Technical Memorandum

Date: July 9, 2019
To: Kristin Marshall and Cindy Dittbrenner
   Snohomish Conservation District
From: Daniel Elefant, PE, Project Engineer, Derek Booth PE, PG, PhD, Senior Reviewer, and Sky Miller PE, Senior Reviewer
RE: Lower Snohomish River District Subsidence and Sedimentation Study (Revision 01)

1.0 Background

The Snohomish Conservation District’s (SCD’s) farmers and residents have observed over time the subsidence of agricultural lands and levees and potential aggradation of river channels. The SCD suspects that agricultural subsidence may be occurring from lack of sediment input to the floodplain, soil compaction, and decomposition of soil organics. This technical memorandum summarizes methodologies and results used to measure and evaluate the magnitude and rate of these changes. Measurements consisted of resurveying elevations in areas that have been surveyed in the past, including monuments and benchmarks, roads, agricultural lands, and levees. Recent river cross-sections and bathymetry data were compared to historical surveys. This evaluation identifies trends and impacts to infrastructure, flood protection, and drainage, in order to assist with maintenance of agricultural activities and flood protection within the extent of the lower Snohomish River (Figure 1).

Cardno’s scope of work for this SCD project comprised the following tasks:
> Task 1 – Data Review and Study Planning
> Task 2 – Subsidence and Sedimentation Study
   - Geodesy and survey-grade global positioning system (GPS)
   - Satellite radar data (InSAR) evaluation
   - Light detection and ranging (LiDAR) difference comparisons
   - Geomorphic and geologic interpretations

The following appendices and higher-resolution maps and graphs accompany this memorandum:
> Appendix A – Examination of InSAR for land subsidence detection in Snohomish County
> Appendix B – Map Plate Sets
   - Map Plate Set 1 – Lower Snohomish 2014 LiDAR Elevation Map
   - Map Plate Set 2 – Cardno Survey Maps
   - Map Plate Set 3 – Difference Digital Elevation Models (DEMs)
2.0 Macroscale Processes: Regional Patterns of Relative Sea-Level Change in Western Washington

No discussion of subsidence for the lower Snohomish can exclude a discussion of regional sea level rise. Though the focus of this study is on absolute subsidence (vertical land movement), it is clear that the flood control districts are most concerned with elevations of the land surface in the context of the potential for flooding due to rising seas and flooding rivers.

2.1 Introduction

The elevation of the ocean relative to its adjacent land surface is of great relevance to a variety of human activities near a coastline. At any given location, this “relative sea level” (RSL) can influence the likelihood of coastal inundation, the intensity of wave action, the level of shallow groundwater tables, and the magnitude of flooding from upland runoff. Changes in RSL over time have two components: the global sea level, termed “eustatic sea level,” which can increase with contributions from melting land-based glaciers and thermal expansion of a warming ocean, and land-level changes, resulting from a combination of natural and (potentially) anthropogenic causes. Where the
rate of eustatic sea-level rise exceeds the rate of land uplift (if any), RSL increases over time and the ocean is perceived to “encroach” upon the land. Where the land is rising faster than the ocean, RSL decreases and the sea will retreat, at least locally. The National Oceanic and Atmospheric Administration (NOAA) reports that the current rate of eustatic sea-level rise is about 3 millimeters per year (mm/year) (0.1 foot/decade; NOAA 2019), with two-thirds of that increase driven by melting glaciers and the remaining fraction by thermal expansion of the ocean.

In contrast to the relatively straightforward causes of eustatic sea-level rise, a variety of processes can alter the elevation of the adjacent land surface. These include:

- Tectonics;
- Unloading of melting ice sheets, and associated forebulge collapse (top left panel, Figure 2);
- Levering of the crust from increased oceanic mass following deglaciation (top right panel, Figure 2); and
- Subsidence from human activity, particularly groundwater extraction and decomposition from tillage.

In addition, the lateral gravitational attraction between the land and the ocean (obviously much less than the vertical attraction by the mass of the earth, but nonetheless present and discernable) can affect RSL near a coastline as a result of the following:

- Loss of lateral gravitational attraction by an ice sheet once it has melted, reducing the landward migration of the ocean (bottom left panel, Figure 2); and
- Redistribution of ice on the interior of a continent to water closer to the coast, which can increase the lateral attraction of the ocean to an extent that higher ocean levels near the coast can cause local crustal depression (bottom right panel, Figure 2).

These mass-redistribution effects of a melting ice sheet, collectively termed “Glacio-Isostatic Adjustments” (GIA) and including most of these listed drivers, is best summarized graphically (Figure 2). In the Puget Lowland, ice-sheet occupation has been a significant driver of RSL in the millennia immediately following deglaciation (about 16,000 years ago), but most studies since Thorson’s (1989) have concluded that the influence of this set of processes largely or completely dissipated in this region many thousands of years ago, and they are no longer affecting RSL today.
Figure 2. Diagrammatic representation of the various glacio-isostatic influences on RSL. Although important components to consider in any RSL model, these particular factors have largely dissipated along the present-day western Washington coastline. Modified from Tamisiea and Mitrovica (2011).

Although GIA is not a significant determinant of RSL in Puget Sound at present, regional tectonics do impose some significant local, ongoing effects. Changes in land-surface elevation can be caused by the same crustal movements that give rise to the recognized faults throughout the region, and that are responsible for some of the most powerful and destructive earthquakes in the region’s history. Ultimately driven by the relative motions of the Pacific plate, the North American plate, and the Juan de Fuca plate as they slide past or over one another (Wells et al. 1998), the modern pattern of horizontal crustal motion is well-documented and striking (Figure 3).
Figure 3. Horizontal movement of the ground surface across the Pacific Northwest as displayed by a network of permanent and transitory global positioning system (GPS) stations. The rate of movement is scaled by the length of the arrows, with the most rapid rates being about 20 mm per year. Note the reduction in rates approaching the Canadian border, reflecting the relatively immoveable buttress of the Canadian Coast Ranges. A consequence of this reduction in rates is the “piling up” of crustal material moving up from the south, leading to broad areas of crustal uplift to accommodate the incoming material. The present study area is highlighted by the red oval. Figure reproduced from McCaffrey et al. (2013).
2.2 Relative Sea Level in Western Washington

