144000	81.7	423.01	1907 to Present[1]

Notes: [1]Actual period of record is July to September 1962, March 1963 to September 1965, and October 1983 to present

Hydrologic analysis for the South Fork Snoqualmie River was completed as part the Levee Characterization project (Tetra Tech, 2014). Flood frequency estimates from that study are summarized in Table 11. Also shown in Table 11 are the computed flood frequency discharges used in the most recent FEMA Flood Insurance Study for the South Fork Snoqualmie River (FEMA, 2017). Differences between these two are the result of different periods of record and different methodologies used in the analysis. Note that at lower frequency events the flow quantile estimates at this location are probably artificially low due to upstream overtopping.

Flow duration analyses were completed for the levee characterization hydraulic investigation including 1-day and 3-day average peak flows and development of balanced flow hydrographs. Flow ramping rate analysis has not been completed for the levee reach, but data available from the levee characterization study would allow this analysis to be made.

Table 11: Annual Peak Discharge Flood Frequency Estimates for South Fork Snoqualmie River at North Bend.

Percent Chance Exceedance	Return Period (years)	2014 Levee Characterization Study Discharges (cfs)	FEMA Published Discharges (cfs)
0.2	500	19,120	19,700
1.0	100	15,650	15,000
2.0	50	12,190	13,000
10.0	10	N/A	9,000

4.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling for the lower South Fork Snoqualmie River was completed in 2001 by King County and was incorporated into the effective FEMA flood insurance study (FEMA, 2017). Modeling was completed using HEC-RAS Version 2.2. Because the South Fork Levees are not certified mapping reflects the composite floodplain developed from modeling conducted “with both levees”, “without right levee” and “without left levee”.

As part of the Levee Characterization project a FLO-2D hydraulic model was created to evaluate potential flood inundation resulting from levee overtopping and seepage (Tetra Tech, 2014). This 1D/2D model could be used to evaluate existing conditions along the river and within the adjacent floodplain although more detailed modeling using a tool such as RiverFlow2D would be preferable for delineating flow paths and inundation characteristics in the floodplain. Seepage modeling was conducted separately

in the Levee Characterization and applied in the FLO-2D model at discrete points determined by the geotechnical analysis to replicate observed flooding landward of the left bank levee downstream of RM 4.2. The analysis included routing of flow overtopping the levees. Levee breach modeling has not been conducted for this system.

4.1.6 Inundation and Breach Progression Mapping

No levee breach inundation modeling and mapping nor breach progression analysis has been conducted for the South Fork Snoqualmie Levees. The FLO2D model developed for the Levee Characterization project could be used for this work.

4.1.7 Recent CIP Projects

King County RFI repair history for the South Fork Snoqualmie levee system is summarized in Table 12.

Table 12: King County River Facility Inventory Repair History for South Fork Snoqualmie River Levees

Facility Name	Facility Type	River Bank	River Mile[1] Downstream	River Mile[1] Upstream	Repairs listed by year				
Prairie Acres LB	Levee	Left	2.08	2.28					
Prairie Acres RB	Levee	Right	2.09	2.28	1978				
Bendigo Lower LB	Levee	Left	2.28	2.55	1977				
Bendigo Lower RB	Levee	Right	2.28	2.54	1988	2018			
Bendigo Upper RB	Levee	Right	2.49	2.88					
Bendigo Upper LB	Levee	Left	2.55	2.89					
Si View Park	Levee	Right	2.88	3.28	1991				
Reif Rd	Levee	Left	2.89	4.77	1987	1991	1996	2011	2017
Si View Levee	Levee	Right	3.28	4.8	1991	1998	2012		
McConky	Levee	Left	4.88	5.21	1977	1978	1988		
Holstein Ext	Levee	Right	4.92	5.39					

Note: [1]River mile identifiers refer to upstream and downstream ends of the levee segment, not necessarily the location of the repair.

King County initiated the Interstate 90 Flood Risk Reduction Project to address potential overtopping of the existing levees from RM 4.0 to RM 5.1 with the goal of identifying alternative solutions to reduce flood risk to I-90. Alternatives considered included various levee setback alignments and gravel management. The alternatives analysis report was published in 2017 (Tetra Tech 2017).

Previous studies have also evaluated the potential flood reduction benefits of gravel removal from the leveed reach (King County 2011), and modifications to the Bendigo Boulevard Bridge to reduce backwater effects caused by the undersized bridge opening (Kato and Warren 2000).

The 2015 South Fork Snoqualmie River Corridor Plan Technical Evaluation report (Tetra Tech) presents potential tools to address problems identified in the 2014 Levee Characterization report (Tetra Tech). Tools focus on addressing hydraulic, geotechnical and ecological problems, providing geotechnically sound levees which can accommodate the 0.2-percent-annual-chance flood with 3 feet of freeboard,

and improving reach ecological conditions. Alternatives included setback levees, levee removal, levee repair, raise in place levees or floodwalls, gravel management, home elevation, bridge culvert replacement, or bridge and culvert improvement.

4.1.8 PL84-99 Status

Currently there are no levees in the South Fork Snoqualmie River levee system that are eligible in the PL 84-99 program because they do not meet USACE rating requirements. King County is initiating an effort in cooperation with USACE to identify what is necessary to re-establish the eligibility of the levees in this system.

4.2 Site Visit/Inspections/Pertinent Observations

RFMS and WSE staff conducted a one day field reconnaissance of the South Fork Snoqualmie River levees on July 5, 2018. No specific deficiencies in the levees were identified during that field visit. RFMS staff have observation-based knowledge of the South Fork Snoqualmie River levees as a result of regular visual inspections at low water conditions as well as during floods. RFMS staff have identified at least two known seepage sites with potential boils, one along the left bank levee near the railroad bridge upstream of W North Bend Way and a second along the left bank near RM 2.7. RFMS will observe and document these sites during high flows this winter to better characterize the extent and risk of the problem.

4.3 Data Gaps

Based on review of available studies, and reports, and discussions with RFMS staff, the following data gaps have been identified

- Characterization of levee breach potential
- Breach modeling for overtopping or seepage failures
- Breach flood progression mapping

4.4 Levee and Channel Characterization (Physical Properties)

A description of the levees and physical properties is included in the Levee Characterization Report (Tetra Tech 2014). The SF Snoqualmie levees were constructed with dredged alluvium including sand and gravel and have moderate shear strength, low compressibility, and moderate to high permeability (GeoEngineers 2014, Aspect, 2017). Levees range in height from 2 to 10 feet from the landside toe, and most areas are less than 5 feet in height. Portions of the levees are lined with revetment or slope up to high ground. Field observations indicate that scour protection exists on the levees and is consistent with original design specifications (Aspect, 2017).

Levees were raised and strengthened by King County in the 1960s to accommodate a design flow of 13,000 cfs (approximately a 50-year event at the North Bend Gage). The levees do not, however, function according to this design flow due to overtopping and do not provide any freeboard. The levees are asymmetrical with the right bank levees higher than the left bank leading to earlier overtopping of the left bank by design. The levees are not certified and not accredited by FEMA as flood control levees.

4.5 Land-Use

The leveed reach of the South Fork Snoqualmie River is in the City of North Bend up to RM 3.1 on the left bank and RM 4.3 on the right bank. The remainder of the containment levee reach is in unincorporated King County. Surrounding land use is described in the Levee Characterization report (Tetra Tech 2014). Land use landward of the levees from RM 2.0 to RM 4.0 includes undeveloped parkland, pasture agricultural land, low-density residential, the Nintendo industrial property and two larger commercial developments on the left bank, and medium-density residential and commercial land use on the right bank. Land use on both sides of the river from RM 4.0 to RM 4.8 is low-density residential. The North Bend Wastewater Treatment Plant (RM 2.1), Bendigo Boulevard South (RM 2.1), and Interstate 90 (RM 4.8) are considered to be critical facilities.

4.6 Hazards

Hydraulic analysis to support evaluation of potential flood hazards associated with both existing conditions and a “future aggradation scenario” were completed for the Levee Characterization project (Tetra Tech 2014). Analyses considered levee overtopping and seepage but did not consider levee breaching. Under existing conditions the model results indicated overtopping along 1,300 feet of levees for the 5 percent annual chance (20-year) flood event increasing to 17,000 feet of overtopping for the 0.2 percent annual chance (500-year) flood. Initial overtopping was simulated along the left bank levee which is lower than the right bank levee. Simulations considering the future aggradation scenario resulted in 770 additional feet of levee overtopping during the 5 percent annual chance flood and an additional 1630 feet of levee overtopping during the 1 percent annual chance flood. Overtopping would result in inundation of North Bend and areas of Unincorporated King County.

Levee stability analyses conducted for the Levee Characterization Study indicated a high potential for levee failure due to scour (Tetra Tech 2014). Potential scour depths ranging from 10.5 to 11.5 feet were calculated at three critical locations corresponding to outside bends in the river channel. In the Levee Characterization report, GeoEngineers recommended additional analyses of scour potential including likely scour progression and impact to the levees (Tetra Tech 2014).

Seepage below and through the SF Snoqualmie levees appears to be widespread. Seepage can pose a risk of promoting piping which may be a critical failure mode for the levees. The Levee Characterization Report noted seepage, toe erosion, or depressions on the levees at a number of locations, representing geotechnical problems with the levees. Overall, the levees are considered “marginally stable to stable under the range of operating conditions normally considered for levees” (Aspect, 2017).

High priority geotechnical or hydrogeological problems with the levee were summarized in the Levee Characterization Report. Areas with the highest potential for failure are shown in Table 13. The rating system in Table 13 used a scale from 1 to 10 with 1 being the least likely to fail and 10 being the highest potential for failure. This list of critical sections in Table 13 does not include the potential for levee failure due to overtopping.

Table 13: Critical Sections Along the South Fork Snoqualmie River Identified in Levee Characterization Report (Tetra Tech 2014).

Location (RM)	River Bank	Description	Rating
2.27	Right	Outside bend, moderate slopes, sparse to no riprap observed within upper 5 feet of riverside slope, riprap observed at toe, nearby bridge abutment, erosion at levee crest	8
2.51	Left	Outside bend to straight, seepage observed from river to landside Jan 09, moderate slopes, severe depression, sparse riprap, nearby bridge abutment	9
2.70	Left	Piping and sand boil observed Jan 09, depression, moderate slopes, sparse riprap	10
3.10	Left	Recent repair completed (issues included seepage from landside river to river, scoured rills and soft areas, near vertical face, rubber tires, nearby flap gate)	7
4.18	Left	Outside bend, narrow levee crest, moderate slopes, seepage reported during 2009 flood.	8
2.47	Right	Culvert penetration at levee bend. Severe riverside slopes water ponding behind peer and seepage noted during Jan 2009 flood	7
4.5 to 4.6	Left	Side channel developing and undercutting riverside toe, severe riverside slope and evidence of slope movement	9

4.7 Risks

Risk associated with breaching of the South Fork Snoqualmie River Levee system has not been evaluated. Existing conditions modeling completed for the Levee Characterization included levee overtopping and seepage analyses. Simulated flooding indicated inundation of structures and roadways in residential areas and portions of downtown North Bend. Levee overtopping in many reaches was simulated at the 5 percent annual chance flood event (20-year event). During the 1 percent annual chance flood (100-year event), overtopping and seepage was estimated to affect a total of 222 properties and 5.5 miles of roadway (this includes some roads impacted by levee overtopping upstream of the subject reach RM 4.85 to 5.9). Under future aggraded channel conditions, this increased to 331 structures and 8.7 miles of road. These risks are based on levee overtopping with the levees remaining in place and do not consider the potential for levee failure due to overtopping or geotechnical failure. Potential problems such as culvert penetrations, vegetation on the levee, or problems where no active failure mode was observed were also not considered.

The Levee Characterization Technical Report (Tetra Tech 2015) summarizes flood risk by levee segment, as follows:

- **Snoqualmie Valley Trail to Bendigo Boulevard North (RM 2.0 – 2.25):** Risks associated with levee overtopping of the left bank levee include inundation of parkland with little to no infrastructure. Overtopping of the right bank levee has the potential to impact critical

infrastructure at the North Bend Wastewater Treatment Plant. Severe toe erosion and high shear stress along of the right bank levee also has the potential to damage the levee.

- **Bendigo Boulevard North to West North Bend Way (RM 2.25—2.45):** Levee overtopping along the left bank contributes to inundation around structure and NW 8th street. Overtopping and seepage on the right bank results in risk of inundation to a number of structures including the North Bend Waste Water Treatment Plant, which is a critical facility.
- **West North Bend Way to Bendigo Boulevard South (RM 2.45—2.85):** Levee overtopping on the left bank contributes to risk of downstream flooding and risk to levee stability. Overtopping on the right bank contributes to risk of flooding downstream
- **Bendigo Boulevard South to RM 3.55 (RM 2.85—3.55):** Levee overtopping on the right bank contributes to risk of flooding of residential and commercial properties in downtown North Bend. Levee overtopping on the left bank contributes to risk of flooding in sparsely developed residential areas and Interstate 90. Toe and erosion and undercutting of the riverside levee toe in this reach contribute to risk of levee failure.
- **RM 3.55 to Interstate 90 (RM 3.55 – 4.85):** Levee overtopping of the right bank contributes to risk of residential structures, downtown commercial areas, and Interstate 90. Toe erosion in this reach contributes to risk of levee failure. Levee overtopping of the left bank contributes to risk of inundation of residential structures, 415th Way SE and Interstate 90. Toe erosion and levee overtopping increase risk of levee failure.
- **Upstream of I-90 (RM 4.85 - 5.39):** Levee overtopping on the right bank contributes to risk of flooding in a sparsely developed area and to flooding of downstream reaches including the City of North Bend. Levee overtopping on the left bank contributes to risk of flooding of sparsely developed residential areas, 415th Way SE, and Interstate 90. Toe erosion and levee overtopping increase the risk of levee failure.

5 Lower Cedar River levees from RM 1.23 to the mouth

5.1 Available Information

5.1.1 Survey/topography

Available topographic data for the Lower Cedar River levees includes LiDAR for various dates including 2005, 2010, 2011, 2013, 2014 and 2016. These data provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach, or for measurement and characterization of the levee itself (height, top width, side slope, etc.).

The City of Renton regularly monitors sediment accumulations within the levee reach by surveying approximately 40 cross sections annually, including 1991, from 1997 to 2012, and from 2014 to 2016 (Renton, 2016). Channel survey in 2016 was completed following dredging of the leveed reach, which removed approximately 96,500 cubic yards of sediment. Many of these cross sections include the riverward side and top of the levee. Survey of the levee top was also completed in 2016 to support the determination of available levee freeboard (Tetra Tech, 2017).

