Technical Memorandum

Date:	July 10, 2019
To:	Chuck Hazelton Stillaguamish Flood Control District
CC:	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:	**Stillaguamish Flood Control District Subsidence and Sedimentation Study – Draft Memorandum**

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1.0 Background

The Stillaguamish Flood Control District (SFCD) has observed over time the subsidence of agricultural lands and levees, deposition of sediment outside of sea dikes, and potential aggradation of the main Stillaguamish River channel. The Stillaguamish River overtops the dikes more frequently now than in the past due to increased tide levels in Port Susan, accretion of estuarine surfaces outside of existing dikes, accumulation of sediments from the 2014 Oso Landslide, and agricultural subsidence 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 re-surveying elevations in areas that have been surveyed in the past, including monuments and bench marks, roads, agricultural lands, and levees. Year 1997 river cross-sections and recent bathymetry data (years 2012 and 2017) 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 SFCD (Figure 1).

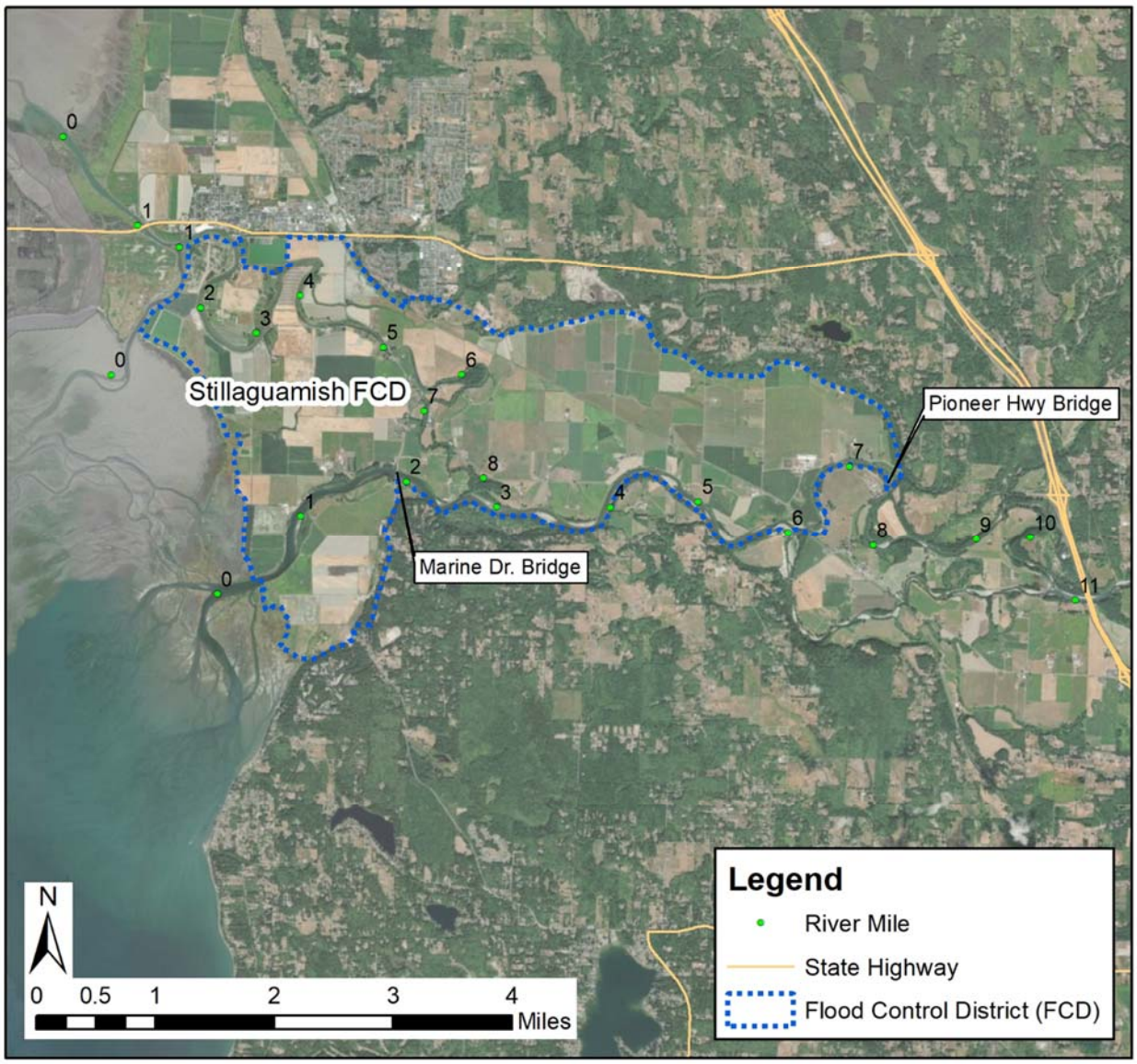


Figure 1. Stillaguamish Flood Control District extents shown on a 2018 aerial with US Geological Survey river miles.

Cardno's scope of work for this SFCD project comprised the following tasks:

> Task 1 – Project Management, Meetings, and Communications

> Task 2 – Data Review

> Task 3 – Topographic Survey

> Task 4 – Subsidence and Sedimentation Study

> Task 5 – Final Reporting and Future Work

The following higher resolution maps and graphs accompany this memorandum:

> Plate Set 1 – SFCD Height Above Water Surface

> Plate Set 2 – Cardno Survey Maps

> Plate Set 3 – Difference Digital Elevation Models (DEMs)

> Plate Set 4 – Survey versus light detection and ranging (LiDAR) Graphs

2.0 Macroscale Processes: Regional Patterns of Relative Sea-Level Change in Western Washington

No discussion of subsidence for the SFCD 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 SFCD is 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 2018), 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 (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.

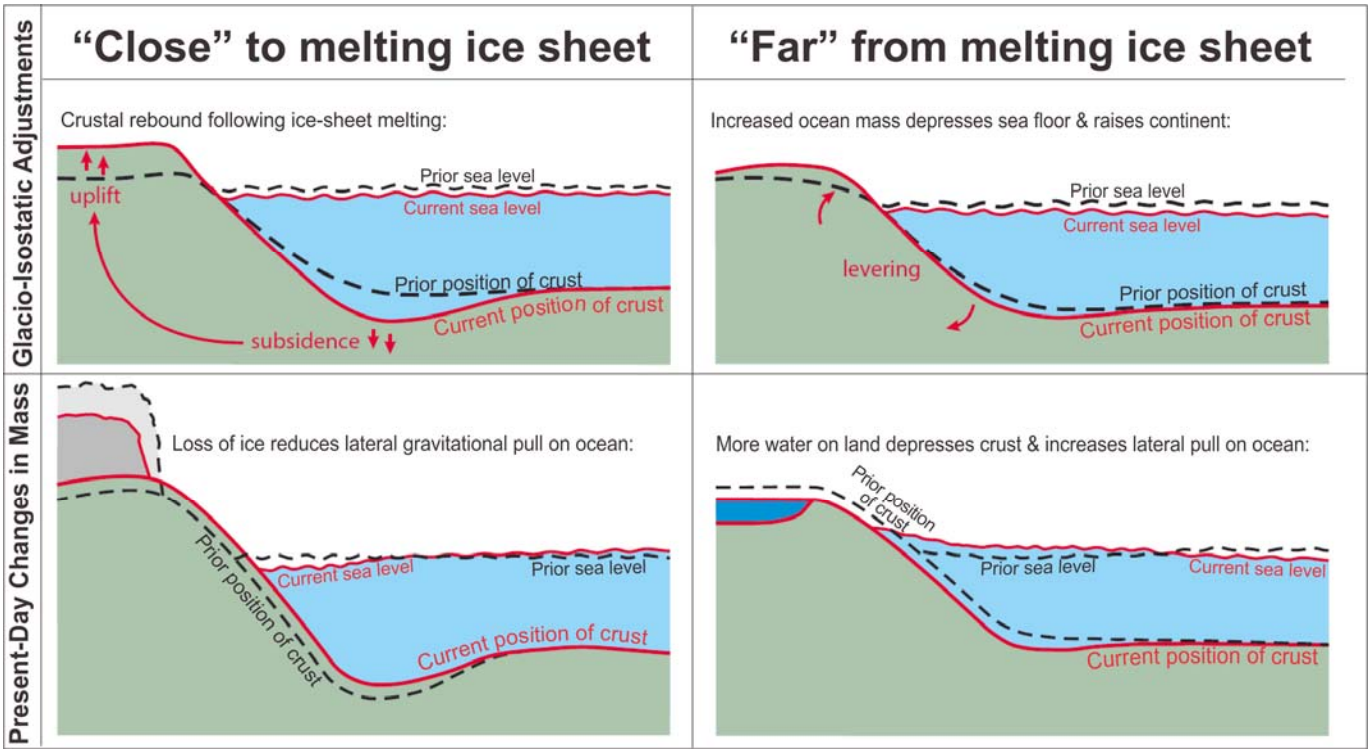


Figure 2. Diagrammatic representation of the various glacio-isostatic influences on RSL. Although important components to consider in any RSL model, these particular factors have largely dissipated along the present-day western Washington coastline. Modified from Tamisiea and Mitrovica (2011).

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).

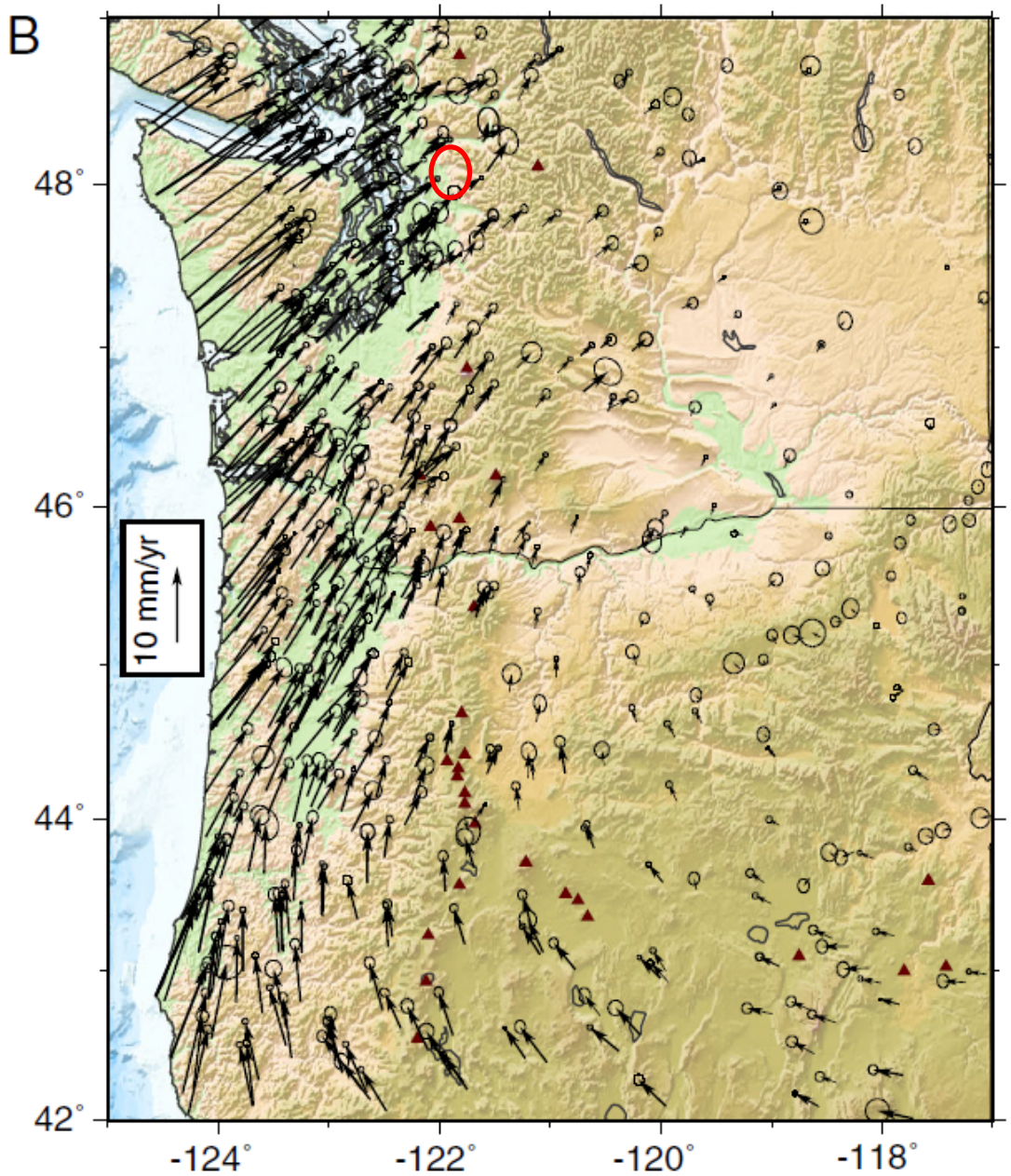


Figure 3. **Horizontal movement of the ground surface across the Pacific Northwest as displayed by a network of permanent and transitory global positioning system (GPS) stations. The rate of movement is scaled by the length of the arrows, with the most rapid rates being about 20 mm per year. Note the 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.

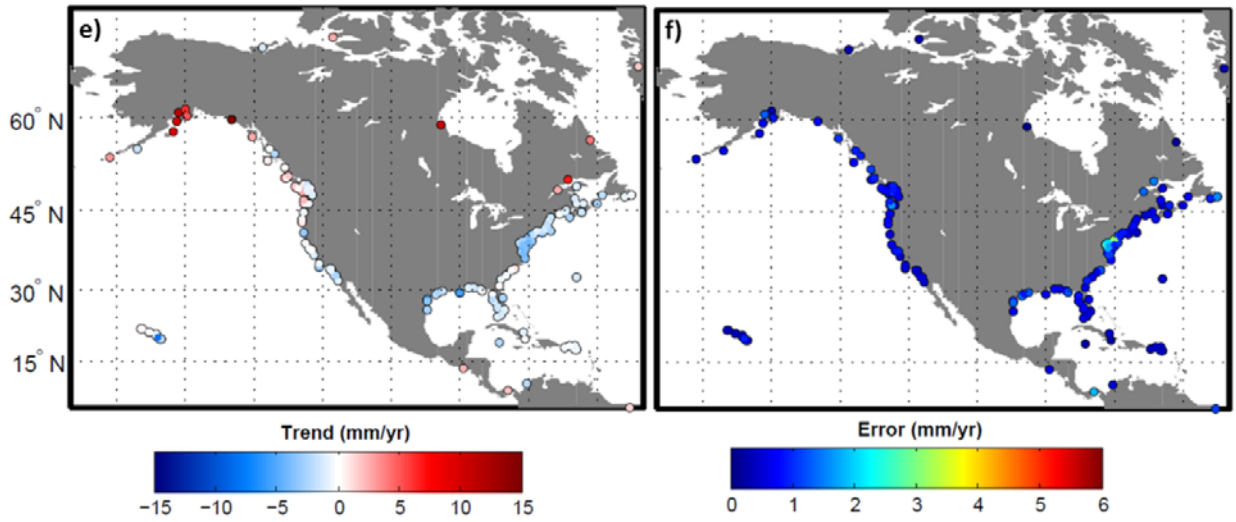


Figure 4. Map of recorded vertical land motion around the North American coastline. Near-stability is shown by the data in the vicinity of the present study area (left panel). The right panel indicates uniformly high-data quality (i.e., low error values) on which these measurements have been based. From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

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 (Snohomish River mouth and Stillaguamish River mouth). Collectively, their key predictions (Figure 5) are:

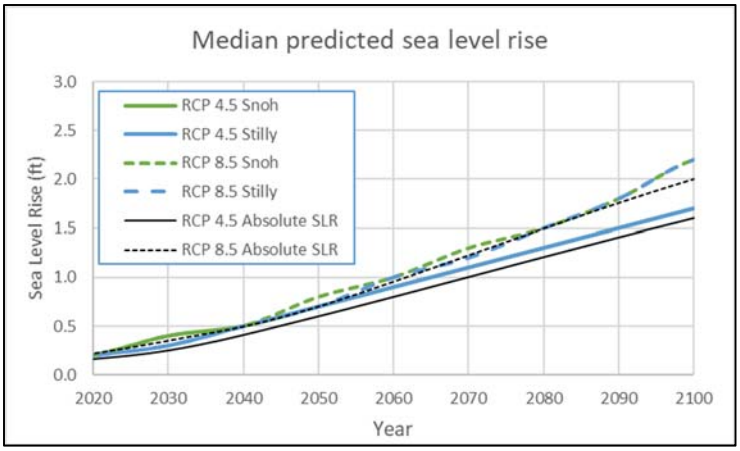
> Little to no independent vertical land movement (no more than about 0.1 foot per century);

> 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.

