New Hampshire DOT Research

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Engineered Log Jam Monitoring along NH Route 16 in Errol, New Hampshire

Final Report

Prepared by University of New Hampshire Department of Civil and Environmental Engineering, College of Engineering and Physical Sciences, in cooperation with the U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

Many roads and highways exist close to streams that exhibit lateral instability (bank erosion). Conventional practices are to armor such locations, and these solutions are expensive, do not provide ecosystem value, and result in high mitigation fees. Natural channel design structures, such as engineered log jams, offer a greener, less expensive alternative to armor solutions. Identifying the benefits of natural instream structures to replace conventional armoring solutions can result in significant cost savings.

NH Route 16 in Errol, New Hampshire, is an example. Extreme bank erosion required road relocation and streambank stabilization. A first for New Hampshire Department of Transportation (NHDOT), an engineered log jam solution was selected for the site and constructed in winter 2020/2021. Bank and channel impact mitigation costs were eliminated with the selection of the engineered log jam solution on the Errol project. Had conventional armoring been selected for this project, bank and channel impact mitigation costs were estimated to be $101,000. Prior to this research, there were no demonstrated and documented information about engineered log jam solutions in New Hampshire, and although employed in the Pacific northwest, there is very limited information nationally as well. This three-year project included eight months of pre-construction monitoring and two years of post-construction monitoring. The monitoring was broken into the following facets: hydraulic, structural, flora, and fauna. In addition, the monitoring provided inspection to assess any need for maintenance or repairs. The research objective was to document all salient aspects of engineered log jams relative to road planning, design, permitting, construction, and maintenance. In addition, stream system changes resulting from the engineered log jam were documented.

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3 March 2023

Introduction

Many roads and highways exist close to streams that exhibit lateral instability (bank erosion). Conventional practices are to armor such locations (rip rap, concrete, sheet pile), and these solutions: are expensive, do not provide ecosystem value, and result in high mitigation fees. Natural channel design structures, such as engineered log jams (ELJ), offer a greener, less expensive alternative to armor solutions: providing equivalent streambank protection, but also creating habitat. Route 16 in Errol, NH (locally known as Dam Road) is an example (Figure 1). Extreme bank erosion along Bear Brook/Magalloway River required road relocation and streambank stabilization. An engineered log jam was proposed at the site. Construction began during the winter of 2020 and the first of its kind project for NHDOT was completed in spring of 2021. Identifying the benefits of natural instream structures to replace conventional armoring solutions could result in significant cost savings on similar DOT projects. For the project in Errol, streambank and channel impact mitigation costs were eliminated with the selection of the engineered log jam solution. Had conventional armoring been selected for this project, bank and channel impact mitigation costs alone were estimated at $101,000. There is no such fee for an ELJ. At this writing, there is no demonstrated and documented information about engineered log jam solutions in New Hampshire, and although ELJ are employed in the Pacific northwest, there is very limited monitoring information nationally.

Objective

The research objective is to document the pre- and post-construction hydraulic, sediment, and ecosystem metrics associated with an engineered log jam designed and constructed to arrest streambank erosion.

Methods

To perform this study, the site was surveyed each year (2019 through 2022) both above and below the waterline. Horizontal and vertical control was based on NH DOT survey benchmarks established for the relocation of Route 16. LiDAR data from the NH GRANIT database was used for topographic data above the waterline. Traditional total station survey techniques were used at the immediate ELJ location. The total station surveys extended from the existing Route 16 elevation to approximately 3 feet below the waterline. Below the waterline, bathymetry was measured with an automated boat-mounted sonar system (Zego Boat survey system). This system included, a 14-foot vessel equipped with the hydrographic survey equipment of a 240 kHz Imagenex Delta-T multibeam sonar and Applanix 320 POS-MV GPS-aided inertial measurement system. The bathymetric surveys were conducted with approximately 20-50 cm horizontal resolution and accurate to about +/- 10 cm vertical resolution (depending on the nature of the substrate). A GPS reference base station was deployed during each survey for differential corrections necessary for improving the accuracy of the GPS data to survey grade quality. Digital elevation maps were constructed with custom post-processing software. In addition, during the Zego surveys, an ADCP (RDI 1200 kHz Sentinal Workhorse ADCP w/ pressure sensor) was deployed to measure current velocity and direction useful for hydraulic model calibration.

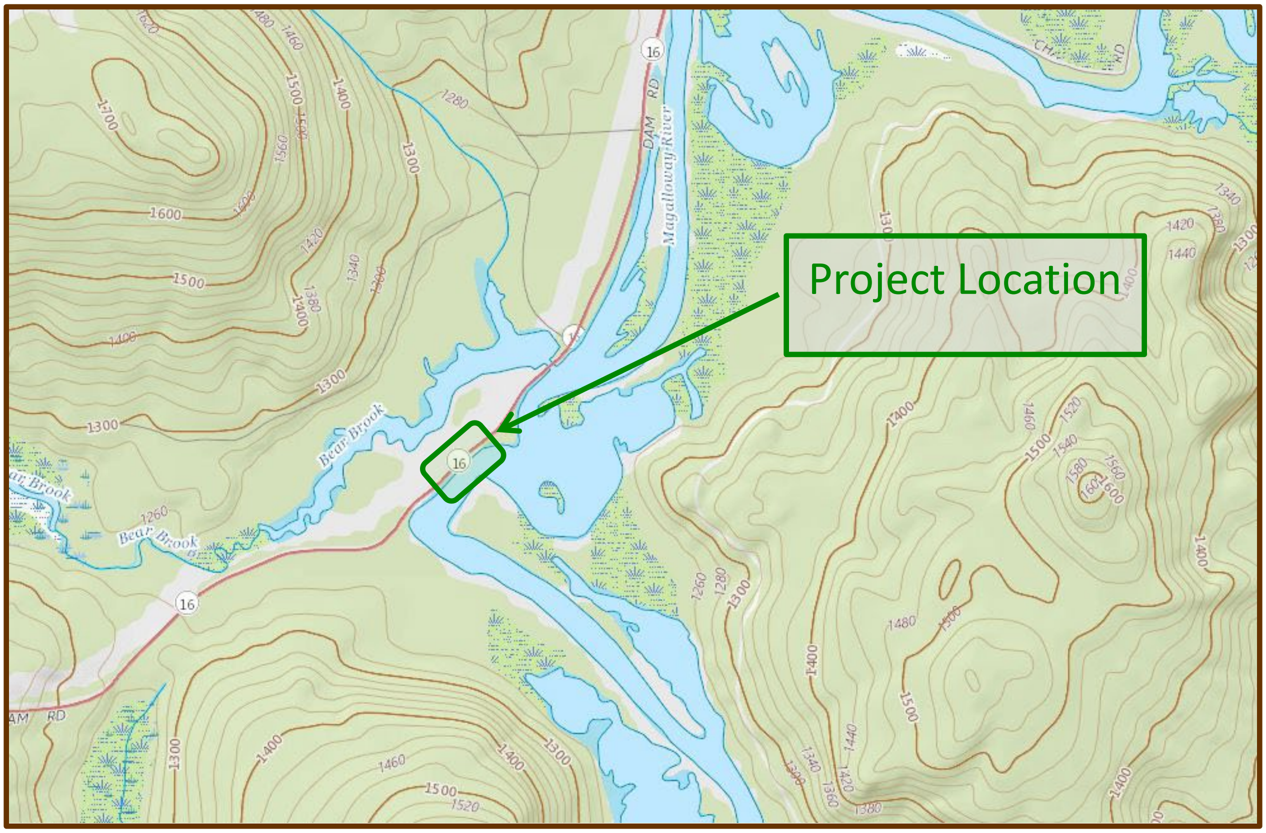

Figure 1. Project location along Route 16.

The hydraulic model used for this project was Aquaveo SMS v13.1. This model was selected in large part because it was the focus of another NHDOT initiative entitled CHANGE (EDC-4 NHI Two-Dimensional modeling at highway crossings). SMS calculates the two-dimensional (depth-averaged) water velocities and stages. In addition to the ADCP deployments for calibration data, HOBO (model U20L-04) pressure transducers were deployed to monitor water stage at specific locations within the model domain. The pressure transducer data were brought to NAVD88 elevations with synoptic water surface elevations shot using a laser level.

Samples of the bank material were taken in order to run a particle size distribution analysis (ASTM D6913). To assess the bank erosion rate at the site as well as other sites (for reference) erosion pins were installed at various locations and read, then re-set annually. An erosion pin is a 3-ft long piece of ½-inch diameter steel rebar that is hammered in horizontally, flush with the streambank. If there is erosion at that location, the rebar is exposed, and the rate of erosion is then equal to the length exposed rebar divided by the time interval since the pin was last re-set flush.

Game cameras were set-up across the river and along the streambank to monitor wildlife. Below the waterline, GoPro videos were recorded and then still shots of any fish were isolated and fish species identified with the assistance of NHF&G and USFWS personnel.

Topographic and Bathymetric Data

Bathymetric surveys with the Zego boat were performed on: 10 July 2019, 17 June 2020, 24 April 2021, and 26 May 2022. Figures 2 through 5 depict the model domain annually from 2019 to 2020. In these Figures, North is rotated 48 degrees clockwise, indicated by the arrows at the bottom left of the Figures. There are no contour lines, but the elevations (feet MSL) are represented by a continuous color fill shown in the legend. Pre-construction images/figures are 2019 and 2020. The post-construction images/figures are 2021 and 2022.

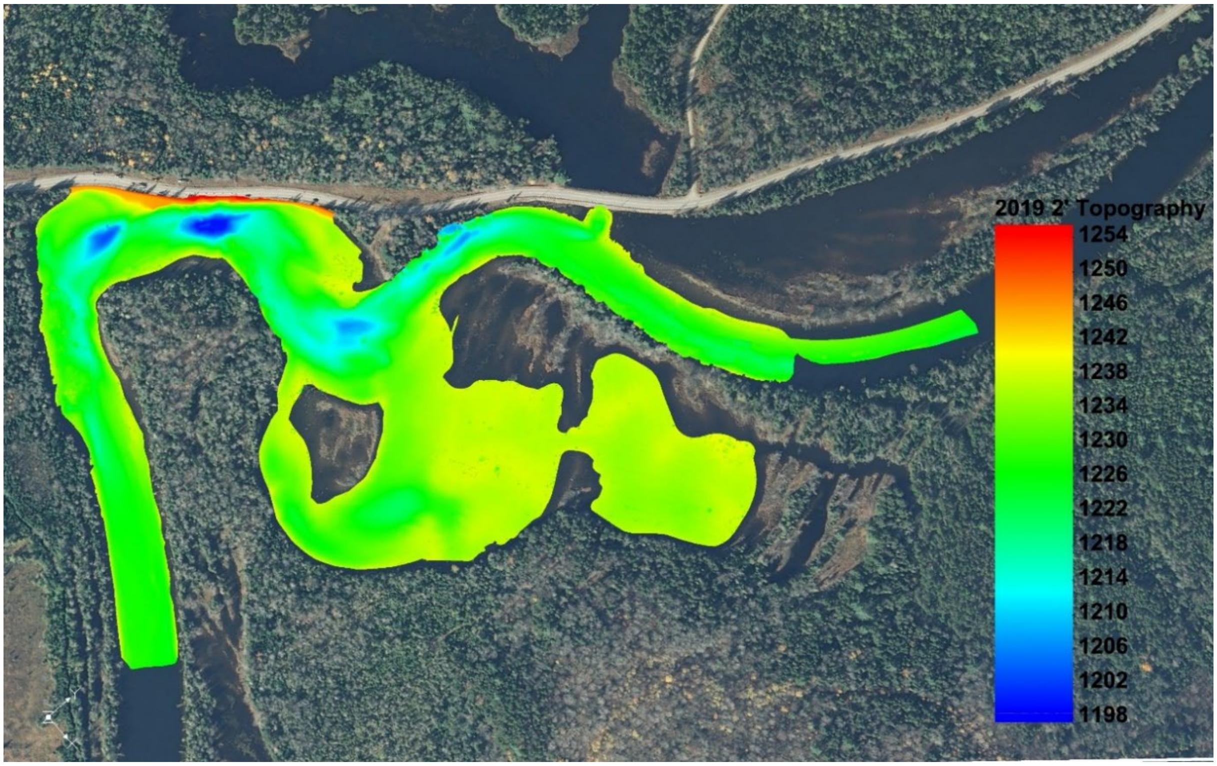

Figure 2. Model Domain Topography and Bathymetry 2019. Legend values are in Feet NAVD88.

