Lower Skykomish River Channel Migration Zone Study

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Executive Summary

Purpose

Like most rivers occupying alluvial floodplains, the Skykomish River moves across its floodplain. This lateral "channel migration" can occur gradually over time as the river erodes one bank and deposits sediment along the other bank. It can also occur suddenly when a channel shifts abruptly to a new location. Channel migration represents a different type of flood hazard than inundation by overbank flow. The area of a floodplain or adjacent uplands that are at risk of encroachment by future channel migration, within a specified timeframe, is referred to as the channel migration zone (CMZ).

The purpose of this study is to delineate a Lower Skykomish River CMZ and identify channel migration hazard areas in a study area extending from river mile (RM) 23.5 (about 3 miles upstream of the city of Gold Bar, Washington) downstream to the confluence with the Snoqualmie River. The results of this study will inform other ongoing evaluations of the risk of flooding and associated riverine hazards associated with high water and resulting channel dynamics.

Study Area Characteristics

In the study area (see Appendix A), both the natural geologic setting and constructed structures strongly influence channel-migration characteristics. The Skykomish River occupies a valley shaped by multiple advances of glaciers, some of which flowed down-valley out of the Cascade Mountains and others that were part of the great continental ice sheets that originated much farther north, advancing down the axis of the Puget Lowland and so pushed *up* the Skykomish River valley along the ice sheets' eastern margin. Today, the valley bottom is largely underlain by gravelly sediment, deposited by the rivers issuing forth from the margin of the most recent ice sheet as it retreated back to the north (about 16,000 years ago) or from the modern-day Skykomish River, and less commonly by clay or bedrock (Booth 1990).

The Skykomish River is a free-flowing, largely unregulated system with only a few tributaries feeding the mainstem along the 23.5 miles of the study area. Riverbank armoring as well as the armored embankments of the BNSF Railroad and US Highway 2 have restricted channel migration across portions of the river's floodplain, together with a number of other public and private levees and revetments. However, active channel migration is common in many locations and has been recorded by maps and aerial photographs dating back to the late-nineteenth and early-twentieth centuries.

For purposes of both analysis and discussion, the study was divided into seven subreaches, varying from 1.2 to 5.2 river miles in length (see Appendix A). Subreach boundaries were drawn on the basis of observed changes in geomorphic form or riverine behavior. The boundaries of the lowermost four subreaches (from the confluence with the Sultan River to the confluence with the Snoqualmie River) are identical to those defined by Snohomish County (2018) for this same 13.5 miles of the Lower Skykomish River.

Methods

This study and its resultant maps rely on historical channel migration patterns and rates to predict future channel migration hazard. Lower Skykomish River channel migration was evaluated and mapped using information from existing studies, field observations, and analyses conducted in a Geographic Information System (GIS). Patterns of channel migration were characterized using historical aerial photographs dating from 1938 through 2018, historical maps dating from 1897 and 1921, and digital topographic information developed from LiDAR (Light Detection and Ranging) collected in 2014 and 2016 (the latter being part of a multi-year program commonly referenced as "the 2017 LiDAR" set).

Channel migration hazards in the Lower Skykomish River were mapped by identifying the component parts of a CMZ as specified by the Snohomish County Code 30.62B.330 (*Erosion Hazard Areas - Channel Migration Zones*) and consistent with Washington State Department of Ecology guidance. CMZ components are defined as follows and described below:

$$CMZ = HMZ + AHZ + EHA – DMA$$

where:

HMZ = Historical Migration Zone,

AHZ = Avulsion Hazard Zone,

EHA = Erosion Hazard Area = Erosion Setback (ES) + Geotechnical Setback (GS), and

DMA = Disconnected Migration Area.

The Skykomish River HMZ includes the area occupied by channels from 1897/1921 to 2018. An "expanded HMZ" ("eHMZ") was also mapped wherever floodplain elevations and landforms adjacent to the HMZ boundary strongly suggested equivalency in geomorphic processes and age. The AHZ includes those areas outside of the HMZ or eHMZ potentially subject to a rapid shift of channel location. An ES was added to the outermost limit of the modern (2018) channel and/or AHZ, using a width calculated from measurements of representative channel-migration rates into different types of terrace deposits throughout the study area, and extrapolating these rates over 100 years of migration. A GS was added to the edge of the ES wherever the latter lay across a terrace higher than 20 feet above the low-water level of the modern channel, to accommodate the potential for additional top-of-slope retreat from erosion at the toe. The DMA was mapped to exclude areas landward of artificial structures deemed likely to limit channel migration, identified on the basis of a public maintenance commitment or prior performance.

Once the CMZ components were mapped and combined to delineate the outer edge of the CMZ, severe and moderate hazard areas were locally discriminated within the overall CMZ on the basis of prior migratory behavior and proximity to the active channel.

Delineation of the CMZ

An unconstrained CMZ was mapped as the combination of the HMZ/eHMZ + AHZ + EHA (comprising the ES and GS). The unconstrained CMZ does not recognize artificial constraints and therefore predicts channel migration in the absence of levees, revetments, and infrastructure. In a majority of the study subreaches, the width of the HMZ/eHMZ constitutes most of the width of the unconstrained CMZ.

The unconstrained CMZ mapping was modified in two ways to produce the CMZ map. First, the DMA was mapped to recognize that certain artificial structures can restrain channel migration. Seven such structures with a maintenance commitment from Snohomish County, the State of Washington, and the BNSF Railroad were considered likely to prevent channel migration. Although other restraining structures lacking these commitments were mapped, they were not included as barriers to migration.

A second modification to the unconstrained CMZ mapping was that severe and moderate hazard areas were mapped within the overall CMZ. Severe hazard areas are composed of the entire eHMZ, those AHZs that originated from the 2018 active channel, and part or all of the EHA (depending on subreach). The present-day active channel is always mapped within the eHMZ and so is a severe hazard area. Using these conventions, the severe hazard area occupies most of the width of the CMZ throughout the study area. Where the mapped area of severe hazard did not extend to the edge of the constrained CMZ, a moderate hazard area was defined in recognition of the reduced (but still present) risk of future channel migration into areas more distant from the active channel.

The result of these two modifications to the constrained CMZ completes the mapping of the Lower Skykomish River CMZ.

This study is based on the use of historical information to predict future hazard; these methods are consistent with the mapping protocols adopted by Snohomish County and with accepted practices and guidance from the Washington State Department of Ecology. They are also largely consistent with, and should be compatible with, the approach taken by King County (2017) for the South Fork Skykomish River, just a few miles upstream of the upper end of the present study area. However, the study is not fully consistent with the Snohomish County Code in that it has not rigorously followed the Forest Practice Board methodology.

Because of the variety of factors affecting channel migration, the river is not assured of occupying all parts of the mapped CMZ within the next 100 years. Conversely, unanticipated changes to future climate, river management, or local conditions may result in the channel, however unlikely, occupying portions of the valley floor beyond the limits of the mapped CMZ at any time in the near or distant future.

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1 Introduction

Over time, the Skykomish River moves across its floodplain. This channel migration can occur gradually as the river erodes one bank and deposits sediment along the other; it can also occur abruptly, when a channel shifts into a new or previously occupied location. Significant amounts of both "gradual" channel migration and abrupt channel shifts may happen during a single flood event.

Channel migration represents a different type of flood hazard than inundation by overbank flow. It can endanger properties located outside of the regulatory floodplain shown on flood hazard and flood insurance maps. Although both channel migration and flood inundation are hazards that may result from flooding, there is no specific correlation between the mapped boundaries of these two distinct hazard areas. The area subject to channel migration hazard within a given timeframe is referred to as the channel migration zone (CMZ). Encroachment through channel migration poses a potential hazard to houses, transportation corridors, and any other permanent structure anywhere within a CMZ.

The historical approach to addressing potential damage from channel migration has been to armor riverbanks with levees or revetments. However, such bank armoring can be expensive to construct and is subject to ongoing flood damage, which requires costly recurring maintenance work. Bank armoring reduces but does not necessarily eliminate the potential for channel migration, and armoring may actually increase the hazard by encouraging development in areas that may still be at risk from either flooding or failure of the armor during an extreme event. It can also create substantial impacts to aquatic habitat.

1.1 Report Purpose

The purpose of this report is to delineate a Lower Skykomish River CMZ and identify channel migration hazard areas in the study area, which comprises the reach of the river extending from river mile (RM) 0.0 (confluence with the Snoqualmie River) to RM 23.5 (just upstream of the river crossing of US Highway 2 above the town of Gold Bar, Washington).

This Lower Skykomish River CMZ map and study relies on historical channel information recorded on multiple maps and airphotos spanning 1897 to 2018; the resultant hazard mapping portrays the past and expected potential for channel movement over time. The results of this study may inform the planning and development of programmatic and capital flood risk reduction projects, and it should be used to highlight areas within the Lower Skykomish River valley that may be at risk from future channel encroachment. It can also identify revetments and other channel-restraining facilities that are important to the current and future protection of buildings and infrastructure.

1.2 Report Approach

This Lower Skykomish River CMZ study provides an overview of geomorphic, geologic, physical, and structural factors affecting channel migration in the study area. Mapping methods and criteria are described in detail. Historical channel migration patterns and rates are evaluated as the basis of predicting future channel migration hazard, making use of guidance provided by Rapp and Abbe (2003), Olson et al. (2014), and the Washington State Department of Ecology (Ecology; 1994–2014). The final determination of channel migration hazard areas is presented in six sets of maps, provided as Appendix A to this report.

For purposes of both analysis and discussion, the study was divided into seven subreaches, varying from 1.2 to 5.2 river miles in length (Map 1, Appendix A). Subreach boundaries were drawn on the basis of observed changes in geomorphic form or riverine behavior; the lowermost four subreaches (from the confluence with the Sultan River to the confluence with the Snoqualmie River) are identical to those defined by Snohomish County (2018) for this same 13.5 miles of the Skykomish River.

1.3 Timeframes Relevant to this Study

A CMZ is defined as the area through which channel migration is predicted to occur within a given timeframe (Ecology 1994–2014; Rapp and Abbe 2003). The timeframe used in this study to map channel

migration hazard is 100 years, consistent with planning timeframes used in documents from the Federal Emergency Management Agency (FEMA) (2013). Coincidentally, it also corresponds almost exactly with the earliest mapping that covers the entire study area (the US Geological Survey [USGS] topographic map of 1921, as supplemented in the lower part of the valley by a map from the late-nineteenth century).

Although the information and methods used in this study constitute the best available science, channel migration is a dynamic process, and the CMZ maps now prepared may become outdated as basin conditions change, new information becomes available, or new analytical tools are developed. As just one example, any geomorphic effects of the peak discharge of February 1, 2020 (likely a decadal flood) have yet to be incorporated into this analysis. Although they are not expected to change the fundamental conclusions or mapped zone boundaries, full analysis of this flood's effects will undoubtedly improve the predictive quality of this study or its successor(s).

1.4 Conventions Used in this Report

The primary units of measurement in this report are United States customary units, but International System of Units (SI units) are also included where convenient. Elevations are based on the NAVD88 vertical datum. Elevations from USGS topographic mapping are corrected to the NAVD88 datum.

Locations along the river are generally identified using river miles. For this report RM 0.0 is located at the confluence of the Skykomish River and the Snoqualmie River (about 3 miles below the City of Monroe) and increase upstream. River miles are established along a channel centerline, and river miles used in this report were developed using orthophotography flown in 2018 and provided by Snohomish County. Note that river miles used in other reports may have different starting points or may be based on a centerline developed from other map sources from different years, and therefore may not coincide precisely with the river miles used here.

Where the discussion refers to features on one side of the river (or river valley), the features are referred to as being either on the "right" or "left." In this report (and, typically, all such reports), this refers to the right or left hand of an observer looking downstream along the channel or valley.

2 Channel Migration Processes in the Study Area

Channel migration occurs by two primary processes in the study area: avulsion and lateral migration. Upstream of the town of Sultan and the confluence with the Sultan River, the main type of channel migration affecting the Lower Skykomish River is avulsion (although lateral migration also occurs); downstream, lateral migration is the dominant process (although avulsions also occur). Avulsion is the rapid and often dramatic shift in the location of the channel (Figure 2-1), typically during a single flood event and often into a prior channel location still expressed at relatively low elevation across the floodplain. Once a high flow breaches the boundaries of the existing channel, it may flow into such low areas in the floodplain and rapidly erode away any intervening high ground that confined its original path.



Figure 2-1 Example of avulsion on the Skykomish River near RM 15.3. 1990 aerial photo at left, 2007 at right (both from Google Earth); flow is right to left with the BNSF Railroad across the top of both images. Note the circled patch of trees that persisted throughout this period, indicating that the channel jumped to the upstream side of this image rather than migrating across the floodplain continuously from south (bottom) to north (top). Images are about 0.6 mile in extent from right to left (east to west).

Lateral channel migration, in contrast, occurs as a more gradual and progressive combination of bank erosion along one riverbank coupled with sediment deposition and revegetation of the opposite bank (Figure 2-2). The result is net movement, or migration, of the channel across the valley bottom. There also may be a down-valley component to the lateral migration. Through time, the down-valley component will result in an area between successive river meanders being affected by channel migration, not just the area extending outward from the channel.



Figure 2-2 **Example of lateral migration on the Skykomish River near RM 0.7. White lines trace the bank position in the year indicated; base image from 2018 (Google Earth). Note the variability in migration rates; in particular, the largest change displayed (2005–2007) spans the flood of record (November 2006). Locally, annual rates of migration exceed 50 feet of bank retreat per year, although the long-term average here is less than half this rate.**

3 Methods

This CMZ study and resultant map rely on historical channel migration patterns and rates to predict future channel migration hazard. Channel migration on the Lower Skykomish River was evaluated and mapped using information from existing studies, field observations, and analyses conducted in GIS Esri ArcMap 10.4. The zones of channel migration hazard were then mapped by identifying the component parts of the CMZs.

3.1 Review of Existing Studies

Information from several existing studies of the geology, geomorphology, hydrology, hydraulics, land use, and other aspects of Skykomish River channel migration forms the foundation of this study. These existing studies include:

- A USGS-published geologic map at 1:50,000 scale that includes nearly the entire the study area down to RM 2 (Booth 1990);
- A geomorphic study of the lower 13.5 miles of the Skykomish River (De Vries 2010);
- An assessment of conditions and conceptual project opportunities between RMs 10 and 13 (Kopp 2017);
- A prior CMZ study of the South Fork Skykomish River, with its downstream end just a few miles upstream of the present study area (King County 2017); and
- A plan for land uses and other actions in the Lower Skykomish River (RMs 0–13.5) (Snohomish County 2018).

3.2 New Field Data Collection

Fieldwork specifically for this study included eight field visits, covering various segments of the study area by raft, from August through October 2019. Fieldwork included identifying bank materials, mapping the extent of bank hardening, identifying the extent of bedrock outcrops on channel banks, conducting pebble counts, assessing avulsion pathways, documenting bank and bar conditions, and assessing slope instability and associated mass-wasting deposits. Field notes, georeferenced photographs, and various locations obtained using a handheld global positioning system (GPS) unit (with a typical positional accuracy of 3–5 meters) were recorded during these visits.

3.3 Historical and Current Information Used in Report

Historical channel positions of the Lower Skykomish River were digitized primarily using historical aerial photography, supplemented with historical maps and Light Detection and Ranging (LiDAR) imagery. Most of the aerial images used in this study were acquired and digitized by Snohomish County staff prior to the initiation of this study. Historical channel locations were digitized in GIS from georectified aerial photos dated 1938 through 2003; orthorectified digital aerials from 2007 to 2018; and georectified maps published by the USGS, one in 1897 (for only the downstream-most 1.8 river miles) and the other in 1921 (covering the remainder of the study area) (Table 3-1). The digitization process included mapping of what is termed here the “active channel” for each photo year, which included a composite of the low-flow channel, bare gravel bars, and patches of apparently young, sparse shrubby vegetation (Collins and Montgomery 2002; O’Connor et al. 2003). All of these images, and the digitized products derived from them, were used to evaluate historical channel change in the study area, although the quantitative analysis of channel migration was conducted only using the GIS tracings from the airphotos from 1938, 1965, 1991, and 2018. The 1897 and 1921 maps could not be sufficiently well-registered with the later airphotos to be useful in the quantitative analysis, but they were invaluable in characterizing the historical extent of channel occupation across the floodplain.

Table 3-1 Imagery Used in the Delineation of Channel Positions

Year	Source	Type	Scale or Resolution	Used to Calculate Rates?
1897	US Geological Survey	Map	1:125,000	
1921	US Geological Survey	Map	1:125,000	
1938	US Army Corps of Engineers	Aerial photo	1:4,800	X
1965	HG Chickering Jr. Inc.	Aerial photo	1:4,800	X
1969	S.A. Newman Forest Engineers Inc.	Aerial photo	1:4,800	
1978	S.A. Newman Forest Engineers Inc.	Aerial Photo	1:4,800	
1984	S.A. Newman Forest Engineers Inc.	Aerial photo	1:4,800	
1991	Sound Aerial Surveys	Aerial photo	1:4,800	X
1998	WA Department of Natural Resources	Aerial photo	1:4,800	
2001	WA Department of Natural Resources	Aerial photo	1:4,800	
2003	Triathalon	Aerial photo	1:4,800	
2007	Snohomish County	Digital aerial	1 ft/pixel (1:610)	
2011	National Agriculture Imagery Program	Digital aerial	1 m/pixel (1:2,000)	
2015	National Agriculture Imagery Program	Digital aerial	1 m/pixel (1:2,000)	
2018	National Agriculture Imagery Program	Digital aerial	0.5 ft/pixel (1:305)	X

The four sets of images, identified in the right-most column in Table 3-1, were selected for quantitative analyses based on their mapping accuracy and their coverage of approximately equivalent time intervals. The 1897 and 1921 USGS maps were useful in assessing general channel character but their accuracy was too poor for use in measuring channel change. The georectification tolerance for the photos was 25 feet as compared to the location of features in the 2015 aerials. The channel tracings, delineated at 1:5,000, fell within anticipated tolerances of 20 feet from the vegetation line, wherever zoomed in to verify.

In addition, a LiDAR-based digital elevation model (DEM) was used to image channels across the floodplain and to generate the Height Above Water Surface (HAWS) map. The aerial survey for the LiDAR was flown during low-water conditions in 2014 below RM 6.35 and in 2017 above that point. Relatively consistent low-flow conditions existed during both surveys, and the difference in water-surface elevations was 0.7 foot at their junction, too small to make any noticeable difference in the subsequent HAWS mapping that was derived from these data.

3.4 Polygon Analysis of Floodplain Reoccupation

Rapp and Abbe (2003: 23) describe polygon analysis as “an analytical tool for measuring changes in the areal extent of fluvial features (bars, active channel, islands).” This approach overlays the area of the active channel traced from an image onto that of prior airphotos and classifies each individual polygon formed by the intersection of these two data sets into one of three categories: (1) the “intersection area,” defined as an area of active channel that falls within the footprint of the previous active channel; (2) the “erosion area,” defined as the area of active channel outside of the previous active channel but within one or more prior year’s active channel areas; and (3) the “new erosion area,” defined as the areas where the channel had eroded into a location that was unoccupied by *any* prior year’s channel areas.

The polygon analysis is particularly useful for estimating rates of floodplain turnover; characterizing the degree to which channels reoccupy prior positions; and identifying broad, systematic trends in channel-migration activity over time and space. Because the results are determined over the aerial extent of a

reach or subreach, however, they are less useful in predicting actual rates or locations of future channel migration. Although Rapp and Abbe (2003) assert the utility of this analysis in determining rates of channel migration, its application remains dependent on knowing the erosion rate of the bank material as well as making assumptions as to the regularity of meander-bend spacing and cross-valley migration (see Rapp and Abbe 2003: 40). We have therefore conducted this analysis to better understand the patterns of channel migration and rates of floodplain turnover, but have not found its application relevant to estimating future location-specific hazards associated with channel migration. The polygon analysis does, however, provide a basis to discriminate "moderate" from "severe" hazard zones within the CMZ, as discussed below.

3.5 Channel Migration Zone Components

Channel migration hazards in the Lower Skykomish River were mapped by identifying the component parts of a CMZ, following the guidance of Rapp and Abbe (2003), Olson et al. (2014), and Ecology (1994–2014). CMZ components are described in the equation below and illustrated schematically in Figure 3-1.

$$CMZ = HMZ + AHZ + EHA – DMA$$

where:

HMZ = Historical Migration Zone

AHZ = Avulsion Hazard Zone

EHA = Erosion Hazard Area = Erosion Setback (ES) + Geotechnical Setback (GS)

DMA = Disconnected Migration Area

Each CMZ component is defined and its mapping methods are described in Section 3.6.

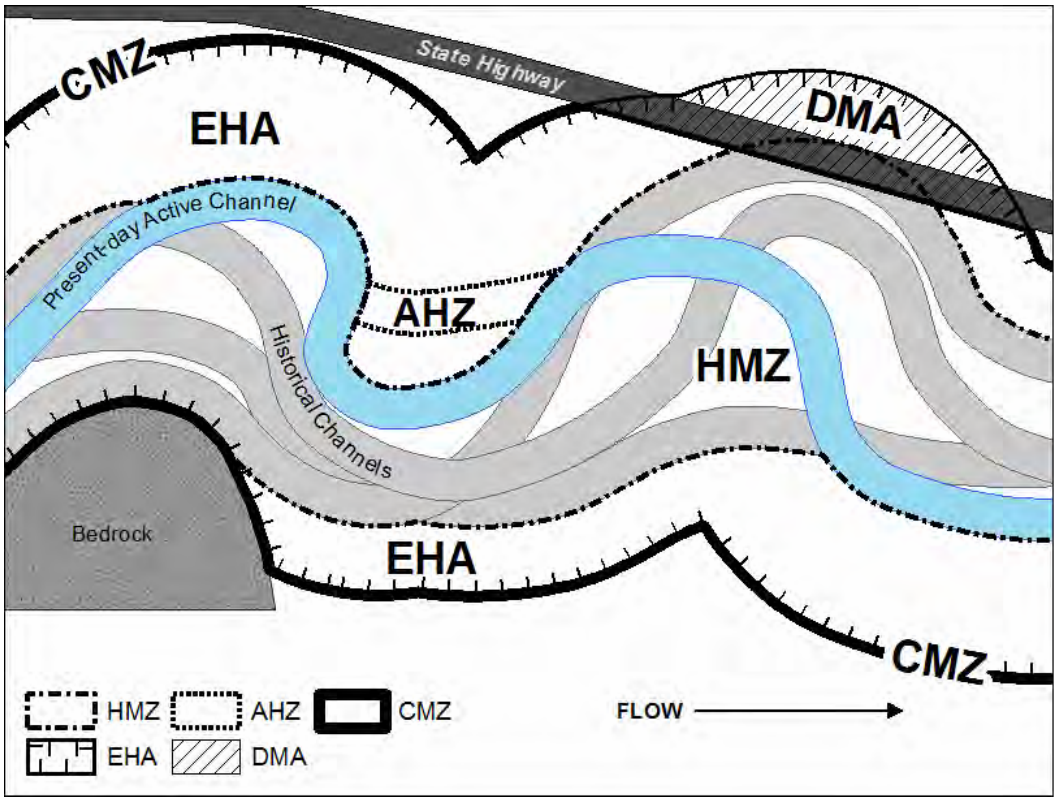


Figure 3-1 Plan view schematic of channel migration zone (CMZ) components (from King County [2017], as modified from Rapp and Abbe [2003]).

3.6 Mapping Criteria and Methods

This section defines each CMZ component and hazard area and describes mapping criteria and methods. As described in Section 3.5, the combination of the following components constitutes the CMZ (CMZ = HMZ + AHZ + EHA – DMA).

After the CMZ was delineated, severe and moderate hazard areas (defined below) were identified within it in recognition that channel migration hazard is not equal throughout the CMZ. In general, any part of the CMZ that is not mapped as a severe hazard area is mapped as a moderate hazard area. The criteria by which parts of the CMZ components are mapped as a severe or moderate hazard area are included with the description of each CMZ component.

3.6.1 Historical Migration Zone (HMZ and eHMZ)

The HMZ is the portion of a CMZ study area that the channel has occupied during the historical record. The HMZ is mapped as the composite footprint of historical active channel locations as identified from the maps and airphotos between 1897 and 2018. The outermost boundary of these channel traces corresponds to the formal definition of the HMZ. Rapp and Abbe (2003: 22) assert that "relic channels on the LiDAR image that are not included in the HMZ were occupied by the channel prior to the historical record; therefore they are not included in the HMZ."

This assertion, however, is not always correct. For the present study, for example, the map and photographic record has a number of lengthy gaps (that from 1938–1965 is particularly long). Thus, the record of channel position over the last century runs a risk of being incomplete, since intermediate-age channel positions not captured in any of the available images would nonetheless be relevant for purpose of hazard zonation. In addition, many areas immediately adjacent to the formally designated HMZ show geomorphic features entirely analogous to those within the HMZ (even if not previously occupied over the last century), offering little basis to fully include the observed channel positions in hazard zonation and yet exclude the former.

To address this incongruity, an "expanded HMZ" ("eHMZ") was also mapped in acknowledgment of the temporal limitations of the existing airphoto coverage, and to ensure that identification of potentially hazardous areas has been aligned with the most reasonable geomorphic interpretation of the Lower Skykomish River valley landforms and channel-migration history (Figure 3-2). The entire HMZ is typically defined as a "severe" hazard area (e.g., Ecology 1994–2014; King County 2017) where not constrained by erosion-resistant structures (see discussion of the DMA, below). The eHMZ is also included in the CMZ but, if appropriate, may be assigned a lower level of hazard severity given uncertainties in the actual age of its most recent channel occupation.

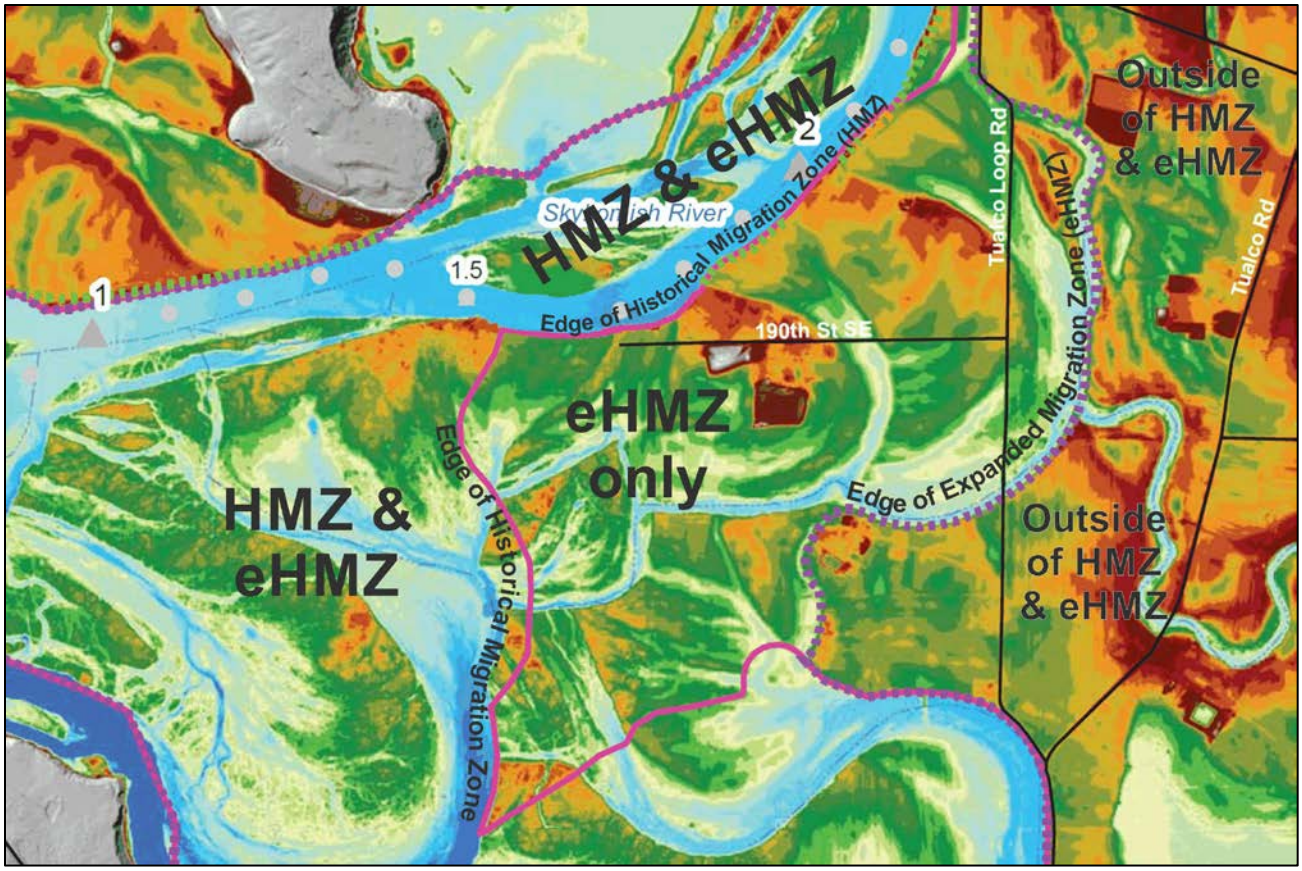


Figure 3-2 Floodplain area between RM 1 and RM 2 (white-backed numbers), illustrating the discrimination of HMZ and eHMZ. Across the boundary between them, no difference in elevation or the "freshness" of the geomorphic features is visible. Although the selected airphotos only shows channels within the boundaries of the HMZ, the expanded area provides a more geomorphically reasonable limit of relatively recent (and potential future) channel occupation. Floodplain elevations are systematically higher outside of the eHMZ boundary. Base map from HAWS imagery (see Appendix A for a full description of the map development and color scheme).

