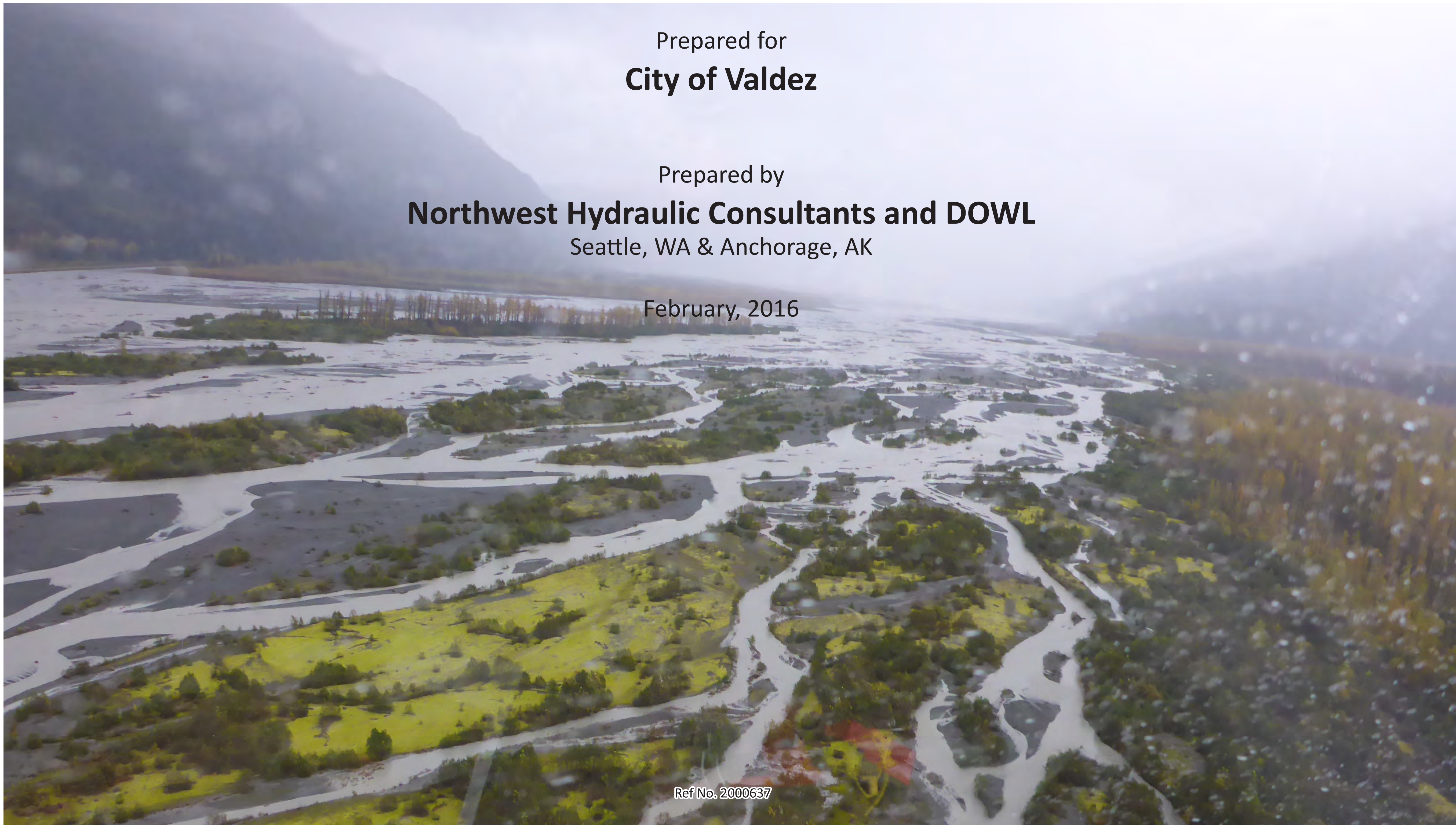
DRAFT Lowe River Geomorphic Atlas and Sediment Budget



Prepared for

City of Valdez

Prepared by

Northwest Hydraulic Consultants and DOWL

Seattle, WA & Anchorage, AK

February, 2016

Ref No. 2000637

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Introduction

The City of Valdez has contracted DOWL with subconsultant Northwest Hydraulic Consultants (NHC) to evaluate the feasibility of utilizing gravel extraction to manage flood and channel migration hazards on and along the lower Lowe River, below Keystone Canyon (the study reach). As a part of Phase 1 of this study, NHC and DOWL staff spent three days evaluating conditions along the Lowe River. We collected photographs, field notes, and sediment samples along the river and on two principal tributaries. The following atlas combines these field observations and geospatial data to present an overview of key geomorphic features and processes operating along the Lowe River.

The atlas starts with a brief summary of basin characteristics and hydrology, focuses on descriptions of individual, approximately 1.5-mile long, river segments shown on the map below, and concludes with summary data describing patterns along the river. These data provide the basis for a sediment budget presented at the end of the document.

Data Sources

This atlas combines field observations and geographic data from a variety of sources:

Geospatial Data

- Landsat Satellite Imagery covering the period 1972-2015 were identified utilizing USGSs LandsatLook viewer http://landsatlook.usgs.gov/viewer.html.
- Historical Aerial photos were provided by the City of Valdez and downloaded from the USGSs archive http://earthexplorer.usgs.gov/.
- 2013 LiDAR topography used to create the floodplain elevation map and for comparison with 2007 LiDAR was provided by the City or Valdez.
- A 2007 LiDAR LAS dataset was available from the USGS archive (Dataset AK_VALDEZB_2007). This was processed into a bare earth DEM by NHC.

Geographic Orientation

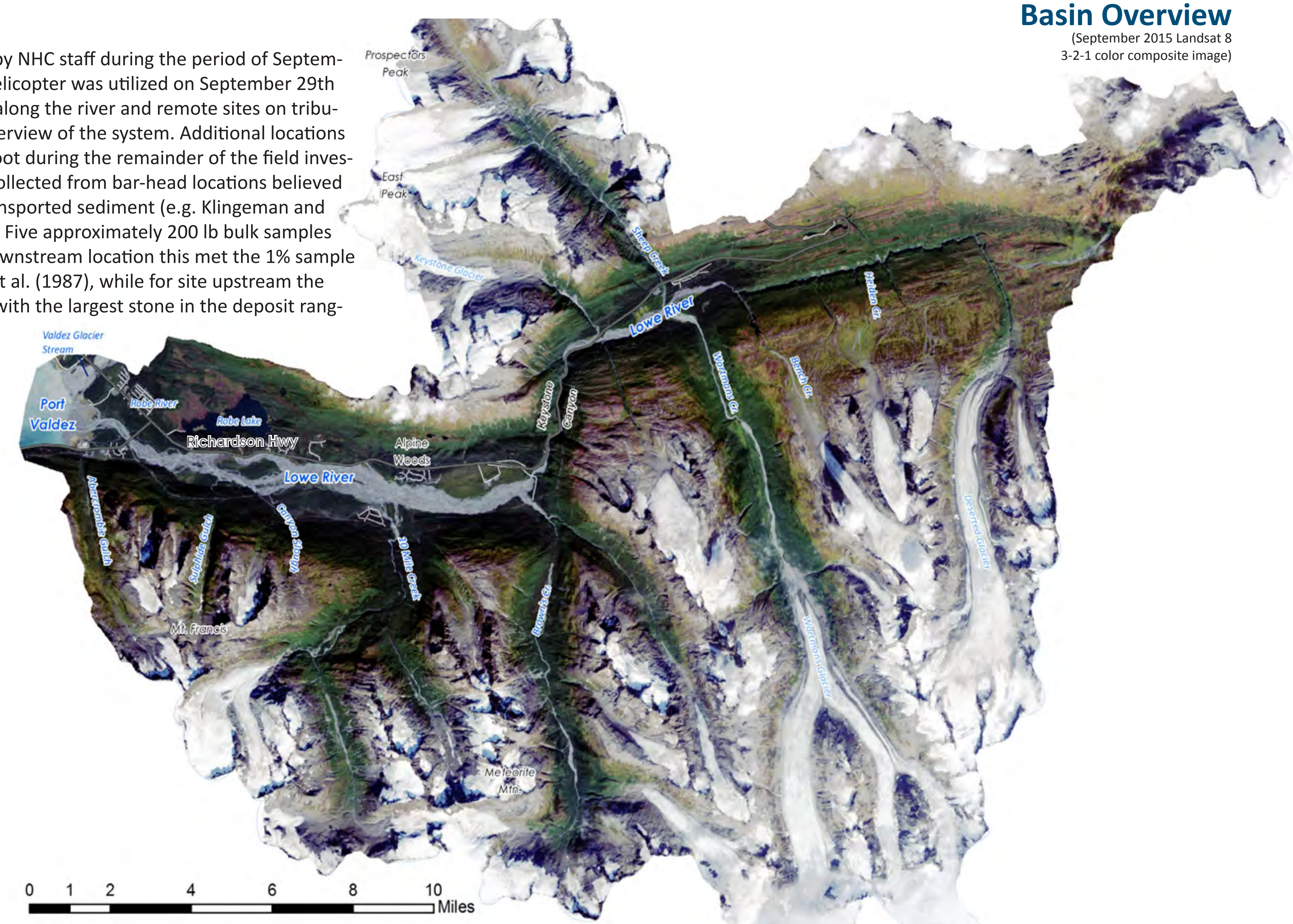
- Locations along the river are referenced in River Miles (RM), as shown on the maps. These are offset by about one mile from Richardson Highway Mileposts, as shown in the map below.
- The terms "left bank" and "right bank" are oriented from the perspective of a person looking downstream

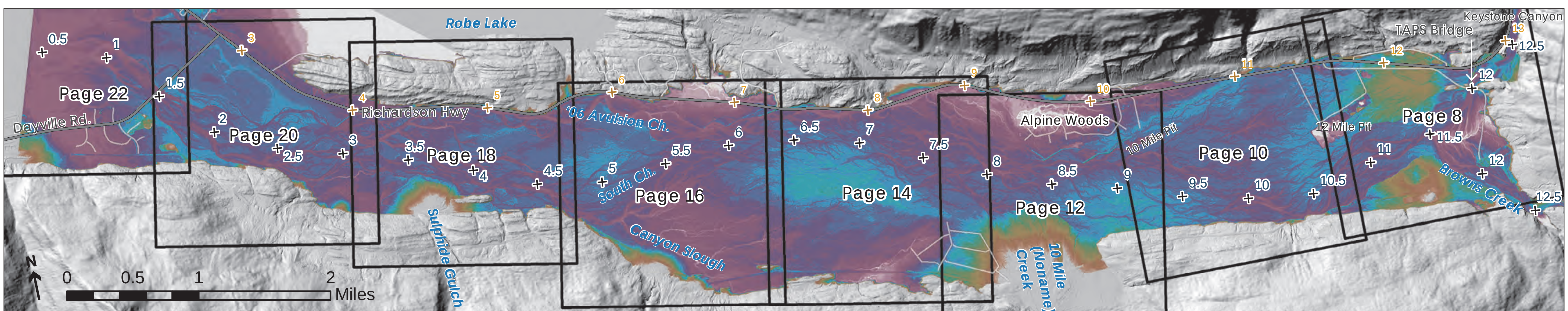
Field Data

Field observations were collected by NHC staff during the period of September 29th through October 1st. A helicopter was utilized on September 29th to access mid-channel gravel bars along the river and remote sites on tributaries and to provide a synoptic overview of the system. Additional locations were accessed by vehicle and on foot during the remainder of the field investigation. Sediment samples were collected from bar-head locations believed to be representative of actively transported sediment (e.g. Klingeman and Emmett, 1982; Parker et al., 1982). Five approximately 200 lb bulk samples were collected. For the furthest downstream location this met the 1% sample criteria recommended by Church et al. (1987), while for site upstream the samples were slightly undersized, with the largest stone in the deposit ranging from 2 to 5% of the sample weight. Bulk samples were paired with 100-stone grid-by-number Wolman (1954) pebble counts, collected with a gravelometer. Additionally, numerous scaled bed images were collected to increase the density of observations possible to collect during a brief field visit.

Basin Overview

(September 2015 Landsat 8 3-2-1 color composite image)





Physiography

The Lowe River drains approximately 350 mi^2 of the Chugach Mountains in Southcentral Alaska. The basin is rugged, and heavily glaciated. Elevations range from sea level to approximately 7,200 ft, well above treeline (~2,500 ft). The mean slope is approximately 22 ± 15° (±1 σ). Analysis of September 1987 and 2015 Landsat imagery suggests that glacial cover of the basin has decreased from approximately 41% to 33% of the total basin area over the intervening time. The cold climate, rugged terrain, and ongoing retreat of glaciers are all factors that will promote high clastic sediment yield.

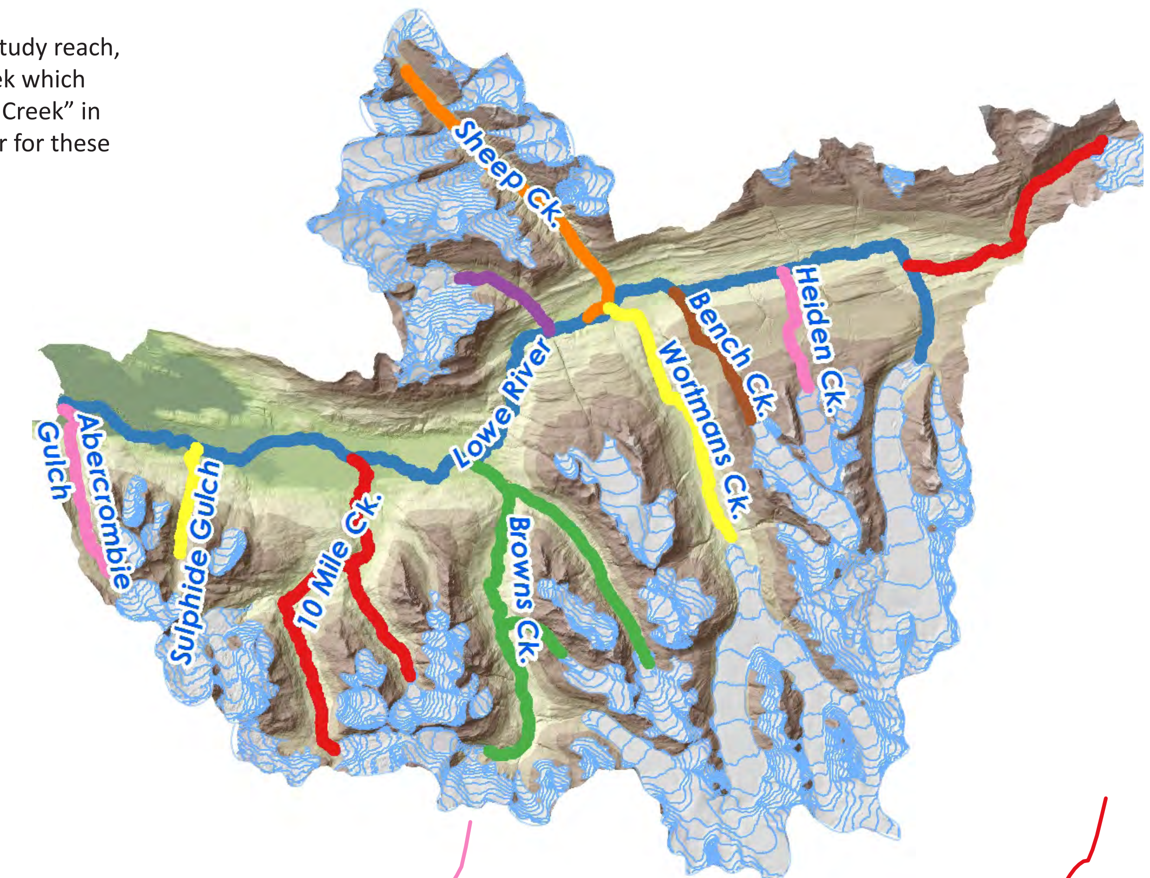
In contrast, the basins geology will promote relatively high suspended sediment yield. Soft metamorphic rocks of the Valdez Group underlie the entire basin. These are mostly dark gray strongly foliated phillitic grawacke with numerous quartz veins. Alignment of muscovite, chlorite, and graphite minerals within the rocks results in strong schistosity (a tendency to break along parallel planes), which results in relatively weak and easily broken down alluvial clasts with a very platy character.

Subbasins

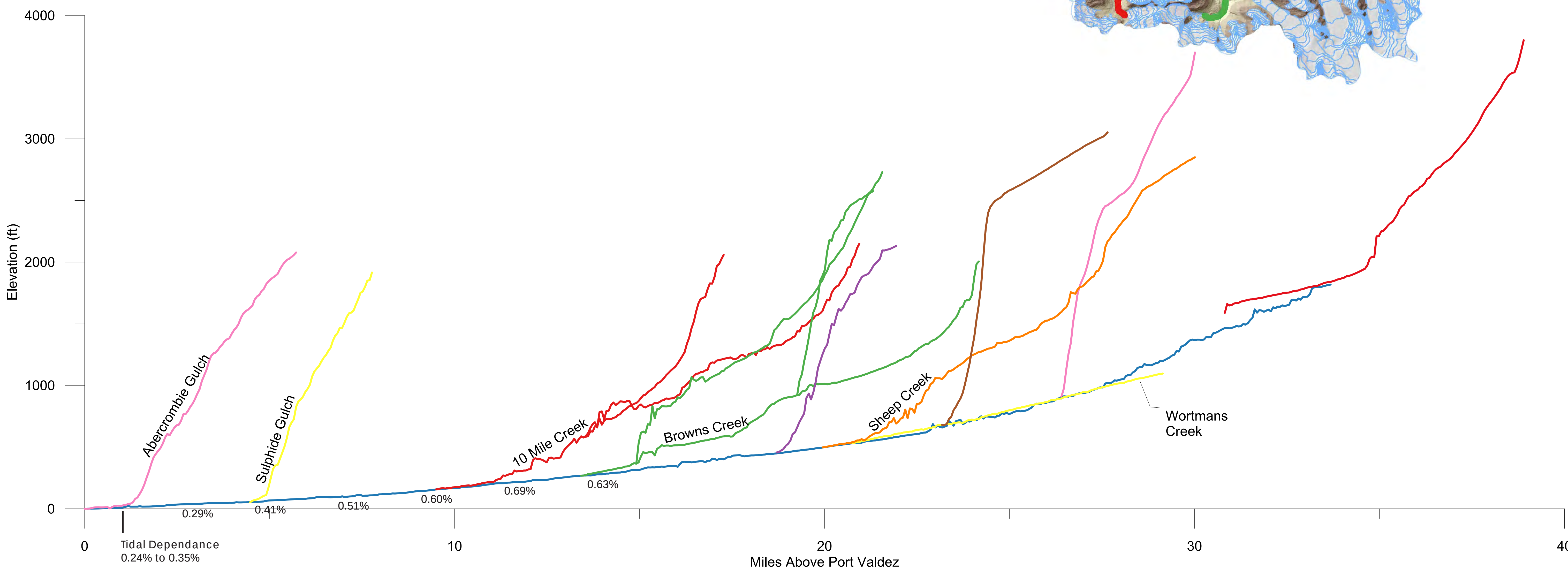
There are three principal subbasins contributing water and sediment to the study reach, the Lowe River above Keystone Canyon, Browns Creek, and an unnamed creek which joins the river near the 10 mile community. This creek will be called “10 Mile Creek” in the remainder of this document. Areas and approximate percent glacial cover for these subbasins and the whole Lowe River basin are shown in Table 1.

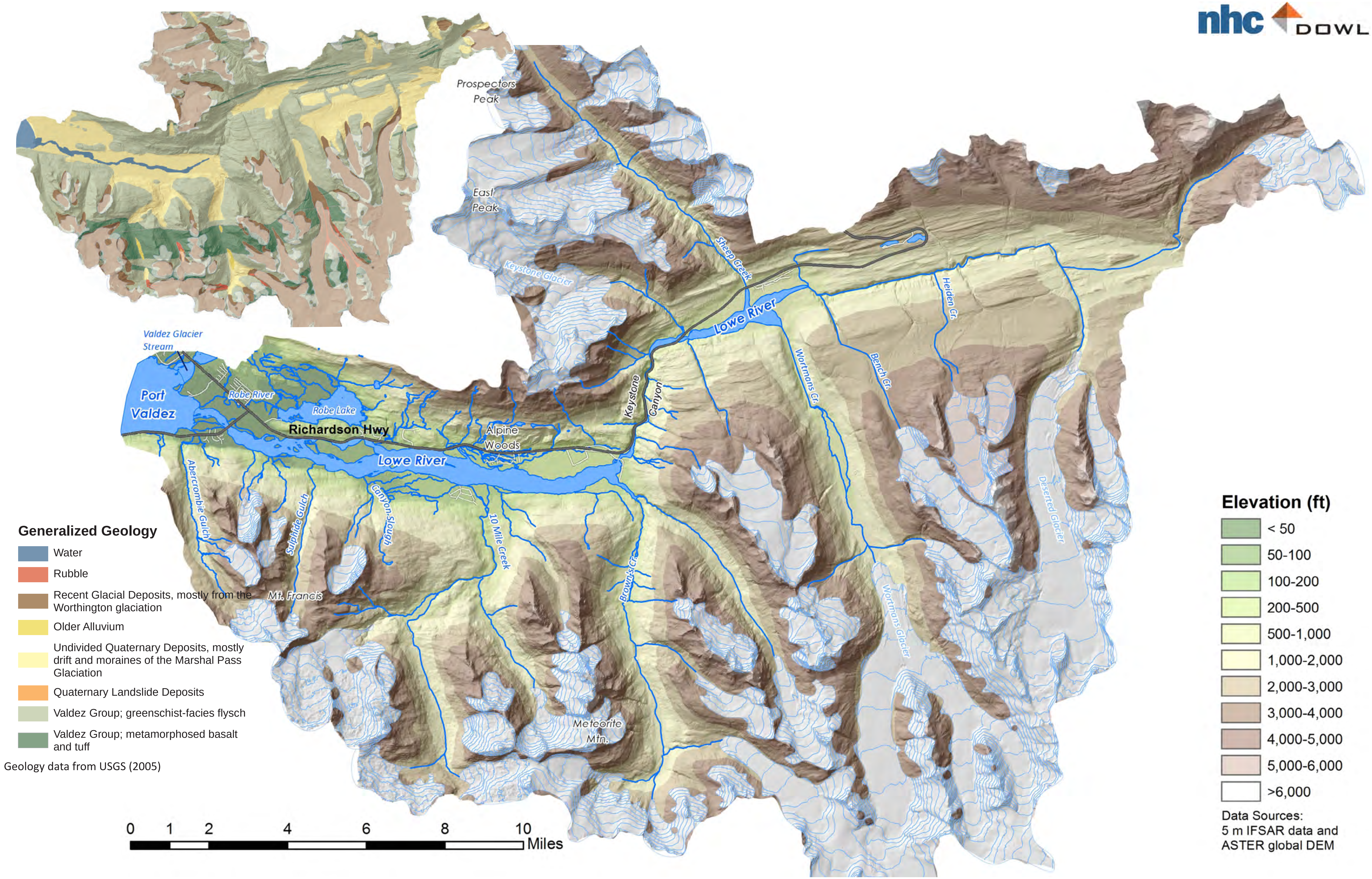
Table 1: Tributary and Glaciated Areas of the Lowe River Watershed

	Keystone Canyon	Browns	10 Mile	Other Tributaries	At Mouth into Port Valdez
Tributary Area (mi^2)	216	52	38	46	352
% of watershed	61%	15%	11%	13%	100%
Glaciated area (mi^2)	91	18	16	1.4	127



Stream Profiles





Prospectors Peak
East Peak
Keystone Glacier
Sheep Creek
Lowe River
Heiden Cr.
Bench Cr.
Wortmans Cr.
Valdez Glacier Stream
Port Valdez
Robe River
Robe Lake
Richardson Hwy
Alpine Woods
Keystone
Canyon
Lowe River
Abercrombie Gulch
Sulphide Gulch
Canyon Slough
10 Mile Creek
Brown's Cr.
Mt. Francis
Meteorite Mtn.
Wortmans Glacier
Deserted Glacier
Generalized Geology
Water
Rubble
Recent Glacial Deposits, mostly from the Worthington glaciation
Older Alluvium
Undivided Quaternary Deposits, mostly drift and moraines of the Marshal Pass Glaciation
Quaternary Landslide Deposits
Valdez Group; greenschist-facies flysch
Valdez Group; metamorphosed basalt and tuff
Geology data from USGS (2005)
0 1 2 4 6 8 10 Miles
Elevation (ft)
< 50
50-100
100-200
200-500
500-1,000
1,000-2,000
2,000-3,000
3,000-4,000
4,000-5,000
5,000-6,000
>6,000
Data Sources:
5 m IFSAR data and
ASTER global DEM

Hydrology*

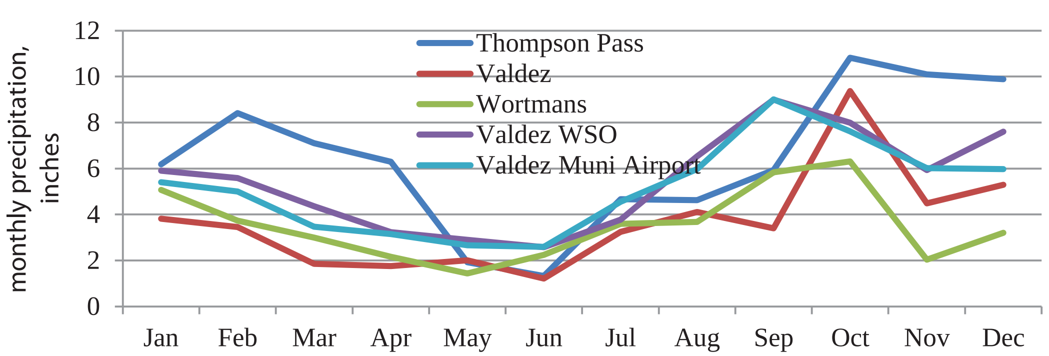
Precipitation and Melt Patterns

Daily precipitation data are available for two stations near the Lowe River, two stations in the Lowe River drainage, and one near the headwaters at Thompson Pass, with elevations ranging from 60 to 2,500 ft.

Although orographic effects are expected to produce higher precipitation at higher elevations, as suggested by the data from the Thompson Pass station, data from two stations at intermediate elevations indicate lower annual precipitation than at the two lowest stations.

The Lowe River is generally in the transitional climate zones. Seasonal patterns of precipitation are shown below. Precipitation from November through March generally occurs as snow, with the period lengthening at higher altitudes. This leads to low runoff throughout the winter, with rising flows during the snow melt season (June and July). Peak flows associated with peak precipitation as rainfall occur in the late summer. September and October are the peak precipitation months at higher elevations (Thompson Pass). At lower elevations, the peak rainfall occurs in August, but this does not coincide with peak runoff.

Although the season of peak runoff historically occurs June through August, corresponding to snowmelt and midsummer rainfall and glacier melt, peak flood events appear to correspond to fall rainfall. The 24-hour precipitation at the Valdez Weather Service Office gage preceding the peak flow of record (42,000 in October 2006) was 4.8 inches, the second highest 24-hour precipitation depth of record at that gage. The highest 24-hour precipitation depth occurred in December 1959, likely as snowfall.