A.



B.

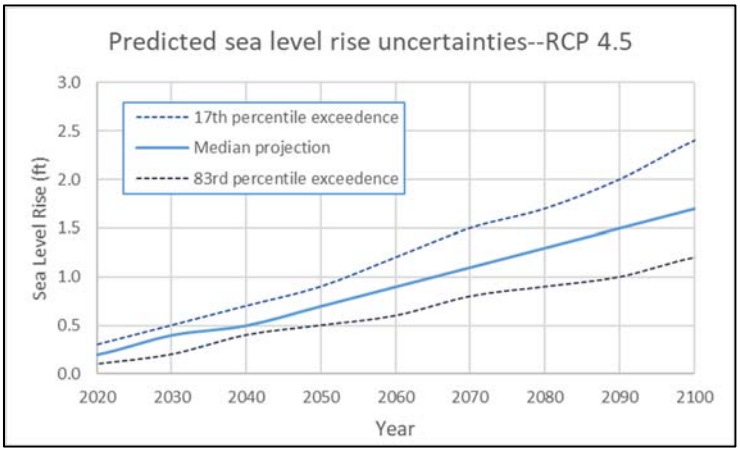


Figure 5. **Plots of RSL for the twenty-first century relative to the average sea level over the 19-year period 1991–2009, graphed from data presented in Appendix C of Miller et al. (2018). RCP 4.5 and RCP 8.5 reflect "low" and "high" greenhouse-gas emission scenarios (Vuuren et al. 2011). Top graph (A) shows the median (50th percentile) probability for 1/10th degree (8-mile diameter) circles that include the mouths of the Snohomish ("Snoh") and Stillaguamish ("Stilly") Rivers. Note the close approximation of the "absolute" (i.e., eustatic) sea-level curve to the RSL curves, reflecting observations that vertical crust movement is almost negligible (see Figure 4). Bottom graph (B) shows the plot of RSL for just the "low" emission scenario for the Snohomish River area (that for the Stillaguamish River area is virtually identical), showing upper and lower uncertainty bands corresponding to one standard deviation around the median projection.**

3.0 Geomorphic Setting

The geomorphology of the lower Stillaguamish River valley is similar to that of other alluvial rivers worldwide: the land surface is higher adjacent to the river (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. For some rivers in the Puget Lowland this pattern is exacerbated because

they flow in a south-to-north-oriented valley (e.g., the Snoqualmie River) 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.

This dichotomy, however, is not a particularly useful classification for the lower Stillaguamish River. The modern form of the lower Stillaguamish River is almost entirely a product of post-glacial processes, but not in the same fashion as the other examples of Collins and Montgomery's post-glacial rivers, because the river has not created its valley form by carving through a recently exposed glacial landscape. Instead, its post-glacial history is dominated by rapidly changing RSL: rapid isostatic uplift followed by an influx of post-glacial but pre-12,500-year-old volcanic sediment from Glacier Peak eruptions, which occurred after virtually all isostatic rebound had finished; continued sea-level rise; and the final attainment of relatively recent quasi-equilibrium with more slowly changing conditions of modern sea-level rise and sediment inputs from the upstream watershed.

Thus, four post-glacial phases in the evolution the lower Stillaguamish River valley can be characterized:

1. Immediately following post-glacial retreat, 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. Following glacier retreat, pulses of Glacier Peak sediment would have episodically choked the lower river and then been flushed away. The sedimentary evidence of those eruptive events is probably long-gone in the lower Stillaguamish River, although some stranded terraces may still record their passing (these are still quite common in the upper North Fork valley). These sediment pulses render any prediction of shoreline location during this period nearly meaningless, since the position of the river mouth probably varied greatly over time during successive deposition–erosion cycles. This phase ended around 12,500 years ago, when sediment deposition around Darrington shunted subsequent Glacier Peak discharges north along the Sauk River to the Skagit River (Tabor et al. 2002).
3. Since 12,500 years ago, the dominant process has been the gradual advance of sea level up and into the lower Stillaguamish River valley. Transgressive sedimentary sequences tend to leave a clear depositional record, for which the high ground adjacent to the river are a credible expression. One would expect the surrounding valley more distant from the river to also aggrade, 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 but punctuated by avulsions where an entirely new course of the river (and thus of deposition) was created through a new portion of the floodplain.
4. Modern levee construction, by limiting the extent of overbank flows, has reduced 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 (natural) levees. Although even the presence of a natural levee reduces 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.

5.

Some observations of diking/levees relative to the natural levees that run adjacent to the lower river are noted below. We use the 1911-avulsion node (i.e., the junction of Hatt Slough and Old Main Channel, Figure 6) as a convenient geographic divide:

> Upstream of the 1911-avulsion node, the natural levees are well established (wide and of consistent height above the river). This section has extensive artificial diking/levees, but a close assessment reveals terrain with no obvious difference in land surface on the riverward and landward sides of those levees/dikes, suggesting that farm fields are not actively subsiding relative to the river. In some locations the constructed levees are built on the flanks of the natural levee. To an observer looking out from the constructed levees this may give an illusion of subsidence that is really just a matter of topographic position.

> Downstream of the 1911-avulsion node, the natural levee splits into two, flanking the paths of the two pre- and post-avulsion channels. In this section is the channel is actively building upward (aggradation discussed in subsequent section) (now more so in the south channel toward Hatt Slough). It is here that LiDAR shows real elevation differences between the natural marsh outside of the levees and the land inside levees, presumably as a result of levee construction. This becomes more obvious downstream toward the delta, suggesting that the riverward floodplain and delta surfaces are growing in elevation relative to the diked farm fields. If this interpretation is correct, the farm fields are not really “subsiding”; rather, the riverward areas are rising (Cardno 2017).

4.0 Methods

4.1 Existing Data Review

Primary elevation datasets considered for this project include the following:

> 1997 Snohomish County cross sections

> 2003 LiDAR Puget Lowlands Quads DEM

> 2012 LiDAR DEM from The Nature Conservancy (TNC)

> 2013 LiDAR DEM from TNC’s Port Susan project

> 2014 LiDAR from the Oso Landslide project

> 2014 topobathy LiDAR from the US Geological Survey

> 2015 LiDAR from Snohomish County

> 2016 bathymetry data for the zis a ba Estuary Restoration Project

> 2017 bathymetry data from Marine Drive to the Hatt Slough mouth

4.2 Project Datums

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 for the SFCD (Vdatum 2019).

4.3 Aggradation Study (Bathymetric Change Analysis)

The 1997 cross-section data were surveyed by Snohomish County's Sky Miller, P.E. on the NGVD29 vertical datum. Cardo converted the 1997 data to the NAVD88 vertical datum for comparison to 2011 bathymetry data from Snohomish County (Figure 6). 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.

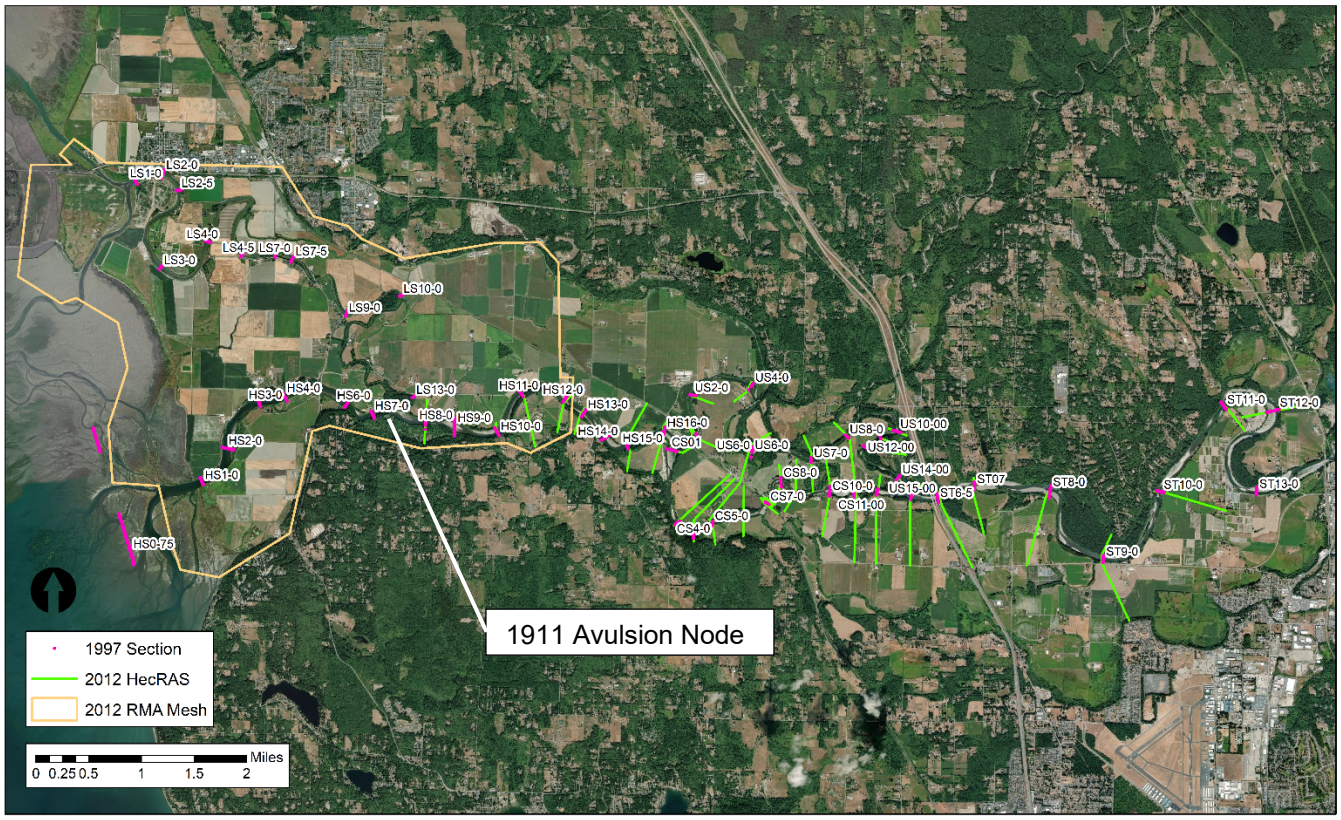


Figure 6. Cross-section locations for comparison of 1997 cross-section data to 2011 bathymetry datasets which fed into two 2012 hydraulic models (2-Dimensional RMA and 1-D HECRAS) .

4.4 Subsidence

4.4.1 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 SFCD.

The overall amount of subsidence relates to a relative comparison of average land-surface elevation inside and outside of the constructed levees. For example, at the zis a ba property in 2017, natural marsh surfaces outside of the levees were around elevation 10 feet NAVD88 and elevations of the agricultural fields were on average 7 feet NAVD88. Assuming that land elevations were equal across the constructed levee prior to construction (though this assumption neglects the presence of natural levees), this would yield a relative subsidence rate of 0.24 inches per year for the 152-year period from levee installation (1863) to 2015 (date of LiDAR flight). This rate would

correspond to a maximum rate of about 0.2 feet of relative subsidence per decade. This is not a measure of absolute subsidence because of likely deposition riverward of constructed levees and compaction landward of 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.

4.4.2 Topographic Survey

Cardno completed a GPS-based real time kinematic (RTK) survey during the week of June 4, 2018, using a Trimble R10 base and rover system (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 using static RTK Trimble R10 base logging every 5 seconds for 4 hours: one solution for Washington State Department of Transportation (WSDOT) Stanwood and one for WSDOT Silvana. At the time of survey, Cardno was not aware of the 1999 Snohomish County report that documents GPS geodetic control for the Stillaguamish levee system. Cardno recommends a full evaluation of this historical geodetic control network with any further subsidence studies.

4.4.3 LiDAR Differencing

LiDAR differencing is the subtraction of one LiDAR dataset from another to create a new DEM called a difference DEM. Difference DEMs were created for this study according to LiDAR acquisition years as follows (Plate Set 3):

1. 2015 LiDAR minus 2012 LiDAR
2. 2015 LiDAR minus 2003 LiDAR quads
3. 2013 LiDAR minus 2005 Mosaic
4. 2012 LiDAR minus 2005 Mosaic
5. 2015 LiDAR minus 2005 Mosaic
6. 2014 LiDAR minus 2005 Mosaic

For the case of the 2014 Oso Landslide LiDAR dataset, the highest returns DEM (vegetation canopy model) was compared to the lowest returns DEM (bare earth model) to make an assessment of whether vegetation tops were actually removed from the bare earth DEM. This was essential to ensure that the difference DEMs represented changes in ground surface elevation and not changes in vegetation growth. Vegetation was not consistently removed from LiDAR DEMs due to differing methodologies used by the providers, so LiDAR differencing analysis was complicated by the varying height of crops.

5.0 Results

5.1 Aggradation Study

A cross sectional area and minimum thalweg analysis confirmed aggradation in the current main channel (Hatt Slough) and the Old Main Channel (Snohomish County weir to Florence, Washington, to Stanwood, Washington). This conclusion is limited to the comparison of 1997 cross sections with modern 2012 bathymetry data (Table 1) because 2016/2017 bathymetry was similar to 1997 bathymetry. Aggradation in the lower Stillaguamish River is consistent with results from R2 Resource Consultant's geomorphic assessment (Devries 2013) and visual observations from Chuck Hazelton in the vicinity of his residence (near cross-section HS3-0), where he has seen growth of gravel bars, especially on the south side of the river.

Table 1. Summary of Aggradation Metrics Considered Showing Thalweg Elevation Change and Cross-Sectional Area Percent Change, refer to Figure 6 for locations.

Cross-Section Name	1997 Thalweg Elevation (ft,NAVD88)	Modern Data Year	Modern Thalweg Elevation (ft,NAVD88)	Change in Thalweg Elevation (ft)	Cross-Section Area Percent Change
CS10-0	15.2	2012	16	1.3	-2
CS11-00	18.9	2012	17	-2.3	-6
CS12-00	18.4	2012	20	1.1	-6
CS8-0*	11.2	2012	11	0.1	-9
CS9-00	4.1	2012	8	3.8	-5
HS1-0	-11.8	2012/2017	-7.7/-10.0*	4.1/1.8	Insufficient Data
HS10-0	-6.5	2012	-6.0	0.5	-1
HS11-0	-2.0	2012	-2.4	-0.4	3
HS12-0	0.3	2012	3.9	3.6	-2
HS13-0	2.1	2012	0.95	-1.1	-9
HS14-0	4.2	2012	5.58	1.4	-1
HS15-0*	4.8	2012	5.8	1.1	-7
HS16-0*	4.9	2012	0.3	-4.5	-17
HS2-0	-8.1	2012/2017	-7.4/-7.3*	0.7/0.8	Insufficient Data
HS3-0	-7.4	2012/2017	-5.1/-6.0*	2.3/1.4	Insufficient Data
HS4-0	-8.7	2012/2017	-3.3/-6.0*	5.4/2.7	Insufficient Data
HS6-0	-1.1	2012	-1.5*	-0.4	Insufficient Data
HS7-0	-8.1	2012	-6.7*	1.4	Insufficient Data
HS8-0	-1.0	2012	-1.6	-0.6	-2
HS9-0	-1.3	2012	2.2*	3.5	Insufficient Data
LS1-0	-1.0	2012	0.7*	1.7	Insufficient Data
LS10-0	2.7	2012	1.8*	-0.9	Insufficient Data
LS13-0	0.9	2012	4.0*	3.1	Insufficient Data
LS2-0	-4.9	2012	-5.8*	-0.9	Insufficient Data
LS2-5	-4.4	2012	-4.9*	-0.5	Insufficient Data
LS3-0	-0.7	2012	-0.1*	0.6	Insufficient Data
LS4-0	0.5	2012	1.2*	0.7	Insufficient Data
LS4-5	-5.6	2012	-2.9*	2.7	Insufficient Data
LS7-0	-1.1	2012	2.0*	3.1	Insufficient Data
LS7-5	1.2	2012	1.3*	0.1	Insufficient Data
LS9-0	-2.8	2012	-0.8*	2.0	Insufficient Data

Cross-Section Name	1997 Thalweg Elevation (ft,NAVD88)	Modern Data Year	Modern Thalweg Elevation (ft,NAVD88)	Change in Thalweg Elevation (ft)	Cross-Section Area Percent Change
ST07*	15.7	2012	19	3.8	-17
ST10-0*	28.5	2012	27	-1.1	-11
ST11-0	31.5	2012	29	-2.8	-9
ST12-0*	33.2	2012	34	0.7	-21
ST6-5	12.4	2012	15	2.6	-8
ST8-0	25.7	2012	25	-0.6	8
ST9-0*	27.0	2012	28	0.8	-8
US1-0	7.2	2012	8	0.3	-9
US10-00	17.6	2012	16	-1.6	-9
US11-00	17.5	2012	17	-0.6	-10
US12-00*	18.1	2012	19	1.0	-15
US14-00*	19.0	2012	20	1.3	-14
US15-00	12.1	2012	15	3.2	-5
US2-0*	8.9	2012	8	-0.7	-21
US4-0	8.0	2012	5	-2.9	-3
US7-0*	11.9	2012	12	0.0	18
US8-0*	15.9	2012	18	1.9	-13

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.