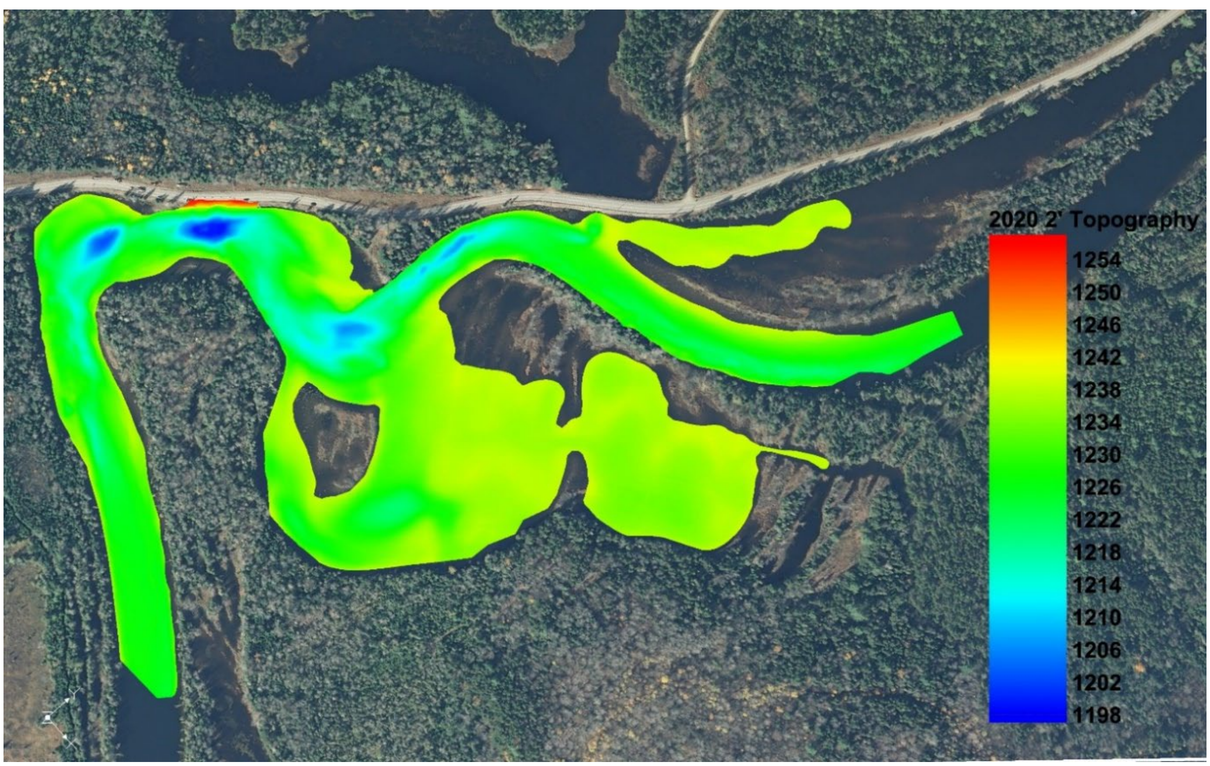

Figure 3. Model Domain Topography and Bathymetry 2020. Legend values are in Feet NAVD88.

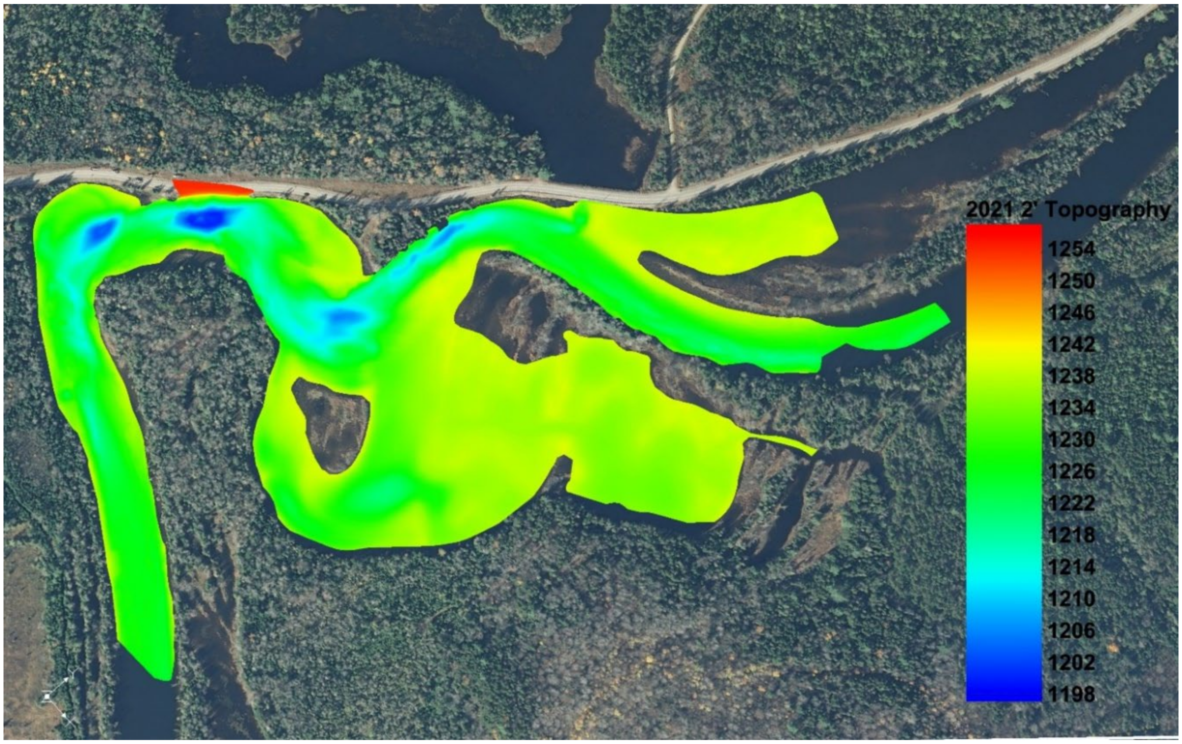

Figure 4. Model Domain Topography and Bathymetry 2021. Legend values are in Feet NAVD88.

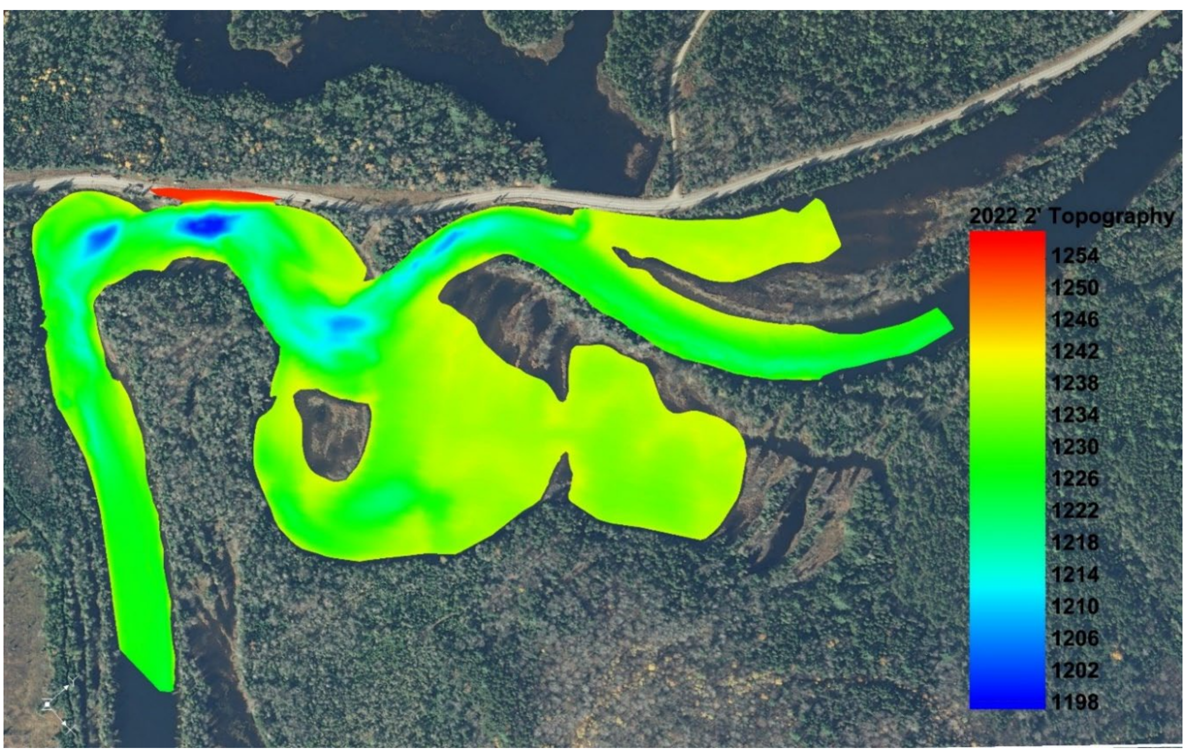

Figure 5. Model Domain Topography and Bathymetry 2022. Legend values are in Feet NAVD88.

Figures 6 – 9 magnify the site location from Figures 2-5. In these figures, the constructed ELJ is represented by the white line at the bank near the road.

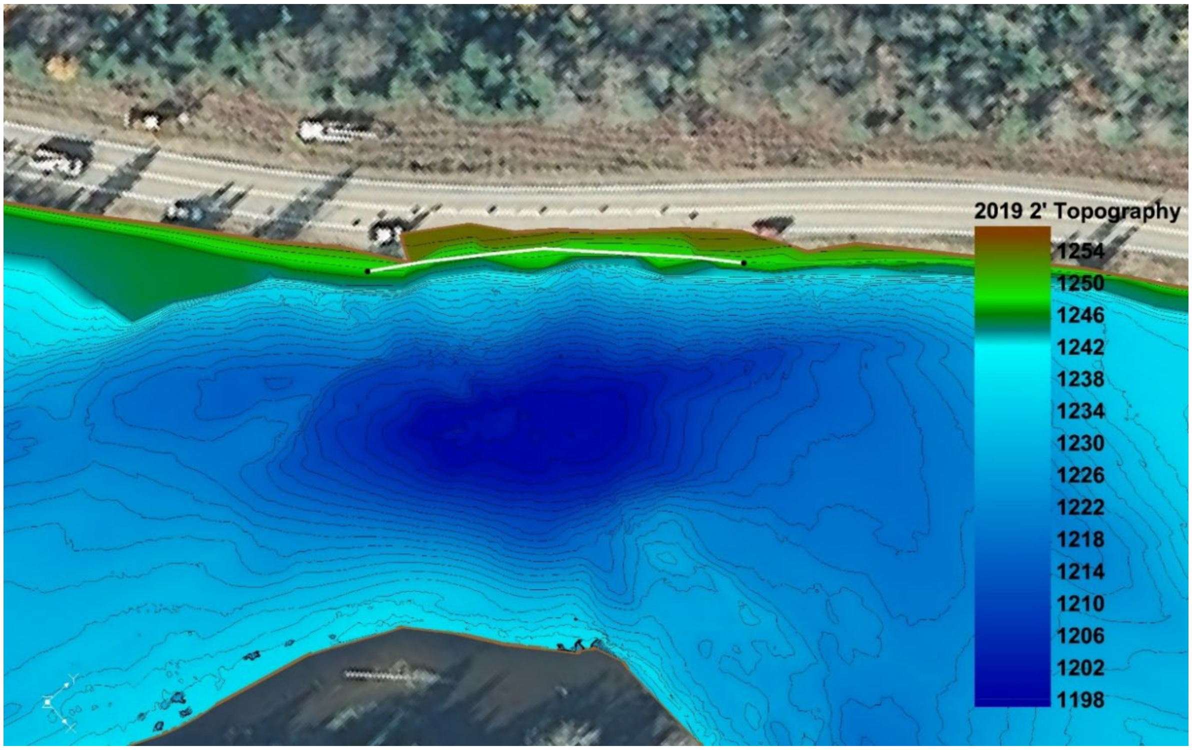

Figure 6. Log Jam Site Topography and Bathymetry 2019. Legend values are in Feet NAVD88.

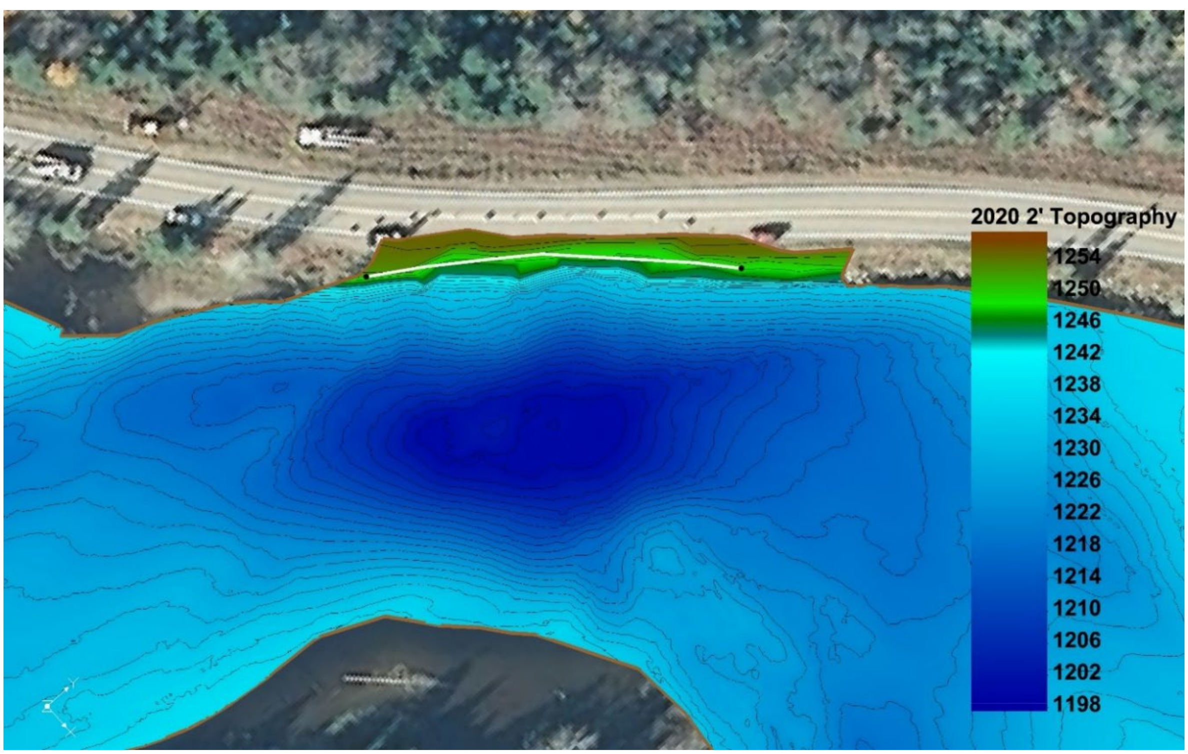

Figure 7. Log Jam Site Topography and Bathymetry 2020. Legend values are in Feet NAVD88.