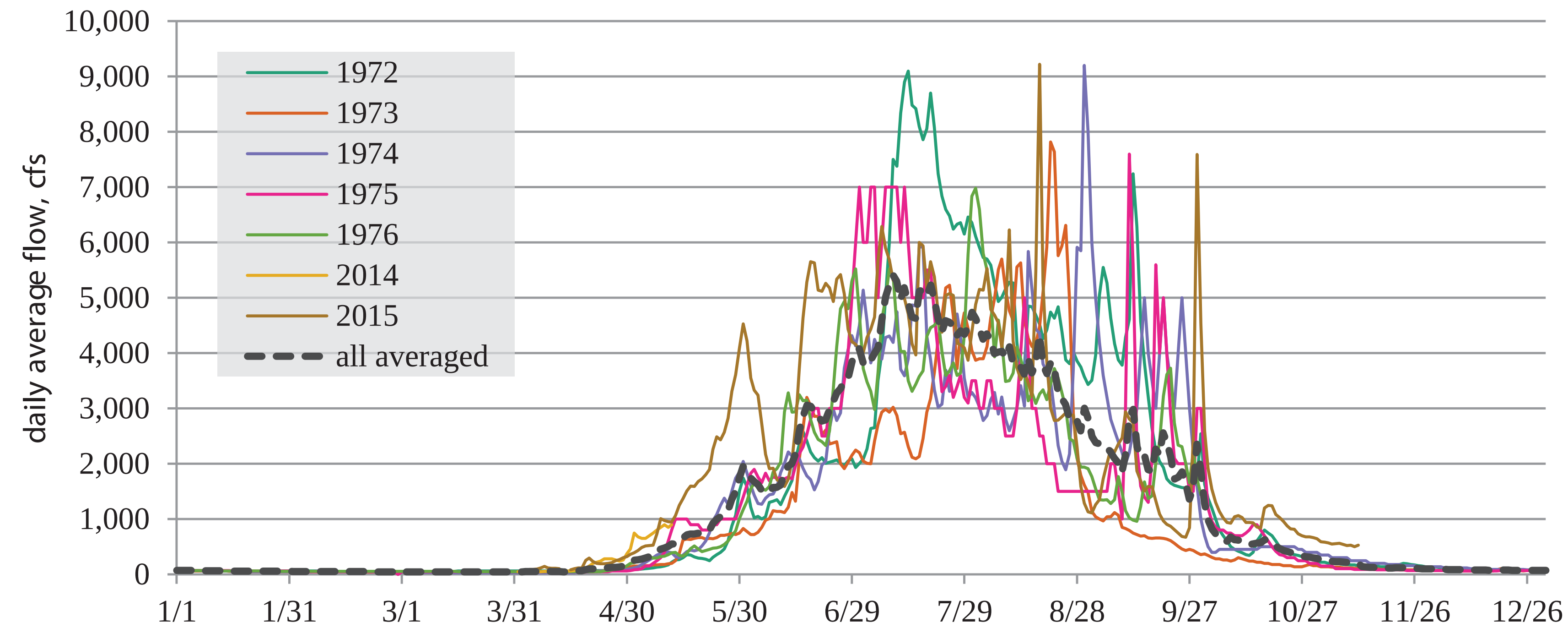
Streamflow

Streamflow has been gaged at several sites in Keystone Canyon, representing runoff from about 61% of the watershed. Published data is available for the stream gages listed in Table 2. Records from United States Geological Survey (USGS) sites 15226500 and 15226600 include five sequential water years (October through September) of data. Although the gage at USGS site 15226620 operated for two summers, the rating curve for 2014 has not been finalized, so only streamflow data for April 2014 and March 2015 through November 2015 are available at that gage.

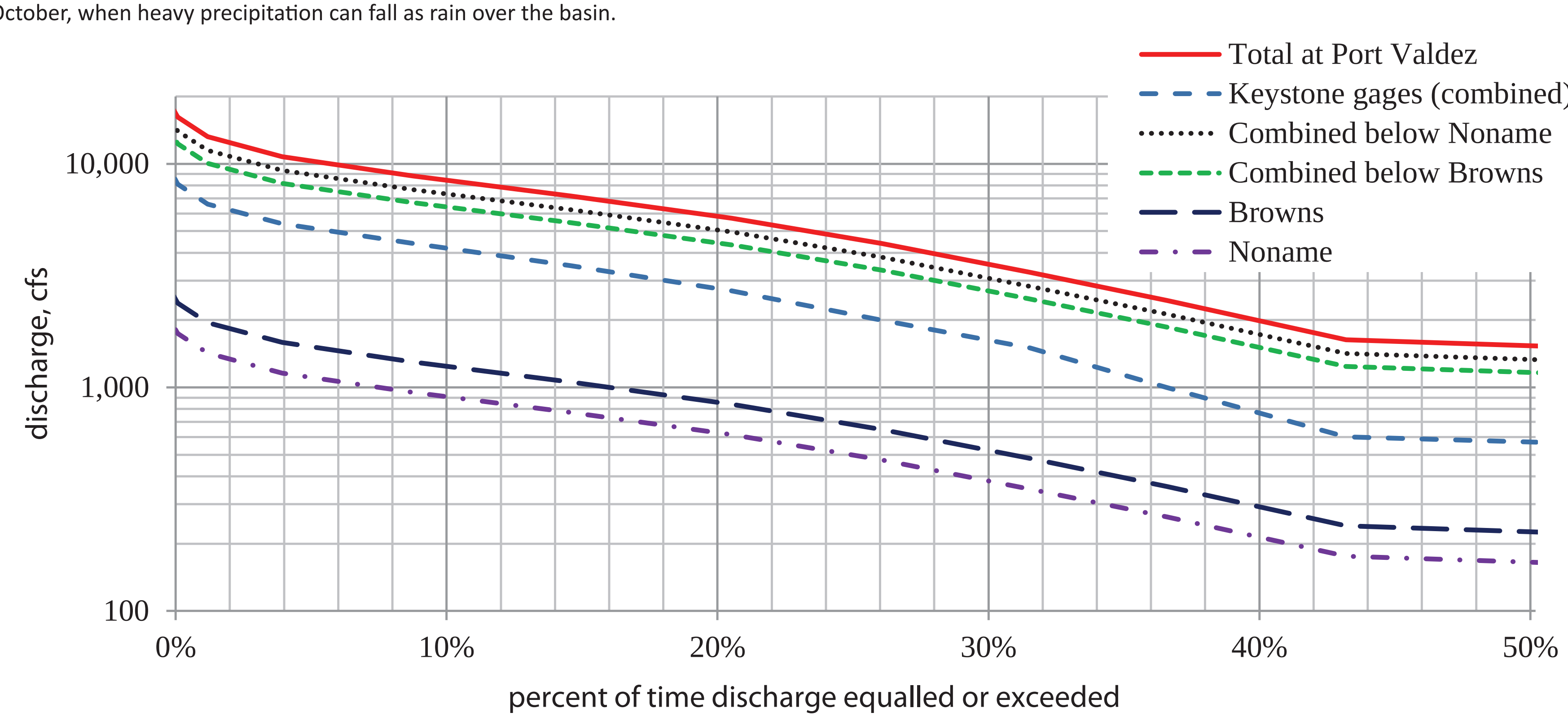
The average annual flow is 917,000 acre-feet, or 1,200 cubic feet per second (cfs), based on the five full years of record (at sites 15226500 and 15226600). This is equivalent to 81 inches of runoff from the watershed above the Keystone Canyon gage.

Table 2: Lowe River Streamgage Data Coverage

USGS Gage No.	Location	Gage Datum*	Area (mi²)	Start Date	End Date
15226500	Lowe R. near Valdez Ak	450	2047	8/1/1971	9/30/1974
15226600	Lowe R. in Keystone Canyon near Valdez	450	211	10/1/1974	6/30/1976
15226620	Lowe R. above Horsetail Falls near Valdez	270	215	4/1/2014	3/2/2015



Lowe River streamflow exhibits a strong seasonal variation as shown above. Winter flows are extremely low, and most (Over 70%) of the annual flow occurs during freshet flows from June through August. Freshet flows are typically between 2,000 and 7,000 cfs, but annual flood peaks tend to occur during the period from late August through early October, when heavy precipitation can fall as rain over the basin.



This flow duration curve shows the cumulative frequency of occurrence of average daily flows at several locations, as a percent of all flows. Although the long-term daily average flow is 1,200 cfs, the median, or 50 percent exceedence flow, is only 321 cfs. The 1 percent exceedence flow is 9,100 cfs. The flow duration curves were extrapolated from the gaged streamflows at Keystone Canyon to Browns and Noname creek tributaries and to the Lowe River below Browns, Lowe River below Noname, and Lowe River at Port Valdez based on cumulative tributary area to each flow point. This approach may underestimate the peak flows on Browns and Noname creek and overestimate them on the mainstem Lowe River. This is because the larger the basin is, the more dampening or attenuation of peak flows there is or that peaks are not all occurring simultaneously at similar magnitudes throughout the watershed. Since there is little data from other similarly situated watersheds, trying to create scaling factors to reflect this may introduce even greater errors than the straight pro-rating method. However, it is an aspect to be aware of.

* This and the following section summarize material reported more fully in DOWL (2016).

Watershed Processes

The alluvium of the broad, braided Lowe River floodplain below Keystone Canyon likely forms a large unconfined aquifer. No data are available on the contribution of groundwater flow to the river. Small mountain streams in the western part of the basin disappear as they descend towards the river. These streams provide recharge to the groundwater system. An upwelling of clear water on a side channel was observed during a site visit in September 2015, although this may have been attributable to a buried culvert outlet.

Historic Peak Flows

Historic annual peak flows have ranged from 9.400 to 42,000 cfs. These floods generally occur as a result of late summer and early autumn. The peak instantaneous discharge of record, 42,000 cfs, occurred on October 9, 2006.

In addition to precipitation events, glacial lake outbursts may also cause peak flows. Four glacial lakes were identified in the Lowe River watershed (Rundquist, 1981): two on Sheep Creek, one on Keystone Glacier, and one on Deserted Glacier. Outflows have been documented on two of these lakes. The upper lake on Sheep Creek released in 1959 and the lake on Keystone Glacier released in 1919, destroying a highway bridge. More recent information on these or other glacial lakes was not found.

A notable flooding event occurred on the Lowe River in January 2014 when an avalanche created a dam, impounding the flow of the Lowe River as it entered Keystone Canyon. Analysis of LiDAR data suggest that the dam impounded 949 to 2,149 acre-feet of water covering 85 to 139 acres. Due to precipitation as rainfall, the flow in the river was higher than its normal winter flow rate. However, peak flows for this event have not been published.

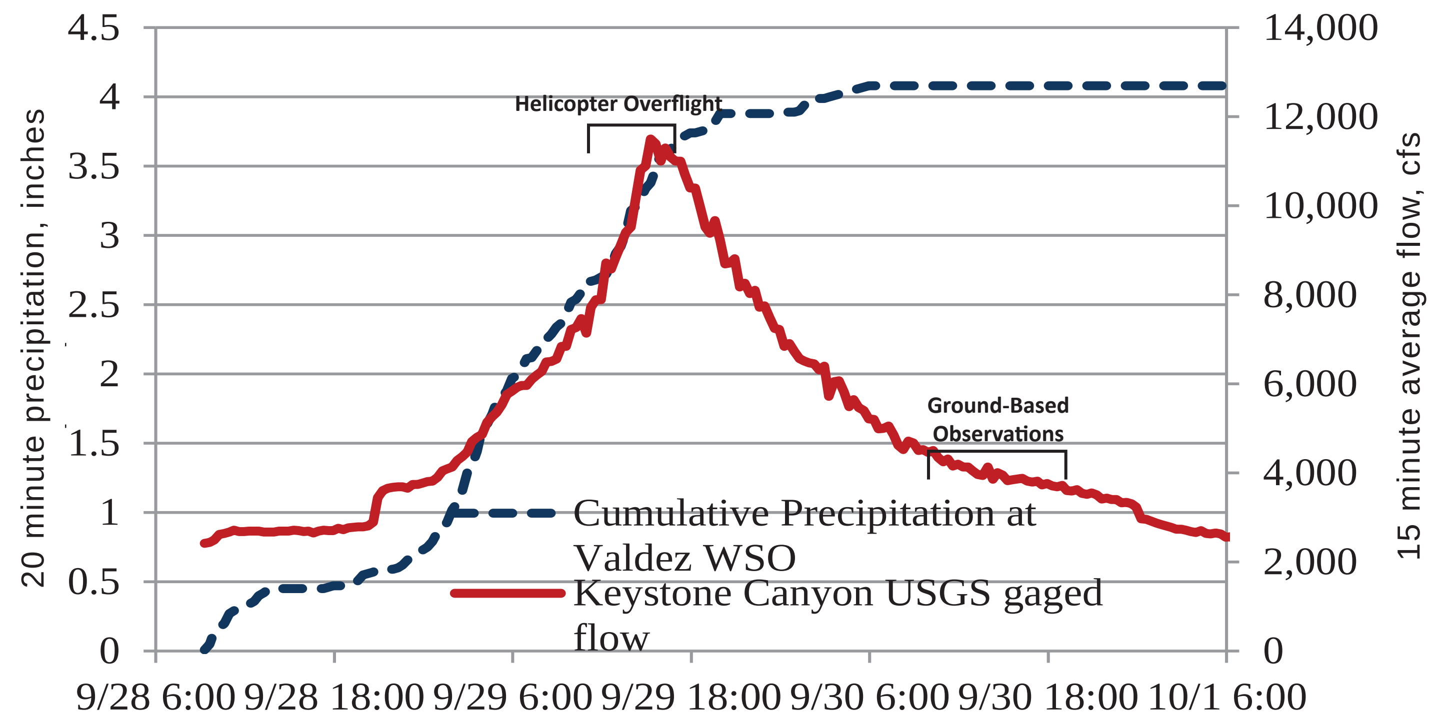
Table 3: Annual Peak flows for Period of Record Tributary and Glaciated Areas of the Lowe River Watershed

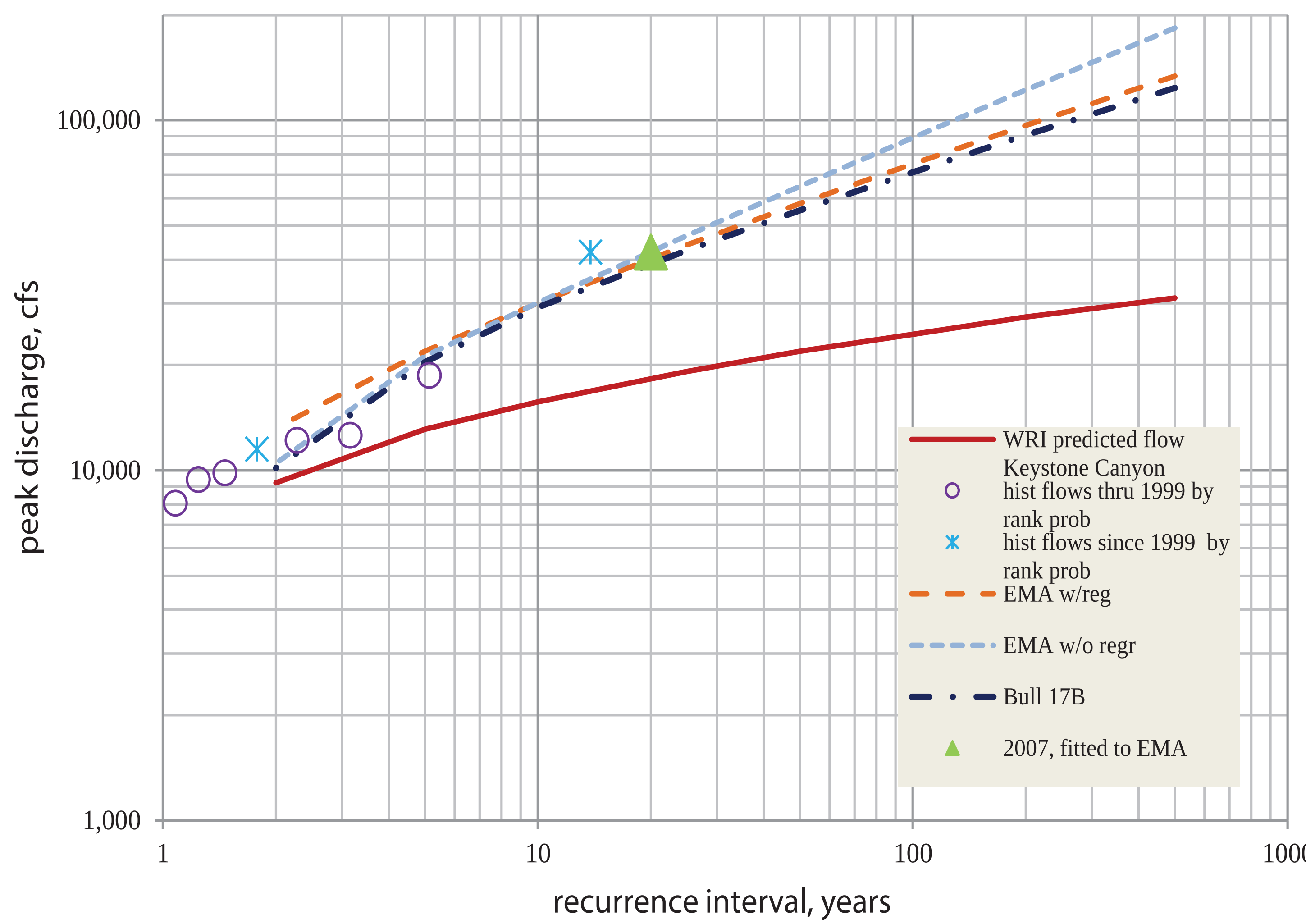
USGS Site	Date	Instantaneous Peak, cfs	Corresponding Daily Average, cfs	Ratio, Instant Peak to Daily Average
15226500	7/13/1972	9,840	9,100	1.1
15226500	8/21/1973	9,400	7,820	1.2
15226500	8/30/1974	12,200	9,200	1.3
15226600	9/11/1975	12,600	7,600	1.7
15226600	8/1/1995	8,500	NA	NA
15226600	9/22/1995	18,700	NA	NA
15226600	10/9/2006	42,000	NA	NA
15226620	9/29/2015	11,500 *	7,590	1.5

Flood Frequency

Because sparse data are available to describe peak flows on the Lowe River, several methods were used to estimate the flood magnitude frequency relationship for the Lowe River. These included the regional WRI USGS regression equation (Curran, et al., 2003) and application of the USGS computer program PeakFQ version 7.1.28513 (Flynn, 2006, as revised in 2014) utilizing three methods: the conventional Bulletin 17B methodology (IACWD, 1982) and the Expected Moments Algorithm (EMA) added to the Bulletin 17B methodology with and without regression information (Cohn et al., 2001). The EMA method, implemented in PeakFQ in 2014, after the USGS regression equations were developed, is considered a more robust methodology, since it considers all peak data, not just systematic gaged data. The USGS regression equation provides the average accuracy equivalent to 0.88 to 3 years of stream gauge record (Curran, et al., 2003 p. 13).

Resulting flood recurrence interval estimates are plotted to the right.





September 2015 Flood and Field Observations

Fieldwork for this project coincided with annual flood peak for water year 2015, which is equivalent to a 2 to 4 year recurrence interval event. The timing of field observations relative to the flood and rapid rainfall-runoff response in the watershed are shown in the rainfall runoff trace of the flood event.

Flood recurrence estimates

Various flood recurrence estimates, plotted above, show a broad range of predictions. The USGS regression equation predicts much smaller peak flows than methods based on the eight years of actual peak flow data available for the Lowe River. Of particular concern is the question of whether the October 2006 flood was an extremely rare (>500 yr recurrence) event that happened to be captured in the peak flow record, or is a more common flow. Comparison of the flood on several other nearby rivers suggests that it was a 20-120 year recurrence interval event regionally, and likely 20-40 year recurrence interval event on the Lowe River.

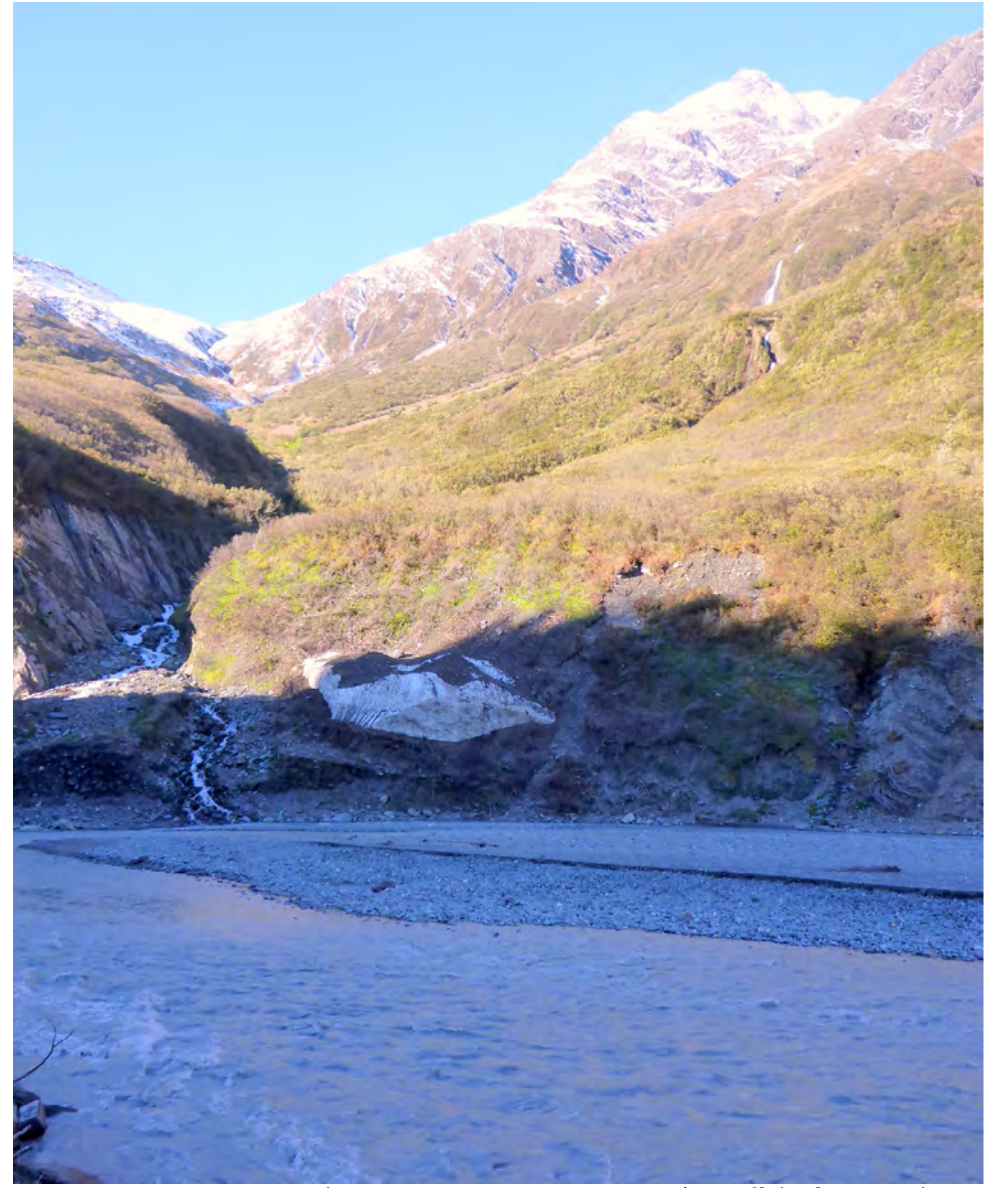
Major Tributaries to the Project Reach.
Upper Lowe River

Above Keystone Canyon, the Lowe River flows for approximately five miles through an alluvial valley that has aggraded on the bottom of a glacially-scoured trough. Above this, the river flows through Heiden Canyon, which appears to have been incised below the depth of glacial scour, and tributaries emerge from hanging valleys, indicating that they are transport or erosional reaches.

The alluvial reach between Heiden Canyon and Keystone Canyon is braided. Typically 2 to 5 channels flow through an active channel that is 400 to 1,300 feet wide. The texture of gravel bars above the entrance to the canyon was similar to those downstream at the head of the project reach.

View upstream from the highest Richardson Highway crossing over the Lowe River.

Approximate location of Pebble count near RM 15.9 representing the sediment feed to Keystone Canyon.



A prominent constriction at the entrance to Keystone Canyon (just off the frame to the left) creates a prominent backwater during flood conditions, resulting in temporary sediment storage just upstream of the entrance to the canyon. This photo shows a gravel sheet that accumulated on the surface of the pictured bar during the September 29, 2015 flood. This deposit was composed of smaller material than the one sampled just upstream.

Also note the debris-flow fan at the base of the gully in the background. Relatively infrequent but large transport events supply sediment to the fan and the Lowe River gradually remobilizes this and transports it downstream. Sediment supply from steep alpine terrain typical of the Lowe River Basin is characteristically high-magnitude low-frequency, but the alluvial reach between Heiden Canyon and Keystone Canyon provides a large reservoir buffering these relatively infrequent events and providing a steady supply of sediment to the canyon.

This is the site where when an avalanche created a dam, impounding the flow of the Lowe River in January 2014. This resulted in a notable flood when the dam the dam impounded 949 to 2,149 acre-feet of water covering 85 to 139 acres. Due to precipitation as rainfall, the flow in the river was higher than its normal winter flow rate. However, peak flows for this event have not been published.

Keystone Canyon

Though the water surface slope through Keystone Canyon is not appreciably steeper than the river either upstream or downstream, the flow is confined to a narrow and deep channel by bedrock and revetments protecting the highway. Therefore, the sediment transport capacity of the river though the canyon is greater than either upstream or downstream because energy available to transport sediment is a function of the water slope and flow depth. This is reflected in very large grainsizes of sediment observed in the canyon.

Richardson Highway crossing over the Lowe River in the middle of Keystone Canyon.

This is the furthest upstream bar where Keystone Canyon begins to widen and the location of the pebble count at RM 12.8.

Browns Creek

Browns Creek joins the Lowe River near the upstream boundary of the study reach. It accounts for approximately 15% of the total Lowe River basin and 20% of the basin area at the confluence. It emerges from a confined valley with a slope of approximately 2.9% about 0.9 miles above the confluence and flows across a 500 to 1,200 ft wide braid plain across a broad alluvial fan with a slope of about 1.2%. These slopes are much steeper than the Lowe River upstream of the confluence (approximately 0.63%).

The bed material of Browns Creek is very broadly graded. It has a high sand fraction (~30% sand) and ranges in size up to small boulders. The slope of the Lowe River is slightly convex at the confluence increasing from 0.63% above the confluence to 0.69% downstream of the confluence, suggesting that coarse sediment contributed by Browns Creek may be acting to control the rivers grade.

View upstream along Browns Creek from location of Sample Browns 1A (mapped on next page)

View downstream along Browns Creek from location of Sample Browns 1B (mapped on next page)

Overview of Browns Creek alluvial fan, looking upstream from the confluence with the Lowe River

10 Mile (Noname) Creek

The 10 Mile Creek alluvial fan protrudes into the Lowe river valley between RM 7.5 and RM 9, pushing the Lowe River away from the left valley wall. The 10 Mile creek basin accounts for approximately 11% of the total basin area and 13% of the basin area upstream of its confluence with the Lowe. 10 Mile Creek itself is steep, with an average slope of approximately 4% above the alluvial fan and an average slope of approximately 2.7% across its alluvial fan which extends about a mile above the confluence with the Lowe.

As with Browns Creek, the bed material of 10 Mile creek is very broadly graded, it has a high sand fraction (~30% sand) and ranges in size up to small boulders, although most of the transported sediment is smaller than 180 mm.

The valley bottom topography and historical aerial and satellite imagery suggest that 10 Mile creek occasionally avulses across its alluvial fan to the west and flows into Canyon Slough before joining with the Lowe River.

Sediment transport functions (p. 28-29) and field observations of very active bed material transport in 10 Mile Creek during the September 2015 flood suggests that 10 Mile Creek transports substantially more bed material than Browns Creek, which is surprising because it has a slightly smaller contributing basin. However, a steep and confined bedrock canyon connects sediment source areas directly to the head of the 10 Mile Creek alluvial fan, while browns creek has a much longer alluvial reach were sediment may be sequestered. In addition, preliminary observations suggest that several glaciers tributary to 10 Mile Creek have anomalously high englacial debris loads (sediment carried in and on the surface of the glacier derived from rockfall, debris flows, landslides, and plucking), which have been observed in other areas to directly correlate to downstream fluvial sediment loads (Czuba et al., 2012).

Overflow path leaving 10 Mile Creek alluvial fan and crossing TAPS access road, flowing into an abandoned gravel pit.

Overview of 10 Mile creek alluvial fan, looking downstream toward the confluence with the Lowe River and to the west downstream along the Lowe River in the background. Note large area of forest recently inundated by alluvium.