5.1.2 Geotechnical and Geomorphic Assessments

A geotechnical evaluation of the levees was completed in 2017 as part of City of Renton's effort to recertify the Lower Cedar River levees (GeoEngineers, 2017). This evaluation identified two areas where the levees are considered to be deficient: One area where the existing floodwall must be extended to provide adequate overlap with the neighboring embankment levee, and another area where the levee width is narrower than USACE minimum recommendations. The report states that, once these deficiencies are addressed, the levees would "meet the geotechnical requirements of 44 CFR 65.10 and USACE Engineering Circular EC 1110- 2-6067 'USACE Process for the National Flood Insurance Program (NFIP) Levee System Evaluation' for the 100-year (1-percent-annual-chance) design flood." A full description of the geotechnical evaluation is included in GeoEngineers report, including analysis of levee stability, seepage, settlement, as well as a description of field exploration and laboratory testing. Structural assessment of levee flood walls was completed by Tetra Tech, including assessment of the concrete floodwalls, joints, gates, rotational stability, and slope stability (2017).

Geology and geomorphology of the basin are summarized in the Cedar River Characterization of Existing Conditions Report (Herrera, 2017). The study includes information about the geomorphic context of the leveed reach including the fact that it is on an alluvial fan and that ongoing sedimentation in the levee reach is significant and requires occasional dredging to maintain flood protection. The lower Cedar River below RM 1.3 is generally straight and confined by infrastructure (levees, roads, trails) such that the channel is not likely to meander and impinge upon the levee. There is, however, significant ongoing sedimentation occurring in the lower Cedar River and this has the potential to affect flood levels and therefore levee breach potential.

5.1.3 Hydrogeologic/Seepage analysis

Seepage analyses were conducted at 13 proposed levee cross sections as part of the levee recertification project (GeoEngineers, 2017). This included analysis under three design conditions: end-of-construction, steady state seepage and rapid drawdown. Based on this analysis the levees were determined to provide an adequate factor of safety against piping failure due to seepage.

5.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS operates several streamflow gaging stations on the Cedar River. The Cedar River at Renton gage is located within the leveed reach and can be used to provide hydrologic data needed for evaluation of the levee. Relevant information for this gage is summarized in Table 14.

Table 14: USGS Streamflow Gage on the Cedar River at Renton

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)	Elevation (NGVD 29)	Period of Record
Cedar River at Renton	12119000	184	15.20	1945 to Present

As described previously SPU operates Masonry Dam on the Cedar River and flows in the Cedar are affected by operations at the dam. The reservoir behind Masonry Dam provides a small amount of dedicated flood control storage. During the summer season water held in storage at the dam is released as needed to supply SPU customers and to augment instream flows. When the reservoir is drawn down it can provide additional, incidental flood control storage. The dedicated and incidental flood control storage at Masonry Dam can capture runoff from flood events, reducing downstream flows. As storage in the reservoir fills, flood control releases are made and downstream flow reductions become less pronounced. Historical gaging records on the Cedar River at Renton gage reflect operations at the dam.

Hydrologic analysis for the Cedar River was completed as part of the Cedar River Levee Recertification Study (Tetra Tech, 2017). Flood frequency analysis for the levee reach is summarized in Table 15. Also shown in Table 15 are the computed flood frequency discharges used in the most recent FEMA Flood Insurance Study of the Cedar River. Differences between these two are the result of different periods of record and different methodologies used in the analysis. Flow duration and flow ramping rate analysis have not been completed for the levee reach, but could be completed using data from the USGS gage at Renton.

Table 15: Annual Peak Discharge Flood Frequency Estimates for USGS Gage 12119000 Cedar River at Renton, WA.

Percent Chance Exceedance	Return Period (years)	Discharges Computed for CIS (cfs)	FEMA Published Discharges (cfs)
0.2	500	15,200	18,400
0.5	200	12,700	
1.0	100	10,900	12,000
2.0	50	9,300	9,860
5.0	20	7,370	
10.0	10	6,040	5,940
20.0	5	4,790	
50.0	2	3,150	

5.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling of the Cedar River within the City of Renton was completed in June 2006 for the most recent FEMA floodplain study. The FEMA modeling used a HEC-RAS one-dimensional (1D) hydraulic model. Other data used in the FEMA study included channel cross section surveys taken from 2005 and the estimated flow quantiles shown in Table 15. The FEMA analysis modeled conditions with the containment levees in place and providing 100-year flood protection, as these were then FEMA accredited flood control features.

For the last several years hydraulic modeling of the leveed reach has been completed annually by the City of Renton using updated channel surveys representing conditions with ongoing sediment aggradation. The most recent modeling by the City was completed in 2017 following dredging throughout the leveed reach (NHC, 2017).

The FEMA model was updated in 2013 by WSE as part of the Cedar River Interactive Mapping Project (CRIMP) (WSE, 2013). That model used topographic and bathymetric data from 2011 LiDAR and 2012 Channel Surveys to define the river channel, existing levees, and the floodplain.

A HEC-RAS 1D/2D model of the lower Cedar River was developed by WSE in 2016 to map inundation limits resulting from levee, floodwall, or bank overtopping. This model was created by updating the 2013 CRIMP model using City of Renton data for 2014 (pre-dredge) and 2016 (post-dredge) channel conditions. Overbank flow areas in the model were defined based on 2011 LiDAR. The model was used to evaluate flooding that would result from overtopping during the 100-year, 200-year, and 500-year flood events. The modeling did not include analysis of levee failure potential, and the levees and floodwalls were assumed to remain in place even when overtopped.

Most recently, Tetra Tech created a hydraulic model of the lower Cedar River by updating the FIS model with post dredge survey (Tetra Tech, 2017). That model is being used to support a Conditional Letter of Map Revision (CLOMR) application to FEMA as part of the levee certification and accreditation process. The CLOMR model was used in a risk and uncertainty (R&U) analysis completed according to USACE guidance (USACE, 2017) to determine the conditional probability of non-exceedance for overtopping at each model cross section. The analysis considered overtopping only and did not evaluate the potential for geotechnical failure.

5.1.6 Inundation and Breach Progression Mapping

No levee breach inundation modeling and mapping nor breach progression analysis has been conducted for the lower Cedar River levee system, although the 1D/2D model developed for the Cedar River Corridor Existing Condition Characterization Report (Herrera, 2017) could be updated to facilitate levee breach analyses.

FEMA floodplain mapping landward of the levees is currently based on 500-year water levels computed using the 2006 steady state model. The levees are provisionally accredited by FEMA as providing 100-year flood protection.

5.1.7 Recent CIP Projects

The lower Cedar River levees are not part of the King County facility inventory and as such King County does not regularly inspect or perform routine maintenance on these levees. The City of Renton

maintains the lower Cedar River levees and floodwalls. Dredging of the lower Cedar River is an essential component of flood protection along the containment levee reach. Dredging of the lower Cedar River was last completed in August 2016 by the City of Renton. Dredging removed approximately 96,000 cubic yards of sediment. Floodwall joints were also repaired in 2016 as part of the dredging project. The City is currently in the process of applying for a Conditional Letter of Map Revision (CLOMR) as part of a process to get the levees accredited by FEMA as providing 100-year flood protection (Tetra Tech, 2017).

5.1.8 PL 84-99 Status

The Lower Cedar River containment levee system includes two levees that are active in the PL 84-99 program. These are the Cedar River Section 205 Left Bank Levee from RM 0.0 to RM 1.23 and the Cedar River Section 205 Right Bank Levee from RM 0.0 to RM 1.15. These levees are administered by the City of Renton and are currently rated as “Minimally Acceptable” by the USACE.

5.2 Site Visit/Inspections/Pertinent Observations

The City of Renton performs annual monitoring of the Lower Cedar River levee system. GeoEngineers and Tetra Tech also recently evaluated the levees as part of the City’s levee recertification efforts. The following two areas were determined to not meet USACE requirements for levee certification:

- The left bank at Station 20+00. At this location the levee transitions from embankment levee to floodwall and GeoEngineers found less overlap than what was indicated in the original flood protection design drawings. Either the sheet pile floodwall or the embankment levee would need to be extended to match the original design, and
- The Left bank downstream of the Logan Avenue Bridge near Station 57+50. The width of the embankment levee crest is narrower than USACE recommended minimum dimensions. GeoEngineers recommends extending the floodwall to the Logan Avenue Bridge or widening the embankment levee.

5.3 Data Gaps

Based on review of available studies, and reports the following data gaps have been identified for the lower Cedar River containment levees:

- Breach modeling for overtopping or seepage failures
- Breach flood progression mapping

5.4 Levee and Channel Characterization (Physical Properties)

The lower Cedar River levee system was constructed in 1998 as part of a joint project by the City of Renton and the USACE. Dredging of the Cedar River channel was done in concert with levee raising, and the resulting levee system was certified by the USACE as providing 100-year flood protection (USACE, 2004). The left and right bank levees are currently both considered provisionally accredited by FEMA and Minimally Acceptable according to the USACE Rehabilitation and Inspection Program (RIP).

Characterization of levee geometric properties (height, top width, side slopes) was completed as part of the City of Renton’s levee recertification effort (Tetra Tech 2017). The levee system consists of earthen embankment levees and sheet pile/concrete floodwalls along both banks. GeoEngineers (2017) reported

that they did not find documentation of levee material composition or quality of construction but they noted that plans for the embankment levees called for construction using "Levee Embankment Material" and that "the levee embankment will be compacted to meet geotechnical seepage and levee embankment integrity criteria". GeoEngineers' geotechnical analysis assumed that the levee embankments were constructed of material similar to common borrow as defined by Washington State Department of Transportation (WSDOT) Standard Spec 9-03.14(3) (GeoEngineers, 2017).

5.5 Land-Use

The Renton Airport and Boeing manufacturing plant are located landward of the Lower Cedar River levees left and right bank, respectively, between approximately RM 0 and RM 1.0. Other land use landward of the Lower Cedar River levees includes residential and commercial structures, Renton High School, ball fields and parks, the Renton Landing commercial area, and industrial areas including the Kenworth Truck Company. There are several residential structures near the levee on the right and left bank of the river between approximately RM 1.0 and RM 1.3.

5.6 Hazards

Hazards associated with the Lower Cedar River levees were characterized for the Cedar River Corridor Plan Flood and Erosion Risk Analysis (Herrera, 2017). That analysis assumed that the levees were not breached. Based on this assumption, the hydraulic modeling showed that the 100-year flow would be contained between the levees but that flows exceeding the 100-year flood could begin to break out upstream of the leveed reach and flood areas behind the levees. Flows higher than the 100-year event could overtop the levee and upstream banks resulting in flooding of structures landward of the levee including the Boeing manufacturing facility and the Renton Airport.

The South Boeing Bridge is a drawbridge that crosses the Lower Cedar River. The bridge impacts the base flood elevation when in the down position and has been observed to catch floating debris. The City of Renton's Flood Master Plan calls for the bridge to be raised during high flows, and for the closure of metal gates to create a continuous flood wall on either side of the raised bridge. Proper function of the bridge and closure of the gates was observed during a high flow event on December 9, 2015 as part of the levee structural assessment (Tetra Tech, 2017). Failure of the bridge to operate as designed could lead to flooding of areas behind the levees, especially if floating debris were to rack up on the bridge.

5.7 Risks

The Lower Cedar River Corridor Plan Flood and Erosion Risk Analysis did not identify any structures at risk of flooding due to levee overtopping or upstream breakout flows during the 100-year flood event. That analysis did identify 540 feet of local roads that would be inundated during the 100-year flood. The analysis concluded that the (post-dredge) levees provide greater than 100-year protection against levee overtopping. Flood risks due to levee breaches were not characterized in that project.

The level of protection provided by the lower Cedar River levees is contingent on maintenance dredging of the Cedar River channel and proper operation of the South Boeing Bridge. The frequency of maintenance dredging is based on observed bed elevation changes. Dredging occurred approximately every 10 years for the first 45 years of the project, once in the 1960s, twice in the 1970s, once in the 1980s, once in 1998, (NHC, 2014) and most recently in 2016 (Tetra Tech, 2017). The City of Renton

initiates a permitting process for maintenance dredging of the river when the bed of the Cedar River channel reaches a pre-determined level. Permitting can take several years and there is increased risk of flooding along the levees, and potential for levee breaches, during the intervening years as bed levels continue to build. If maintenance dredging were not to occur for any reason the levees and floodwalls would be at substantially increased risk of failure.

6 Lower Green River from RM 30.9 (Lone's Addition levee) to RM 11.0 (Black River Pump Station)

6.1 Available Information

6.1.1 Survey/topography

Although this chapter includes the entire lower Green River levee system from RM 30.9 to RM 11.0 there are actually only three reaches along the Green that are truly containment levees: right bank from Horseshoe Bend to Desimone (RM 26.1 to 14.5), left bank Auburn from Lone's addition to Reddington (RM 30.9 to 28.35) and left bank Tukwila 205 (RM 16.7 to 12.45). The remainder of the Green River levee system is comprised of high ground in the form of natural river banks or revetments and non-containment levees. Available topographic data for the Lower Green River levees includes LiDAR or aerial photogrammetric data for various dates including 2003, 2006, 2011 (Briscoe only), 2013 (Reddington only), 2014 (for the Green River SWIF) and 2016. These data provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach, or for measurement and characterization of the levee itself (height, top width, side slope, etc.).

Channel cross section surveys are available for the entire containment levee reach from FEMA floodplain mapping studies in 1986 and 2006/2007. Many of the cross section locations from the FEMA studies were reoccupied in 2011 for a levee scour assessment by the City of Kent. Additional channel cross section and bathymetric surveys were taken at various times since 2007 for shorter reaches within the containment levee system. These include surveys done by King County, the City of Kent, Muckleshoot Tribe and private parties.

6.1.2 Geotechnical and borings

Unlike many of the other containment levee systems in King County, significant subsurface explorations have been conducted for levees in the lower Green River containment system. In 1988, the County completed geotechnical investigations for levee improvements along two sections of the Green River levee, one in Kent (right bank from RM 24.33 to 24.93) and one in Tukwila (left bank from RM 13.22 to 13.49). Those investigations included borings and subsurface explorations at eight locations. In 2007, the County completed 14 geotechnical subsurface explorations along the Green River between RM 6.3 and 32.0 as part of the Green River Flood Analysis and Risk Assessment Project (S&W 2007a). Deterministic slope stability analyses were also completed for eight discrete locations along the containment levee system (S&W, 2007b).