2.2.1 Present Rates of Vertical Land Movement

These prior studies have provided the framework for more recent, and ongoing, reconstructions and projections of vertical land motion and RSL. A recent global compilation of satellite and ground-based measurements shows a general pattern of stable to slightly decreasing land elevations around much of the North American coastline (Figure 4), with notable exceptions in northeastern Canada (where isostatic rebound from deglaciation is still occurring), southern Alaska (associated with the convergence of the northern end of the Pacific plate with the North American plate along the Denali fault), and the northwest Washington–British Columbia coast, where the distribution of lateral crustal movement described above gives rise to local zones of both modest uplift and modest subsidence. Although not readily discernable at the scale of this map, the present study area is in an area of measured near-zero vertical change.

![Figure 4. Map of recorded vertical land motion around the North American coastline. Near-stability is shown by the data in the vicinity of the present study area (left panel). The right panel indicates uniformly high-data quality (i.e., low error values) on which these measurements have been based. From Appendix 2 of Pfeffer and Allemand (2016).](image)

2.2.2 Implications for RSL over the Next Century

These findings provide a useful framework for anticipating and interpreting recent models predicting RSL along the western Washington coastline. Sea level is rising at most locations in or near Puget Sound. At the Seattle tide gauge, one of the longest-running gauges in Puget Sound, sea level rose by +8.6 inches from 1900 to 2008 (+0.8 in./decade) (Mauger 2015). The most recent study by Miller et al. (2018), provides a set of useful summary projections well-aligned with the present study’s areas of interest (i.e., Snohomish River mouth and Stillaguamish River mouth). Collectively, their key predictions (Figure 5) are:

> Little to no independent vertical land movement (no more than about 0.1 foot per century);
> No significant differences in uplift rates between the two river mouths;
> Rates of future RSL rise between 1.5 and 2 feet per century; and
> A degree of uncertainty that is significant but does not materially alter the overall projections or their likely consequences on coastal activities in the twenty-first century.
3.0 Geomorphic Setting

The geomorphology of the lower Snohomish River valley is similar to that of other alluvial rivers worldwide: the land surface is higher adjacent to the river (refer to Map Plate Set 1) because the river is the primary source of sediment. This results in greater deposition and thus aggradation close to the river, with the influence of this process declining as flows move out across the floodplain. This pattern is particularly prominent in the first 2 miles.
of river as it emerges from the valley confined by the uplands of Cathcart (to the west) and Lord Hill (to the east),
crossing the broad downstream valley past its confluence with the Pilchuck River at the crest of a topographic
ridge, with lower valley-bottom farmlands to both the west and east. This position seemingly defies logic—the river
is found at the high point of the landscape, not at the bottom. It makes sense only upon recognizing that it reflects
progressive build-up of the land surface from the sediment carried (and then deposited) by the river itself.

For rivers in the Puget Lowland such as the Snohomish, this pattern is exacerbated because they flow in a south-
to-north-oriented valley that was previously graded to an obverse slope, wherein late-glacial drainage flowed
“down” (i.e., north-to-south) along what subsequently became the up-valley direction once the ice sheet had
disappeared (Collins and Montgomery 2011). Isostatic rebound (the uplift of the crust following removal of an ice
sheet) further amplified this pattern (i.e., greater uplift to the north, because the original ice-sheet depression of the
crust was greater in the north) for those rivers flowing in north–south valleys. Collins and Montgomery (2011) called
these “glacial” rivers, acknowledging a valley form inherited from ice-sheet erosion, and contrasted them with “post-
glacial” rivers that cross-cut the glacially inherited topography. The Snohomish River is a near-ideal example of this
pattern, one that is interrupted only by the short reach of the river between the Snoqualmie-Skykomish confluence
and Shadow Lake (below Cathcart) to avoid the blockage of the broad north-trending valley of the Snoqualmie
River at the town of Monroe by late-glacial outwash (Booth 1990).

Integrating the post-glacial history of the river with that of more regional changes over the past 16,000 years, three
phases in the evolution the lower Snohomish River valley can be characterized:

1. Immediately following post-glacial retreat (about 16,000 years ago), the dominant process was rapid isostatic
rebound, with a total uplift of approximately 140 meters (Thorson 1989). Presumably, all Puget Sound rivers
downcut rapidly in response to this rising land surface, maintaining (as much as possible) a base level
consistent with the resulting rapid drop in relative sea level (~102 mm/year; absolute sea level was also rising
at this time, but not nearly as rapidly as isostatic uplift). The lower river valley may have had a canyon form with
a dynamic but basically Sound-ward moving river mouth. As isostatic rebound slowed, likely in less than 2,000
years following glacial retreat, the shoreline position would have roughly stabilized as the rates of rising land
surface and sea level roughly coincided. The valley would have gradually broadened out as the river
established a more "typical" migratory lowland planform.

2. Subsequently, the dominant process has been the continued, gradual advance of sea level up and into the
lower Snohomish River valley, forming what is now Possession Sound. This sea-level transgression reduces
river-channel gradients and so induces greater sediment deposition, for which the high ground adjacent to the
river is a credible expression. One would expect the surrounding valley more distant from the river to also
aggregate, although at a lower rate than the river-proximal zone. Topographic relief would therefore be amplified
over time, with this process likely accelerated under a persistently rising sea level. Avulsions, where an entirely
new course of the river (and thus of deposition) shifts this depositional pattern into new portion of the floodplain,
have left a record of previously abandoned river positions (particularly to the southwest of Ebey Island).