Thalweg changes and cross-sectional area changes were quite varied. Generally, modest aggradation was calculated for channels with an overall +1.0 foot Thalweg increase and a decrease of 5.0 % to cross-sectional area for green zones denoted in Figure 7. In addition, to aggradation in the lower main channel, the Hatt Slough delta (current river mouth delta) has expanded spatially to the west on the order of 200 to 600 feet (Figure 7). The delta surface itself has experienced about 1 foot of average aggradation (Figure 8).

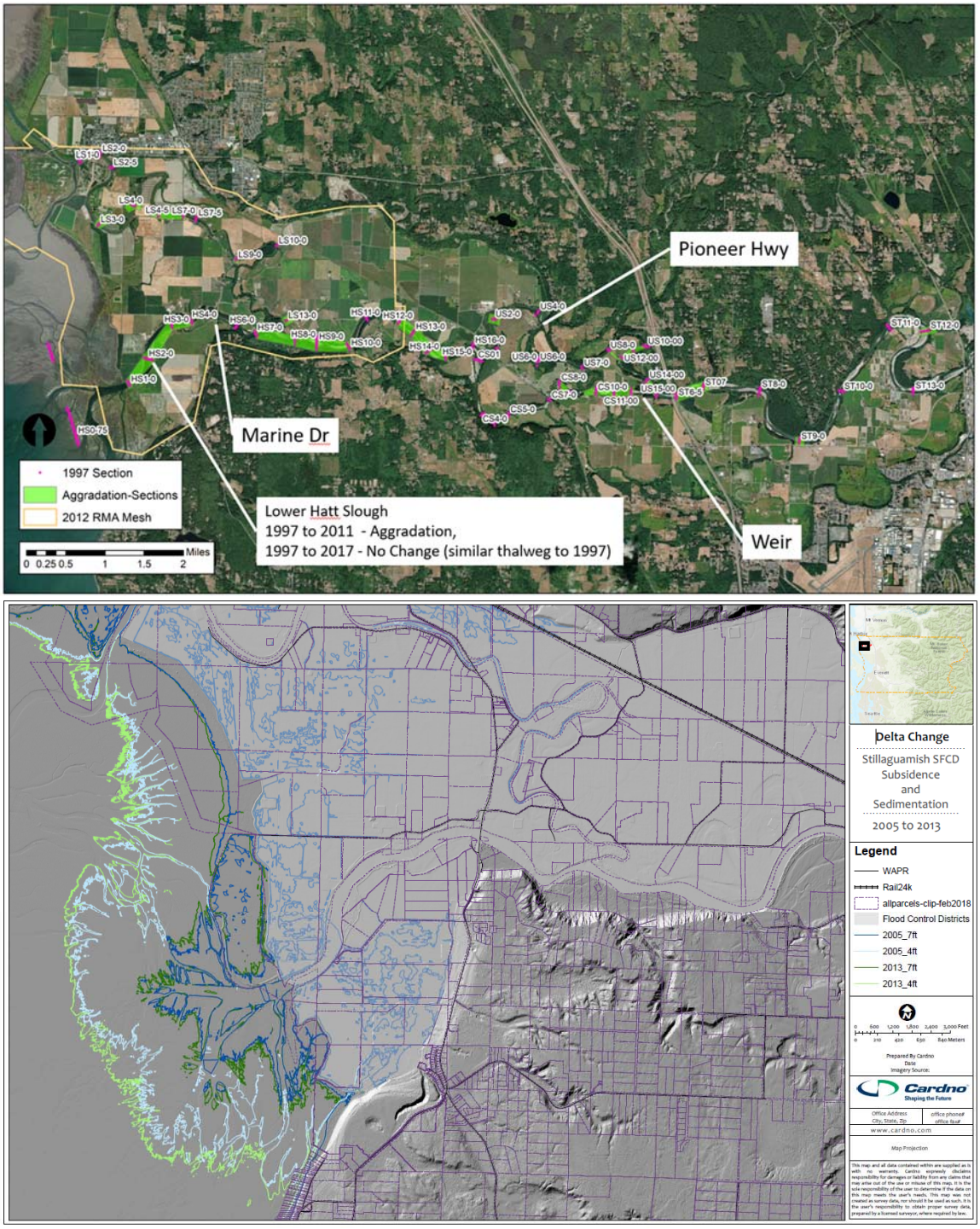


Figure 7. **1 foot of vertical aggradation was calculated for both the lower channels and the delta surface. At top, aggradation resulted for green zones for the lower channel over a 14-year period. At bottom, progradation of the current river mouth delta at Hatt Slough for the 10-year time period from 2003 to 2013 with 1 foot of vertical aggradation as shown in the following figure.**

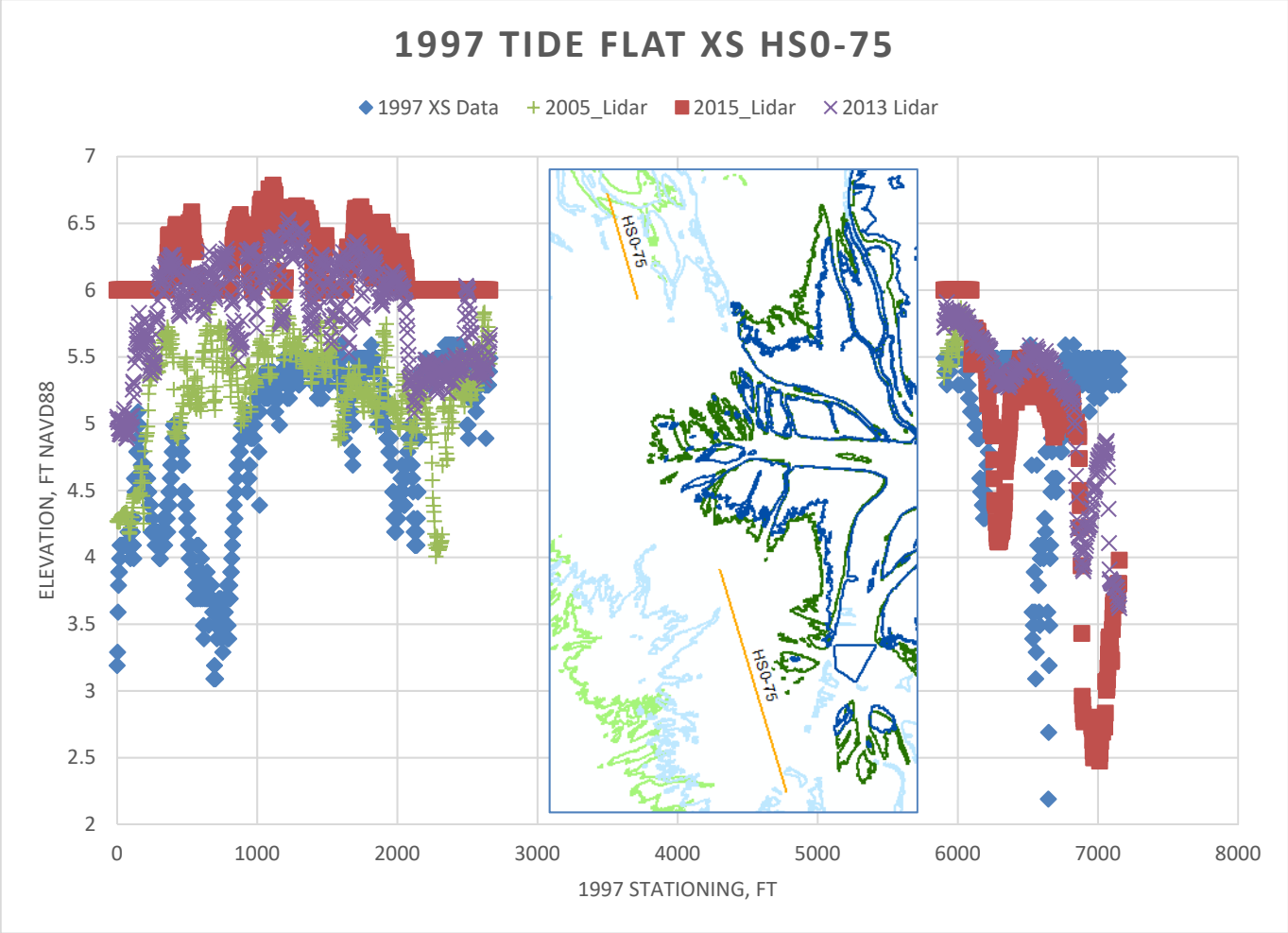


Figure 8. 1997 cross-section HS0-75 traversed the current delta and comparison to modern LiDAR suggests about 1 foot of aggradation over a 17-year period.

Cardno did not fully process comparisons of the 1997 XS data to 2016 and 2017 bathymetry data (collected by Gravity, Inc) since the 2011 bathymetry datasets were deemed more accurate and sufficient to quantify aggradation trends. Figure 9 shows an example comparison of 1997 XS data versus 2012 XS data and an example comparison of 1997 and 2017 bathymetry. The 2016 (zis a ba) and 2017 (Hatt Slough) bathymetry data was produced as 30-foot resolution grids and, thus, not easily comparable to the 1997 data. Furthermore, aggradation and sedimentation from the Oso landslide (March 22, 2014) was not evaluated in this study since the material has most likely migrated out of the out of the lower main channels to cause increased delta progradation and aggradation of the marsh surface. For a more detailed discussion of the Oso landslide, please refer to *Sediment Transport Processes in Response to Estuary and Salmon Recovery Efforts and the SR530 (Oso) Landslide* (Grossman and Curran 2015) and Cardno's *Conceptual Design Report: Hatt Slough Estuary Restoration Project* (Cardno 2017).

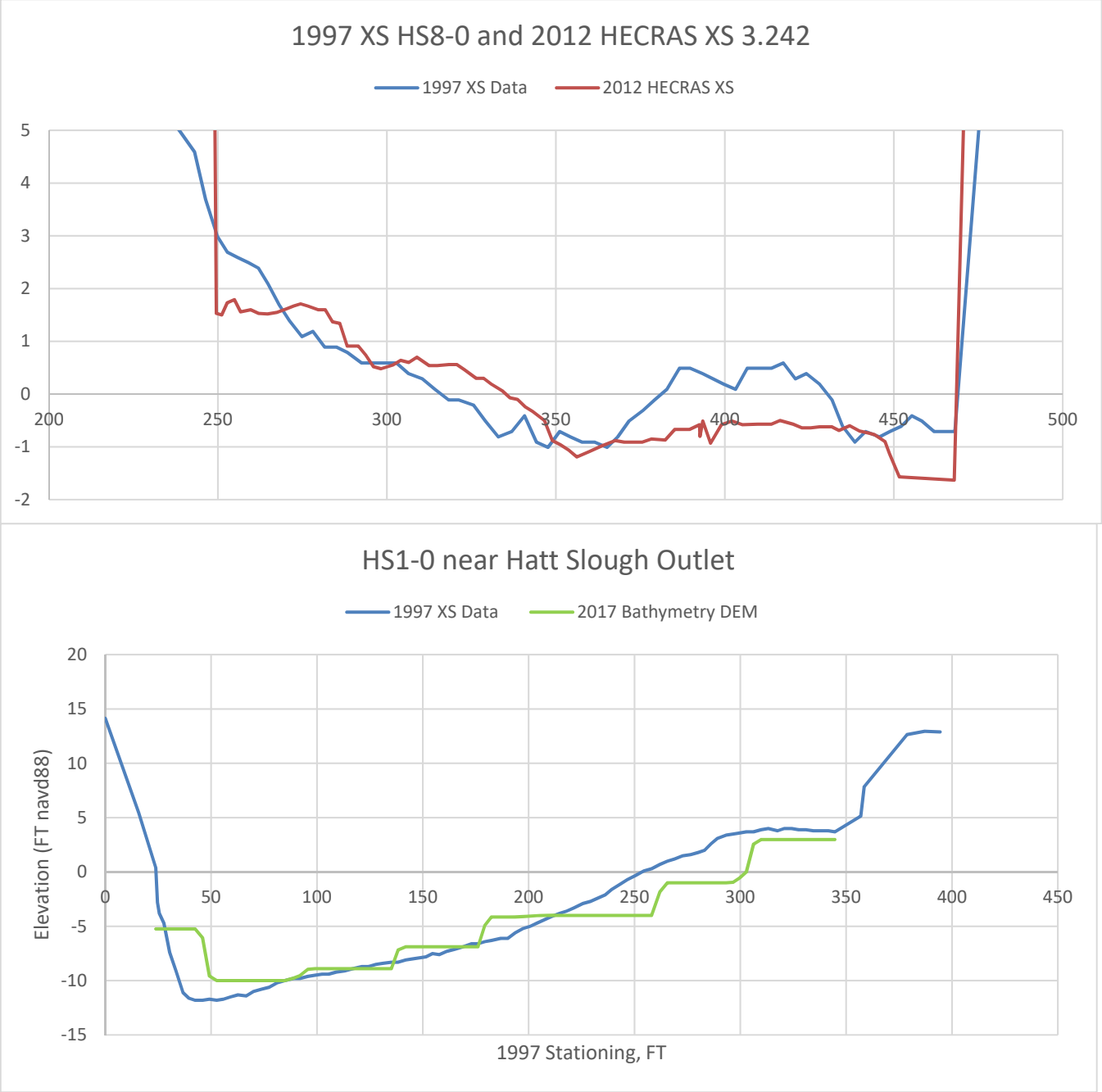


Figure 9. **At top, example cross-section output comparing 1997 data to 2012 HECRAS cross-section data. At bottom, example cross-section output comparing 1997 data to 2017 bathymetry. The 2017 data were available for analysis but were not considered in this study due to the gridded nature of the dataset leading to false flat areas in the bathymetry. If flat areas were removed via interpolation, 1997 and 2017 bathymetry would be quite similar.**

5.2 Subsidence Study

5.2.1 2018 Topographic Survey versus LiDAR

Topography data from years 2003, 2005, 2012, 2013, and 2015 were obtained utilizing LiDAR. The ground elevation values from the 5 years of LiDAR topography were compared with ground survey data collected in 2018 as quality control verification of LiDAR and to identify the incremental changes in vertical elevation. This comparison determined the magnitude of ground subsidence throughout years 2003 to 2018. However, quality control of LiDAR determined that vertical difference uncertainty was high (±0.5 feet) for comparisons of 2010 to 2015 LiDAR for agricultural fields to the older LiDAR dataset flown in 2003 due to differences in LiDAR point processing, flight patterns, crop height differences, and methods for constructing DEMs.

Roads and rail centerlines did not experience any significant vertical land movement. LiDAR surveys of roads and rail centerlines throughout the SFCD reveal vertical stability over the last decade (Figure 10 and Table 2). The 2018 Cardno topographic survey also showed little to modest vertical movement for road surfaces.