In addition to those studies there have been significant geotechnical investigations, including subsurface explorations, borings, and slope stability analyses conducted as part of levee certification studies or other projects including the following:

- Foster Park Levee Certification Report (GeoEngineers, 2010a)
- Hawley Road Levee Certification report (GeoEngineers, 2010b)
- Horseshoe Bend Levee Certification Report (GeoEngineers, 2010c)
- Boeing Levee RM 17.01 – 17.84 CLOMR Application (2011)
- SR516 to S 231st Levee Green River Right Bank CLOMR Application (2011)

- Briscoe and Desimone Levees, Green River Right Bank RM 14.3 to 17 CLOMR Application (2011)
- Russel Road Lower-Lowest Levee certification Report (2011)
- 180th to 200th Street Levee Setback Study (2012)
- Reddington Levee Setback and Extension feasibility report (2011)
- Green River Geotechnical Investigation of Frager Road Levee (Hart Crowser 2012)
- Tukwila Levee Accreditation Phase 1 – Engineering Analyses and Improvement Identification (NHC 2015)
- Report: Preliminary Embankment and Foundation Stability Analysis, Tukwila 205 Levee Certification (AMEC 2015)

A review of available geotechnical assessments and subsurface explorations related to five PL 84-99 levees within the lower Green River containment levee system was prepared for the Green River SWIF (King County 2016, Appendix C).

6.1.3 Hydrogeologic/Seepage analysis

Seepage and stability analyses were conducted in 1999 for the Segale Levee located on the left bank just south of S 180th Street in Tukwila. Those analyses are documented in the following reports:

- Levee Seepage Evaluation, Proposed Warehouse Building, (GeoEngineers, 1999)
- Seepage and Stability Analyses, Segale Levee, (S&W, 1999)

More recently seepage and groundwater evaluations were completed in 2007 for the Green River Flood Analysis and Risk Assessment Project (S&W, 2007a) and as part of each of the following levee certification studies:

- Foster Park Levee Certification Report (GeoEngineers 2010a)
- Hawley Road Levee Certification report (GeoEngineers, 2010b)
- Horseshoe Bend Levee Certification Report (GeoEngineers, 2010c)
- Boeing Levee RM 17.01 – 17.84 CLOMR Application (2011)
- SR516 to S 231st Levee Green River Right Bank CLOMR Application (2011)
- Briscoe and Desimone Levees, Green River Right Bank RM 14.3 to 17 CLOMR Application (2011)

6.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS operates several streamflow gaging stations on the Green River. The USGS gage on the Green River near Auburn provides the most useful long term flow data for the containment levee reach. Relevant information for that gage is summarized in Table 16. A newer gage, installed in 2011 is located on the Green River at S 200th Street in Kent. Although the period of record for this gage is too short for reliable flow frequency analysis the gage could be used to evaluate ramping rates (drawdown) during recent flood events. The USGS gage at Tukwila, near the downstream end of the containment levee reach could also be used to evaluate drawdown conditions. Flow data are not available for the Tukwila gage, only stage data.

Table 16: USGS Streamflow Gage on the Green River near Auburn.

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)[2]	River Mile (mile)	Period of Record
Green River near Auburn	12113000	399	32.0	1938 to Present[1]
Green River at 200th Street	12113000	451	17.0	2011 to Present
Green River at Tukwila	12113350	440	12.4	2007 to Present

Note: [1] The USGS has collected streamflow data on the Green River near Auburn since October 1936. However, only the data subsequent to the construction of Howard Hanson dam in 1961 would be useful for characterizing current conditions in the containment levee reach.
[2] Drainage areas obtained from USGS website. The apparent anomaly of having a downstream gage with smaller basin area was not investigated for this report.

Flow frequency analysis for the Green River was most recently conducted for the Green River SWIF (King County 2016). Flow frequency quantiles from that analysis are shown in Table 17. Also shown in Table 16 are flow frequency quantiles from the effective FEMA study for the Green River and the preliminary FEMA DFIRM study. Flow duration and ramping rate studies have been performed for various projects along the river. Data from these studies as well as data for the USGS gages in Kent and Tukwila are available for characterizing hydrologic conditions within the containment reach.

Table 17: Annual Peak Discharge Flood Frequency Estimates for the Green River in the Leveed Reach

Percent Chance Exceedance	Return Period (years)	FEMA Preliminary Discharges (cfs)[1]	FEMA Effective Discharges (cfs)	Green River SWIF (cfs)[2]
0.2	500	13,460	12,000	18,800
1.0	100	12,810	12,000	12,000
2.0	50	12,420	12,000	12,000
10.0	10	11,230	12,000	12,000

Notes: [1] From King County Green River Flood Analysis and Risk Assessment Project (NHC, 2007)
[2] As computed by the USACE (2012) (as included in King County, 2016); 18,800 cfs is median estimate from USACE

6.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling of the Green/Duwamish River was completed by King County in 2010 for an appeal of FEMA's preliminary Green River Digital Flood Insurance Rate Map (DFIRM). The modeling for the King County study included the development of a FLO2D hydraulic model of the overbank areas landward of the containment levees. FEMA style levee failure analyses, wherein conditions are simulated with entire levee sections removed, were completed for that project. Realistic levee breach scenarios were not modeled for the FEMA appeal but were evaluated in a related study of levee breach potential and flood risks. Levee fragility curves characterizing the potential for failure of the levees due to various failure mechanisms (seepage, seismic, rapid drawdown, etc.) were developed for eight locations along the lower Green River levee system. The area that would be impacted by a failure at each of the eight

locations was delineated using simulations with the FLO2D model. Land-use and simulated inundations were used to estimate the potential damages associated with failure at each of the eight locations.

Potential inundation and damage resulting from four levee failure scenarios were further analyzed for a range of flood events to support the SWIF Interim Report (King County, 2016). Failure modes analyzed included levee breach prior to overtopping, levee overtopping with breach, and levee overtopping without breach. Only the levee failure prior to overtopping and levee overtopping without breach were explicitly modeled. Four breach locations were selected for analysis based on review of existing geotechnical, geomorphic, hydraulic, and economic factors. Inundation extents from impacts due to levee breach following overtopping (not explicitly modeled) were created through a combination of breach model runs and existing condition model runs.

6.1.6 Inundation and Breach Progression Mapping

Problems identified at Howard Hanson dam during and after the January 2009 flood event led the USACE to modify operations at the dam for a period of time while necessary repairs were completed. During the period of modified operations the potential for high flows along the lower Green River levee system was significantly increased compared to historical conditions. In light of this increased potential for high flows, the USACE and King County conducted analyses of inundation progression across the floodplain in the event of a levee breach. Several locations were selected for simulating a levee breach failure and the timing of inundation progression across the floodplain was simulated and mapped (NHC, 2010). Because the breach progression mapping was based on much higher discharges than the current conditions listed in Table 17 (as controlled by the repaired dam) the 2010 mapping is not directly useful to evaluating flood hazards under current conditions. However, the same tools and approach as used in the 2010 study could be applied using current conditions flows to develop breach progression maps for potential levee breaches under current flow conditions.

6.1.7 Recent CIP Projects

Levee repair work by King County along the Green River containment levee system is summarized in the following table:

Table 18: King County River Facility Inventory Repair History for Lower Green River Levees

Facility Name	Facility Type	River Bank	River[1] Mile D/S	River[1] Mile U/S	Repairs listed by year			
Ft. Dent	Levee	Right	11.02	11.84				
Family Fun Center	Levee	Right	12.03	12.23				
White Swan Left	Levee	Left	12.25	12.27				
Tukwila 205-Van Warden	Levee	Left	12.45	13.04	1976	2017		
Tukwila 205-Christensen Rd	Levee	Left	13.04	14.31	1985	1986	1992	2015
Tukwila 205-Lily Pointe	Levee	Left	14.31	14.56	1973	2009		
Desimone	Levee	Right	14.48	15.45	1967	1984	2015	
Tukwila 205-Segale	Levee	Left	14.56	14.89	1966	1984	1996	2015
Tukwila 205-Ratola	Levee	Left	14.89	15.75				

Briscoe Meander	Levee	Right	15.45	16.17	1959			
Tukwila 205-GACO Western	Levee	Left	15.73	15.88				
Tukwila 205-Gunter	Levee	Left	15.88	16.71	1960	1967	1971	2018
Briscoe	Levee	Right	16.17	16.24				
Briscoe School	Levee	Right	16.24	17.00	1971	2007	2016	
Tukwila 205-Cutoff	Levee	Left	16.71	16.77				
Christian Brothers	Levee	Right	16.99	17.19	1968	1975		
Boeing Setback	Levee	Right	17.05	17.83	1996	2001		
Boeing	Levee	Right	17.50	17.84	1996			
Boeing Floodwall	Levee	Right	17.83	17.05				
Russell Rd Lowest	Levee	Right	17.85	18.25				
Russell Rd Lower	Levee	Right	18.66	19.23	1997			
Somes Dolan 1,2&3	Levee	Right	19.23	19.69	1959	1963		
Russell Rd Upper	Levee	Right	19.69	20.40	1959			
Narita 1&2	Levee	Right	20.40	21.27	1959	1963	1998	2008
Myers Golf	Levee	Right	21.28	21.83	2008			
Pipeline	Levee	Right	21.83	21.91	1962	2000		
Okimoto	Levee	Right	21.91	22.04	1993			
County Road #8	Levee	Right	22.99	23.17	1974			
Corps 68th AV S	Levee	Left	23.50	23.59				
Breda	Levee	Right	24.44	25.14	1996	2009		
Plemmons	Levee	Right	25.14	25.32	1972	1996	2007	2009
Nursing Home	Levee	Right	25.32	26.03	1982	1996	2009	2015
Nursing Home Extension	Levee	Right	26.03	26.13	2015			
Reddington	Levee	Left	28.35	29.49	2014			
Galli's Section	Levee	Left	29.49	29.68	1997			
Dykstra	Levee	Left	29.68	30.80	1964	1995	2009	2016
Pig Farm	Levee	Right	30.41	30.58	1964			
Lone's Addition	Levee	Left	30.80	30.90	1992			

Note: [1]River mile identifiers refer to upstream and downstream ends of the levee segment, not necessarily the location of the repair.

6.1.8 PL84-99 Status

The Lower Green River containment levee system is comprised of a number of distinct levee facilities. Table 19 provides an overview of the facilities that are currently active within the PL 84-99 Program. In 2016 King County completed the System Wide Improvement Framework (SWIF) Interim Report for the Green River (King County, 2016). A SWIF Interim Report is an integrated approach to resolve identified

deficiencies in PL 84-99 levee systems in order to retain eligibility under the PL 84-99 program. The interim report was submitted to the USACE by the FCD in 2016, and accepted by the USACE in 2017.

Table 19: Green River Levee Facilities Active in the PL84-99 Program (from King County 2016)

PL 84-99 Levee System Name	Facility Name	Segment Length	USACE Inspection Rating
Tukwila 205 #1	Tukwila	4.1786	Minimally Acceptable
Lower Green Right Bank (#2)	Desimone – Briscoe School	2.2024	Minimally Acceptable
Lower Green Right Bank (#2)	Boeing	0.8453	Minimally Acceptable
Lower Green Right Bank (#2)	Lower Russell Road – Holiday Kennel	0.9427	Unacceptable
Lower Green Right Bank (#2)	Upper Russell Road Somes-Dolan	1.0287	Minimally Acceptable
Lower Green Right Bank (#2)	Kent Shops - Narita	0.9325	Minimally Acceptable
Lower Green Right Bank (#2)	Meyers Golf	0.76	Minimally Acceptable
Signature Point (#3)	Signature Point	1.0795	Minimally Acceptable
Horseshoe Bend (#4)	Horseshoe Bend	1.8452	Minimally Acceptable
Galli/Dykstra Reddington (#5)	Reddington	0.9043	Acceptable
Galli/Dykstra Reddington (#5)	Galli	0.2315	Minimally Acceptable
Galli/Dykstra Reddington (#5)	Dykstra	1.0514	Minimally Acceptable

The SWIF Report (2016) and Interim SWIF Progress Report (2018) contain descriptions of each of these levee facilities including deficiencies identified by the USACE and corrective actions completed or proposed by the FCD to resolve deficiencies.

6.2 Site Visit/Inspections/Pertinent Observations

RFMS staff have observation-based knowledge of the lower Green River levees as a result of regular visual inspections at low water conditions as well as during and after floods. As part of the PL 84-99 program, federal levees are inspected annually, and local levees are inspected bi-annually in conjunction with the Corps. King County's interim Green River SWIF identified seven locations for capital projects within the Green River Levee system. Problem identification statements from the SWIF interim report (King County 2016) are summarized below:

- Lower Russell Road (RM 17.85 – 19.25) - This levee is rated 'Unacceptable' by the USACE due to a slope deficiency at river mile 18.6. USACE PL 84-99 eligibility inspections identified additional deficiencies including encroachments, animal burrows, erosion, debris, and settling. There has also been significant scour and damage to the levee toe and embankment at RM 18.6 between 2012 and 2015. Levee overtopping in this project area is expected to occur when flows at the Auburn gage are between 15,100 and 18,800 cfs, which is an approximately 350 to 500-year flood event.
- Tukwila 205 (RM 15.55-15.88): Segale-Green and Gaco-Western - This PL 84-99 levee segment is rated as 'Minimally Acceptable' by the USACE due to slope deficiencies: River mile 15.7 (oversteepened slopes range from 1.25H to 1.33H:1V); RM 15.4 to 15.7 (oversteepened slopes

that are approximately 1.4:1). The Tukwila certification study currently underway measured 1.33:1 slopes at RM 15.86. That study calculated a Factor of Safety (FOS) for rapid drawdown of 0.74 and steady state seepage of 0.88 at RM 15.86. These are below the minimum Factor of Safety of 1.0 from the USACE manual. Additionally, river bed scour in this reach between 1986 and 2011 showed erosion of 7 feet at RM 15.85 and 4.1 feet at RM 15.59 over 25 years. This indicates that the river is actively down cutting in the vicinity of the levee, leading to further over-steepening of the slopes.