3. Modern levees, by limiting the extent of overbank flows, have reduced distant floodplain deposition more than
river-proximal deposition. This has further amplified topographic relief across the floodplain. Bottomlands are
always the first to flood by virtue of topography, and now they are even more flood-prone if/when levees
overtop because sediment accretion has not kept pace with that along the active channel and adjacent levees.
Although the presence of a levee will reduce the intrinsic flooding risk, because a larger discharge is required to
overflow the immediate vicinity of the channel, any levee (natural or constructed) can also increase the hazard
associated with the flooding that does occur: any overtopping of levees caused by even small peak flow
increases could presumably cause flood impacts over a large area.
4.0 Methods

4.1 Existing Data Review

Primary elevation datasets considered for this project include the following:

> 2001 topographic survey dataset from Rick Vining with Snohomish County
> 2005/2006 LiDAR Puget Lowlands Quads DEM
> 2009 LiDAR Snohomish River Estuary
> 2014 LiDAR from the King County Cedar Deliverable #1 (WSI 2014)

The horizontal datum for this project was NAD 1983 (2011) State Plane Washington North FIPS 4601, feet US. Datasets in different horizontal datums were projected to the project datum.

The vertical datum for this project was NAVD88 in US feet on Geoid03. Datasets taken on other geoids or older vertical datums were shifted as appropriate. Comparisons of LiDAR on Geoid12b did not require vertical adjustment to Geoid03 since these systems are within ±0.008 feet of each other (Vdatum 2019).

4.2 Aggradation Study (Bathymetric Change Analysis)

One prior geomorphic study from R2 Resource Consultants informed this sedimentation study:

1. 2015 Reach Scale Geomorphic Analysis of Hydraulic, Hydrologic, and Sediment Conditions in the Snohomish River Between SR 522 and Ebey Slough (DeVries 2015)

Cardno also considered the following studies, which include bathymetry datasets as shown in Figures 6 and 7:

3. Snohomish River – HEC-RAS one-dimensional (1D) model (2011)

The HEC-RAS 1D model and effective FEMA UNET model consist of individual cross-sections cut from combined bare earth LiDAR with bathymetric data and Snohomish County’s original Full Equations model, respectively. The surveyed bathymetry dataset from 2003 to 2005 was provided in point data form that was converted to a more practical terrain surface. Similarly, the 2017 HEC-RAS 2D model dataset was extracted in the form of a terrain surface. While most of the datasets were spatially aligned with the Snohomish River, the 2011 HEC-RAS 1D model and Effective FEMA UNET model were not. The potential errors due to spatial variation are discussed further in Section 4.2.1.

Bathymetric charts have bathymetry incorporated into their imagery. Pulling this bathymetry (often in the form of soundings) onto modern spatial and vertical datums would be very costly. The following datasets include river bathymetry as images and could be considered in future river studies but were not addressed here:

1. NOAA Nautical Chart 18444 (NOAA 2009)
   a. Years: 1975 to 2009 every 2 years
   b. Upriver Extent: east side of Smith Island
2. NOAA Nautical Chart 6441 (NOAA 1973)
   a. 1967 to 1973
3. T-sheet Year 1884 – planform only, no soundings
4. Historical H-Sheets would require a datum shift that accounts for historical sea level rise
   a. 1886, soundings in feet mean lower low water (MLLW) for July 27 to August 2, 1886 (up to 18 feet, then fathoms)
   b. 1917, soundings in feet MLLW for July 27 to August 2, 1886 (up to 18 feet, then fathoms)
   c. H-sheets may be considered for geomorphic interpretation of this study’s aggradation results, but soundings will not be adjusted onto the modern NAVD88 vertical datum.

Cardno did not consider USGS cross section data for this study since none was available.

Changes in cross sections were tracked using two metrics: cross-sectional area and minimum bed elevation. Cross-sectional area was calculated utilizing water surface elevations defined at top of bank. Significant reductions in cross-sectional area coupled with increases in minimum bed elevation may be interpreted as channel aggradation; conversely, increases in cross-sectional area and decreases in minimum bed elevation could signify channel degradation.

Figure 6. Cross-section locations for comparison of 2011 HEC-RAS cross-section data to 2003–2005 surveyed bathymetry dataset and terrain from the 2017 HEC-RAS 2D model.

4.2.1 Potential Errors

Potential errors arose in the analysis as spatial variations with cross-sectional datasets were encountered. While the 2003–2005 surveyed bathymetry points and 2017 2D HEC-RAS model terrain datasets were spatially...
consistent with present and historical aerial imagery, the mid to upper Snohomish River reaches (South Ebey Island to Skokomish and Snohomish River confluence) from the HEC-RAS 1D model cross-sectional dataset were shifted away from the Snohomish River alignment. Figure 7 presents the Snohomish River and 1D HEC-RAS model alignment variations.

Locations of the comparison cross-sections cut from the spatially aligned terrains (2017 2D HEC-RAS model and 2003–2005 surveyed bathymetry dataset) were identified following similar alignment curvatures from the 2011 HEC-RAS 1D dataset. Therefore, due to the difficulty in accurately locating comparison cross-sections that match spatially, the cut cross-sections represent generalized cross-sectional areas and minimum bed elevations such that errors were introduced.

Figure 7. Spatial variations in 2011 HEC-RAS 1D datasets along the Snohomish River alignment.

4.3 Subsidence

4.3.1 Minimum Rates and Data Precision

Land subsidence can occur over multiple time scales associated with multiple different processes. This project aimed to quantify absolute (overall) subsidence within the lower Snohomish River from the upstream ends of the French Slough and Marshlands Flood Control Districts (FCDs) to the downstream end of Ebey Island (Drainage District 1).
The overall amount of subsidence relates to a relative comparison of average land-surface elevation inside and outside of the constructed levees. Any methodology for detecting 10 years of absolute subsidence would require sufficient precision to detect no more than 0.2 feet of vertical land loss with a standard error of less than ±0.1 foot.

