12787 Gateway Drive South | Seattle, WA 98168 | 206.241.6000 | www.nhcweb.com

nhc
northwest hydraulic consultants

NHC Ref. No. 2004712

September 14, 2021

King County Water and Land Resources Division
201 S. Jackson St., Suite 5600
Seattle, WA 98104

Attention: **Judith Radloff**

CC: **Brian Reznick (Shannon & Wilson)**

Re: **Final Hydrologic and Hydraulic Approach- Lower Raging River**

This document presents the approach to the hydrologic and hydraulic analyses to be performed for the Lower Raging River as part of the Levee Breach Analysis Mapping and Risk Assessment Project (Project). This memorandum is one of the deliverables under King County contract E00670E20, Task 300, subtask 5.

1 GENERAL CONSIDERATIONS

The existing studies and models for both hydrology and in-channel and floodplain hydraulics for the Raging River are limited and dated. There may be valuable information such as relic cross-sections available, but for this river, all-new modeling and hydrologic analyses will be required.

2 HYDROLOGIC APPROACH

The hydrologic approach for the Raging River study area requires significant new analyses, as existing studies on the Raging River are outdated or non-existent. The analyses will include a coincident peak analysis with the Snoqualmie River to determine appropriate boundary conditions for the hydraulic model; a frequency analysis on the Raging River gage (12145500) peak annual flows as well as on the 3hr, 24hr, and 72hr volumes; development of balanced flood hydrographs to use as inflow boundary conditions for the hydraulic model (Section 3); and climate change analyses and scaling of those balanced hydrographs by an appropriate factor to develop future conditions flood hydrographs. This section discusses each of these tasks in more detail.

2.1 Raging-Snoqualmie Coincidence

The scope of work for the lower Raging River calls for a joint-coincidence analysis with Snoqualmie River floods. Gages are located nearby the confluence on both the Raging and Snoqualmie Rivers (Figure 2.1 and Table 2.1). The Raging River gage is located approximately 2.5 miles upstream of the confluence with the Snoqualmie; the gage on the Snoqualmie River (12144500) is located approximately 4 miles upstream of the confluence. Both gages have continuous hourly flow records dating from the late 1980s to present, with long periods of daily data.

Table 2.1 Nearby gages and periods of record

Gage Number	Gage Name	Hourly Data (or finer)	Daily Data	Annual Peaks
12145500	Raging River near Fall City	May 1988 - Present	1945-Present	1945-Present
12144500	Snoqualmie River near Snoqualmie	October 1987 - Present	1898-Present	1958-Present