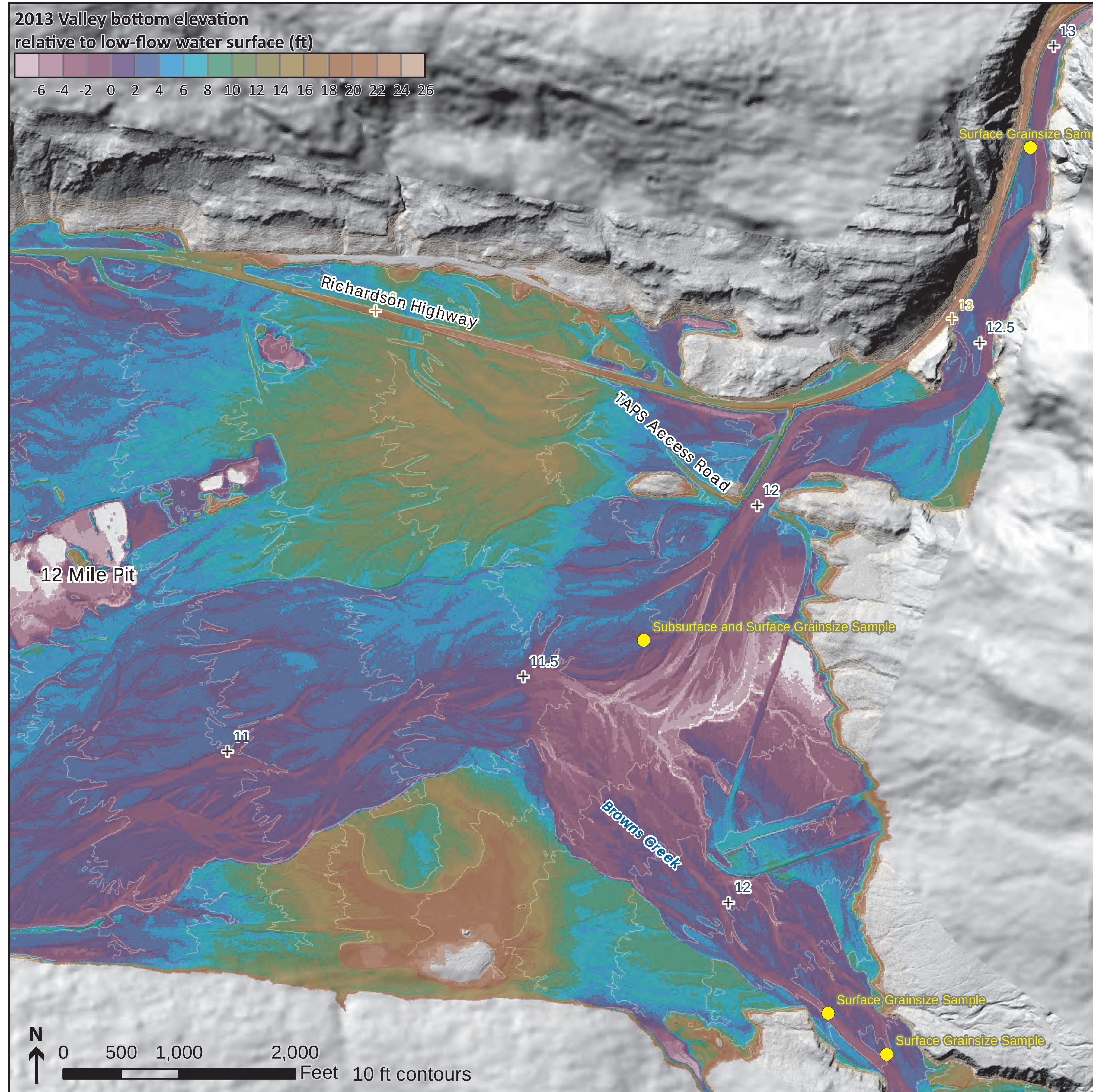
Ground-based view of the head of the 10 Mile Creek alluvial fan. Note the high proportion of surface sand but overall coarse texture of the bed material.

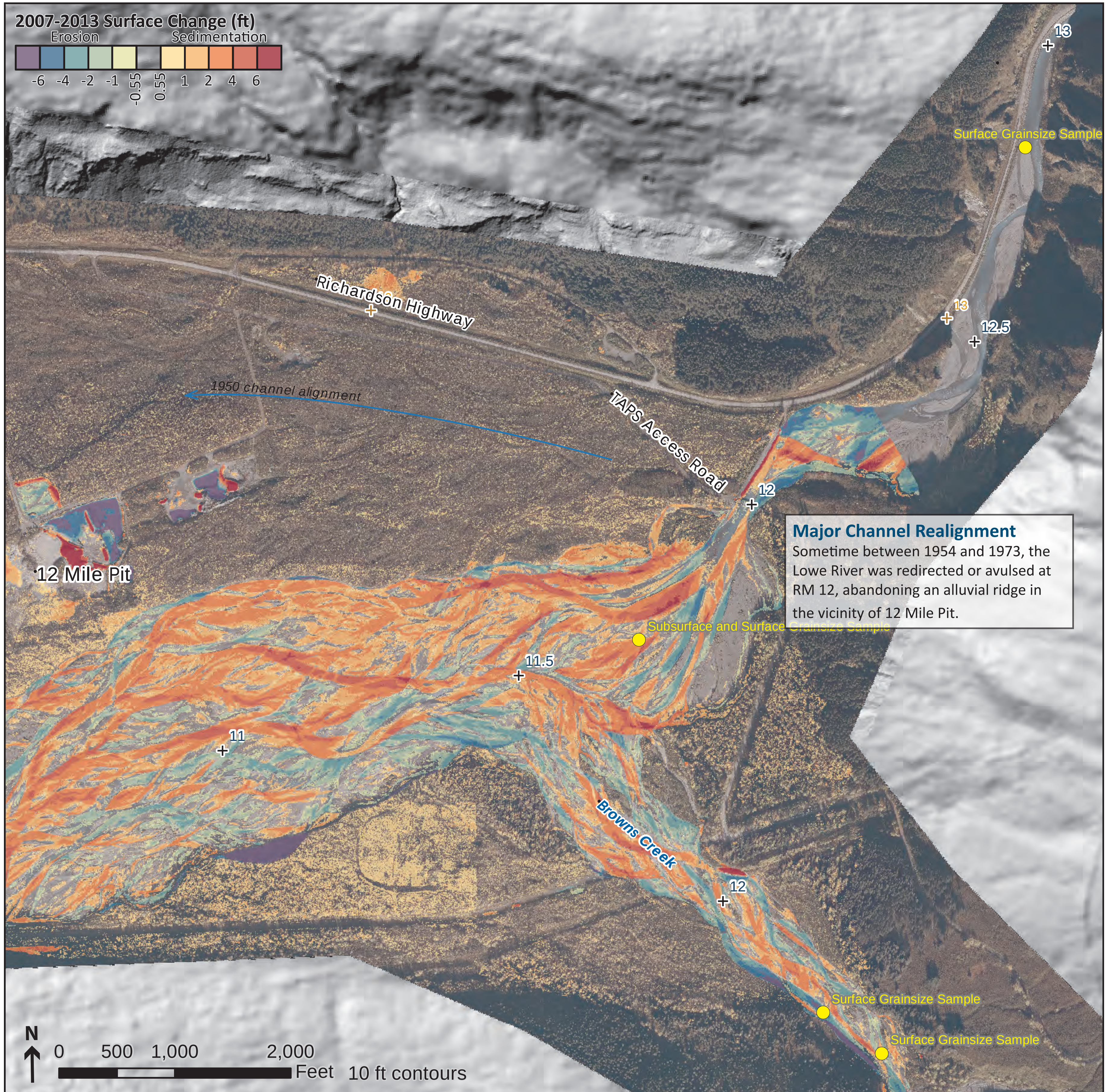
Geomorphic Conditions RM 13-11

- The Lowe River leaves the completely confined Keystone Canyon at approximately RM 12.75, but remains moderately confined until it emerges into a broad alluvial plain after passing through the TAPS Access Road Bridge (TAPS Bridge) at RM 12. This configuration is relatively new, however. Major river training works constructed sometime between 1950 and 1973 diverted the river upstream of the head of its historic alluvial fan which appears as a sloping terrace on the right bank between RM 11 and 12.
- Although a large volume of material has been excavated from the 12 Mile Pit, active channel has not yet interacted with this pit and it appears to have not influenced the active channel morphology.
- During field observations at noon on September 30th, active bedload transport was revealed by the sound of collisions between gravel and the piers of the TAPS Bridge. Assuming a 45-minute delay for discharge at the TAPS Bridge relative to the gage in Keystone Canyon, then the discharge was about 4040 cfs at the time of this observation. 24 hours later, with an estimated flow of 2,300 cfs no bedload transport was noted at this location.

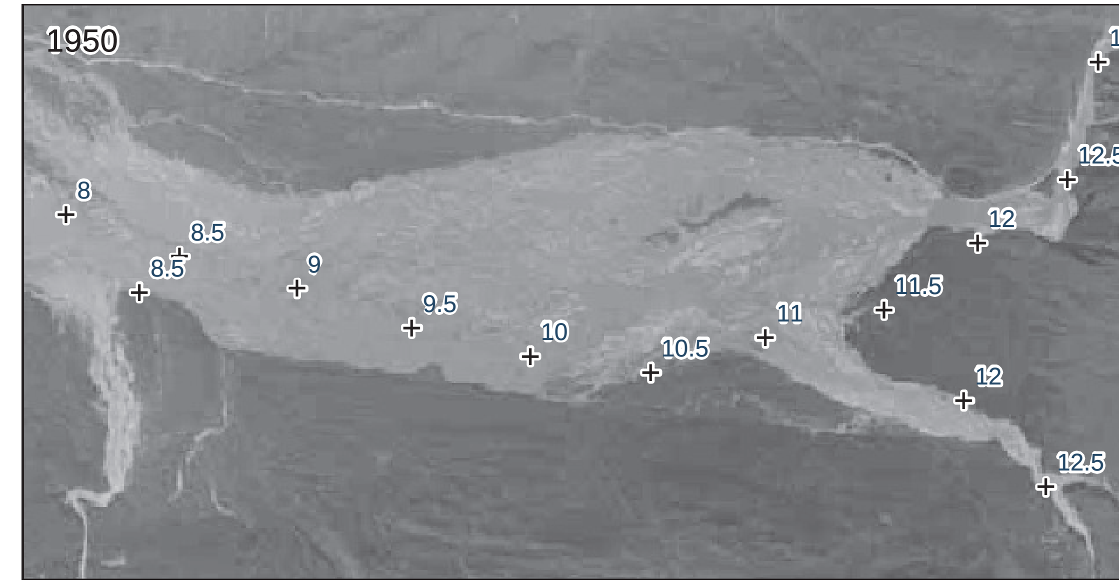
View downstream along RB revetment towards TAPS Bridge at RM 12.

Location of Bulk Sample 1 and D_{50} values of several surface grainsize distributions from scaled images illustrating heterogeneity of bar surface.

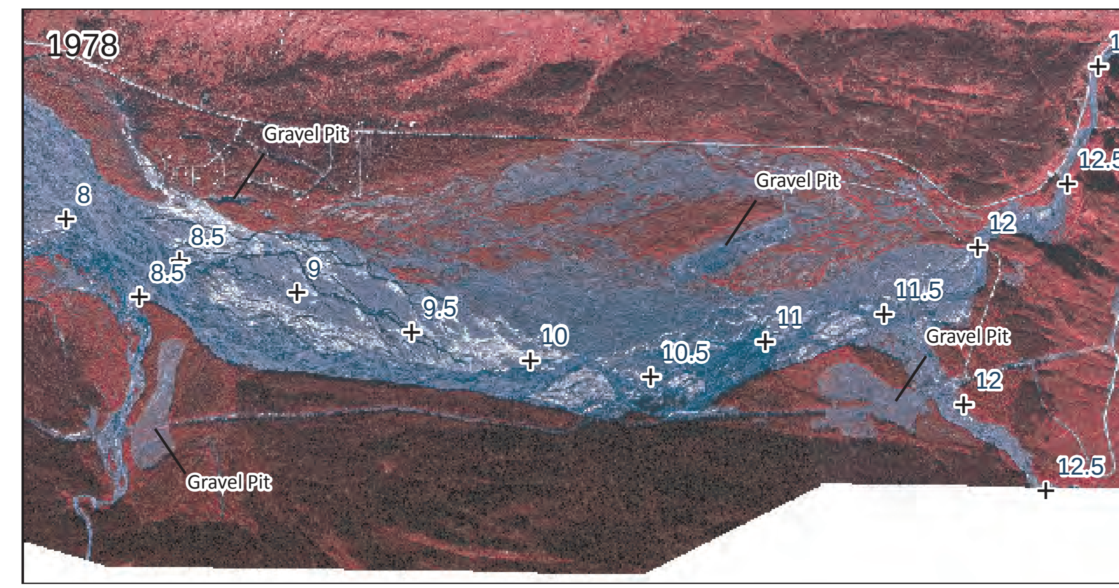




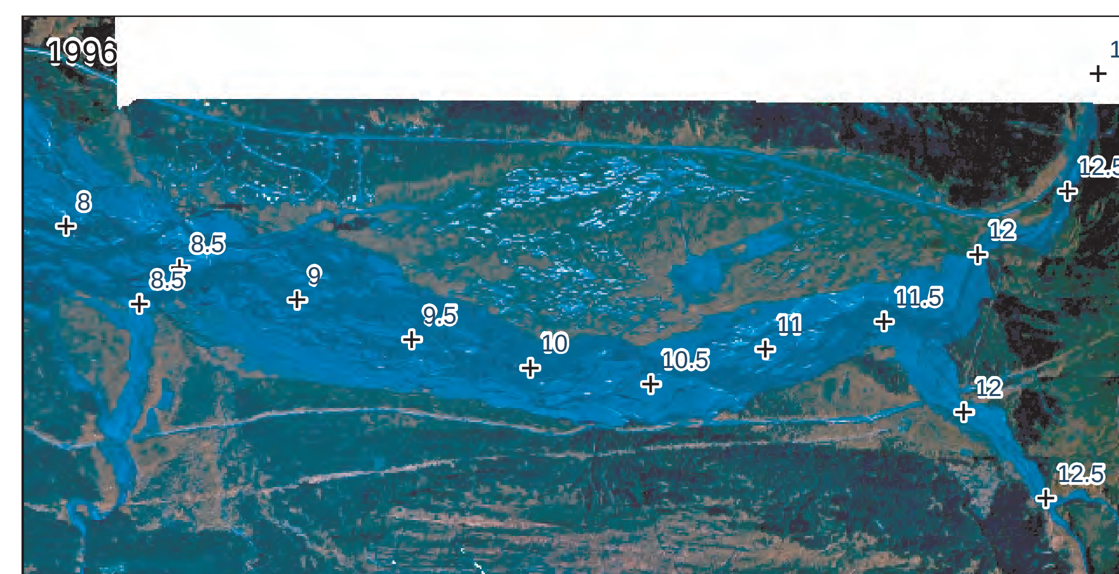
2007-2013 Surface Change (ft)
Erosion
Sedimentation
-6 -4 -2 -1 -0.55 0.55 1 2 4 6
Richardson Highway
1950 channel alignment
TAPS Access Road
12 Mile Pit
Surface Grainsize Sample
Subsurface and Surface Grainsize Sample
Browns Creek
13
12.5
12
11.5
11
Major Channel Realignment
Sometime between 1954 and 1973, the Lowe River was redirected or avulsed at RM 12, abandoning an alluvial ridge in the vicinity of 12 Mile Pit.
N
0 500 1,000 2,000
Feet
10 ft contours



1950
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13



1978
Gravel Pit
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13



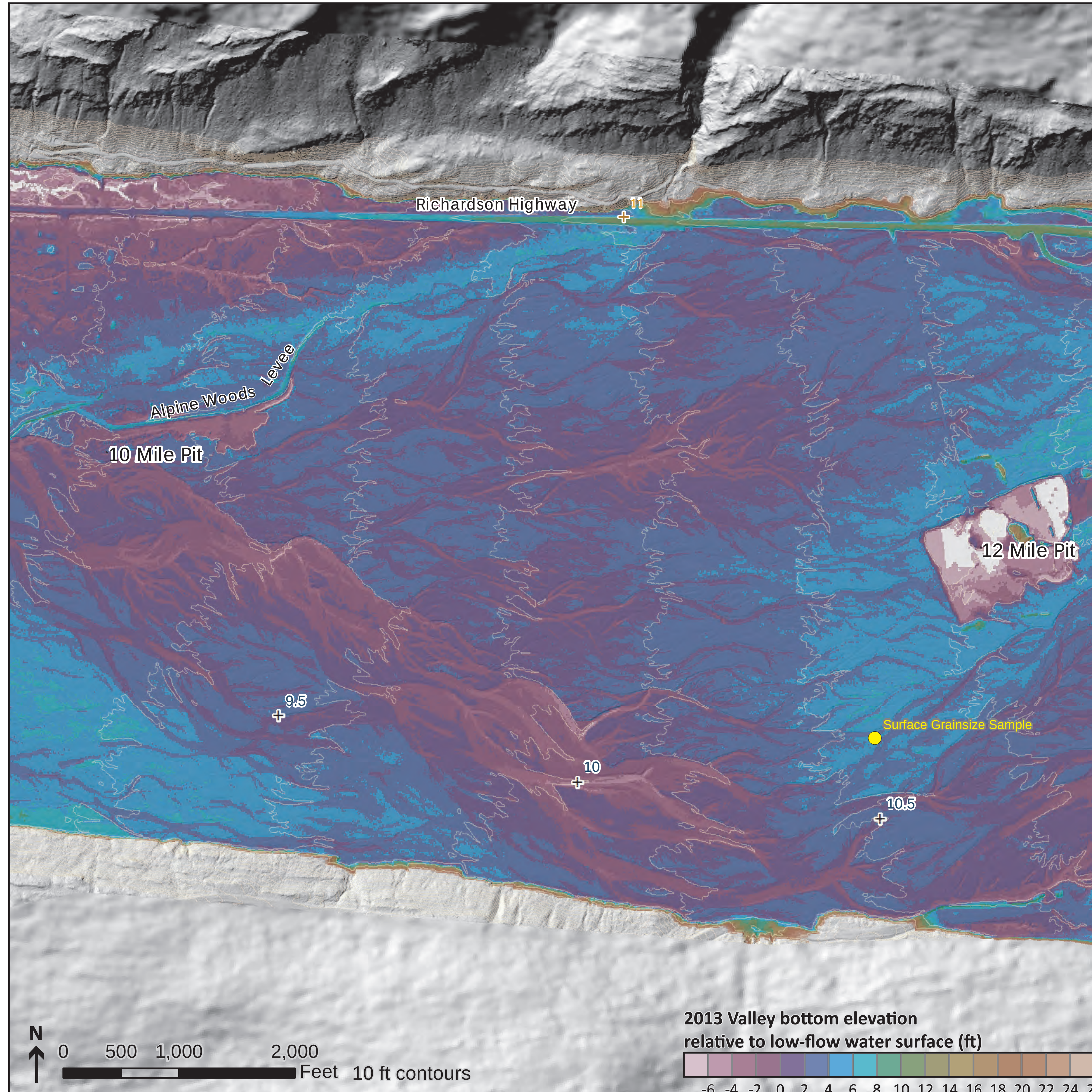
1996
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13

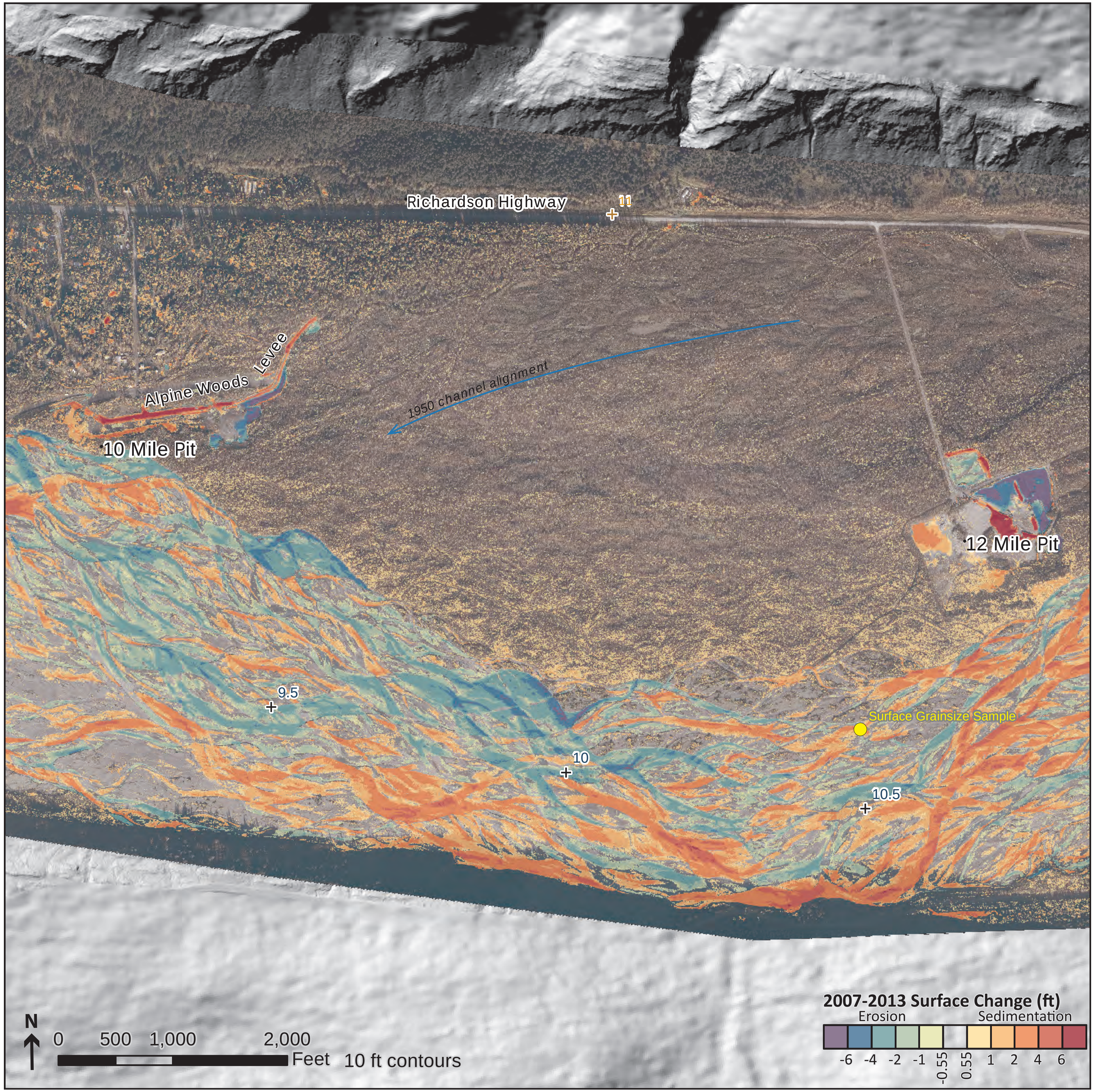
Geomorphic Conditions RM 11-9

- Channel training upstream at RM 12 reduced the active channel width in this reach from over one mile to less than 1/2 mile.
- The alignment of dominant channel(s) in this reach is extremely unstable upstream of RM 10 in the Satellite record (page 24), but has been more stable between RM 9 and 10 with a preferential path crossing from the left valley wall to the levees protecting Alpine Woods on the right.
- Channel migration has nearly intersected the floodplain excavation at 10-mile pit. The presence of the pit may promote future abrupt lateral channel migration towards the levees protecting Alpine Woods.
- Overall, the river has been shifting towards the north bank over the past decade. Erosion has been concentrated on the right bank, while bars on the left bank have continued to grow.

10 Mile Pit is located just riverward of the uppermost Alpine Woods Levee, the revetted structure on the left side of the frame.

View looking upstream from approximately RM 10. Note 12 Mile pit on the north side of the river (left of the frame).





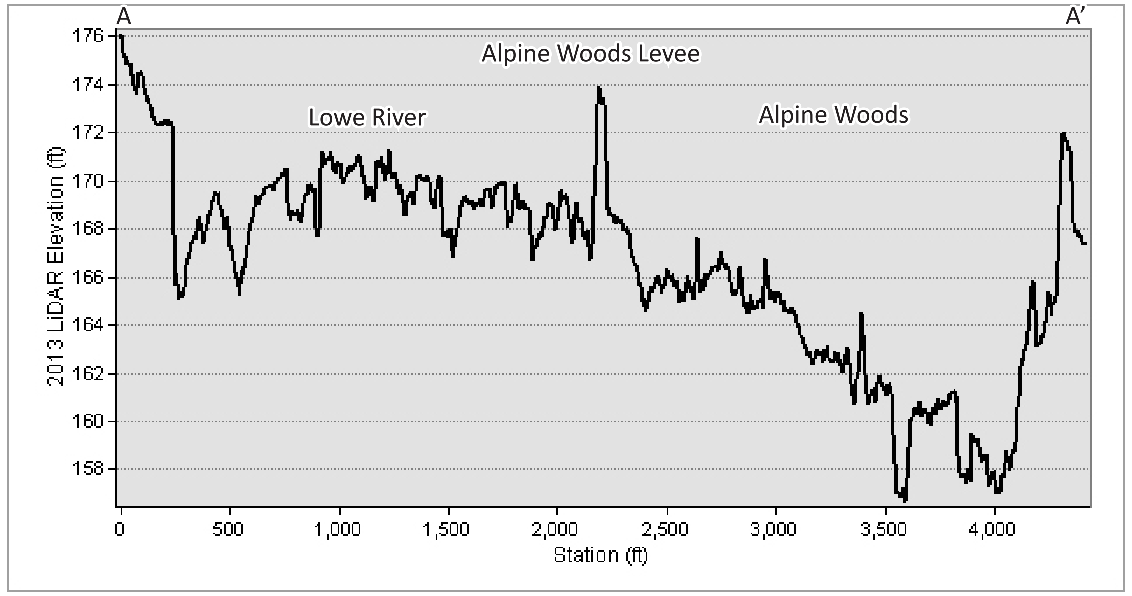

Pebble Count Lowe 10 was located at the head of a significant bar splitting a side channel toward the right bank margin of the braid plane.


View upstream from approximately RM 10 showing extremely broad braidplane.

Geomorphic Conditions RM 7.5-9 (see next page for figures)

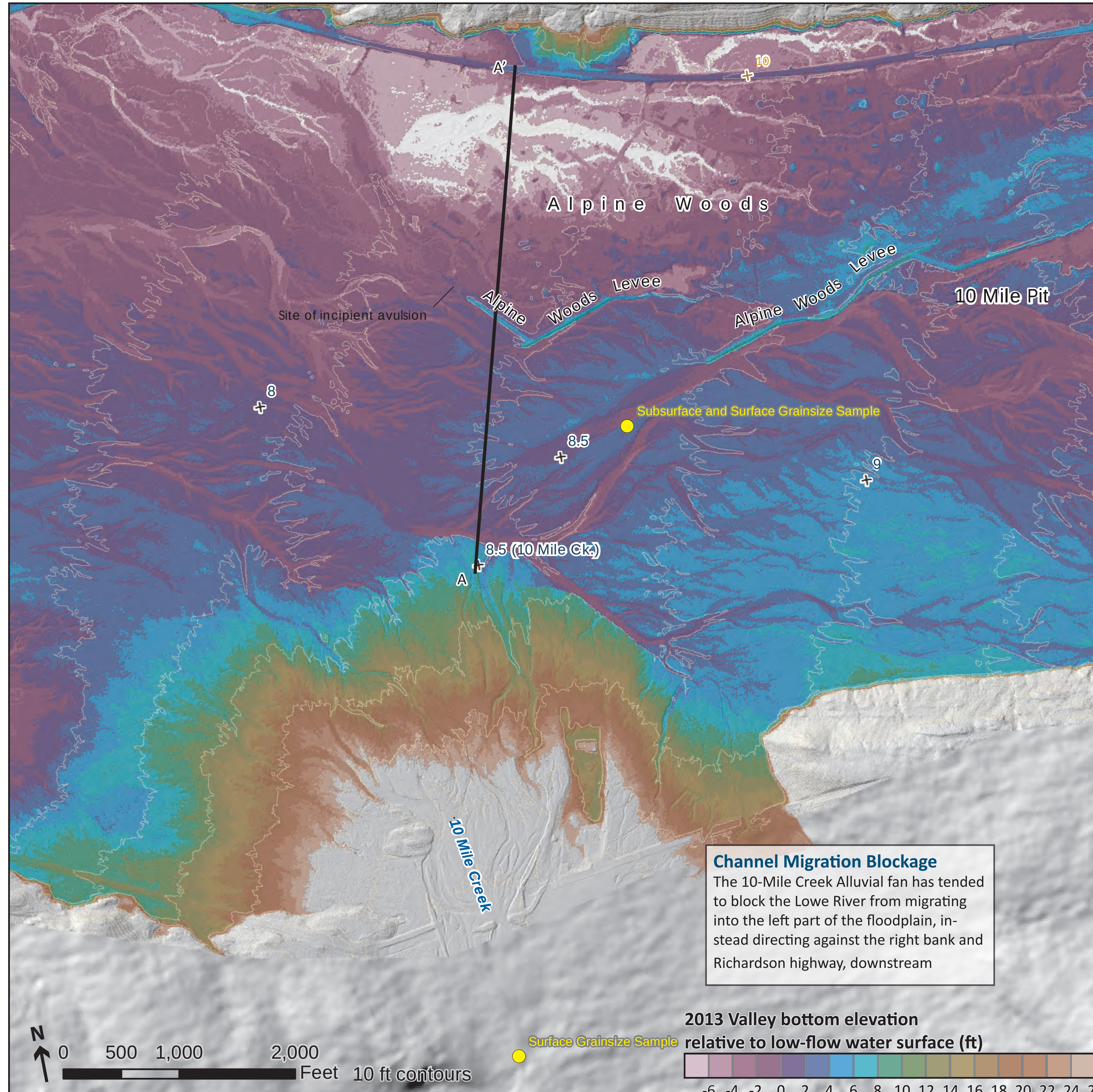
- Levees protecting the Alpine Woods community act as spur dikes, focusing flow from upstream at their tips. This flow then produces persistent scour at the levee tips, which pulls the dominant channel towards the levee and has focused sediment deposition towards the center and left bank of the channel.
- The Alpine Woods community is located at a very low elevation relative to the active Lowe River channel. The channel is perched approximately 10 feet above the floodplain. Assuming 30 years of differential aggradation to create this offset suggests an aggradation rate of approximately 4 in/year.
- There is substantial likelihood of channel avulsion into the Alpine Woods community, either downstream of the existing levee protection or in the event that the levees protecting the community overtop. Continued channel aggradation will likely exacerbate this risk in the future.