3.6.2 Avulsion Hazard Zone

The AHZ is the area outside of the HMZ and eHMZ that is subject to avulsion hazard, the potential for a rapid shift of the overall channel position that occurs by occupation or reoccupation of a new position without progressive bank erosion and migration. To define the AHZ, low-lying areas were identified using the HAWS map, which illustrates the difference in elevation between the water surface during low-flow conditions and the adjacent valley-bottom topography (an example of this map is shown in Figure 3-2; a complete set of HAWS maps for the study area is shown on several of the map sets of Appendix A).

Potential avulsion pathways were included in the AHZ if they met all four of the following criteria:

1. The spillway into the prospective avulsion channel lay no more than about 12 feet above the low-water surface as defined by the HAWS mapping (approximately 5 to 8 feet above the level of the field-determined "bankfull" channel, given a maximum 3-foot variation in water levels when the different LiDAR surveys were conducted), and so potentially overtopped during moderate-to-large flood events.
2. The slope ratio (avulsion pathway slope to main channel slope) is greater than about 4 (Slingerland and Smith 1998), as estimated from the HAWS map and LiDAR DEM.

3. The substrate in the banks and bed or floodplain of the potential avulsion pathway is erodible material (i.e., not bedrock).
4. The potential pathway shows topographic evidence of prior channel occupation.

Other factors considered by prior guidance documents, such as large woody debris loading, details of the channel-bank materials and soil erodibility (beyond bedrock/non-bedrock), or the presence/absence of forested land cover on the intervening floodplain, appear to be transitory factors (considering a 100-year timescale) or irrelevant to avulsion processes occurring in this valley (or both transitory and irrelevant). In addition, most identified avulsion pathways lie within the HMZ and so are already identifiable as being within a "severe" hazard zone—thus the incremental value of detailed evaluation of all such potential avulsion pathways would be minimal. However, for those few channels that would expand the CMZ should they ever be occupied, more careful mapping was done to better discriminate an AHZ lying outside of the HMZ and/or the eHMZ.

3.6.3 Erosion Hazard Area

The EHA delineates the areas outside of the eHMZ and AHZ that may be susceptible to bank erosion from (1) streamflow and/or (2) mass wasting that has been initiated by current fluvial processes or that may be initiated by future channel migration (Rapp and Abbe 2003). These two components of the EHA, denoted as the Erosion Setback (ES) and the Geotechnical Setback (GS), address the potential expansion of the CMZ beyond the eHMZ and AHZ via bank erosion of the channel along one of those boundaries, and the likely retreat of steep slopes composed of unconsolidated materials when oversteepened by erosion at their base.

The size and locations of the ES were determined by first importing the edges of the 2018 active channel into GIS. For purposes of defining the ES, the "active channel edge" was then expanded to include any identified avulsion pathways that originate along the 2018 channel edge. This addition reflects the potential for the modern flow of the river to switch abruptly into any such channel, and so become the edge of the new active channel with essentially no delay. The process of bank erosion and channel migration would then begin anew from this edge, entirely equivalent to what had previously constituted the "present-day" active channel.

The next step in defining the ES requires estimating a typical amount of migration that might be expected outward from the present-day active channel edge (see above) over a 100-year period. Because of the extreme heterogeneity of channel- and floodplain-bounding materials, and the highly variable geomorphic behavior of the Skykomish River along the 23.5 miles of the study area, uniformly spaced transects used to calculate subreach-averaged rates of migration (as suggested, for example, by Rapp and Abbe [2003]) were judged inappropriate and so not used here. Instead, representative locations throughout the study area were identified on the basis of bounding terrace or floodplain material (bedrock or unconsolidated sediment), height of that terrace or floodplain above the modern low-water elevation of the river (from the HAWS map), absence of constraining levees or revetments, and the orientation of the river relative to that boundary (e.g., inside or outside of a bend, along a straight segment). The relatively modest number of sites over the 23.5-mile-long study area reflects the length of channel that has shifted primarily by avulsion (rendering any measure of "channel migration rates" meaningless) and the extensive armoring of the banks by both public and private revetments, which compromise any estimate of "representative" rates. This results in a less numerous, but more relevant, set of representative channel-migration rates that can be applied, as appropriate, to every segment of the river (Table 3-2).

Table 3-2 Localities Identified for Generation of Representative Channel Migration Rates

Type of Boundary (heights from HAWS map)	Subreach (see Appendix A)	RM	From Year	To Year	Migration Distance (ft)	Rate (ft/yr)	Notes
Upper floodplain (12–20')	7	22.0	1965	2018	104	2.0	Outside bend
High terrace (>20')	7	21.3	1938	2018	237	3.0	Landslide
High terrace (>20')	7	21.0	1965	1991	143	5.5	Adjacent to landslide, outside bend
Lower floodplain (7–10')	7	19.5	1938	2018	594	7.4	Outside bend
High terrace (>20')	7	18.7	1965	2018	155	2.9	Outside bend
Mid-level floodplain (9–12')	6	18.2	1991	2018	550	20.4	Clay in bank, outside bend
High terrace (>20')	6	17.8	1991	2018	232	8.6	Clay in bank, outside bend
Mid-level floodplain (9–12')	6	16.4	1991	2018	609	22.6	Outside bend
Bedrock	5	12.5	1938	2018	0	0.0	Outside bend
Lower floodplain (7–10')	3	9.5	1965	2018	27	0.5	Straight segment
Upper floodplain (12–20')	3	7.2	1965	2018	50	0.9	Outside bend
Bedrock	3	6.7	1938	2018	0	0.0	Straight segment
Lower floodplain (7–10')	2	4.5	1991	2018	300	11.1	Straight segment

Note: Where rates were not constant over a range of multiple airphoto years, the most rapid period of migration at each location was recorded to provide a conservative estimate. Boundary type was determined by direct field observation (in the case of bedrock) or by height relative to the low-water surface, from the HAWS map.

Reorganizing these data by channel boundary displays the degree to which channel boundary influences migration rates (Table 3-3). These results show the overriding importance of bedrock, where it does occur, and the broad but quite variable resistance provided by floodplain and terrace sediments of increasing height above the river.

Table 3-3 Findings Shown in Table 3-2 Clustered by Boundary Type

Type of Boundary	Rate (ft/yr)	Notes
Bedrock	0.0	Outside bend
Bedrock	0.0	Straight segment
Lower floodplain (7–10')	7.4	Outside bend
Lower floodplain (7–10')	0.5	Straight segment
Lower floodplain (7–10')	11.1	Straight segment
Mid-level floodplain (9–12')	20.4	Clay in bank, outside bend
Mid-level floodplain (9–12')	22.6	Outside bend

Type of Boundary	Rate (ft/yr)	Notes
Upper floodplain (12–20')	2.0	Outside bend
Upper floodplain (12–20')	0.9	Outside bend
High terrace (>20')	3.0	Landslide
High terrace (>20')	5.5	Adjacent to landslide, outside bend
High terrace (>20')	2.9	Outside bend
High terrace (>20')	8.6	Clay in bank, outside bend

Note: The relatively poor association of boundary type with migration rates suggests that local conditions are also significant in determining actual rates at specific locations.

These findings have been summarized into simplified "rules" for delineating the ES as a potential expansion of the CMZ. Consistent with the Ecology (1994–2014) guidelines, a 100-year time horizon was assumed to define the ES for applying averaged rates to the active channel edge (Table 3-4).

Table 3-4 Presumptive Distances of Potential Channel Migration over a 100-year Planning Horizon, Measured from the Outer Edge of the Modern Channel or Avulsion Pathway, Based on the Average of Observed Rates Listed in Table 3-3

Type of Boundary	Potential Migration per 100 Years (ft)
Bedrock	0
Floodplain & terrace (height > 12')	500
Floodplain (height < 12')	1,000

Specific conditions in a few locations made for localized exceptions to these general rules. Above RM 22.0, the absence of any significant channel migration over the entire photographic period of record superseded these rules, and no additional ES was applied. Similarly, between RM 22.0 and 21.0, the upstream ends of several alcoves entering a pre-1921 channel included in the eHMZ were not included in the unconstrained (or final) CMZ, given their position and upstream elevations.

Where the outermost limit of the ES lay across an erodible terrace (i.e., not bedrock) greater than 20 feet in height above the low-water surface as identified on the HAWS map, an additional GS of 100 feet was applied to that boundary (Figure 3-3). Because the ES boundary is drawn at the base of the slope, this setback distance must approximate both the likely non-vertical angle of the future ground surface plus a reasonable building setback from a steep erodible slope face. Although the actual separation between the bottom and top of the slope will differ for terraces of different heights, a reasonable and uniform setback is appropriate for planning purposes, absent site-specific information. In a few localities, landslides adjacent to the CMZ and mapped on the Washington State Geology and Earth Resources website (https://geologyportal.dnr.wa.gov/#natural_hazards) or otherwise recognized from fieldwork for this project have been marked by an asterisk, indicating that greater GS might be warranted in these locations but would require additional investigation.

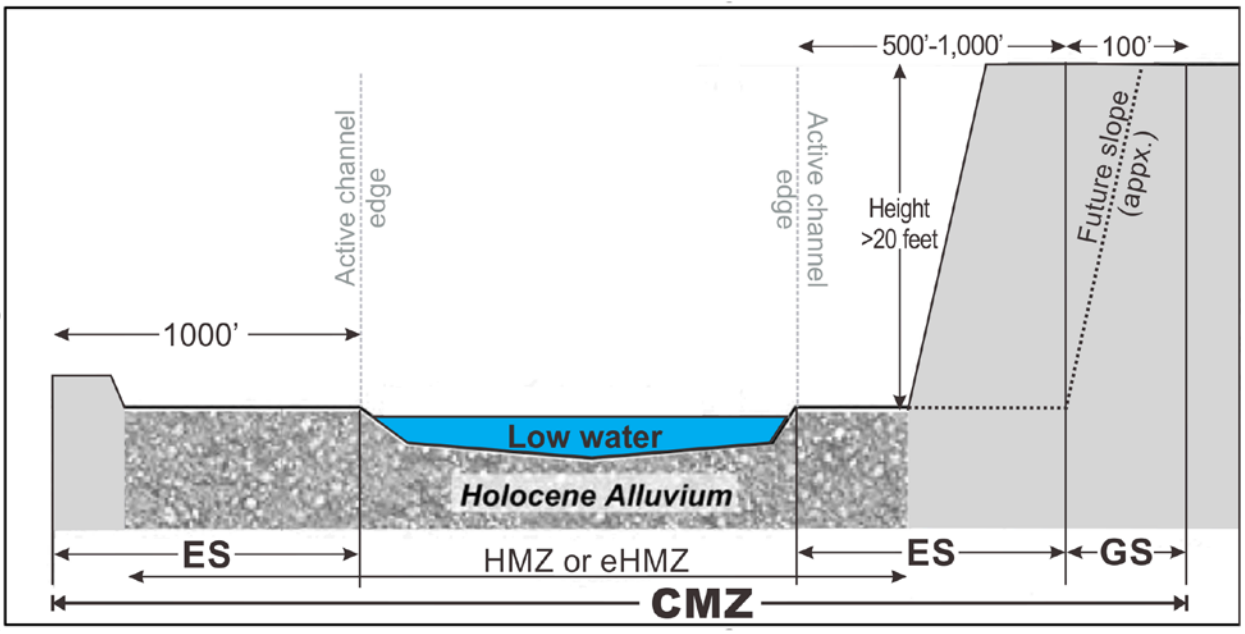


Figure 3-3 Cross-section schematic of the historical migration zone (HMZ or eHMZ), erosion setback (ES), geotechnical setback (GS), and their aggregation into a CMZ. Figure modified from King County (2017), using the criteria developed here for the Lower Skykomish River.

This approach is similar to, but also distinct from, prior applications of this general methodology. For example, King County (2017) discriminated between appropriate setback distances from the active channel and setback distances from the HMZ where *not* currently adjacent to the active channel (using 100 years of future migration at the average annual rate for the former, and only 50 years of future migration for the latter). That study also applied a different size of ES where bordering avulsion pathways that are not presently within the HMZ (50 to 25 years of migration, depending on the time of last occupation of the avulsion pathway). This approach reflects the more confined, bedrock-bounded valley of the Upper Skykomish River, but if applied here would likely understate the potential risk associated with the dynamic nature of the Lower Skykomish River as it moves through the present study area.

3.6.4 Disconnected Migration Area

The DMA is the area located landward of an artificial structure that is likely to restrain channel migration. In other words, the DMA is an area that would be subject to channel migration were it not for the presence of the artificial structure. The criteria for evaluating the likelihood of restraining channel migration in Washington Administrative Code 173-26-221(3)(b) is stated as follows:

> *Within incorporated municipalities and urban growth areas, areas separated from the active stream channel by legally existing artificial channel constraints that limit channel movement should not be considered within the channel migration zone.*

> *All areas separated from the active channel by a legally existing artificial structure(s) that is likely to restrain channel migration, including transportation facilities, built above or constructed to remain intact through the one hundred-year flood, should not be considered to be in the channel migration zone.*

> *In areas outside incorporated municipalities and urban growth areas, channel constraints and flood control structures built below the one hundred-year flood elevation do not necessarily restrict channel migration and should not be considered to limit the channel migration zone unless demonstrated otherwise using scientific and technical information.*

Olson et al. (2014) state that all structures considered to be barriers to CMZs must also be "legally existing" structures, which are defined under the Shoreline Management Act definition for floodways (Revised Code of Washington 90.58.030) as those "...flood control devices maintained by or maintained under license from the federal government, the state, or a political subdivision of the state." Thus, by strict definition, only structures with a public agency commitment for maintenance should be considered a barrier to channel migration.

An additional precedent, however, offers support for a modestly expanded perspective that also includes the BNSF Railroad embankment, which parallels the north side of the HMZ from RM 4.6 to the upper end of the study area, as a barrier to migration. Snohomish County Code 30.91C.067 states "All areas separated from the active channel by a legally existing artificial structure(s) that is publicly maintained and likely to restrain channel migration, including transportation facilities, built above or constructed to remain intact through the one hundred-year flood, shall not be considered to be in the channel migration zone. Areas behind natural or manmade features which limit channel migration that allow fish passage shall not be included in the channel migration zone." The empirical evidence demonstrates that the embankment has not been breached at any time since 1921, the age of the oldest USGS topographic map coverage, including all subsequent airphotos. This record of resilience includes the November 6, 2006, flood of record at the USGS gage near Gold Bar, which covers 92 years and so records an approximate 100-year flood (120-year recurrence, according to Watershed Science & Engineering [2018]).

Thus, the final set of facilities that have been assumed to create a DMA behind them, based on the applicable state and county codes, are as follows (Table 3-5; see also Map Set 1, Appendix A).

Table 3-5 Facilities Considered Adequate to Preclude Channel Migration and Create a Disconnected Migration Area Behind Them

Name	From RM	To RM	Riverbank
Schlamp levee	1.56	1.69	Left
Hansen levee	2.48	2.87	Right
Haskell Slough levee	5.82	6.06	Left
Fern Bluff levee	7.88	8.07	Right
311th Ave plug levee	13.78	13.84	Left
Startup training levee	17.21	17.51	Right
Startup levee	17.51	19.1	Right
BNSF Railroad revetment	4.6	22.1	Right

Other named structures along the river that do *not* meet this definition, and so do not affect the final delineation of the CMZ, are listed in Table 3-6.

Table 3-6 Facilities *Not* Considered Adequate to Preclude Channel Migration and Not Affecting the Location of the Final CMZ Boundary

Name	From RM	To RM	Riverbank
Park Place levee	2.88	3.67	Right
Groeneveld levee 2	13.1	13.2	Right
Sultan training levee	13.16	13.5	Right
Groeneveld levee	13.84	14.01	Left

In addition, more than three dozen other segments of bank armoring were mapped during the 2019 field work. They were mapped during the course of fieldwork, but for purposes of this CMZ analysis were not considered barriers to future migration.

4 Distribution and Magnitude of Channel Migration

As the presumptive driver of channel migration, occurrences of moderate and high discharges in the Skykomish River are likely to have been reflected in the magnitude of channel changes over time. Although various indices of "moderate and high discharge" have been used in past studies (e.g., the aggregate discharge-over-threshold of Konrad et al. [2011] on the Green River, King County, Washington), the most straightforward is simply the maximum peak discharge for each water year. Those data (Figure 4-1) suggest that the pre-1965 period should show somewhat less dramatic changes than the interval from 1965 to 1991 (which included the second-largest flood on the river in 1990), or from 1991 to 2018 (which included the flood of record in 2006).

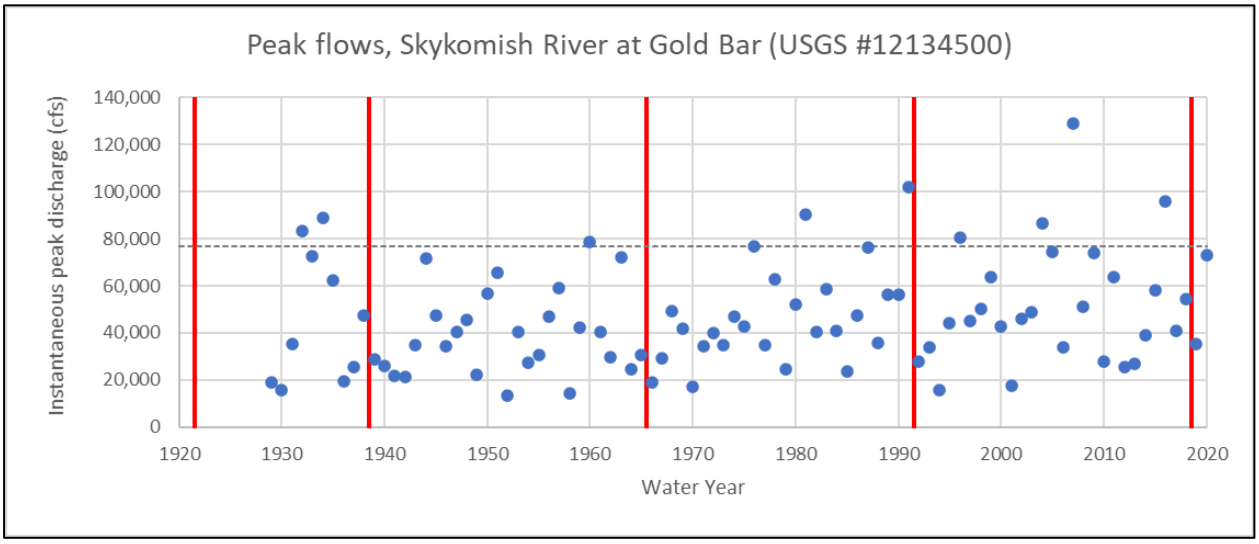


Figure 4-1 Annual maximum instantaneous peak discharges on the Skykomish River at the USGS Gold Bar gage. Red lines delineate the time of the five maps and airphotos used in the migration analysis. The dashed line at 77,300 cubic feet per second highlights the approximate magnitude of a 10-year flood (from WSE 2018).

An additional variable influencing channel migration, however, is the history of levee and revetment construction throughout the valley. Review of maps and airphotos indicates that some barriers to migration were in place prior to the 1921 map, whereas others appear to have been constructed between 1921 and 1938 (e.g., Figure 4-2). For example, Northwest Hydraulic Consultants (2000) identified this period as including the initial construction of a levee at the mouth of Haskell Slough. Levee and revetment construction almost surely continued through the middle twentieth century, similar to the history of other western Washington rivers.

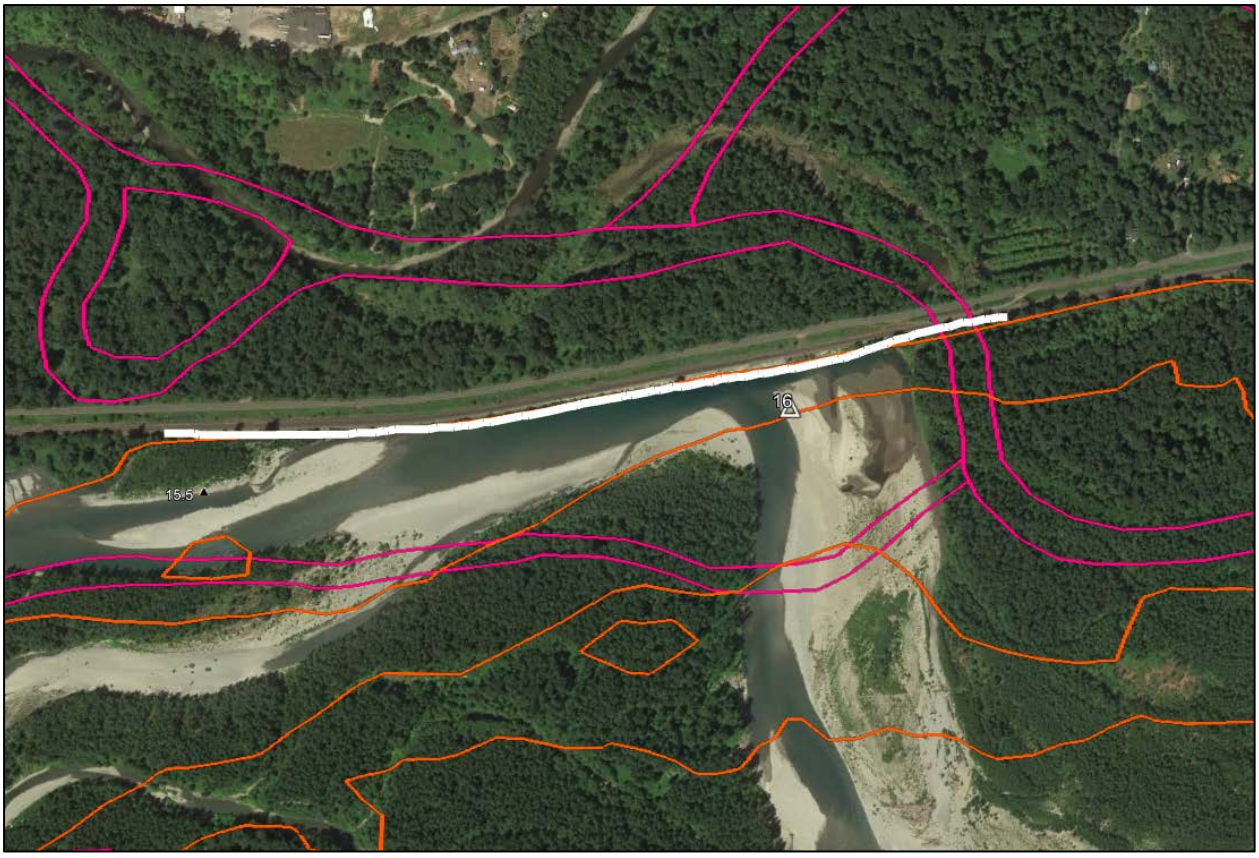


Figure 4-2 The middle of subreach 6, showing the trace of the 1921 channel (magenta) crossing the eventual path of the railroad embankment (just east of RM 16; the extent of modern riprap highlighted in white). This pathway was blocked as of 1938 (orange channel tracing) and thereafter. The 2018 active channel is visible in the underlying airphoto (from Google Earth). Labeled triangles specify the river mile upstream of the Snoqualmie River confluence.

Other examples testify to a period of continued levee/revetment construction during the period from 1938 to 1965 (e.g., Figure 4-3).

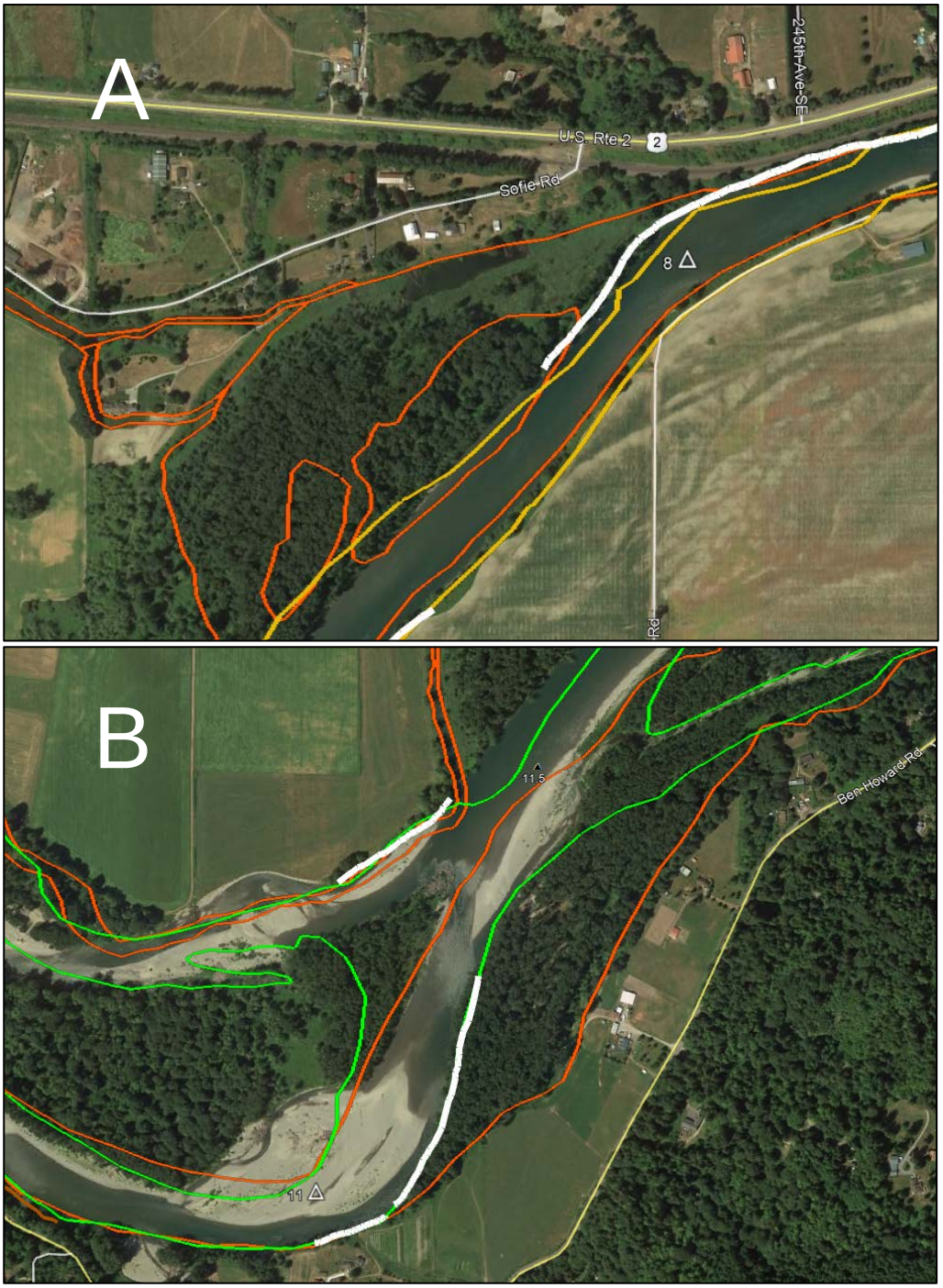


Figure 4-3 **Levees and revetments (thick white lines) as observed during fieldwork in 2019, relative to the boundaries of the active channel in 1938 (orange lines) and in 1965 (yellow lines, panel A), 1991 (green lines, panel B), and 2018 (the airphoto base map).**
(A) The "Fern Bluff" levee had truncated the 1938 flow path by 1965; the channel has maintained its position against the levee since that time.
(B) The unnamed private revetment confined the left bank of the active channel by 1991; as of 1965, a side channel was still present that crossed the present location of the revetment. Labeled triangles specify the river mile upstream of the Snoqualmie River confluence.