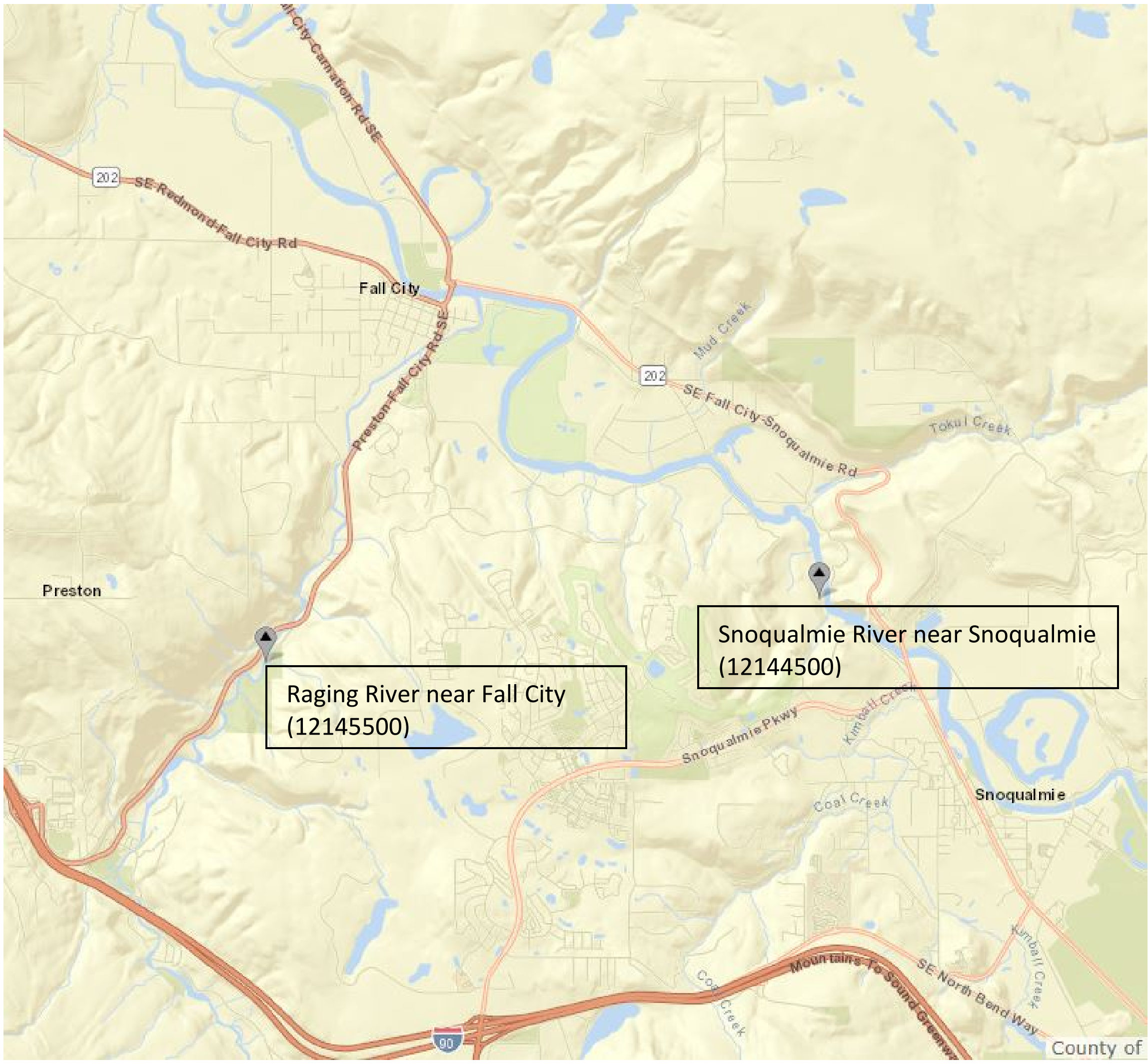

Figure 2.1 Gage locations

The purpose of the joint-coincidence analysis is to understand the effects that Snoqualmie River flows have on flood levels and levee performance in the lower Raging River. To carry out the analysis, NHC will create a 1D HEC-RAS model of the two rivers from their respective gages down through Fall City. The Snoqualmie portion of this model will be adopted from existing models, the Raging portion will be all new and created from recent topobathymetry. The area of interest for this model is the confluence region and the lower portion of the Raging River. The downstream boundary of the model will use an FIS cross-section sufficiently far below the confluence that boundary condition assumptions will have a minimal effect on hydraulics in the area of interest. No calibration is necessary for the Raging portion of the model to conduct the coincident analysis since the model will only route floodwaves; roughness values from the existing FEMA model will be adopted. This 1D model is unique to the joint-coincidence analysis; a more detailed 2D model (described in Section 3) will be developed for the main hydraulic tasks.

The period in which hourly river flow data is available (late 1980s to present) will be simulated in the HEC-RAS model. Based on a cursory review of the hourly gage data, there is a high degree of coincidence in the flow records.

Annual instantaneous peak stages will be extracted at the confluence of the rivers and at locations of interest along the lower reach of the Raging River that may be hydraulically influenced by Snoqualmie River flows. A frequency distribution will be fit to this data to allow estimation of annual exceedance probability stages and uncertainty bounds at each location.

Output from the coincident-peak analysis will be used for several purposes. First, the stage-frequency distribution at the confluence is needed for modeling discrete events and levee breaches as part of the hydraulics task. Each Raging River flood return interval to be modeled will have a target Snoqualmie River stage at the confluence developed from the coincident peak analysis. Second, the variability in stage near the confluence for a given flow within the Raging River will also inform the stage-uncertainty function for the economic model.