- Tukwila 205 (RM 14.6-14.75): Ratolo levee segment - This PL 84-99 levee segment is rated 'Minimally acceptable' by the USACE due to a slope deficiency at RM 14.6 (oversteepened slopes from 1.25H:1V for 200-300 feet). The Tukwila certification study measured 1.64:1 slopes at RM 14.72. That study calculated a Factor of Safety for rapid drawdown of 0.69 at RM 14.72. This is below the minimum acceptable FOS of 1. River bed scour in this reach between 1986 and 2011 was modest (approximately 1 foot), but there is one known deep scour hole downstream of RM 14.5.
- Tukwila 205 (RM 13.40-13.58): Christensen Road - This PL 84-99 levee segment is rated 'Minimally acceptable' by the USACE due to a slope deficiency at RM 13.4 to 13.5 (over steepened slopes from 1.33 to 1.25H:1V for 1000 feet). The preliminary Tukwila certification study measured 1.4:1 slopes at RM 13.53. That study calculated a FOS for rapid drawdown of 0.7 at RM 13.53. River bed scour in this reach between 1986 and 2011 was modest (approximately 1.2 feet).
- Horseshoe Bend (RM 24.26-24.47): McCoy - This PL 84-99 levee segment is rated 'Minimally acceptable' by the USACE due to a slope deficiency at RM 24.3 (oversteepened slopes from 1.3 to 1.7H:1V for 500 feet). The City of Kent constructed a secondary containment levee in this reach, set back from the river's edge, which is currently not part of the federal levee. The only remaining structure between the two levees is a Puget Sound Energy facility. The Horseshoe Bend Levee Certification Report calculated FOS values for rapid drawdown of 1.08 and 1.55 at about RM 24.3 and RM 24.4, respectively. River bed scour in this reach between 1986 and 2011 was 2.7 feet at RM 24.24.
- Horseshoe Bend (RM 24.47-24.7): Breda - This portion of the Horseshoe Bend levee does not meet recommended structural engineering design standards. The existing levee system is vulnerable to undercutting by scour due to narrow channel confinement, together with marginal stability resulting from over-steepened levee slopes and recent fill placement to achieve freeboard along the levee crest. Recent improvements were made to the downstream levee by the City of Kent (secondary containment levee from RM 24.3 to 24.47) and upstream by the USACE (2009 repair of launchable toe rock and embankment from RM 24.79-25.01). The Horseshoe Bend Levee Certification Report calculated a FOS for rapid drawdown of 1.005 at RM 24.57. That is the lowest FOS along the entire Horseshoe Bend levee and barely above the minimum FOS (1.0) from the USACE manual. River bed scour in this reach between 1986 and 2011 was 3.7 feet at RM 24.59.
- Horseshoe Bend (RM 25.4-25.65): Nursing Home - This capital project area contains a 'Minimally acceptable' deficiency by the USACE at RM 25.5 (over steepened slopes from 1.25 to 1.7H:1V for 225 feet). The Horseshoe Bend Levee Certification Report calculated a FOS for rapid

drawdown of 1.01 at RM 25.57. This is barely above the minimum FOS (1.0) from the USACE manual. River bed scour just upstream of this reach between 1986 and 2011 was 1.3 feet at RM 25.85.

6.3 Data Gaps

The lower Green River levee system was studied extensively under the SWIF (2016) and as part of earlier studies by King County (S&W, 2007a). In addition levee certification studies by Kent and Tukwila resulted in significant data collection efforts including numerous subsurface explorations and geotechnical studies. However, despite all of these studies the internal character of the levees is still somewhat unknown because detailed construction records for much of the levee system do not exist. An exception to this is the Reddington levee, setback and re-constructed in 2013-14, locations of all PL 84-99 repairs done by the USACE from 2008-2016, and secondary containment levees or floodwalls, built by Kent between 2012 and 2016. Furthermore there has not been a comprehensive analysis of levee breach potential or mapping and risk analysis evaluation for current hydrologic conditions.

6.4 Levee and Channel Characterization (Physical Properties)

The lower Green River levee system is generally characterized by levees that are wide, moderately tall, and topped in most sections with a paved trail or road. There is rock toe protection along some of the levees that comprise the containment system, but the current conditions are not well known. In some places the levees are higher relative to the backside ground making those locations more susceptible to failure due to seepage. The internal composition of the levees has been studied in many locations but there are still uncertainties about this because detailed construction records for the levees are not available, except during the past two decades.

6.5 Land-Use

Land Use in the Lower Green River Valley is described in the SWIF Interim Report (King County 2016). Almost 75% of the land use within the containment levee reach is classified as “developed”. The existing levees protect areas of Kent, Auburn, Renton and Tukwila with land use including a mixture of industrial, commercial, and residential development, as well as significant infrastructure comprised of state highways, railroads, local roads and utilities. Land-use is generally more rural residential on the left (west/south) side of the river upstream of S 200th Street. Downstream of S. 200th Street and along the right (east/north) side of the river land-use is typically higher density residential, commercial, and industrial. Unincorporated King County and the Lower Green Agricultural Production District is on the left bank, largely between SR-516 and S. 277th Street.

6.6 Hazards

The Green River SWIF characterized flood hazards along the lower Green River containment levees. Potential hazards associated with the levees include:

- River bed erosion and incision lowered the channel bed by one to two feet between 1986 and 2011, and up to four to 10 feet at numerous outside bends. River channel incision poses a hazard to structural stability of the levees.

- Portions of the levees do not meet USACE factors of safety for levee stability. Existing levees are vulnerable to failure and require regular maintenance to reduce flood risks. Common potential failure modes include rapid drawdown, seismic, and under-seepage.
- River embankments are susceptible to overtopping in some locations during the 2-year flood (9,000 cfs) and would overtop in multiple locations at higher flows (e.g., greater than 12,600 cfs) and inundate areas landward of the levees.

6.7 Risks

Major flooding has the potential to substantially impact people, structures, infrastructure, and businesses within the Lower Green River Valley. The SWIF interim report details flood simulation and inundation mapping for a range of flows up to the 500-year flood event. Levee overtopping during the 500-year flood event would inundate 7,400 acres of the valley and impact 9,000 commercial, residential and industrial structures, and 1,400 acres of prime agricultural land. Land use at risk of flooding due to levee overtopping (without breach) includes[1]:

- 22,000 residents living in portions of the valley that may be inundated from a 500-year flood event
- $7.3 billion in floodplain structures and contents 100,000+ jobs (REI Corporate Offices, Boeing, Amazon Fulfillment Center, Starbucks Roasting Plant and many other small, intermediate and larger sized companies)
- 100 million square feet of warehouse and distribution space

Floodplain inundation and risk resulting from potential levee breaches was also evaluated as part of the SWIF. Four levee locations (Tukwila 205, Meyer's Golf, Horseshoe Bend, Dykstra) were selected for breach simulation based on both their estimated potential for levee failure as well as the consequence if the levee were to breach at these locations. Inundation mapping was completed to delineate areas at risk of flooding. Risk, in terms of expected annual damage, was then determined for each failure location as well as the combined risk of all four locations (King County, 2016).

[1] Source: Green River Interim SWIF (King County, 2016)

7 South Fork Skykomish River Town of Skykomish Left Bank Levee RM 16.42 to 15.85

7.1 Available Information

7.1.1 Survey/topography

A segment of the left bank levee on the South Fork Skykomish River from RM 15.85 to RM 16.42 provides flood containment when combined with the right bank containment provided by the SR 2 road embankment. Although this is not a containment levee system in the same sense as the other five levee systems, potential risk to the town of Skykomish is sufficient to include it in this analysis. Available topographic data for the Town of Skykomish Left Bank Levee includes LiDAR for various dates including 1999, 2002, 2004, 2007, 2009, 2010, 2011, 2012, 2013 and 2016. These data would allow measurement and characterization of the levee geometry (height, top width, side slope, etc.). The LiDAR would also provide a reasonable basis for numerical modeling of overland flows, for example as a result of a levee breach.

7.1.2 Geotechnical and Geomorphic Assessments

A channel migration study for the South Fork Skykomish River was done by King County in 2017. https://www.kingcounty.gov/services/environment/water-and-land/flooding/maps/migration/draft-south-fork-skykomish-cmz.aspx

7.1.3 Hydrogeologic/Seepage analysis

No hydrogeologic or seepage analyses have been conducted for the Town of Skykomish Left bank levee system.

7.1.4 Hydrologic data (Peaks, durations, ramping rates)

The USGS currently operates a gaging station on the South Fork Skykomish River in the Town of Skykomish. However, this gage has only been in place since October 2016 so the flow record is not long enough for flow frequency analyses. Previously there was a USGS gage on the South Fork Skykomish near Skykomish which operated between 1930 and 1970. That gage could be used to estimate hydrologic data for evaluation of the levee. Relevant information for these gages is summarized in Table 20.

Table 20: USGS Streamflow Gages on the S.F. Skykomish River near Skykomish

USGS Gage Name	USGS Gage Number	Drainage Area (sq. mi.)	Elevation (NGVD 29)	Period of Record
South Fork Skykomish River in Skykomish	12131500	243	900	2016 to Present
South Fork Skykomish River near Skykomish	12130500	153	1035.16	1930-1970

Hydrologic analysis for the South Fork Skykomish River was completed as part of the South Fork Skykomish Flood Study (Harper Righellis, 1995). That study computed flow frequency quantiles for the South Fork Skykomish River using the gage near Skykomish (12130500) as well as other basin flow gages.

Flood frequency analysis for a location near the levee reach is summarized in Table 21. Flow duration and flow ramping rate analyses have not been completed for the levee reach but could be completed using data from the USGS gages listed in Table 20.

Table 21: Annual Peak Discharge Flood Frequency Estimates for South Fork Skykomish River near Town of Skykomish.

Percent Chance Exceedance	Return Period (years)	FEMA Published Discharges (cfs)
0.2	500	71,600
1.0	100	54,300
2.0	50	47,400
10.0	10	32,200

7.1.5 Hydraulic modeling and Levee Failure Analysis

Hydraulic modeling of the South Fork Skykomish River within Town of Skykomish was completed in June 1995 for the most recent FEMA floodplain study (Harper Righellis, 1995). The FEMA modeling used a HEC2 one-dimensional (1D) hydraulic model. Other data used in the FEMA study included channel cross section surveys taken from 1993 and topography derived from orthophotography from 1993 and the estimated flow quantiles shown in Table 21.

7.1.6 Inundation and Breach Progression Mapping

Levee breach inundation modeling and mapping or breach progression analysis has not been conducted for the Town of Skykomish left bank levee system.

7.1.7 Recent CIP Projects

Recent repairs on the Town of Skykomish Left Bank Levee occurred in 1986, 2016, and 2017. Based on paper records at King County there were a number of older repairs of the rock face of the levee dating back to the 1960s. All these repairs involved placing rock on the eroded face of the levee. The two most recent repairs have included coir wraps and willow lifts. The RFI repair history for the Town of Skykomish Left bank levee system is provided in Table 22.

Table 22: King County River Facility Inventory Repair History for SF Skykomish River Levees

Facility Name	Facility Type	River Bank	River Mile[1] Downstream	River Mile[1] Upstream	Repairs listed by year		
Town of Skykomish LB	Levee	Left	15.85	16.42	1986	2016	2017

Note: [1]River mile identifiers refer to upstream and downstream ends of the levee segment, not necessarily the location of the repair.

7.1.8 PL84-99 Status

The Town of Skykomish Left Bank Levee is not in the PL84-99 program.

7.2 Site Visit/Inspections/Pertinent Observations

The Town of Skykomish Left Bank Levee is inspected during floods as part of King County's Flood Patrol program. Post flood inspections are also conducted after significant events on any river and would occur on the South Fork Skykomish for all facilities including the Town of Skykomish Left Bank Levee.

7.3 Data Gaps

Based on review of available studies, and reports the following data gaps have been identified for the Town of Skykomish Left Bank Levee:

- Evaluation of levee materials and construction (geotechnical evaluation)
- Updated hydraulic evaluation to estimate overtopping frequency and duration characteristics
- Breach modeling for overtopping or seepage failures
- Breach flood progression mapping

7.4 Levee and Channel Characterization (Physical Properties)

The construction date of the Town of Skykomish Left Bank Levee is unknown. The levee has been inspected and repaired by King County since at least the 1960s.

Characterization of levee geometric properties (height, top width, side slopes) has not been completed, but could be done using recent LiDAR data. The southern part of the levee consists of earthen embankment levees and ties into high ground at its upstream and downstream ends. Documentation of levee material composition and quality of levee construction was not found.

7.5 Land-Use

The potentially affected portion of the Town of Skykomish landward of the segment of the Town of Skykomish levee that functions as a levee contains residential structures, commercial structures, and a school.

7.6 Hazards

Hazards associated with the Town of Skykomish Left Bank Levee have not been characterized. Flows lower than the 100-year event could overtop the levee near its downstream end. The number and frequency of repairs along the Town of Skykomish Left Bank Levee suggest that the levee is susceptible to erosion.

7.7 Risks

The potential for overtopping the Town of Skykomish Left Bank levee places at risk a number of structures landward of the levee including the residential and commercial structures and the school. Quantifying this risk will require determining the flow rate at which overtopping begins and the depth, duration, and extent of floodplain inundation.

The protection provided by the Town of Skykomish Left Bank Levee is contingent upon maintenance and monitoring of recent repair sites.

8 Findings

8.1 Work That's Been Done

This initial levee characterization evaluated available information for each of the containment levee study areas and identified data gaps and needs for additional study. While it was generally found that the available information on levee breach potential was not adequate to identify specific locations where breaches would be most likely to occur, the evaluation did note that WLRD staff regularly inspect each of the levees approximately every two years or more frequently and conduct additional inspections during and after large flood events. Problems identified during these inspections are prioritized for remediation as part of the County's flood hazard management program. This level of inspection and remediation helps to reduce the potential for levee breaches by correcting obvious deficiencies but the potential for breaching due to internal conditions in the levees, for example seepage or piping, is difficult to characterize for many of the levees because of the lack of necessary data.

Significant subsurface explorations and seepage analyses have been conducted on the Green River levee system, primarily in relation to levee certification studies by the Cities of Kent and Tukwila. The studies include all or part of many King County facilities as highlighted in Figure 6. To certify these levees, the Cities have performed studies to ensure they meet the requirements of Section 65.10 of the CFR including criteria related to embankment protection, embankment and foundation stability, and settlement. It is therefore reasonable to assume that once these levees are certified they have a lower potential for breaching than non-certified levees.

A geotechnical evaluation of the lower Cedar River levee system was completed in 2017 as part of City of Renton's work to recertify the lower Cedar River levees (GeoEngineers, 2017). This evaluation identified two deficiencies which required corrections. The evaluation concluded that once those deficiencies were addressed, the levees would "meet the geotechnical requirements of 44 CFR 65.10 and USACE Engineering Circular EC 1110- 2-6067 'USACE Process for the National Flood Insurance Program (NFIP) Levee System Evaluation' for the 100-year (1-percent-annual-chance) design flood."

For most of the levee systems included in this study, the potential for levee overtopping has been evaluated either as part of a recent FEMA floodplain mapping study or for other hydraulic analysis projects. Recent hydraulic models are available for the Tolt (2011), South Fork Snoqualmie (2014), Cedar River (2016) and Lower Green River (2016). These models generally provide adequate information to determine the frequency and magnitude of overtopping of different levee segments and could be used to analyze conditions within the channel for evaluation of seepage or other non-overtopping breaches. An exception to this is the Raging River for which the most recent hydraulic modeling dates back to the early 1990s. Updated hydraulic modeling would be needed in that system to determine the potential for levee overtopping and to characterize in channel conditions. The South Fork Skykomish River also only has outdated modeling but the hydraulic modeling will be updated in 2018 as part of a new flood study planned by King County RFMS.