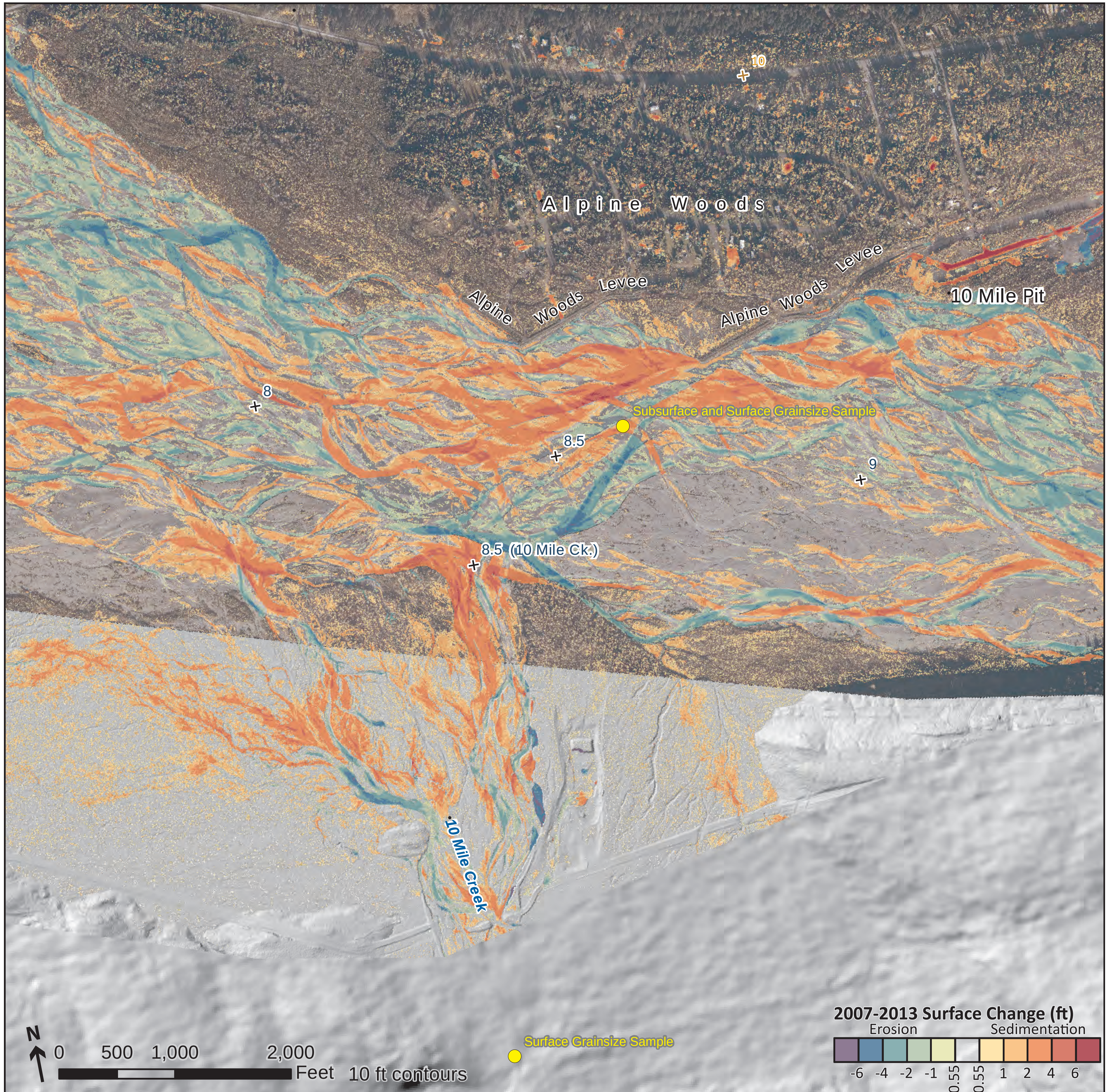
Geomorphic Conditions RM 7.5-9 (Continued)



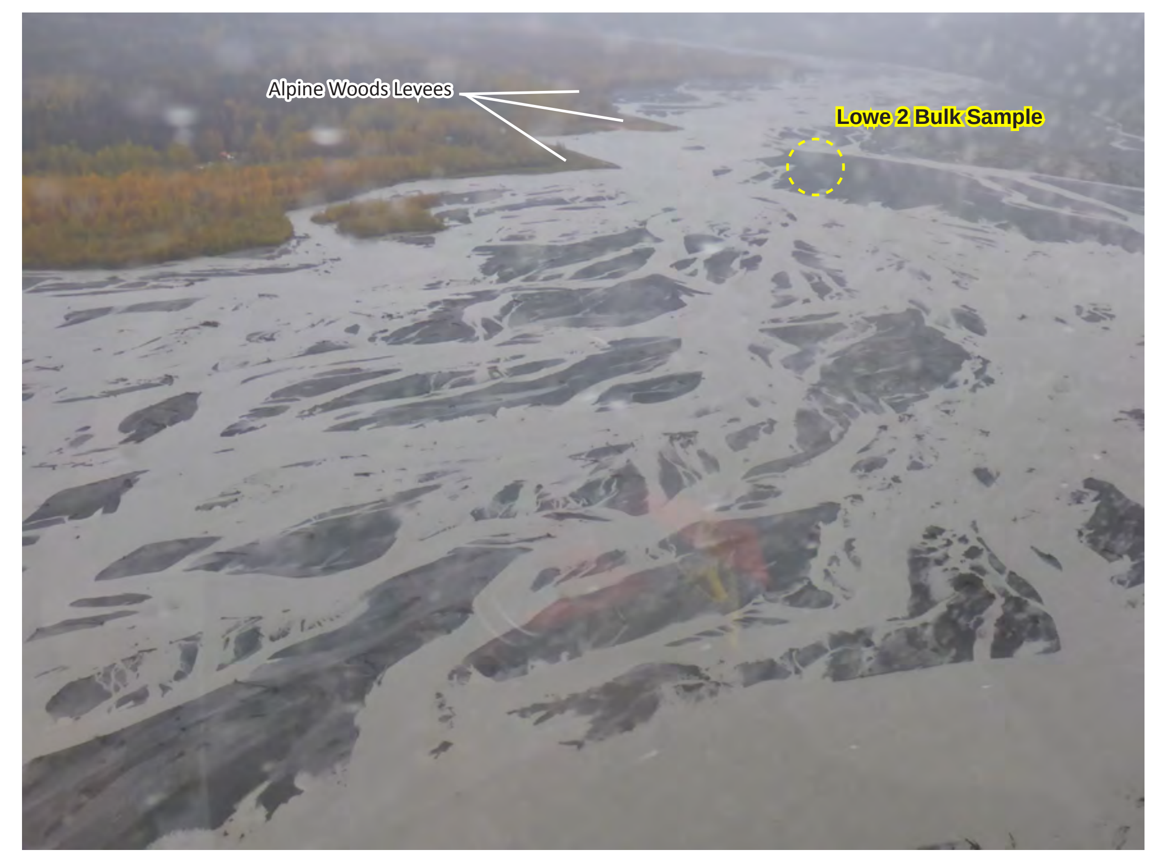
Cross section illustrating extremely low floodplain elevations in the area of the Alpine Woods community. The Alpine Woods levees have prevented the channel from migrating into this area for approximately 30 years, preventing bed material sedimentation. Progressive accumulation of sediment in the channel has perched it approximately 8-10 feet above the floodplain in this area, suggesting a local aggradation rate of 3-4 in/yr.

Incipient avulsion channel formation approximately 50 ft downstream of the lowest Alpine Woods Levee. Extremely low floodplain elevations on the north side of the floodplain attract flow during flood conditions.





Levees protecting Alpine Woods from flooding concentrate flow at their tips. This flow prevents sediment from accumulating locally and "traps" the channel against the levee.



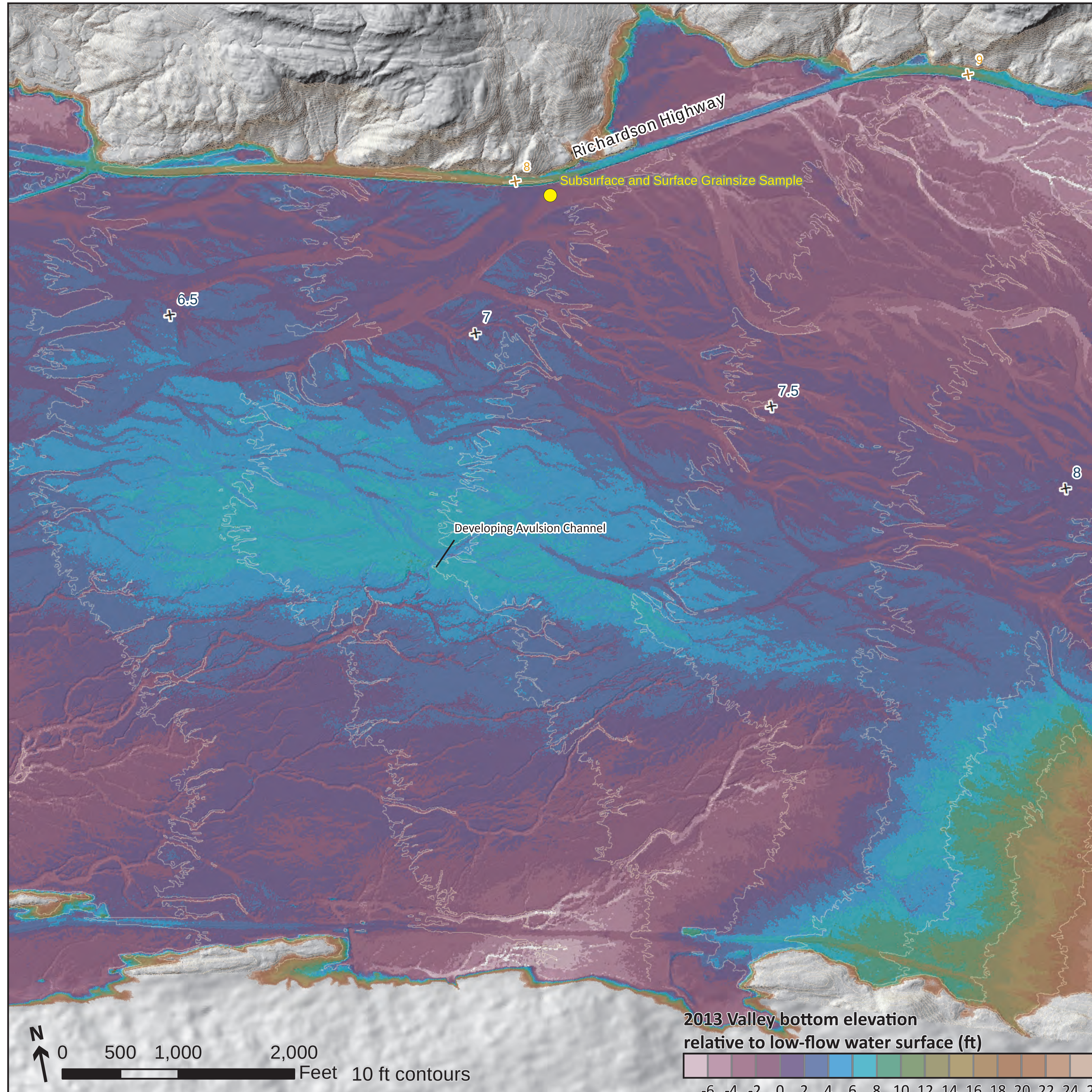
View along Lowe River looking upstream from approximately RM 8 showing flow concentration along Alpine Woods Levees and the location of Bulk Sample Lowe 2.

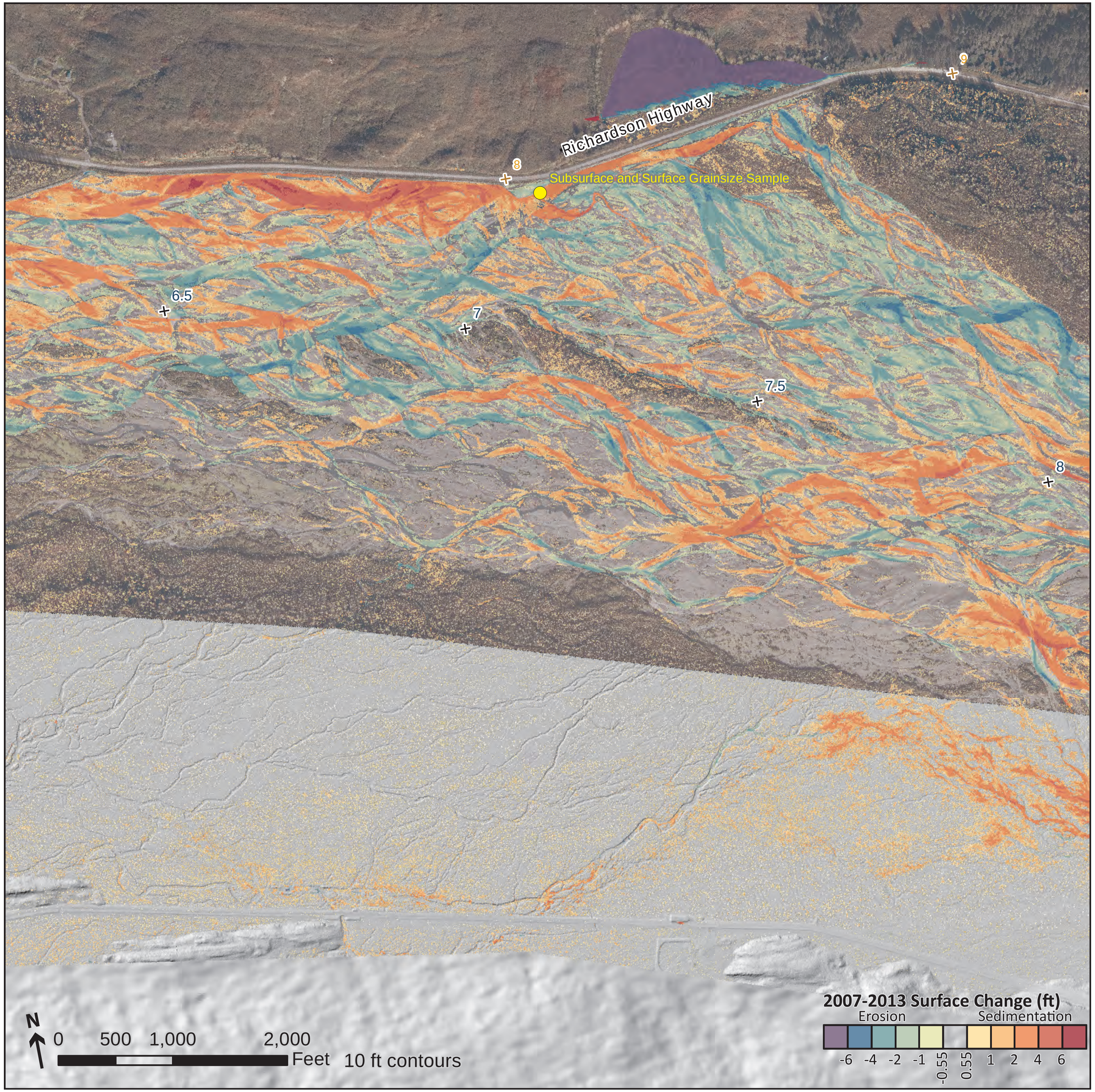
Geomorphic Conditions RM 6-7.5

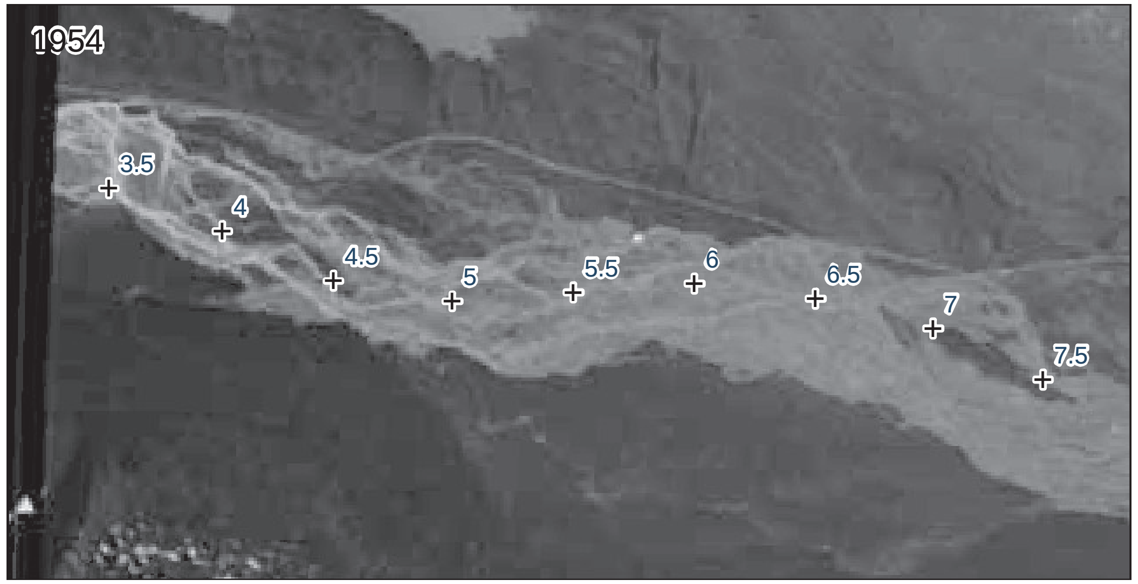
- The 10 Mile Creek alluvial fan upstream has tended to block channel migration into the southern part of the valley bottom in this area over the recent geologic past. Because sediment accumulation is concentrated near the active channel, the southern part of the floodplain is very low relative to the active channel and channel avulsion through this area is possible.
- 5 to 9 feet of difference in elevation between the active channel and floodplain embayment landward of the highway between mile marker 8 and 9 indicates the magnitude of aggradation since the highway segment was constructed, which was sometime prior to 1954 and probably after 1920. The aggradation rate at this location, then can be estimated to have been between 0.5 and 2 inches per year.

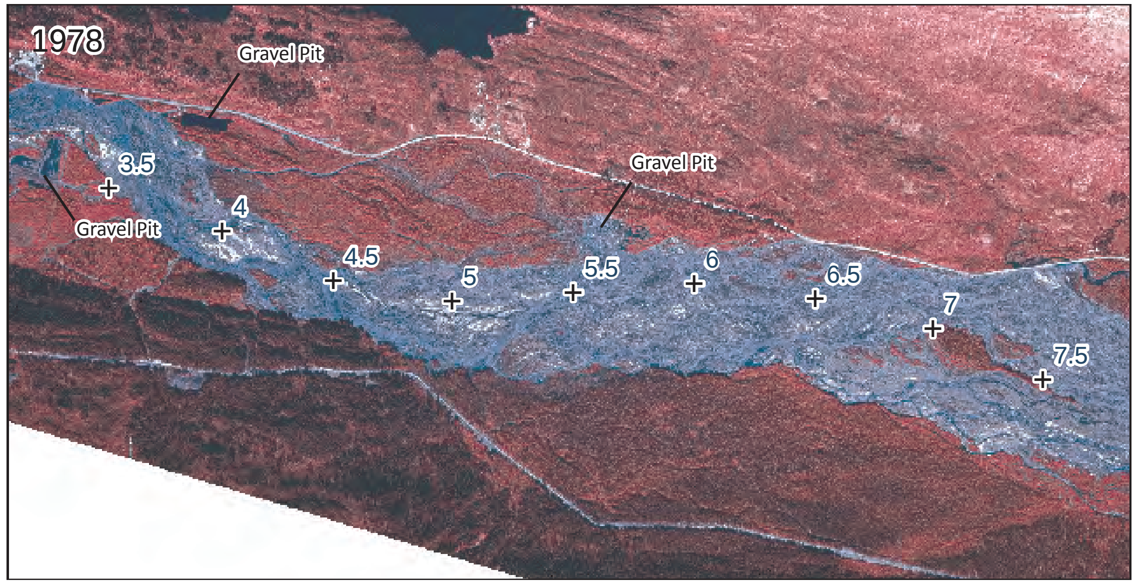

Location of bulk sample Lowe 5.

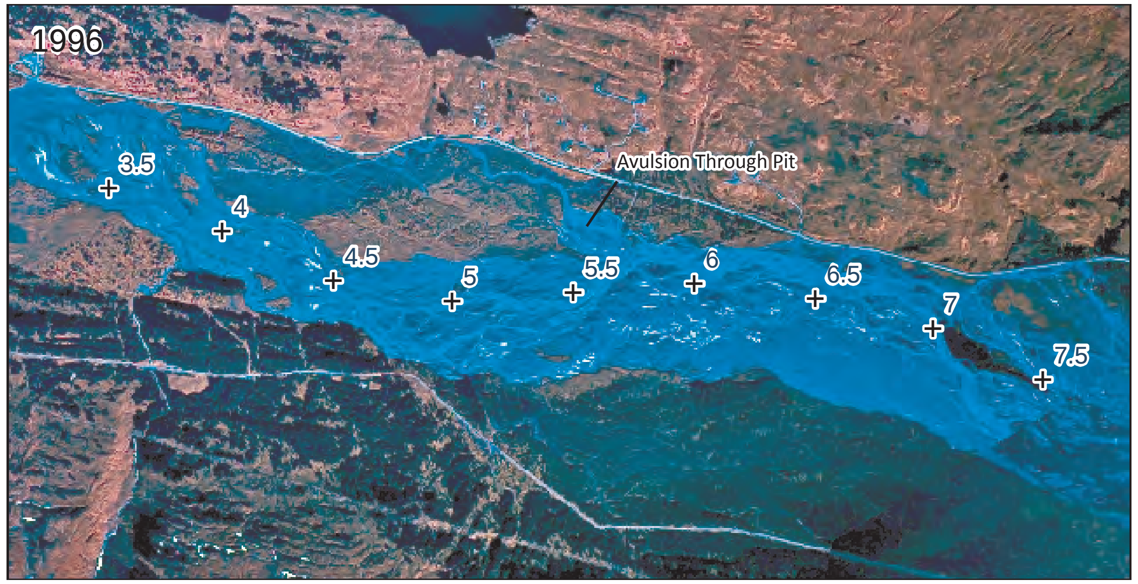

Avulsion channel leaving the left bank of the Lowe River at approximately RM 7.




Richardson Highway
9
8
Subsurface and Surface Grainsize Sample
6.5
7
7.5
8
2007-2013 Surface Change (ft)
Erosion
Sedimentation
-6 -4 -2 -1 -0.55 0.55 1 2 4 6
N
0 500 1,000 2,000
Feet
10 ft contours


1954
3.5
4
4.5
5
5.5
6
6.5
7
7.5


1978
Gravel Pit
Gravel Pit
Gravel Pit
3.5
4
4.5
5
5.5
6
6.5
7
7.5

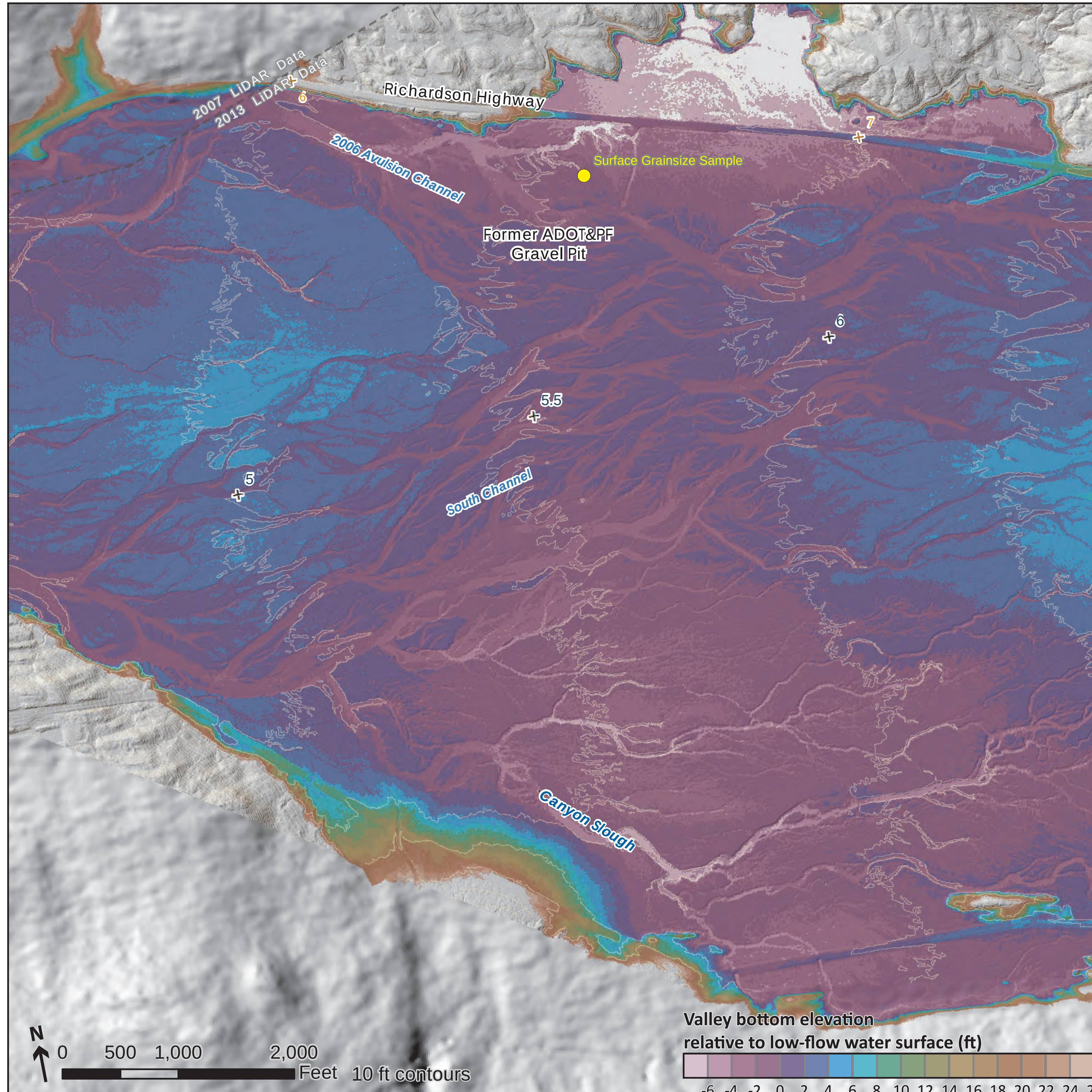

1996
Avulsion Through Pit
3.5
4
4.5
5
5.5
6
6.5
7
7.5

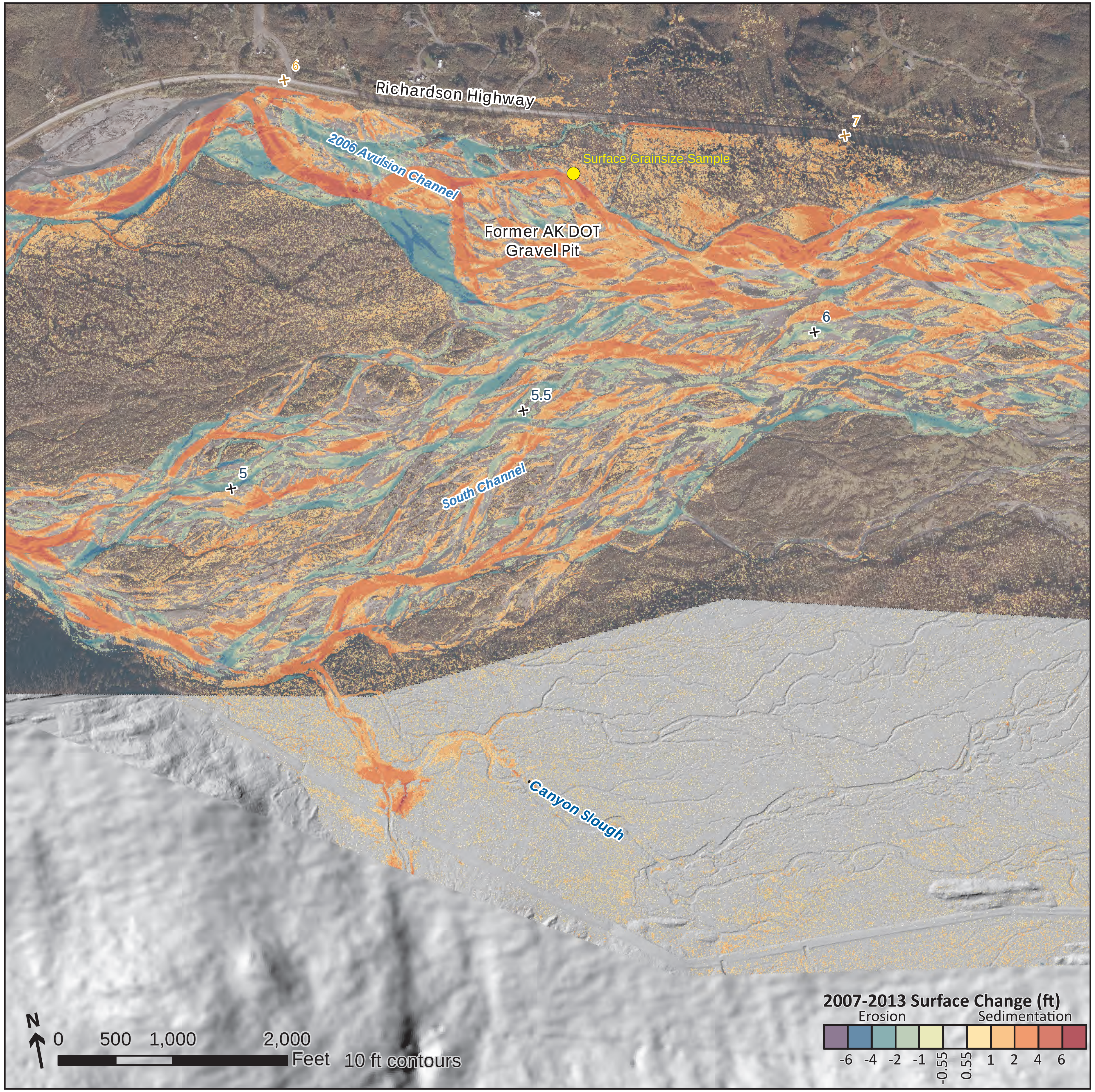
Geomorphic Conditions RM 4.5-6

- Satellite images suggest long-term sediment accumulation between RM 6 and 7.5 has been concentrated towards the left side of the active channel, behind the set of islands between RM 6.5 and 7.6. The dominant channel has rarely been in this area, and sediment bars have either persisted for a long period of time or become vegetated.
- 5 to 9 feet of difference in elevation between the active channel and floodplain embayment landward of the highway between near mile marker 7 suggests the channel aggradation rate here has been about the same as in the segment upstream (0.5 to 2 in/yr).
- A large avulsion occurred at RM 5.5 through an ADOT&PF floodplain gravel pit. A small channel formed during the early 1990s and then most of the flow switched into this path as a consequence of the 2006 flood. Since then, gravel bars have prograded into the breach and the channel has widened. Presently, the flow is approximately equally split between the 2006 avulsion channel and South Channel.