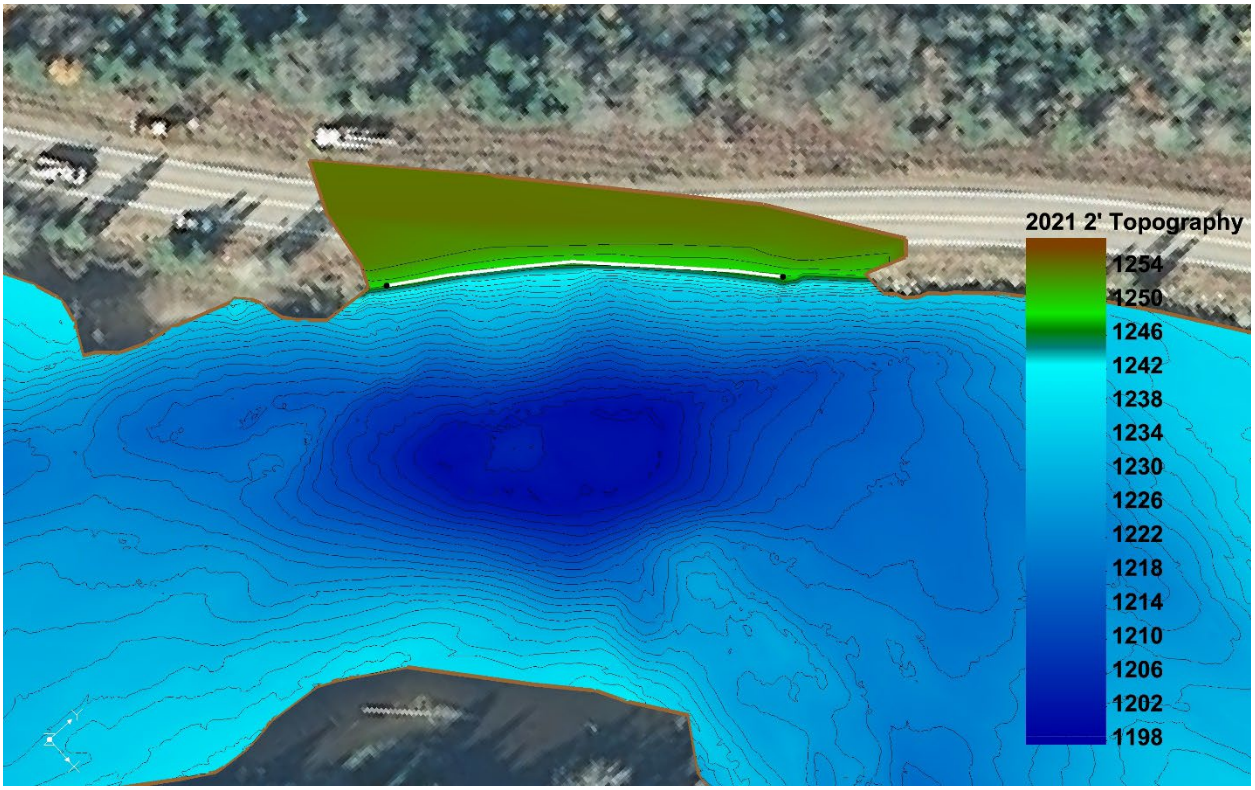

Figure 8. Log Jam Site Topography and Bathymetry 2021. Legend values are in Feet NAVD88.

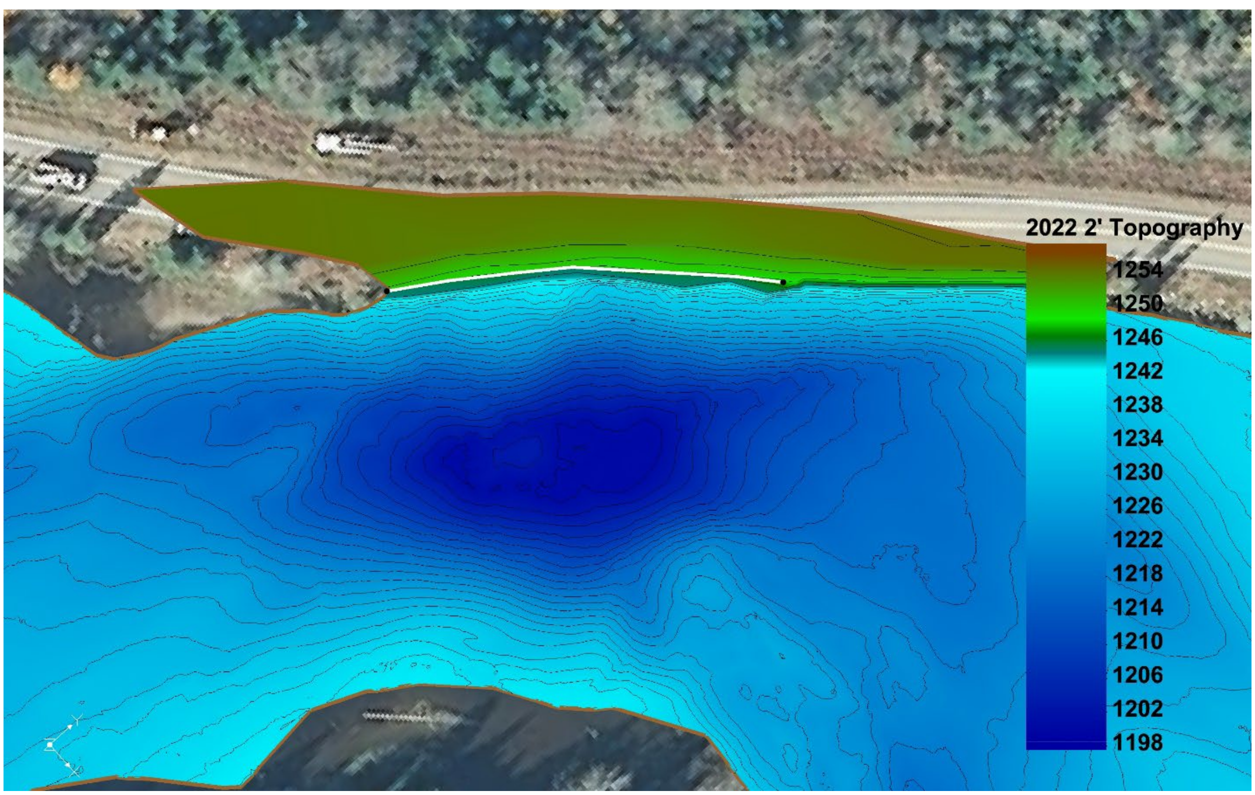

Figure 9. Log Jam Site Topography and Bathymetry 2022. Legend values are in Feet NAVD88.

The data from Figures 6 through 9 were compared year to year in order to assess overyear changes in the vicinity of the ELJ (Figures 10 – 12). Each image has the base elevation set to the earlier of the two years listed in the Figure title, and the comparison surface is the later year. For example, Figure 10, the comparison between 2019-2020, the elevation from 2019 is the base and 2020 is compared to this base. The comparison is then the difference between surfaces via the later year's elevation minus the earlier years' elevation. Therefore the Figures show the net gain or loss in elevation from one year to the comparator year. Red coloring indicates a higher elevation (deposition) in the later year compared to the earlier year, and green indicating a lower elevation (erosion). Gray indicates a net zero change. Contours are one-foot intervals and are in feet, north is rotated 48 degrees clockwise, indicated by the arrows at the bottom left of the Figures. In these Figures, the white line represents the ELJ location, and the two gray lines represent the break point between two different data sources (the total station bank survey and the Zego boat bathymetry). Notice that most of the largest differences between surfaces occur at the break point between surveys – for the most part, these locations should be ignored, as the surveys (especially the total station of the bank) rarely have overlapping points and the triangulation and connection of the bank survey to the bathymetric points can yield some large differences year to year. This is simply a source data fault. A large loss of material is evident between 2020-2021, which is simply due to the fact that the ELJ was installed by cutting back into the streambank. Interestingly, it might be noticed that the comparisons of 2020-2021 and 2021-2022 are almost inverted. Comparing 2020-2022, the image evens out more showing some aggradation and erosion but not in the inverted fashion of the year-to-year comparisons. This could be in part due to: construction in 2021 altering sediment transport (the floating silt fence was still in place during the 2021 bathymetric survey) with a more natural regime establishing in 2022 after the floating sit fence was removed; natural or seasonal/hydrologic variations in sediment transport; and/or the seasonal operations of the dam.

In all Figures 2 through 9, a very deep hole is evident in the river immediately in front of the ELJ. This feature is most likely the direct result of hydraulic attack at this location as a direct consequence of the very tight meander bend.

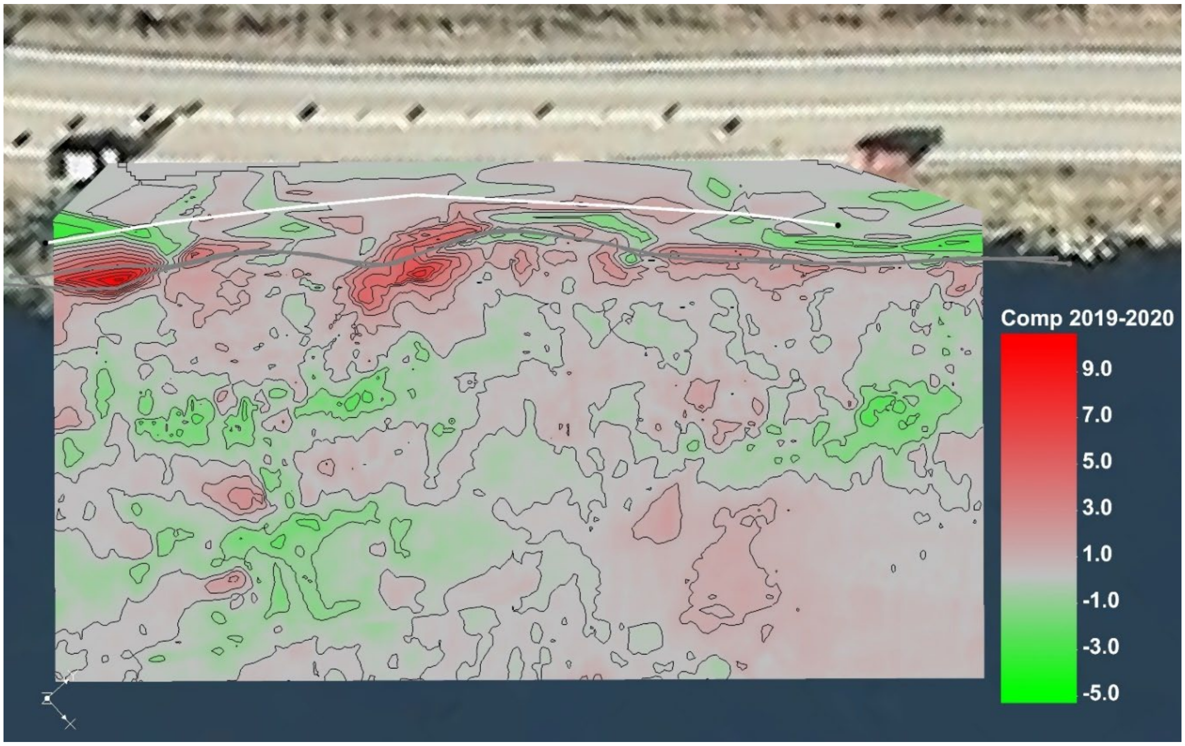

Figure 10. Surface elevation comparison from 2019 to 2020 Red means deposition from 2019 to 2020, Green is erosion. Values are in feet.

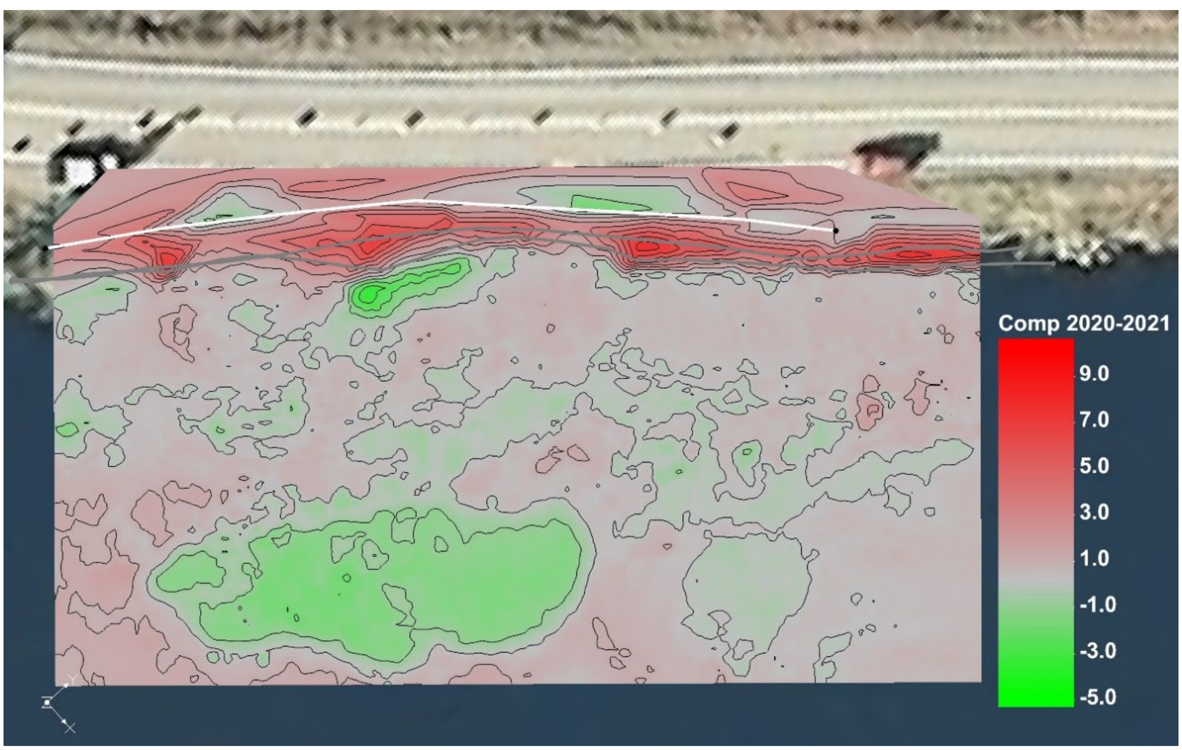

Figure 11. Surface elevation comparison from 2020 to 2021 Red means deposition from 2020 to 2021, Green is erosion. Values are in feet.