As noted previously King County operates a flood warning program to warn residents and agencies of impending flooding on major rivers. In most locations the warning system provides at least 2 hours lead time before floodwaters reach potentially damaging levels. When high water conditions are imminent, the County activates its Flood Warning Center. County staff at the Flood Warning Center monitor gages

continuously and take actions based on anticipated river conditions. The FWC uses a four-phase warning system with the phase indicating the expected severity of flooding and guiding the County's response. When a Phase 3 (moderate flooding) threshold is reached on any of the major rivers in the County, flood patrols are dispatched to observe conditions at flood protection facilities along the river.

8.2 Critical Data Gaps

In general, there is a lack of available data to identify the levee locations most susceptible to geotechnically-related breaches in each of the study areas. The most significant missing data includes comprehensive information on the subsurface composition and condition of the levees and hydrogeologic (groundwater and seepage) analyses. As-built plans are only available for a few of the levees in the study area, specifically those that have been rebuilt recently such as the lower Tolt River setback levee, lower Cedar River levee/floodwall, and Reddington, portions of Briscoe-Desimone, Boeing, Upper Russell, and PL 84-99 repairs conducted by the USACE on the Green River between 2008 and 2016. As described previously, a number of geotechnical and hydrogeologic investigations have been conducted on the Green River and Cedar River levee systems primarily related to levees proposed for certification. Similar studies, at the same level, are not available for the other levee systems.

Hydraulic modeling reflecting current channel conditions is available for most of the containment levees. An exception to this is the lower Raging River where the most recent FEMA hydraulic modeling was based on 1993 channel conditions; although, there is a version of that model with updated (2015) cross-section data that was used to assess gravel removal (but not a flood study). The available modeling for the Raging River is not sufficient to identify locations of potential levee overtopping or the magnitude of overtopping flows on that system.

The only levee system for which any levee breach modeling or breach flood wave progression analysis has been conducted is the Green River. In 2008-2009 NHC conducted an evaluation assuming geotechnical (piping) breaches at 8 locations coincident with the 2-, 10-, 100-, and 500-year floods (NHC, 2009). In 2009-2010 NHC conducted additional hydraulic modeling and analysis for the USACE and King County to evaluate potential overtopping breaches and/or flood wave progression across the floodplain under the "impaired condition" of Howard Hanson Dam (NHC, 2010). The Green River SWIF team evaluated potential inundation and damage resulting from four levee failure scenarios for a range of flood events to support the SWIF Interim Report (King County, 2016). Failure modes considered for the SWIF included levee breach prior to overtopping, levee overtopping with breach, and levee overtopping without breach. The SWIF evaluations used a combination of breach model runs and existing condition model runs to delineate potential consequences of flooding. The SWIF did not, however, evaluate all possible failure locations or prioritize necessary improvements.

Table 23 summarizes the most important data gaps related to evaluation of risks due to potential levee breaches for each of the six containment levee systems.

Table 23: Summary of Data Gaps by Levee System

Containment Levee System	Critical data gaps
Lower Tolt River Levee System	▪ Design documentation or as-built drawings for levees ▪ Geotechnical and subsurface explorations ▪ Seepage Analyses ▪ Identification of locations of highest breach potential ▪ Inundation mapping of potential levee breach hazard area
Lower Raging River Levee System	▪ Design documentation or as-built drawings for levees ▪ Geotechnical and subsurface explorations ▪ Seepage Analyses ▪ River hydraulic modeling for current channel conditions ▪ Identification of locations of highest breach potential ▪ Inundation mapping of potential levee breach hazard area
South Fork Snoqualmie River Levee System	▪ Design documentation or as-built drawings for levees ▪ Additional Geotechnical and subsurface explorations ▪ Seepage Analyses ▪ Identification of locations of highest breach potential ▪ Inundation mapping for seepage or overtopping breach failure
Lower Cedar River Levee System	▪ Seepage Analyses ▪ Identification of locations of highest breach potential ▪ Levee or floodwall breach (failure) analysis ▪ Inundation mapping of potential levee breach hazard area
Lower Green River Levee System	▪ Design documentation or as-built drawings for older levees ▪ Identification of locations of highest breach potential ▪ Inundation mapping of potential levee breach hazard area (some of this is available from SWIF for six areas)
South Fork Skykomish Levee	▪ Design documentation or as-built drawings for levees ▪ Geotechnical and subsurface explorations ▪ Seepage Analyses ▪ River hydraulic modeling for current channel conditions ▪ Identification of locations of highest breach potential ▪ Inundation mapping of potential levee breach hazard area

8.3 Recommendations for Additional Data Collection and Studies

Table 24 provides recommendations for additional data collection or studies needed to adequately characterize flood risk due to levee breaching for each of the King County containment levee systems. It is difficult to prioritize these recommendations between the different levee systems because the level of information currently available does not allow quantification of the potential risks due to levee breaching. It is preferable that the studies listed in Table 24 be conducted for the entire containment levee reach to allow a comprehensive evaluation of risk. However, because future funding is not known at this time thus, this work may be limited, priority segments within each levee system have been

identified based on a qualitative assessment of the potential risk (potential for failure and consequences).

Table 24: Summary of Recommended for Additional Data Collection and Studies by Levee System

Containment Levee System (and prioritization)	Recommended Additional Data Collection or Studies
Lower Tolt River Levee System Priorities: 1) Holberg RB levee 2) Left bank Hwy to Trail Bridge Levee 3) Lower Tolt LB and Frew Upper 4) Lower Frew (currently being studied) and Lower Tolt RB (reconstructed recently and low risk)	▪ Evaluate Levee Breach Potential: Characterize levee geometry (height, width, side slopes, etc.), hydrologic properties (ramping rates, flow durations, peak water levels), and conduct geotechnical analyses, subsurface explorations, and seepage analyses as needed to develop levee probability of failure curves for the levees. ▪ Characterize Risks Due to Levee Breach: Using the levee breach potential data and available hydraulic modeling identify levees with the highest risk due to breaching[2]. Develop maps showing the inundation area resulting from a levee breach and maps showing the progression of breach flood waves across the floodplain for each potential breach location. ▪ Develop emergency action plan, including notification procedures and delineation of evacuation routes for affected residents for any breach locations found to be at high risk of failure.
Lower Raging River Levee System Priorities: 1) LB Mouth to Bridge 2) LB Bridge to Bridge 3) RB Bridge to Bridge 4) RB Mouth to Bridge	▪ Hydraulic modeling of lower Raging River: Develop and apply a new hydraulic model of the lower Raging River to identify locations of potential levee overtopping and to characterize in-channel hydraulic characteristics as need for levee breach evaluations. ▪ Evaluate Levee Breach Potential: Characterize levee geometry (height, width, side slopes, etc.), hydrologic properties (ramping rates, flow durations, peak water levels), and conduct geotechnical analyses, subsurface explorations, and seepage analyses as needed to develop levee probability of failure curves. ▪ Characterize Risks Due to Levee Breach: Using the levee breach potential data and the new hydraulic modeling identify levees with the highest risk due to breaching. Develop maps showing the inundation area that would result from a levee breach and maps showing the progression of breach flood waves across the floodplain for each potential breach scenario. ▪ Develop emergency action plan, including notification procedures and delineation of evacuation routes for affected residents for any breach locations found to be at high risk of failure.

[2] Risk is determined based on both the potential for failure and resultant consequences

South Fork Snoqualmie River Levee System Priorities: 1) Reif Road Levee 2) Bendigo Upper Left Bank Levee	▪ Evaluate Levee Breach Potential: Characterize levee geometry (height, width, side slopes, etc.), hydrologic properties (ramping rates, flow durations, peak water levels), and conduct additional geotechnical analyses, subsurface explorations, and seepage analyses as needed to develop levee probability of failure curves. ▪ Characterize Risks Due to Levee Breach: Using the levee breach potential data and available hydraulic modeling identify levees with the highest risk due to breaching. Develop maps showing the inundation area resulting from a levee breach and maps showing the progression of breach flood waves across the floodplain for each potential breach location. ▪ Develop emergency action plan, including notification procedures and delineation of evacuation routes for affected residents for any breach locations found to be at high risk of failure.
Lower Cedar River levee System Priorities: 1) RB Levee 2) LB Floodwall	▪ Evaluate Levee or Floodwall Breach Potential: Use available data on levee and floodwall geometry, hydrologic conditions, and geotechnical conditions to develop levee and floodwall probability of failure curves. ▪ Characterize Risks Due to Levee Breach or floodwall failure: Using the levee breach potential data and the available hydraulic model identify locations with the highest risk from breaching. Develop maps showing the inundation area resulting from a levee breach and maps showing the progression of breach flood waves across the floodplain for each potential breach location. ▪ Develop emergency action procedures and delineation of evacuation routes for affected residents for any breach locations found to be at high risk of failure.
Lower Green River Levee System Priorities: 1) Levees not previously included in certification studies 2) Other levees	▪ Evaluate Levee Breach Potential: Use levee geometric and hydrologic properties and geotechnical data to develop levee probability of failure curves. ▪ Characterize Risks Due to Levee Breach: Using the levee breach potential data and available hydraulic modeling identify levees with the highest risk of breaching. Develop maps showing the inundation area resulting from a levee breach and maps showing the progression of breach flood waves across the floodplain for each potential breach location. ▪ Develop emergency action plan, including notification procedures and delineation of evacuation routes for affected residents for any breach locations found to be at high risk of failure. ▪ Summarize and synthesize data available from existing CLOMR reports and Tukwila Levee Certification Study.

Town of Skykomish Left Bank Levee System Priorities: 1) Raised levee segment downstream of 5TH St N Bridge	▪ Hydraulic modeling: Develop and apply a new hydraulic model of the SF Skykomish River to characterize potential for levee overtopping and to determine in-channel hydraulic characteristics as need for levee breach evaluations. ▪ Evaluate Levee Breach Potential: Characterize levee geometry (height, width, side slopes, etc.), hydrologic properties (ramping rates, flow durations, peak water levels), and conduct geotechnical analyses, subsurface explorations, and seepage analyses as needed to develop levee probability of failure curves. ▪ Characterize Risks Due to Levee Breach: Using the levee breach potential data and the new hydraulic modeling develop a map showing the inundation area that would result from a levee breach and a map showing the progression of a potential breach flood wave across the floodplain for raised levee segment. ▪ Develop emergency action plan, including notification procedures and delineation of evacuation routes for affected residents if levee found to be at high risk of failure.

8.4 Cost Estimate Ranges for Additional Data Collection and Studies

The recommendations for additional study described in Table 24 generally fall into four categories: 1) hydrologic analysis, 2) river hydraulic modeling and analysis, 3) geotechnical evaluation, and 4) breach inundation mapping and characterization of risks. Updated river hydraulic modeling is required for two of the levee systems, the Raging River and the South Fork Skykomish. RFMS will be initiating a flood study for the SF Skykomish River in early 2019, and this will include new topographic and bathymetric data and the development of a new hydraulic model. That model could be used to evaluate in-channel hydraulic conditions for purposes of a levee assessment. Thus the only levee system that requires development of a new hydraulic model is the lower Raging River. It is estimated it would cost $75,000 to $100,000 to develop a model to support levee breach analyses for that system.

For the other river systems included in this analysis, up-to-date river hydraulic models are already available. These would be used to develop information regarding levee overtopping (location, frequency, duration) and in-channel hydraulic characteristics (stage duration and drawdown rates). Additional hydrologic analysis, including ramping rate and flow duration analysis, would be needed for each of the levee systems. It is estimated that the additional hydrologic and hydraulic analyses would cost $15,000 to $75,000 per levee system, with the exception of the Green River system which would be more costly due to its length and the complexity of flow conditions resulting from hydraulic interactions with Mill Creek and Mullen Slough near RM 23.5.

Geotechnical analysis is needed on almost all of the levee systems. The primary scope elements needed to complete the geotechnical analysis include the following:

- Data gathering and site reconnaissance to identify the areas where analysis is most needed, determine layout of soil borings, and identify levee cross-section survey and right-of-entry needs for further investigations. Document geotechnical conditions along the levee in accordance with USACE Flood Damage Reduction Segment/System Inspection Report guidelines. As appropriate,

the levee would be subdivided into reaches with similar characteristics for focusing subsurface explorations and future analysis.

- Developing a Site Exploration Work Plan and completing a sufficient number of explorations at the inboard and outboard toes and along the levee crest to characterize the levee and adjacent subsurface materials and the levee structural characteristics. Explorations would include borings, test pits, CPT soundings, and potentially geophysics, along with in-situ permeability and strength testing. Obtaining an in-water work permit from USACE will be needed for drilling on the river-side of the levee.
- For purposes of cost estimating the following assumptions are made:
  - Borings and/or CPTs are taken every 500 feet along the levee alignment and are extended to a depth of about 25 feet.
  - Half the borings will be completed as monitoring wells.
  - Test pits to be dug every 500 feet along the levee alignment.
  - Five in-situ hydraulic conductivity tests per mile.
  - Three days of field geophysics data collection per mile.
- Characterize collected samples (i.e. unit weight, soil gradations, Atterberg Limit, moisture content) and perform engineering tests (i.e. consolidation, direct shear).
- Engineering analyses for seepage and underseepage, settlement, embankment stability for levee geometry. Levee structural and slope stability assessment under USACE Case II and Case III, seepage, and settlement analyses:
  - Case II - Rapid drawdown. This case represents the condition whereby a prolonged flood stage saturates at least the major part of the upstream embankment portion and then falls faster than the soil can drain. This causes the development of excess pore water pressure which may result in the upstream slope becoming unstable.
  - Case III - Steady seepage from full flood stage (fully developed phreatic surface). This condition occurs when the water remains at or near full flood stage long enough so that the embankment becomes fully saturated and a condition of steady seepage occurs. This condition may be critical for landside slope stability.
  - Through-seepage and underseepage analysis and continuity across the levee
  - Settlement of the levee embankment will be analyzed using Settle3D to assess the potential and magnitude of future losses of freeboard.
- Development of flood stage versus probability of failure curves (also known as fragility curves) based on the geotechnical conditions of the levee in combination with the levee geometries and hydraulics

The table below summarizes the estimated costs for the geotechnical analyses described above on a per mile basis of levee segment:

Task	Total
Task 1 - Project Kickoff	$3,500
Task 2 - Data Review and Geologic Site Recon	$12,000
Task 3 - Subsurface Explorations[1]	$60,000

Task 4 - Lab Testing		$17,000
Task 5 - Analyses		$25,000
Task 6 - Deliverable		$28,000
Task 7 - PM		$12,500
	Estimated Total Cost Per Mile	$158,000

[1] Does not include permitting costs

A total of approximately 33.33 miles of publicly owned or managed levees are included in this analysis and thus the cost for comprehensive geotechnical analyses of all containment levee systems would be in the range of $5 million. However, the Cedar and Green River levee systems have had considerable geotechnical analyses done on them for certification and other previous studies, therefore it is reasonable to assume the costs for those systems would be lower on a per mile basis. The South Fork Snoqualmie River levees have also had some geotechnical analyses done in recent years between Bendigo Boulevard and I-90, so the level of effort for those levees could be reduced somewhat as well. Estimated adjustments to unit costs for these systems would be as follows:

- South Fork Snoqualmie River – estimated to be 50 to 60 percent of the typical, per mile cost.
- Lower Cedar River – estimated to be 10 to 20 percent of the typical, per mile cost.
- Lower Green River – estimated to be 15 to 40 percent of the typical, per mile cost.