The polygon analysis described in Section 3.4, although not used here for delineating the CMZ, nonetheless can provide useful insight into the spatial and temporal behavior of the Skykomish River. Its primary limitation lies in the nature of the map-based 1897/1921 data relative to the 1938 and later airphoto data sources. Although linework traced from those maps are useful for delineating the limits of channel occupation across the floodplain in the early part of the twentieth century, they are not directly comparable to the airphoto tracings of the active channel given their inaccuracies and so were of limited use in comparative, quantitative analyses.

With acknowledgment of the complications of historically varying flood discharges, progressive levee construction, and limited accuracy of the oldest map sources, the polygon analysis reveals several findings:

1. With a few exceptions, the active channel area (Figure 4-4) has declined over time. This pattern is seemingly absent in the first interval (1897/1921 to 1938), but the change in data sources and the likely limitations of channel tracing on a topographic map provide a probable explanation for this seeming anomaly. The increase in active channel area in subreach 6 (and, to a lesser extent, in subreach 7) between 1965 and 1991 reflects the broad expanse of bare gravel bars left in the wake of the November 1990 flood, second-largest on record and occurring only a few months prior to the 1991 airphoto.
2. The broad decline in active channel area from 1938 through 2018 cannot be explained by changes in flood regime (see Figure 4-1). It likely reflects a continued increase in bank armoring throughout much of the twentieth century, which muted (or, locally, halted altogether) channel migration activity.
3. With only one exception, subreaches 2, 3, 4, and 5 have migrated little beyond their previously established migration boundaries, and with rates that have broadly declined since the 1938 baseline (Figure 4-5). The only exceptions to this pattern are a dramatic expansion, by 1965, of what had been a small side channel in 1938 in subreach 4 between RM 11.4 and 10.0, and continued downvalley translation of the meander bend associated with this expanding side channel into previously unoccupied floodplain areas after 1991 (Figure 4-6).
4. Subreaches 6 and 7 show the greatest effects on channel changes from the 1990 flood, with moderate expansions in active channel area, particularly into previously unoccupied parts of the floodplain, as of 1991. An even larger flood in 2006 showed similar but more muted effects, presumably because the expansion into once-occupied floodplain in 1990 has left less available area for “first-time” (over the 80-year airphoto record, at least) occupation.

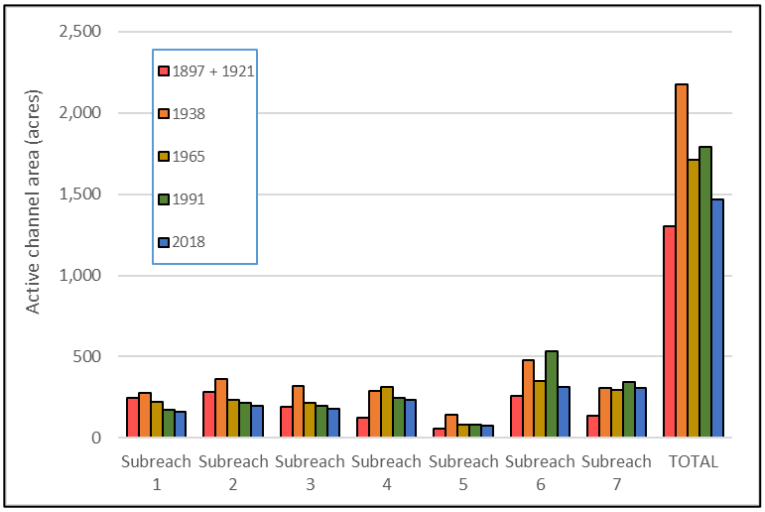


Figure 4-4 Overall active channel area recorded by the five periods of map/airphoto analysis, separated by subreach and also aggregated over the entire study area (right-hand cluster).

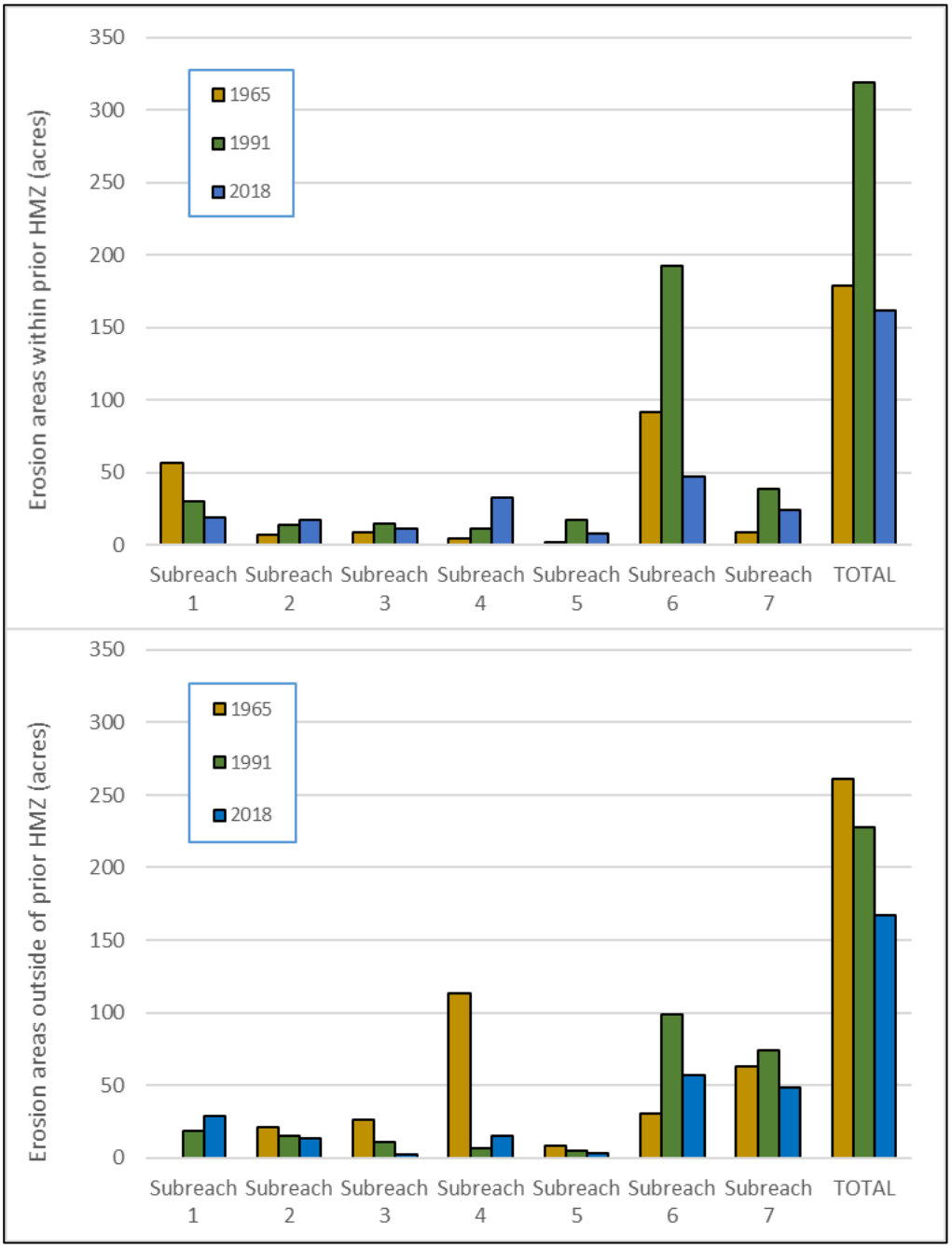


Figure 4-5 **Areas of active channel occupation beyond the prior airphoto's active channel boundaries. These two graphs distinguish between areas outside of the prior active channel but still within the historical migration zone, as defined by all prior airphotos/maps (top), and areas that expand the previously defined historical migration zone. Note that the earliest "baseline" condition is defined by the earliest airphoto (1938); thus, the first period of change can only be defined with the 1965 airphotos (data for previously eroded areas as of 1938 are incomplete in subreach 1, owing to limited coverage from the 1921 map).**

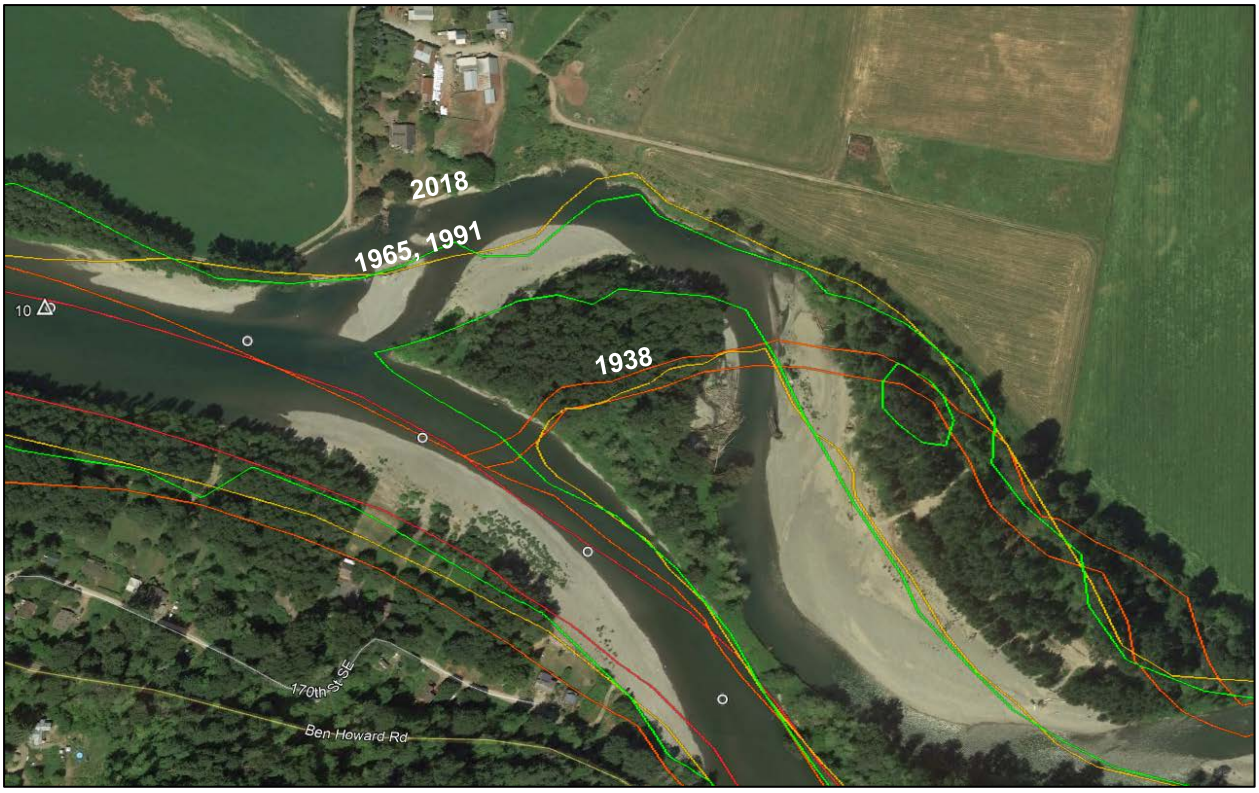


Figure 4-6 Side-channel expansion upstream of RM 10 (white triangle at left edge of photo). What was a narrow channel about 50 feet wide in 1938 (orange line) widened to over 400 feet by 1965 (yellow line), with continued translation downvalley up until at least 2018 (green line = 1991; airphoto base = 2018).

These patterns become even clearer if we omit the incongruous map-based channel traces (i.e., from 1897/1921) and normalize the active channel area by the corresponding subreach length (Figure 4-7). This display emphasizes the near-monotonic decline in active channel area over the last 80 years, the somewhat unusual behavior of subreach 4 in the 1938 to 1965 period, and the dramatic (and unique, within the study area) response of subreach 6 to the 1990 flood.

Several additional patterns are suggested:

- Subreach 6 is by far the most active and dynamic in the study area, as reflected in the data from all years but particularly from 1991.
- In subreach 5, the multiple channels across the central and southern floodplain were almost entirely abandoned post-1938, resulting in the greatest year-on-year decline in active channel area.
- From subreach 3 downstream to the confluence with the Snoqualmie River, active channel areas from the same year tended to increase downstream. This might reflect the modest progressive increase in drainage area and/or a similarly modest decrease in the length of armored banks.
- Subreach 7 is the least variable over time, and consistently amongst the subbasins with the smallest (length-normalized) active channel area. This likely reflects its confinement in the upper 1.5 miles by high, glacial-age outwash terraces; by erosion-resistant bedrock that crops out irregularly along the south side of the river at and above RM 21.4; and the pre-1938 levee along the BNSF Railroad that protects the town of Gold Bar. Although the floodplain widens appreciably below RM 19.5, not until the river gets to about RM 17 (inside subreach 6) have the historical active channels made full use of the available floodplain width.

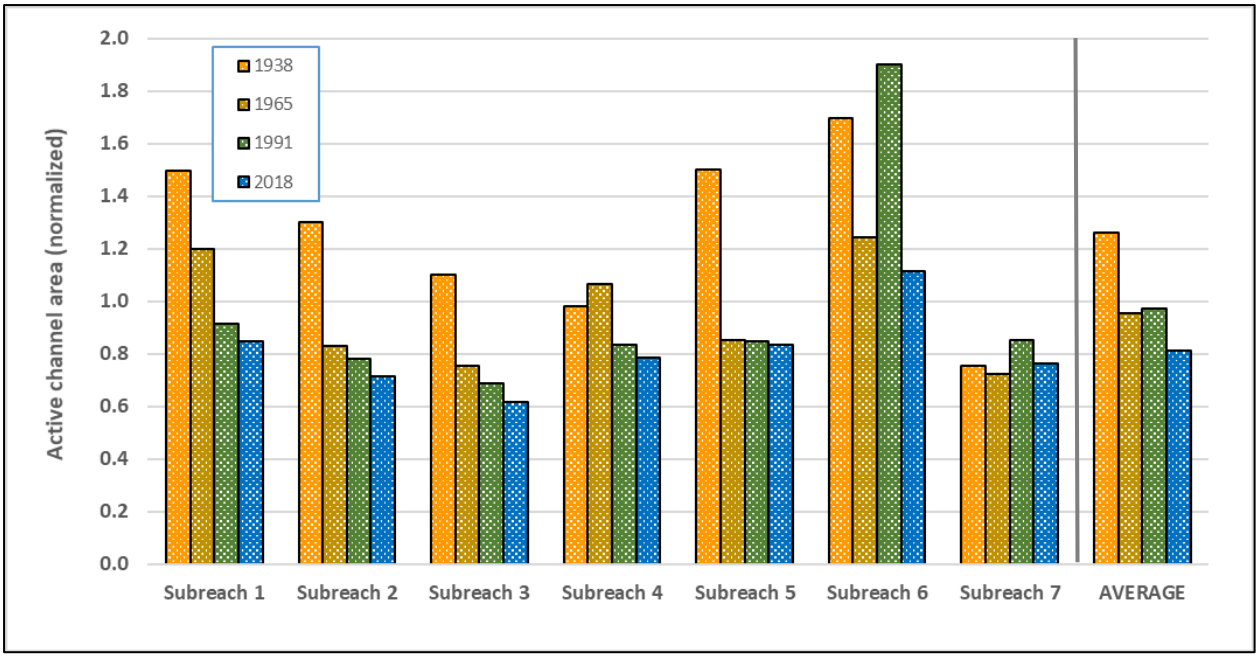


Figure 4-7 Active channel area, normalized by subreach length and scaled such that the average over all years and all subreaches = 1.000.

5 Channel Migration Hazards on the Lower Skykomish River

The methods described in Section 3 are used in this section to predict future limits of channel migration within the study area. The resulting identified channel migration hazard areas and the final CMZ are described below and presented in Appendix A.

5.1 Delineation of Channel Migration Hazard Areas

The channel migration hazards associated with each CMZ component are summarized as follows.

5.1.1 Historical Migration Zone and Expanded Historical Migration Zone

Historical active channel boundaries were traced from the location of channels on the 1897/1921, 1938, 1965, 1991, and/or 2018 airphotos (as displayed on Map Set 2 of Appendix A, which also includes a number of intermediate years' channel positions). The outermost limits of these tracings were used to define the HMZ boundary. In a number of locations, an expanded boundary was recognized (the eHMZ) that included additional areas of the floodplain inferred to reflect a geomorphically equivalent history of recent channel occupation (see Map Set 3, Appendix A). The HMZ, which is the area directly observed on airphotos to have been occupied by the channel at some time since 1921, is included in the CMZ and constitutes the majority of its identified area. The eHMZ is also included within the CMZ since its geomorphic expression, and presumably its potential for (re)occupation in the future, is judged to be equivalent or near-equivalent to that of areas within the HMZ. In one area noted in Section 3.6.3 (at RM 20–21), small channels mapped as part of the eHMZ were not included in the CMZ given the implausibility of their future occupation by the mainstem river.

5.1.2 Avulsion Hazard Zone

AHZs include topographic features on the floodplain that have the potential to convey water diverted from the mainstem, and to then enlarge by headcutting and scour until they convey sufficient flow to become the mainstem channel. Map Set 4 (Appendix A) shows potential avulsion pathways based on elevation, morphology, and orientation. The outer edge of any avulsion pathway extending beyond the limit of the HMZ or eHMZ was drawn at the obvious margin of the topographic channel. This boundary defined the edge of the AHZ.

5.1.3 Erosion Hazard Area/Erosion Setback

ES boundaries are established from the edges of the active (2018) channel, including any identified avulsion pathways that originate along the 2018 channel edge, to account for potential future migration of the channel beyond its past or present positions. The width of the ES was determined by the nature of the adjacent terrace (see Section 3.6.3) and is shown on Map Set 5 (Appendix A). This map set also identifies those areas where the channel edge associated with the ES could be active only in the absence of all constraints to channel migration—thus, they lie within the DMA and depend on the continued presence of a restraining structure to remain inactive.

5.1.4 Erosion Hazard Area/Geotechnical Setback

An EHA/GS of 100 feet was added to the outer edge of the ES at locations where the ES encountered a non-bedrock landform that was greater in height than 20 feet above the low-water surface, as determined by the HAWS mapping. Together with the ES, the GS is shown on Map Set 5.

5.1.5 Disconnected Migration Area

DMAs are those areas that would otherwise be mapped within a CMZ but are excluded because they are located behind a publicly maintained levee or revetment or because they are located behind a railroad alignment that has previously withstood major floods, and are assumed will continue to be defended from channel encroachment. Eight such structures provide significant protection to much of the developed land

north of the Skykomish River (Table 3-5), in total removing a considerable portion of what would otherwise be part of the CMZ from the risk of channel migration.

5.2 Channel Migration Hazard Maps

For the current study area, the unconstrained CMZ has been defined as the outermost extent of the eHMZ and AHZ, plus the appropriate 100-year migration buffer (Table 3-4) that defines the ES (plus an additional 100 feet for the GS, where appropriate).

Areas within the HMZ, AHZ, and EHA (including the ES and GS) were combined to form an unconstrained CMZ, as shown in Map Set 5 (Appendix A). The unconstrained CMZ does not recognize artificial limitations on river position and therefore reflects potential channel migration in the absence of such constraints.

The final CMZ map was prepared by modifying the unconstrained CMZ in two ways. First, the effects of artificially constructed constraints on channel migration were recognized by mapping a DMA, removing from the final CMZ those parts of the floodplain behind a publicly maintained revetment or the BNSF Railroad.

The second modification to the unconstrained CMZ map was to delineate “severe” and “moderate” hazard areas within the overall CMZ. This delineation recognizes that channel migration hazard is not equal throughout the CMZ, given the intuitively obvious need for the river to migrate through areas proximal to the HMZ before threatening areas set farther back. King County (2017) addressed this by simply splitting the ES evenly, with the area closest to the HMZ or AHZ judged to have a “severe” hazard and the remaining area of the ES (+ GS, if present) assigned a “moderate” rating. This approach would also be credible here, but the differing behavior of the river in subreaches 1, 6, and 7 relative to the remainder of the study area (see Figure 4-5) suggests an alternative approach.

Following the guidance of prior CMZ studies, areas within the CMZ of the Lower Skykomish River showing historical channel occupation (i.e., the HMZ) are uniformly assigned a “severe” hazard rating within the CMZ, along with any portion of the AHZ extending beyond the HMZ but within the “active channel edge” (i.e., both the 2018 channel and the outer edge of any avulsion pathway that originates from the 2018 channel). Beyond these areas, the polygon analysis (Section 4) provides a basis for identifying a potentially lower level of hazard. The calculation of “new erosion areas” (i.e., areas lying outside of the previously defined HMZ into which the river has migrated) reflects the river’s past history of moving beyond its prior limits (Table 5-1 and Figure 5-1); this past behavior characterizes its potential to continue such expansion into the future. The minimum subreach-averaged rate from the three periods covered by airphotos (1938–1965, 1965–1991, and 1991–2018) for each subreach is provided in Table 5-1 to highlight the minimum migration rates (i.e., the most restrained behavior) of each subreach over the photographic record.

Table 5-1 New Erosion Areas, by Year and by Subreach, from the Polygon Analysis of Section 3.4

Subreach # and Length (miles)		New Erosion Area						Subreach Minimum Rates	
		Area by Year (acres)			Normalized by Subreach Length (ft/yr)				
		1965	*1991*	*2018*	*1965*	*1991*	*2018*	*ft/yr*	*ft/100 years*
1	2.4	N/A	18.8	28.3	N/A	2.5	3.6	2.5	248
2	3.6	20.9	15.3	13.0	1.8	1.3	1.1	1.1	111
3	3.7	25.9	10.6	2.0	2.1	0.9	0.2	0.2	16
4	3.8	113.4	6.4	15.3	9.1	0.5	1.2	0.5	54
5	1.2	8.4	4.7	2.9	2.2	1.2	0.7	0.7	73
6	3.6	30.0	98.3	57.0	2.5	8.7	4.8	2.5	255
7	5.2	62.5	74.1	48.3	3.7	4.5	2.8	2.8	284

Note: Normalizing the areas by the subreach length (by river mile) gives an index of the lateral movement of the channel over the period between airphotos (26 or 27 years, depending on the interval). 1965 values are measured relative to historical channel locations through 1938 (whose data for previously eroded areas are incomplete in subreach 1, owing to limited coverage from the 1921 map).

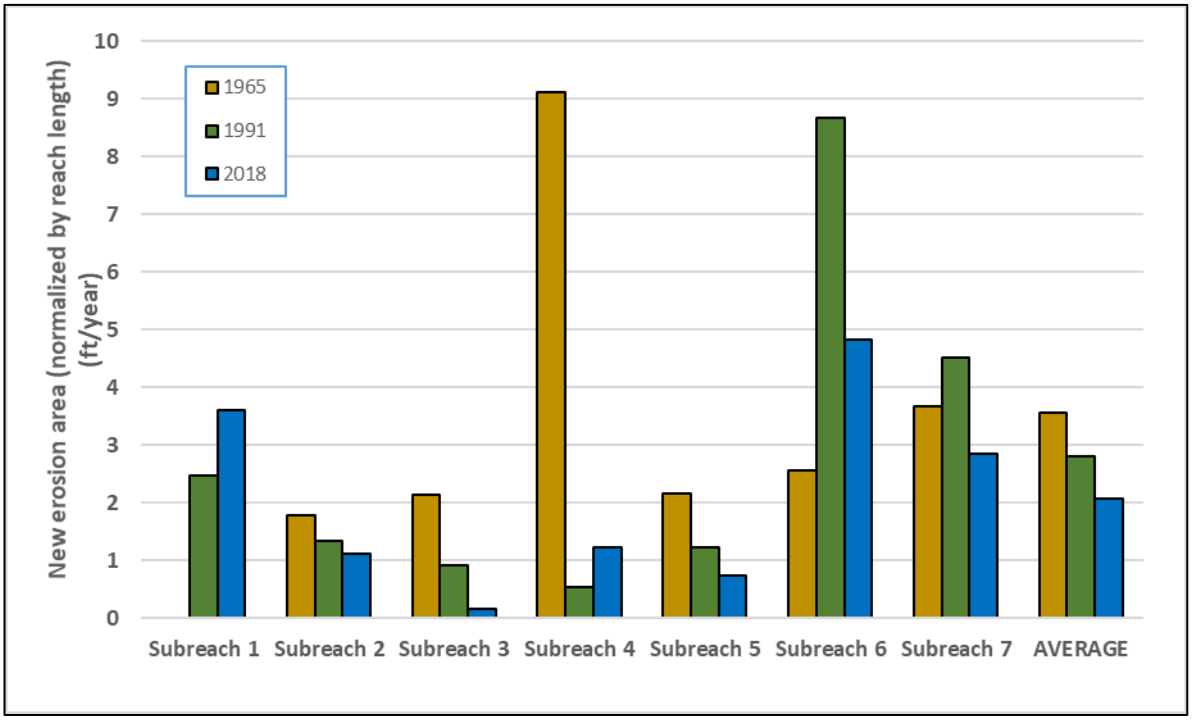


Figure 5-1 The length-normalized data of Table 5-1, graphed for ease of comparison (compare to Figure 4-5, which plots raw areas without normalizing by length of the subreach). Note (1) the progressive decline over time in the average rate, as previously noted in Section 4; (2) the relatively active behavior of subreaches 1, 6, and 7 relative to subreaches 2–5 (with one obvious exception); and (3) the maximum recorded average rate (subreach 4, 1938–1965), which suggests that an erosion setback of 1,000 feet (10 feet × 100 years) is defensible but probably conservative in most settings.

Guided by these results and the framework of King County (2017) and others, only the inner half of the ES should be designated as a “severe” CMZ in subreaches 2, 3, 4, and 5, similar to the approach used in prior CMZ studies; the remainder of the EHA should be designated “moderate.” The entirety of the EHA (ES + GS) should be maintained as a “severe” CMZ in subreaches 1, 6, and 7, given the greater observed magnitude of historical channel migration in these subreaches. However, this locally more conservative approach (i.e., designating the entire CMZ as “severe” in selected subreaches) changes the mapped severity level for only a few limited areas of current development: the residential development along Dorman Road (RM 20.6–20.9); about 500 feet of Mann Road near RM 16.5; a few houses against the railroad tracks on Skywall Drive (RM 14.8); and potentially one or two structures along Tualco Road (RM 2.1).

The result of these modifications to the unconstrained CMZ completes the Lower Skykomish River CMZ map, presented in Map Set 6, Appendix A.

6 Limitations

This study's use of historical information to predict existing and future hazard is consistent with adopted mapping protocols and accepted practices and guidance from the Washington State Department of Ecology (Ecology 1994–2014 and associated references). However, the study is not fully consistent with the Snohomish County Code in that it has not rigorously followed the Forest Practice Board methodology.

Because some factors affecting channel migration are stochastic in nature, the channel is unlikely to occupy all parts of the mapped CMZ within the next 100 years. This mapping is the best representation to date of channel migration hazards in the study area but channel migration also could extend beyond the mapped CMZ limits within the next 100 years. The CMZ map should be updated every 20 years. Portions of the CMZ map may be revised at a timeframe shorter than 20 years if local changed conditions warrant.

This study did not evaluate the potential effect of channel migration on flood inundation hazard, the potential effect of channel migration on slope stability, or the potential effect of landslides on channel migration, and it did not incorporate ongoing evaluations of the structural stability of existing levees or revetments.