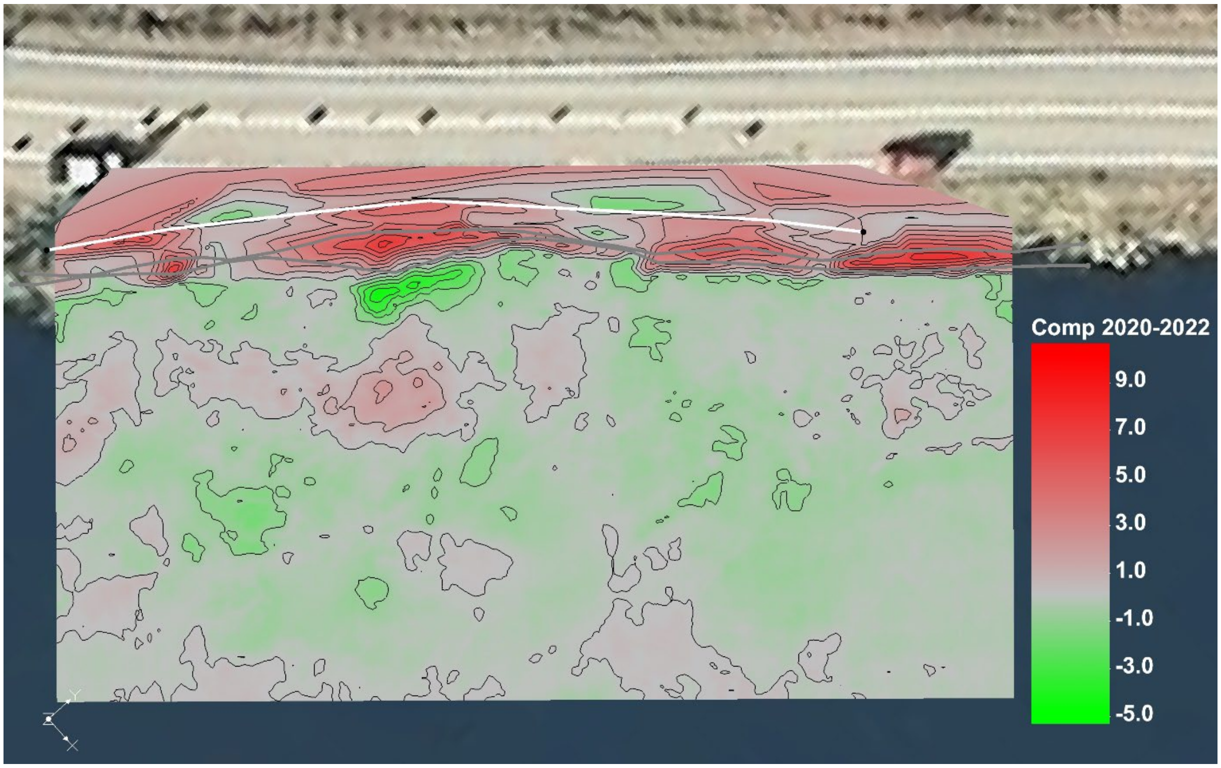

Figure 12. Surface elevation comparison from 2020 to 2022 Red means deposition from 2020 to 2022, Green is erosion. Values are in feet.

An interesting observation from the 2020 to 2022 comparison is away from the ELJ in the river. Approximately 40 feet away from the ELJ, there is an almost continuous parallel line of erosion under the water.

Table 1 displays the streambank erosion rates at the ELJ site and the two reference sites. The construction of the ELJ has arrested streambank erosion whereas the streambank erosion at the two reference sites continues.

Erosion Pins

In 2019, personnel with USFWS assisted in the selection of reference streambanks where erosion was evident, and which could be compared to the ELJ site and how erosion proceeded at those sites after it was arrested at the ELJ site. Two sites upstream from the ELJ were selected (Figure 13). The first site was close to a campground site and referred to as the Campground site (Figure 14). The second site was just on the New Hampshire side of the Maine-New Hampshire border and referred to as the State Line site (Figure 16). The Campground site did not have as extreme a bank height as the ELJ, however was on a very tight meander bend like the ELJ. Unvegetated, failed banks and fallen trees bore witness to erosion there. The State Line site was not on a tight meander bend but has a bank height greater than the ELJ. The State Line site demonstrated excessive erosion evidenced by undercut, unvegetated, steep banks and fallen trees.

Figure 13. Reference streambank erosion sites (red = Campground, Orange = State Line)

Figure 14. Campground streambank reference site. Yellow circle is location of bar sediment samples

Figure 15. Installation of erosion pin EP R3 at Campground site.

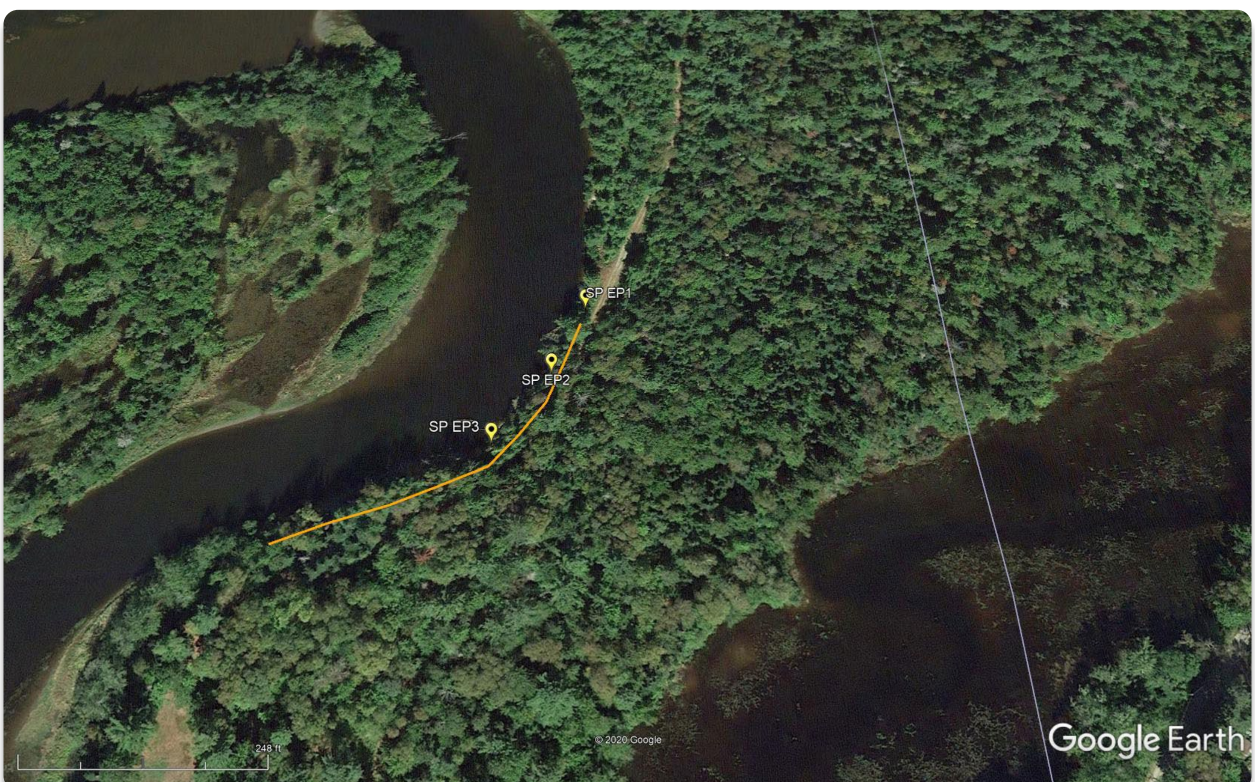

Figure 16. State Line streambank reference site.

Figure 17. High bank height and steep slope at State Line streambank

Table 1. Measured erosion rates at selected streambanks

Site	Erosion Pin	Erosion Rate (ft/year)
State Line	EP1	1.5
	EP2	1.5
	EP3	1.5
Canoe Launch	EP1	0
	EP2	1
	EP3	1
	EP4	0.1
ELJ Site	EP1	1
	EP2	1
	EP3	1

In addition, although not studied specifically, it was noted that boat wakes almost always resulted in small amounts of particle mobilization and bank erosion. This factor was undoubtedly also a factor in the original streambank erosion.

Sediment Particle Size Distributions

Sediments were sampled at the locations of erosion pins (ELJ site and Campground site) as well as across the river from the Canoe Launch site on a point bar (Table 2). The sediments at the location of the ELJ as well as at the reference streams banks are uniform sands for the most part.

The uniformity coefficients ($Cu = D_{60}/D_{10}$) for the most part are in the single digits, indicating very uniform materials. For 1 mm sand-sized particles, a shear stress of 0.015 psf is sufficient to mobilize them when using Leopold, Wolman, and Miller sediment competence method. When using Shields method and Meyer-Peter, Mueller dimensionless critical shear stress, a 1 mm sand particle moves at a shear stress of 0.016 psf, which is a very consistent estimate between the two critical shear stress different methods.

Table 2. Particle Size Distributions for Various Locations

Site	D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	D_{90} (mm)	Cu	Classification
Route 16 ELJ EP3 Upper	0.07	0.25	0.41	3.5	5.9	medium sand
Route 16 ELJ EP3 Lower	0.1	0.29	0.34	1.8	3.4	medium sand
Route 16 ELJ EP1 Upper	0.12	0.4	0.46	2.8	3.8	medium sand
Route 16 ELJ EP1 Lower	0.02	0.33	0.39	0.43	19.5	medium sand
Campground EP4 Upper	0.07	0.17	0.2	0.42	2.9	fine sand
CampgroundEP4 Lower	0.11	0.3	0.32	0.41	2.9	medium sand
CampgroundEP3 Upper	0.13	0.39	0.41	0.85	3.2	medium sand
CampgroundEP3 Lower	0.12	0.56	0.85	4	7.1	coarse sand
Campground Point Bar Waterline	0.26	0.37	0.39	0.53	1.5	medium sand
Campground Top of Point Bar	0.2	0.35	0.37	0.42	1.9	medium sand

Hydraulic Modeling

The hydraulic modeling software SMS v13.1 was used for the project and is a graphical user interface built to run the command-line SRH-2D program, which performs hydraulic calculations (energy, continuity, momentum) in two dimensions. This is a depth-averaged two-dimensional hydraulic model. Vertical acceleration forces in the water column, such as in deep holes are not modeled as discussed on pg. 22. The model requires the same inputs as more common one-dimensional models: topography; roughness; boundary conditions (BCs); discrete calculation locations; and model scenarios with their appropriate controls.

Two primary models were built, one for the pre-construction topography/bathymetry and one for post-construction. The models shared much of the same information – the boundary conditions, model scenarios, discrete elements, and model scenarios (flows, stages) all remained the same. Topography and roughness are the only differences between the models, with those differences consisting only of the constructed ELJ and immediately surrounding lands. The pre-construction model input used data collected in 2020, rather than 2019, for the sole reason that the bathymetry covered a larger area and was already processed. The post-construction model used data collected in 2022, which was the only complete and confident data set after construction as the erosion control sediment barrier was still in place at the site during the 2021 bathymetric survey.

Topography for the model covered a relatively large area (530 ac) and main channel length (11,600 feet) using data from five sources, spatially shown in Figure 18. Most of the terrain remained the same between the pre- and post-construction models. Only the surveyed bank and surveyed bathymetry changed, though away from the site the surveyed bathymetry differences were minor. Bathymetry (blue polygon) for the submerged land surrounding the site was obtained from UNH CCOM annual surveys. Bathymetry created (yellow polygons) to extend the model domain was accomplished using a standard cross section form (standard bank slopes and variable bottom widths) in the main channel, as well as approximate oxbow and side channel depths. For ELJ proximal dry land topography, the site was surveyed annually by UNH (very small red polygon) and lands in the ROW adjacent to the site surveyed once in 2017 by NHDOT (magenta polygon). This topography remained the same between the two models even though the road was moved as part of this project. Since model results did not put water at the elevation of the road, this did not affect model performance. The former road was more or less left in place and is at an elevation higher (elev. 1,254.0’) compared to the highest ever reported water elevation (elev. 1,251.5’). All remaining topography was obtained from the 2017 Umbagog LiDAR points, downloaded from the GRANIT LiDAR Project.


Figure 18 - Topographic data sources

The pre- and post-construction topography at and in the immediate vicinity of the site may be found in Figures 19 and 20.