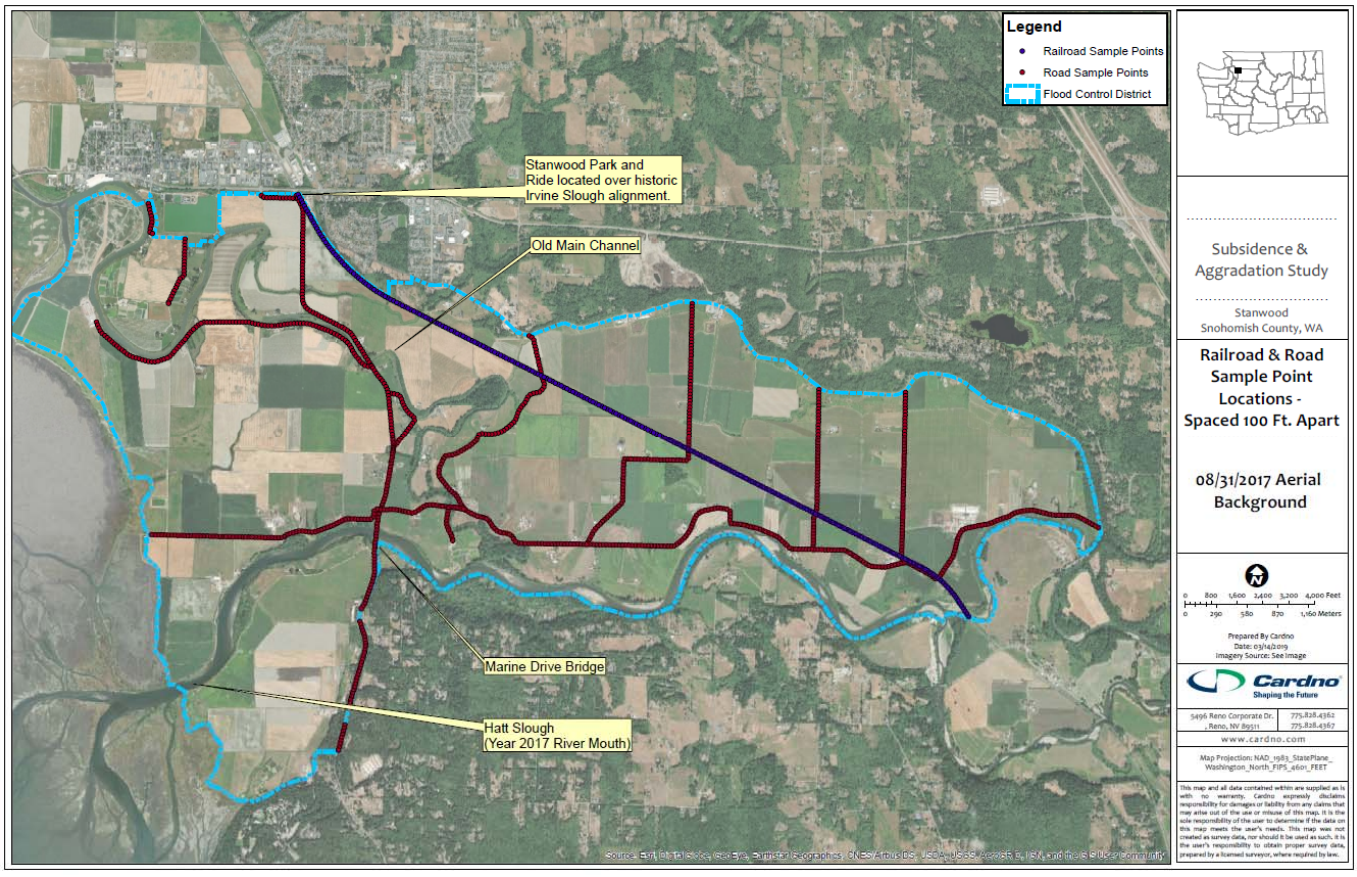


Figure 10. Map of roads and rails within the SFCD selected for LiDAR difference comparisons.

Table 2. Averaged Vertical Difference between 2003 LiDAR Base Values and 2014 and 2015 LiDAR

Comparison Areas	2015−2003 Delta Values	2014−2003 Delta values
Road Samples	0.0	0.0

Railroad Samples	0.0	0.2

Note: SFCD public roads and rail centerlines were sampled at a point every 100 feet.

To provide a spatial reference for the survey versus LiDAR comparisons, the data were grouped into four categories: Levees, Roads, Agricultural, and Natural areas. The Levees category consists of comparisons from areas named Levee 5, Norman Road, Norman Overbank, Sea Dikes, and Flood Gates. The Roads category compared roadways along 28th Ave Northwest and 36th Ave Northwest. Agricultural sections -1, -2, and -3 were three separate comparison areas from the Agricultural category. Finally, the Natural areas category consisted of both the floodgate area with connection between Hatt Slough and the Port Susan Restoration Project and Chuck Hazelton's gravel bar. All graphic and spatial figures for the comparison results are shown in Plate Set 4.

Based on the collected survey and LiDAR data, comparisons indicate that the majority of the analyzed land categories experienced vertical movement of less than a foot between 2003 and 2018 (Table 3). Areas such as the new Zis a ba crossdike, Flood Gates, and Sea Dikes experienced increases in ground elevation of greater than 1 foot since these areas were built up through levee improvements.

Table 3. Average Vertical Difference between 2003 LiDAR Elevations and Five Subsequent Surveys: 2005, 2012, 2013, and 2015 LiDAR Surveys, and the 2018 Cardno GPS Survey.

Average Delta Values				
Comparison Areas	**2012−2003 Delta Values**	**2013−2003 Delta Values**	**2015−2003 Delta Values**	**2018−2003 Delta Values**
Constructed Levees				
Levee 5	0.16	0.26	0.40	0.51
Norman Road	-0.03	-0.03	-0.30	0.46
Norman Overbank	-0.01	-0.01	-1.74	-0.96
Sea Dikes	0.21	3.79	4.87	4.77
Flood Gates	0.12	-0.61	-2.28	1.15
Roads				
28th Ave Northwest	-0.01	-0.01	0.02	-0.04
36th Ave Northwest	0.01	0.01	-0.10	-0.08
Agricultural Areas				
Ag -1	-0.10	-0.10	-0.23	-0.50
Ag -2	-0.26	-0.26	-0.22	-0.40
Ag -3	-0.27	-0.27	-0.32	-0.80

Summary results are grouped by three land types (constructed levees, roads, and agricultural areas). Positive values indicate aggradation, while negative values indicate subsidence. In general, agricultural areas show the most consistent pattern of subsidence (though highest uncertainty); roads the greatest stability (with highest certainty); and constructed levees the greatest variability due to improvements and maintenance operations.

Of all of Cardno's surveyed areas, only the agricultural sections show consistent subsidence (Table 3). However, the true magnitude of this subsidence rate is uncertain, because the degree of vegetation removal during

processing of the 2003 LiDAR (and the existing vegetation heights) are unknown. Furthermore, the fields had rows, deep tilling, mechanical leveling, and machine ruts that were likely of a similar magnitude as that of the measured differences in land-surface elevation.

5.2.2 LiDAR Differencing

Difference DEMs (Plate Set 3) confirm that the Stillaguamish River delta west of the sea dikes is aggrading (building vertically) and prograding (building laterally to the west) in the vicinity of the current Hatt Slough mouth. However, the delta is eroding south of Leque Island and southwest of the Southpass mouth of the Old Main Channel of the Stillaguamish. This conclusion is consistent with the work of other researchers (e.g., Grossman and Curran 2015).

SFCD agricultural fields have an inconclusive subsidence signal. Data suggest that the parcels northeast of the railroad may have subsided 0.3 feet from 2003 to 2015. However, the standard deviation of LiDAR difference was even greater, on the order of ±0.6 feet, due to dense crop tops not removed from the LiDAR DEMs (Figure 11 and Table 4). The effect of crops on the LiDAR difference DEMs tended to follow parcel lines, which further supports inconclusive results for localized subsidence. Comparisons of crop canopy heights and bare earth models for the 2104 Oso Landslide LiDAR dataset suggested crop heights of more than 1 foot, which support the inference of confounding crop heights. Thus, a topographic survey-based methodology would be the only means for confirming subsidence; future surveys should seek to reoccupy those 1997 points where they fall on the floodplain.

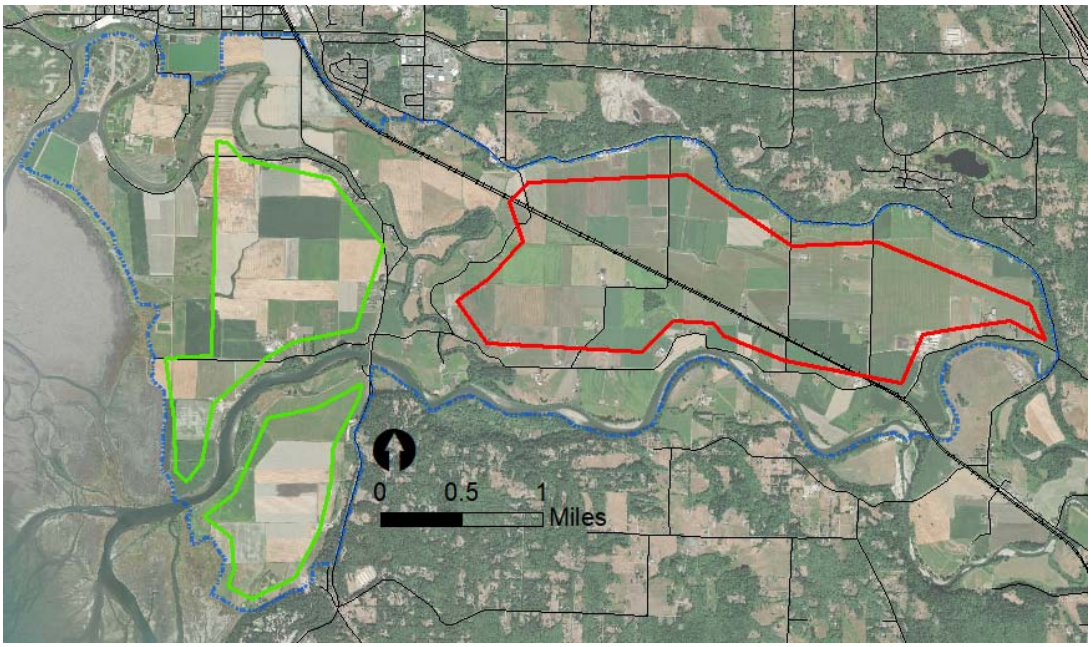


Figure 11. Zones used to calculate LiDAR differencing statistics between 2015 LiDAR and 2003 LiDAR: lower downstream zones outlined in green (2 zones, on Florence Island and south of Hatt Slough); upper zone outlined in red.

Table 4. Average Vertical Difference between 2003 LiDAR Base Values and 2015 LiDAR for Upper and Lower Zones (see Figure 11) within the SFCD

Comparison Areas	2015−2003 Difference Average	2015−2003 Difference Standard Deviation
Lower Zone	-0.3	0.5 feet

Upper Zone	-0.3	0.6 feet

Note: Negative values may indicate subsidence, but standard deviations indicate inconclusive results.

5.2.3 Survey Benchmark Comparisons

> *WSDOT Stanwood (TR2700) Benchmark Subsidence*: This benchmark has subsided about 0.5 feet in just under 3 years (9/8/2015 to 6/4/2018) as verified by the Cardno survey analysis and corroborated in discussion with Gavin Schrock of WSDOT's survey control group. This benchmark lies in the Stanwood Park and Ride Lot, which has experienced a similar level of subsidence as is evident in the failing asphalt, potholes, and small dips throughout the area. The likely cause of this significant localized subsidence is the parking lot's proximity to the historical alignment of Irvine Slough. The park and ride is likely falling into the slough due to compressible organic soils.

> NGS benchmarks along railroad: buried since last retrieval and, thus, not found.

> *WSDOT Silvana (TR0161):* no subsidence detected with comparison of OPUS solution (average of 4 hours static RTK logging every 5 seconds) to WSDOT published data.

> County Benchmarks: reoccupied but no published values were found. We suggest contacting county surveyors to determine if they have published vertical control for Olson Road and 28th Avenue NW; however, LiDAR differencing suggests that these roads have not moved vertically in the last decade.

6.0 Discussion

6.1 Future Aggradation Trends

The lower Stillaguamish River is experiencing a general trend of aggradation, which 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 Stillaguamish 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. A hydraulic modeling study completed in 2013 found that:

> With dredging of the Old Main Channel, the maximum reduction in peak stage was less than 0.1 ft near the head of the Old Stilly Channel. The change was almost negligible (0.01 ft or less) on the floodplain. (Huang and DeVries 2013)

6.2 Subsidence Trends and Rates

Based on our analysis of the data characterizing land-surface changes over the last 15 years, there is little direct evidence for regional subsidence. Uncertainty in the LiDAR comparisons exceed the magnitude of elevation change that may have occurred, and benchmark resurveys suggest at most localized subsidence in known problematic locations. These datasets are not conclusive; improving their future reliability is addressed in the next section. 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). 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% higher, with the consequences felt at every location throughout the region.

7.0 Next Steps and Future Solutions

Given the relative magnitudes and degree of certainty in the effects considered in this report, we suggest that the SFCD focuses most urgently on adapting and planning for SLR and changing river hydrology.

Next steps:

1. Survey transects across agricultural fields focusing on areas northeast of the railway near relict channel threads that LiDAR differencing showed as suspect for subsidence between 2015 and 2005.
2. Reoccupy 1997 cross-section locations on the floodplain (very limited areas).
3. Reoccupy and assess vertical land movement at benchmarks associated with the 1999 David Evans and Associates GPS geodetic control study.

Big ideas to discuss:

1. Managed retreat
2. Estuary avulsion predictions to locate strategic areas for levee lowering and/or upgrades: Backwater controls of avulsion location on deltas (Chatanantavet 2012, Ganti 2016, Lamb 2012)

8.0 References

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Height Above Water Surface (HAWS) Map

Stillaguamish Flood Control District

Stillaguamish Flood Control District
Snohomish County, WA

Legend

- Flood Control District
- Levee

Height Above Water Surface (ft.)

-3 0 5 10 15 20 25

0 0.25 0.5 Miles

Prepared By Cardno
Date: March 2019
Imagery Source: Snohomish County 2015 LiDAR

Cardno

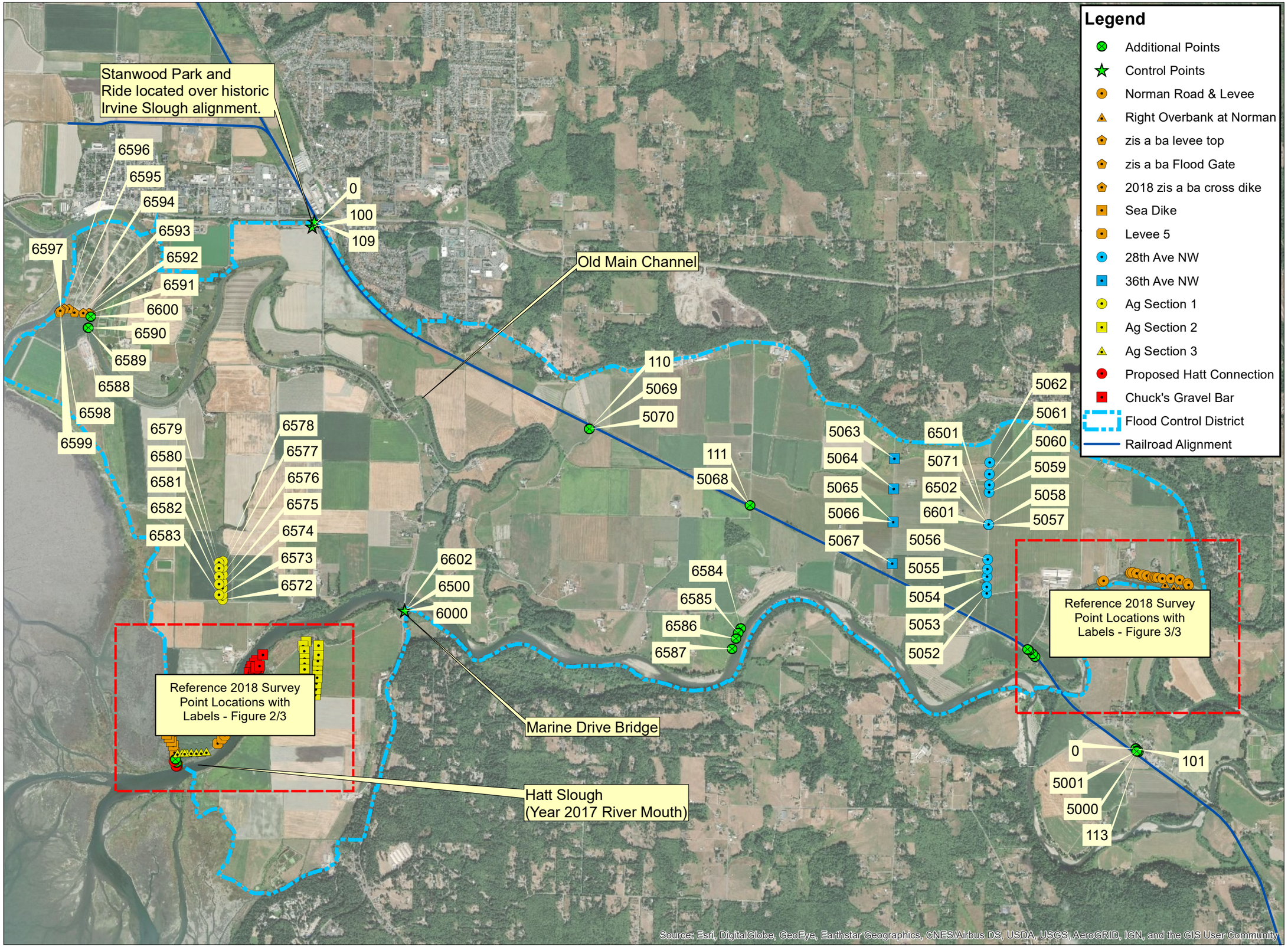
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Legend