4.3.2 Topographic Survey

Cardno completed a GPS-based real time kinematic (RTK) survey from March 6 to 8, 2019, using a Trimble R10 base and rover system (Map Plate Set 2). Cardno focused survey efforts on the acquisition of points to represent roads, levees, agricultural field transects, and limited natural areas for the purposes of comparing survey topography to historical LiDAR datasets. Cardno created two control points on Geoid03 using static RTK Trimble R10 base logging every 5 seconds for 4 hours: one solution for Washington State Department of Transportation (WSDOT) GP31096-99 (ID 2333) and one for the historical benchmark “#2012” at the French Slough Pump Station (DEA 2000). The survey team was unable to verify vertical benchmarks used during Rick Vining’s year 2001 topographic survey because Snohomish County did not have adequate records detailing geoids and vertical datums. At the time of the Cardno survey, we were aware of the year 2000 Snohomish County report that documents GPS geodetic control for the Snohomish levee system (DEA 2000). We assumed Vinning’s survey had ties to this geodetic control; however, we were unable to verify in the field. Cardno recommends a full evaluation of this historical geodetic control network with any further subsidence studies.

4.3.3 LiDAR Differencing

LiDAR differencing is the subtraction of one LiDAR dataset from another to create a new DEM called a difference DEM. A difference DEM was created for this study according to the LiDAR acquisition years as follows (Map Plate Set 3): 2014 LiDAR minus 2005 LiDAR.

For each LiDAR dataset, the first returns vegetation canopy model called the digital surface model (DSM) was compared to the last returns bare earth DEM (bare earth model) to remove vegetated areas from the analysis. This was essential to ensure that the difference DEM represented changes in ground surface elevation and not changes in vegetation growth.

In order for the LiDAR datasets to be used for the analysis of subsidence and sedimentation, the level of accuracy of LiDAR returns needs to be taken into account. LiDAR accuracy is measured by comparing LiDAR point data collected on open, bare earth surfaces with ground survey point data in the same area. Each dataset was assessed for accuracy by their respective data acquisition company. Table 1 summarizes the accuracy of each dataset.

Table 1 LiDAR Accuracy

<table>
<thead>
<tr>
<th>Absolute Accuracy of LiDAR Datasets</th>
<th>2014 Cedar Watershed LiDAR&lt;sup&gt;1&lt;/sup&gt;</th>
<th>2005–2006 Snohomish County LiDAR&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVA (1.96*RMSE)</td>
<td>0.167 ft 0.051 m</td>
<td>0.514 ft 0.157 m</td>
</tr>
<tr>
<td>Average Δz</td>
<td>-0.028 ft -0.009 m</td>
<td>Average Δz +0.033 ft +0.010 m</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.085 ft 0.026 m</td>
<td>RMSE 0.262 ft 0.080 m</td>
</tr>
<tr>
<td>Standard Deviation (1σ)</td>
<td>0.081 ft 0.026 m</td>
<td>Standard Deviation (1σ) 0.262 ft 0.080 m</td>
</tr>
</tbody>
</table>

<sup>1</sup> Source: WSI 2014.

<sup>2</sup> Source: TerraPoint USA and David Evans and Associates 2007.
For the purposes of this analysis, low to zero vegetation pixels were identified as areas of the derived vegetation height raster (DSM minus bare earth model) in which the vegetation height was between −0.2 ft and 0.2 ft. This was done to account for the various uncertainties and deviations in the LiDAR datasets, while maintaining sufficient data for analysis. The original LiDAR bare earth DEMs were clipped to these pixels to isolate data to areas of low to zero vegetation.

The resultant difference DEM of the clipped 2014 and 2005–2006 LiDAR datasets now yield an accurate representation of localized subsidence and sedimentation. Negative (−) values in the data represent subsidence, while positive (+) values represent sedimentation, or aggradation. Values between −0.5 ft and 0.5 ft were classified as uncertain due to the accuracy of the LiDAR datasets, assessment of the low to zero vegetation pixels, and agricultural activity. Values less than −10 feet and values greater than 10 feet were classified as outliers and were not part of the analysis.

### 4.3.4 InSAR

Scott Henderson and David Schmidt of the University of Washington partnered with Cardno to assess viability of using satellite radar to assess subsidence for the lower Snohomish River valley. Methods and results of this study were summarized in their report, attached as Appendix A.

### 5.0 Results

#### 5.1 Aggradation Study

Overall analysis of the lower Snohomish River determined stable channel bathymetry from year to year. This result was generally consistent with several past studies. As discussed in Section 5.1.3 herein, aggradation is only observed in reach sections between river miles 6 to 8 and 11 to 17 (see Figure 7 and Table 1). Figure 9 presents an example comparison cross-section utilized in this bathymetric study. The following summarizes conclusions related to Snohomish County’s 1990 assessment of aggradation in the lower Snohomish River main channel:

“Snohomish County surveyed the river and slough cross-sections at approximately one-half mile intervals in 1988. This survey was conducted to provide input to a mathematical model used to simulate river flows. At each section, a boat equipped with an electronic depth recorder was used to plot the channel bottom contour across the channel. This resulted in 70 cross-sections to be used as input to the hydraulic model. Also, comparisons were made with the cross-section locations surveyed by the Corps in 1978. These comparisons show that very little change had occurred to the river channel, except in locations that are dredged periodically” (Snohomish County Surface Water Management 1990).

#### 5.1.1 Lower Reach (I-5 Bridges to South Ebey Island)

This study did not complete an analysis of aggradation for this lower reach. The channel here is likely to remain stable with no significant changes. This conclusion was confirmed in the 1990 Snohomish County assessment and in GeoEngineers’ 2011 geomorphic assessment, which stated that “A comparison of current channel bathymetry with as-builts of the I-5 Bridge over Union Slough indicates there has been no observable change in channel floor elevation in more than 40 years. The lack of bank armoring and/or protection of the I-5 bridge abutments and piers is a strong indicator of stable channel conditions since construction of I-5” (GeoEngineers 2011).