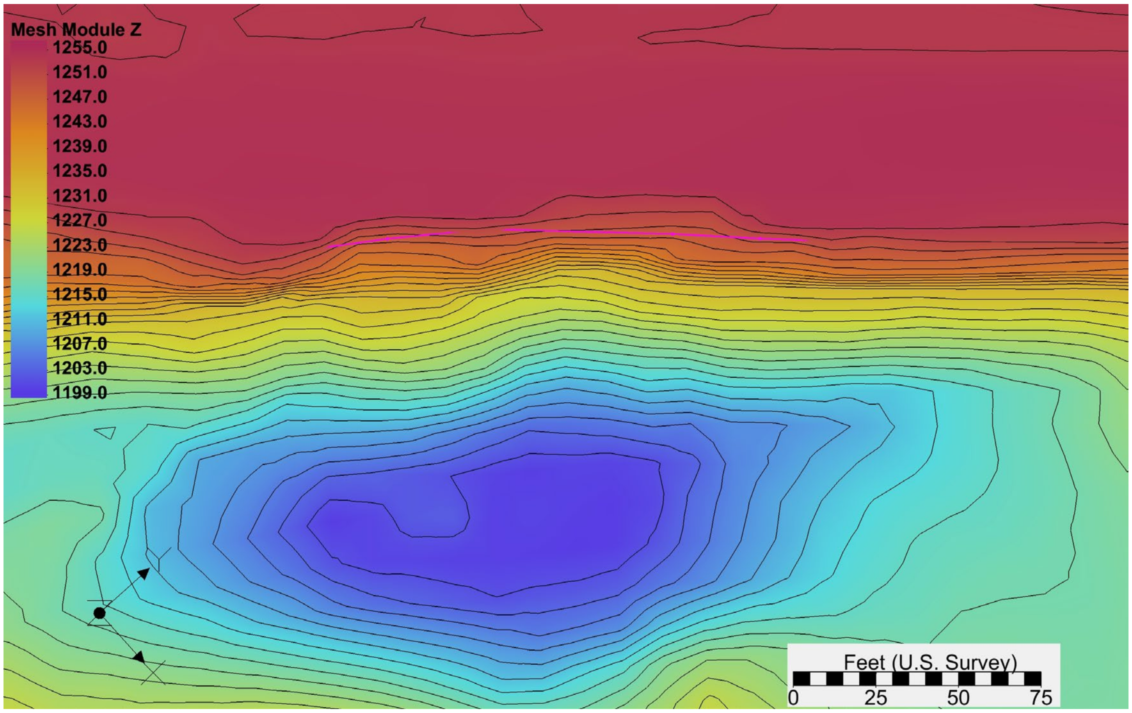

Figure 19 - Pre-construction topography at project bank. Pink line represents constructed ELJ. Legend elevations in NAVD88.

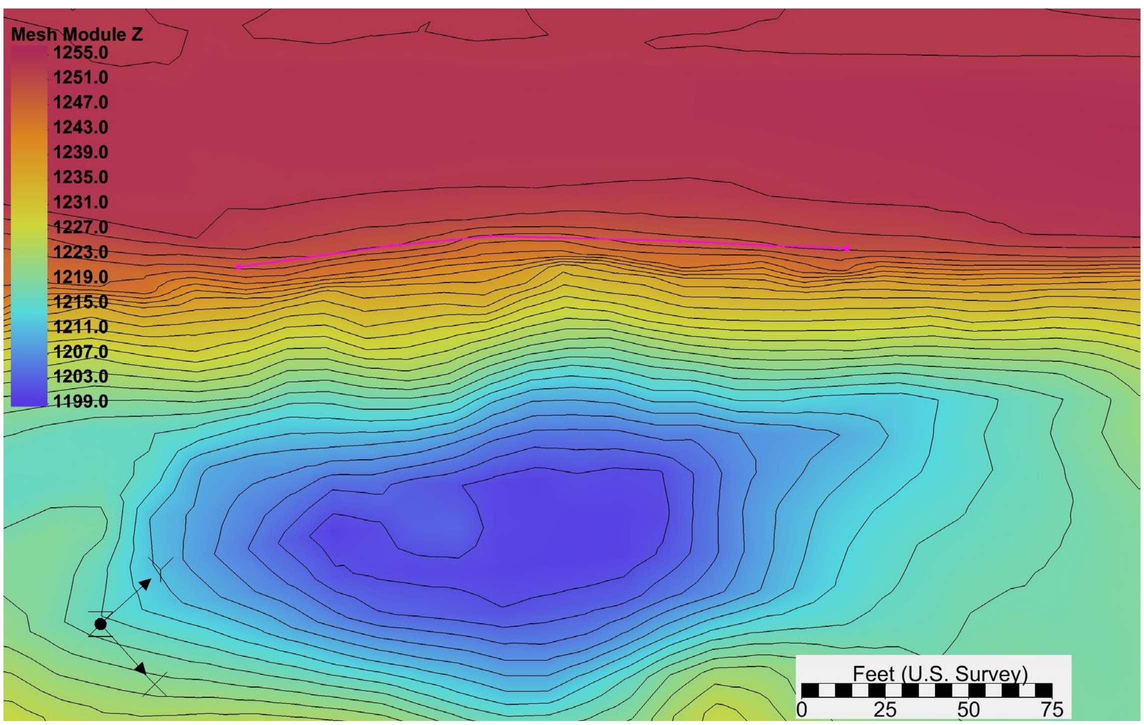

Figure 20 - Post-construction topography at project bank. Pink line represents constructed ELJ. Legend elevations in NAVD88.

Initial estimates of the model domain were dictated by the CCOM survey bathymetry (set the model domain limits at the survey limits). Initial modeling using these limits indicated that the model would benefit by extending the domain both upstream and downstream to straighter portions of the river where the velocity field was strongly two dimensional, and the dominant direction parallel to the streambanks. Slope of the river water surface from the Errol dam to USFWS headquarters, measured as part of a project in 2011, was surveyed to be very flat at 0.00324%, which is expected in a large impoundment such as this. Setting the downstream BC far enough away to eliminate its influence at the project site is nearly impossible in an impoundment, so it was moved to the next downstream location where the river was relatively straight and without adjacent 'still' water dead zones. The upstream BC was moved to the location where elevations were above the highest-ever reported site water surface elevation (WSEL) and did not have adjacent still water. The model domain is depicted in Figures 18, 21 and 22. Note that in these Figures there is actually 'still' water to river left of the upstream model domain BC, however there it is separated from the main channel by land at the required high elevation. In order to extend the model to these boundaries, bathymetry was created, informed by the CCOM surveys, using a standard cross section form (constant bank slopes with variable streambed widths) for the main channel and estimated spot elevations at connected oxbows. Both BCs

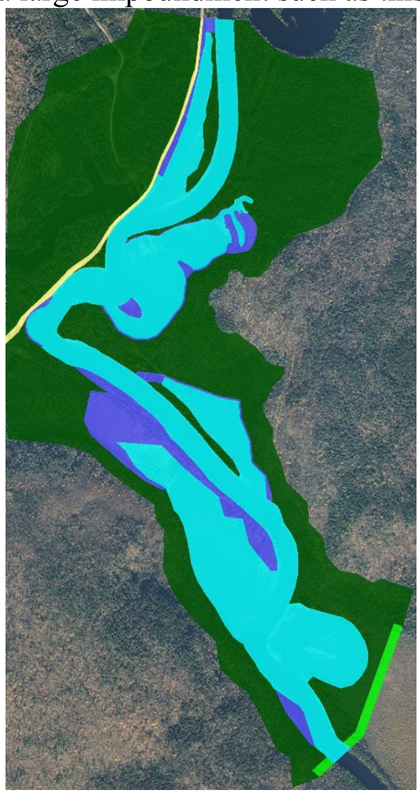

Figure 21 - 2020 Materials

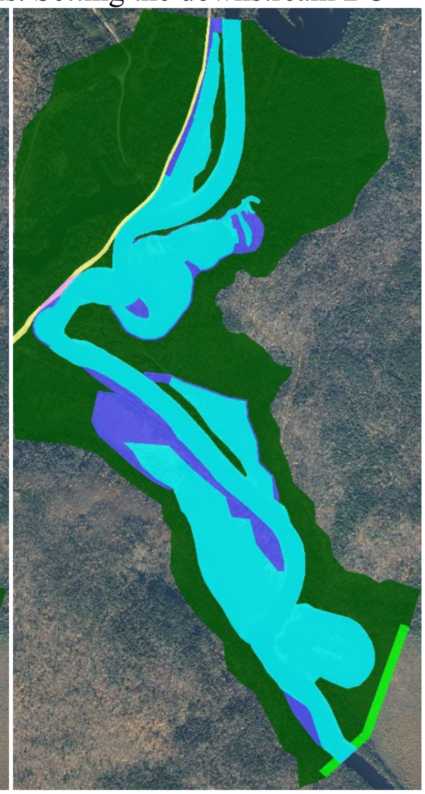

Figure 22 - 2022 Materials

	Color and Texture	Name	Manning's N
1		unassigned	0.02
2		Floodplain - Dense	0.15
3		Floodplain - Light	0.075
4		Floodplain - Marsh	0.065
5		Channel	0.025
6		ELJ	0.035
7		Floodplain - Grass Shrub	0.05
8		Floodplain - Cleared	0.035

Figure 23 – Model domain, materials and roughness values

are shown in Figure 18, represented by the magenta lines at the top (upstream) and bottom (downstream) of the image.

Boundary conditions (BCs) were set at the upstream and downstream limits of the model domain. For all model scenarios, the upstream BC was input as a constant flow and the downstream BC set to a constant water surface elevation. The values for each depended on the scenario being run and explained in the following paragraphs.

Roughness was defined using Manning's n values appropriate to the terrain within the model. All values were visually estimated in the field at the site and all lands adjacent to water. Remaining areas were estimated using aerial imagery with an understanding of the approximate terrain. Roughness values are entered spatially into the model, shown in Figures 21 and 22, where the only difference is at the site – barely visible at the upper-middle left side of the images. For simplicity, material polygons were reduced to one of seven classifications, shown in Figure 23, with values representing an average for the land cover type. The Unassigned (row 1) coverage is a null placeholder required by the model.

Discrete elements (calculation locations) for the model were made using polygons containing boundary lines with defined vertices. The boundary lines follow important and/or notable topography and enclose individual polygons, and vertex spacing defines element size within each polygon. Within the channel, elements are primarily quadrilaterals, which improve modeling accuracy and generally align with the direction of flow. Floodplains and connected oxbows consist of triangular elements which are better for locations where flow direction is variable and/or unknown. For the area surrounding the project site, elements are shown in Figure 24 in yellow lines, overlaying the topography. Topography is displayed with 2-ft interval black contour lines and continuously color-filled as defined by the legend, with the shading indicative of elevation relative to the average WSEL, 1245'. The constructed ELJ is represented by the magenta line near the center of the image, and the scale shown at the bottom-right corner. Elements remained the same between the two models so comparisons could be directly made.

Model scenarios were chosen to represent a range of conditions the site is subject to, though none involve extreme events, for example the 100-yr flood. This streambank has been failing for years and is composed of materials easily moved by most flows. In natural rivers, sediment transport is most effective at the bankfull flow – commonly approximated as the 2-yr flood, though the actual bankfull flow event for any river is highly variable and depends on many features of the river and watershed. Unlike natural river systems which have one true underlying stage-flow relationship, the site is influenced by dam operations downstream. It is not uncommon for there to be multiple stages at one observed flow – dam operations often result in highly variable upstream elevations sometimes within one day with a (mostly) constant flow. Therefore, in addition to more traditional analyses where the only real variable controlling model scenarios might be flood event inflows, the scenarios had variable downstream WSELs, defined using the historic dam operation controls stated by the dam owners[1]. The scenarios were further refined by defining a specific time period – annual or seasonal – for which flow statistics and dam operations would be interpreted.

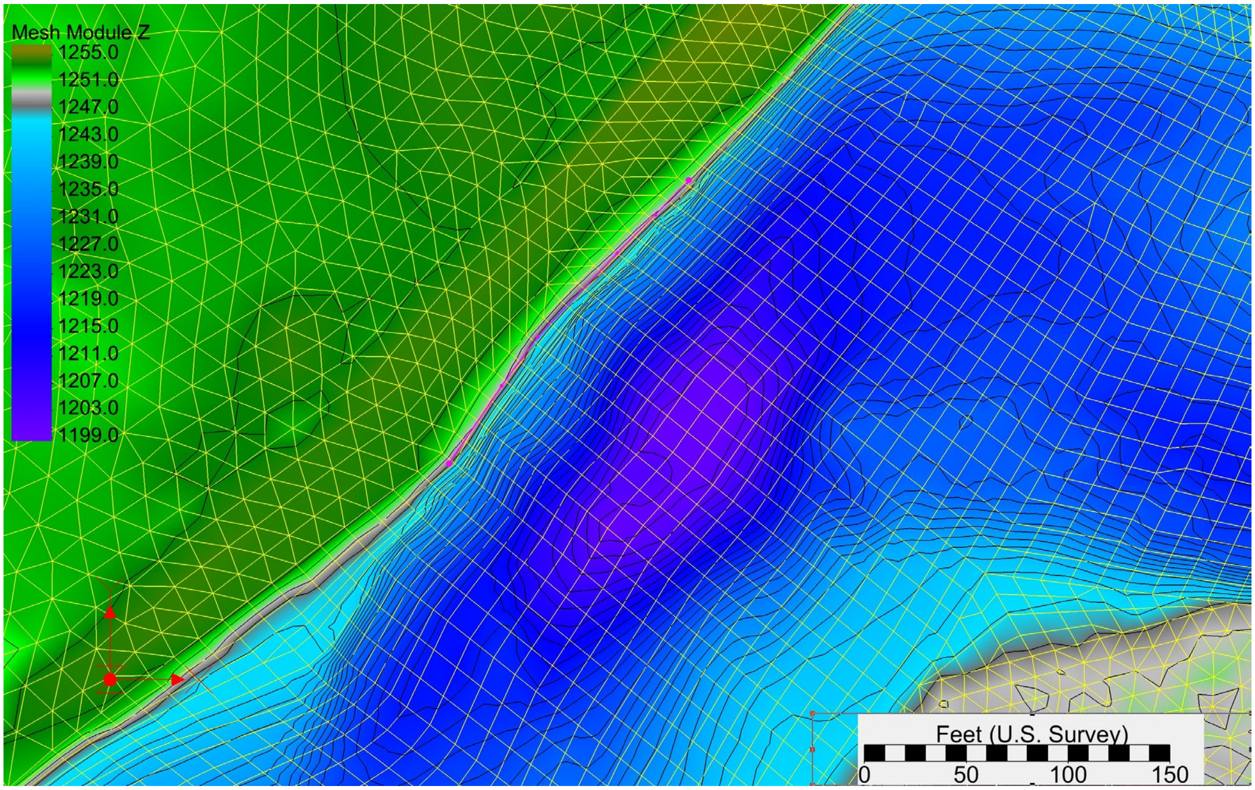

Figure 24 – Model terrain (for 2022 conditions) and mesh elements (for both models). Legend elevations are in feet NAVD88.