- Additional Points
- Control Points
- Norman Road & Levee
- Right Overbank at Norman
- zis a ba levee top
- zis a ba Flood Gate
- 2018 zis a ba cross dike
- Sea Dike
- Levee 5
- 28th Ave NW
- 36th Ave NW
- Ag Section 1
- Ag Section 2
- Ag Section 3
- Proposed Hatt Connection
- Chuck's Gravel Bar
- Flood Control District
- Railroad Alignment



Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations with Labels - Figure 1/3

08/31/2017 Aerial Background

0 810 1,620 2,430 3,240 4,050 Feet
0 280 560 840 1,120 Meters

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Date: 10/30/2018
Imagery Source: See Image

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Shaping the Future

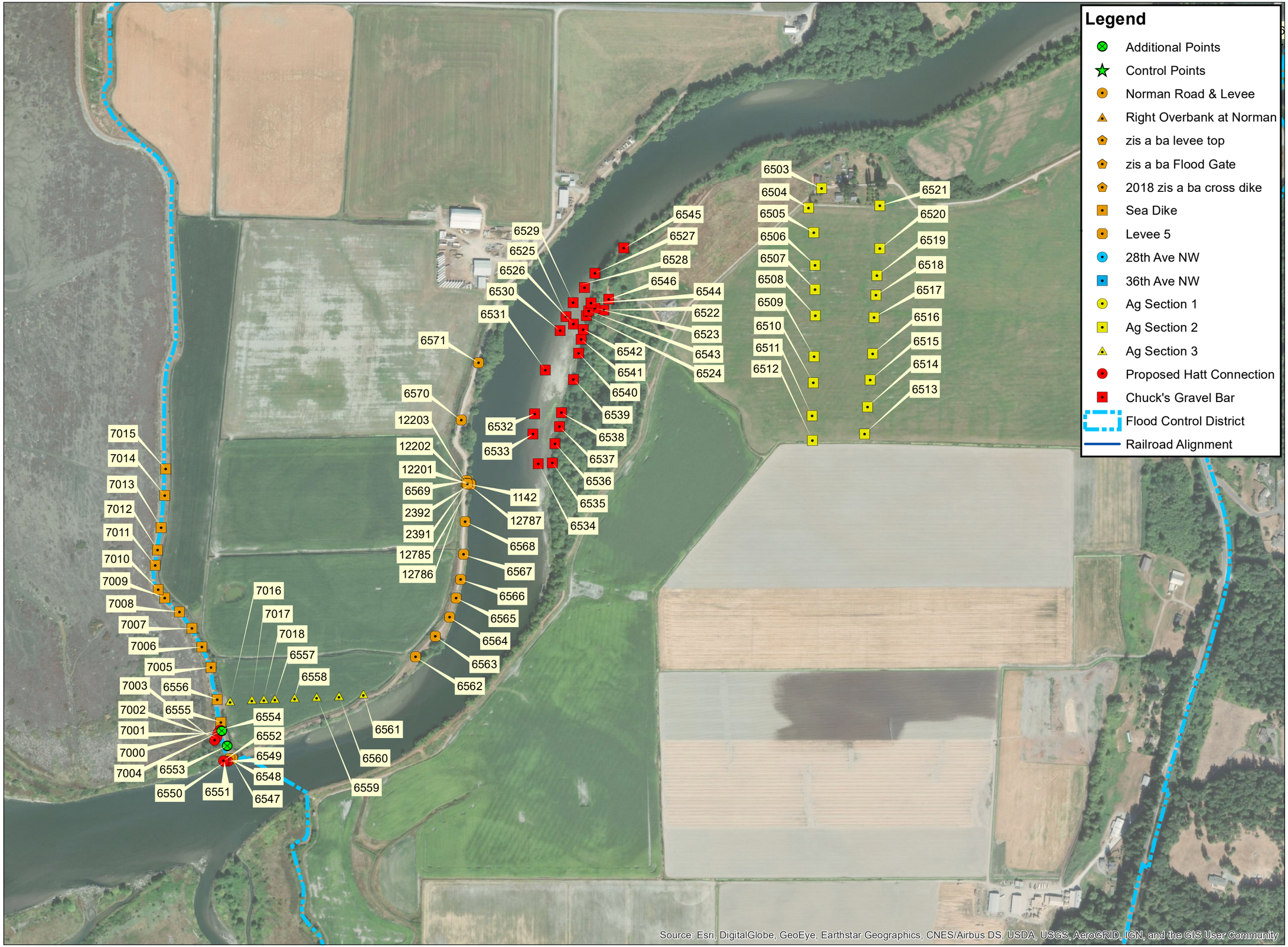
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Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations with Labels - Figure 2/3

08/31/2017 Aerial Background

0 180 360 540 720 900 Feet
0 60 120 180 240 Meters

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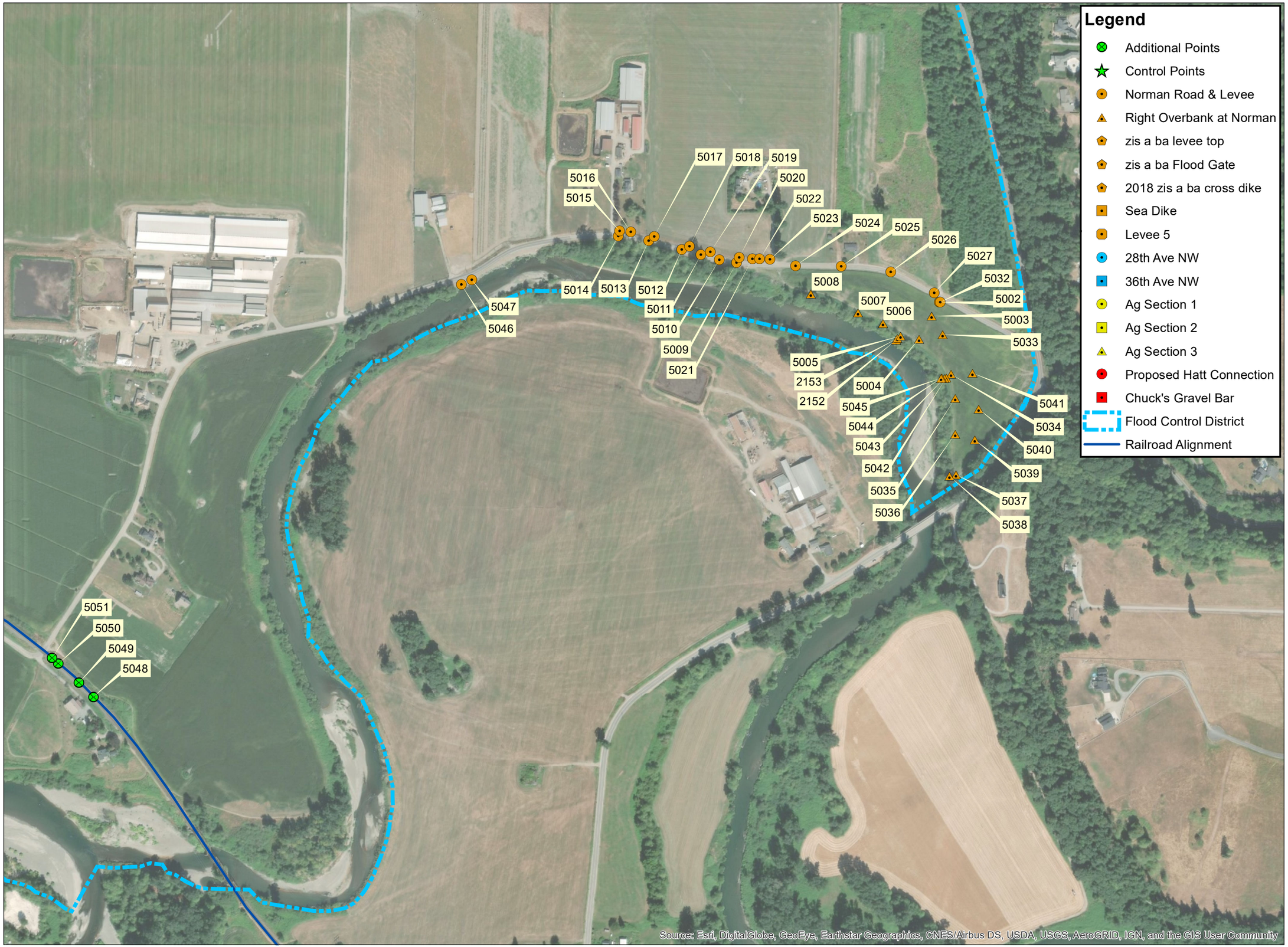
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Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations with Labels - Figure 3/3

08/31/2017 Aerial Background

0 150 300 450 600 750 Feet
0 50 100 150 200 Meters

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Stanwood Park and Ride located over historic Irvine Slough alignment.

Old Main Channel

Marine Drive Bridge

Hatt Slough (Year 2017 River Mouth)

2012-2005 (feet)

-0.8 - -0.8
-0.7 - -0.6
-0.5 - -0.4
-0.3 - -0.2
-0.1 - 0
0.1 - 0.2
0.3 - 0.4
0.5 - 0.6
0.7 - 0.8
0.9 - 1
1.1 - 1.2

Legend

- Additional Points
- Control Points
- Norman Road & Levee
- Right Overbank at Norman
- zis a ba levee top
- zis a ba Flood Gate
- 2018 zis a ba cross dike
- Sea Dike
- Levee 5
- 28th Ave NW
- 36th Ave NW
- Ag Section 1
- Ag Section 2
- Ag Section 3
- Proposed Hatt Connection
- Chuck's Gravel Bar
- Flood Control District

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations: 2012 LiDAR - 2005 LiDAR Difference DEM

08/31/2017 Aerial Background

0 800 1,600 2,400 3,200 4,000 Feet
0 290 580 870 1,160 Meters

Prepared By Cardno
Date: 03/14/2019
Imagery Source: See Image

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Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

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Date: 03/14/2019
Imagery Source: See Image

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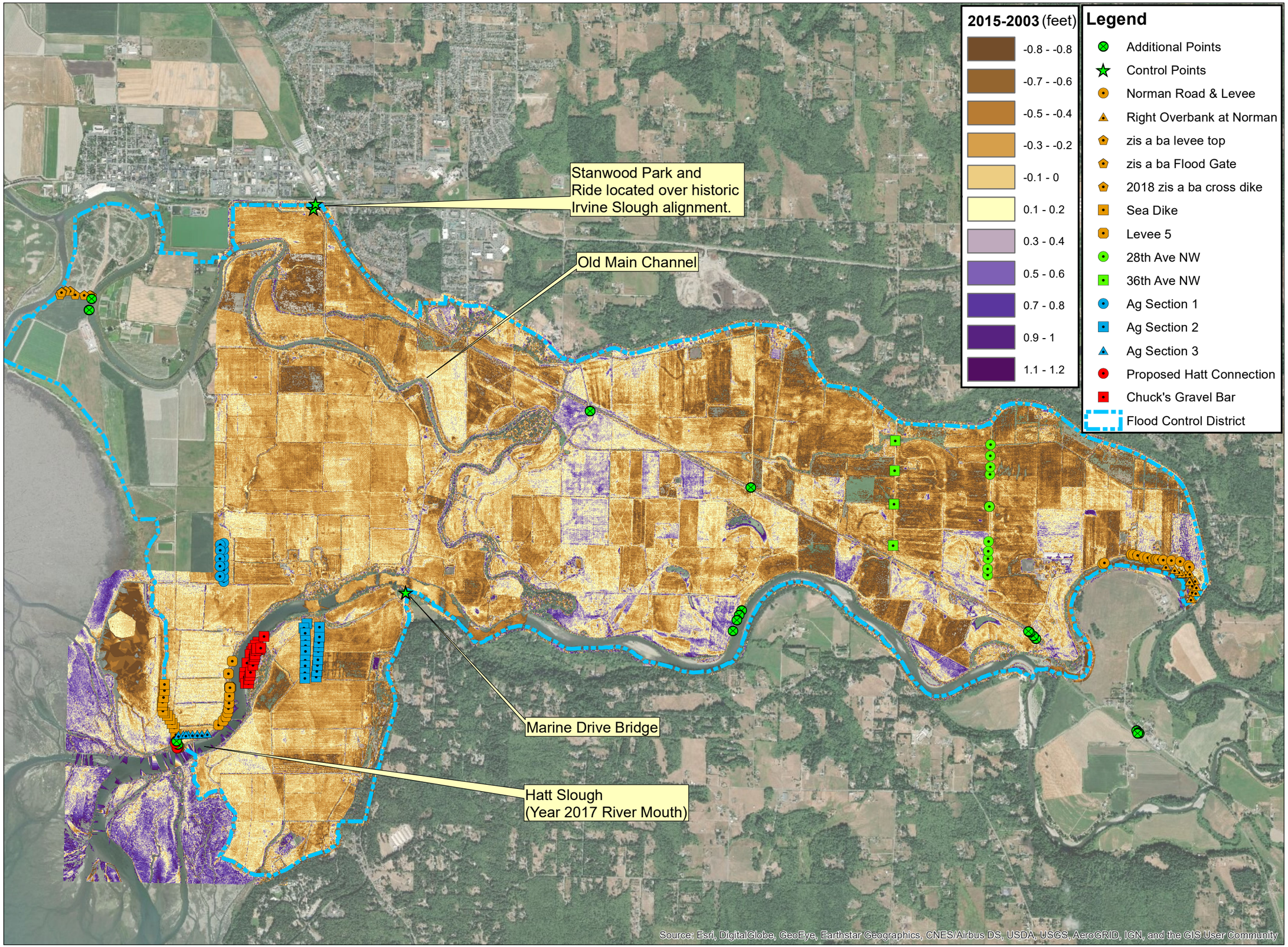
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Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



2015-2003 (feet)

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- -0.7 - -0.6
- -0.5 - -0.4
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- -0.1 - 0
- 0.1 - 0.2
- 0.3 - 0.4
- 0.5 - 0.6
- 0.7 - 0.8
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Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations: 2015 LiDAR - 2003 LiDAR Difference DEM