#### 5.1.2 Middle Reach (South Ebey Island to Hwy 9 Bridge)

Due to the lack of data, analysis of the middle reach of the Snohomish River was inconclusive. However, similar to the conclusions for the lower reach (Section 5.1.1) and based on the geomorphic assessment report by R2 Resource Consultants (Devries 2015), the bathymetry for the middle reach is mostly stable with only slight cyclical changes from year to year.
5.1.3 **Upper Reach (Hwy 9 Bridge to Skokomish and Snohomish River Confluence)**

Analysis of the upper reach concluded that aggradation occurs between river miles 6 to 8 and 11 to 17 (see Table 2; see Figure 6 for cross-section locations and river miles) of the Snohomish River during the comparison of 2011 and 2017 HEC-RAS datasets. The typical thalweg trend and cross-sectional area results, shown in Figure 8 and Table 2, respectively, concur with the compared and projected results from R2 Resource Consultants’ geomorphic assessment (Devries 2015). The upper reach may experience modest aggradation into the future.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Comparison of longitudinal thalweg elevation profiles from 2001 Effective FEMA UNET model, 2003–2005 surveyed bathymetric data (one point in this reach), and 2017 HEC-RAS model datasets (see Figure 6 for river miles reference).
Table 2  Summary of Aggradation Metrics Considered Showing Thalweg Elevation Change and Cross-Sectional Area Percent Change for the Upper Snohomish River Reach, refer to Figure 6 for cross-section locations.

<table>
<thead>
<tr>
<th>Cross-Section Name</th>
<th>2011 HEC-RAS Dataset Thalweg Elevation (ft.) (NAVD88)</th>
<th>Modern Data Year</th>
<th>Modern Data Thalweg Elevation (ft.) (NAVD88)</th>
<th>Change in Thalweg Elevation (ft.)</th>
<th>Cross-Section Area Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS - 19</td>
<td>-21.1</td>
<td>2003-05/2017</td>
<td>-14.8/-15.3</td>
<td>6.3/5.8</td>
<td>Insufficient Data/-3%</td>
</tr>
<tr>
<td>XS - 18</td>
<td>-19.3</td>
<td>2017</td>
<td>-20.8</td>
<td>-1.5</td>
<td>4%</td>
</tr>
<tr>
<td>XS - 17</td>
<td>-15.4</td>
<td>2017</td>
<td>-16.7</td>
<td>-1.3</td>
<td>6%</td>
</tr>
<tr>
<td>XS - 16</td>
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<td>1.9</td>
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</tr>
<tr>
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<tr>
<td>XS - 14</td>
<td>-14.1</td>
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<td>2.2</td>
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</tr>
<tr>
<td>XS - 13</td>
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<td>XS - 12</td>
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<td>-1.1</td>
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<td>XS - 11</td>
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<tr>
<td>XS - 9</td>
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<td>-0.4</td>
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<td>XS - 8</td>
<td>-3.9</td>
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<td>1.9</td>
<td>5.8</td>
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<tr>
<td>XS - 7</td>
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<td>XS - 6</td>
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<tr>
<td>XS - 5</td>
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<tr>
<td>XS - 4</td>
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<tr>
<td>XS - 3</td>
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<td>XS - 2</td>
<td>7.7</td>
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<td>9.1</td>
<td>1.4</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>XS - 1</td>
<td>11.1</td>
<td>2017</td>
<td>10.9</td>
<td>-0.2</td>
<td>-2%</td>
</tr>
</tbody>
</table>

Note: Most cross sections experienced aggradation.

* Denoted areas may have exaggerated reported cross-section area percent change as a result of variation between survey data breadth. These tend to be shallower cross sections where bank height and extent vary substantially relative to the total channel depth or geometry discrepancy.
5.2 Subsidence Study

5.2.1 2019 Topographic Survey versus LiDAR

Topography data from years 2005 to 2006, and 2014, were obtained utilizing LiDAR. The ground elevation values from the two separate LiDAR datasets were compared with ground survey data collected in 2019 as quality control verification of LiDAR and to identify the incremental changes in vertical elevation (refer to Map Plate Set 2). This comparison determined the magnitude of ground subsidence through 2005–2006 to 2019. However, quality control of LiDAR determined that vertical difference uncertainty was high (±0.5 feet) for comparisons of each dataset for levee sample points due to differences in LiDAR point processing, flight patterns, crop height, methods for constructing DEMs, and likelihood of levee maintenance during different years (Figure 10 and Table 3).
However, the identified agricultural zone located in the French Slough FCD east of the Snohomish River and southeast of Snohomish did experience some modest subsidence (Figure 11 and Table 3).
Figure 11. Map of Cardno 2019 survey points selected to overlap precisely with Rick Vining’s 2001 dataset for assessment of agricultural subsidence.

Table 3 Averaged Vertical Difference between 2005–2006 LiDAR Base Values, 2014 LiDAR, and 2019 Ground Survey

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural Samples</td>
<td>-0.6 ± 0.4</td>
<td>-0.4 ± 0.3</td>
<td>-0.2 ± 0.2</td>
</tr>
<tr>
<td>Levee Samples</td>
<td>-0.1 ± 0.7</td>
<td>-0.2 ± 0.6</td>
<td>+0.2 ± 0.3</td>
</tr>
</tbody>
</table>

To provide a spatial reference for the survey versus LiDAR comparisons, the data were grouped into two groups: levee samples and agricultural samples.
Figure 12. Map of agricultural sample points overlaid onto low to zero vegetation raster pixels.

Survey point elevations generally support subsidence of 0.6 ± 0.5 feet of standard deviation as determined through LiDAR differencing discussed in Section 5.2.2. Thus, the 2019 Cardno survey confirmed a range of subsidence from 0.1 feet to 1 foot for the time period 2019 to 2006.

5.2.2 LiDAR Differencing

Difference DEMs (refer to Map Plate Set 3) confirm that the FCD agricultural fields east and west of the Snohomish River, just south and southeast of Snohomish, Washington, experienced minor subsidence. Statistical analysis of these subsidence zones suggested subsidence of 0.6 feet from 2006 to 2014 (Figure 13 and Table 4). The low to high range of subsidence is determined to be 0.1 feet to 1 foot when accounting for a standard deviation of 0.5 feet which encompasses likely sources of error.
Figure 13. Zones used to calculate LiDAR differencing statistics between 2014 LiDAR and 2005–2006 LiDAR: zones located in flood control districts south and southeast of Snohomish outlined in black.