Note however that the breach risk assessment requires fragility curves for all levees so even the Green, Cedar, and SF Snoqualmie Rivers would require some additional work to facilitate levee breach assessments. Cost data for geotechnical analyses are summarized in Table 25.

Once the characteristics of river flows and stages are evaluated and levee fragility curves are developed the levee breach risk analysis would include:

- Simulating floodplain inundation areas and depths associated with specific levee breaches
- Evaluating floodplain land-use and damage potential for each breach location
- Establishing depth-damage functions for floodplain infrastructure
- Estimating damages (costs) due to breach inundations
- Synthesizing breach potential, flood frequency, and damage data into an assessment of risk for each potential breach location

The evaluation of potential levee breach risks (e.g. the combination of breach probability and consequences) is typically done using the USACE Flood Damage Assessment software (HEC-FDA). Preparing the required information for this software would require economic analysis in addition to the hydraulic and geotechnical analyses described above. It is estimated that applying HEC-FDA to each of the seven King County containment levee systems would cost between $500,000 and $1,000,000 and the total cost to develop the necessary data and perform comprehensive levee breach analyses for each of the levee systems included in this study would be between $3.0 million and $4.4 million as summarized in Table 25.

Table 25: Summary of Estimated Costs for Recommended Additional Data Collection and Studies

Containment Levee System	Recommended Additional Data Collection or Study	Cost Range	
Lower Tolt River Levee System	Hydrologic and hydraulic analyses to define channel hydraulics	$25,000	$50,000
	Levee geotechnical analyses and fragility curve development	$607,000	$675,000
	HEC-FDA Modeling and Risk Assessment	$100,000	$150,000
	Sub-total	$732,000	$875,000
Lower Raging River Levee System	Hydraulic model development	$75,000	$100,000
	Hydrologic and hydraulic analyses to define channel hydraulics	$25,000	$35,000
	Levee geotechnical analyses and fragility curve development	$405,000	$450,000
	HEC-FDA Modeling and Risk Assessment	$50,000	$75,000
	Sub-total	$555,000	$660,000
SF Snoqualmie River Levee System	Hydrologic and hydraulic analyses to define channel hydraulics	$35,000	$50,000
	Levee geotechnical analyses and fragility curve development	$494,000	$593,000
	HEC-FDA Modeling and Risk Assessment	$75,000	$125,000
	Sub-total	$604,000	$768,000
Lower Cedar River Levee System	Hydrologic and hydraulic analyses to define channel hydraulics	$25,000	$30,000
	Levee geotechnical analyses and fragility curve development	$38,000	$75,000
	HEC-FDA Modeling and Risk Assessment	$100,000	$150,000
	Sub-total	$163,000	$255,000
Lower Green River Levee System	Hydrologic and hydraulic analyses to define channel hydraulics	$50,000	$150,000
	Levee geotechnical analyses and fragility curve development	$538,000	$1,075,000
	HEC-FDA Modeling and Risk Assessment	$200,000	$500,000
	Sub-total	$788,000	$1,725,000
SF Skykomish River Levee System	Hydrologic and hydraulic analyses to define channel hydraulics	$15,000	$25,000
	Levee geotechnical analyses and fragility curve development	$90,000	$99,000
	HEC-FDA Modeling and Risk Assessment	$15,000	$25,000
	Sub-total	$120,000	$149,000
	Grand Total (rounded)	$3,000,000	$4,400,000

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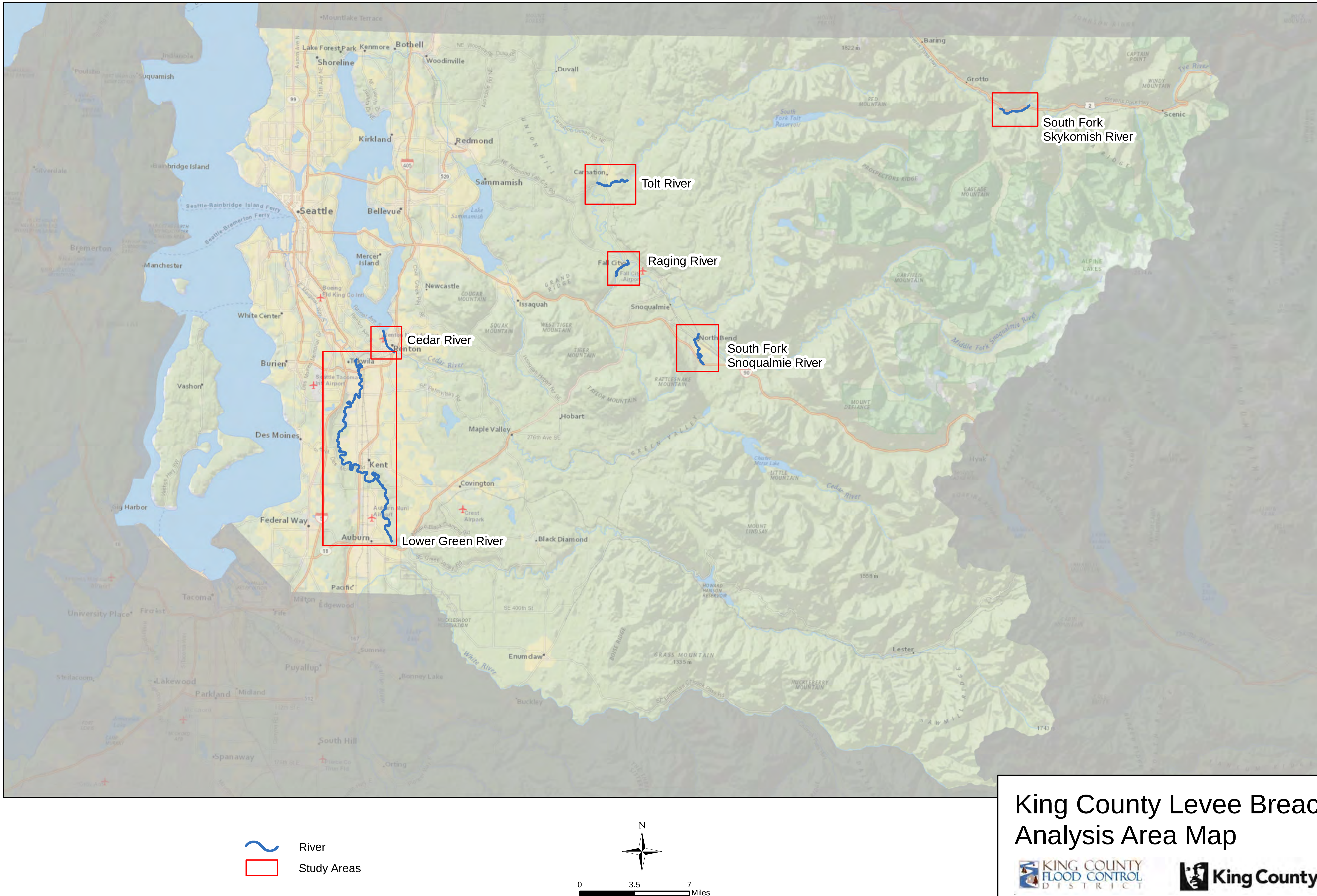
Figures



King County Levee Breach Analysis Area Map

KING COUNTY FLOOD CONTROL DISTRICT

King County

Figure 1

Levee facility names shown are from King County River Facility Inventory (RFI)

Figure 2

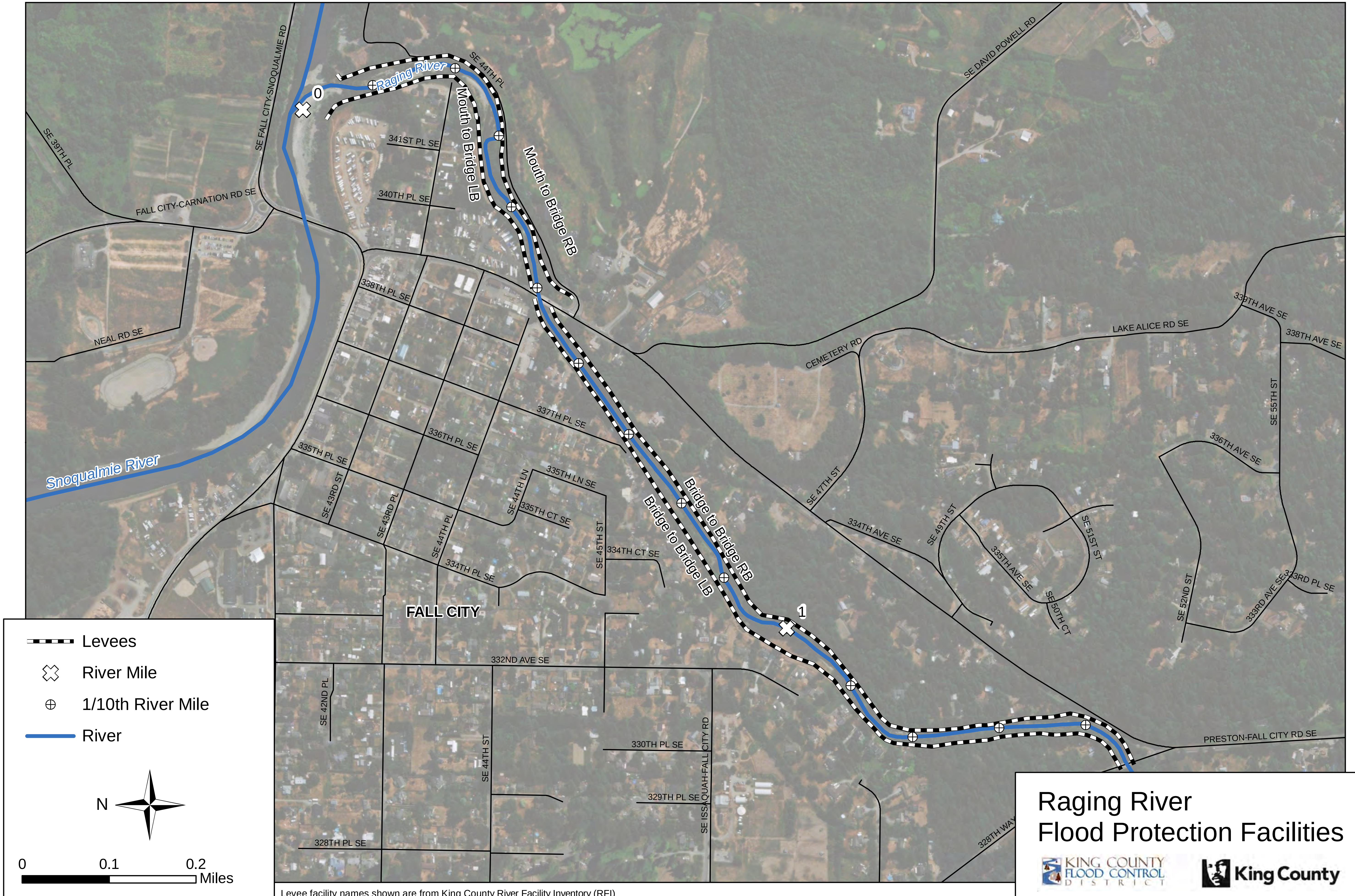
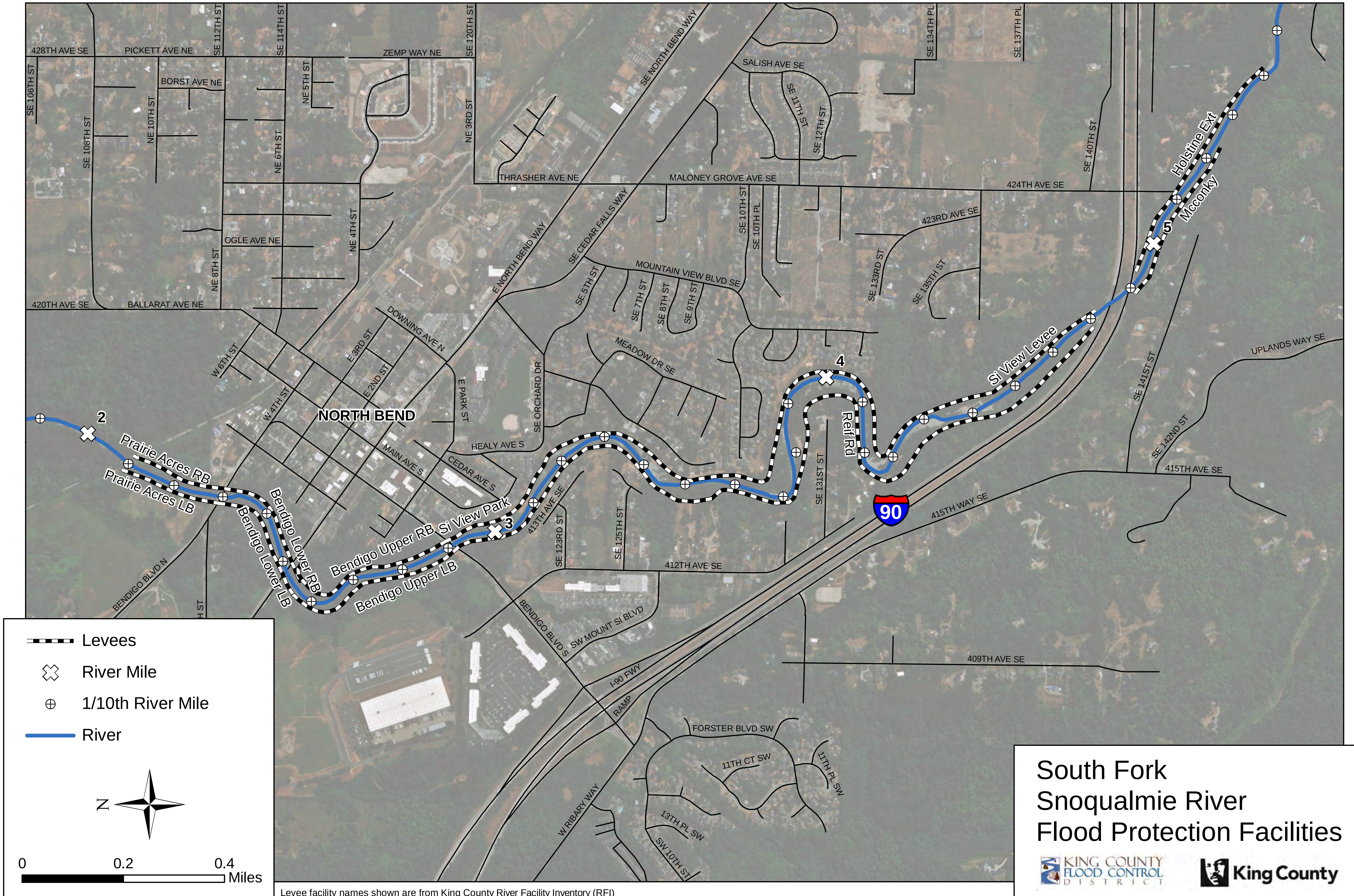
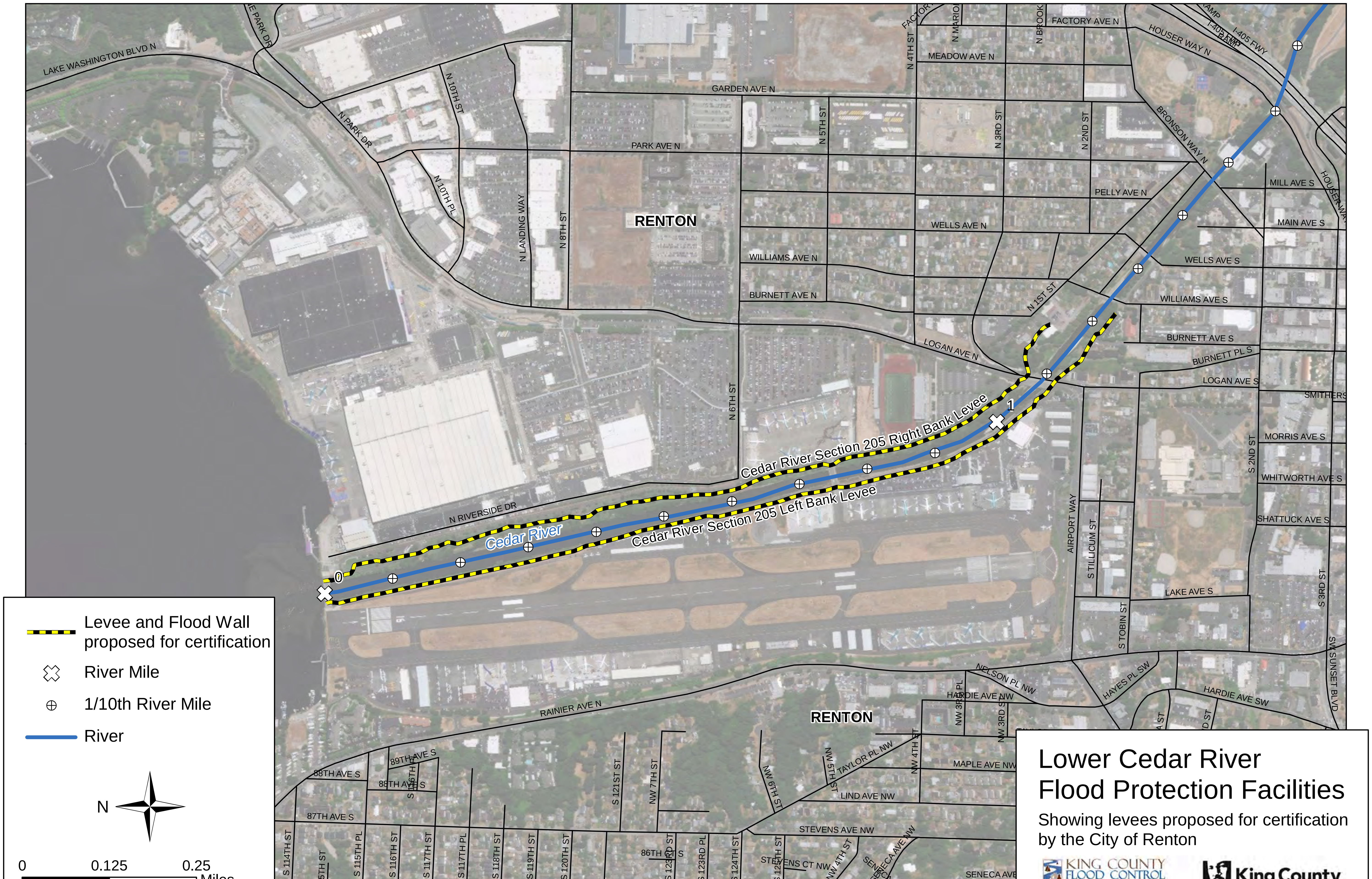