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Lower Skykomish River
Channel Migration Zone
Study

APPENDIX A

MAPS

Appendix A Maps

Map 1. Levees and Revetments

Map 2. Historical Channels [7 panels]

Map 3. Height Above Water Surface and HMZ/eHMZ Boundaries [7 panels]

Map 4. Avulsion Pathways [7 panels]

Map 5. Erosion Hazard Area and Unconstrained CMZ" [7 panels]

Map 6. Lower Skykomish River Channel Migration Zone [7 panels]

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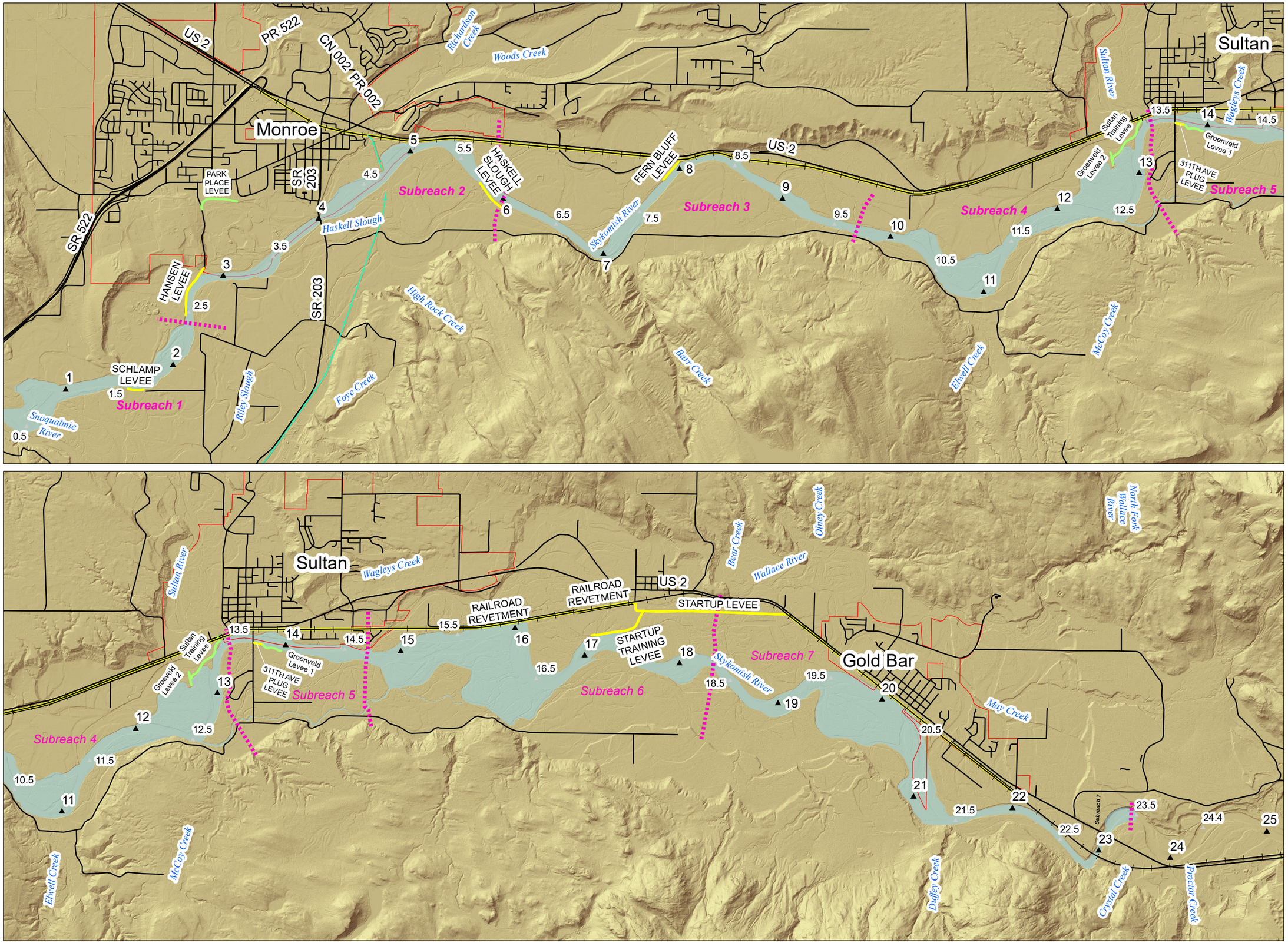
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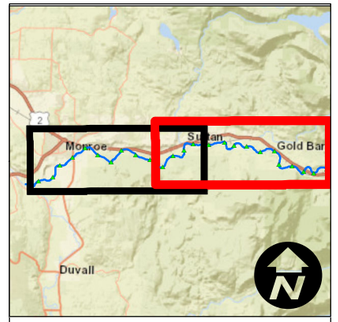
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Levees & Revetments

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

- Abandoned Railroad
- BNSF Railroad
- Maintained Levees & Railroad
- Levees Not Maintained by County
- Subreach Boundaries
- Roads
- River Miles
- 2018 Active Channel
- City Limits

0 1,300 2,600 3,900 5,200 6,500 Feet
0 460 920 1,380 1,840 Meters

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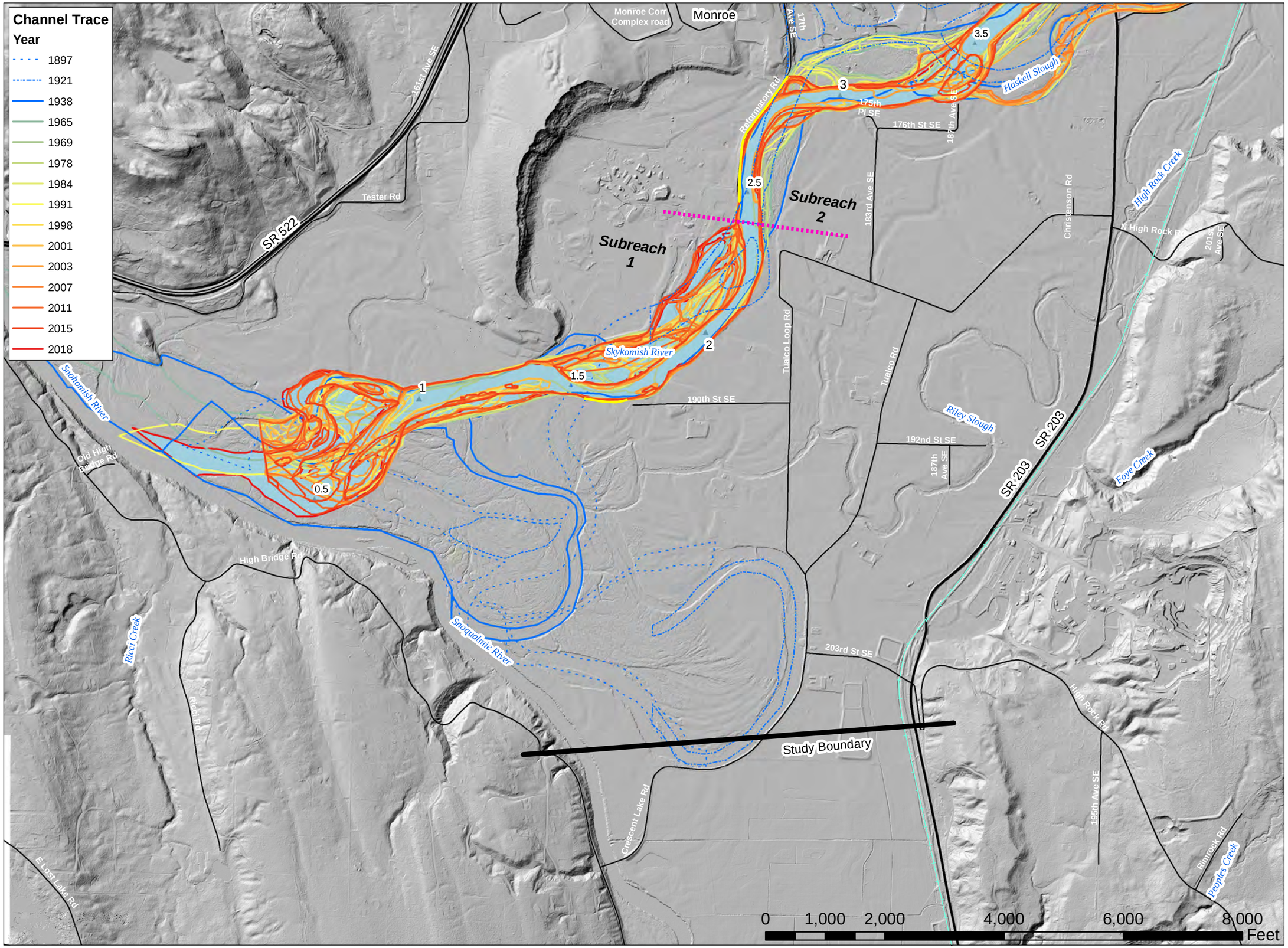
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Historical Channels

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Snohomish County, WA

- BNSF Railroad
- Abandoned Railroad
- Maintained Levees & Railroad
- Levees Not Maintained by County
- Subreach Boudaries
- 2018 Active Channel
- Roads
- State Hwy
- River Miles

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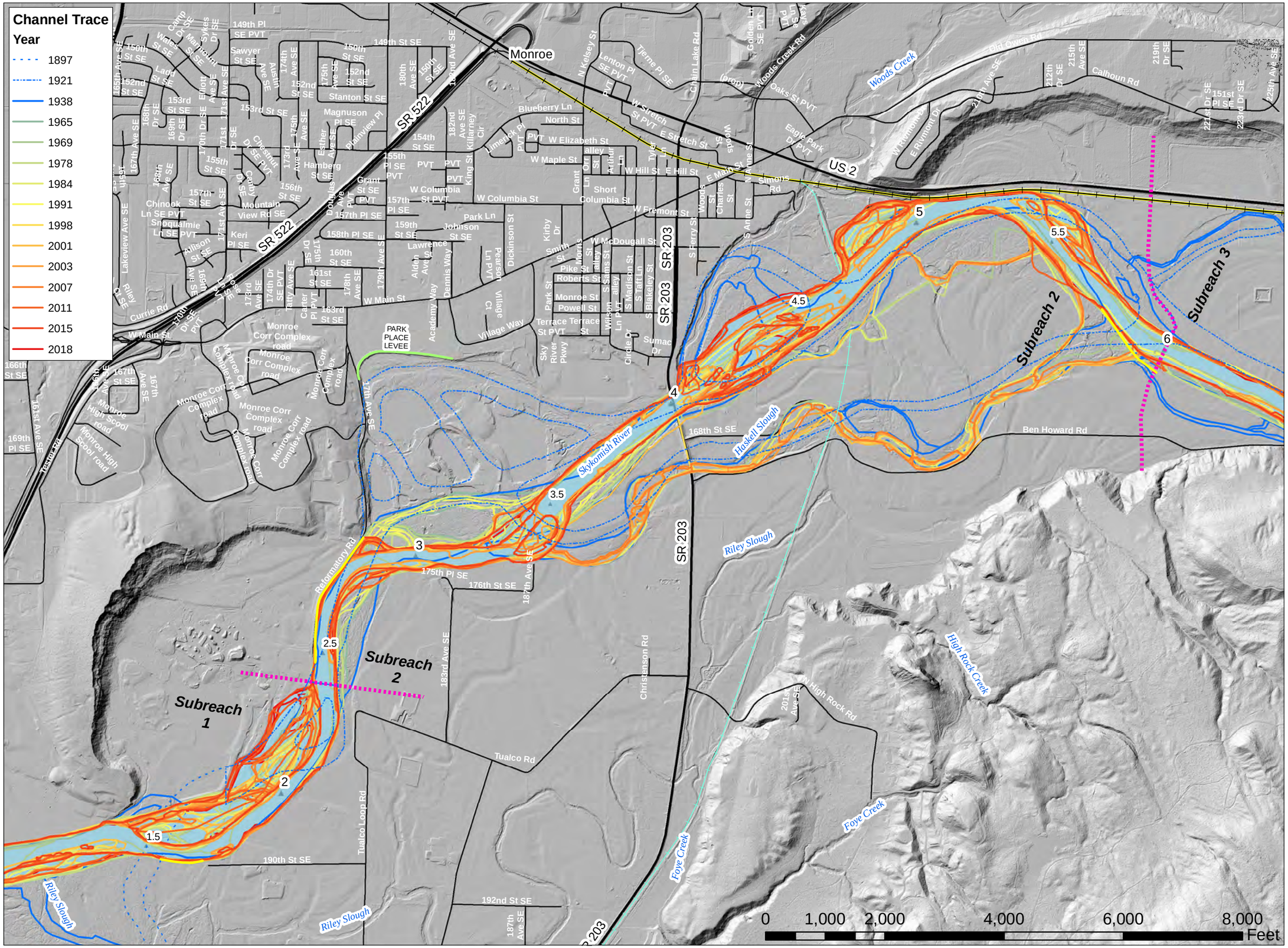
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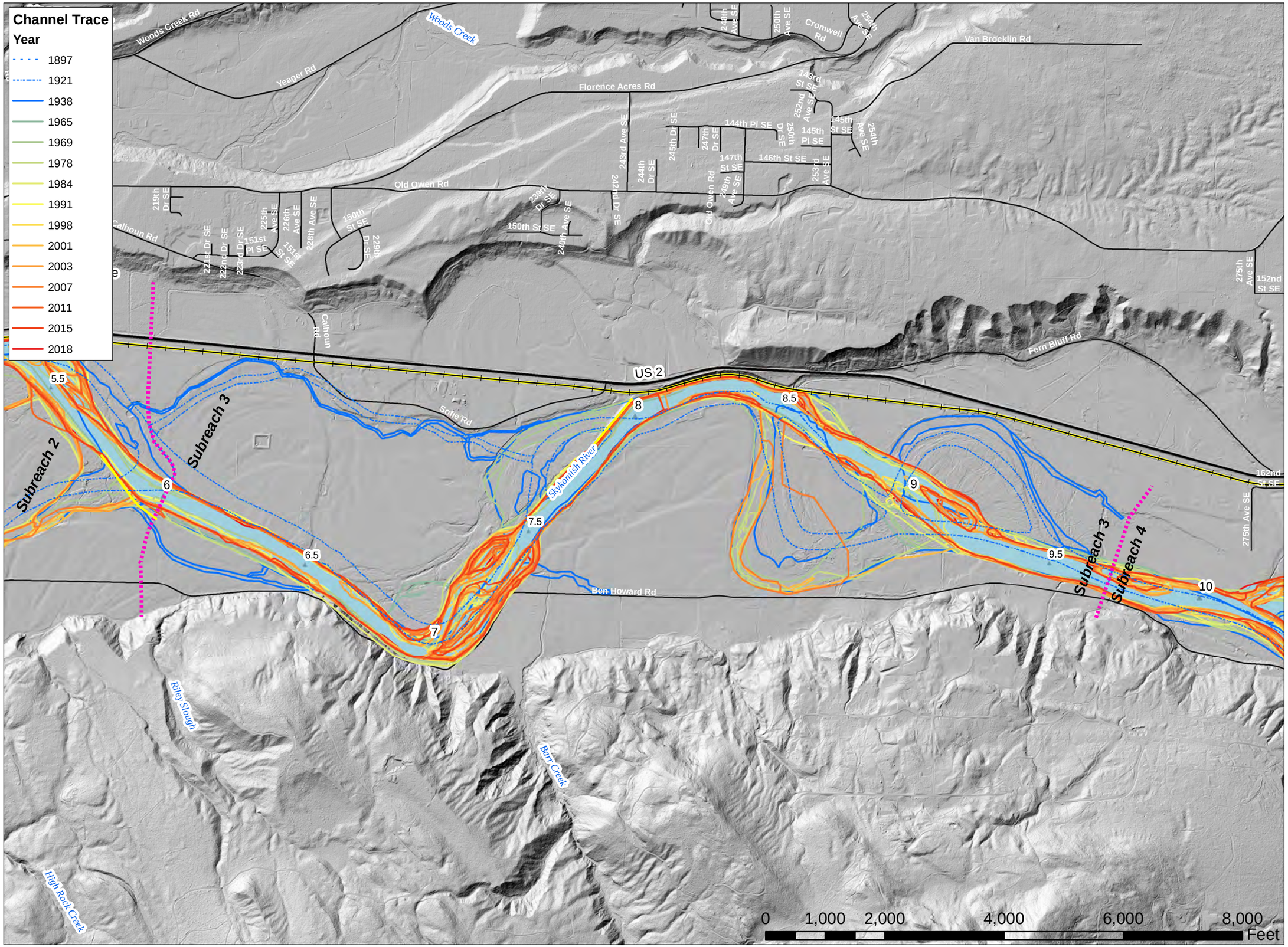
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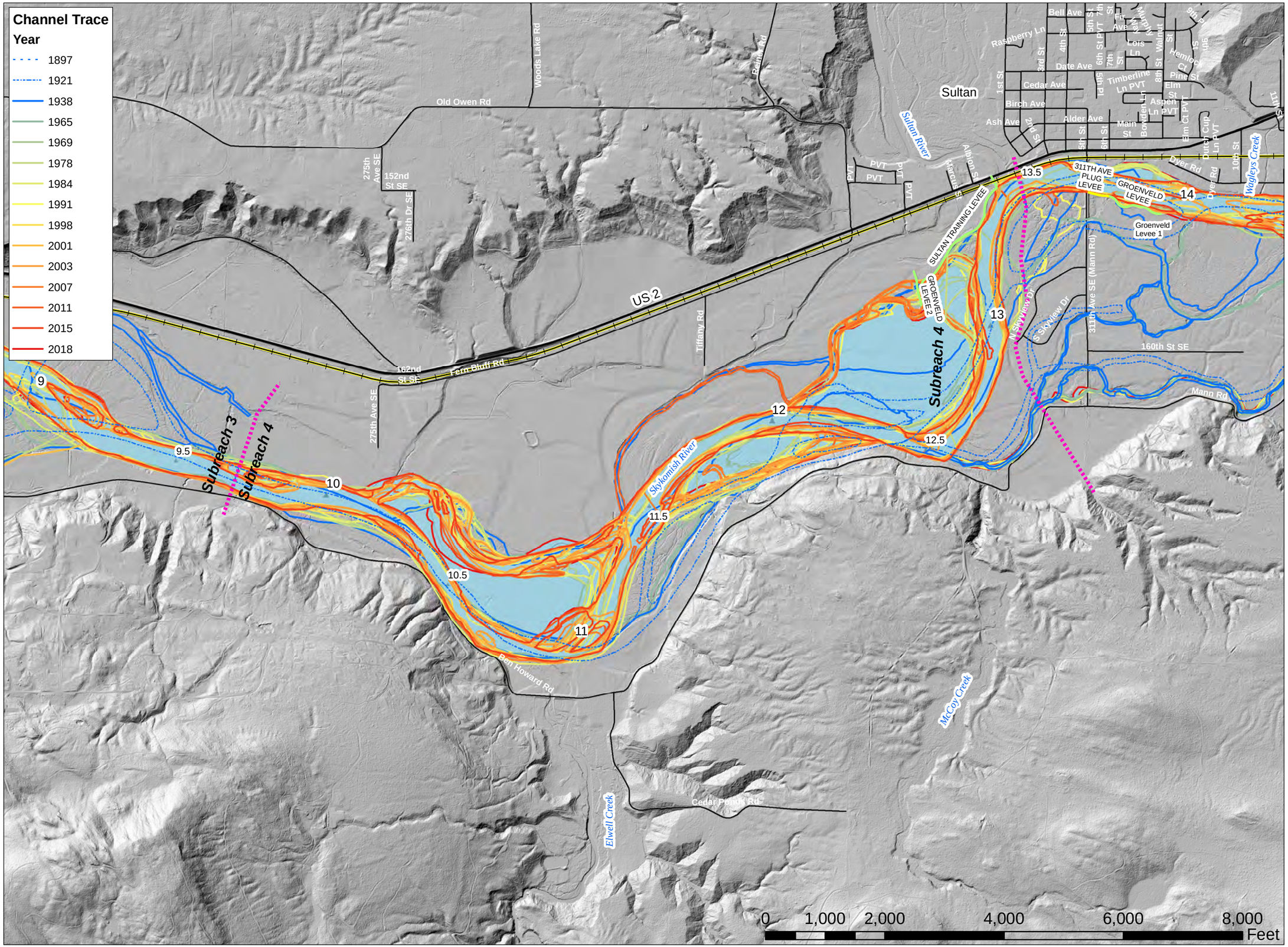
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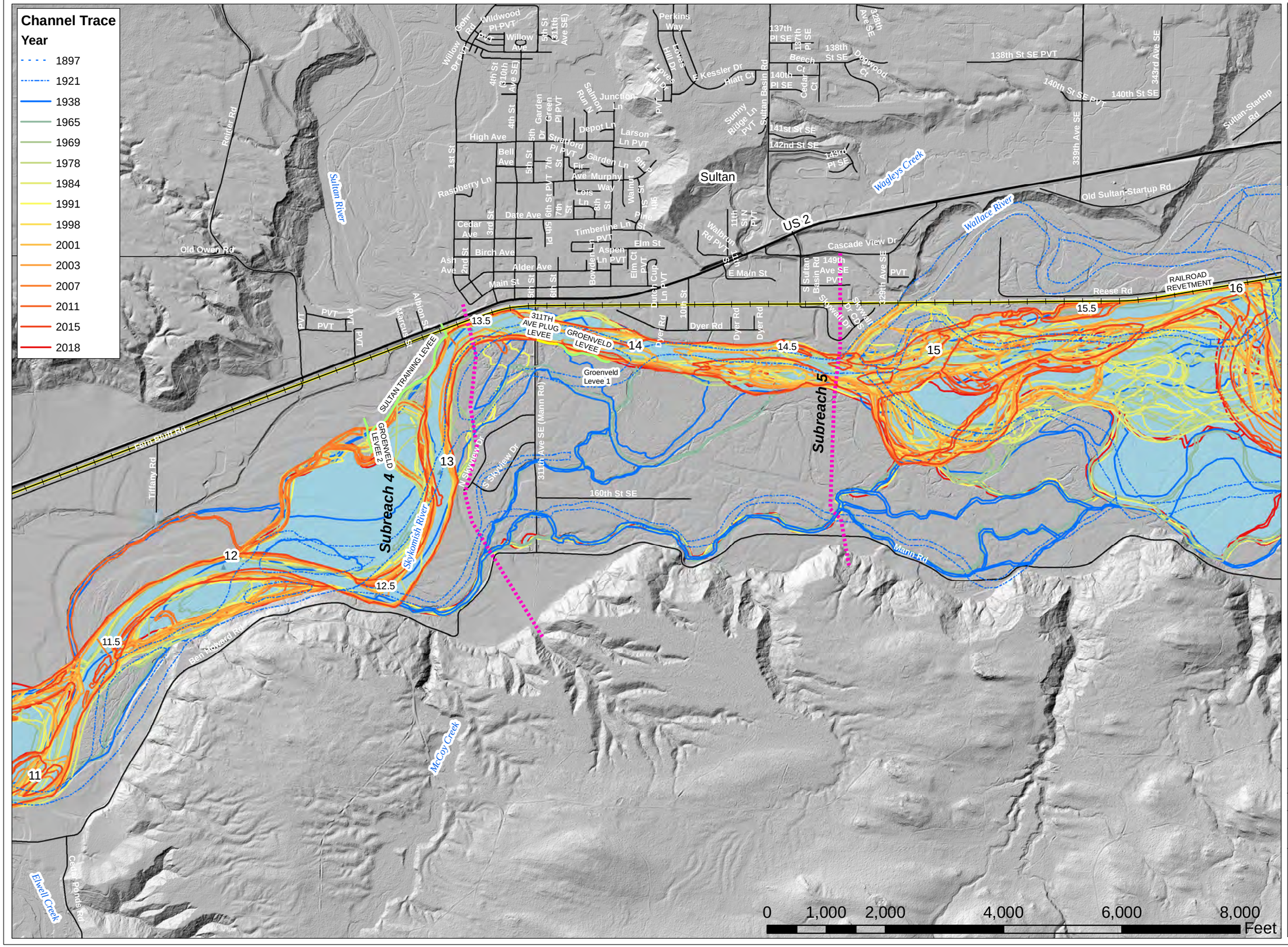
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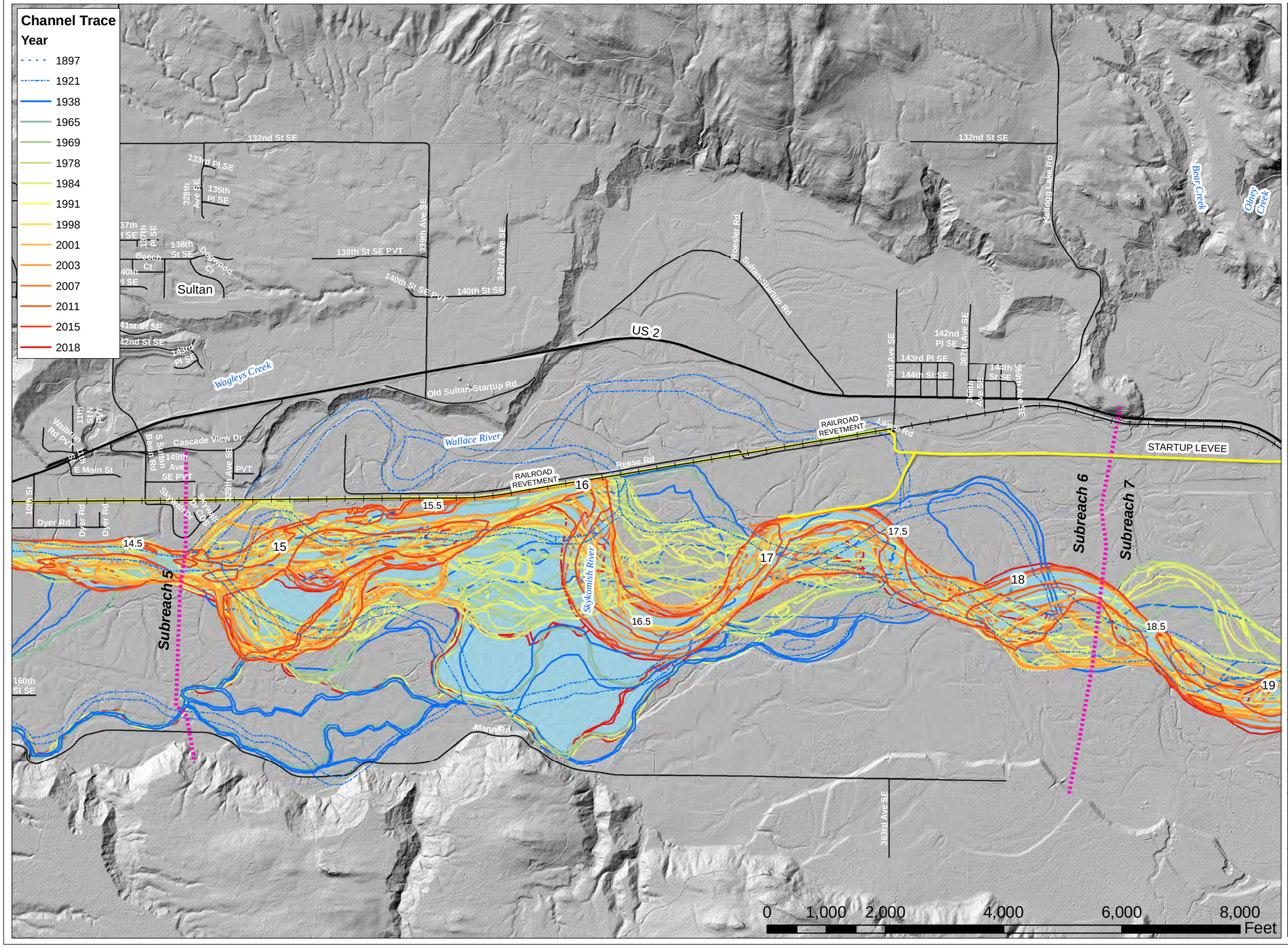
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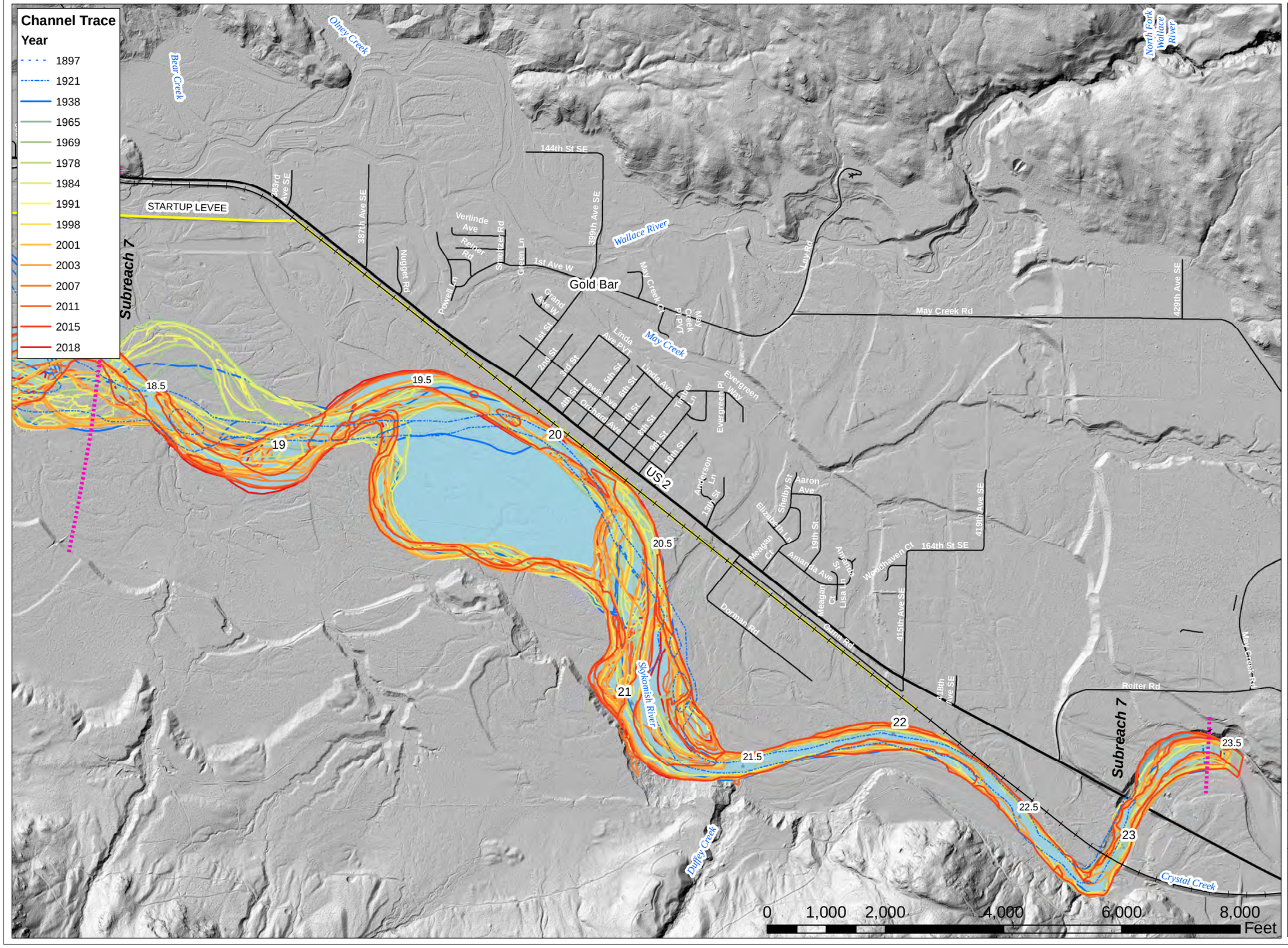
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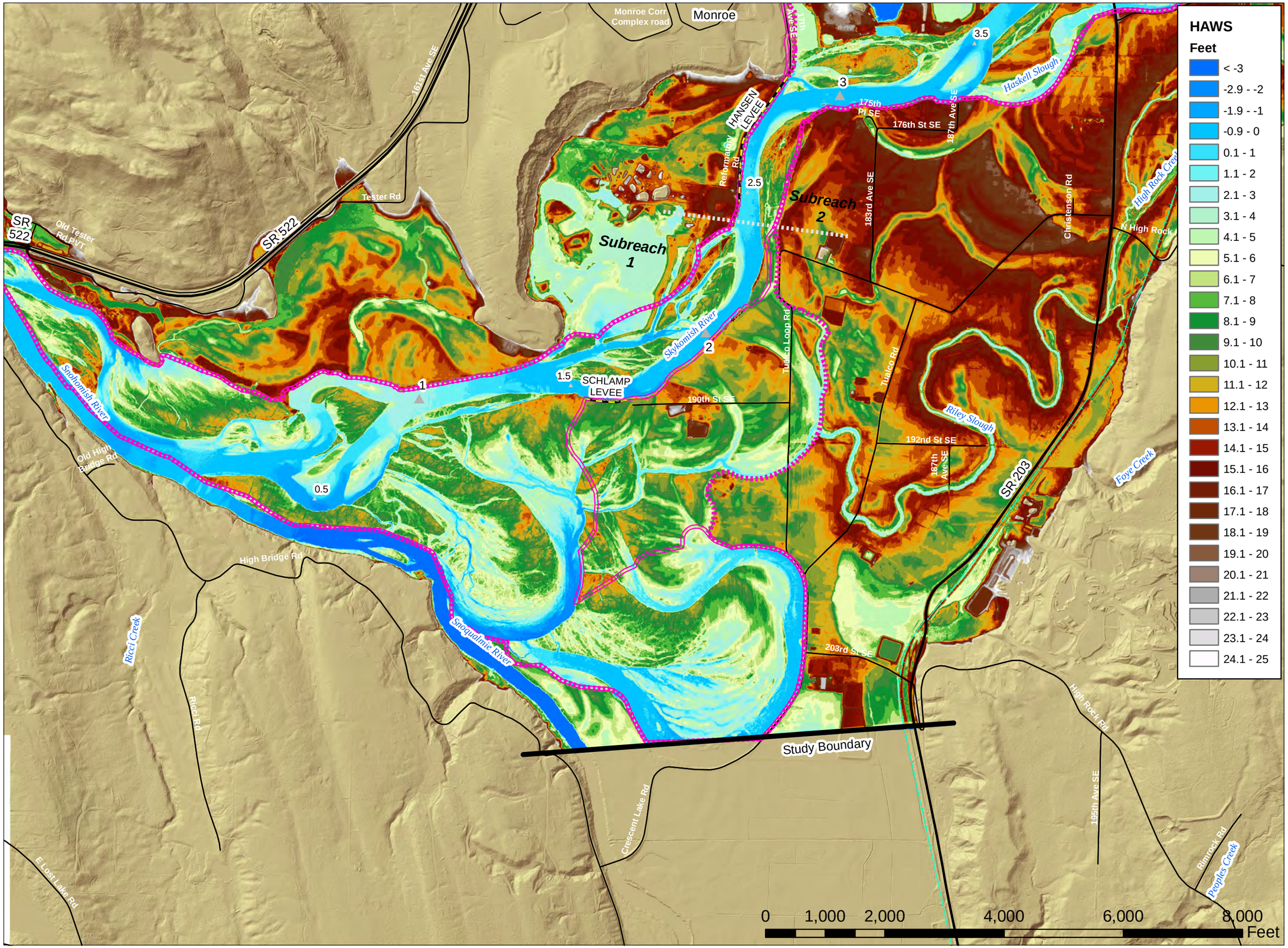
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HAWS