No readily available source of high-resolution information (flow, water surface elevation, turbine flow, number of gates open) existed regarding operations of the downstream dam. However, the current owners were able to provide a 7-year (starting when the current owners bought the dam 2014 - 2020) hydrograph of daily operating elevation[2] for the gate(s) at the dam which control water elevations upstream. No record was kept of the size or number of gates (there are six 10'x15' and five 12'x16' gates at the dam) in use during any day, which meant that for modeling purposes, the WSEL used for the model downstream BC needed to be estimated from the gate operating elevation records. The gate elevations provided by the dam owner were used as the WSEL at the dam, and this elevation was then translated upstream to the model downstream BC

[1] From the document *Balancing Act: The Lakes of the Upper Androscoggin – Operation of the Androscoggin River Storage System and the Effect on Summer Lake Levels* by FPL Energy, Maine Hydro

[2] *Daily operating elevation*, as it is understood, is similar to the *average daily flow* statistic. As it was explained, the value given for any one day referred to the planned/reported controlling elevation of one or more gates at the dam. While there may have been one or more operations during the day, the value given is the most significant.

using the distance to the BC from the dam and an approximate water surface slope, surveyed in 2011 as part of a separate project.

Long term flow statistics (flow duration curve - FDC) at the site were processed using a calculated long-term hydrograph consisting primarily of gaged and reported flow values, plus accounting for all ungaged drainage area. At the site, the watershed is 437 square miles. Of that amount, 152 square miles has flow observed by USGS gage 01052500 – Diamond River near Wentworth Location (80 years of record). Another 214 square miles had flow estimates at the Aziscohos Dam, obtained from the dam owner. The flows from the remaining 17 square miles of ungagged watershed were calculated using a linear drainage-area-weighting method with the USGS gage flows acting as the baseline. The flow record at the site is the sum of these three hydrographs. FDC results at the site may be found in Table 3 (Pe = exceedance probability, Q10 means that 10% of all observed flows equaled or exceed 1,146 cfs).

Table 3 - FDC Results at the Site

Pe	Flow ID	Annual	Winter	Spring	Summer	Fall
-	-	cfs	cfs	cfs	cfs	cfs
0.99	Q99	375	460	401	355	433
0.95	Q95	408	496	512	390	469
0.90	Q90	460	582	565	403	491
0.85	Q85	496	614	593	426	504
0.80	Q80	540	650	666	452	518
0.75	Q75	572	682	758	485	543
0.70	Q70	594	690	808	524	562
0.60	Q60	659	712	929	581	601
0.50	Q50	712	743	1,146	642	639
0.40	Q40	771	776	1,420	700	666
0.30	Q30	878	820	1,891	756	736
0.20	Q20	1,146	955	2,580	877	857
0.10	Q10	1,766	1,471	3,856	1,123	1,230
0.05	Q5	2,727	1,694	5,118	1,577	1,535
0.01	Q1	5,250	3,094	7,759	3,014	3,345

A total of five model flow/stage scenarios (Table 4) were built to represent the range of conditions from highly erosive (high flow and high WSEL) to less erosive (low flow and low WSEL). Flow values are the input to the upstream BC. The WSEL values dictate the WSEL used at the model's downstream BC. The description of each scenario is described in the middle column(s).

Table 4 - Boundary Conditions for Model Scenarios

#	ID	Flow & WSEL Definitions		Flow (cfs)	WSEL (ft)
1	AvAnMin	7-year Average Annual Minimum Flow at a Low WSEL		887	1,244.67
2	AvAnMax	7-year Average Annual Maximum Flow at a high WSEL		8,934	1,249.72
3	AvAnAvg	7-year Average Annual Flow at an Average WSEL		2,320	1,245.87
		Flow Statistic	WSEL Statistic	Flow (cfs)	WSEL (ft)
4	Q10AnAvg	Annual FDC q10	Average Annual	1,766	1,245.87
5	SprQ01Min	Spring FDC q01	Average Spring Minimum	7,759	1,244.95

For the first three scenarios, statistics were performed using flows and WSELs spanning the time period for which downstream WSELs were obtained (seven years). The data do not span a significant enough period to have confident FDC statistics (the method would be applicable to WSEL as well) performed. Instead, simple statistics were calculated to generally describe conditions for both flow and WSEL. The ID in the first column is simply the name used for the model files (input, output) for that model run.

The final two scenarios use the same description, statistics, and data set as described previously, but use FDC statistics calculated using the full set of flows at the site (80 years).

Hydraulic Modeling Results

Pre-and post-construction modeling results appear in pairs of figures from Figure 25 through 44: each pair of figures representing the pre- and post-construction results of the 5 scenarios of Table 4. The first figure in each pair of figures is a plan view of the site with topography (white, 2-ft interval contours; velocity vectors (black arrows); and color shading for shear stress). At the same time in the first of each pair of figures, three transects are delineated ("arcs" as they are referred to in the model). Bed shear stress along these transects is plotted in the second of each pair of figures. In the shear stress plots, the horizontal axis is the distance from the landward end of the transect. For example, in Figure 25 on Arc 3, the edge of water is at approximately 25 feet. There is a scale in the first of the pair of figures and the transects (arcs) are delimited in 10-ft increments that line-up with the horizontal scale on the second of each pair of figures.

Modeling results between the pre- and post-construction sites reveal that shear stress right at the bank is minimal for most ordinary flows, and is relatively similar between the pre- and post-ELJ scenarios (Figures 26, 30, 32, 36, 40, and 42). Shear stress at the ELJ increases compared to the bare bank due to increased roughness, though this does not translate to increased erosion due to the composition of the ELJ itself.

The sediments composing the pre-construction bank are estimated to be *mostly mobile* (up to D_{75}) at a shear stress of 0.015 psf. A 1mm particle is larger than about 75% of the particles on the streambank at the site (Table 2). The 1 mm particle moves when the shear stress equals or exceeds 0.015 psf. The median particle size at the site (Table 2) is about 0.3 mm, which moves at a shear stress of 0.0044 psf. D_{10} at the site (Table 2) is about 0.08 mm (considered a very fine sand) and moves at a shear stress of 0.0012 psf. It is safe to say that at the site, when the shear stress exceeds 0.001 psf, some sediment is moving. There are locations along the ELJ that do exceed this critical shear stress (0.001 psf) in both pre- and post-construction for certain flow scenarios (Figures 34 and 44). Therefore, episodically sediment is mobile at those locations under those conditions in the pre-construction state. Away from the streambank, this critical shear stress value (0.001 psf) is exceeded in most of the modeled scenarios. In viewing the velocity vectors (black arrows) in Figures 24, 26, 28, 30 and 32, it may be seen that at the upstream end of the ELJ and just farther upstream, there is a large swirling eddy in which velocity vectors point upstream along the streambank. This eddy is evident in the larger scale plan views of Figures 45 and 46 and was observed with the real-time Zego measurements. This eddy results from the immediately upstream very tortuous channel geometry and point of land observable in Figure 2. Just downstream of this eddy and along the ELJ, flow and operational WSELs result in the velocity vectors directly striking the bank and then running parallel to the bank. Given the nature of the bed topography (the very large "hole" in the river in front of the ELJ) and the upstream eddy zone to the north of the site, there is most likely a significant amount of vertical component to the velocity vector (a large, three-dimensional vortex) acting along the bank which is not accounted for in this two-dimensional model. Anecdotal support of downward vertical velocities near the site was shared with the project team during site visits, where observers had witnessed whirlpools at and around the bank. In one instance, the witness mentioned seeing a 'whole tree' being swallowed. Despite the computational power of the 2D modeling software, vertical movement is not modeled.

Looking at the pre-construction site in Figures 25, 26, 27, and 28, the first scenario (Figures 25 and 26) is a low flow at a low water surface elevation and the second scenario (Figures 27 and 28) a very high flow and a high-water surface elevation. In the first scenario, streambank particles are stable, and in the second the particles are mobile. These two scenarios bracket the range of sediment stability conditions over a normal year.

In Figures 29 to 32, low water surface elevation and high flow (Figures 31 and 32) result in smaller cross-sectional area and therefore higher velocities and near bank shear stress compared to higher water surface elevation and lower flow.

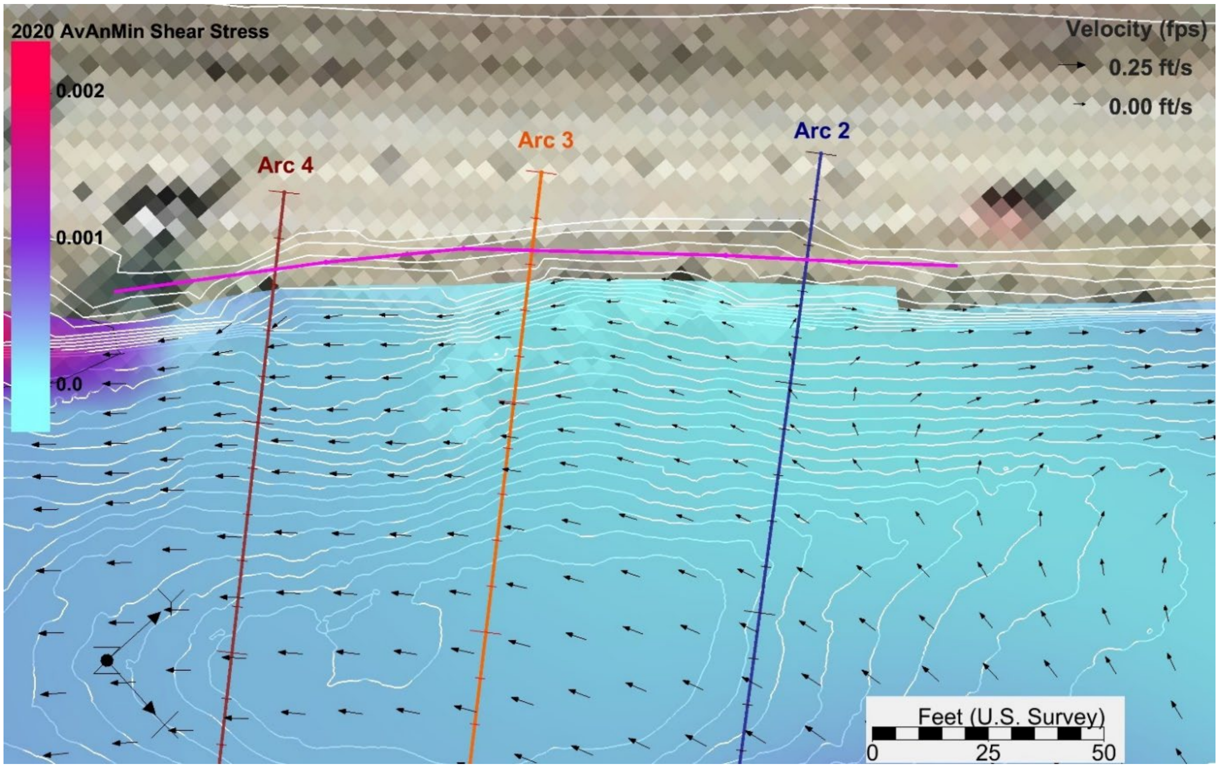

Figure 25. Pre-construction bank shear stress for the AvAnMin scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

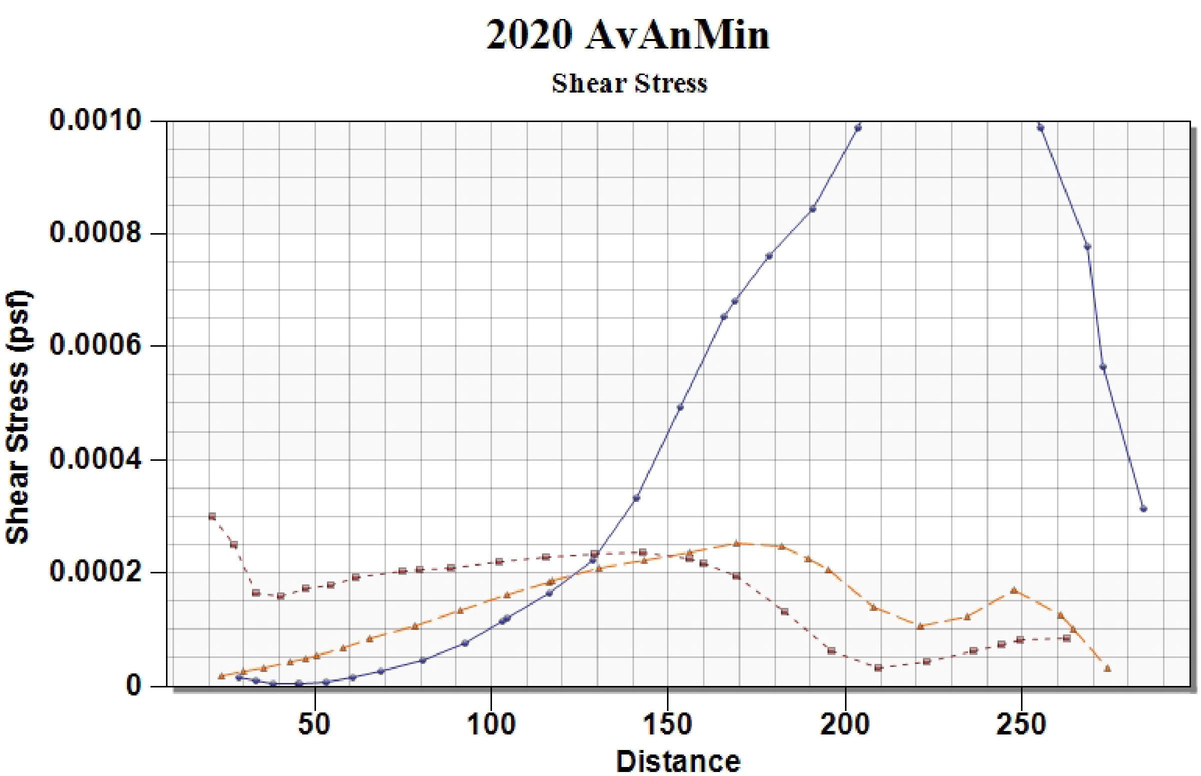

Figure 26. Bed shear stress for transects in Figure 25.