Table 4. Average Vertical Difference between 2005–2006 LiDAR and 2014 LiDAR for Zones (see Figure 11) within FCDs south and southeast of Snohomish

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Zones in FCD</td>
<td>-0.6 feet</td>
<td>0.5 feet</td>
</tr>
</tbody>
</table>

Note: Standard deviation includes ± 0.2 ft deviation from assuming low to zero vegetation is between -0.2 ft and +0.2 ft.

5.2.3 Survey Benchmark Comparisons

Cardno recommends that Snohomish County reevaluate all published elevations presented from the year 2000 GPS Geodesy for Snohomish River Floodplain (David Evans and Associates 2000). No reliable conclusions related to vertical land movement were obtained during the Cardno 2019 survey effort because of limited time and ability to recover all benchmarks associated with year 2001 study.
5.2.4 InSAR

The InSAR study was not able to detect any significant vertical land movement over short time spans for bulk areas of the lower Snohomish River—the FCDs and drainage districts (Appendix A). Analysis of vertical land movement over longer time spans may not be successful due to incoherence of results influenced by changing vegetation heights in agricultural fields. Future applications of InSAR should focus vertical land movement on paved and urbanized surfaces.

6.0 Discussion

6.1 Future Aggradation Trends

The lower Snohomish River is experiencing no significant aggradation or degradation. Isolated reaches near the FCDs had a mixed trend of modest aggradation and channel reaches with no significant changes. For example, RM 12 to RM 17 thalwegs increased 1 to 3 feet between 2001 and 2017, but cross-sectional area did not change. A mixture of these trends will continue into the future. Aggradation increases the risk of flooding and levee failure from overtopping. In the past, dredging might have been considered an option for mitigating this risk, but dredging along the lower Snohomish River cannot reduce future aggradation inputs and would impair critical deep-pool habitat for endangered sturgeon. In addition, it would not accomplish its primary goal of lowering flood stage.

6.2 Subsidence Trends and Rates

Based on our analysis of the data characterizing land-surface changes over the last 10 to 15 years, there is little direct evidence for regional subsidence. Generally, the uncertainty in the LiDAR comparisons exceed the magnitude of elevation change that may have occurred, and benchmark resurveys suggest at most localized subsidence in possible problematic locations. These datasets are not conclusive. However, they limit the likely magnitude of ongoing regional subsidence to no more than 0.2 feet per decade, and probably much less than this amount (if at all). Isolated localized areas within the eastern portion of Marshlands FCD and western portion of French Slough FCD may have experienced subsidence ranging from 0.1 to 0.5 foot per decade as discussed in Section 5.2.2. Of greater concern should be the rising RSL, whose ongoing encroachment into the region is certain, and for which this rate is only a mid-point value: future rates could be almost 50 percent higher, with the consequences felt at every location throughout the region.

7.0 References


prepared for the Puget Sound Partnership and the National Oceanic And Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. doi:10.7915/CIG93777D


VDATUM. 2019. Welcome to VDATUM. Version 3.9, NOAA. Available at: https://vdatum.noaa.gov/.


Examination of InSAR data for land subsidence detection in Snohomish County, WA

10/03/2018

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Summary and Primary Findings

- We explored the potential for using satellite radar data (a.k.a. InSAR) to identify subsidence in the Stillaguamish and Snohomish river valleys.
- We find no evidence for a broad land subsidence signal (greater than 10's-of-cm) across the Stillaguamish and Snohomish river valleys in the limited InSAR data analyzed. Vertical tectonic subsidence rates are likely to be small (<1mm/yr), inferred from Miller et al. (2018). Thus the surrounding bedrock is likely to be fairly stable, and suitable for vertical control.
- Some InSAR data suggest that small, localized, and possibly seasonal subsidence may occur over short periods of time. This might be attributed to spatially variable soil conditions such as found in abandoned river cutoffs or ponds, although field reconnaissance would be required to further explore the cause and geological setting.
Introduction

Land subsidence is typically a consequence of the compaction of sediments. This subsidence can become prominent on deltas when there is a lack of sediment replenishment from rivers (e.g. Syvitski, 2008), or by the pumping of groundwater in confined aquifers which allows for the compaction of pore space (e.g. Schmidt and Burgmann, 2003). Information about where land subsidence is occurring, and the magnitude of that subsidence can be valuable for land-use planning and remediation. Interferometric Synthetic Aperture Radar (InSAR) is a promising technology for measuring such subsidence occurring at cm/yr rates across 1-10,000 km^2 areas (e.g. Simons and Rosen 2015). In this exploratory study, we examined the available InSAR data covering Snohomish County, Washington State with the goal of identifying regional or localized land subsidence. Our analysis focused on the Stillaguamish and Snohomish River Valleys and urban areas, including Everett, Snohomish, Marysville, Arlington, and Stanwood.
Figure 1: Overview map of study area. Black polygon is Snohomish County, Washington State. Pink polygons are regions of interest in the Stillaguamish and Snohomish River Valleys, the teal polygon includes major urban areas at the mouth of the Snohomish River.

InSAR data are formed from radar chirps that are sent from an orbiting satellite and backscattered off of the earth's surface. Both the backscattered amplitude and phase of the electromagnetic signal are recorded by the satellite. Using data from repeated passes of the satellite, the change in phase can be measured with great precision using interferometric techniques, revealing subtle changes the distance from the orbiting satellite and the ground. This change in phase can be interpreted as a change in the surface elevation over a period of time. This phase map is referred to as an “interferogram”.