Feet

- < -3
- -2.9 - -2
- -1.9 - -1
- -0.9 - 0
- 0.1 - 1
- 1.1 - 2
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- 23.1 - 24
- 24.1 - 25



Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

- Riprap Along River's Edge
- Clay Along River's Edge
- Bedrock Along River's Edge
- Maintained Levees and Railroad
- Levees Not Maintained by County
- HMZ - Expanded
- HMZ
- Subreach Boundaries
- Roads
- State HWY
- Abandoned Railroad
- BNSF Railroad
- River Miles

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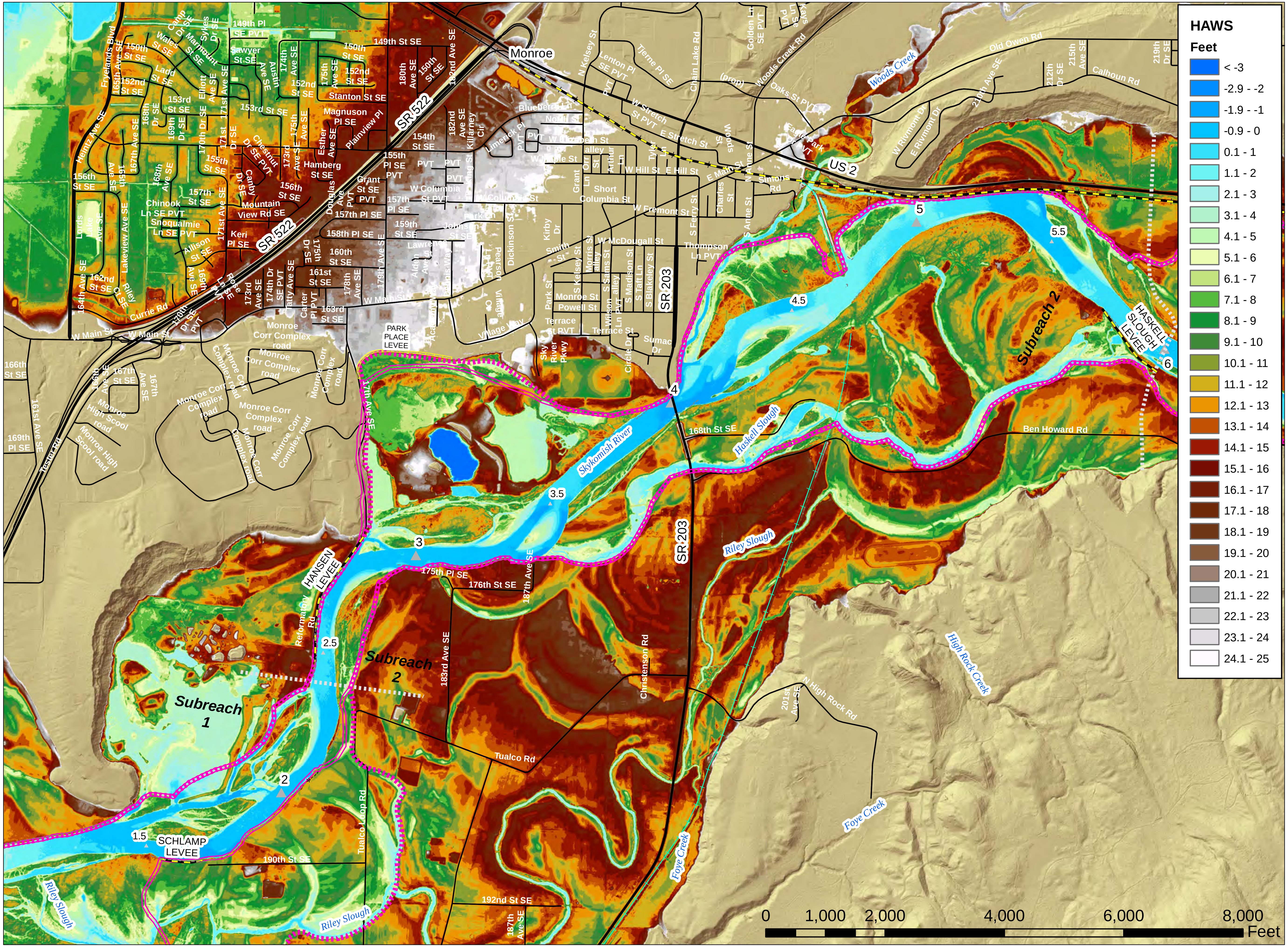
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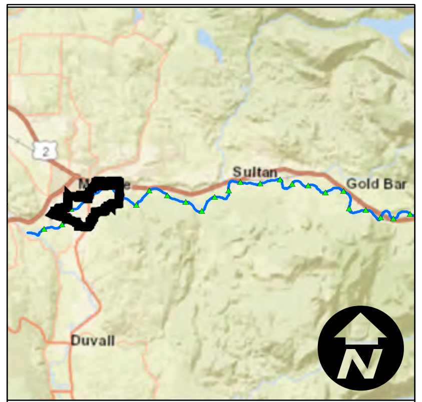
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Water Surface from 2014 and 2017 LiDAR

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Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

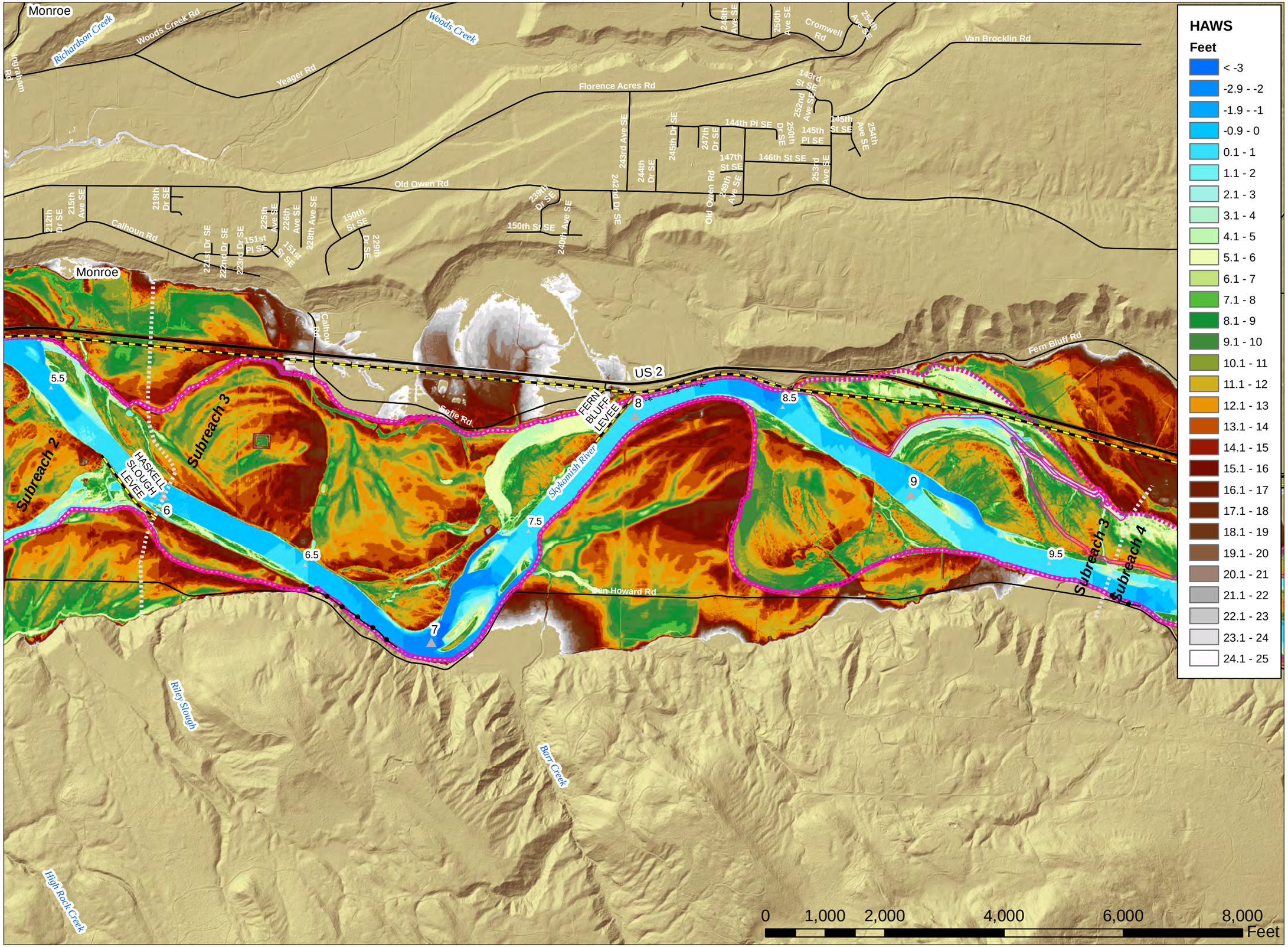
- Riprap Along River's Edge
- Clay Along River's Edge
- Bedrock Along River's Edge
- Maintained Levees and Railroad
- Levees Not Maintained by County
- HMZ - Expanded
- HMZ
- Subreach Boundaries
- Roads
- State HWY
- Abandoned Railroad
- BNSF Railroad
- River Miles

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Water Surface from 2014 and 2017 LiDAR

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HAWS
Feet

- < -3
- -2.9 - -2
- -1.9 - -1
- -0.9 - 0
- 0.1 - 1
- 1.1 - 2
- 2.1 - 3
- 3.1 - 4
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- 23.1 - 24
- 24.1 - 25



Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

- Riprap Along River's Edge
- Clay Along River's Edge
- Bedrock Along River's Edge
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- River Miles

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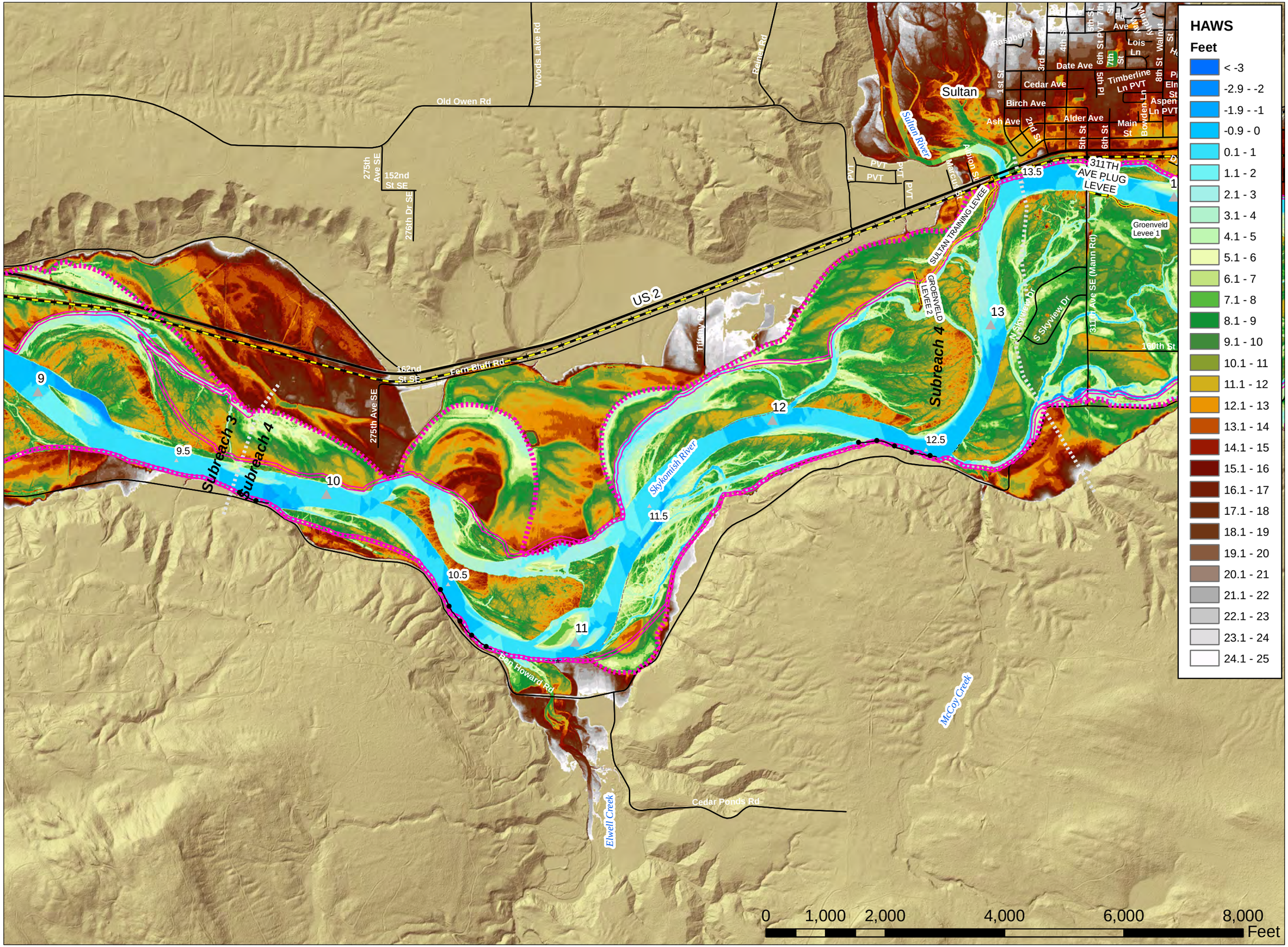
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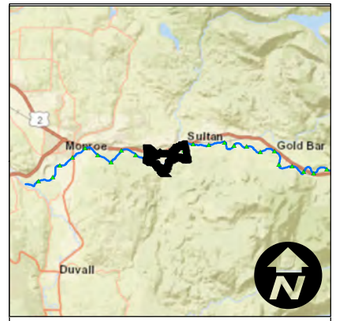
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Water Surface from 2014 and 2017 LiDAR

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Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

- Riprap Along River's Edge
- Clay Along River's Edge
- Bedrock Along River's Edge
- Maintained Levees and Railroad
- Levees Not Maintained by County
- HMZ - Expanded
- HMZ
- Subreach Boundaries
- Roads
- State HWY
- Abandoned Railroad
- BNSF Railroad
- River Miles

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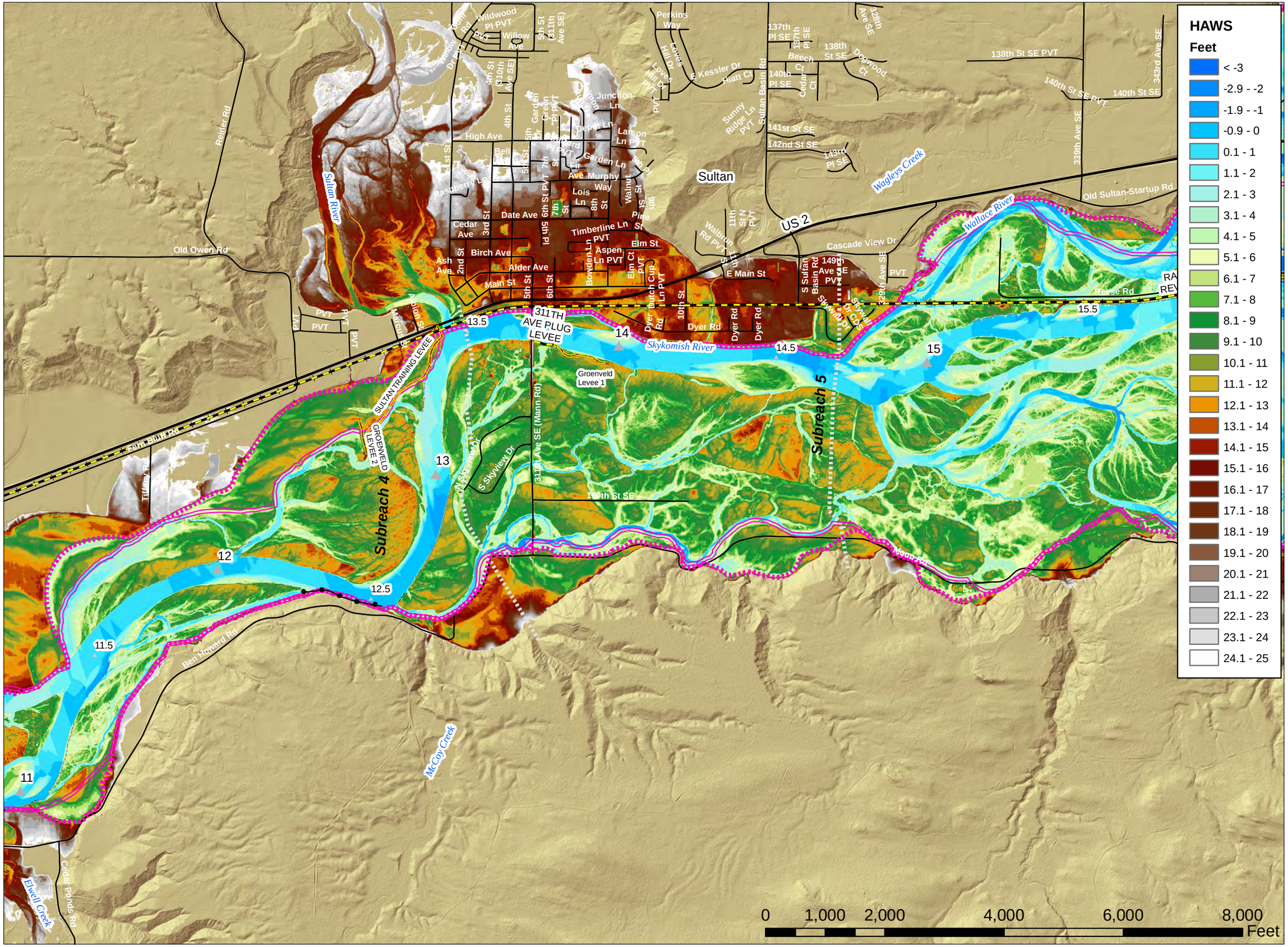
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Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

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Snohomish County, WA

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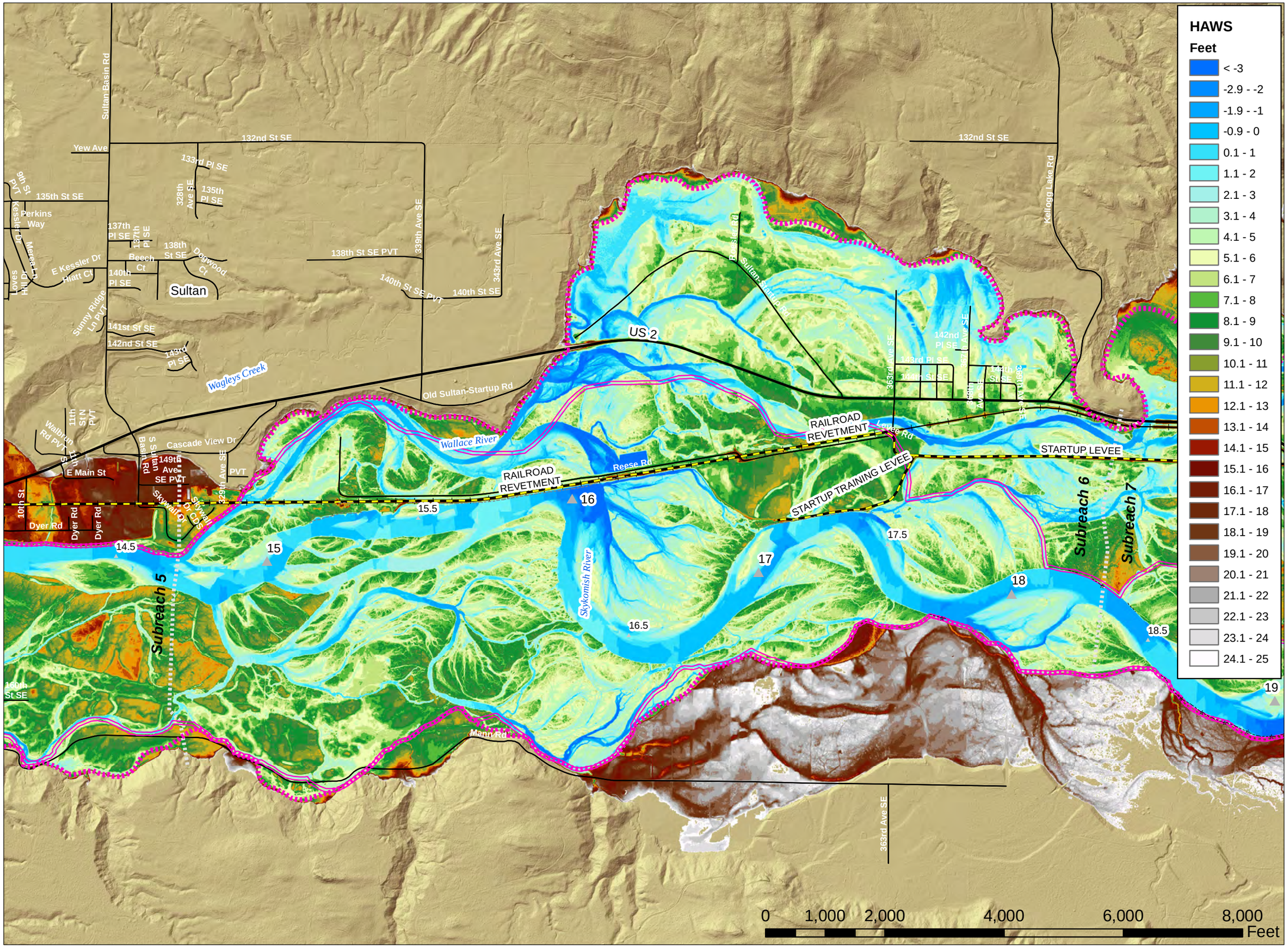
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Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