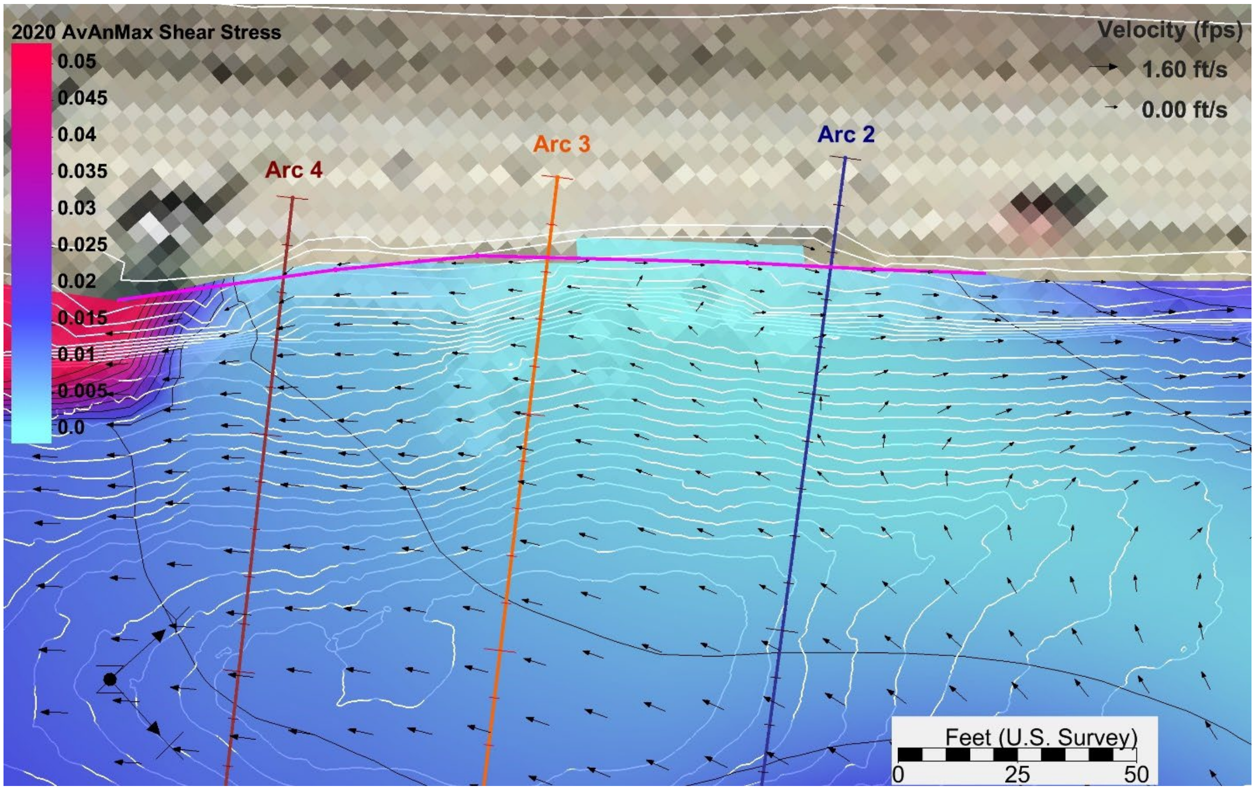

Figure 27. Pre-construction bank shear stress for the AvAnMin scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

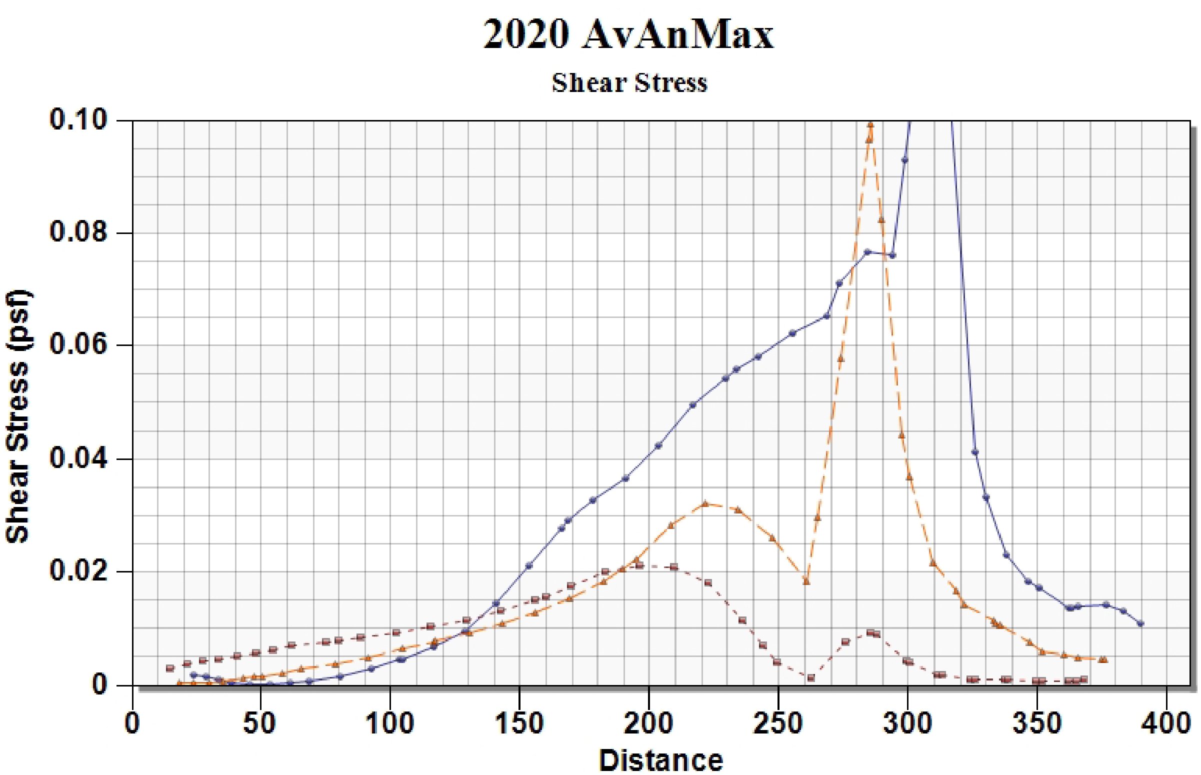

Figure 28. Bed shear stress for transects in Figure 27.

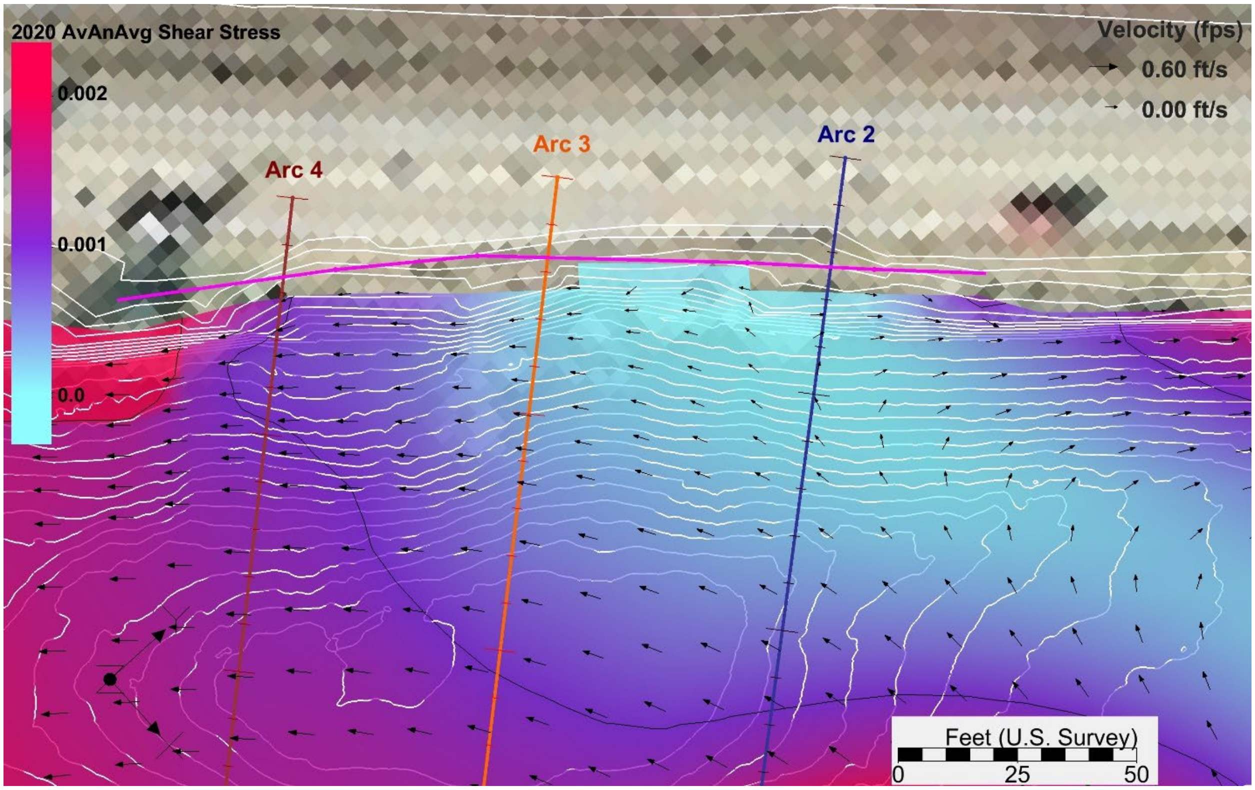

Figure 29. Pre-construction bank shear stress for the AvAnAvg scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

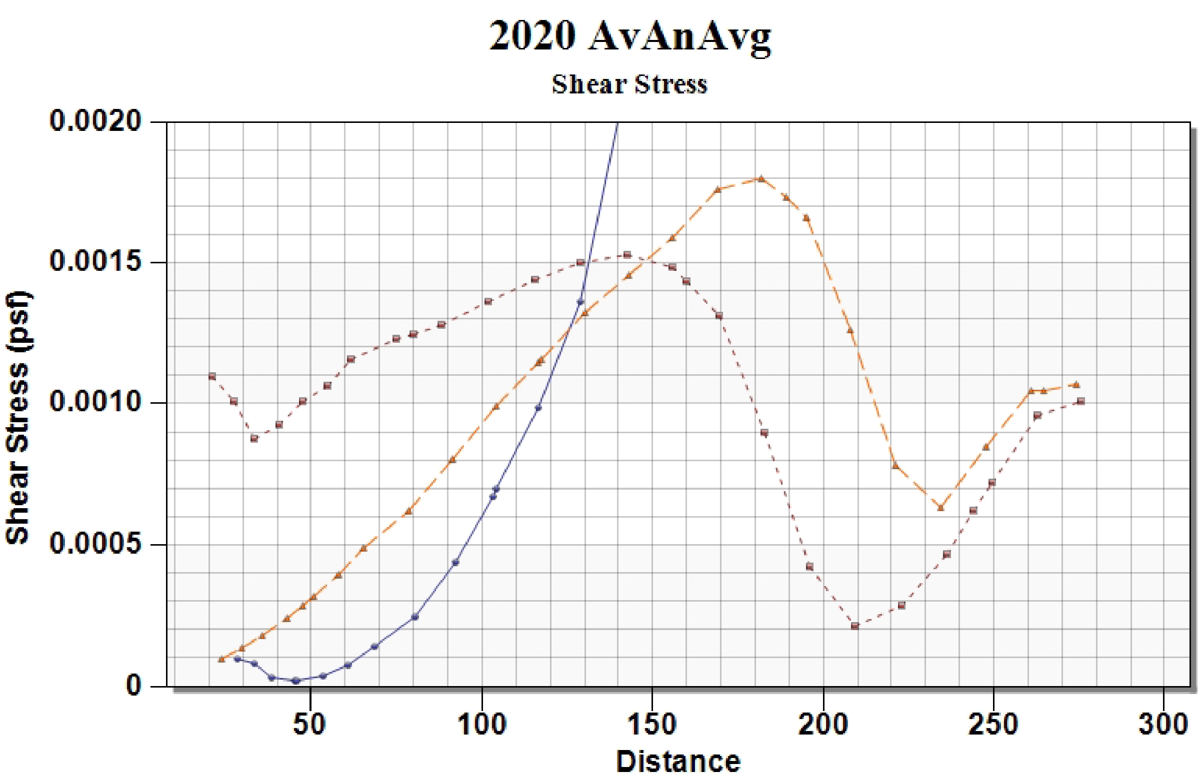

Figure 30. Bed shear stress for transects in Figure 29.