Although the theory will not be discussed in detail here, it is important to describe a few important characteristics of interferograms. First, interferometric coherence is a measure of the spatial correlation of phase differences (e.g. Zebker and Villasenor, 1992). If images are
“incoherent” no information can be gleaned regarding elevation change. Loss of coherence (or loss of signal) occurs for two reasons: First, “temporal decorrelation” is the loss of coherent phase due to naturally occurring changes in surface scattering properties over time - for example tilled versus untilled agricultural areas. Second, “geometric decorrelation” is caused by large differences in the satellite position between two dates. This distance is typically described by “perpendicular baseline”, which is the satellite separation perpendicular to the viewing direction. Coherence therefore depends on both properties of the sensor (e.g. radar wavelength, orbital control) and properties of the ground (e.g. land cover type, seasonal change, weather). For successful interferometry it is important to process many interferometric pairs to see what geometric and temporal separations give sufficient coherent phase in any region of interest.

We compiled a database of freely available InSAR data for Snohomish from the ERS, Envisat, ALOS, and Sentinel satellites. Observations go back to 1992, but the observation frequency and sensor capabilities have changed significantly up to the present day. In fact, there are hundreds of acquisitions (Appendix C), so we chose a representative sample of scenes from each sensor that cover a variety of time spans and perpendicular baselines. We also chose dates from multiple seasons, but selected mostly summer scenes since drier conditions tend to yield better coherence. We did not consider restricted data (CSK, TSX, RS2, ALOS2) in this study, which costs $700 or more per scene. The major goals of this study were to 1) evaluate the quality of available data, and 2) if possible, quantify regional or localized zones of surface elevation change that may be attributed to land subsidence.

Results

Here we present several characteristic interferograms from each of the sensors we examined. A full table of processed data is in Appendix A. We attempted to process as many as 25 interferograms, with just over half yielding reasonable results. However, data quality (coherence) was generally lacking in non-urban areas. For brevity, we show 4 examples from our results.
**Figure 2:** An interferogram from the ALOS satellite with the best coherence (i.e. best data quality) obtained in this study. Color scale represents millimeters of line-of-sight (LOS) displacement between the observation dates (46 days) relative to an arbitrarily chosen reference location (black square). Much of the small-scale variability in the LOS-displacement (purple to pink hues) is likely attributable to subtle variations in atmospheric water vapor variation, which can delay the radar signal. Several small wavelength features appear which could merit further investigation (e.g. Tulalip river basin). This summer pair from 2007 has a temporal baseline of 46 days and perpendicular baseline of 255 meters. Islands appear yellow due to unwrapping offsets (uncorrected error). The speckled nature of the signal within the region-of-interest polygons is due to temporal coherence in these predominantly agricultural regions. We do not find evidence of any significant land movement (>1cm).
Figure 3: An interferogram from the ERS satellite with the smallest possible temporal baseline of 35 days, between August 08, 1997 and September 12 1997. The perpendicular baseline is 152 meters. Only the lowland urban corridors retain coherence, so longer time periods are not promising. Regions of poor coherence that were unsuccessfully unwrapped are masked out. Urban corridors provide good coherence because buildings are stable and efficient reflectors of the radar signal. The appearance of distinctly colored zones (purple, pink, orange, yellow), is due to uncorrected unwrapping errors. But within each color patch, the deformation is stable.
Envisat interferogram with a relatively small temporal baseline (105 days) and perpendicular baseline (115m). Similar to our observations with ERS, only the lowland urban corridors retain coherence of monthly time separation, so longer time periods are not promising. Regions of poor coherence that were unsuccessfully unwrapped are masked out. The appearance of distinctly colored zones (purple, pink, orange, yellow), is due to uncorrected unwrapping errors - relative displacements within each zone are consistent, but points between zones can not be compared.

**Figure 4:** Envisat interferogram with a relatively small temporal baseline (105 days) and perpendicular baseline (115m). Similar to our observations with ERS, only the lowland urban corridors retain coherence of monthly time separation, so longer time periods are not promising. Regions of poor coherence that were unsuccessfully unwrapped are masked out. The appearance of distinctly colored zones (purple, pink, orange, yellow), is due to uncorrected unwrapping errors - relative displacements within each zone are consistent, but points between zones can not be compared.
Sentinel-1

Figure 5: Sentinel-1 interferogram spanning 12 days, demonstrating the retention of coherence over short time spans (at least for summer acquisitions). While we don’t expect to observe significant ground deformation over 12 days, an ongoing time series of short time-spans could be generated going back to the start of the Sentinel-1 archive (10/2014), if rapid deformation detection is of interest.

Conclusions

1) There are hundreds of SAR scenes available in free archives covering Snohomish county and spanning 1992 to the present.

2) Geometric decorrelation limits the number of useable image pairs for the previous generation of SAR satellites (ERS, Envisat, ALOS). Furthermore, temporal decorrelation is significant for all sensors present for time periods greater than several months. Only Urban areas and low elevation grasslands retain coherent phase signals over many months, and consequently multi-year interferograms are unlikely to detect low amplitude (<cm/yr subsidence) in non-urban areas.
3) Small (<10km) regions of coherent phase change are visible in several areas for short-time span ALOS pairs (e.g. the Tulalip Creek basin, 2007/08/06 - 2007/06/21) where subtle short-term deformation is possible.

4) For the data examined, there are no indications of large (>10s of cm) relative subsidence signals in coherent areas. Note that recent work by Miller et al. (2018) from GPS and spirit leveling surveys spanning the past several decades suggests that the I-5 corridor in northern Puget Sound may be subsiding at small rates of 0-1 mm/yr (Figure 6). However, this signal is very long wavelength (spanning 100’s km), and is driven by regional tectonics. This suggests that bedrock and land outside of the estuaries should be fairly stable.

Figure 6: Vertical land movement inferred from regional leveling, GPS, and tide gauges averaged over decades. Figure reproduced from Miller et al. (2018).