Raging River
Flood Protection Facilities
KING COUNTY FLOOD CONTROL DISTRICT
King County
Levees
River Mile
1/10th River Mile
River
N
0
0.1
0.2
Miles
Levee facility names shown are from King County River Facility Inventory (RFI)
Raging River
Snoqualmie River
Mouth to Bridge LB
Mouth to Bridge RB
Bridge to Bridge LB
Bridge to Bridge RB
0
1
FALL CITY
SE FALL CITY-SNOQUALMIE RD
SE 39TH PL
FALL CITY-CARNATION RD SE
NEAL RD SE
SE 44TH PL
341ST PL SE
340TH PL SE
338TH PL SE
337TH PL SE
336TH PL SE
335TH PL SE
335TH LN SE
335TH CT SE
334TH CT SE
334TH PL SE
334TH AVE SE
SE 43RD ST
SE 43RD PL
SE 44TH LN
SE 45TH ST
332ND AVE SE
330TH PL SE
329TH PL SE
328TH PL SE
SE 42ND PL
SE 44TH ST
SE ISSAQUAH-FALL CITY RD
328TH WAY
SE DAVID POWELL RD
CEMETERY RD
LAKE ALICE RD SE
339TH AVE SE
338TH AVE SE
SE 55TH ST
336TH AVE SE
SE 47TH ST
SE 49TH ST
335TH AVE SE
SE 51ST ST
SE 50TH CT
SE 52ND ST
333RD AVE SE
333RD PL SE
PRESTON-FALL CITY RD SE

Figure 3



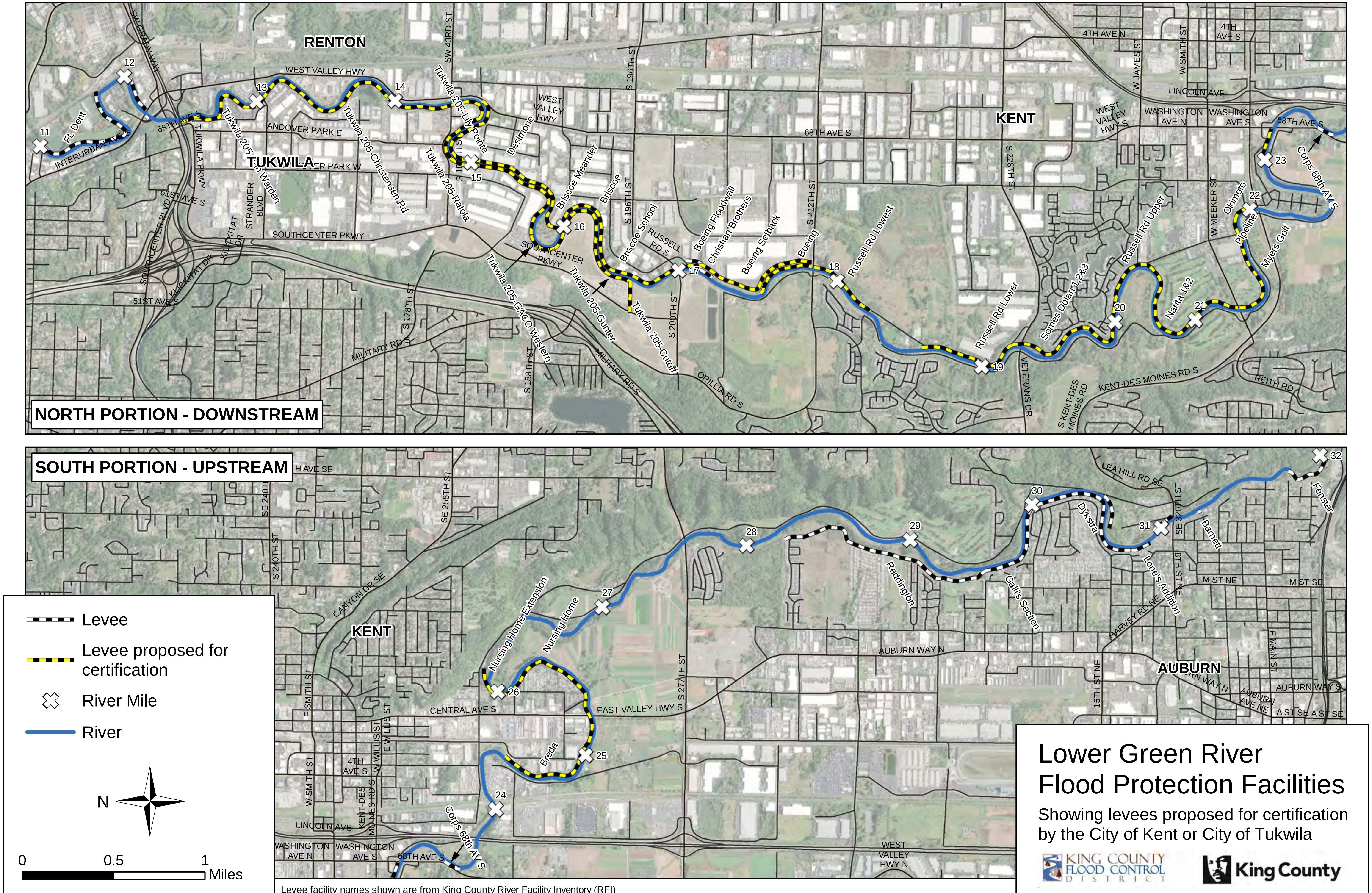
Levee facility names shown are from King County River Facility Inventory (RFI)

Figure 4



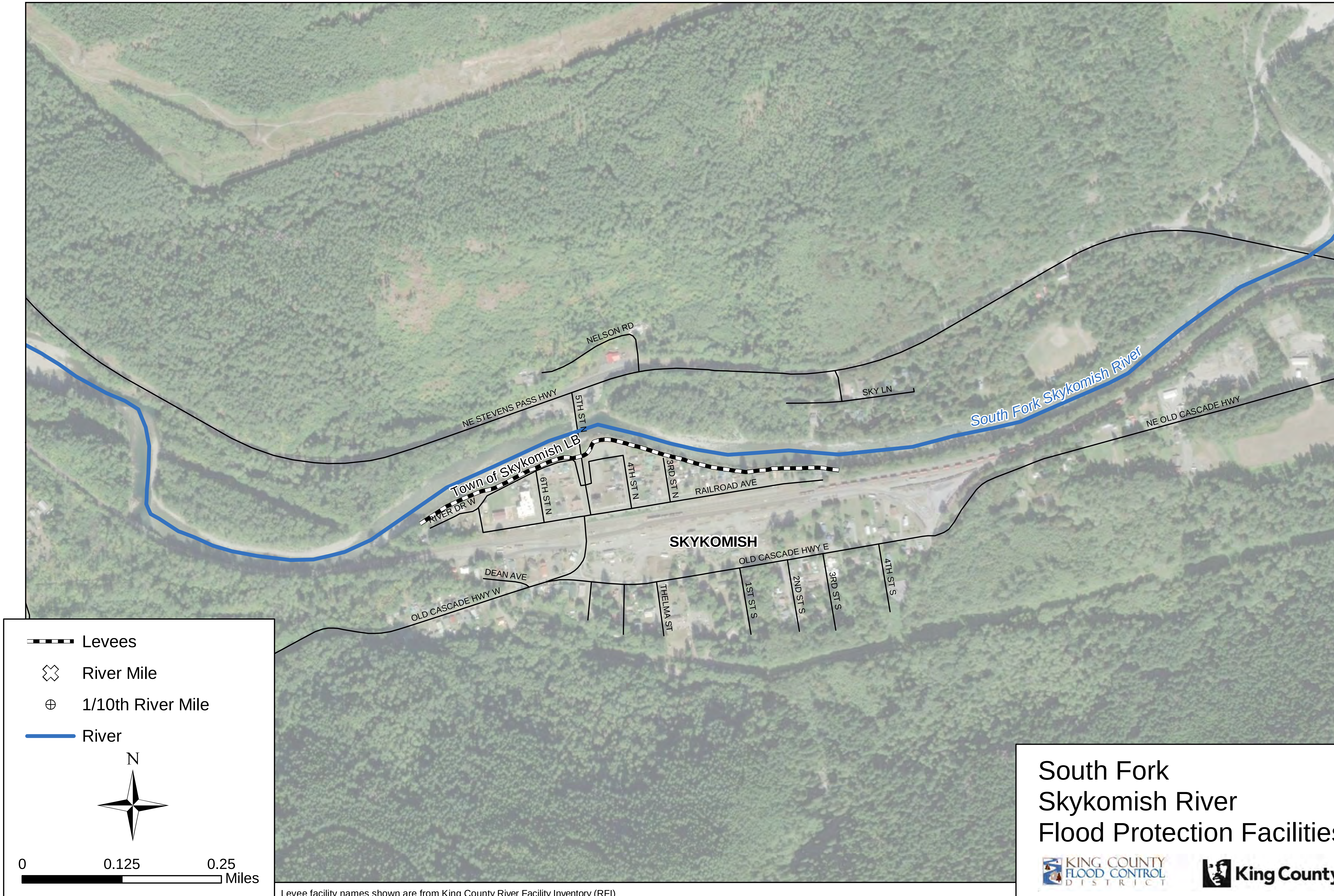
Levee facility names shown are from USACE PL84-99 Program

Figure 5



Levee facility names shown are from King County River Facility Inventory (RFI)

Figure 6



Levee facility names shown are from King County River Facility Inventory (RFI)

South Fork
Skykomish River
Flood Protection Facilities

KING COUNTY FLOOD CONTROL DISTRICT

King County

Figure 7

Appendix A –List of Acronyms

Abbreviation	Definition
CFR	Code of Federal Regulations
DNRP	Department of Natural Resources and Parks
DOE	Department of Ecology
EAP	Emergency Action Plan
ESF	Emergency Support Function
FEMA	Federal Emergency Management Agency
KCFCD	King County Flood Control District
KCOEM	Office of Emergency Management (King County)
KCWLRD	King County Water and Land Resources Division
NFIP	National Flood Insurance Program
WAC	Washington Administrative Code

Appendix B - Glossary of Terms Used in This Document

0.2-Percent-Annual-Chance Flood—The flood that has a 0.2-percent chance of being equaled or exceeded in any given year (also known as the 500-year flood).

1-Percent-Annual-Chance Flood— The flood that has a 1-percent chance of being equaled or exceeded in any given year (also known as the 100-year flood).