08/31/2017 Aerial Background

0 800 1,600 2,400 3,200 4,000 Feet
0 290 580 870 1,160 Meters

Prepared By Cardno
Date: 03/14/2019
Imagery Source: See Image

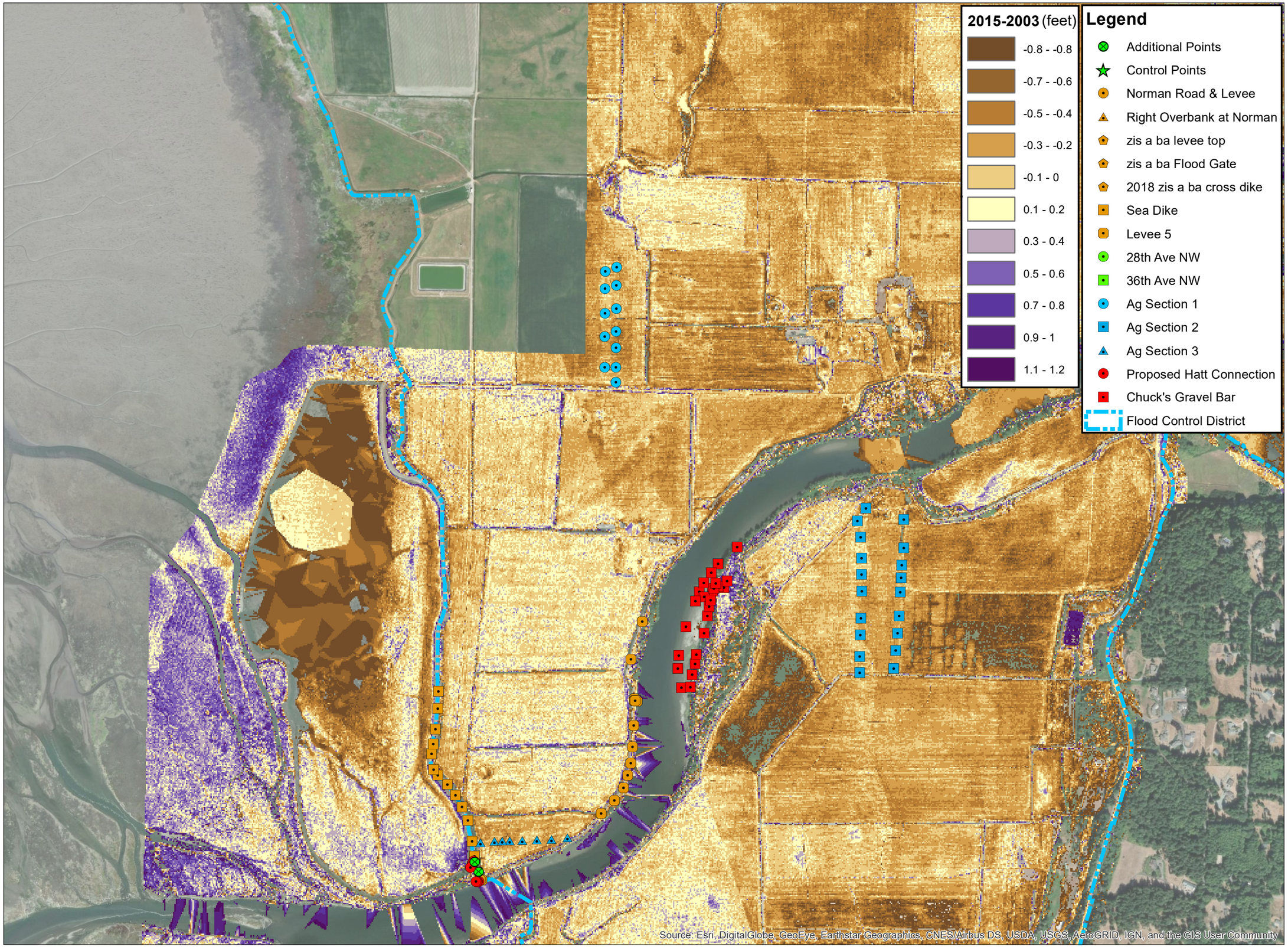
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Map Projection: NAD_1983_StatePlane_ Washington_North_FIPS_4601_FEET

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Subsidence & Aggradation Study

Stanwood
Snohomish County, WA

2018 Survey Point Locations: 2015 LiDAR - 2003 LiDAR Difference DEM

08/31/2017 Aerial Background

0 270 540 810 1,080 1,350 Feet
0 90 180 270 360 Meters

Prepared By Cardno
Date: 03/14/2019
Imagery Source: See Image

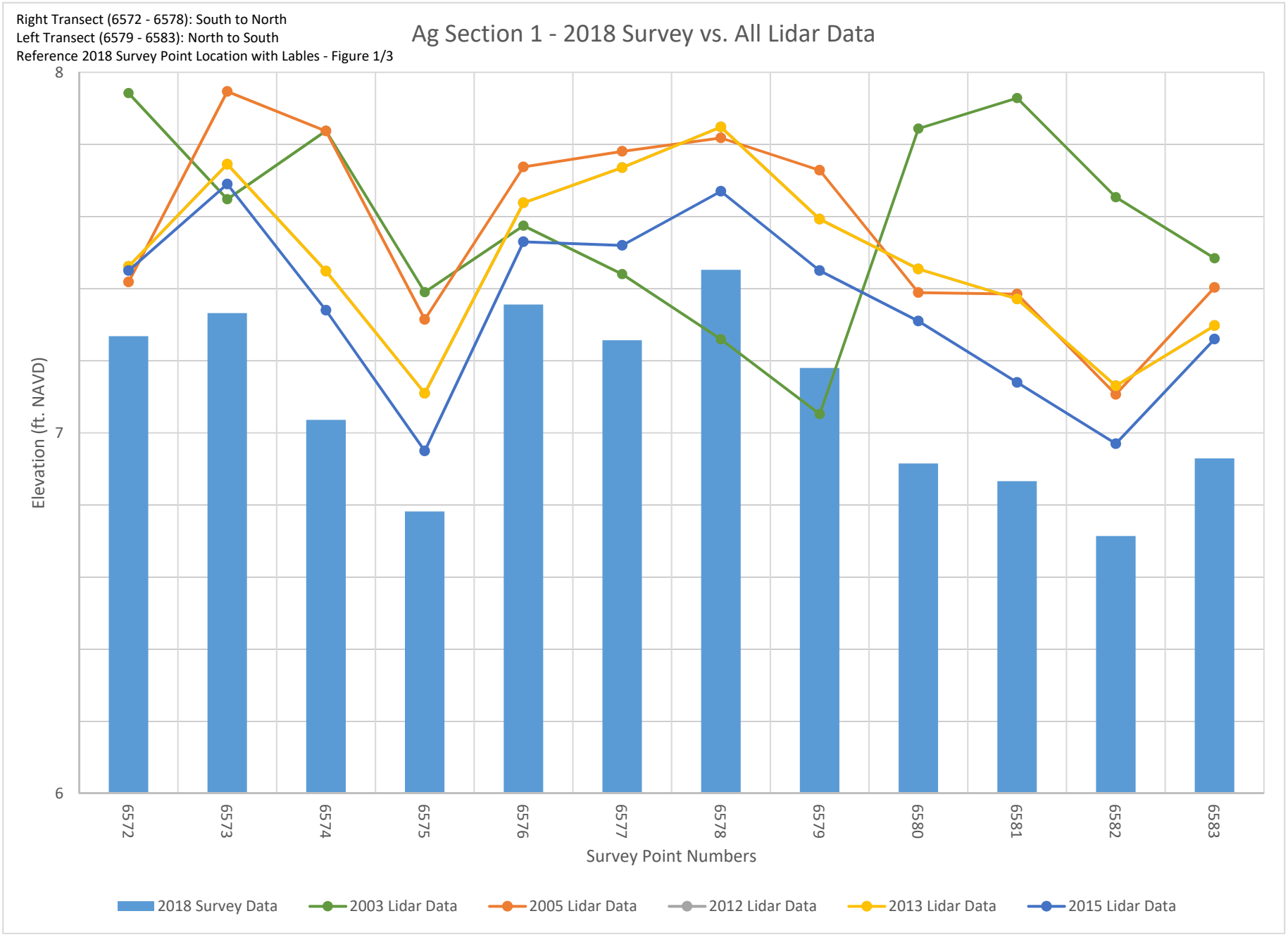
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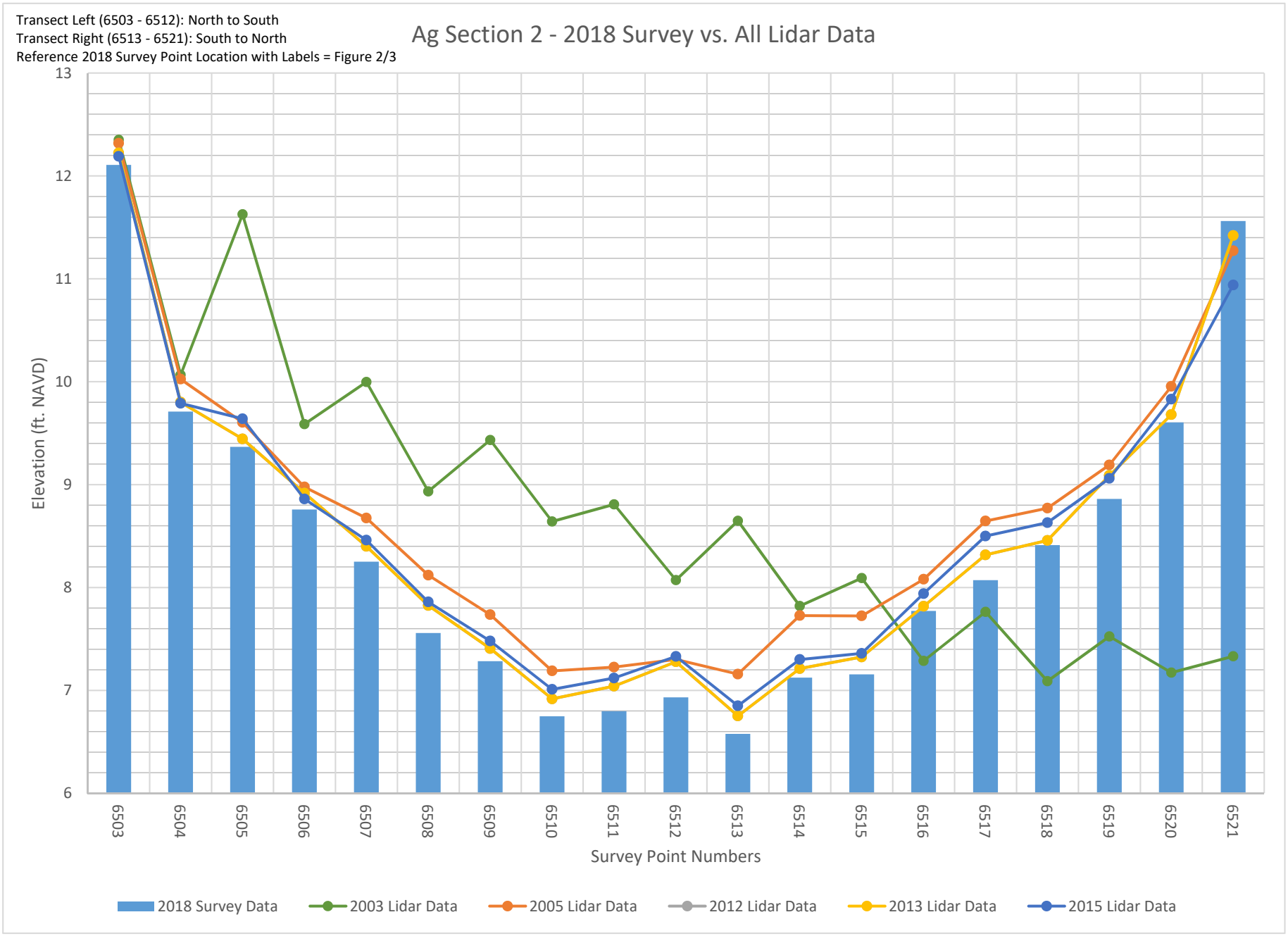
Map Projection: NAD_1983_StatePlane_Washington_North_FIPS_4601_FEET

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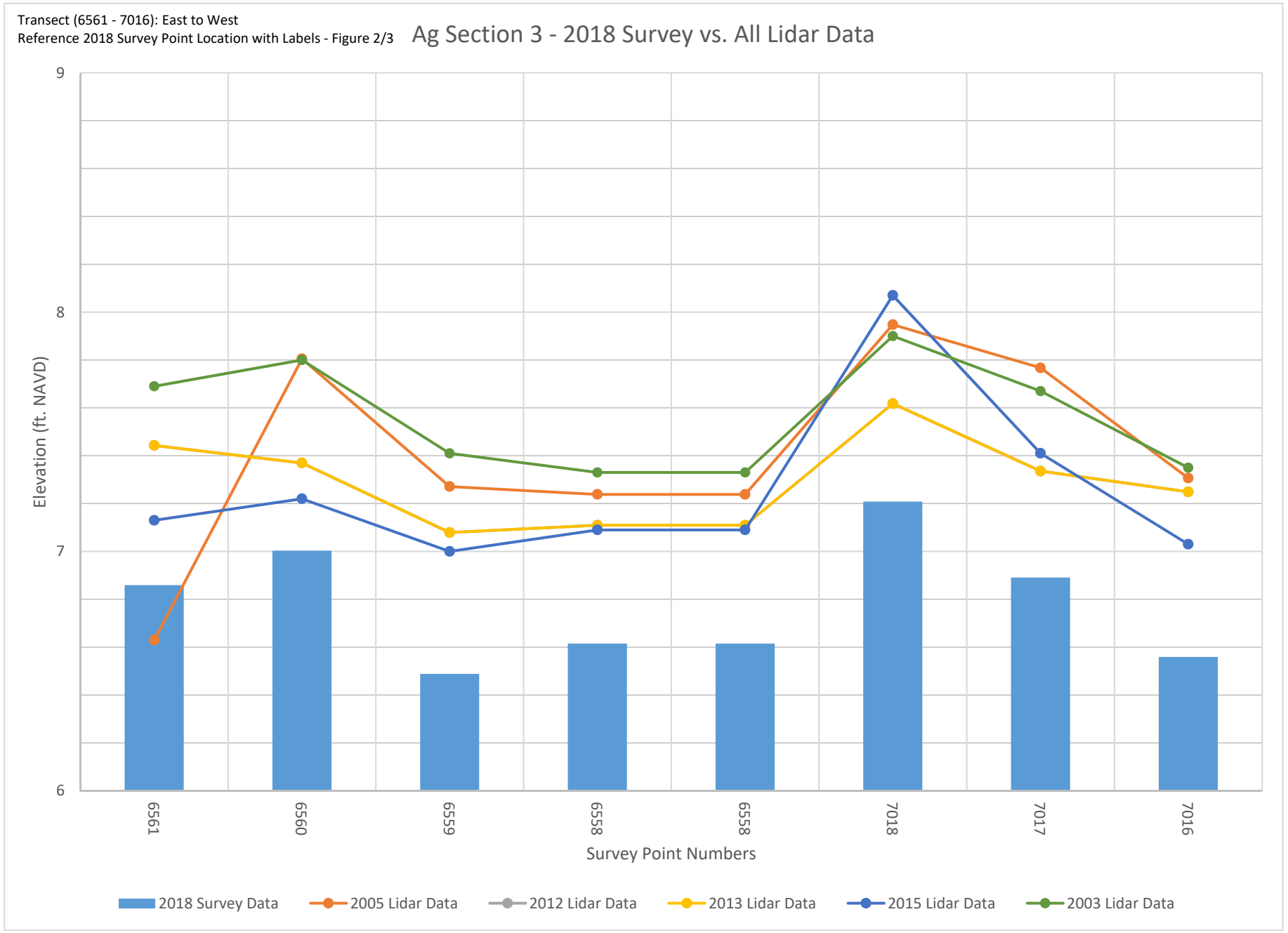
Right Transect (6572 - 6578): South to North
Left Transect (6579 - 6583): North to South
Reference 2018 Survey Point Location with Lables - Figure 1/3



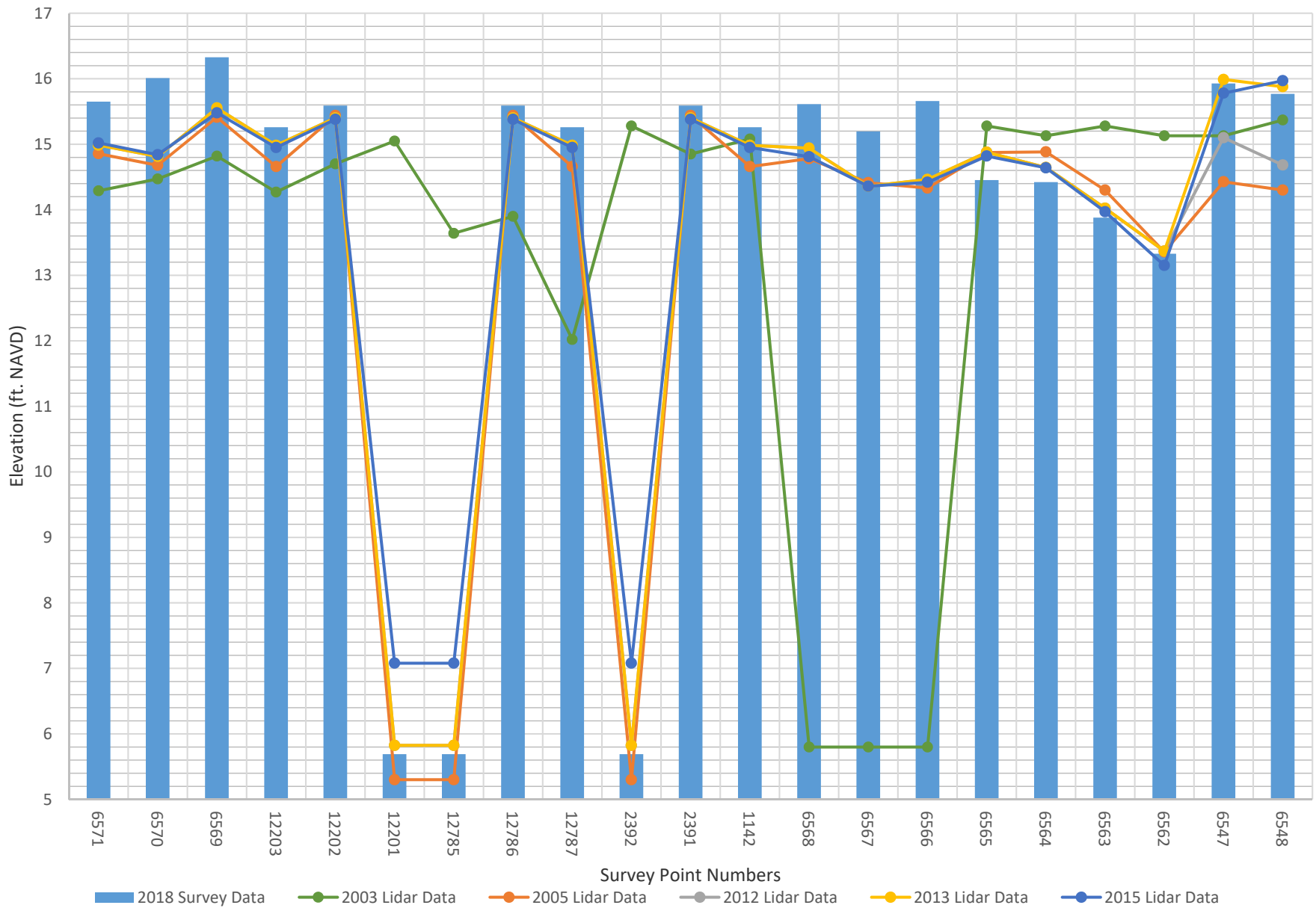
Transect Left (6503 - 6512): North to South
Transect Right (6513 - 6521): South to North
Reference 2018 Survey Point Location with Labels = Figure 2/3