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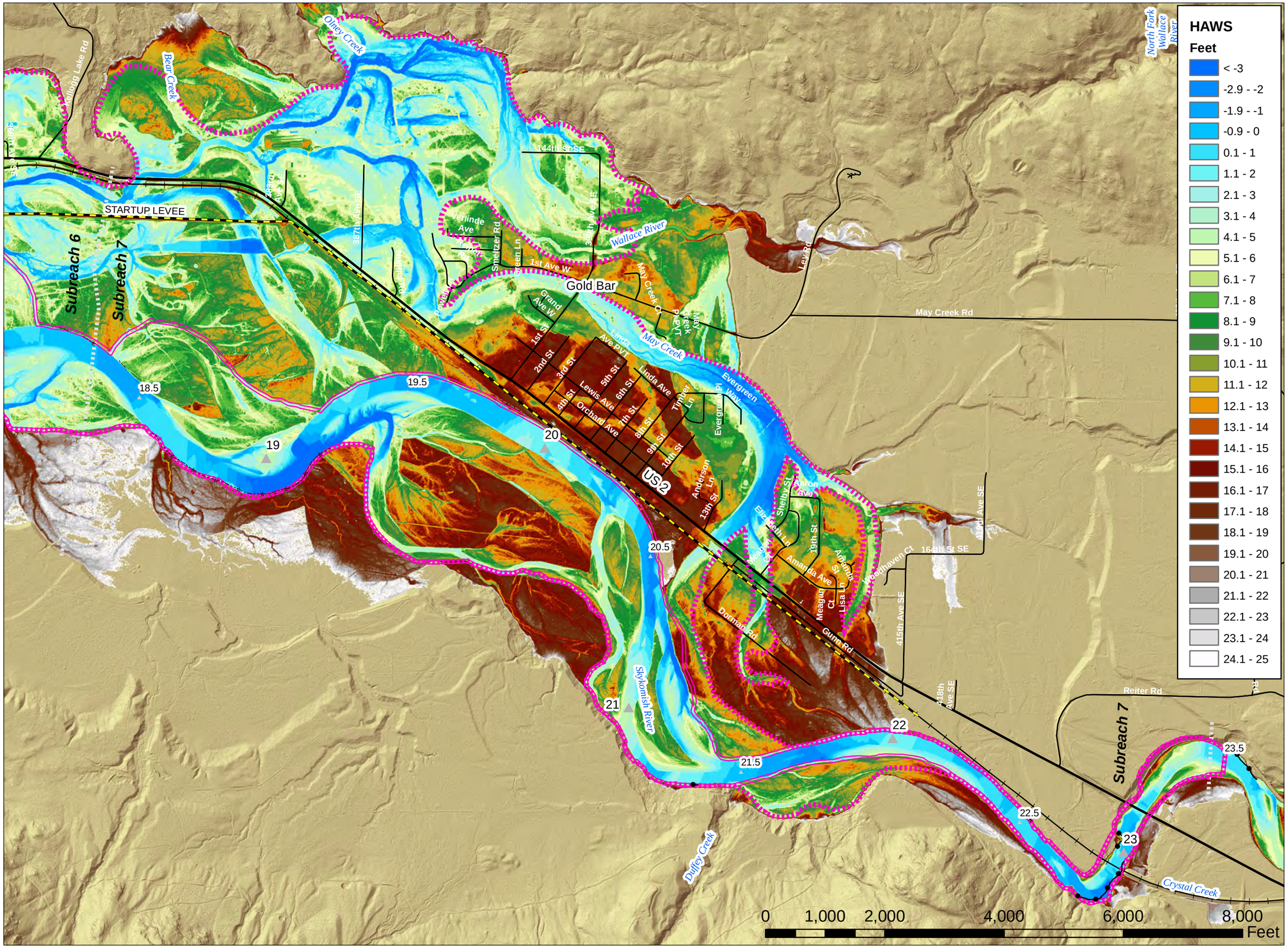
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Height Above Water Surface and HMZ/eHMZ Boundaries

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

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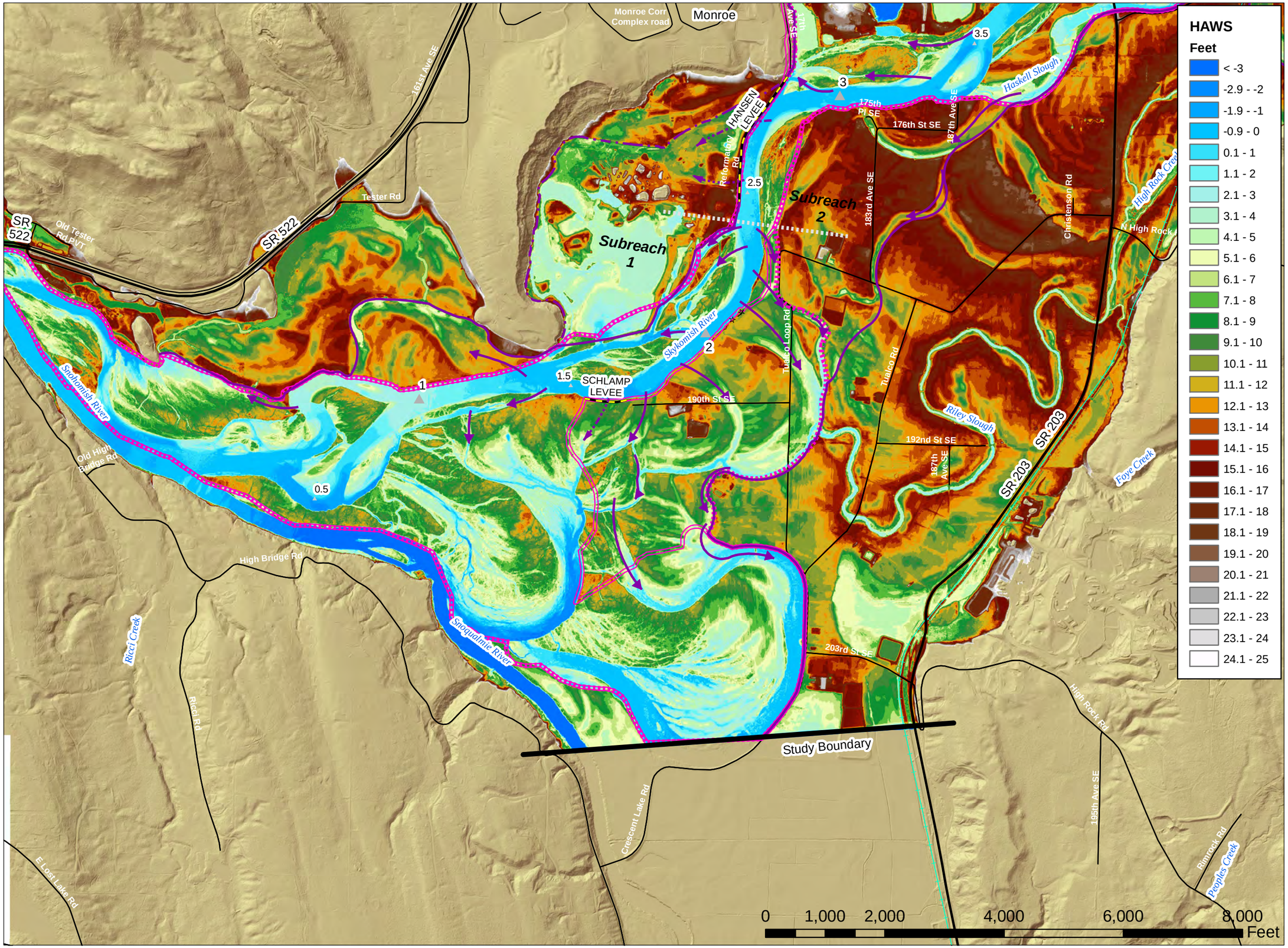
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

Avulsion Pathways

- Avulsion Path
- Avulsion Path w/o Migration Barrier
- Clay Along River's Edge
- Bedrock Along River's Edge
- Maintained Levees and Railroad
- Levees Not Maintained by County

Avulsion Channel Edge

- Avulsion Channel
- Avulsion Channel w/o Migration Barrier
- HMZ - Expanded
- HMZ
- Subreach Boundries
- Roads
- State Hwy
- Abandoned Railroad
- BNSF Railroad
- River Miles

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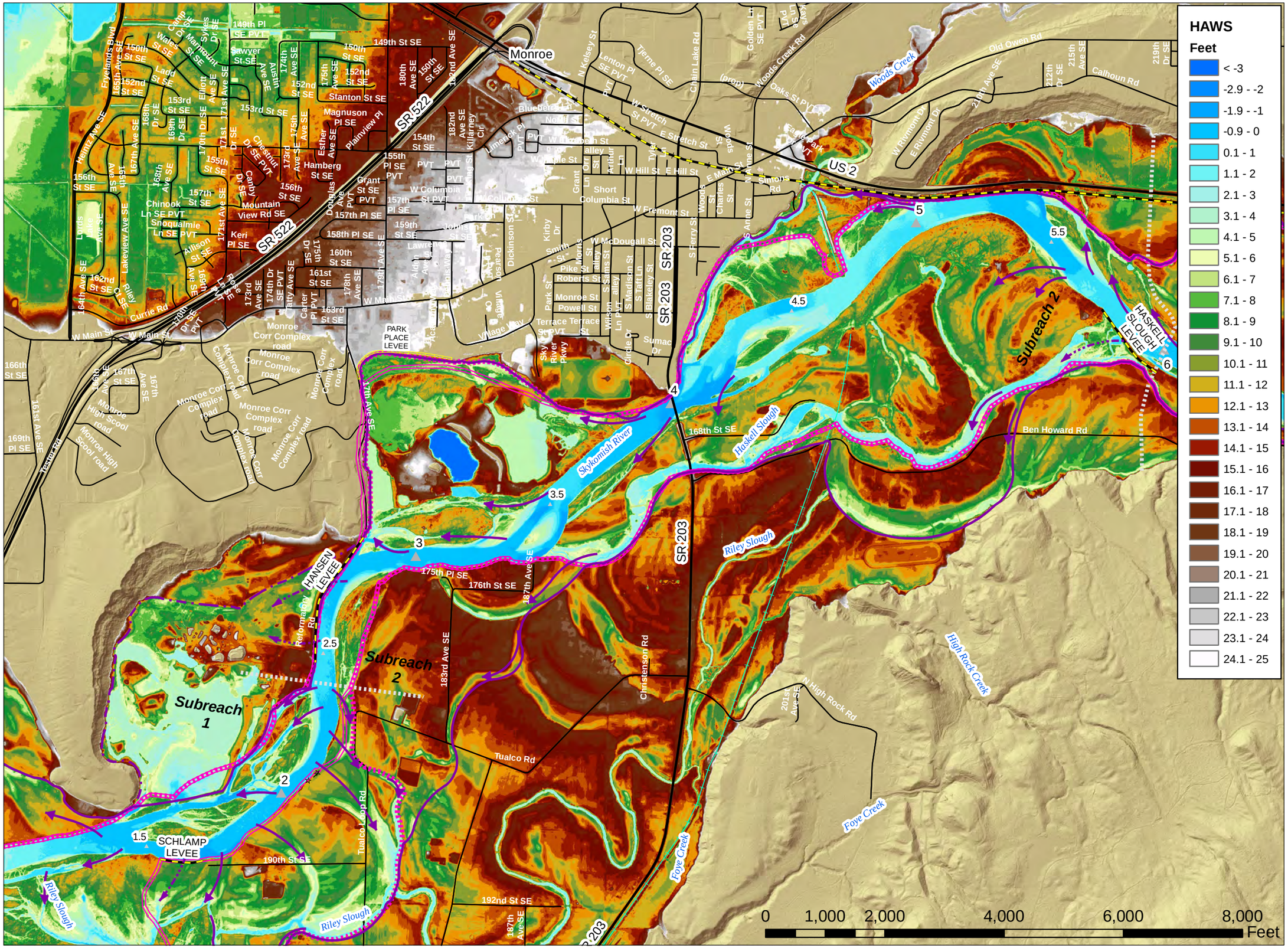
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

Avulsion Pathways
- Avulsion Path
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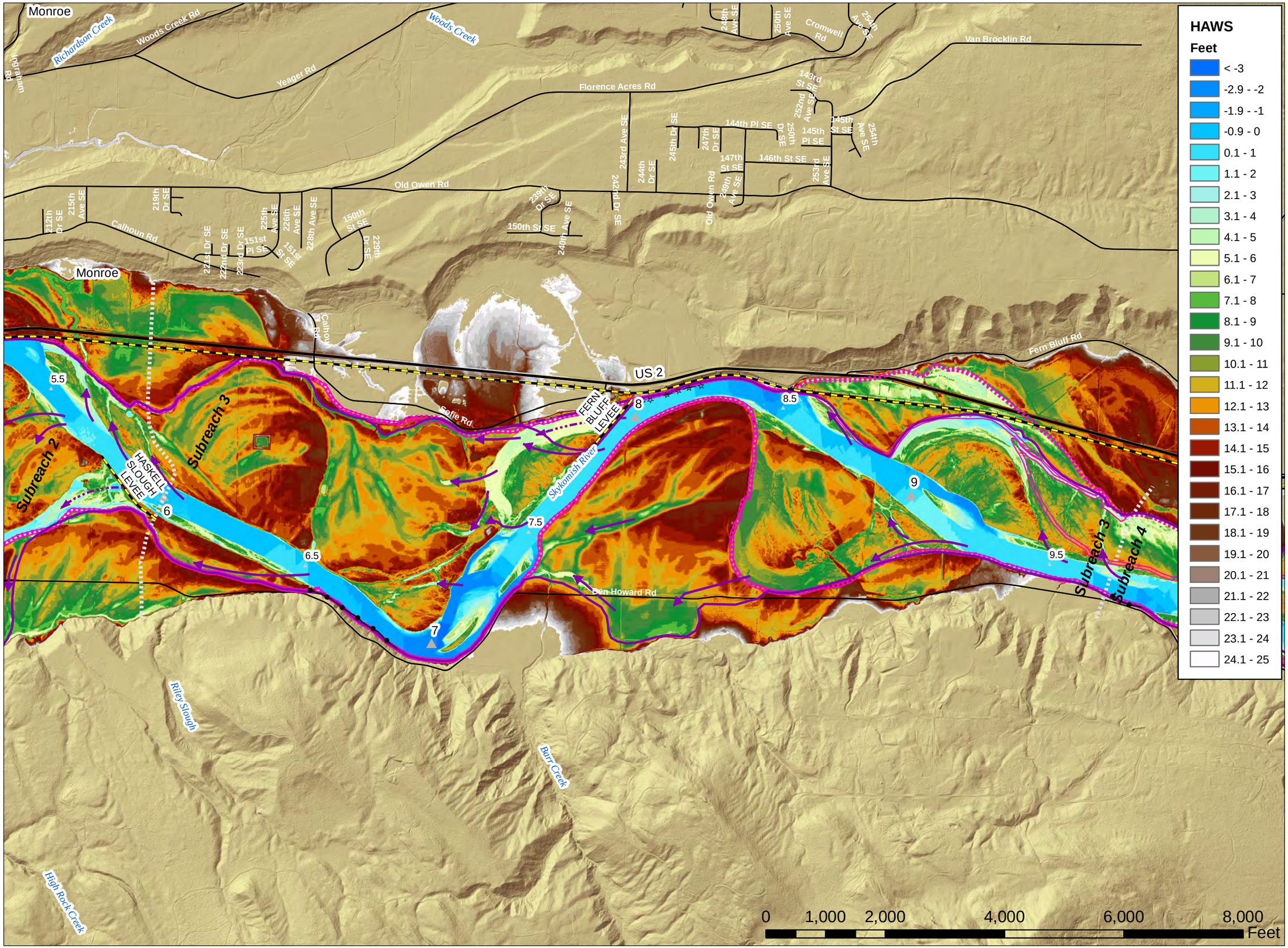
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

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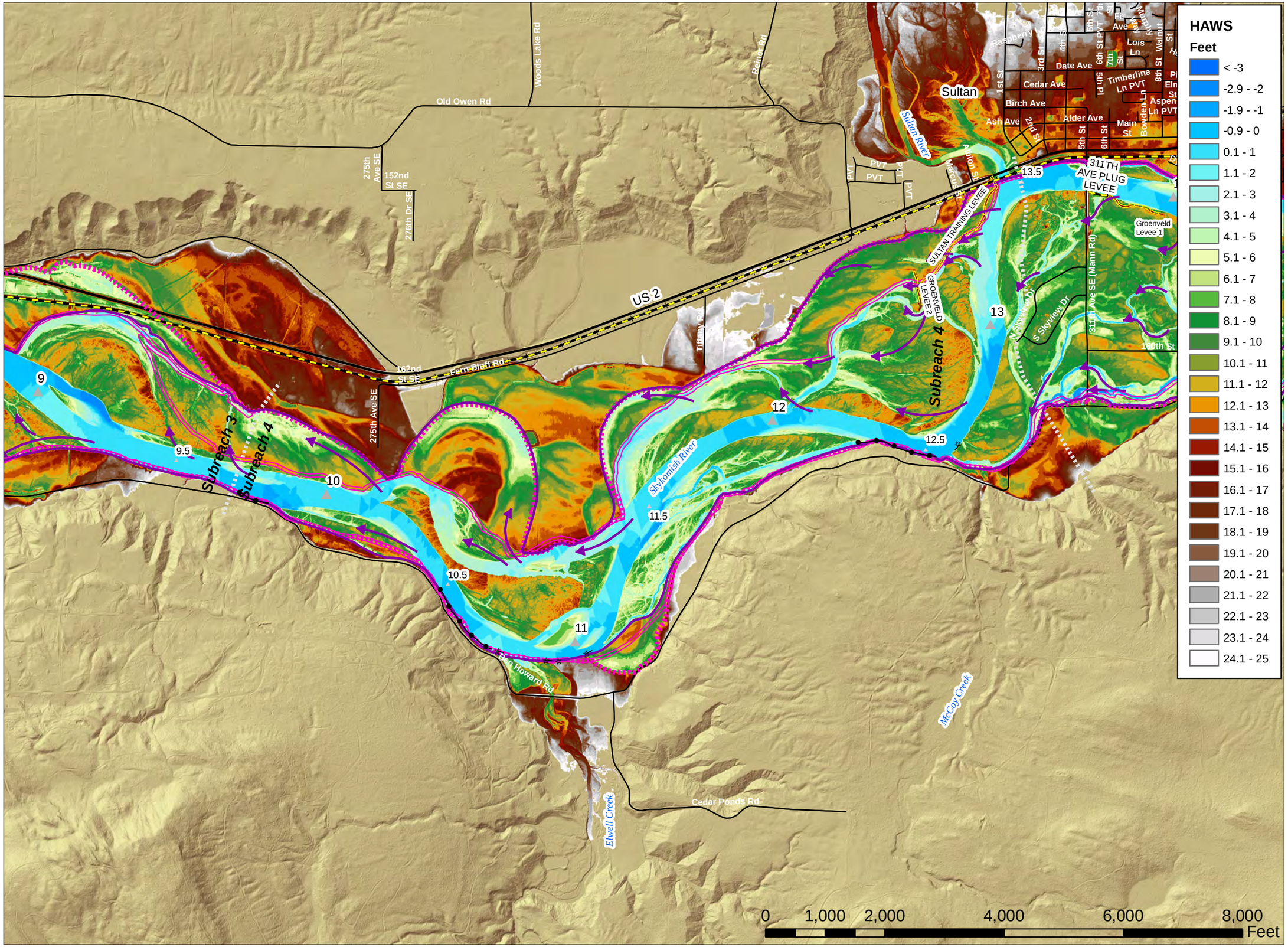
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

Avulsion Pathways
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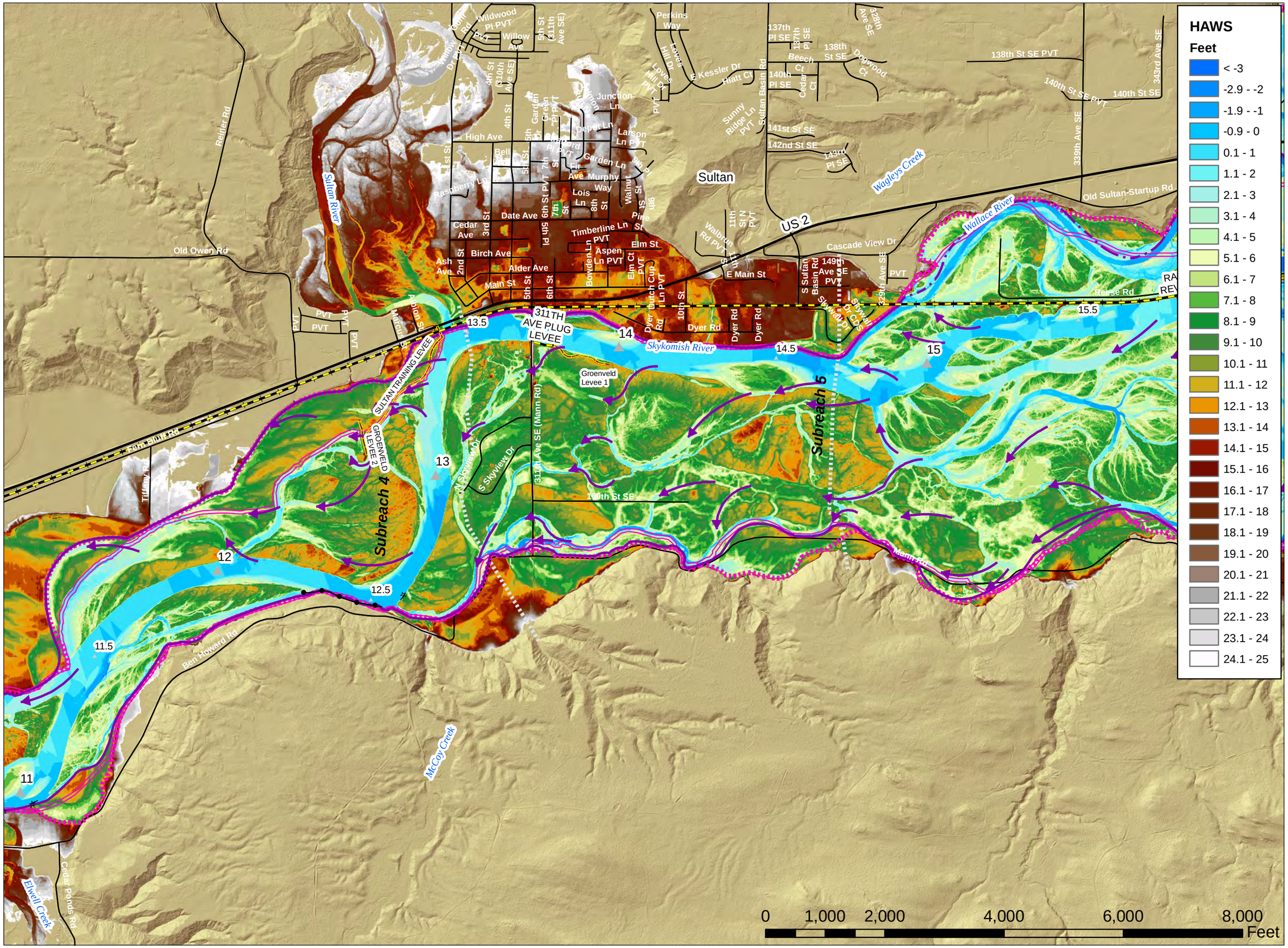
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
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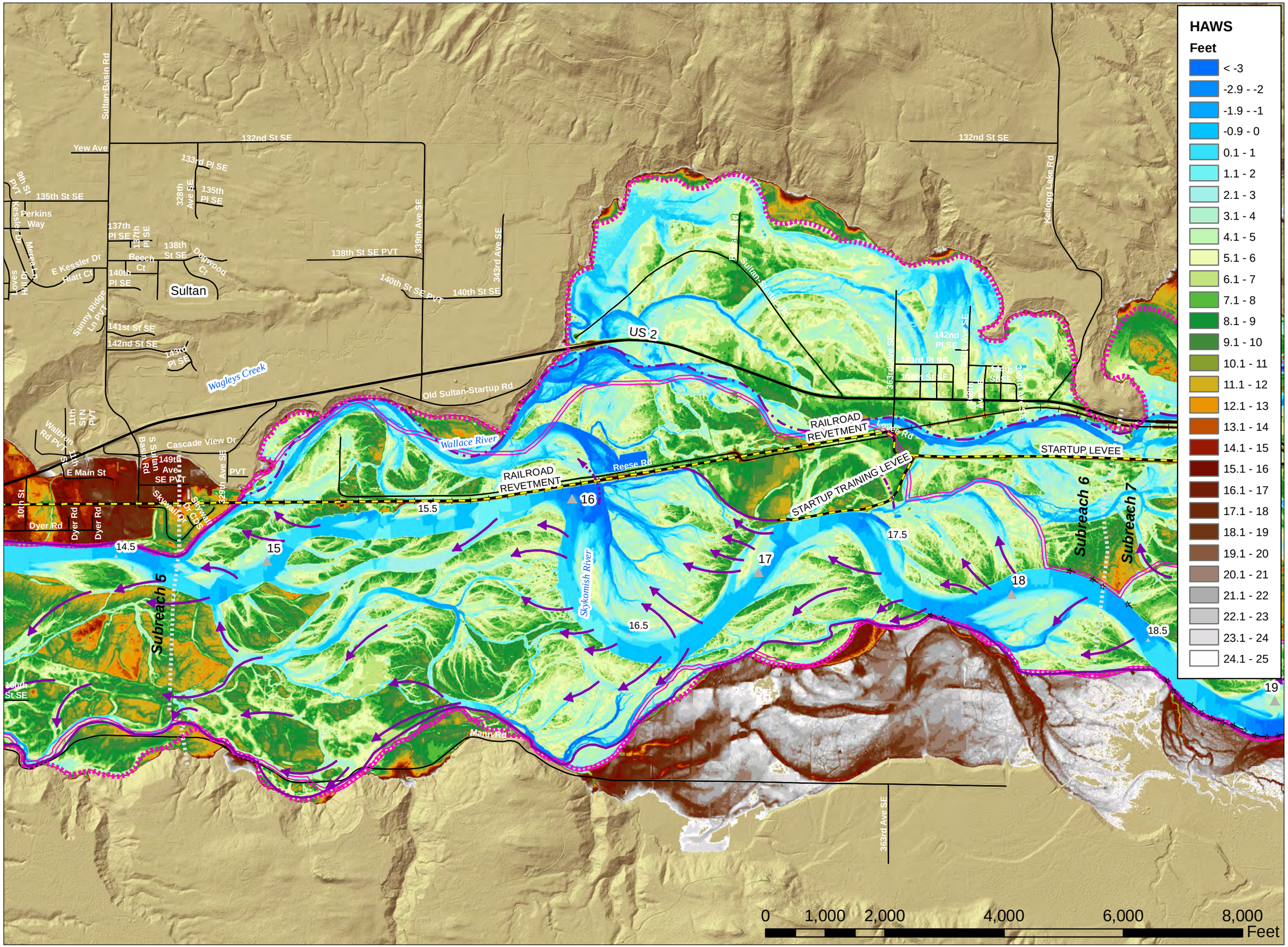
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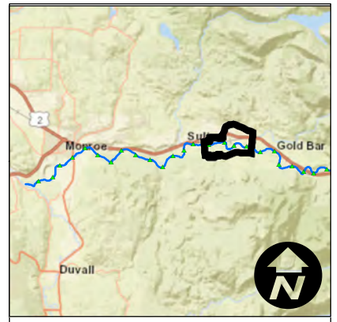
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