2.2 Balanced Hydrographs

A frequency analysis will be performed on the Raging River gage (12145500) peak annual instantaneous flows as well as on the 3hr, 24hr, and 72hr volumes for 1945-2021[1]. The Log-Pearson Type 3 methods described in Bulletin 17C[2] will be used. Balanced hydrographs will then be developed by scaling a historical flood hydrograph to match the frequency results (peak and volume) for a given return period. Hydrographs will be developed for floods ranging from the zero-damage event to the 500-year flood with climate change. Note that because the period of hourly flow records (Table 2.1) is significantly shorter than the annual peaks record, the frequency analysis of the volumes will use a shorter period of record than the analysis of the peaks. In selecting the historical flood for scaling, consideration will be

---

[1] For the current water year of 2021, the peak flow is not yet available and will be replaced by the 15-minute peak flow.

[2] England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2019, Guidelines for determining flood flow frequency—Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.

given to selecting an event with a well-shaped hydrograph that is amenable to scaling. A cursory review of notable floods indicates that the December 2015 event may be suitable for this purpose, but other events will be evaluated.

2.3 Future Hydrologic Conditions

The approach to estimation of future conditions flows was developed in concert with Guillaume Mauger from the UW Climate Impacts Group (CIG). Future conditions hydrographs will be developed by scaling the existing-conditions balanced hydrographs using multiplication factors derived from hydrologic projections for the Raging River at Fall City stream gauge calculated by CIG at the University of Washington[3]. The hydrologic projections used were based on Global Climate Model (GCM) climate projections and the application of the Variable Infiltration Capacity (VIC) hydrologic model. The climate projections were for Representative Concentration Pathway (RCP) 8.5, which represents a future pathway of global greenhouse gas emissions and atmospheric concentrations leading to an average rate of 8.5 Watts/m^2 above pre-industrial net radiative flux. RCP 8.5 is the highest of the future pathways for which a large number of global climate models were run to obtain future climate projections.

Flood quantiles were calculated by CIG for return periods up to 500 years for 1hr, 24hr, and 72hr durations, for each GCM for the historical period and the future time horizon of interest, defined by the water years 1981-2010 and 2040-2069 (the “2050s”). Quantiles were calculated by CIG by fitting a generalized extreme value (GEV) distribution to the series of annual maximum hourly flows.

A step-by-step description of this process is provided below:

(a) NHC will calculate a percent change in peak flow for each GCM and each return period for the 1hr, 24hr, and 72hr durations. This is the ratio of CIG’s 2050s flow quantile divided by the matching observed (current condition) flow quantile. The percent change will vary between GCMs, and the median, minimum and maximum value will be recorded.

(b) Observed flow quantiles (current conditions) will be calculated by NHC as described in Section 2.2. NHC and CIG discussed whether the period of observed data should be adjusted to align with the CIG model’s historical period (1981-2010), but the consensus was that natural variability is greater than any trends in the GCMs during the early part of the 21st century; therefore, all observed annual peak flows will be used to compute the observed flow frequency quantiles.

---

[3] CIG’s stream flow projections for the Raging River at Fall City will be downloaded from the following site. This is an updated dataset that includes peak flow quantiles up to the 500-year level and durations as fine as hourly, compared to the older dataset used for the Tolt River which only included quantiles up to the 100-year level and a 3hr duration:
https://data.cig.uw.edu/picea/mauger/2020_12_SnohoCounty_Flooding/DATA/pub/snoho_wrf_results/RagingRNrFallCity/

(c) The balanced hydrographs (Section 2.2) developed to reflect the observed quantiles in (b) will be modified by applying the median 1hr, 24hr, and 72hr duration percent changes calculated in (a), yielding the expected future conditions balanced hydrographs for the 2050s.

(d) Flood quantile confidence limits are required for input into the HEC-FDA model. For current conditions the confidence limits will be generated using standard methodology from the Bulletin 17C analysis. These confidence limits are generated solely based on the historic gage record. For future conditions, application of statistically based confidence limits based on the short term GCM periods (30-years) results in very large error bands. The approach taken for this study will be to use the highest and lowest of the individual GCM projections as the upper and lower confidence limits. This range of projections represents an attempt to capture some of the very wide range of uncertainty faced in this type of study, which is not possible to quantify completely. Sources of uncertainty include future global emissions of greenhouse gases, natural climate variability, limitations of global climate models, the regional climate model used for downscaling and the statistical adjustment of its results, the application of the hydrologic model, and the fitting of extreme-value distributions to time series of relatively short length.