Lowe 12 sample was not collected from a bar head, but rather this eroding bank because no bars were accessible in this area during field work.

View Looking up the South Lowe River channel from approximately RM 5.3.





View looking down 2006 Avulsion Channel from approximately RM 6 through site of infilled gravel pit.

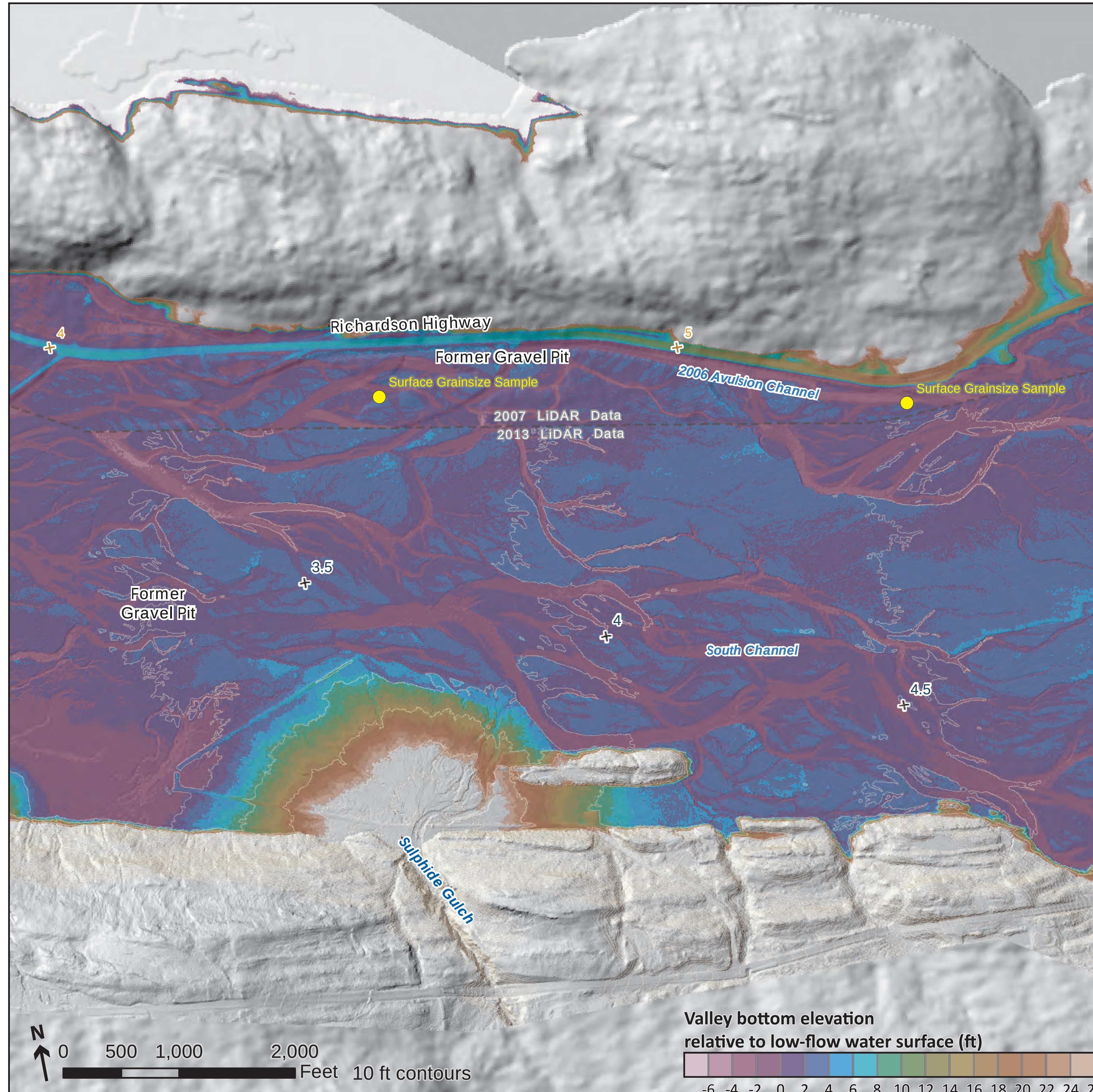
Flow along and towards Richardson Highway near Milepost 7. The highway has blocked most sedimentation from the pond area on its landward side. Bar tops in the main river channel are perched 10-12 feet above this pond. This segment of the highway was constructed prior to 1954, so the aggradation rate has been on the order of 2 in/year.

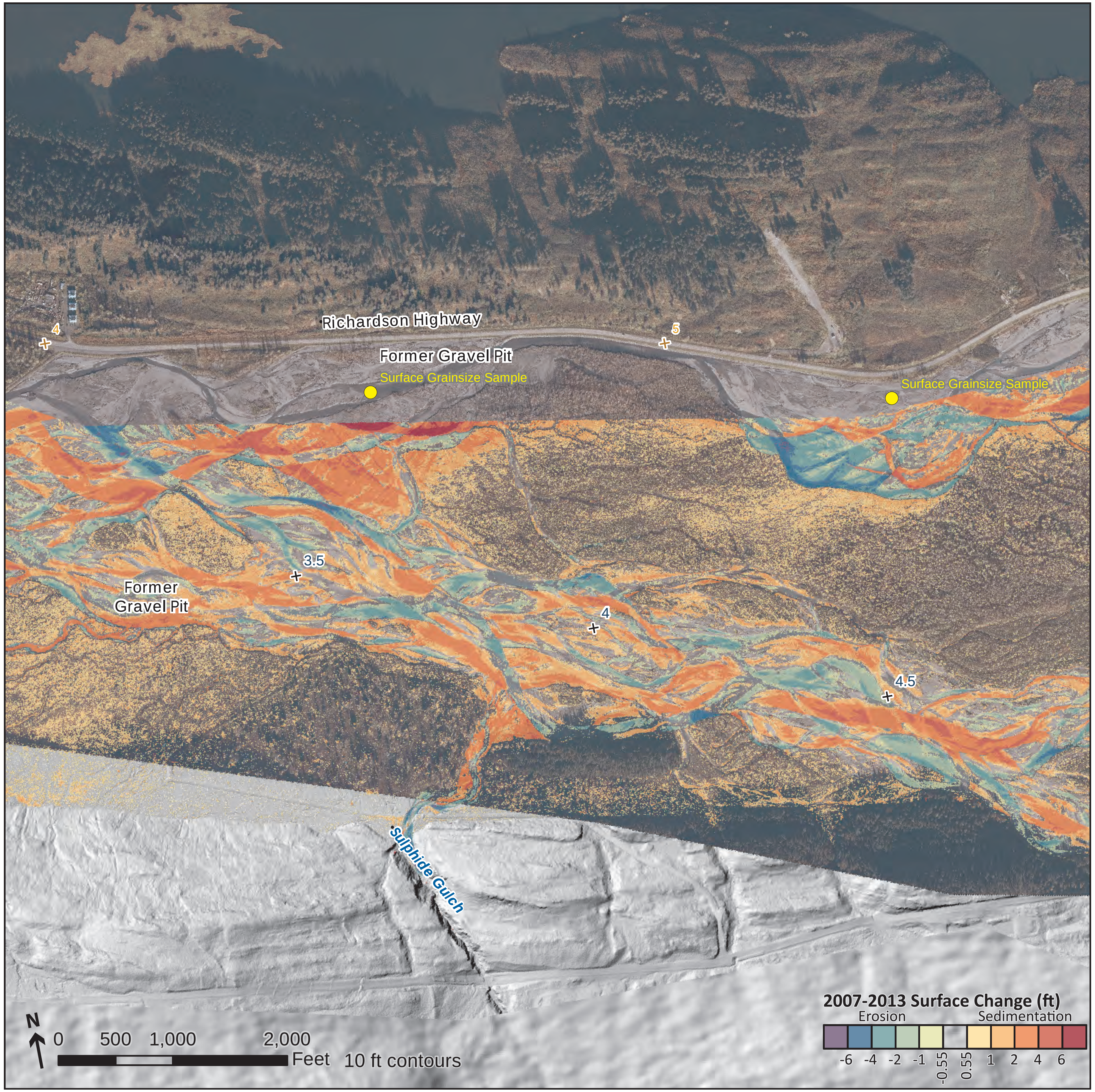
Geomorphic Conditions RM 3.5-4.5

- Gravel bars have prograded into and widened the 2006 avulsion channel to approximately RM 4.1. by 2013. Below this, the channel is free of bars, straight, and relatively deep. Approximately 150 acres of floodplain have been converted to active channel along the avulsion path. If a typical difference between the thalweg elevation and bar surfaces of 6 ft is assumed, this indicates this branch of the river has turned over around 1.5 million cubic yards of sediment between 2006 and 2013.
- Geomorphic indicators suggest pronounced recent aggradation in the right bank area missing 2013 LiDAR coverage. Though the total volume cannot be quantified with available data, net aggradation can reasonably be assumed and the aggradation estimate from the area of LiDAR overlap can be considered a minimum for this area of the river.

Simplified channel along downstream portion of 2006 avulsion channel in the vicinity of Highway Mile-post 5.

Inundation of floodplain forest between 2006 Avulsion channel and main channel near RM 3.7 suggesting pronounced aggradation.





Location of Sample Lowe 6 looking upstream along 2006 Avulsion Path toward location of filled gravel pit.

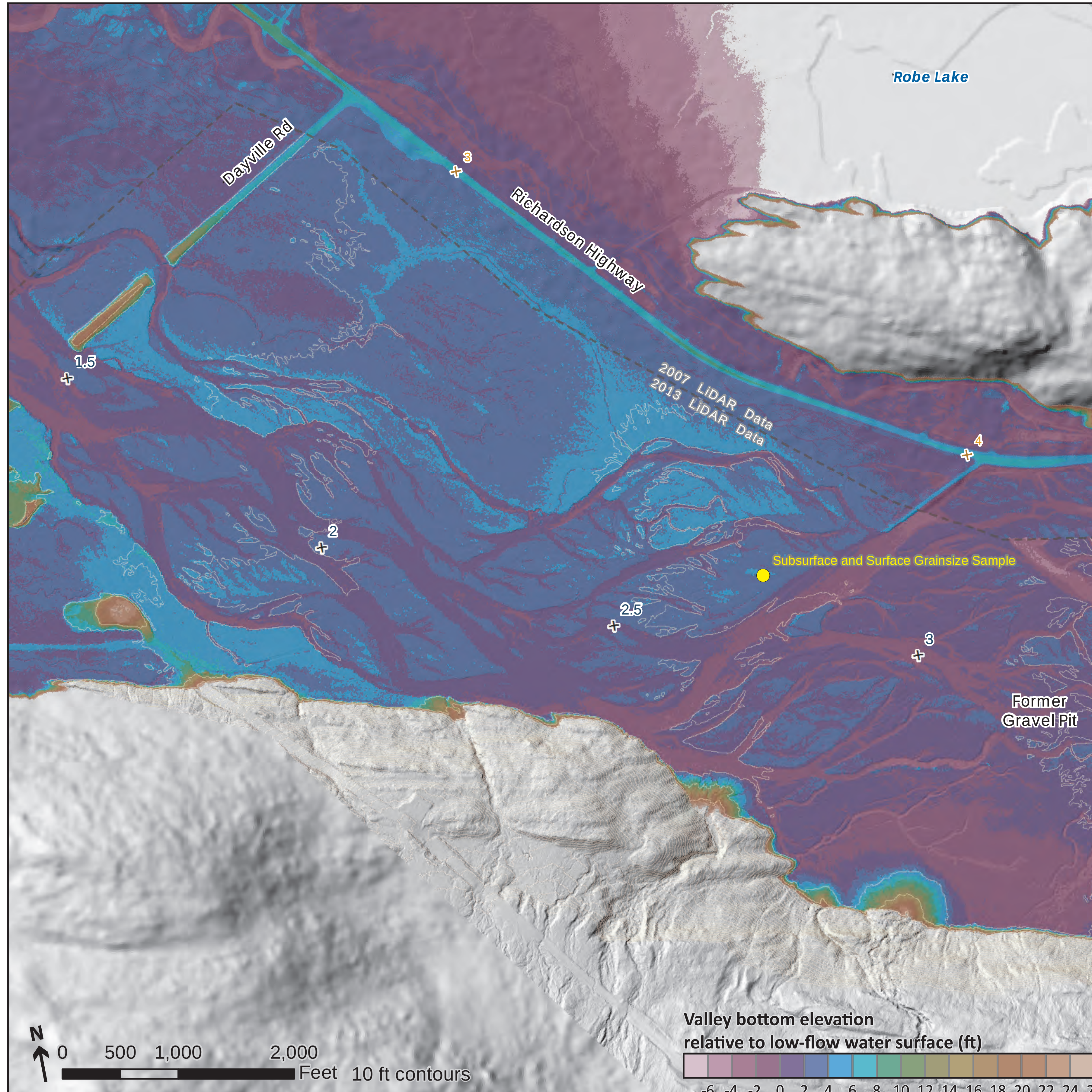
Location of Sample Lowe 7 is on the bar barely visible on the lower right part of the frame.

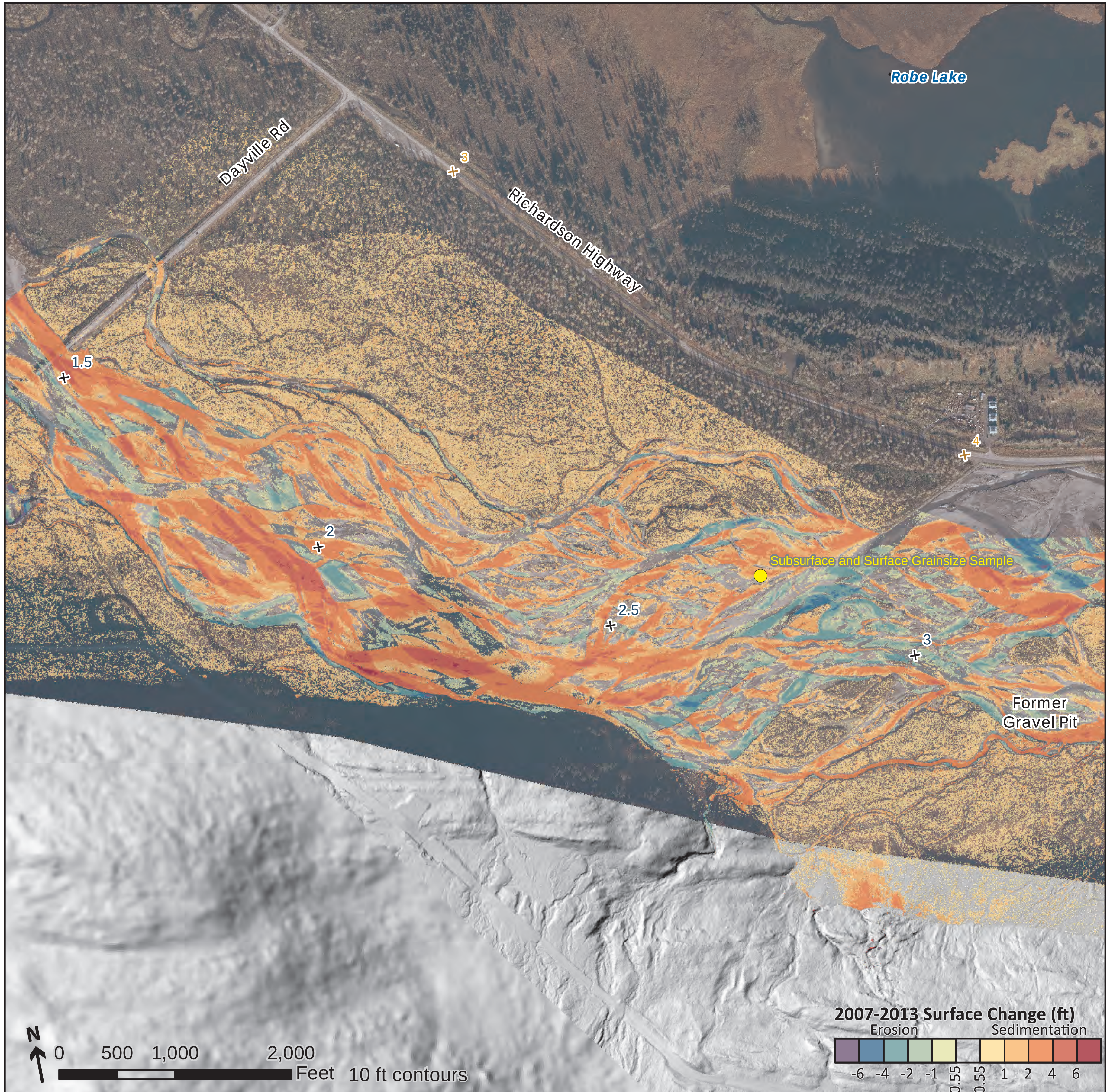
Geomorphic Conditions RM 1.5-3.5

- A large floodplain mine pit on the left bank was excavated sometime prior to 1978, presumably during the early 70s associated with construction of the Trans Alaska Pipeline.
Landsat data show an avulsion through this pit initially forming as a small side channel between 1984 and 1986, and then enlarging to capture the dominant channel between 1987 and 1989. Since 1989, active channels have disproportionately followed this avulsion alignment.
- The spur dike at RM 4 intercepts flow from across the floodplain and both concentrates it at the spur's tip and deflects it across the active channel towards the left bank, which has resulted in persistence of active channels at the dike and cutting across the braid plane downstream.
- Between RM 2 and 2.5, the dominant channel alignment runs into the left valley wall, which turns it back into the middle of the floodplain. The Dayville Rd. Bridge approach roadway funnels flow through the bridge opening, and has maintained a persistent channel alignment through the bridge.
- 2007 LiDAR data show the offset in floodplain elevations across the Richardson highway range from 2-5 feet between milepost 3 and 4.1, suggesting the long term aggradation rate in this area has been in the range of 0.3 to 1.1 in/yr., which is somewhat slower than indicated in upstream reaches.
- Harris Sand and Gravel presently removes an unknown volume of bed material from the channel at the Dayville Road Bridge, which may contibute to relative stability of the dominant channel position in this area (p. 25).

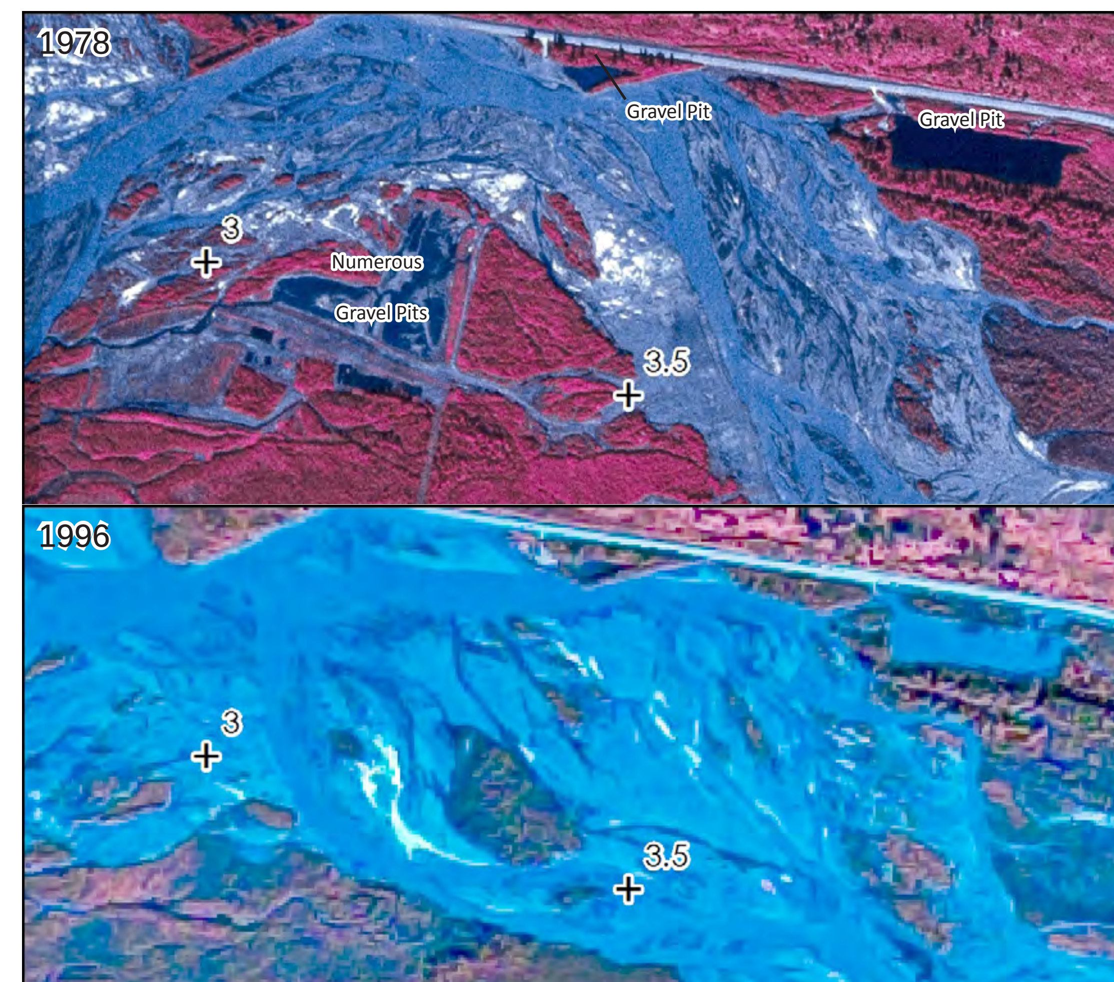
View looking downstream of the Dayville Rd. Bridge during flood conditions.

Site of sample Lowe 3.





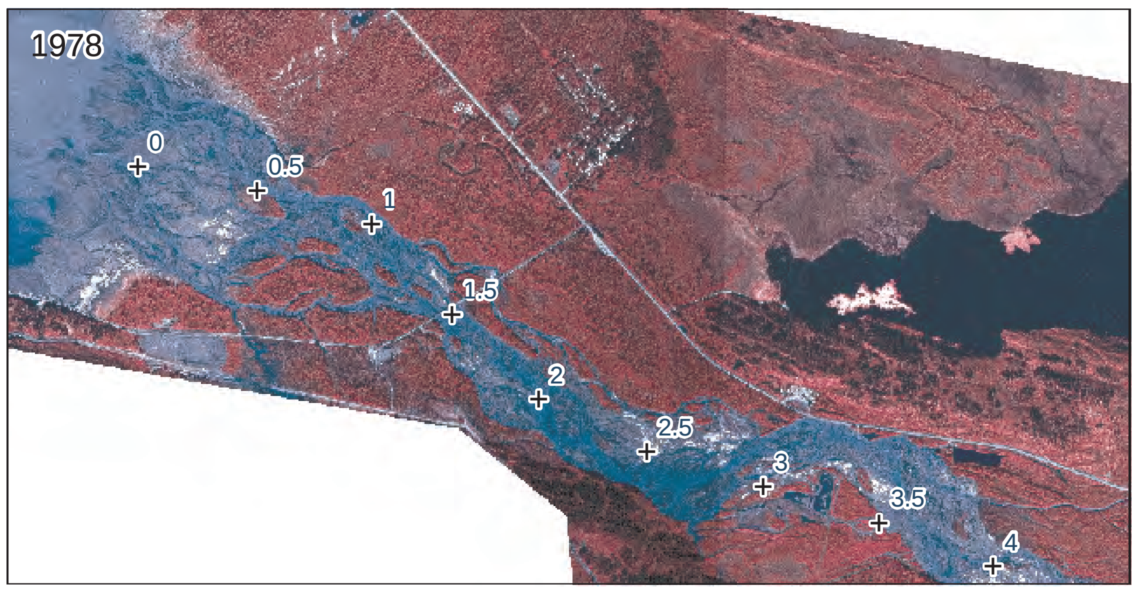
View upstream from approximately RM 2 towards confluence of Avulsion Channel and South Channel.