Avulsion Pathways

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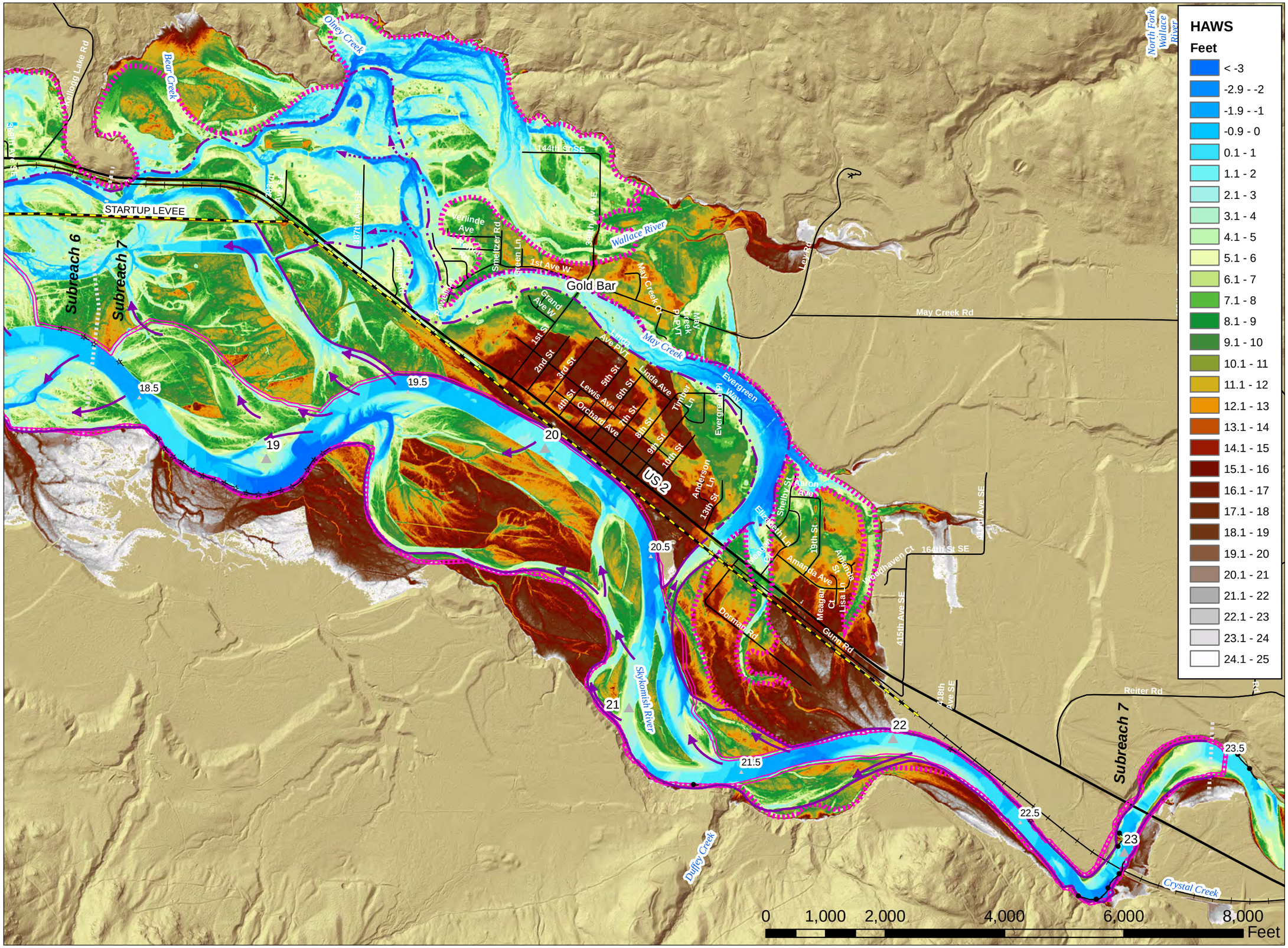
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Avulsion Paths

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

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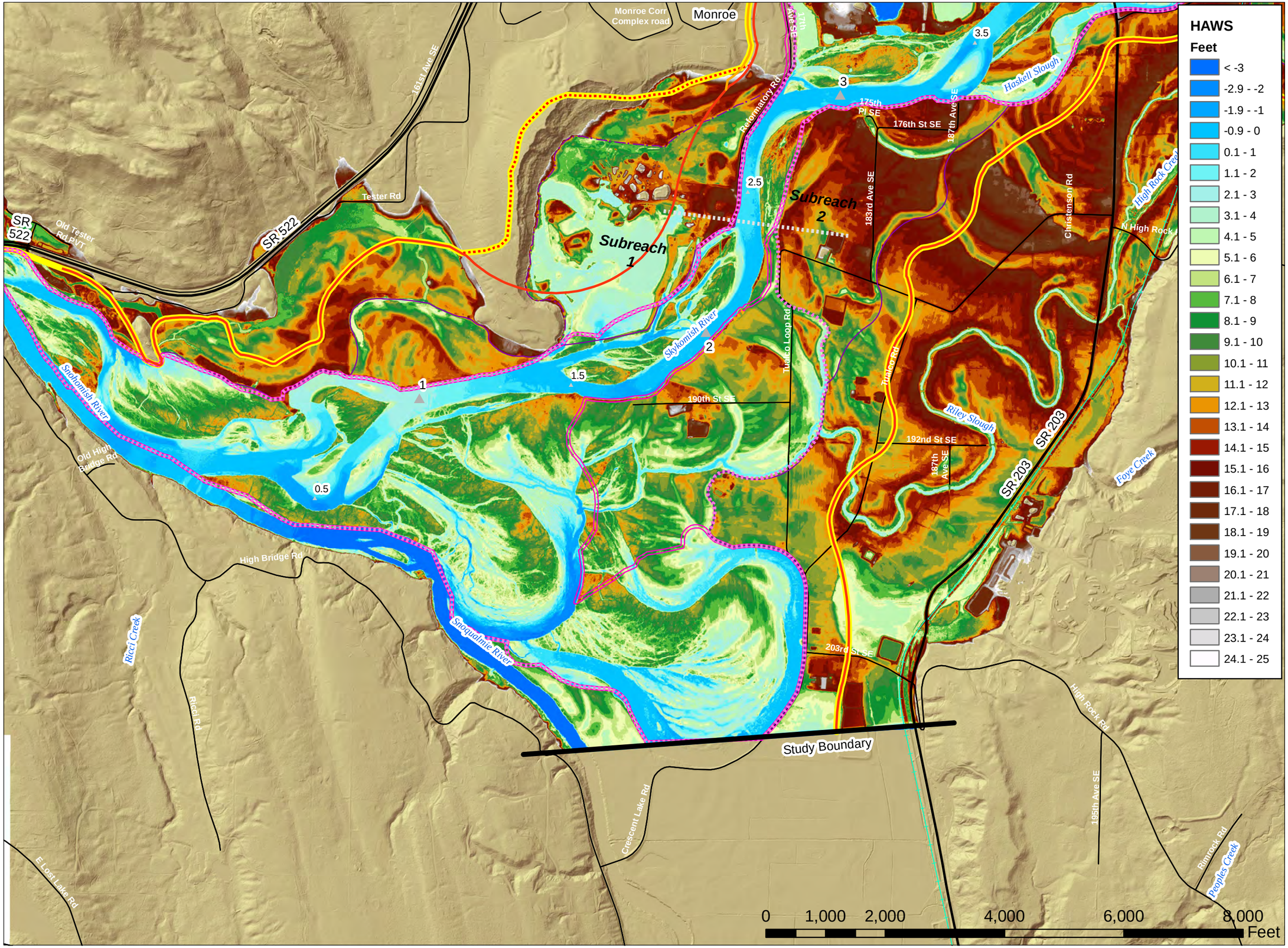
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Erosion Hazard and Unconstrained CMZ

Geomorphic Flood Hazard Risk on the Lower Skykomish

Surface Water Management
Snohomish County, WA

- Geotechnical Setback
- Clay Along River's Edge
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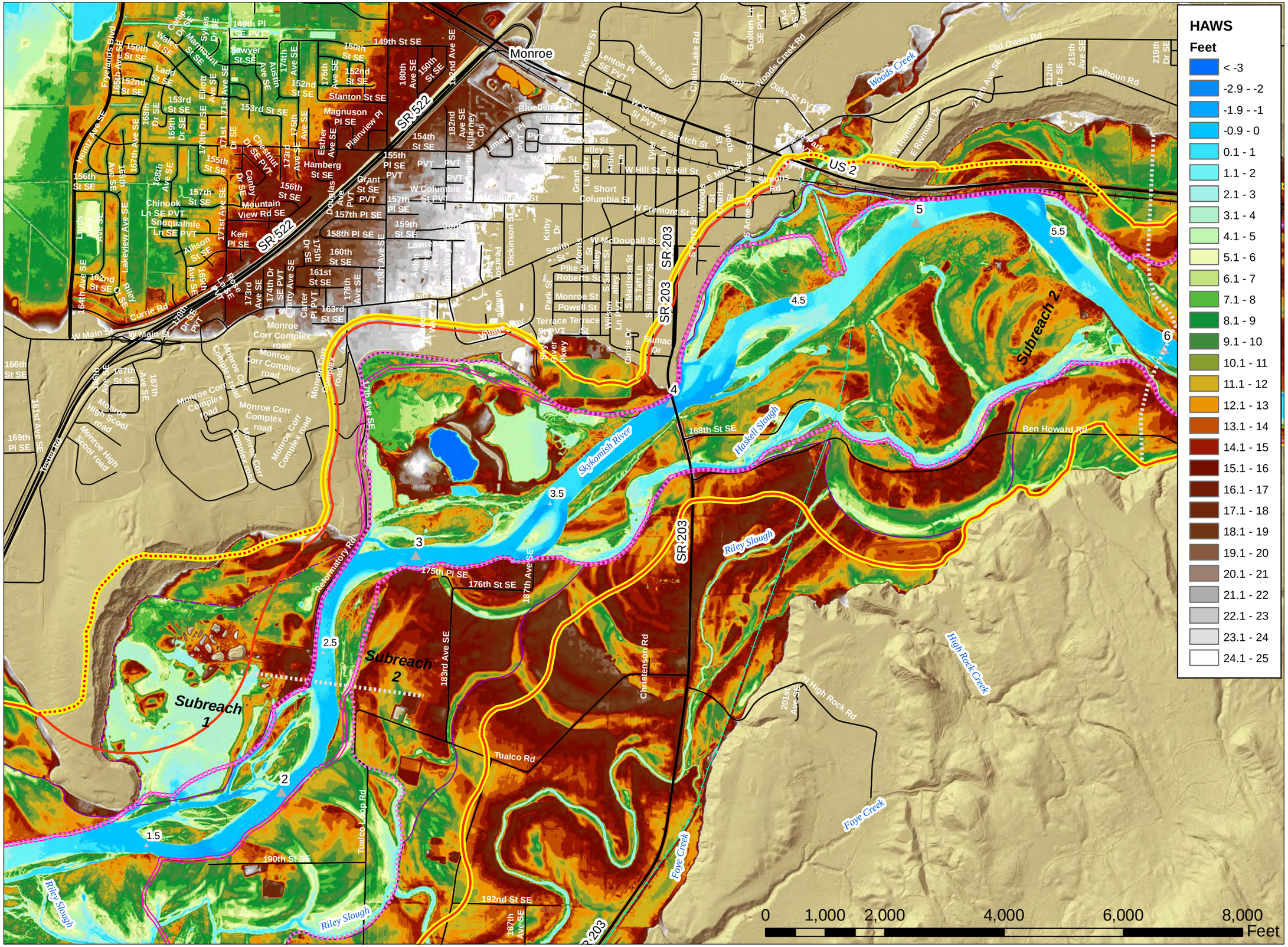
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Erosion Hazard and Unconstrained CMZ

Geomorphic Flood Hazard Risk on the Lower Skykomish

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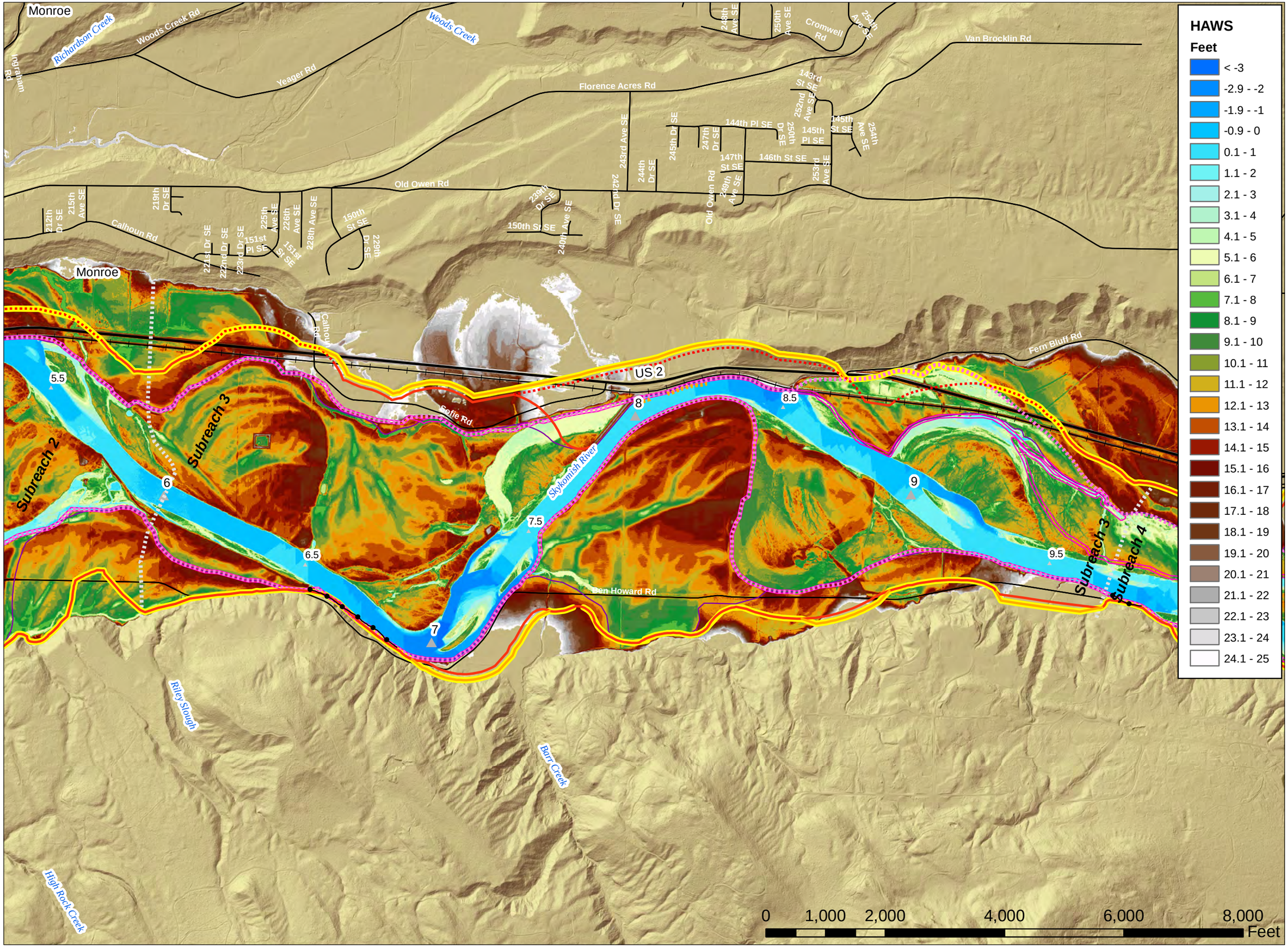
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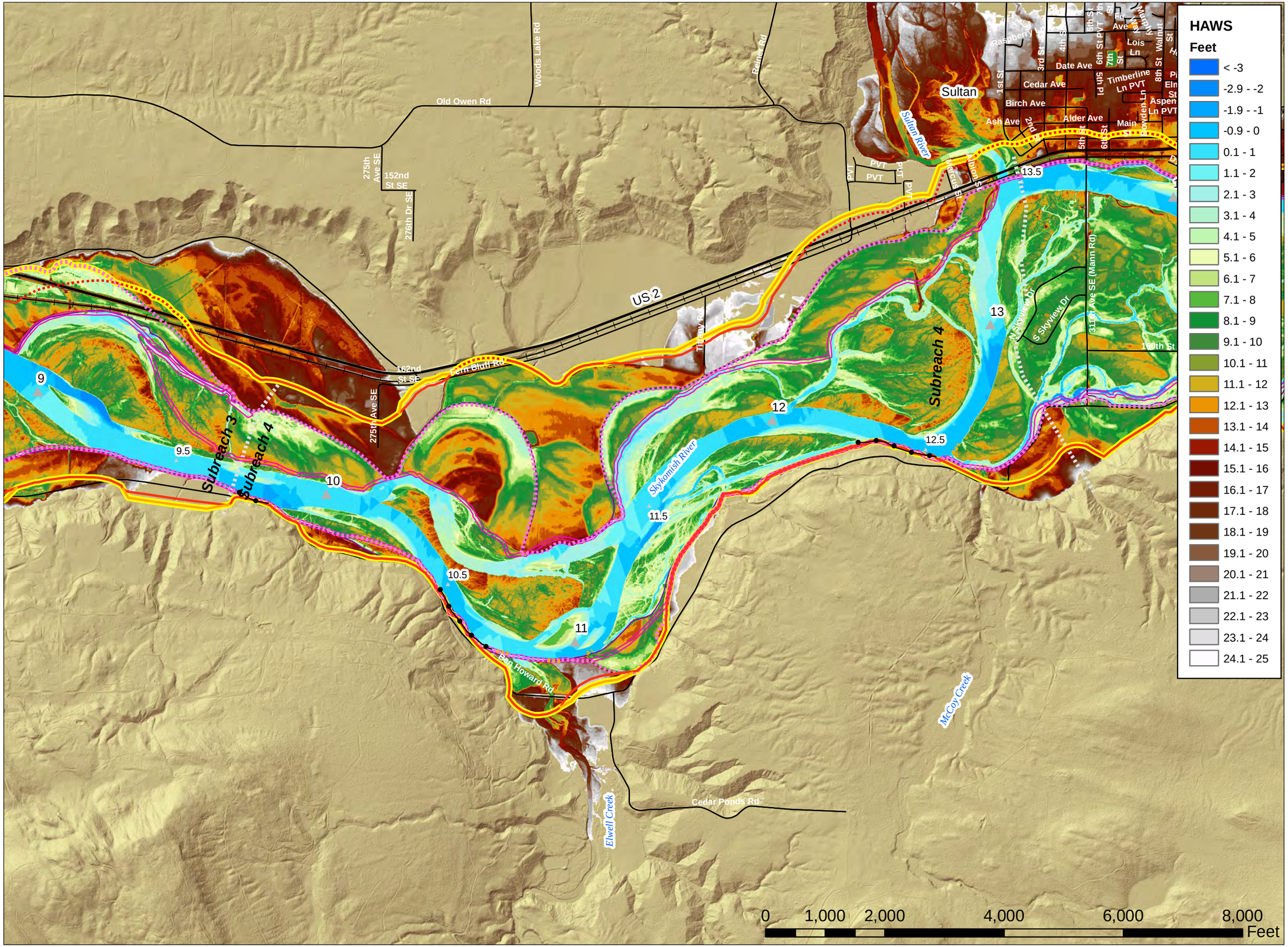
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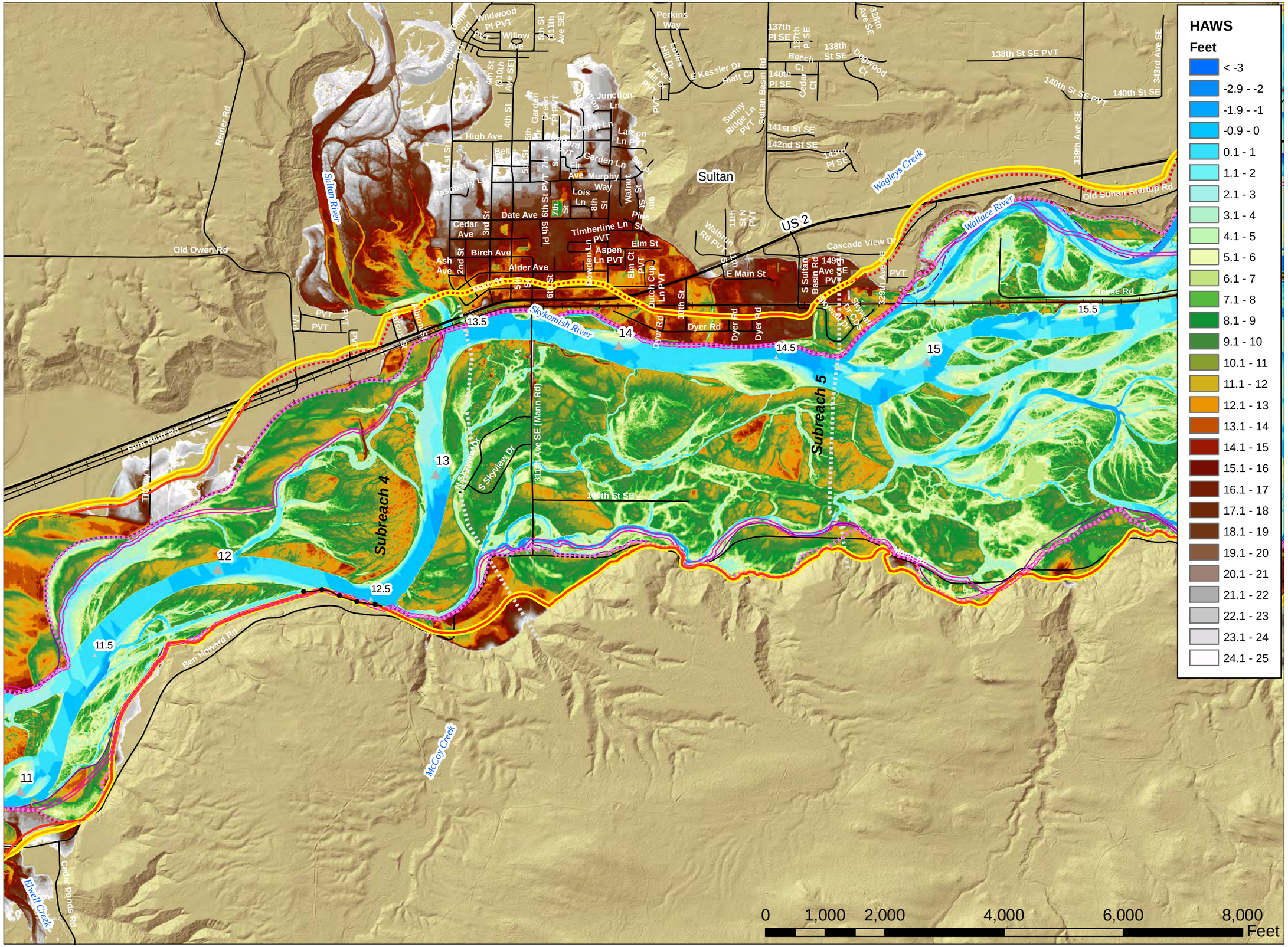
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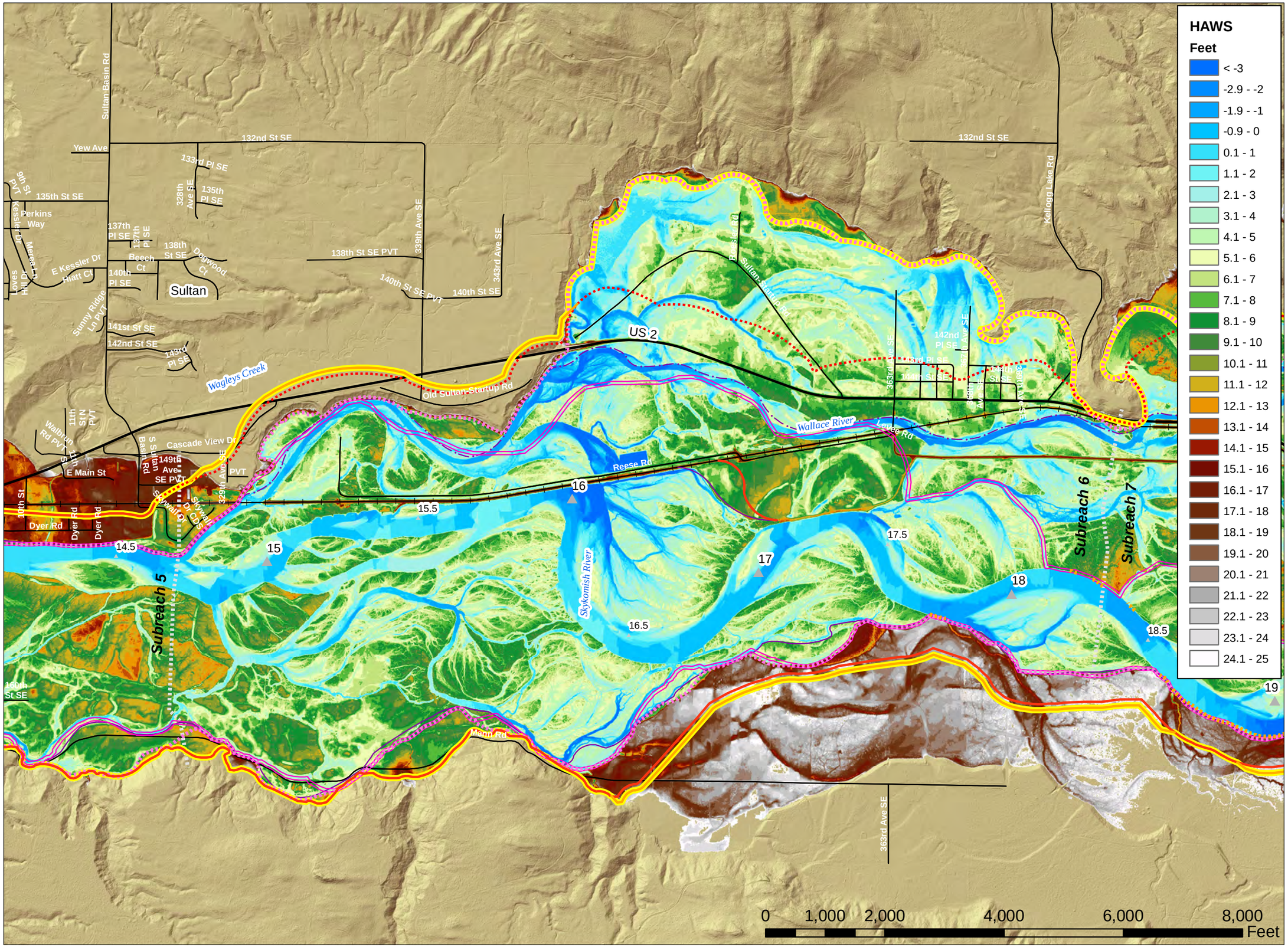
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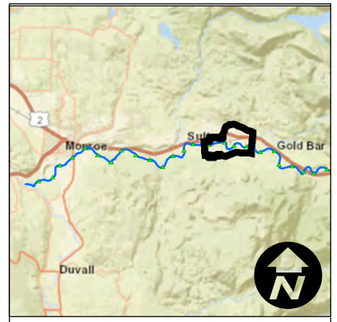
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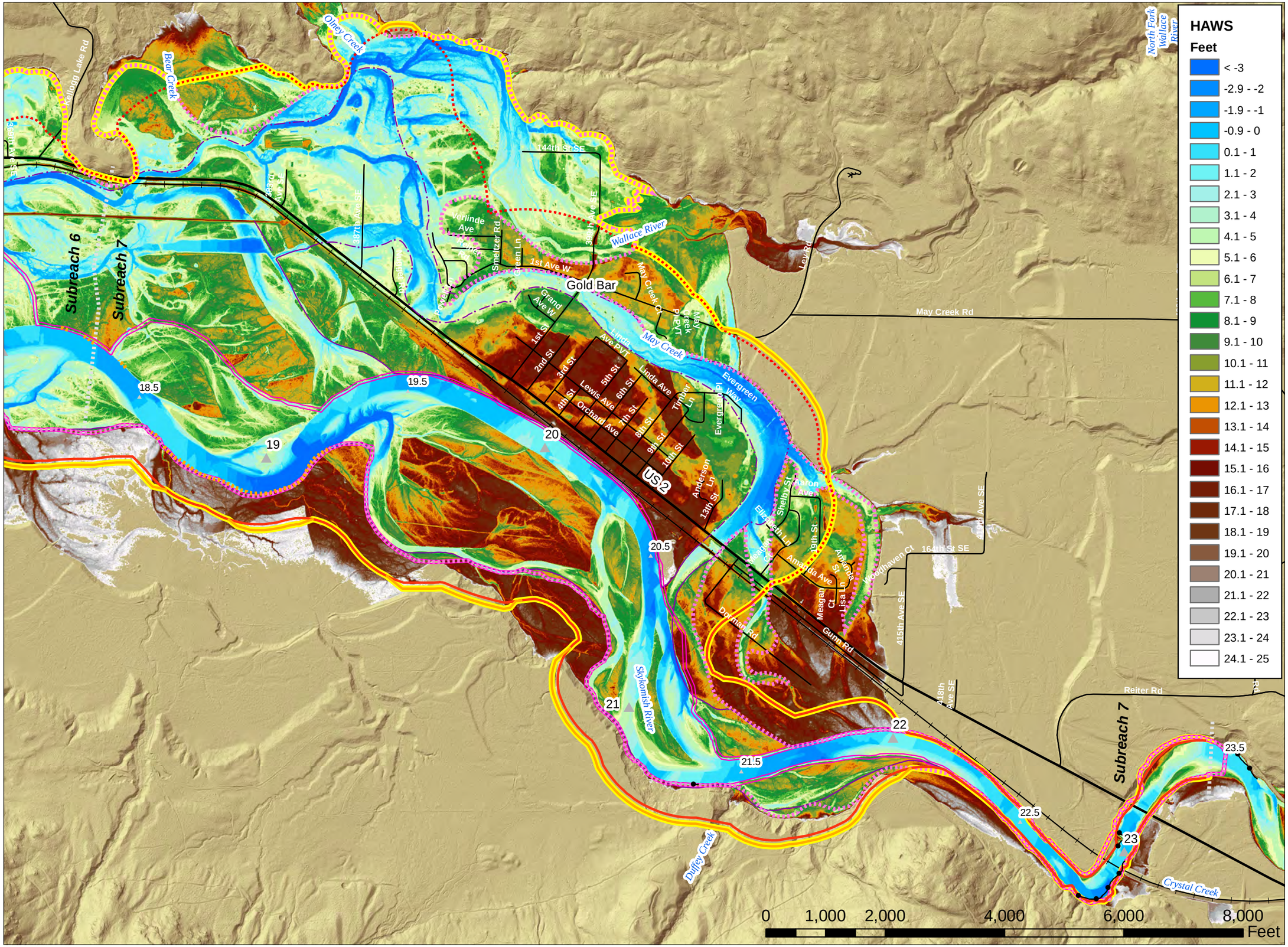
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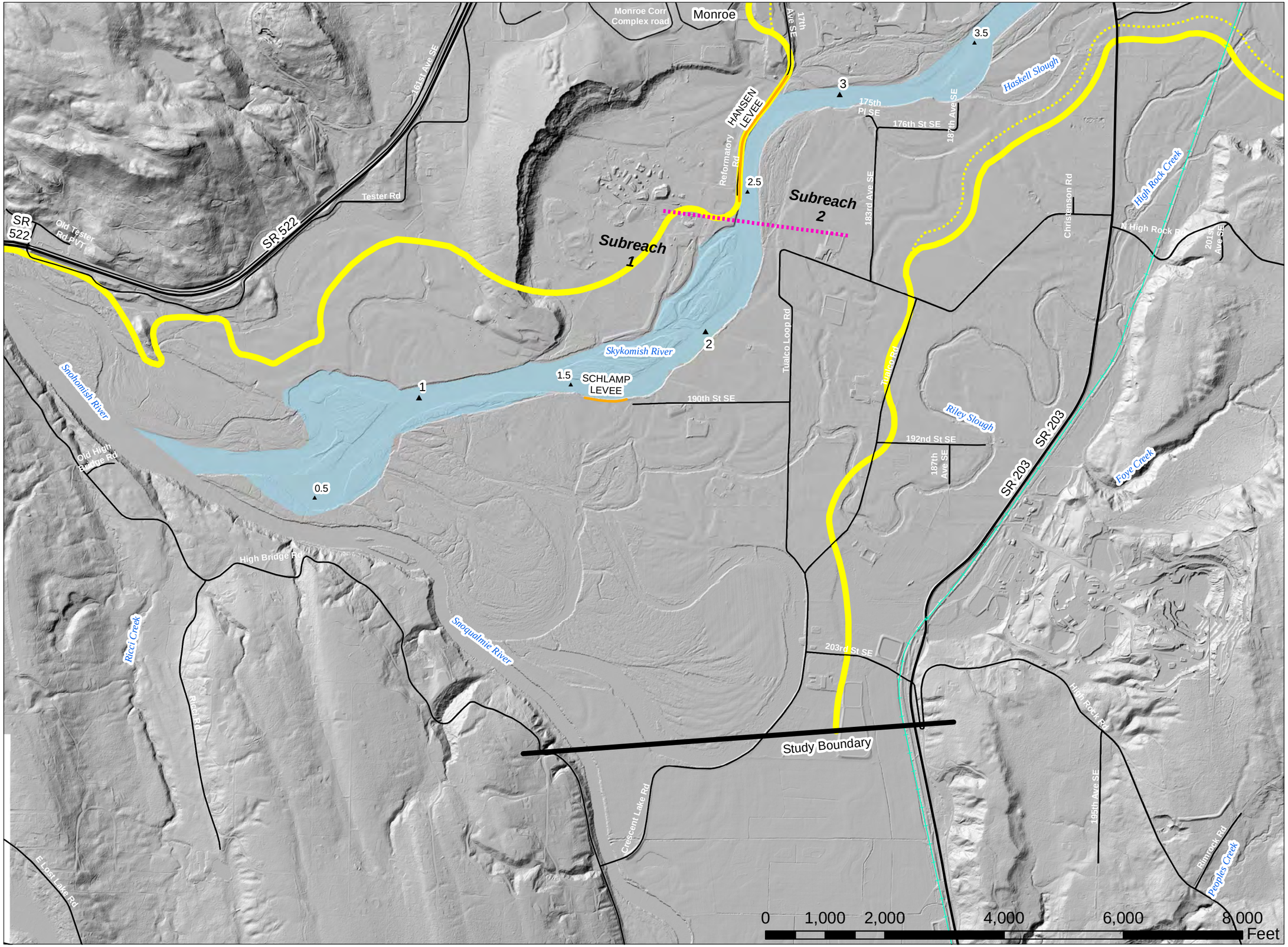
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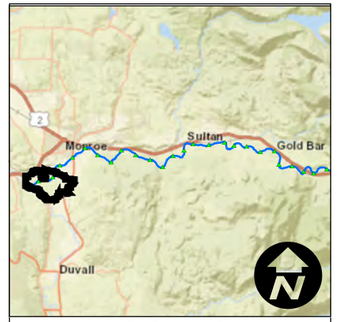
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Snohomish County, WA