While the CIG projected peak flows used in this analysis are hourly and the observed quantiles will be based on instantaneous peaks, there is a high degree of correlation between Raging River instantaneous peaks and peak hourly flows, as shown in Figure 2.2. Therefore, the different temporal resolutions of the two datasets is not a concern.

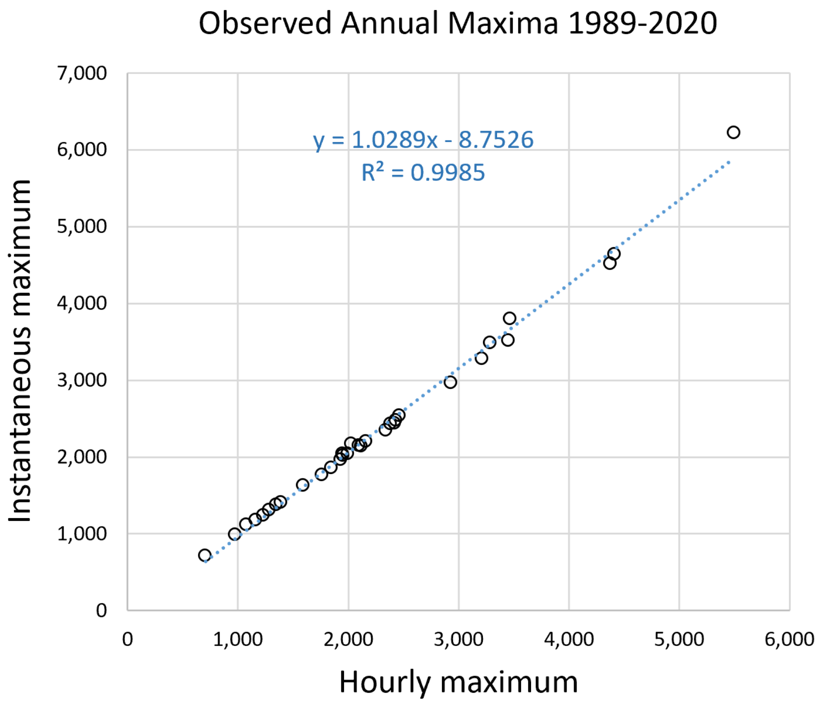

Figure 2.2 Relationship between hourly and instantaneous maximum (peak) flow each water year in the overlapping period of the two records, 1989 to 2020.

3 HYDRAULIC APPROACH

3.1 Model Platform

The hydraulic model will be HEC-RAS version 6.0.0.

3.2 One-Dimensional (1D) vs. Two-Dimensional (2D)

A full 2D model of the lower Raging River and a portion of the Snoqualmie River will be developed. The 'classic' full momentum 2D solver will be used. The model area extents are shown in Figure 2.1.

3.3 Mesh Resolution and Timestep

The project purpose is to accurately characterize floodplain inundation depths and extents under various breach scenarios. In the main channel, accurate water surface elevations are desired, but the ability to resolve fine scale features such as eddies is not required. In addition, there are advantages in terms of both speed and stability to using larger mesh elements. Floodplain mesh elements can also be larger, as extensive use of breaklines will allow larger elements while still providing accurate routing of floodplain flows. For the Raging River, consideration will be given to using small enough cells in the Fall City area that individual building structures can be modeled accurately. For levees, a breakline will be placed along the crest of the levee, and the cell on the landward side will extend beyond the levee toe- this is important for model stability and accuracy during breach simulations. An initial estimate of the number of mesh cells required to cover the domain in Figure 3.1 with cells small enough to resolve buildings in Fall City is approximately 450,000. A HEC-RAS model with this number of cells would be pushing the limit of reasonable run-times; our first attempt at the mesh will include cells small enough to render individual buildings, but we may be forced to coarsen the mesh to obtain a workable model.

HEC-RAS 2D results are often sensitive to mesh size, so the mesh will be constructed to allow simulation of all floods and all potential breach locations without modification of the mesh for any given flood event or breach scenario.