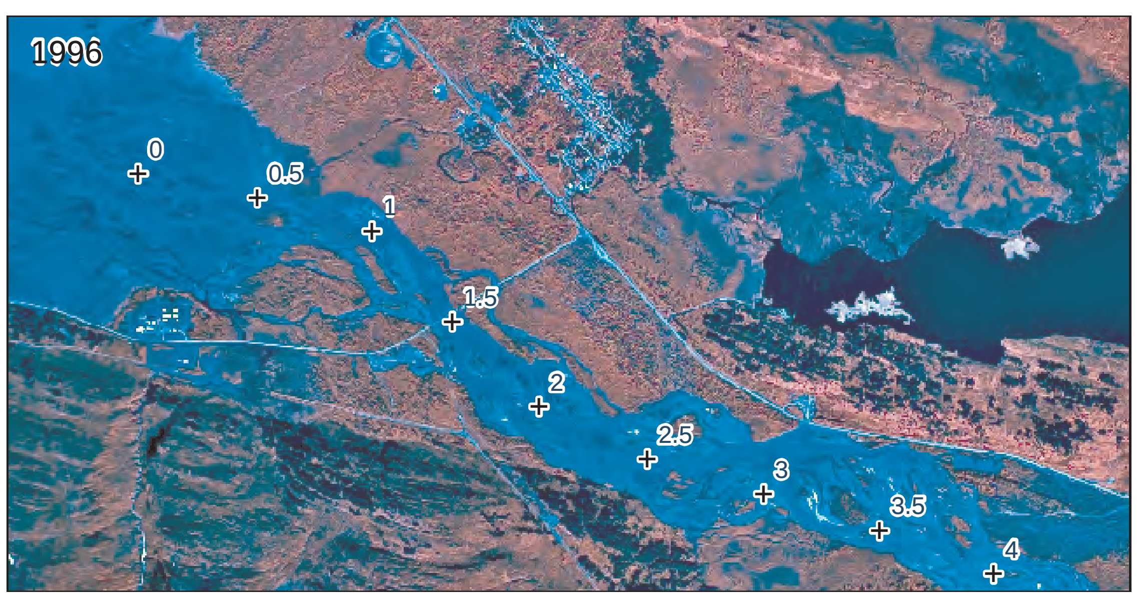


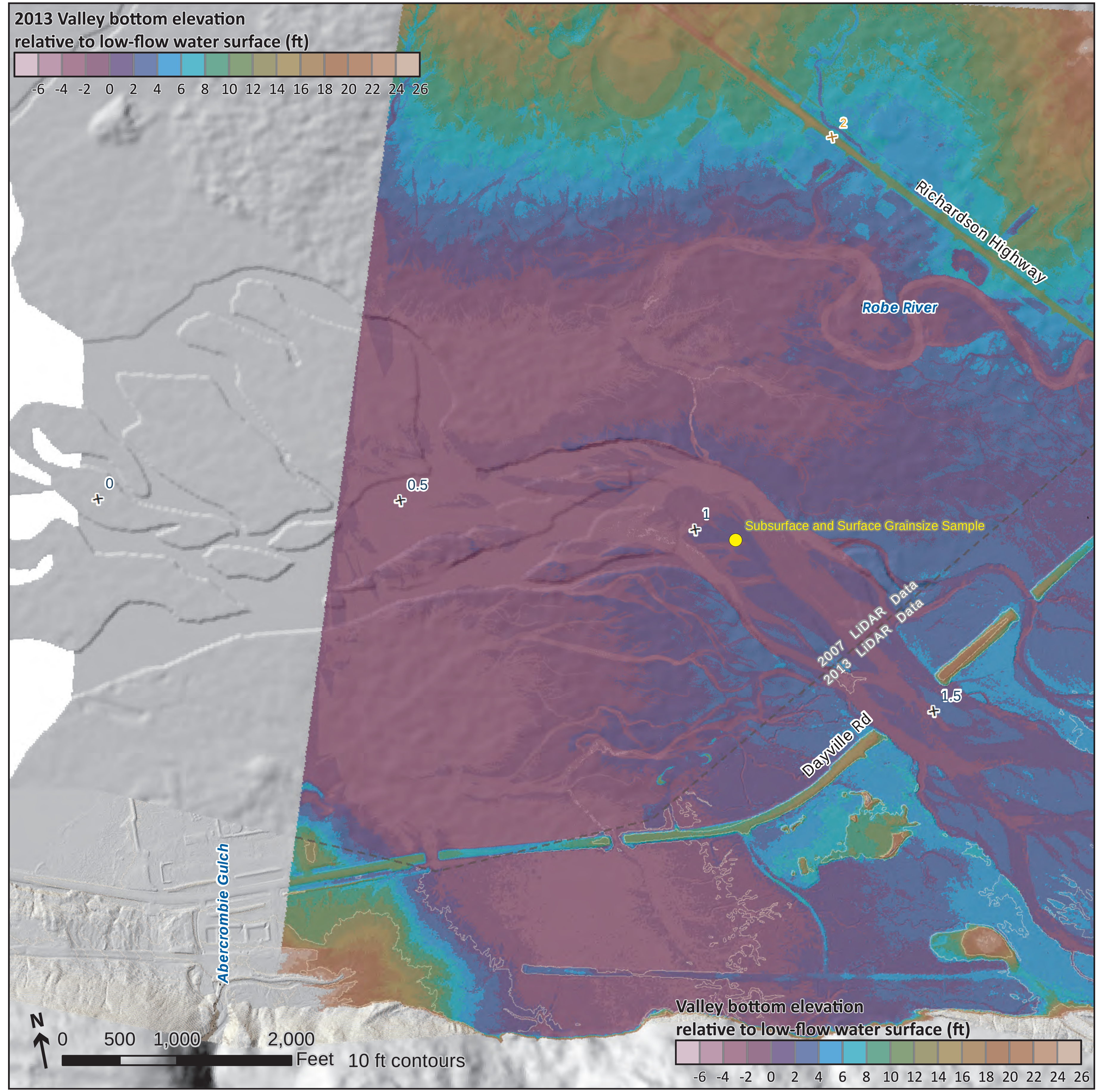
Gravel pits, particularly those on left bank between RM 3 and 3.5 have strongly influenced this reach.

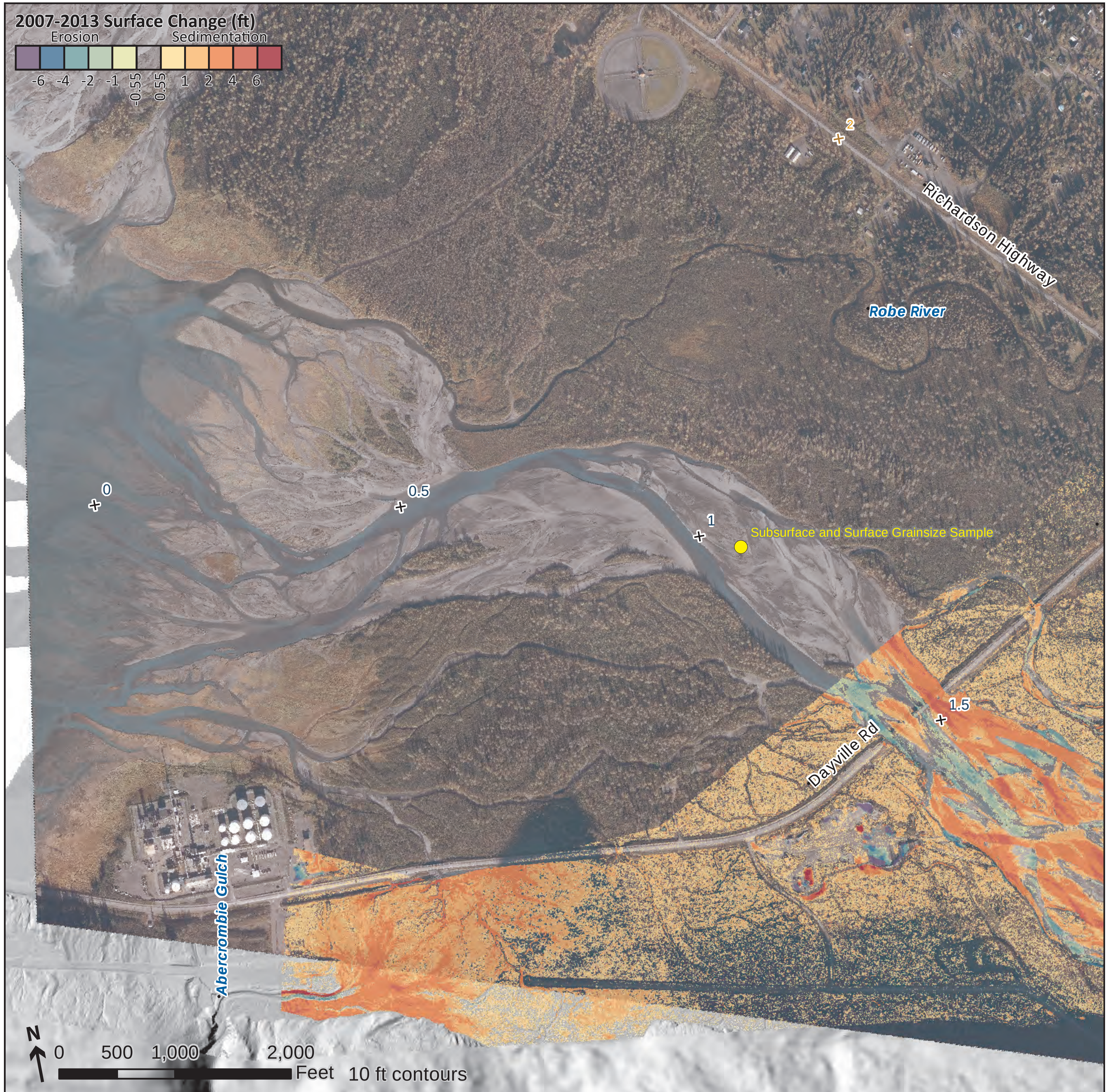
Geomorphic Conditions RM 0-1.5

- This reach is dominated by Lowe River Delta, where hydraulics are controlled by both upstream flow from the river and tides in Port Valdez. The upstream extent of tidal influence is probably at approximately RM 0.8, estimated using the tidal datum adjustment described below and assuming a very limited backwater length given the steep slope of the river.
- Gravel up to 45 mm dominated the bed material downstream to the lowest observed bar near RM 1. Given the large range of tidal elevations, gravel is believed to be flushed across the delta and into deep water during high flow in the Lowe River and low tide conditions.
- Delta progradation is not apparent in comparison with historical aerial photos. The Lowe River Delta failed in a catastrophic submarine landslide triggered by the 1964 Great Alaska Earthquake (e.g. Parsons et al 2014). Failed areas may have created a large volume of deep-water accommodation space for sedimentation, so that a large volume of delta sedimentation may occur without causing delta progradation.
- NOAA has not published a relation between the local tidal datum and orthometric elevations. The elevation of tidal marshes, which corresponds to a typical mean higher water elevation (18 ft tidal datum) is approximately 15 ft orthometric. Approximate orthometric elevations for other tidal elevations can then be calculated from the tidal datum offset by -3 ft; this procedure results in elevations of approximately 10 and 5 ft geodetic for the mean sea level and mean low water, respectively.









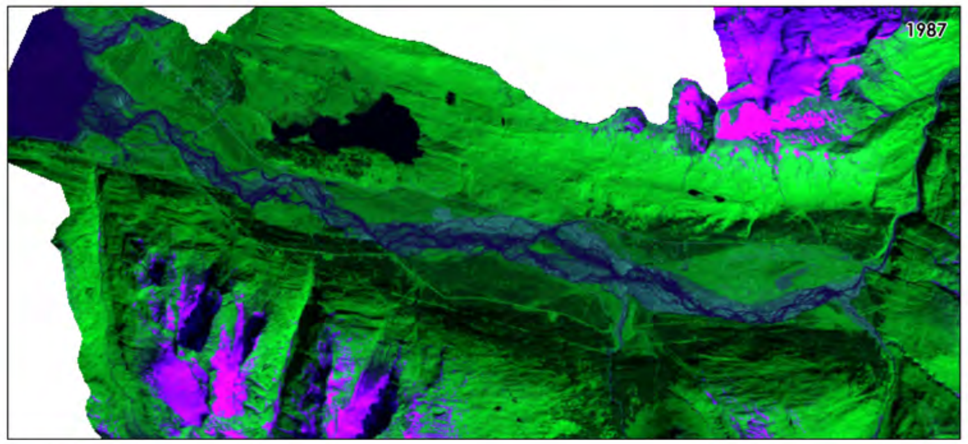
Site of Sample Lowe 4.

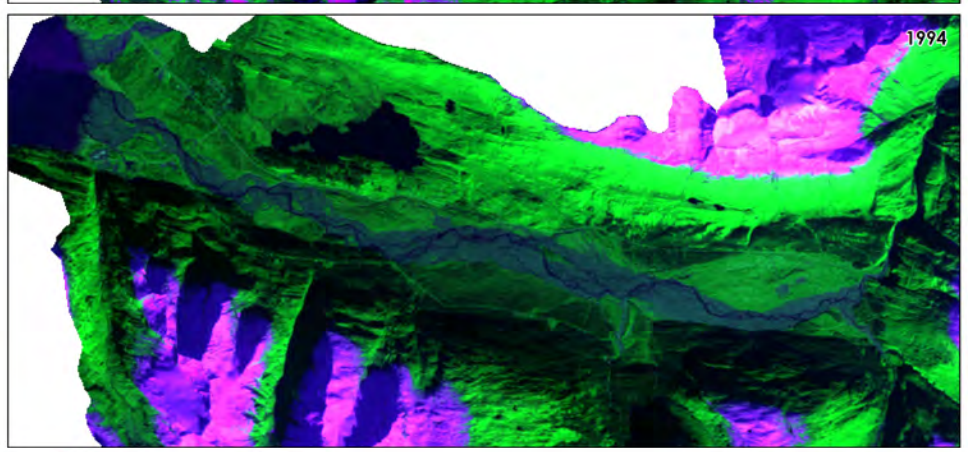

View looking upstream along the bar towards the Lowe 4 bulk sample. Not the abundance of surface sand.

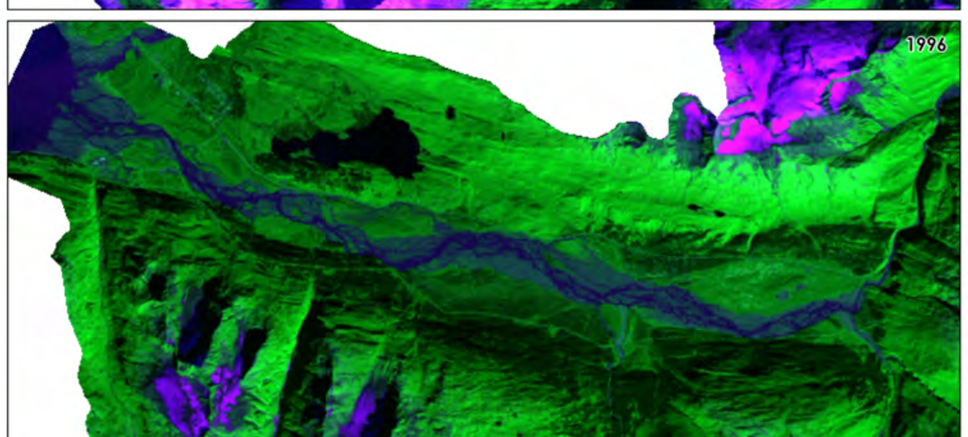
Long-term channel changes

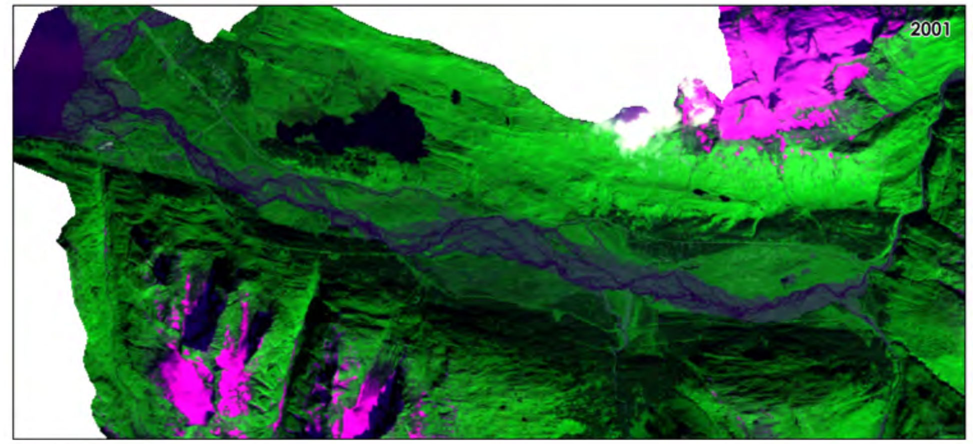
Landsat Satellite imagery provide a view of the study reach with high temporal definition, but low spatial resolution. The following pages illustrate long-term changes in the channel morphology, as observed from this dataset. The valley bottom area was classified into areas of water, sediment bars, and vegetated floodplain from satellite images using the semi-automated image classification toolbox in QGIS, and then manually corrected. Because of the limited resolution of Landsat data areas with many small channels may be miscategorized, but differentiation between the active channel and floodplain is quite good.

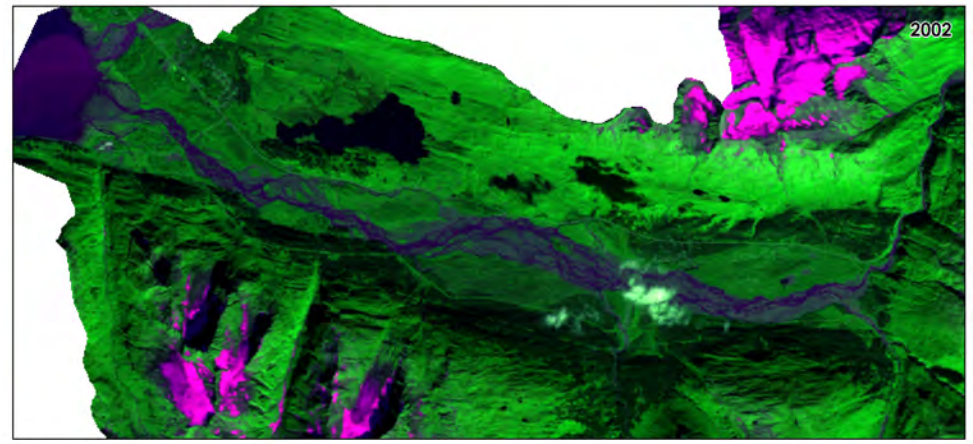
From this classified dataset, it is possible to determine the age of various channel features, and relative stability of the wetted channel positions and the active channel, as shown on the next page. Selected satellite images are also shown, but an animated sequence of available satellite images showing historic changes to the study reach can be accessed online: http://i.imgur.com/P95IAsV.gifv.