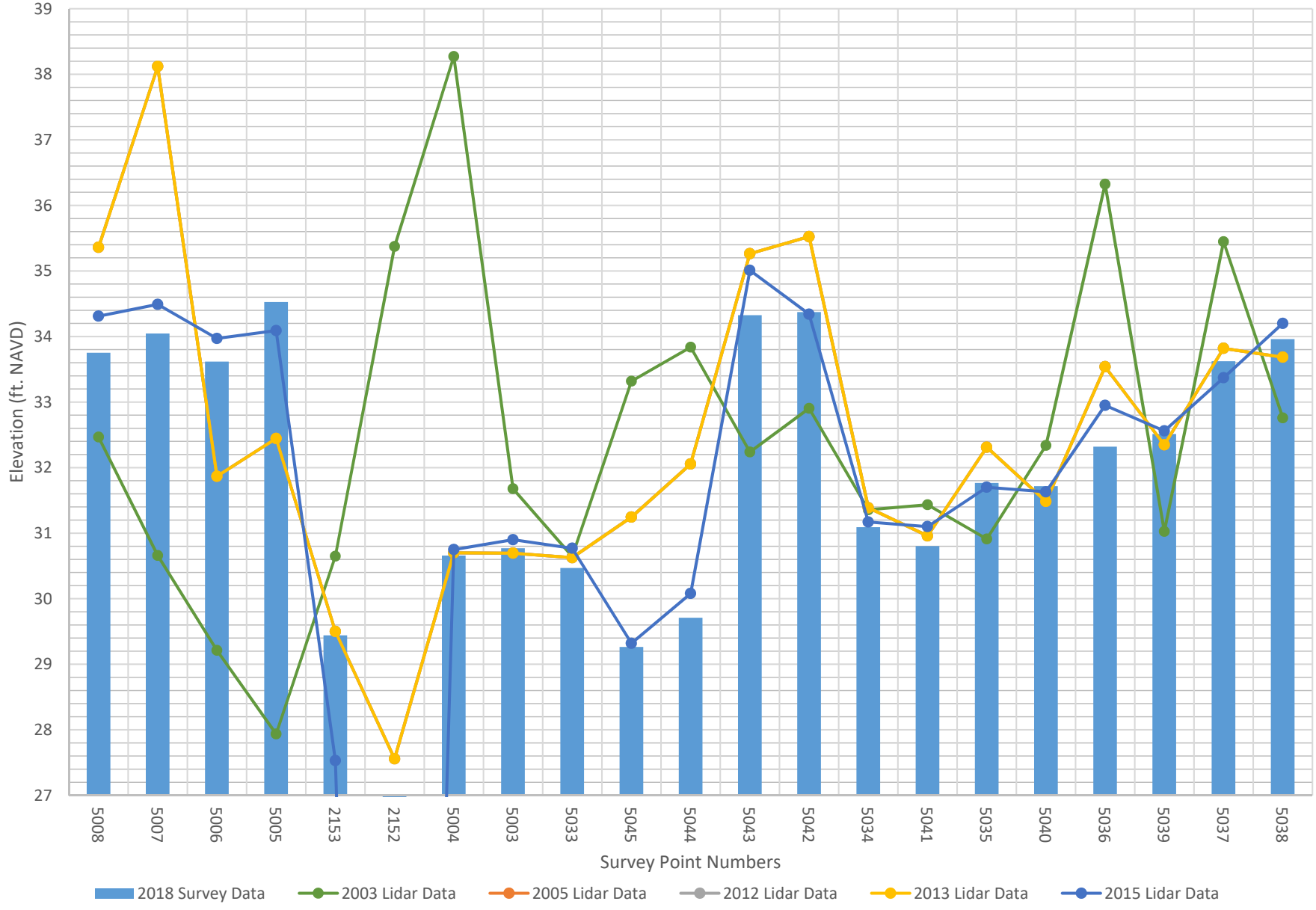
Transect (6561 - 7016): East to West
Reference 2018 Survey Point Location with Labels - Figure 2/3



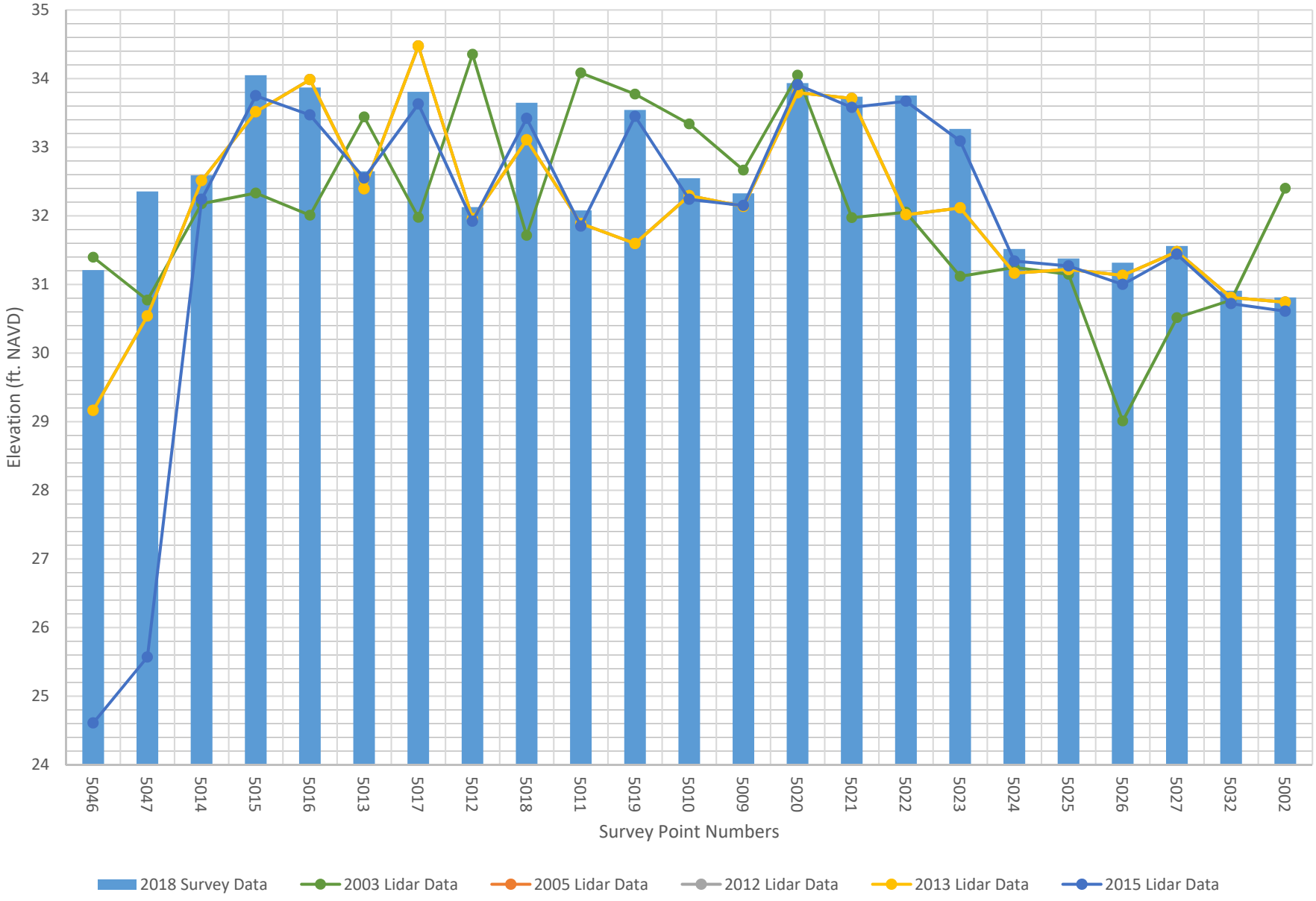
Transect (6571 - 6548): North to South
Reference 2018 Survey Point Locations with Labels - Figure 2/3



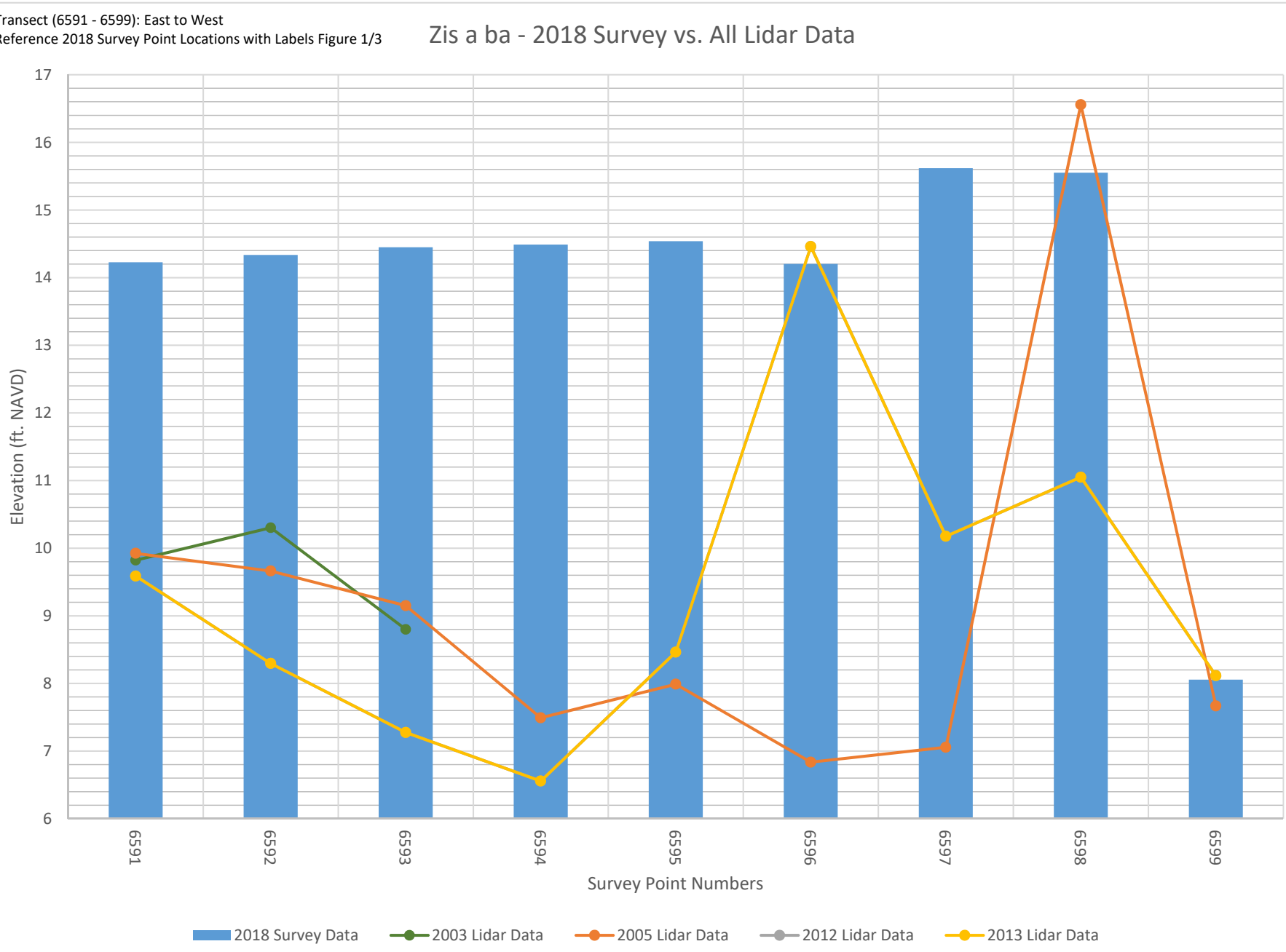
Transect (5008 - 5038): Northwest to Southeast
Reference 2018 Survey Point Locations with Labels
- Figure 3/3



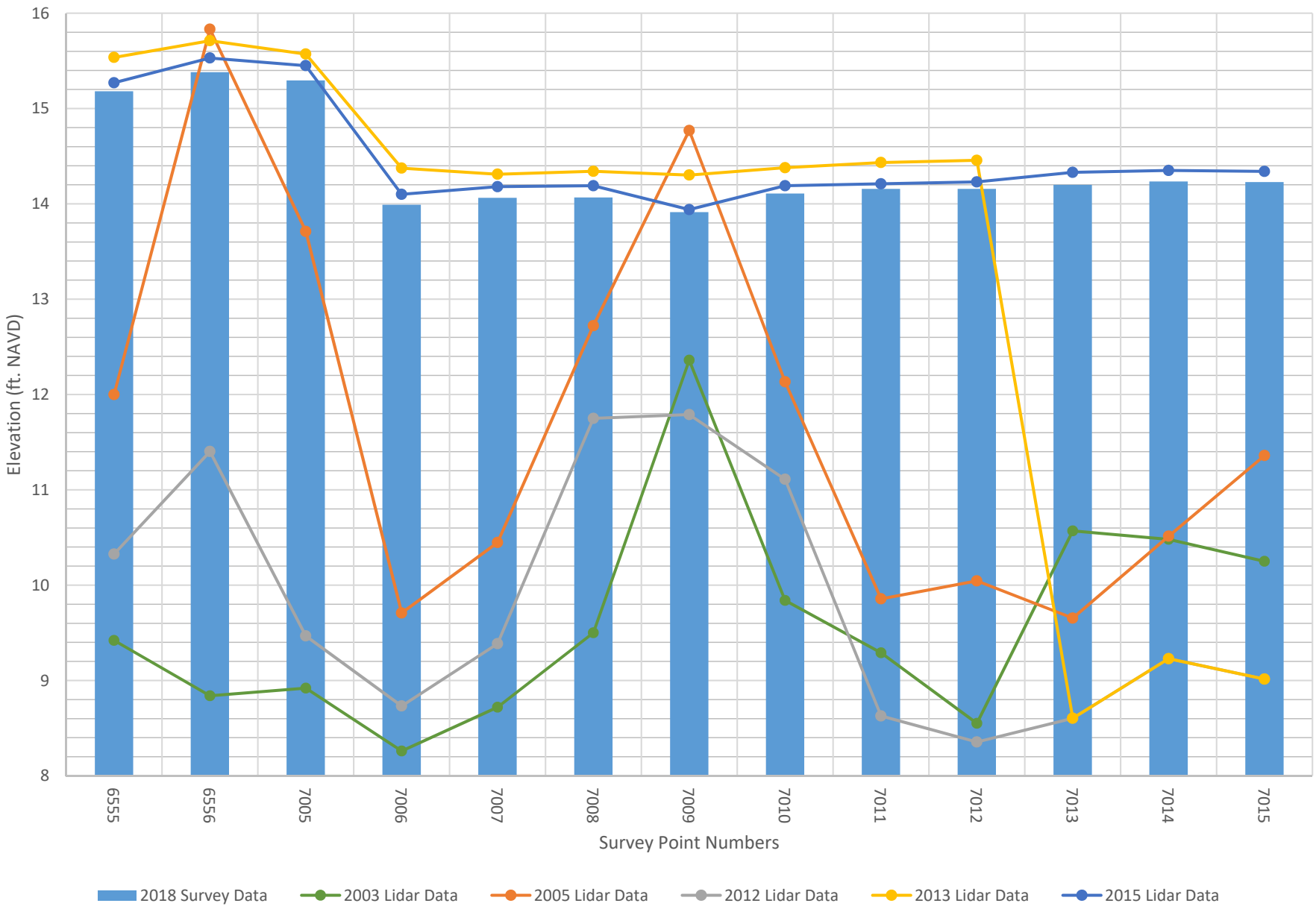
Transect (5046 - 5002): West to East
Reference 2018 Survey Point Location with Labels
- Figure 3/3