Timestep selection is related to the mesh resolution- finer meshes require smaller timesteps in general. The timestep will be selected such that courant numbers in the main areas of interest within the domain are approximately 2 or less. The 'classic' full momentum 2D solver uses an implicit scheme that is stable and capable of giving good results with courant numbers greater than 1, but the courant number will be monitored to ensure it does not exceed reasonable bounds.

3.4 Surface Representation

The topobathymetry received from King County covers the full anticipated model domain and represents the most up-to-date information available so will serve as the terrain data source for the model except for levee crests, which will be taken from the ground survey. Consideration was given to using the surface from the Fall City Restoration Project, but the bathymetry in that project surface has been superseded by 2020 topobathymetry collected by Quantum Spatial.

The source datasets will be merged and converted to a terrain file in RAS Mapper. The resolution of the terrain will be 3ft or finer.

3.5 Landcover and Roughness

A landcover layer for the study area will be delineated using three data sources: the most recent aerial image available, a buildings layer (discussed separately below), and estimated vegetation height derived from the difference between bare earth and first return LiDAR data (DSM minus DTM). We anticipate delineating approximately 8-12 distinct landcover types. Discretizing the landcover types will be done at a consistent scale throughout the model domain. We will re-use the Fall City Restoration Project's landcover layer for the portion of the model domain that it occupies. Roughness values for each landcover type will be determined by calibration (Section 3.9), literature review, and comparison to the calibrated Fall City Restoration Project model.

Building outlines are available for the majority of structures through the free Microsoft AI buildings layer in GIS. We will compare the most recent aerial image to the Microsoft buildings layer, and manually add any additional buildings greater than approximately 2,000 sq ft that are not included in the Microsoft data. This structure layer will be identical to the one used for the economic analysis. If the selected grid resolution (see Section 3.3) supports typical building scale resolution, then the building outlines will be included in the landcover layer and will be assigned an extremely high Manning roughness value, such as 5-10. This will allow water to enter the buildings, which is important for damage computations, but not actively flow through them, while allowing extraction of depth at the building centroid for the HEC-FDA analysis. If the grid resolution is coarser than the typical building size, then using roughness values that represent the average effects of building blockages and surrounding land will be used.

3.6 Infrastructure

Open culverts 24-inches in diameter or larger that pass through levees, elevated roads and other important hydraulic controls will be included in the hydraulic model possible. Flapgate culverts 48-inches in diameter or larger will be included. Fall City has very limited stormwater infrastructure; two outfalls through the levee were observed during the site visit. A stormwater detention pond with a flapgate outfall to the Raging River was observed along the left bank (RM 0.9), and along the right bank a stream outfall was observed at RM 0.6. While an interior drainage analysis is not part of this scope, we will estimate tailwater conditions at breach locations if necessary, such as at a stormwater pond.

There are two bridges in the proposed model domain; the Preston Fall City Road SE bridge near Fall City and the 328th Way SE bridge at the upstream end of the levee study reach. There are two potential ways these bridges could be represented in the model, depending on the selected terrain resolution and whether the bridge deck interacts with the flow. If the piers are at least as wide as the terrain raster (typically 3 feet) and the bridge deck is well above the water surface in all flows to be modeled, then no specific bridge deck representation is necessary, but in-channel piers will still be represented by incorporating them into the terrain and forcing cell faces to align with pier centerlines. Where bridges may go into pressure flow or the terrain resolution is not fine enough to accurately represent individual piers, the bridge deck and all piers will be added to the model as a bridge structure (rather than terrain edits) using as-built or surveyed information for low chords, piers and railing elevations.

Levees and embankments will be coded into the model as hydraulic structures. The choice of using the 2D equations or weir flow equations over the structure will be dictated by the height of the structure above natural ground, and the expected tailwater conditions at the peak of the flood. For non-breaching levee segments, those with highly inundated tailwater conditions will use the 2D flow equations. Levees that maintain a significant head difference at flood peak (approximately three feet or more) from the river to the floodplain will use the weir equations. For breaching levee segments, the same guidelines will be used to select an initial breach flow equation. However, the 2D equations are generally much more stable for most breach scenarios, especially with high tailwaters and breaching below floodplain elevations. If results from breach modeling using the weir flow equations are not stable, a comparison run using the 2D equations should be performed and differences in results in terms of inundation depths and extents examined. If results are similar, the 2D equations should be used.