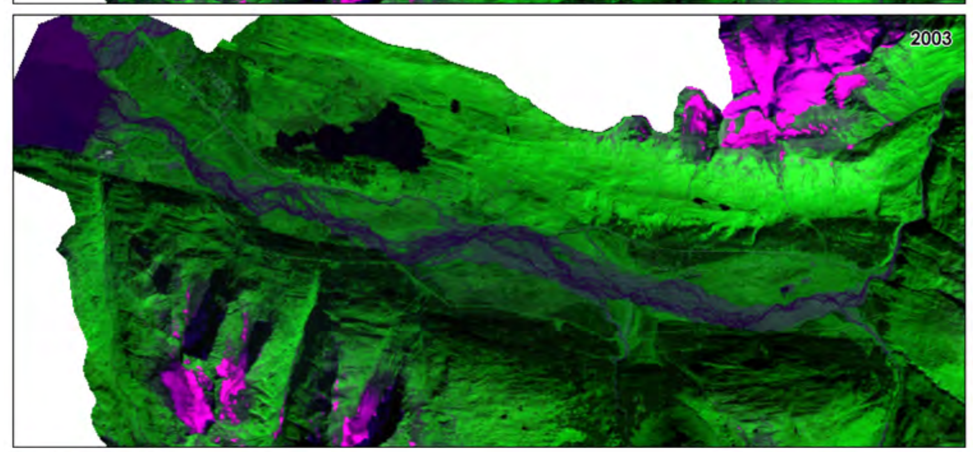


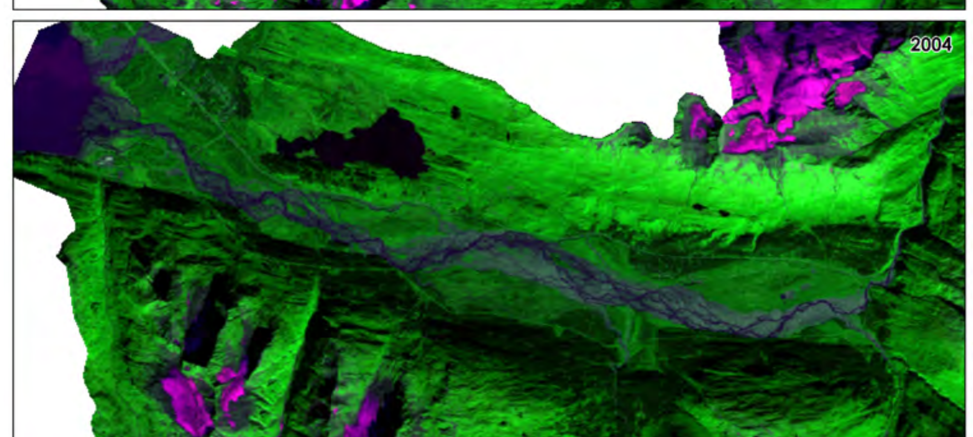


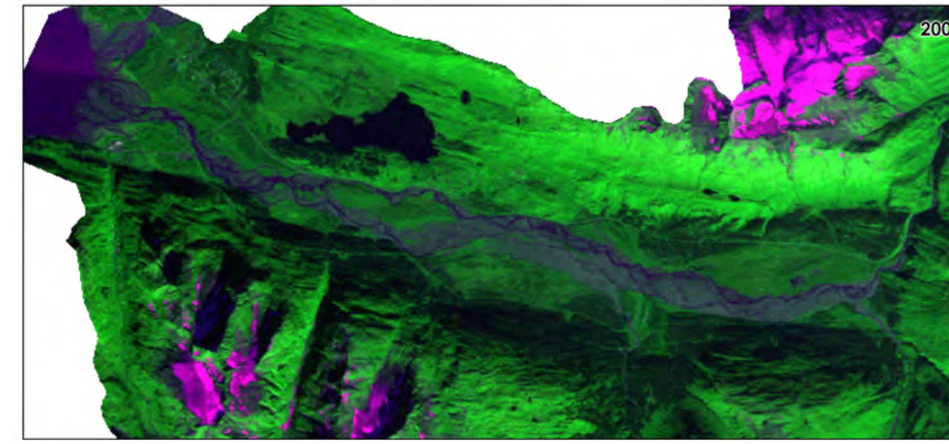


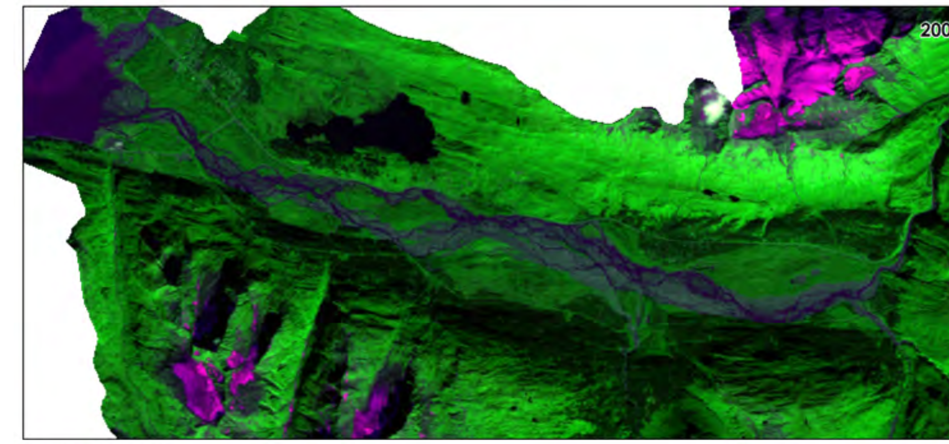


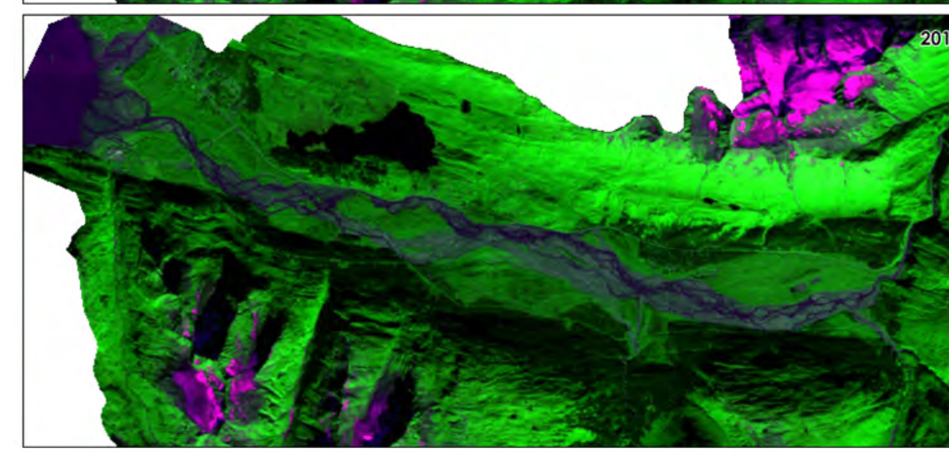


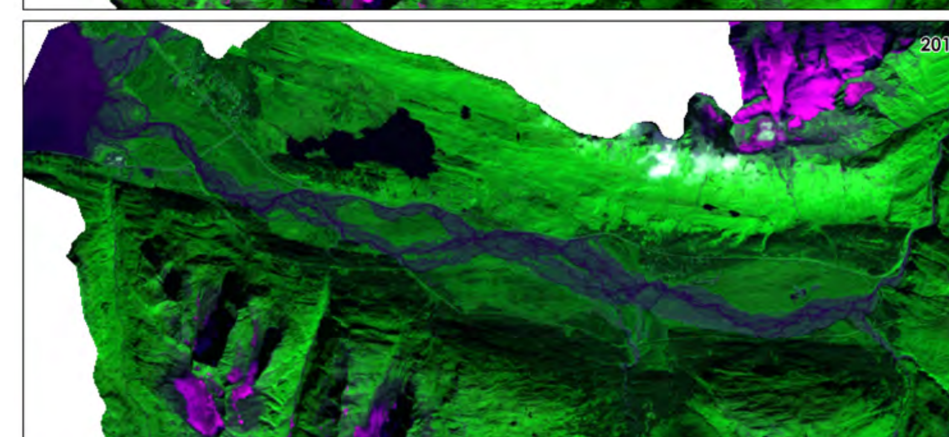




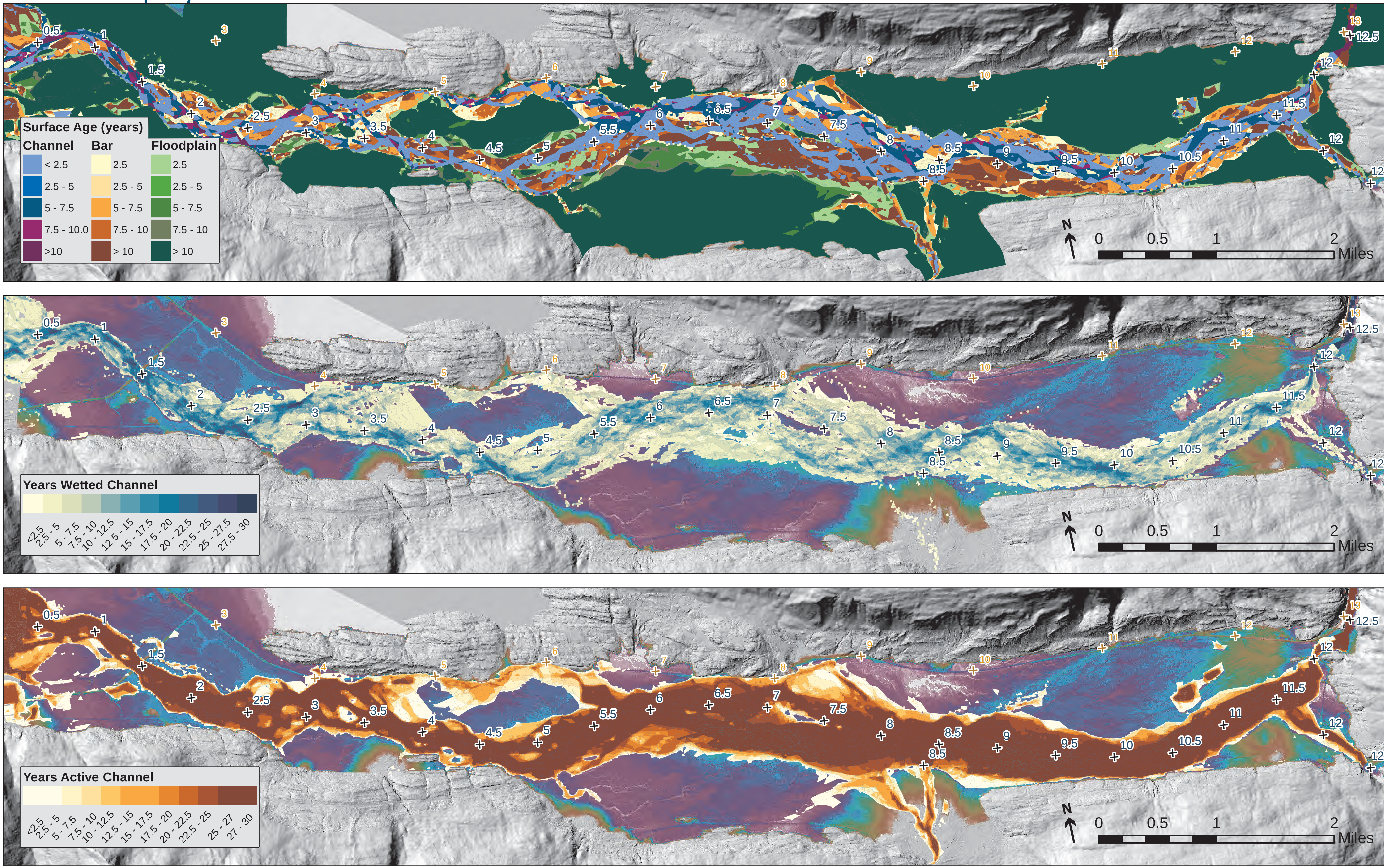








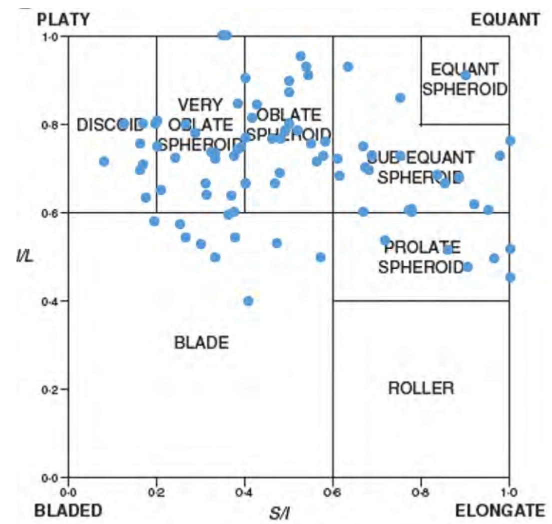
Historic Channel Occupancy Tracks



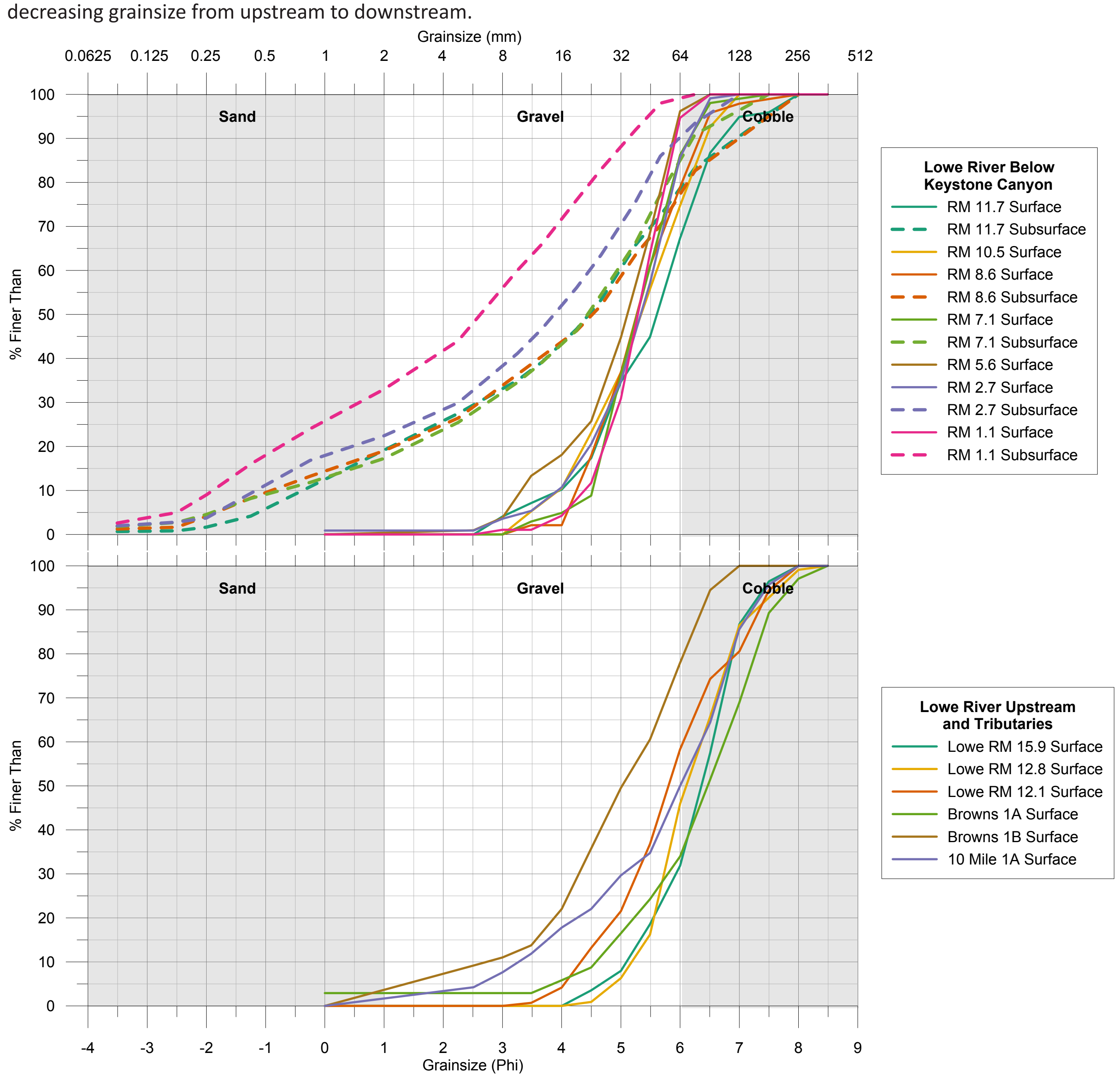
Grainsize Distributions

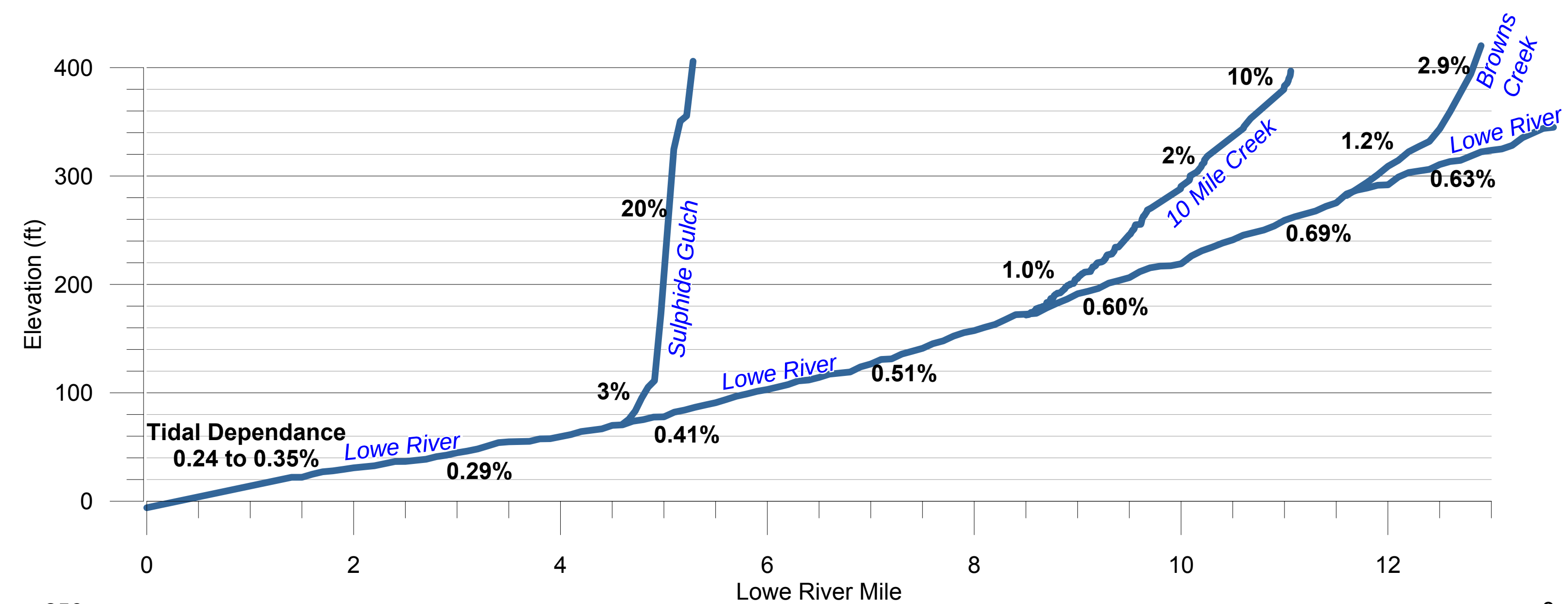
The surface sediment texture on the Lowe River and its tributaries exhibits high local heterogeneity resulting from locally variable hydraulic conditions in the braided channel network and active sediment transport over a wide range of flow conditions. Samples collected from bar heads, thought to be representative of the dominant material in transport are dominated by cobble and gravel size sediment. These show some slight downstream fining trend. The median grainsize (D50) changes little, but the coarsest grainsizes present generally decrease from upstream to downstream.

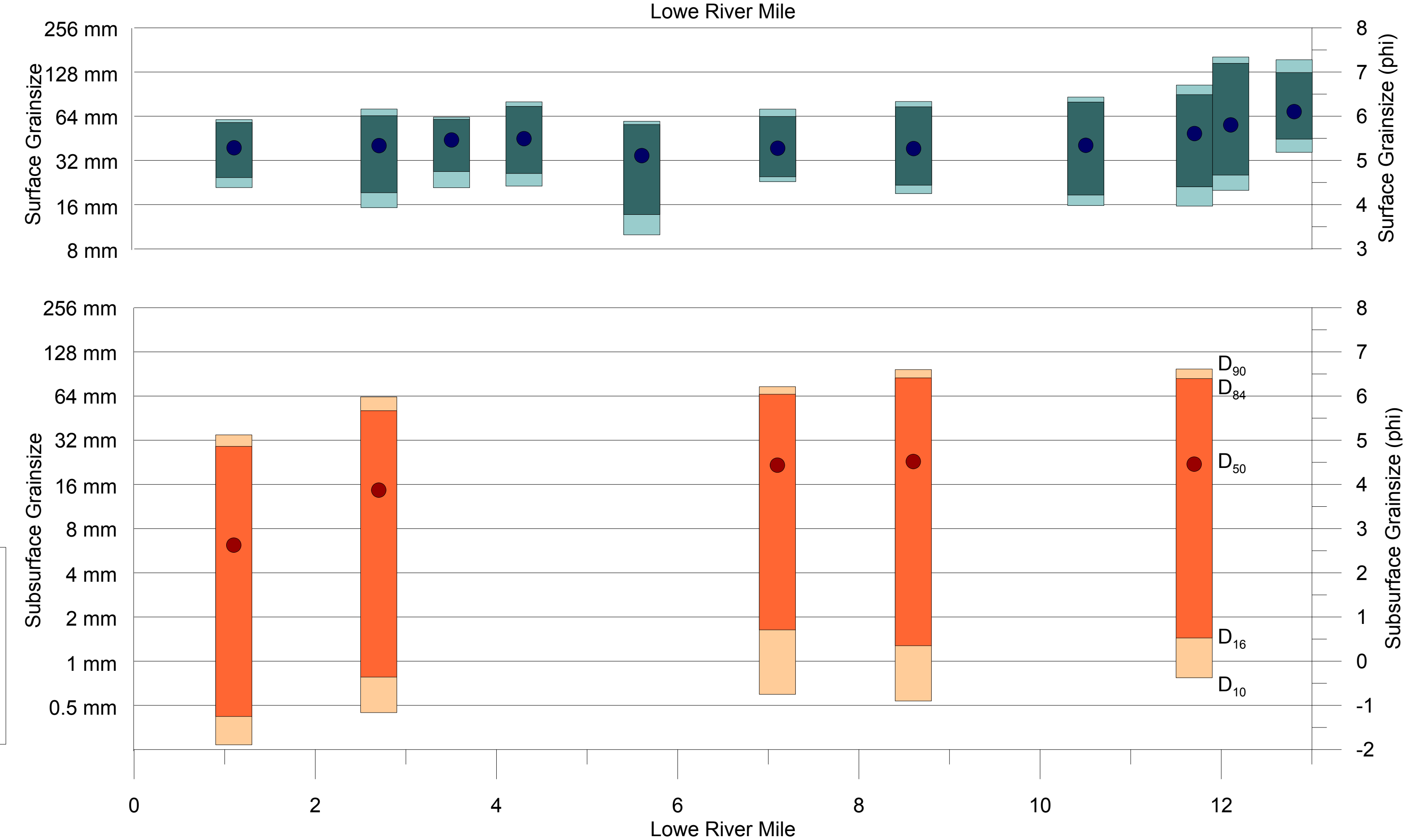
The subsurface sediment is also composed mostly of cobble and gravel size sediment but also has an appreciable (~20%) sand fraction. There is very little silt and finer sediment in the bed material. The set of bulk sediment samples shows a better defined pattern of decreasing grainsize from upstream to downstream.



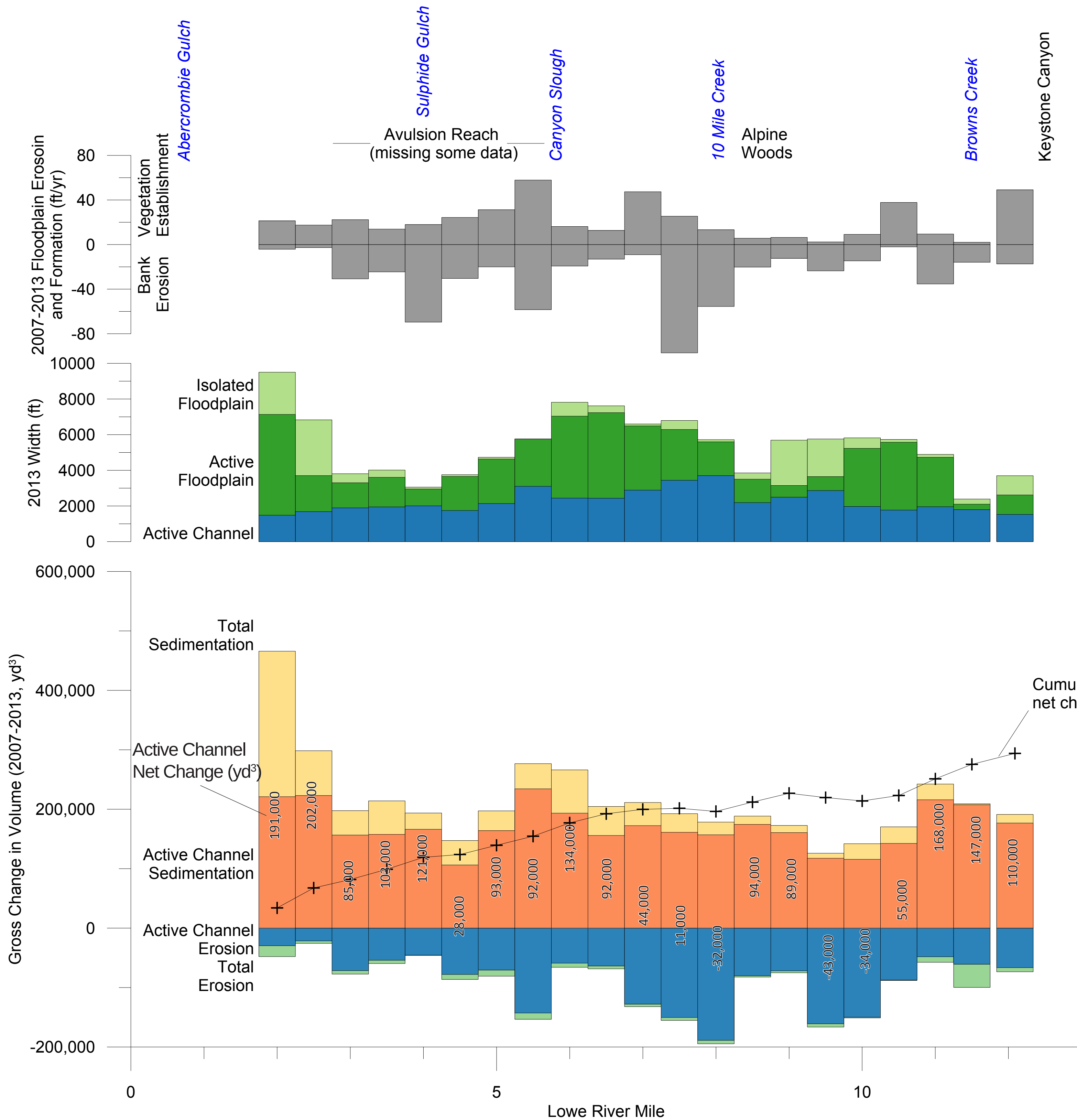
Left: Tri-axial measurements were collected at the “Lowe 10” pebble count. Lowe river bed material is unusually discoid due to the schistosity of the source rock, which may increase their mobility relative to typical sub equant spheroid particles with the same nominal b-axis diameter.







2007-2013 Geomorphic Change

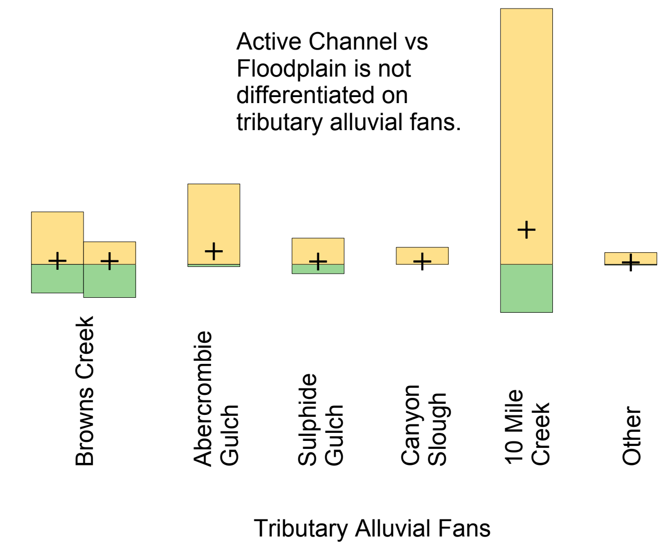


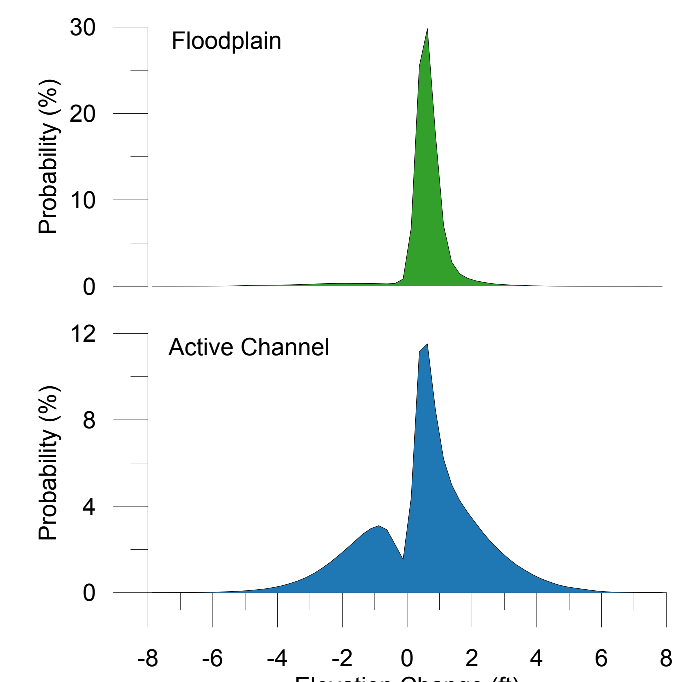
Two LiDAR datasets are available showing the lower Lowe River, one from 2007 (USGS, 2012) and another from 2013 (Quantum Spatial, 2014). Both were acquired during low-flow conditions when water depths on the Lowe River are believed to have been very small, and so a direct comparison can be made between the two surfaces to evaluate the volume of sediment accumulated in the river during the intervening time period. The comparison of the two surfaces, shown in pages 9 to 23 includes several tributary alluvial fans and the entire active channel area of the Lowe between the Dayville Rd. Bridge and Keystone Canyon except a small area in the vicinity of the 2006 avulsion path between RM 4 and 6.

The 2007 data were acquired from USGS Earth Explorer as a classified LAS format with a pulse density of 5.6/m². They had been collected during the period October 7 and 31, during low-flow conditions. Bare earth and water hit points were then gridded to a 1m bare earth DEM using linear interpolation to fill gaps in the bare earth point cloud coverage. The 2013 data were provided by the City of Valdez, processed from point data with a pulse density of at least 6.4/m² into various formats including LAS and a hydro flattened bare earth DEM with 3.0 ft grid cell size. These data were acquired on September 28th and October 6th.

A summary of the observed geomorphic change and comparison to areas of bank erosion and sedimentation and basic planform morphology are shown here. By summing the net value for each river segment, the total net volume sediment accumulation in the active channel can be calculated to be 1.76 million cubic yards between 2007 and 2013, which works out to an average rate of 294,000 yd³/yr. The volume of sediment accumulated in the avulsion channel between RM 4 and 6 is unknown. It can assumed to be positive because the adjacent main channel aggraded and a large area of drowned forest was observed in the area during Fall 2015 fieldwork, indicating channel aggradation has recently occurred. In addition, nearly 400,000 yd³ of sediment accumulated on the alluvial fans of tributary streams.

The rate of aggradation can be calculated by dividing the volume of accumulated sediment by the area over which it was distributed. Between RM 1.5 and 12, the average rate of aggradation in the active channel was 0.38 in/yr and in the whole area of connected floodplain was 0.52 in/yr. These values are within, but on the low side of long-term aggradation rates evaluated at sites where the floodplain has been isolated from the active channel, which range from 0.2 to 4 in/yr. Because of the conservative approach to filtering the LiDAR difference data, it is not surprising that the rate computed over the relatively short period between the LiDAR datasets would be lower than indicated by long-term offset between the active floodplain and isolated areas of the floodplain.





Methodology Note: Detection of geomorphic change between raster surfaces is a somewhat complex process that depends on the confidence in elevation estimates for each individual raster (e.g. Wheaton et al., 2010), and so the method applied here is briefly summarized below. To help address this, the comparison used a simple and conservative method to filter out digital elevation model (DEM) uncertainty and find areas of 'real change.' The method, described by Nelson and Dubé (2015), utilizes the slopes of the compared surfaces and a threshold below which changes are assumed to be noise (in this case set to be 0.55 ft). Comparison of stable road surfaces surrounding the Lowe River (the Richardson HWY and TAPS access road) showed a consistent mean bias placing the 2013 surface 0.76 ft below the 2007 surface, and so the comparison was adjusted by adding this offset. The standard deviation (σ) of the bias difference is 0.18 ft, suggesting that the threshold value of 0.55 ft (3σ) should mask out approximately 99% of the noise in the dataset. This method is conservative, because utilization of a threshold mask excludes some volume of small but real topographic change. Bar heights above the low flow water surface on the Lowe are typically 4 to 8 ft, much larger than this threshold, and so the volume of sediment movement associated with topographic changes less than the threshold is probably trivial.

Lowe River Sediment Budget

Three largely independent methods are available to evaluate the volume of sediment transported into the Lowe River below Keystone Canyon:

• application of traditional sediment transport functions to principal tributaries,
• development of a drainage basin-scaled estimate of total sediment yield, and
• computation of a morphologic sediment budget by evaluating change in bed elevation over time.

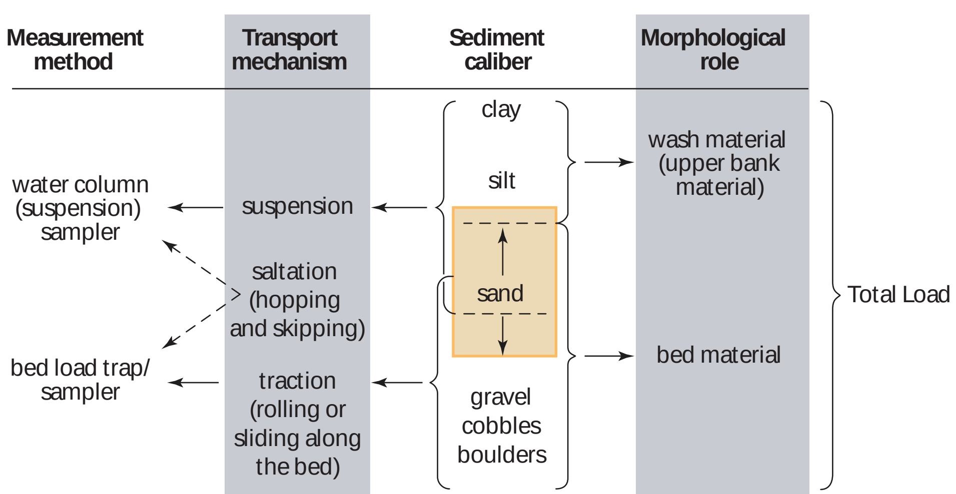
Each of these approaches carries particular assumptions and limitations, and so the best approach is to utilize all available information to determine both a best estimate and range of plausible values for the system.

A fluvial sediment budget applies the principal of conservation of mass to quantitatively account for the rates of production, transport and discharge of sediment in a river (Marston and Marcus in Goudie, 2004). At the reach scale in a river, a sediment budget consists of three fundamental terms, the mass of sediment transported into the reach from upstream (Q_{bi}), the mass of sediment exported out of the reach downstream (Q_{bo}), and the change in storage (ΔS), which includes the mass of sediment added to or removed from storage in the reach through bed aggradation or incision and/or bank erosion or accretion. The three terms are related by the simple equation

$$\Delta S = Q_{bi} - Q_{bo}.$$

Comparison of sediment transport rates with volumetric change requires that the bulk weight of sediment in the river bed be defined. In this case we have assumed a bulk weight of 1.3 t/yd^3.

Before discussing the details of each approach, it is critical to define the different components of a rivers sediment load. The total load of a river is traditional divided by two overlapping categorizations; one depends on the method of measurement, while the other is defined by the materials morphologic role, as shown in the definition figure below. When evaluated by morphological role, the total load is divided into wash material and bed material. The bed material load consists of sand and larger material found on the bed and in bars of a river, while the wash material consists of sand, silt and clay. This material, once entrained by the flow is transported out to the ocean or accumulates in deposits in the floodplain. When evaluated by measurement method, the total load is divided into suspended load and bed load. While there is significant overlap between the two definitions, suspended load does contribute some material to the bed. The focus of this study is to estimate the bed material load of the river.



Overlapping definitions partitioning of the total (solid) load of a river by morphologic role, sediment caliber, transport mechanism, and measurement methods (adapted from Church 2006).

Morphologic Estimate

The most certain element of the sediment budget for the Lowe River is the change in storage, which can be calculated from the LiDAR surface comparison. Based on the estimate of 1.76 million cubic meters of bed material accumulation between 2007 and 2013, the total bed material accumulation rate in the area of the comparison can be computed as **294,000 yd^3/yr,** with 292,000 yd3/yr accumulating above the Dayville Rd. Bridge. In addition, 397,000 yd^3 of sediment accumulated in alluvial fans of tributary streams (Table 4) for an additional bed material input of 66,000 yd^3/yr.

Table 4: Alluvial Fan Sedimentation

Location	Net Observed Sedimentation (yd^3)
Abercrombie Gulch Fan	90,000
Sulphide Gulch Fan	19,000
Canyon Slough Fan	20,000
10 Mile Creek Fan	240,000
Browns Creek Fan	15,000
Other small tributary fans	13,000
Sum	397,000

Gravel, however, is transported past the Dayville Road Bridge onto the Lowe River Delta and so these values can only constrain a minimum estimate of bed material supply to the Lowe River below Keystone Canyon. Evidence for gravel transport past the Dayville Road Bridge includes the strong aggradational trend just upstream of the bridge, the presence of gravel on the river’s delta, and dynamic channel shifting that occurs on the delta.