2-Percent-Annual-Chance Flood—The flood that has a 2-percent chance of being equaled or exceeded in any given year (also known as the 50-year flood).

10-Percent-Annual-Chance Flood—The flood that has a 10-percent chance of being equaled or exceeded in any given year (also known as the 10-year flood).

10-Year Flood—See 10-Percent-Annual-Chance Flood.

44 CFR Section 65.10 Requirements—See Section 65.10 Requirements.

50-Year Flood—See 2-Percent-Annual-Chance Flood.

100-Year Flood—See 1-Percent-Annual-Chance Flood.

500-Year Flood—See 0.2-Percent-Annual-Chance Flood.

Accredited Levee System—A levee system that FEMA has shown on a Flood Insurance Rate Map (FIRM) or Digital Flood Insurance Rate Map (DFIRM) as providing protection from the 1-percent-annual-chance or greater flood. This determination is based on the submittal of data and documentation as required by Section 65.10 of the NFIP regulations. The impacted area landward of an accredited levee system is shown as Zone X (shaded) on the FIRM or DFIRM except for areas of residual flooding, such as ponding areas, which are shown as Special Flood Hazard Area.

As-Built—A term used to describe mapping and mapping-related data that reflect conditions within a floodplain based on flood-control and other structures being completed.

Base Flood Elevation (BFE) —The elevation of a flood having a 1-percent chance of being equaled or exceeded in any given year.

Berms—Horizontal strips or shelves of material built contiguous to the base of either side of levee embankments for the purpose of providing protection from underseepage and erosion, thereby increasing the stability of the embankment or reducing seepage.

Breach—See Levee Breach.

Critical Features—Integral and readily identifiable parts of a levee or other flood protection system, without which the flood protection provided by the entire system would be compromised.

Digital Flood Insurance Rate Map (DFIRM)—A FIRM that has been prepared as a digital product, which may involve converting an existing manually produced FIRM to digital format, or creating a product from new digital data sources using a Geographic Information System environment. The DFIRM product allows for the creation of interactive, multihazard digital maps. Links are built into an associated database to allow users options to access the engineering backup material used to develop the DFIRM,

such as hydrologic and hydraulic models; Flood Profiles; data tables; DEMs; and structure-specific data, such as digital elevation certificates and digital photographs of bridges and culverts.

Effective Map—The NFIP map issued by FEMA that is in effect as of the date shown in the title block of the map as “Effective Date,” “Revised,” or “Map Revised.”

Eligible Levee—A levee categorized as "active" in the U.S. Army Corps of Engineers (USACE) Rehabilitation and Inspection Program (RIP), for which USACE can provide assistance under Public Law 84-99 to repair damage caused by a flood event.

Federal Emergency Management Agency (FEMA)—The component of the U.S. Department of Homeland Security that oversees the administration of the NFIP.

Federally Authorized Levee System—A levee system that was designed and built by the U.S. Army Corps of Engineers in cooperation with a local sponsor and then turned over to that local sponsor to operate and maintain.

Flood—A general and temporary condition of partial or complete inundation of normally dry land areas from (1) the overflow of inland or tidal waters or (2) the unusual and rapid accumulation or runoff of surface waters from any source.

Flood Fighting—Actions taken immediately before or during a flood to protect human life and to reduce flood damages, such as evacuation, emergency sandbagging and diking, and providing assistance to flood victims.

Flood Insurance Rate Map (FIRM)—The insurance and floodplain management map produced by FEMA that identifies, based on detailed or approximate analyses, the areas subject to flooding during a 1-percent-annual-chance flood event in a community. Flood insurance risk zones, which are used to compute actuarial flood insurance rates, also are shown. In areas studied by detailed analyses, the FIRM shows BFEs and/or base flood depths to reflect the elevations of the 1-percent-annual-chance flood. For many communities, when detailed analyses are performed, the FIRM also may show areas inundated by 0.2-percent-annual-chance (500-year) flood and regulatory floodway areas.

Flood Insurance Study (FIS) Report—A document, prepared and issued by FEMA, that documents the results of the detailed flood hazard assessment performed for a community. The primary components of the FIS report are text, data tables, photographs, and Flood Profiles.

Flood Protection System—Those physical works for which funds have been authorized, appropriated, and expended and which have been constructed specifically to modify flooding in order to reduce the extent of the area subject to a “special flood hazard” and the extent of the depths of the associated flooding. Flood protection systems typically include hurricane tidal barriers, dams, reservoirs, levees, or dikes.

Floodwall—Concrete wall constructed adjacent to streams for the purpose of reducing flooding of property on the landside of the wall. Floodwalls are normally constructed in lieu of or supplement levees where the land required for levee construction is too expensive or not available.

Freeboard—A factor of safety usually expressed in feet above a flood level for purposes of floodplain management.

Hazard—An event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, and other types of loss or harm.

HAZUS - A nationally applicable standardized methodology distributed by FEMA that contains models for estimating potential losses from earthquakes, floods, and hurricanes. HAZUS uses Geographic Information Systems (GIS) technology to estimate physical, economic, and social impacts of disasters.

Interior Drainage—Natural or modified outflow of streams within a levee-impacted area for the conveyance of runoff.

Interior Drainage Systems—Systems associated with levee systems that usually include storage areas, gravity outlets, pumping stations, or a combination thereof.

Levee—A man-made structure, usually an earthen embankment, designed and constructed in accordance with sound engineering practices to contain, control, or divert the flow of water so as to provide protection from temporary flooding.

Levee Breach—A rupture, break, or gap in a levee system that causes flooding in the adjacent area and whose cause has not been determined.

Levee Failure Breach—A rupture, break, or gap in a levee system that causes flooding in the adjacent area and for which a cause of failure is both known and occurred without overtopping. An investigation is usually required to determine the cause.

Levee-Impacted Area—The floodplain area landward of a levee system for which the levee system provides some level of flood protection or risk reduction.

Levee Overtopping—Floodwater levels that exceed the crest elevation of a levee system and flow into levee-impacted areas landward of the levee system.

Levee Overtopping Breach—A rupture, break, or gap in a levee system that causes flooding in the adjacent area and whose cause is known to be a result of overtopping.

Levee Owner – a Federal or State agency, a water management or flood control district, a local community, a levee district, a nonpublic organization, or an individual considered the proprietor of a levee.

Levee System—A flood protection system that consists of a levee, or levees, and associated structures, such as closure and drainage devices, which are constructed and operated in accordance with sound engineering practices.

Non-Federal Levee System—A levee system that was designed, built, operated, and maintained by an entity other than a Federal agency.

National Flood Insurance Program (NFIP)—Federal Program under which flood-prone areas are identified and flood insurance is made available to the owners of the property in participating communities.

Provisionally Accredited Levee (PAL)— A designation for a levee system that FEMA has previously accredited with providing 1-percent-annual-chance protection on an effective FIRM or DFIRM, and for which FEMA is awaiting data and/or documentation that will demonstrate the levee system's

compliance with the NFIP regulatory criteria cited at 44 CFR Section 65.10. A PAL is shown on a DFIRM as providing 1-percent-annual-chance flood protection, and the area landward of the levee is shown as Zone X (shaded) except for areas of residual flooding, such as ponding areas, which will be shown as an SFHA.

Pumping Stations—Pumps located at or near the line-of-protection to discharge interior flows over or through the levees or floodwalls (or through pressure lines) when free outflow through gravity outlets is prevented by high exterior stages.

Ramp Rate – see ramping rate

Ramping Rate – the speed with which flows (and river stages) rise or fall on a river. Some levee failures, especially sloughing failures, and dependent on the rate of fall of the water levels in the river and as such these need to be evaluated as part of the geotechnical investigations of the levee.

Rehabilitation and Inspection Program (RIP)—The Rehabilitation and Inspection Program is the U.S. Army Corps of Engineers' program that provides for inspection of flood control projects, the rehabilitation of damaged flood control projects, and the rehabilitation of federally authorized and constructed hurricane or shore protection projects.

Ring Levees—Levees that completely encircle or “ring” an area subject to inundation from all directions.

Sand Boils—The volcano-like cones of sand that that are formed on the landward side of a levee system when the upward pressure of water flowing through soil pores under a levee (underseepage) exceeds the downward pressure from the weight of the soil above it.

Secondary Levees—Levees that are riverward of the main or principal levees. The level of protection of a secondary levee is always less than the level of protection provided by the main or principal levee.

Section 65.10 Requirements—The NFIP regulatory criteria for the evaluation and mapping of areas protected by levee systems, which are presented at Title 44, Chapter 1, Section 65.10 of the Code of Federal Regulations.

Seepage - The continuous movement of water through the soil of a levee.

Setback Levees—Levees that are built landward of existing levees, usually because the existing levees have suffered distress or are in some way being endangered, as by river or stream migration.

Special Flood Hazard Area (SFHA)—The area delineated on an NFIP map (FHBM, FIRM, or DFIRM) as being subject to inundation by the 1-percent-annual-chance flood. SFHAs are determined using statistical analyses of records of riverflow, storm tides, and rainfall; information obtained through consultation with a community; floodplain topographic surveys; and hydrologic and hydraulic analyses.

Spur Levees—Levees that project from main levees and serve to protect the main levees from the erosive action of stream currents. Spur levees are not true levees; they are training dikes.

Tieback Levees—Levees that extend from the main levees along a river, lake, or coast to bluff line (high ground) and are part of the system of protection.

Training Levees—Levees that are designed to direct flow in a river to protect property from the erosive action of stream currents. Training levees do not provide containment of floodwaters.

Appendix C - list of documents reviewed

Levee Breach Analysis, Phase 1 Reference Document Tracking List		Nov-18
	Document	**Document type**
	Countywide	
1	Hydrology Summary	Digital
2	Climate Change Impacts on Flooding (King County) 2010	Digital
3	King County Dam Safety Emergency Planning Gap Analysis Report (TetraTech) 2017	Digital
4	Dam Safety Staff Report Memo Sept. 26, 2017	Digital
5	Emergency Management Plan ESF 3	Digital
6	2-17-18 King County Flood Warning Instruction Book_Public	Digital
7	1993 King County Flood Hazard Management Plan Appendix B	Scan
8	WDOE Statewide Levee Inventory 2010	Digital
9	Recent Levee Inspection Summary Table	Digital
	Green River	
1	City of Kent Levee CLOMRs	
2	- Horseshoe Bend Levee	Hard Copy
3	- Hawley Road Levee	Hard Copy
4	- Foster Park Levee	Hard Copy
5	- Boeing Levee	Hard Copy
6	- SR 516 to S 231st Way Levee	Hard Copy
7	- Briscoe and Desimone Levees	Hard Copy
8	Tukwila 205 Levee - Certification Study Documentation (NHC)	Not obtained
9	- 205 Levee Geotechnical Boring Data - USACE	Hard Copy
10	Frager Levee (Hart Crowser)	Not located
11	Green River SWIF - especially appendices B&C	Digital
12	Capital Project Reports (various)	Hard Copy
13	Green River Levee Assessment (S&W) 2009	Digital
14	Green River Breach Progression Modeling/Mapping (NHC) 2010	Digital
15	Green River Corridor Plan	Hard Copy
16	EIS for Green River Corridor Plan	Hard Copy
17	Advisory Committee Report for Corridor Plan	Hard Copy
18	Map of Green River Levee Vulnerabilities	Hard Copy
19	Spreadsheet: Lower Green RepairRecords_091213	Digital
20	Desimone Levee Damage Report (Kent) 2014 or 2015 or 2016	Not obtained
21	Segale Levee Design Report (RW Beck and/or S&W) 1996?	Hard Copy
22	Tech Memo 900.20-1, Geotechnical Exploration Methods and Results, Green River Levee Assessment (S&W) 2007	Hard Copy
23	Tech Memo 900.50-1, Deterministic Slope Stability Analyses, Green River Levee Assessment, (S&W), 2007	Hard Copy
24	Seepage and Stability Analyses, Segale Levee Boneyard Development (S&W) 1999	Hard Copy
25	Geotechnical Engineering Services Report, Levee Seepage Evaluation, Proposed Warehouse Building Development, Tukwila (GeoEngineers) 1999	Hard Copy
26	Geotechnical Report, Green River Levee Improvements (S&W) 1988	Hard Copy

	Cedar River	
1	Cedar Falls Dam Breach Analysis (WEST) 2018	Digital
2	USACE 205 Project Annual Inspection Reports, 2013 through 2016	Digital
3	Lower Cedar River Sedimentation measurements and modeling (NHC) multiple	Not obtained
4	Lower Cedar River Levee Geotechnical data (USACE) - Renton Levee Certification Folder, App. I	Digital
5	2016-17 Post-Dredge Cedar River Scour Monitoring Report (nhc for Renton) 2018	Digital
6	Cedar River Flood Damage Reduction Study Project Report (USACE) 1997	Digital
7	Cedar River Corridor Existing Conditions Char. Rpt (Herrera et al) 2017	Digital
8	Logan Avenue Bank Stability Assessment (nhc for Renton) 2017	Digital
9	Flood and Erosion Risk Analysis (Herrera) 2017	Digital
10	Lower Cedar Gravel Study (Perkins) 2003	Digital
11	Cedar River Section 205 Levee System FEMA CLOMR Final (TetraTech for Renton) 2018	Digital
12	Cedar River Corridor Plan, Lower Cedar River HEC-RAS 1D/2D Modeling (WSE memo to KC), 2016	Digital
	South Fork Snoqualmie River	
1	SF Snoqualmie Corridor Plan	Digital
2	SF Snoqualmie Levee Levee Characterization Report	Digital
3	SF Snoqualmie Levee Levee Characterization Report Appendices	Digital
4	SF Levee Deficiency Report	Digital
5	i-90 Flood Risk Reduction Alternatives Analysis Report Appendices (TT), 2017	Digital
	Lower Raging River	
1	Lower Raging River Levee Study (Sue Perkins - early 1990s)	Scan
2	Mouth to Bridge (right) Repair	Verbal
3	Culvert Repair	Verbal
4	Sinkhole Repair	Verbal
5	Table of Data on Levee construction/age/quality for CMZ Study	Digital
6	OEM Evacuation Plan	Not obtained
	Lower Tolt River	
1	Holberg Flood Hazard Reduction Project Design Report, 1994	Digital
2	Lower Tolt Corridor Study	Digital
3	Lower Tolt Reconnection Project	Hard Copy
4	Levee Repair Projects (Girl Scout Camp Levee, 2 others)	Verbal
5	Tolt River CMZ Study (for discussion of Avulsion Pathways)	Scan
6	Lower Tolt River Floodplain Reconnection Project Design Report, 2008	Digital
7	Geotechnical Investigation, Lower Tolt River Floodplain Reconnection Report, 2006	Digital
8	As-Built Drawings, Lower Tolt River Floodplain Reconnection Phases 1&2, 2012	Digital