The selected calculation method for a levee segment will be fixed for all flows (i.e., do not switch between the weir equation and 2D equations for different floods). Once the levee breach locations are determined, a short unique hydraulic structure line will be created that covers only the breach area and a short distance on either side. This will enable 1) better quantification of breach hydraulics versus potential levee overtopping nearby, and 2) allow the use of 2D equations for the breach even if the adjacent levees are using the weir flow equation.

3.7 Model Extents

The model will encompass the Raging River from approximately 1,000 feet downstream of the Carmichael Road bridge (RM 2.1) to the mouth at the Snoqualmie River. The Snoqualmie River will also be included in the 2D model. Figure 3.1 shows the approximate model bounds that will be used. This boundary is an initial estimate of the region necessary to include to ensure that all building structures that may be impacted by a levee breach are included, and that the boundary conditions are sufficiently far from the main area of interest so as to avoid boundary condition affects. The boundary is subject to refinement as the study progresses and more information about model behavior is gained.

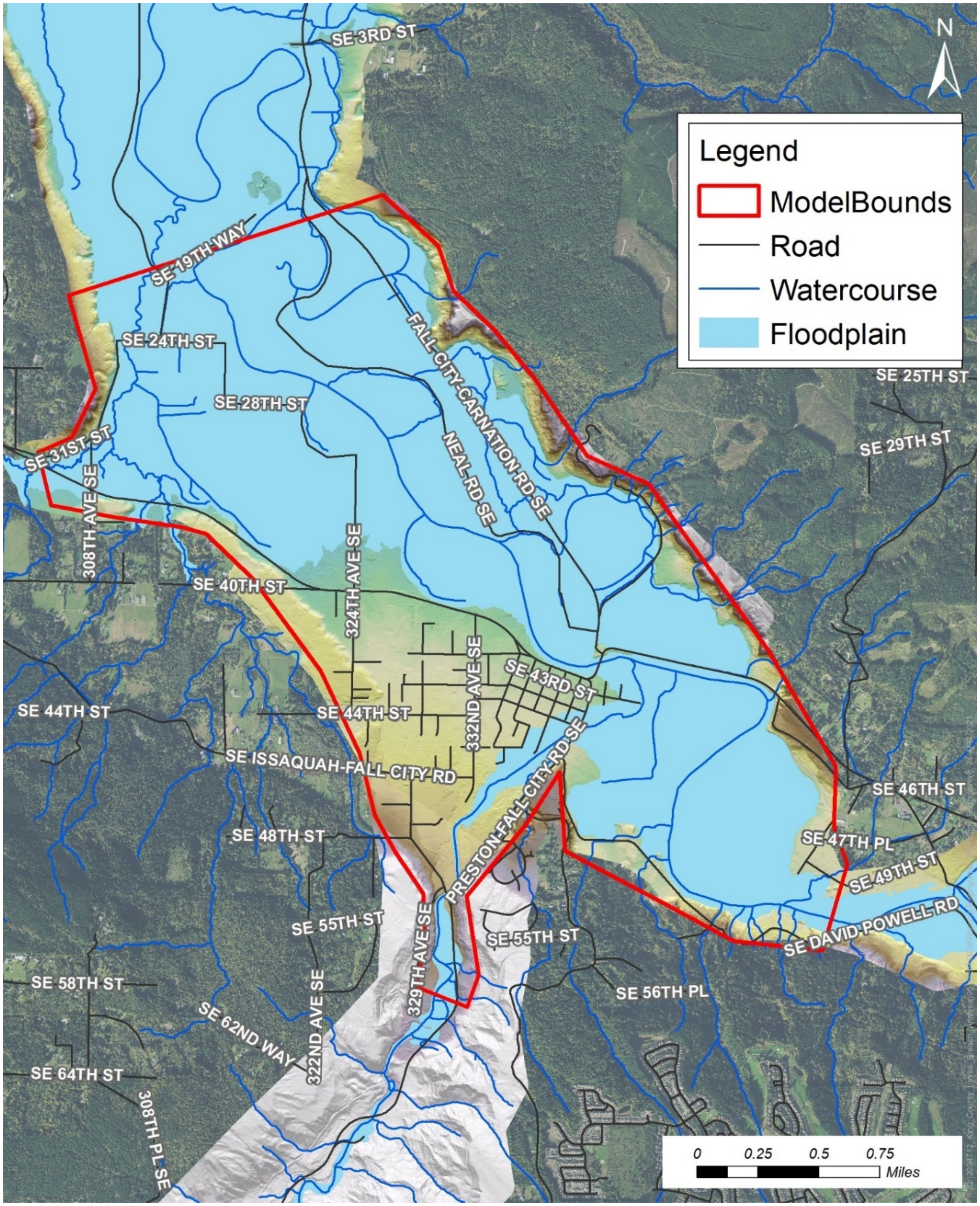

Figure 3.1 Proposed Model Extents (subject to refinement as model development progresses)

3.8 Boundary Conditions

Inflow boundary conditions will be specified for both the Raging and Snoqualmie Rivers. The Raging River inflow will be one of the balanced hydrographs described in Section 2.2. The Snoqualmie River inflow will be a scaled synthetic hydrograph informed by the joint coincidence analysis. This hydrograph will be adjusted such that the model produces the target stage at the confluence determined by the joint coincidence analysis. Note that the Snoqualmie River inflow does not need and will not have a return period associated with it, although based on the apparent close degree of coincidence we expect the Snoqualmie River inflows will have return periods that approximately match the magnitude of the Raging River inflow event return period. CIG projections and/or well shaped historic floods will be used as a starting point for the Snoqualmie River scaled hydrographs. The downstream boundary will be a rating curve from either the existing FEMA Snoqualmie River model or the Fall City Restoration Project RiverFlow2D model.

3.9 Calibration