Sediment Transport Function Based Approach

The morphologic estimate provides a fairly well constrained estimate of the ΔS term of the budget but no information related to sediment input or export from the reach. Sediment transport functions based on the channel hydraulics and grainsize distributions can be used to evaluate these terms, but are subject to substantial uncertainty (probably approximately ± 50-100%) . In particular, estimation of sediment transport rates in braided rivers from channel hydraulics is extremely complex due to the strongly non-linear relationship between bed shear stress and sediment transport rates, so that traditional cross-section averaging of hydraulic parameters prior to computation of transport rates tends to underestimate the actual transport rate (e.g. Ferguson, 2003; Bertoldi et al., 2009). Therefore, sediment transport was evaluated at four sites where the channel was relatively confined: at the TAPS Bridge, near the heads of the Browns Creek and 10 Mile Creek alluvial fans, and just upstream of the Dayville Road Bridge.

Sediment transport rates were calculated utilizing the BAGS spreadsheet calculator (Pitlick et al., 2009) using the local bed slope, grain roughness, and surveyed cross sections. These were then converted to annual volumes by applying the flow duration curves shown on page 4 and a bulk density of 1.3 tons/yd^3. Bulk subsurface grainsize distributions were utilized at the TAPS Bridge and upstream of the Dayville Road Bridge (samples 1 and 4, respectively), that paired the sample from the first major bar downstream of the cross section with hydraulics at the cross section. The Parker and Klingeman (1982) bedload transport function was used at these sites where subsurface grainsize data was available. No subsurface data were collected at Browns Creek and 10 Mile creek, and so the surface grainsize distributions Browns 1A and 10 Mile 1A surface samples with 17% sand and Wilcock and Crowe (2003) sediment transport function was used. Resulting estimates are shown in Table 5.

Table 5: Sediment Transport Function Based Estimates

Q_{bi}:	Lowe R. @ TAPS bridge	Browns Creek	10 mile creek
	686,437 yd^3/yr	46,725 yd^3/yr	408,726 yd^3/yr
Q_{bo}:	Lowe R. above Dayville Rd. Bridge		
	413,325 yd^3/yr		

Basin Scaling Estimate

The basin scaling estimate provides a check to confirm that the morphologic and sediment transport-based estimates are rational given what is already known about conditions in the basin. Workers seeking to understand sedimentation processes in Port Valdez have constructed sediment budgets for the deep water portion of the port based on both one-year of observation of suspended load in tributaries (Sharma and Burbank 1973 in Naidu and Klein, 1988)) and benthic sedimentation rates (Naidu and Klein, 1988). These estimates provide close agreement that about 2.63 million tonnes (Mt) of fine sediment accumulate annually in the basin, this material is equivalent to the wash load of the tributary streams. Of this total, 0.36 Mt is explicitly attributed to Shoup Glacier, which is a tidewater glacier flowing into Shoupt Bay, an arm off the northwestern edge of Port Valdez. In order to estimate the total Yield for the Lowe River, the remainder must be partitioned by the basin area and characteristics of contributing catchments. In this case, the contributing catchments are all quite similar, with the exception that some flow through significant lakes. The table below shows the resulting partitioning of the total sediment supply to Port Valdez by basin. Depending on the assumed trap efficiency of lakes, the total estimated wash load for the Lowe River ranges from 1.4 to 1.6 Mt/yr (Table 6).

In order to use this value to estimate the bed material load, it is necessary to estimate the proportion of the total load that is wash load. Without significant local calibration data in basins with similar physiography, this estimate is subject to substantial error. The best tool available for estimate it is the empirical dataset gathered by Turowski et al. (2010), who gathered data on the bed load and suspended load partitioning of large number of rivers and streams and evaluated the influence of basin area and glacial cover. Based on the basin area, 82% of the total load is expected to be suspended load, but streams with larger glacial cover tend to have higher bed load fractions, and so a value approaching the lower bounding envelope of 55% may apply in this basin. Using this range of values and the range of wash load estimated presented above, the total estimated bed load for the river would be 250,000 to 715,000 t/yr.

An approximate conversion from bed load to bed material load can be obtained from the proportion of sand and finer material in the bulk bed samples collected as a part of this study. These five samples ranged from 17% to 33 % sand (by weight) with an average value of 22% sand. The bed material load is the bedload plus the interstitial sand deposited on the bed from suspension, and so would be about 22% greater than the estimates presented above (310,000 to 872,000 t/yr). Finally, applying a bulk density of 1.3 t/yd^3 then gives a total bed material volume transport estimate of **239,000 to 671,000 yd^3/yr.**

Table 6: Basin Scaling Estimate of Total Yield for Lowe River

			Suspended Load Estimate (t/yr)		
				lake trap efficiency	
Contributing Basin	Area (mi2)	% of basin area	simple basin area scaling	50%	90%
Mineral Creek	45	7%	153,000	174,000	195,000
Valdez Glacier (above lake)	140	21%	468,000	267,000	60,000
Valdez Glacier Stream (below lake)	39	6%	130,000	148,000	167,000
Local Tributaries (below lakes)	56	8%	188,000	214,000	240,000
Local Tributaries (above lakes)	24	4%	81,000	46,000	10,000
Lowe River	370	55%	1,241,000	1,413,000	1,589,000

Sediment Budget Summary

Results of the three independent methods for estimating the sediment budget for the Lowe River are broadly consistent, suggesting a bed material transport rate on the order of 500,000 yd^3/yr. Sediment transport calculations suggest the highest total flux, with a total input of 1.1 Million yd^3/yr, output of 410,000 yd^3/yr, and change in storage (including alluvial fan deposition) of 680,000 yd^3/yr. Because the change in storage parameter is relatively well known, the best available estimate of the sediment budget for the system can be obtained by scaling the sediment transport function results down by about half to fit the known aggradation. The conceptual diagram to the right shows the resulting completed sediment budget, which suggests a total bed material input of approximately 537,000 yd^3/yr, output of 194,000 yd^3/yr, and change in storage of 292,000 yd^3/yr along the Lowe River and 51,000 yd^3/yr on the alluvial fans of Browns and 10 Mile Creeks.

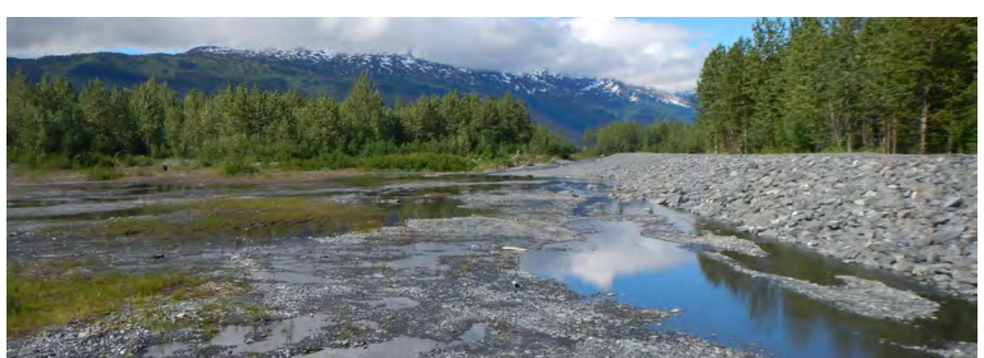
Management Implications

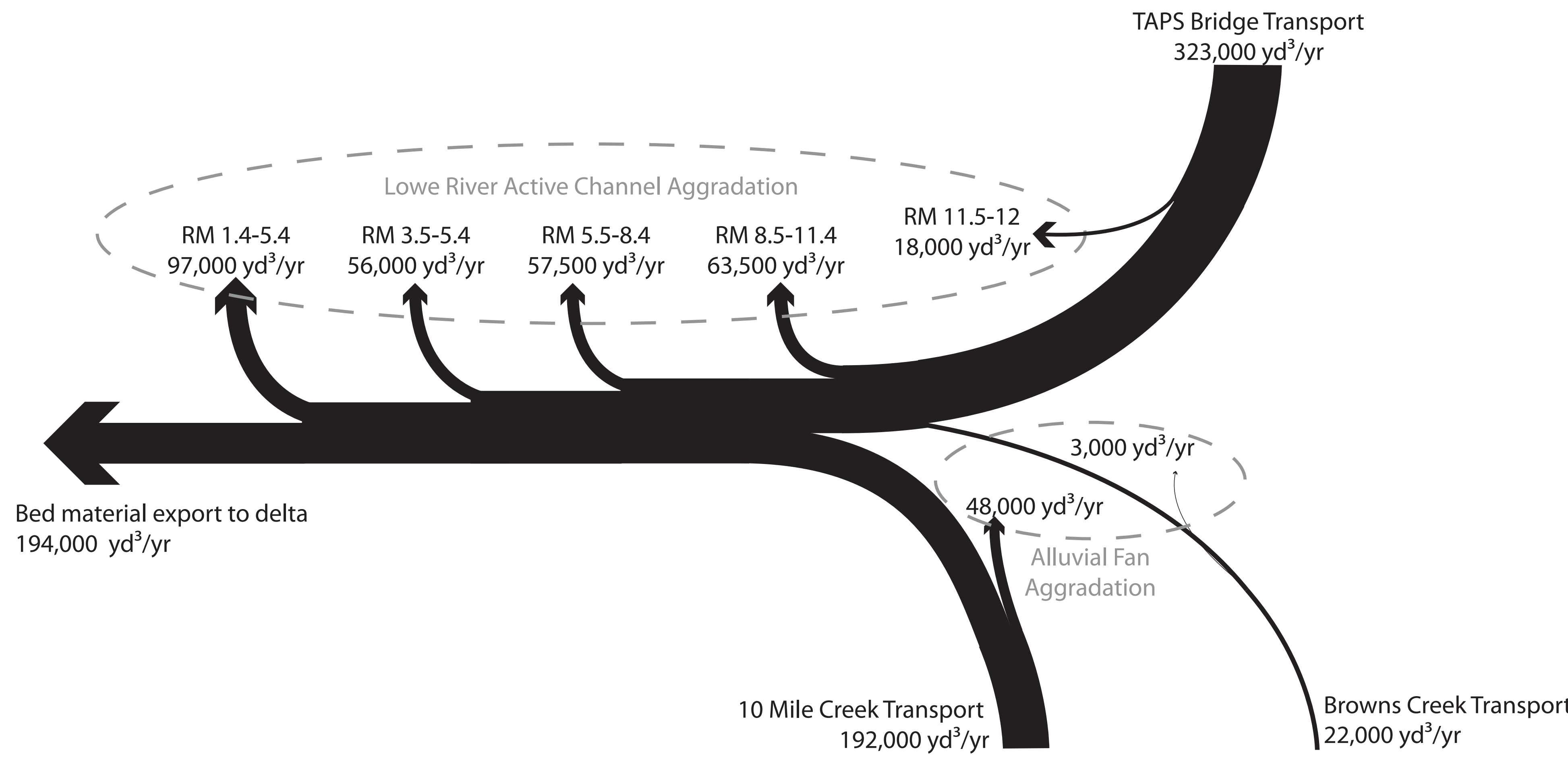
- Aggradation is expected to continue along the whole river profile indefinitely. A long-term gravel removal program would need to remove material from the bed at approximately the net aggradation rate (300,000 yd^3/yr) to eliminate this trend.

- Several large floodplain gravel pits appear to have triggered channel avulsions in the past, and the 10 mile gravel pit upstream of the Alpine Woods Levees is positioned to pull channel migration towards the levees in the near future. Continued expansion of floodplain mine pits is not recommended in areas adjacent to important infrastructure.

- Smaller interventions, such as excavation of pilot channels in the braid plain, may be an effective tool for managing channel migration and erosion hazards over a period of years to one or two decades. These can be designed to cut through high topography formed by dominant channel-proximal sedimentation and to direct the dominant channel into lower regions of the floodplain away from key infrastructure. To avoid adverse impacts to the channel morphology, these excavations should mimic the width, depth, and slope of natural channels. Because sedimentation is concentrated near the dominant channel(s) such a strategy may increase the hazard of catastrophic avulsions, however, over a period of decades to a century.

- Given the bed material sediment budget of the river and size of typical channels and bars the minimum volume for pilot channel excavations is likely around 10,000 yd^3, while the largest appropriate individual pilot channel excavations would be around 100,000 yd^3. Features at the smaller margin of appropriate sizes would not be expected to persist through any bed-mobilizing flows, but may initiate channel formation by the river itself. Larger features may last up to a couple of years.





Above: Gravel-pit excavation just riverward of levee protecting Alpine Woods community.

Right: Flooding behind levee threatening Alpine Woods community during September 29th, 2015 flow event.

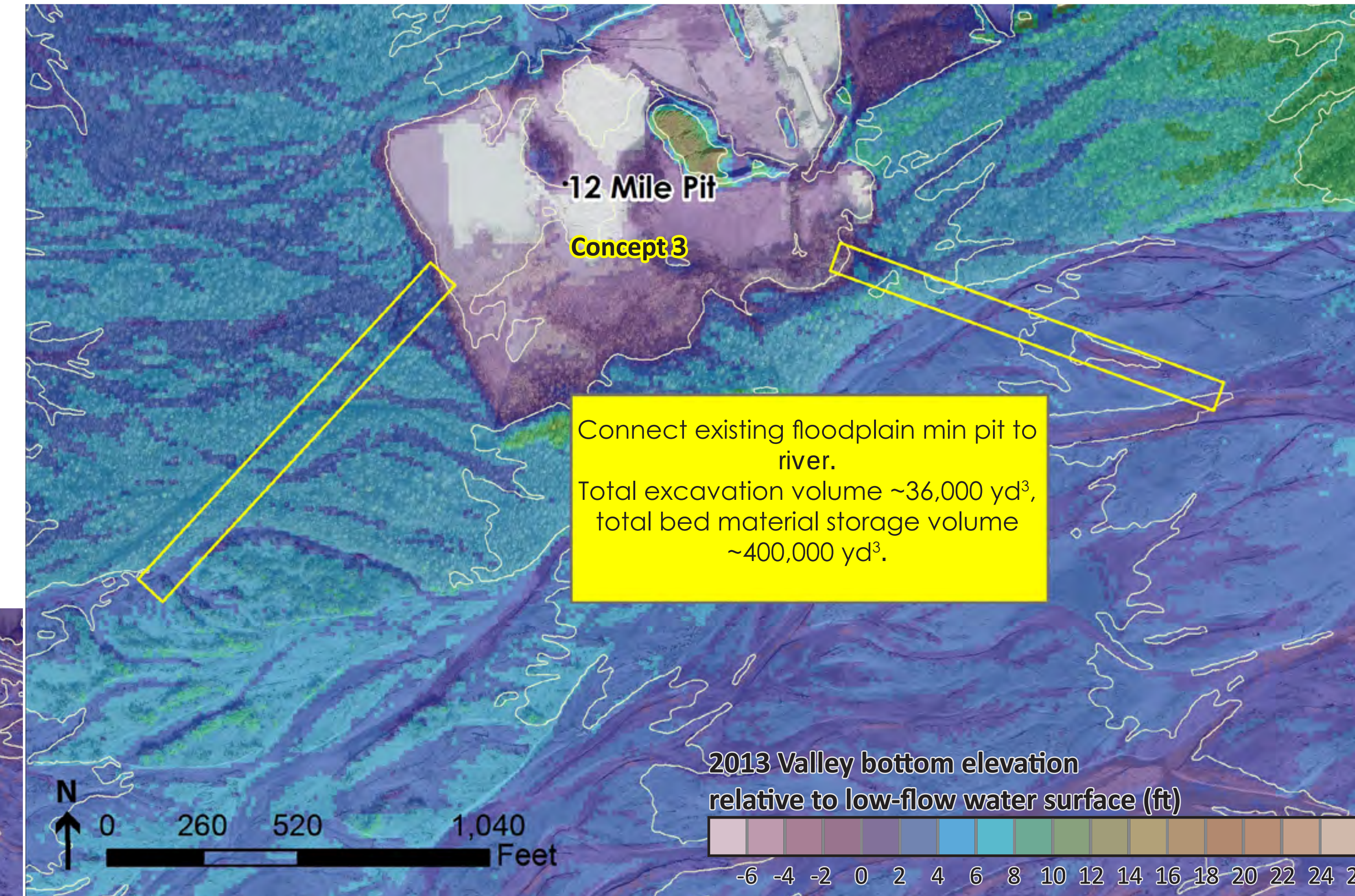
Example Project Concepts

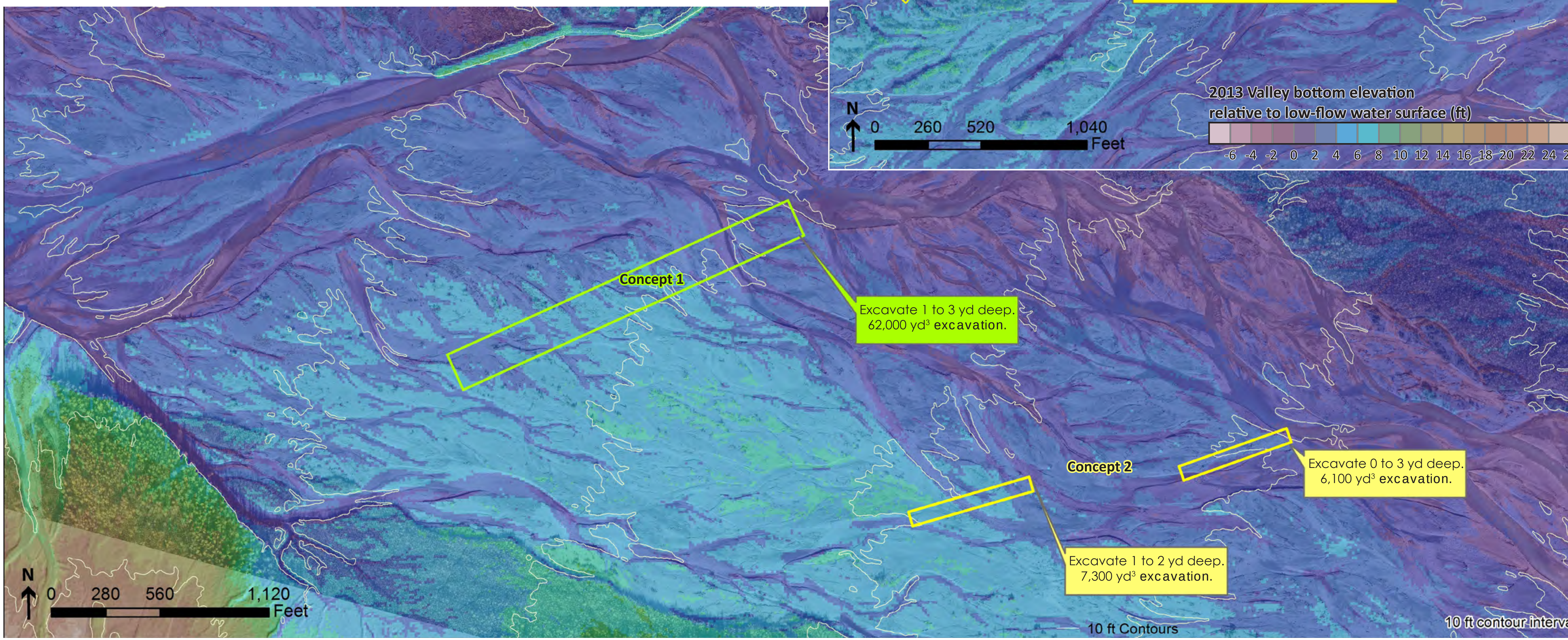
The graphics below and on the following page illustrate several possible projects of varying scale intended to temporarily alleviate channel migration pressure against the Alpine Woods Levees, assuming the 2013 topography for illustration purposes (actual projects would be designed from aerial photos and/or ground survey shortly before excavation). These concepts have been prepared to help illustrate the scale and type of interventions that would be required to potentially mitigate against long-term aggradation. Additional detailed studies and design work would be required to develop specific projects and to assess project impacts and mitigation requirements.

Concept 1, illustrated in green below, would involve removal of approximately 62,000 yd^3 of sediment from the floodplain and cause the dominant channel to avulse past the middle Alpine Woods levee and re-enter the presently active channel zone near the 10-Mile Creek alluvial fan. It is large enough that its impact may persist through several flood seasons.

Concept 2, illustrated in yellow below, involves two smaller excavations connected opportunistically through an existing braid channel. These excavations, with a combined volume of approximately 13,400 yd^3, would likely split the dominant channel and increase engagement of the left bank portion of the braid plain. Given their small size relative to the bed material transport rate of the river, their influence may be wiped out over the course of a single freshet season or significant autumn flood. The resulting channel configuration would be difficult to predict.

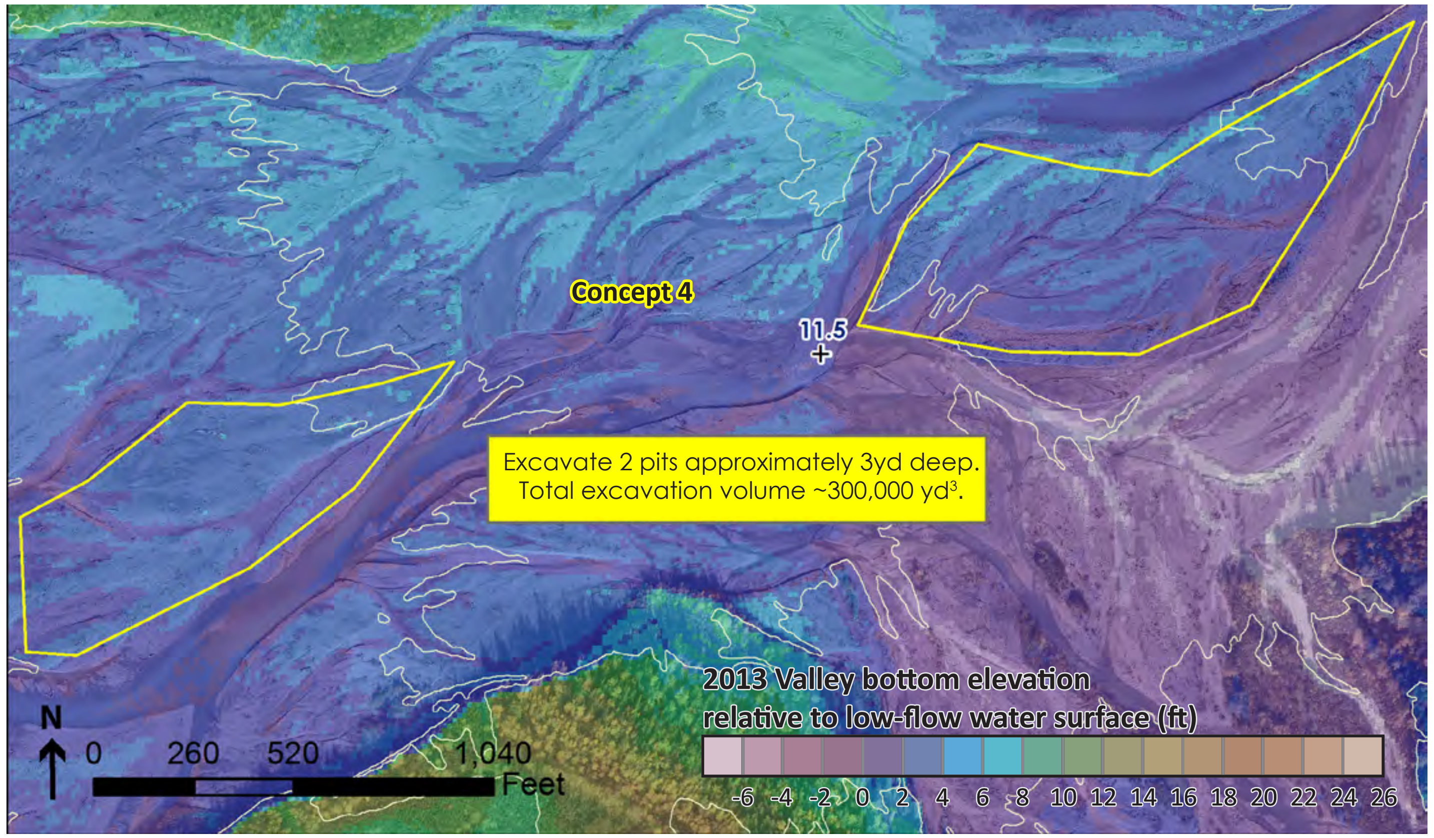
Concept 3, illustrated to the right, utilizes the possibility of connecting 12 Mile pit to the active channel, which provides the opportunity to store a large volume of gravel with relatively little excavation effort. Other similar floodplain pits could be excavated in areas where an avulsion through the pit would not pose a hazard to infrastructure and eventually would be connected to the channel. Implementation of this concept may slightly increase channel migration hazards to the upstream portion of the Alpine Woods Levees, but careful design could mitigate that risk.

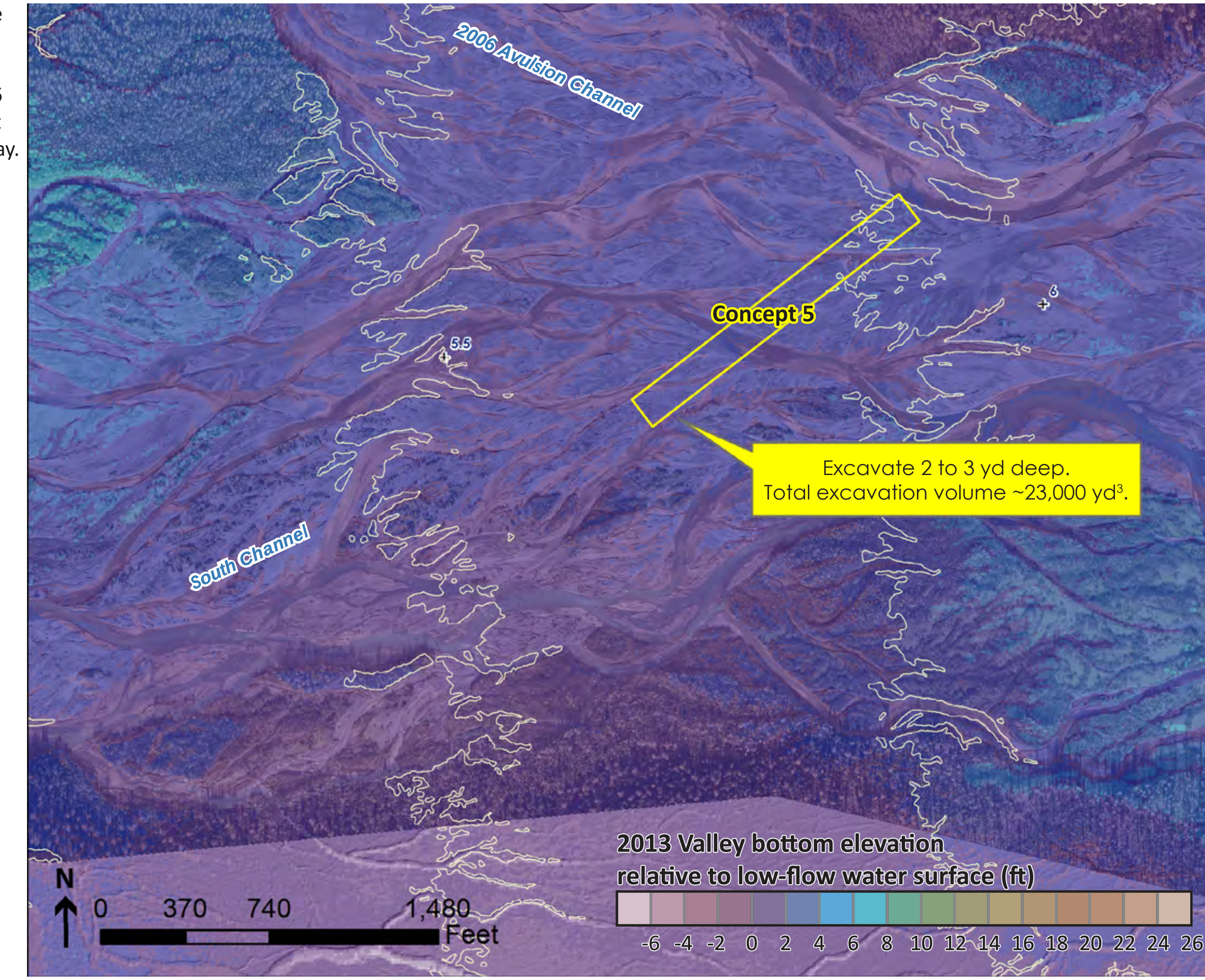




Concept 4, below, is an example of the scale of excavation that would be required annually to approximately counter the reach-wide aggradation trend. Excavations could be concentrated towards the head of the reach, as illustrated here, or distributed along the reach.

Concept 5, right, is an example of a moderate scale excavation intended primarily for river training. This excavation would reduce the proportion of the flow split entering the 2006 avulsion channel and reduce pressure against revetments protecting the Richardson Highway.





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