Recommendation for future work

We are only able to do a cursory analysis with this study. However, it would be possible to utilize more advanced processing techniques which might yield better results. Given the large amount of data available through the space agencies, and retention of coherence in urban areas for multi-year interferograms, it would be interesting to process a time series using all available data. Averaging many interferograms may permit detection of low amplitude signals in urban areas. ALOS coherence is much better compared to the other sensors considered, which is most likely due to its higher resolution pixels and L-band wavelength. The ALOS-2 sensor is currently acquiring L-band scenes over snohomish county, but data must be purchased. NASA plans to launch the NiSAR L-band mission in 2021 which will provide a robust data set for future study. For future monitoring of Snohomish county it is advisable to use this L-band data.
References


Appendix A: Data processed

<table>
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<th>Pair</th>
<th>Temporal Baseline [days]</th>
<th>Perpendicular Baseline [m]</th>
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<td></td>
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<tr>
<td>19970912-19970808</td>
<td>35</td>
<td>152</td>
<td>Coherent in urban areas</td>
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<tr>
<td>20070622-20060707</td>
<td>350</td>
<td>109</td>
<td>Completely decorrelated</td>
</tr>
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<td>20080711-20060707</td>
<td>735</td>
<td>52</td>
<td>Completely decorrelated</td>
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<td>20080711-20060428</td>
<td>805</td>
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<td>Limited coherence in lowlands</td>
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<td>20080711-19970808</td>
<td>3990</td>
<td>6</td>
<td>Completely decorrelated</td>
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<td><strong>Envisat</strong></td>
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<td>Coherent in urban areas</td>
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<td>315</td>
<td>187</td>
<td>Coherent in urban areas</td>
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<td>700</td>
<td>11</td>
<td>Limited coherence in lowlands</td>
</tr>
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<td>20080711-20050617</td>
<td>1120</td>
<td>43</td>
<td>Limited coherence in lowlands</td>
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<td>Limited coherence in lowlands</td>
</tr>
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<td>ALOS (t218, f950)</td>
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<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------</td>
<td>--------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>20070806-20070621</td>
<td>46</td>
<td>255</td>
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</tr>
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<td>20100929-20100629</td>
<td>92</td>
<td>700</td>
<td>Excellent coherence</td>
</tr>
<tr>
<td>20071106-20070621</td>
<td>138</td>
<td>1014</td>
<td>Excellent coherence, orbital ramp</td>
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<td>20100629-20100211</td>
<td>138</td>
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<td>20100929-20080323</td>
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<td>1104</td>
<td>1311</td>
<td>Limited coherence in lowlands</td>
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<tr>
<td>20101114-20071106</td>
<td>1104</td>
<td>762</td>
<td>Decent coherence</td>
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<td>20180706-20180624</td>
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</tr>
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<td>20180706-20170711</td>
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<td>20180609-20170720</td>
<td>324</td>
<td>12</td>
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<td>20180609-20150713</td>
<td>1062</td>
<td>50</td>
<td>Limited coherence in lowlands</td>
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</table>

Appendix B: Processing details

ERS and Envisat data was obtained from the European Space Agency (ESA) in SLC format using the (https://earth.esa.int/web/guest/eoli) tool. ALOS and Sentinel data was obtained from the Alaska Satellite Facility (https://vertex.daac.asf.alaska.edu).

Data was processed with ISCE Software version 2.2.0 (https://winsar.unavco.org/software/isce) using the SRTM 30-m DEM (https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table/srtmgl1_v003). ERS, Envisat, and ALOS were processed with the default parameters of the StripmapApp.py program, and Sentinel interferograms were processed using TopsApp.py.

Figures were generated with a power spectral filter applied and areas of coherence < 0.3 masked.
Appendix C: Available data

Figure C.1: ERS tracks with imagery covering Snohomish County area of interest (purple dashed line)

Figure C.2: Timeline of ERS acquisitions for tracks shown in C.1
Figure C.3: Envisat tracks with imagery covering Snohomish County area of interest (purple dashed line)

Figure C.4: Timeline of Envisat acquisitions for tracks shown in C.3
Figure C.5: ALOS tracks with imagery covering Snohomish County area of interest (purple dashed line)

Figure C.6: Timeline of ALOS acquisitions for tracks shown in C.5
Figure C.7: Sentinel-1 tracks with imagery covering Snohomish County area of interest (purple dashed line)

Figure C.8: Timeline of Sentinel-1 acquisitions for tracks shown in C.7
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Legend
- Survey Point Locations
- Flood-Control-Districts

Subsidence & Sedimentation Study
Snohomish Conservation
Snohomish County, WA

2018 Survey Point Locations with Labels - Figure 3/5

08/31/2017 Aerial Background

Prepared by Cardno
Date: 09/5/2019
Imagery Source: See Image

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The map data used for this study was acquired using the following sources:
- Snohomish River
- Snohomish Conservation
- Snohomish County, WA

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo,
Legend

- Survey Point Locations
- Flood-Control-Districts

2018 Survey Point Locations with Labels - Figure 5/5

08/31/2017 Aerial Background

Subsidence & Sedimentation Study
Snohomish Conservation
Snohomish County, WA

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Subsidence & Sedimentation Study
Snohomish Conservation Snohomish County, WA

Legend
- Flood-Control-Districts
- Diking-Districts
DD13

2014-2005/06 Difference DEM
-37 - -10 (Outlier)
-9 - -5
-5 - -3
-3 - -1
-1 - -0.5
-0.5 - 0.5 (Uncertain)
0.5 - 1
1 - 3
3 - 5
5 - 10
11 - 69 (Outlier)

Legend
- Flood-Control-Districts
- Diking-Districts
DD13

2014 LiDAR -
2005/06 LiDAR
Difference DEM:
Diking Districts
08/31/2017 Aerial
Background

Snohomish River

08/31/2017 Aerial
Background

Legend
- Flood-Control-Districts
- Diking-Districts
DD13

2014-2005/06 Difference DEM
-37 - -10 (Outlier)
-9 - -5
-5 - -3
-3 - -1
-1 - -0.5
-0.5 - 0.5 (Uncertain)
0.5 - 1
1 - 3
3 - 5
5 - 10
11 - 69 (Outlier)

Legend
- Flood-Control-Districts
- Diking-Districts
DD13

2014 LiDAR -
2005/06 LiDAR
Difference DEM:
Diking Districts
08/31/2017 Aerial
Background

Snohomish River