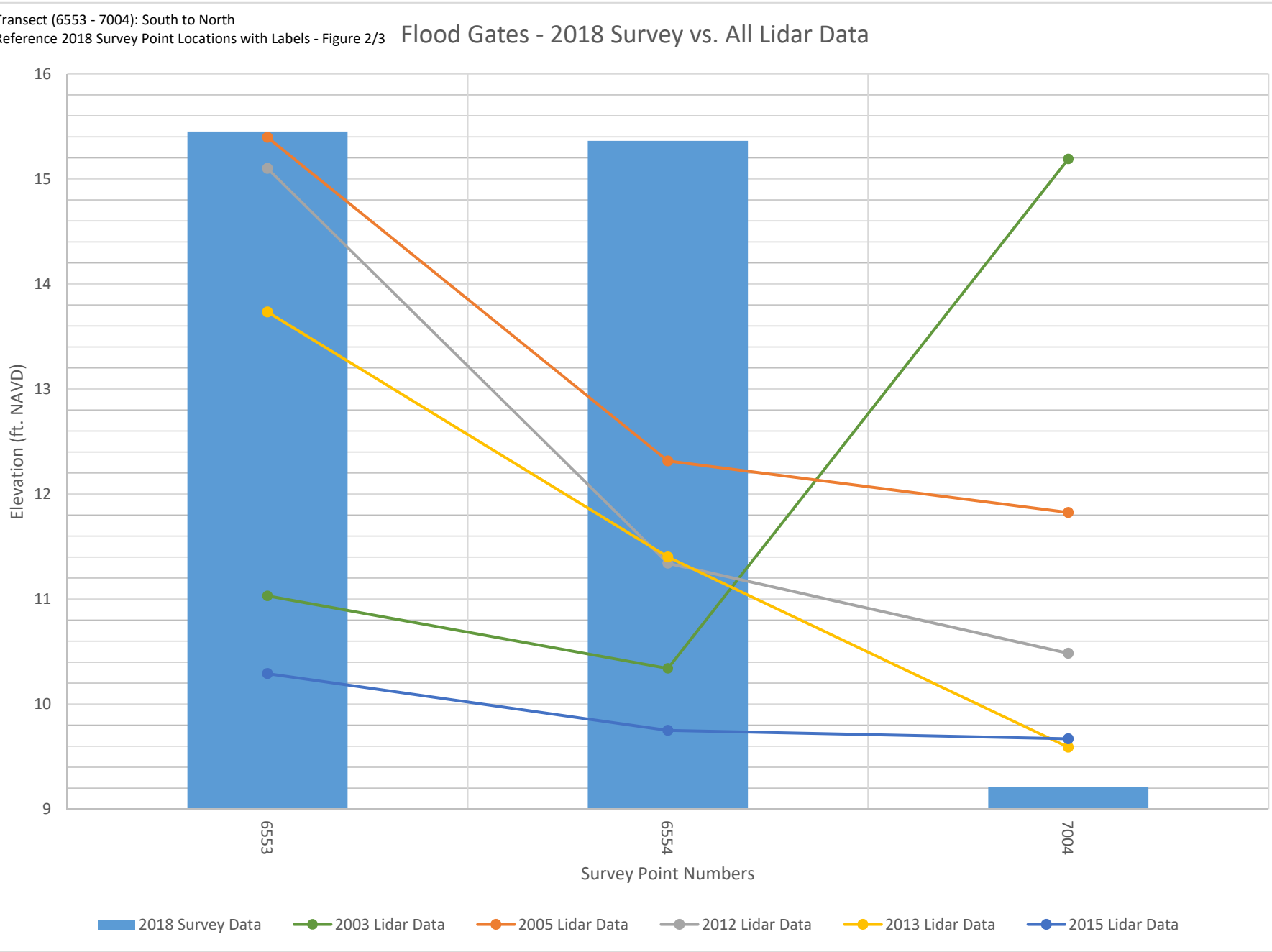
Transect (6591 - 6599): East to West
Reference 2018 Survey Point Locations with Labels Figure 1/3



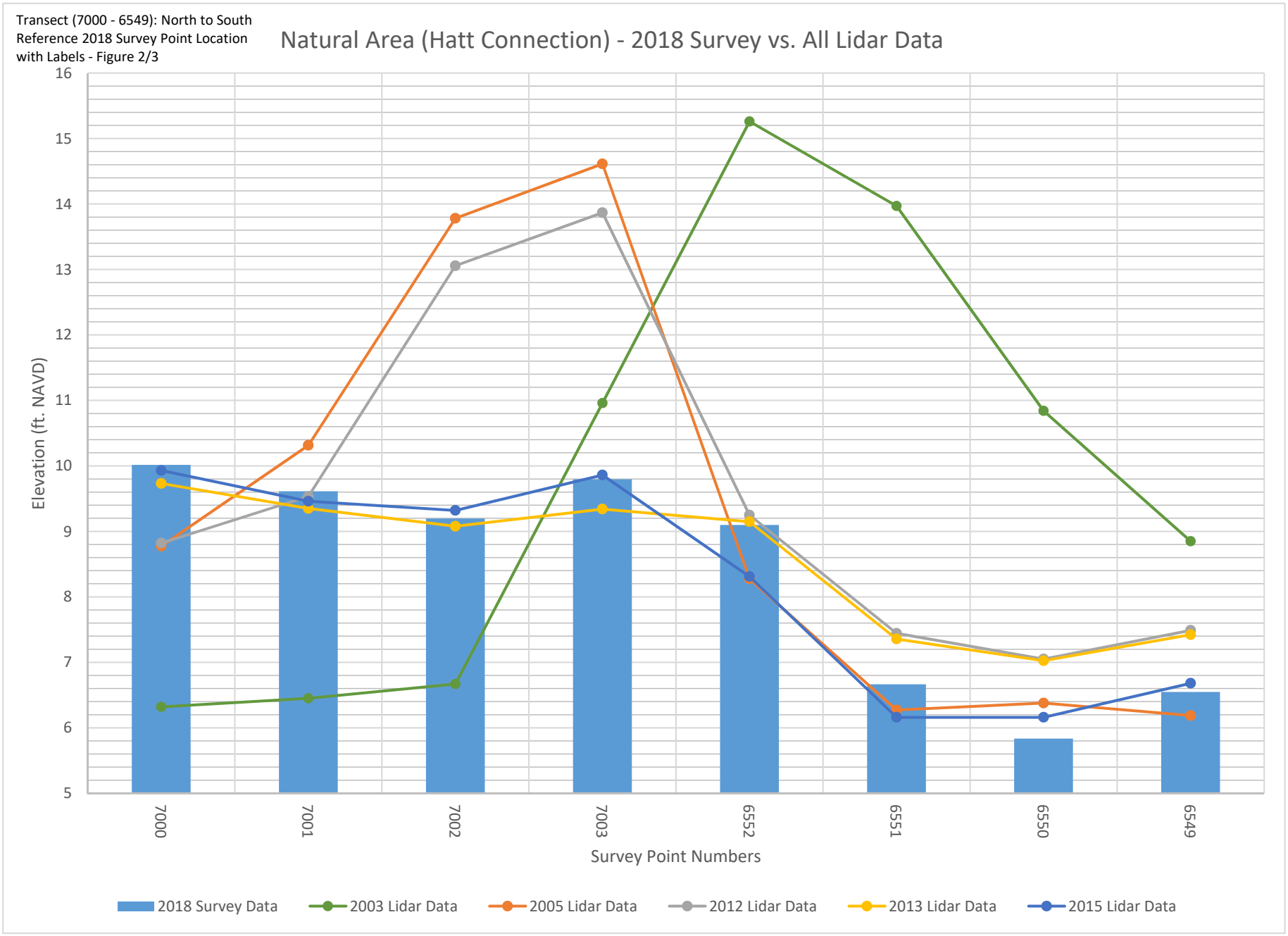
Transect (6555 - 7015): South to North
Reference 2018 Survey Point Locations with Labels - Figure 2/3



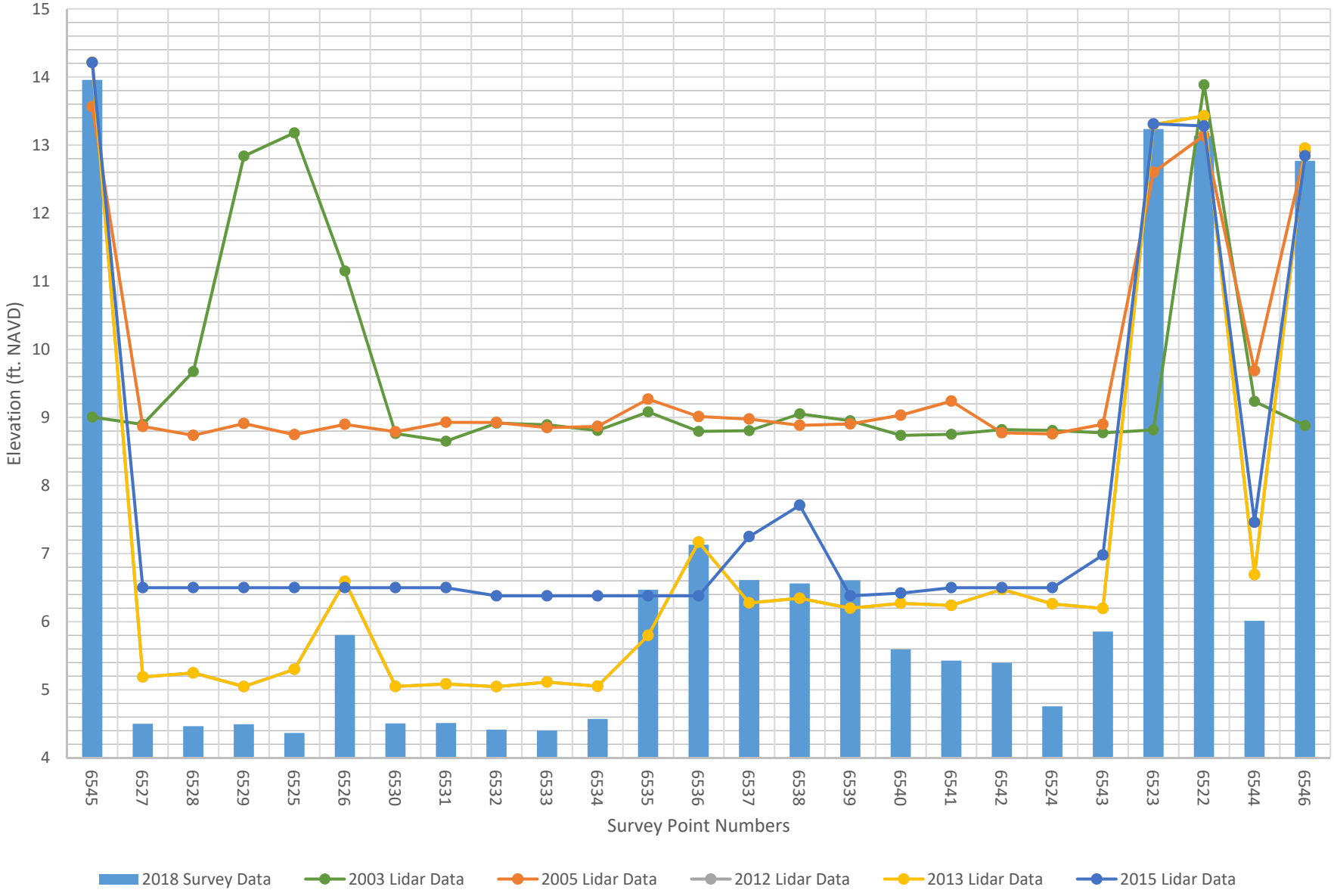
Transect (6553 - 7004): South to North
Reference 2018 Survey Point Locations with Labels - Figure 2/3



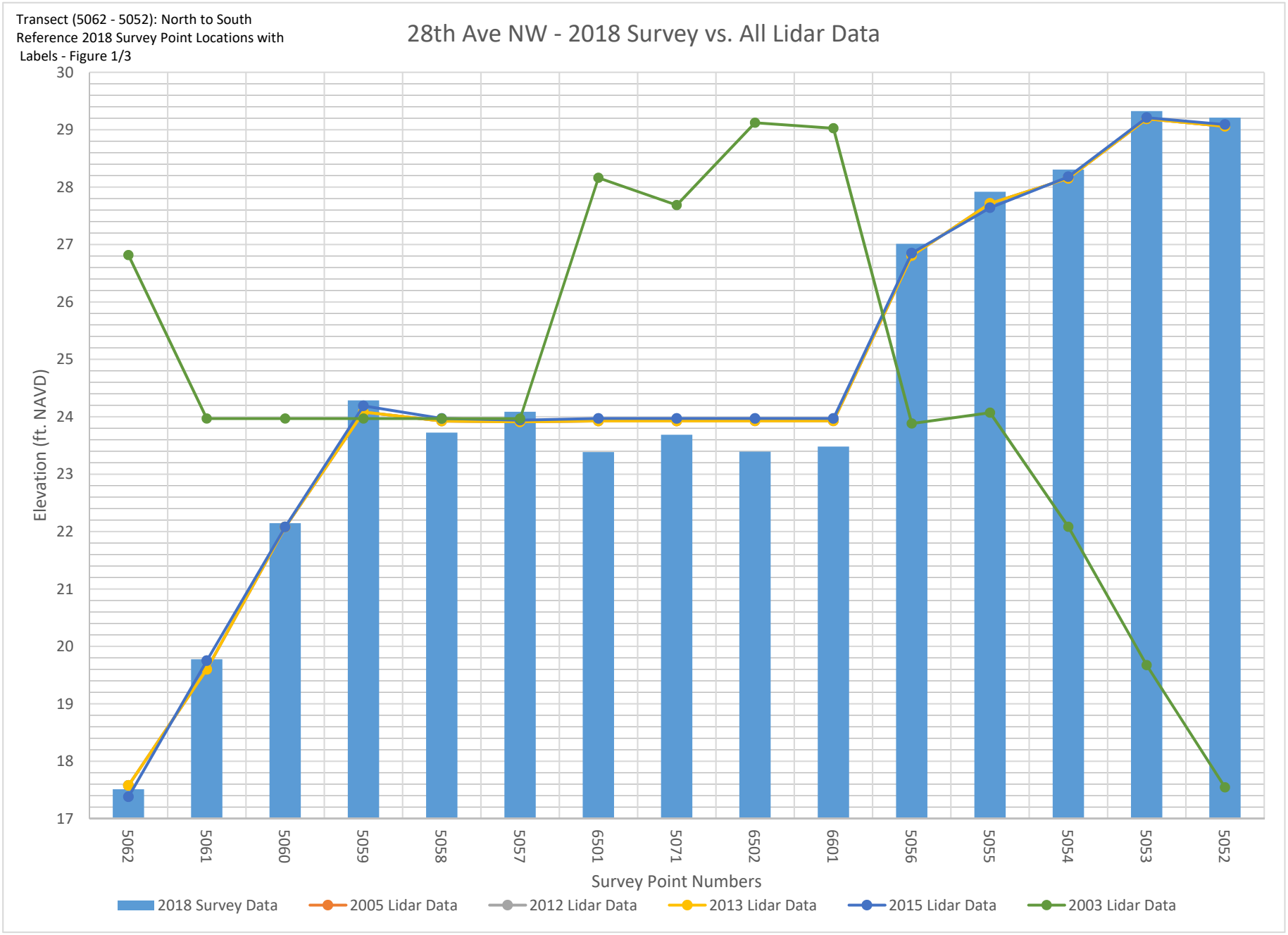
Transect (7000 - 6549): North to South
Reference 2018 Survey Point Location
with Labels - Figure 2/3



Left Transect (6545 - 6534): North to South
Right Transect (6535 - 6546): South to North
Reference 2018 Survey Point Location with Labels - Figure 2/3



Transect (5062 - 5052): North to South
Reference 2018 Survey Point Locations with Labels - Figure 1/3



Transect (5063 - 5067): North to South
Reference 2018 Survey Point Locations with Labels - Figure 1/3