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- CMZ - moderate/severe
- River Miles
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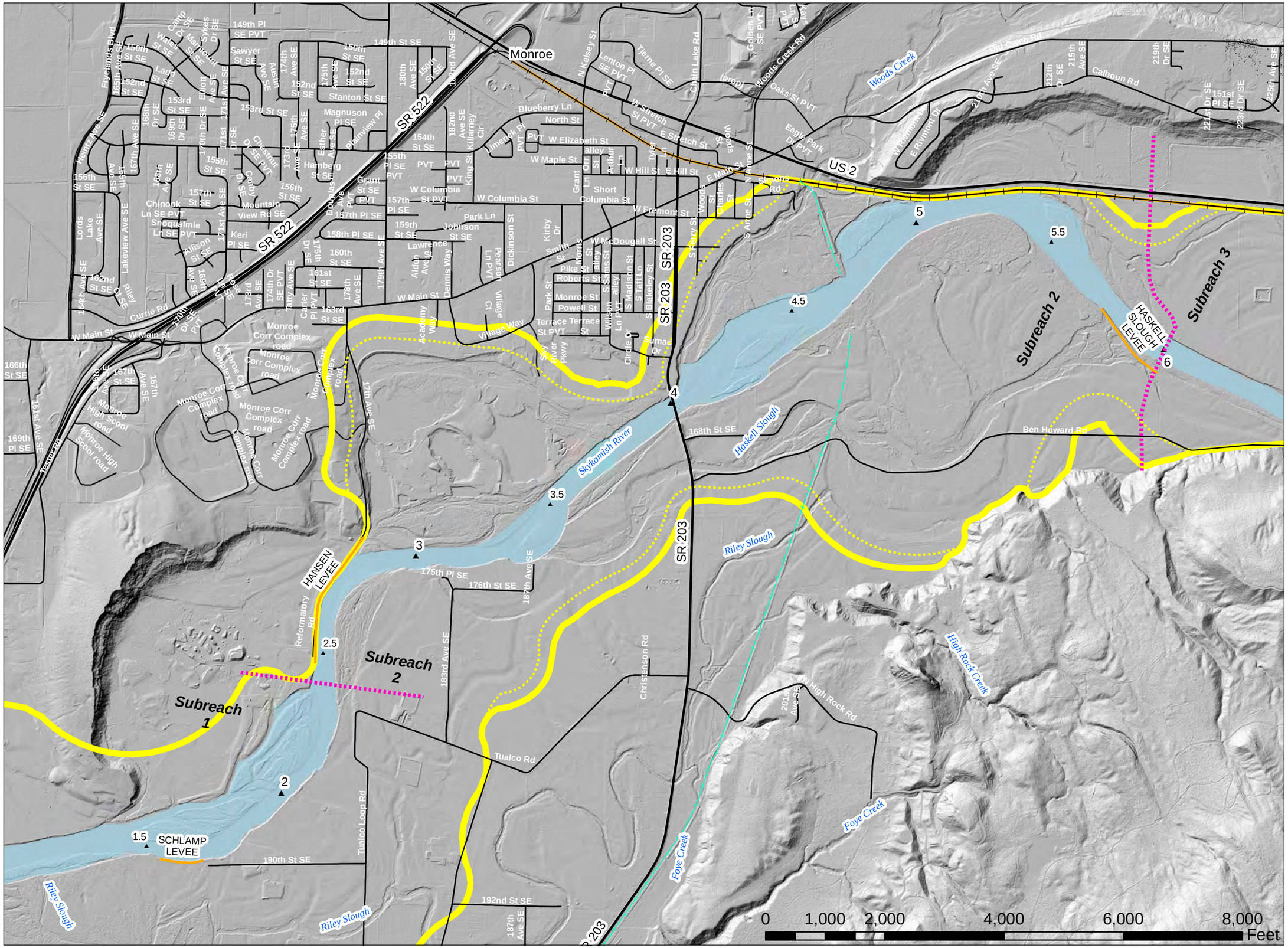
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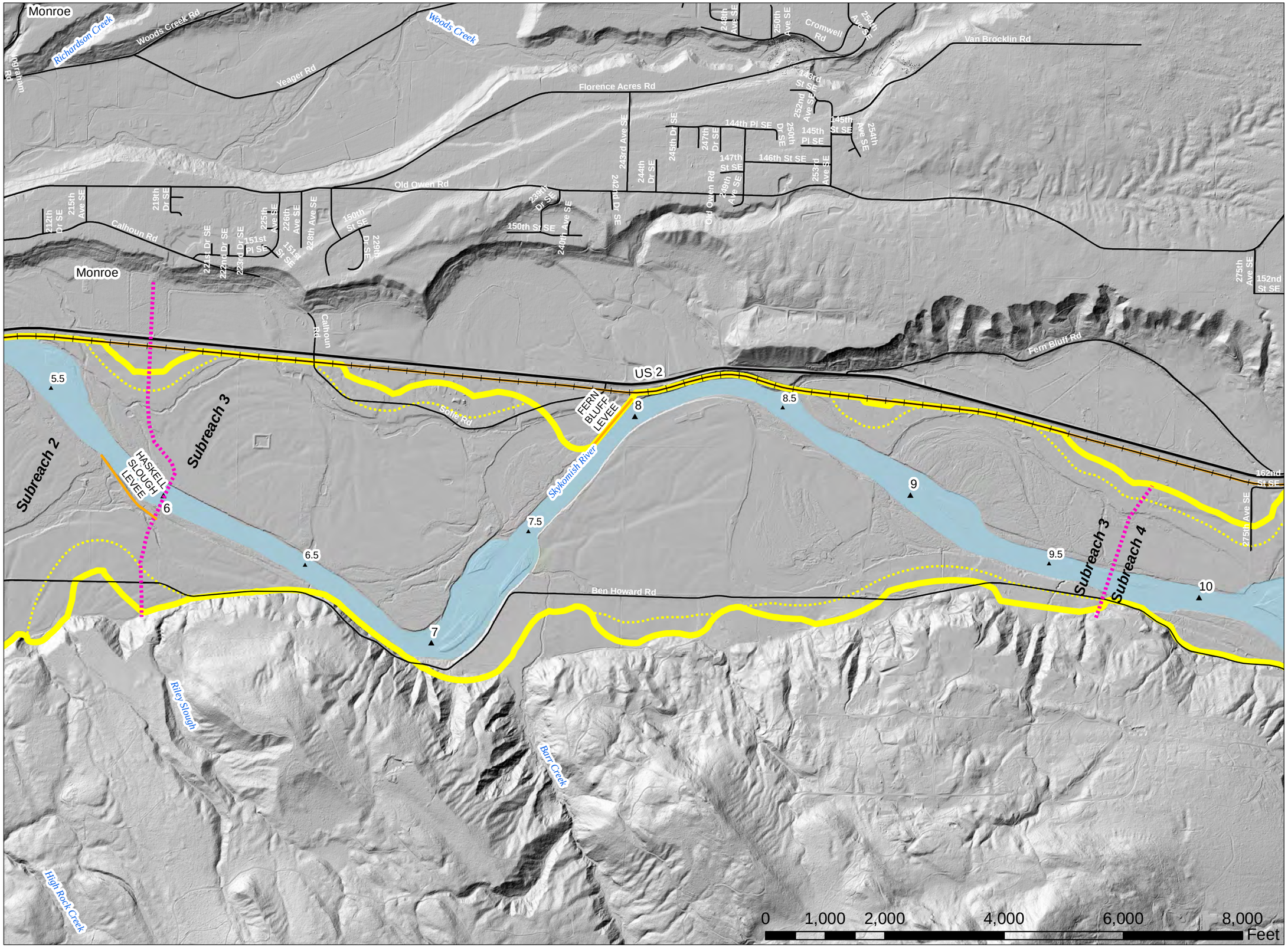
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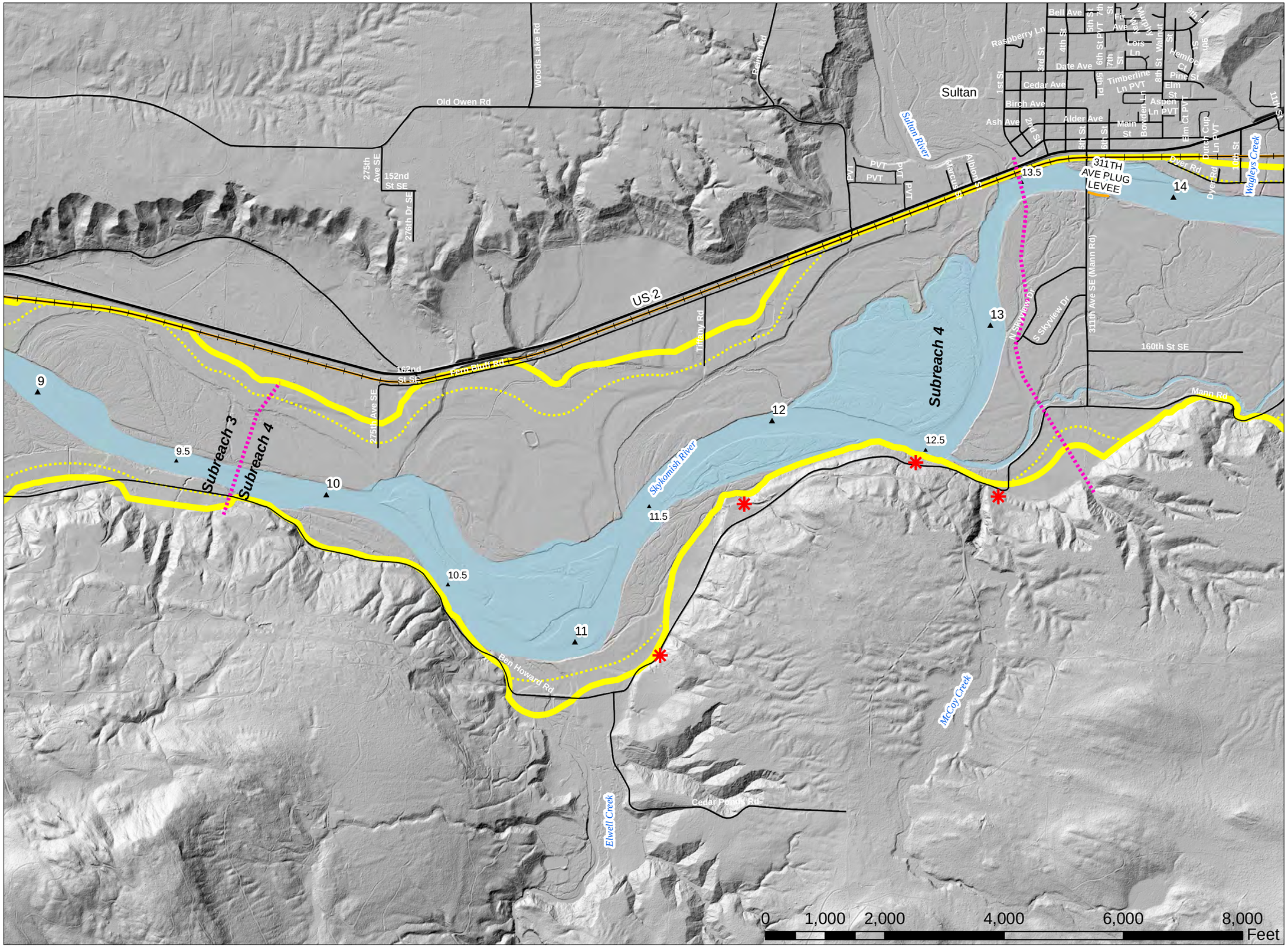
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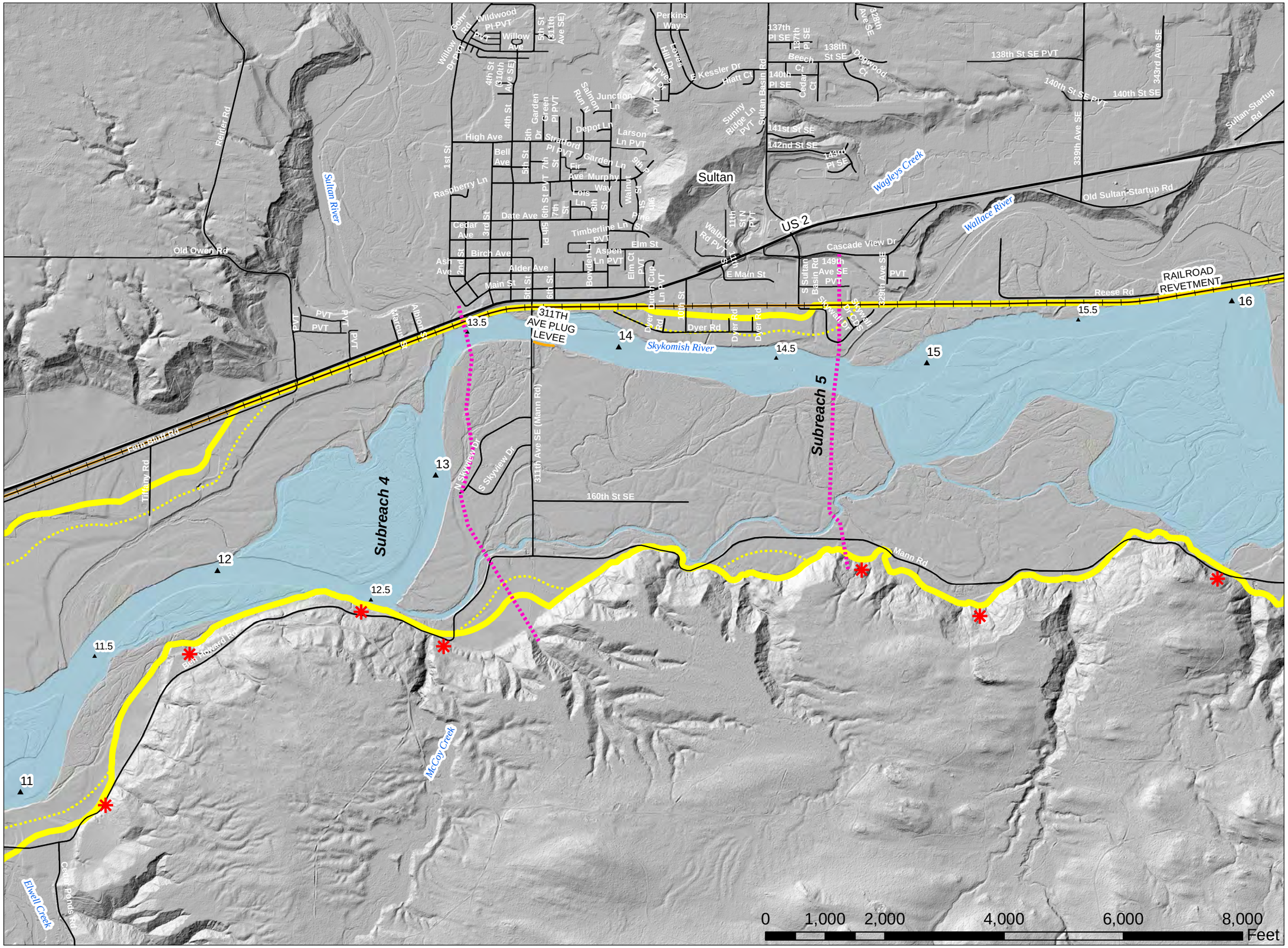
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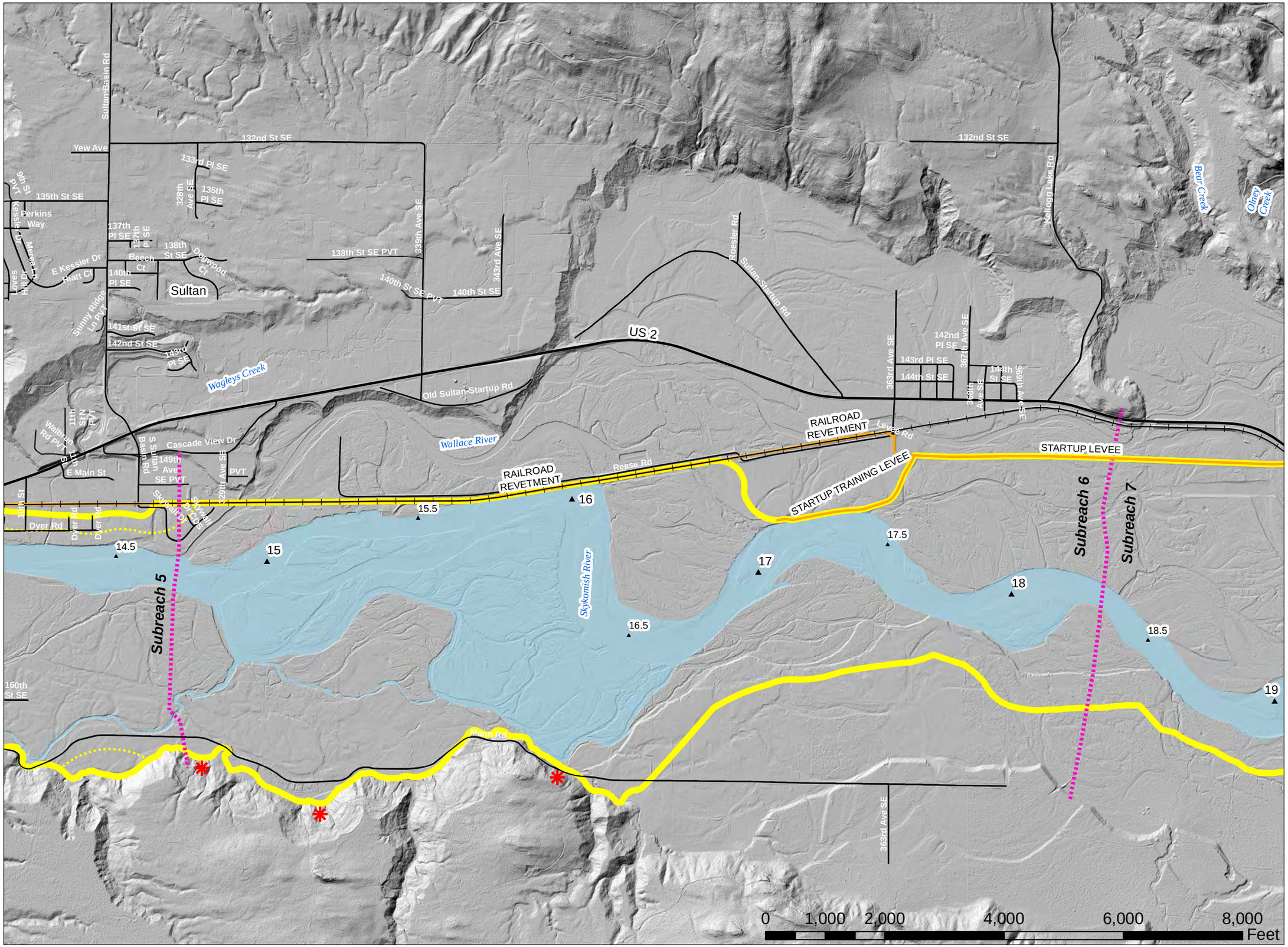
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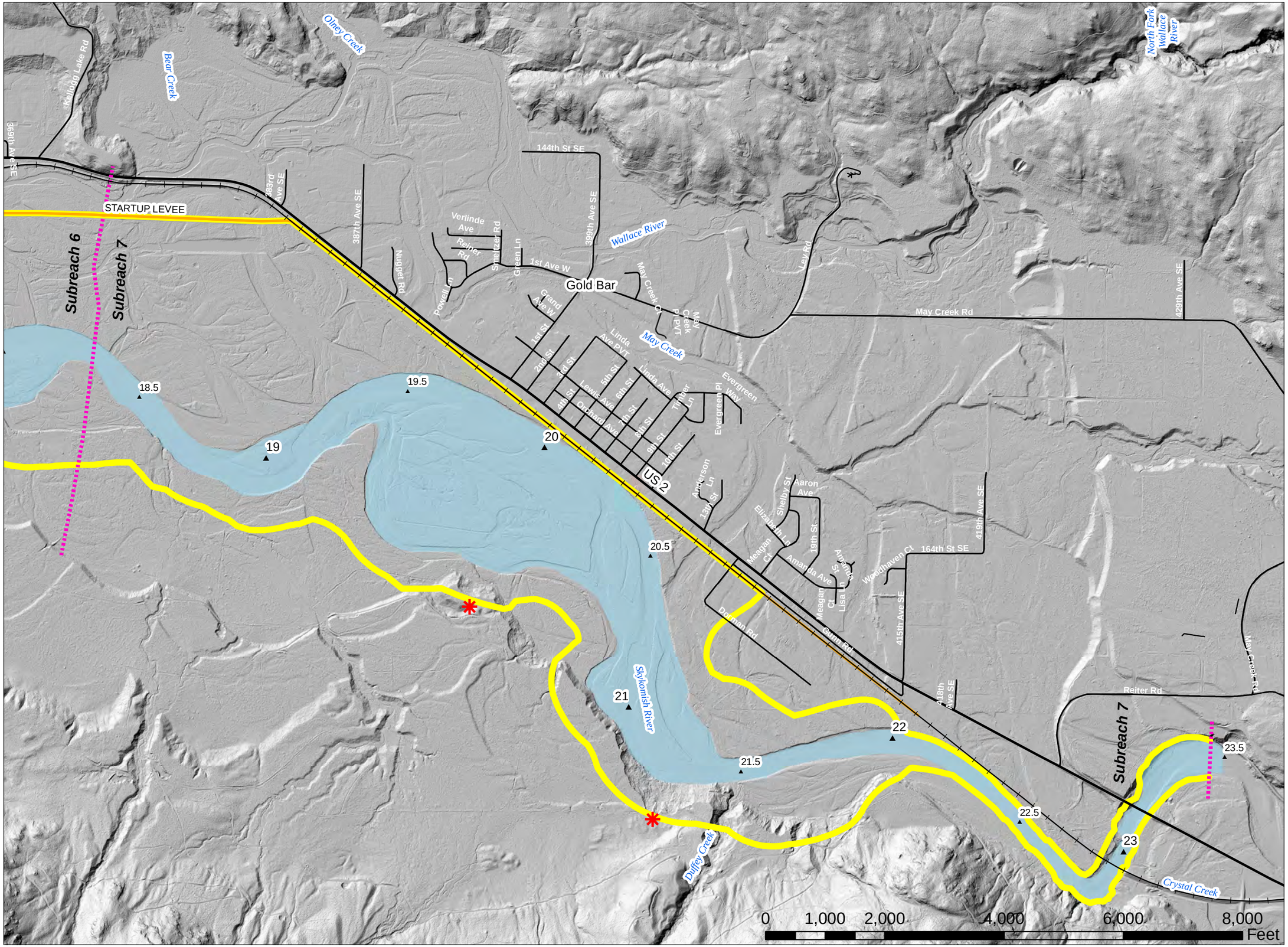
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