The Snoqualmie River portion of the model will be calibrated by comparison to oblique air photos provided by King County, and by comparison to other King County models in the vicinity (FEMA FIS HEC-RAS model, Fall City Restoration Project RiverFlow2D model). The Raging River portion of the model will be calibrated using high-water marks and oblique air photos provided by King County. Because the Raging River lacks direct connections to the floodplain, it will be difficult to identify reliable water levels from the air photos. There is one area with a large, relatively flat bench inside the left bank levee near RM 1.0 that will be examined closely to help identify flood water levels from the photos.

The calibration will vary the main channel roughness values to match the observed data to the degree possible. A model result within a half-foot of the observed data is considered a good match, as there are a number of plausible reasons for this degree of divergence (estimation error of high-water marks, gage measurement error of boundary conditions, a model's inherent inability to resolve every feature of the bed). The flood event(s) chosen for the calibration will be determined by data availability and recency; it appears there will be little High-Water Mark (HWM) data available for calibration of the Raging River. A search for flood photos on the King County iMap site shows photos of the Raging River during November 2006, January 2009, and December 2015. Of these, the 2006 flood photos appear most valuable for estimating HWMs as this is the only flood that inundated the flat bench near RM 1.0.

3.10 Sensitivity Testing

Sensitivity testing will be performed on the calibrated model. Initial tests will determine optimum mesh resolution. Other sensitivity tests that will be run include:

1. Time step
2. Roughness
3. Downstream Boundary Condition
4. Weir Flow Coefficients (if using weir flow equations for levees)

The effects of these values on water surface elevations will be considered when entering stage uncertainty functions in HEC-FDA. Flow sensitivity will be evaluated by running the suite of balanced hydrographs needed for HEC-FDA.

3.11 Quality Control

A Quality Control (QC) check will be performed by an experienced HEC-RAS modeler not directly involved in the model development. This QC check will occur at key stages in model development: model geometry, hydrology and calibration, and calculation settings and results. The QC process will be documented in the subtask 6 Hydrology and Hydraulics Technical Memorandum. The Federal Highway Administration 2D model checklist provided by the County will be adopted for QC purposes for this project.

3.12 Levee Breach Simulations

A detailed levee breach methodology for subtask 7 work will be provided separately.

Sincerely,

Northwest Hydraulic Consultants Inc.

ALEXANDER JAMES ANDERSON
50821

Alex Anderson, PE