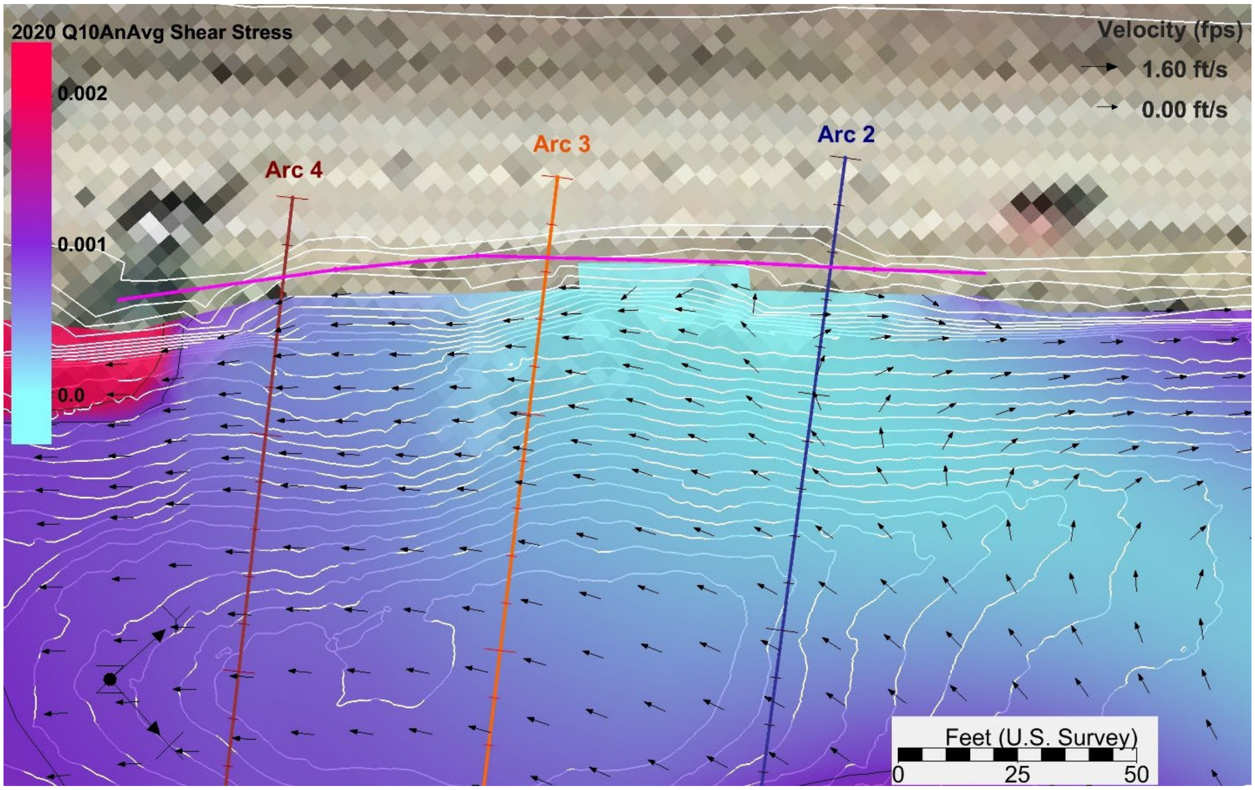

Figure 31. Pre-construction bank shear stress for the Q10AnAvg scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

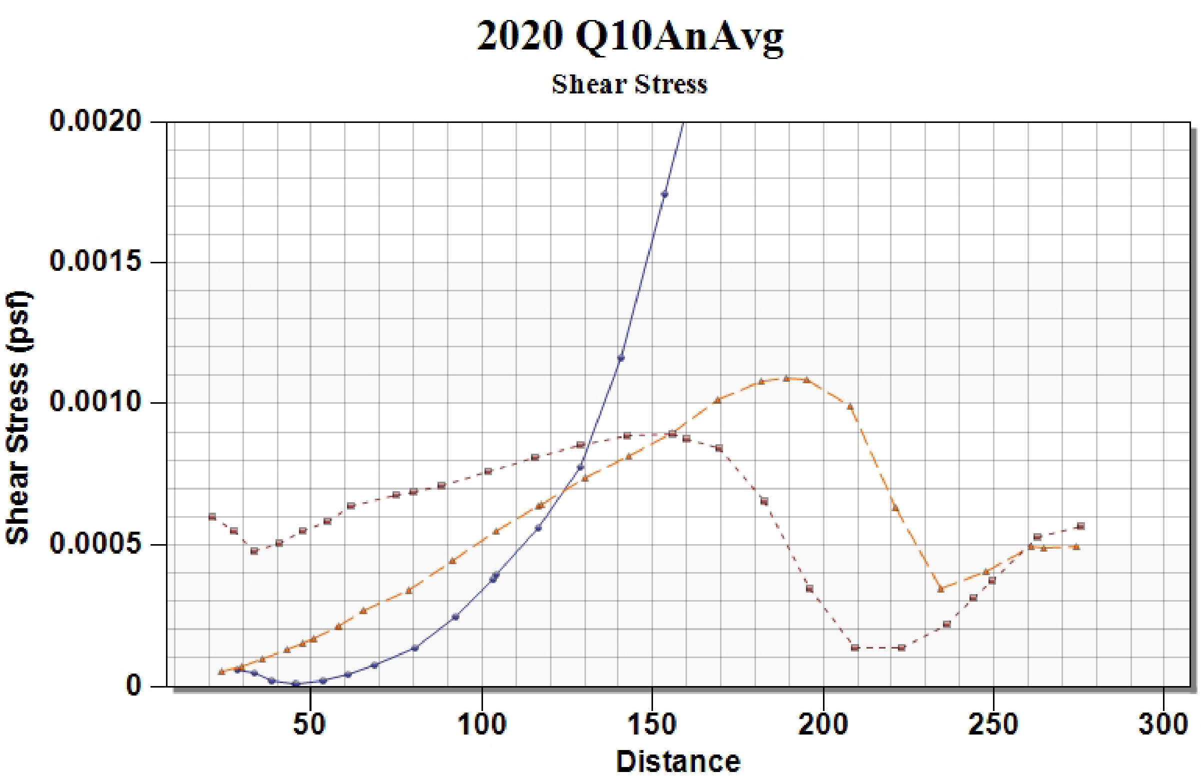

Figure 32. Bed shear stress for transects in Figure 31.

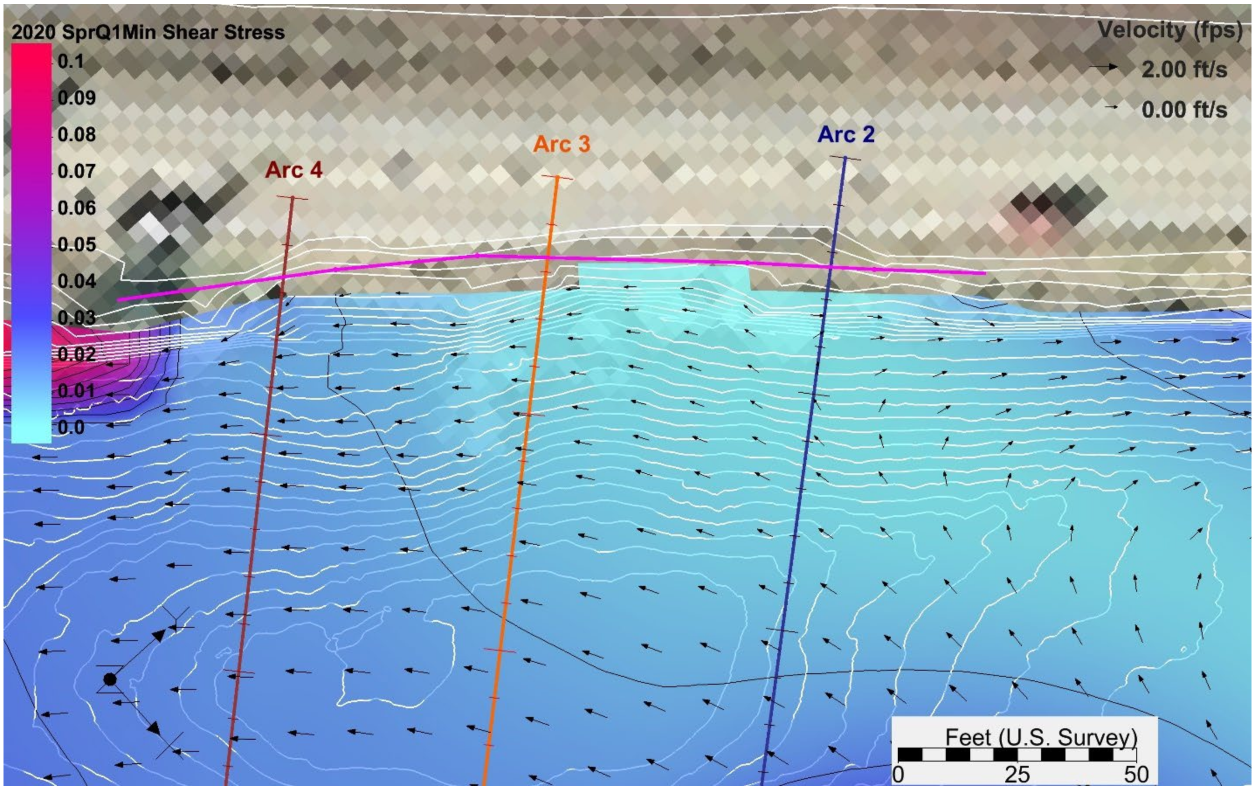

Figure 33. Pre-construction bank shear stress for the SprQ1Min scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

Figure 34. Bed shear stress for transects in Figure 33.

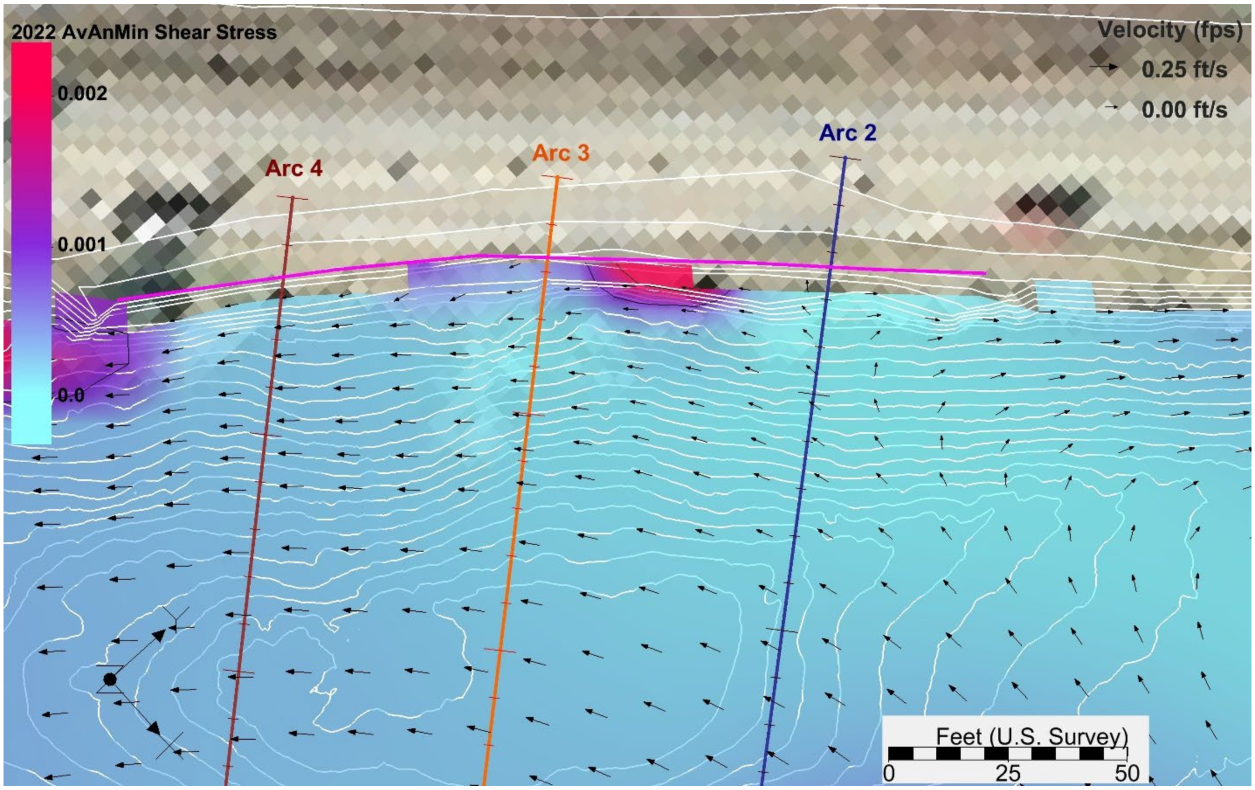

Figure 35. Post-construction bank shear stress for the AvAnMin scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

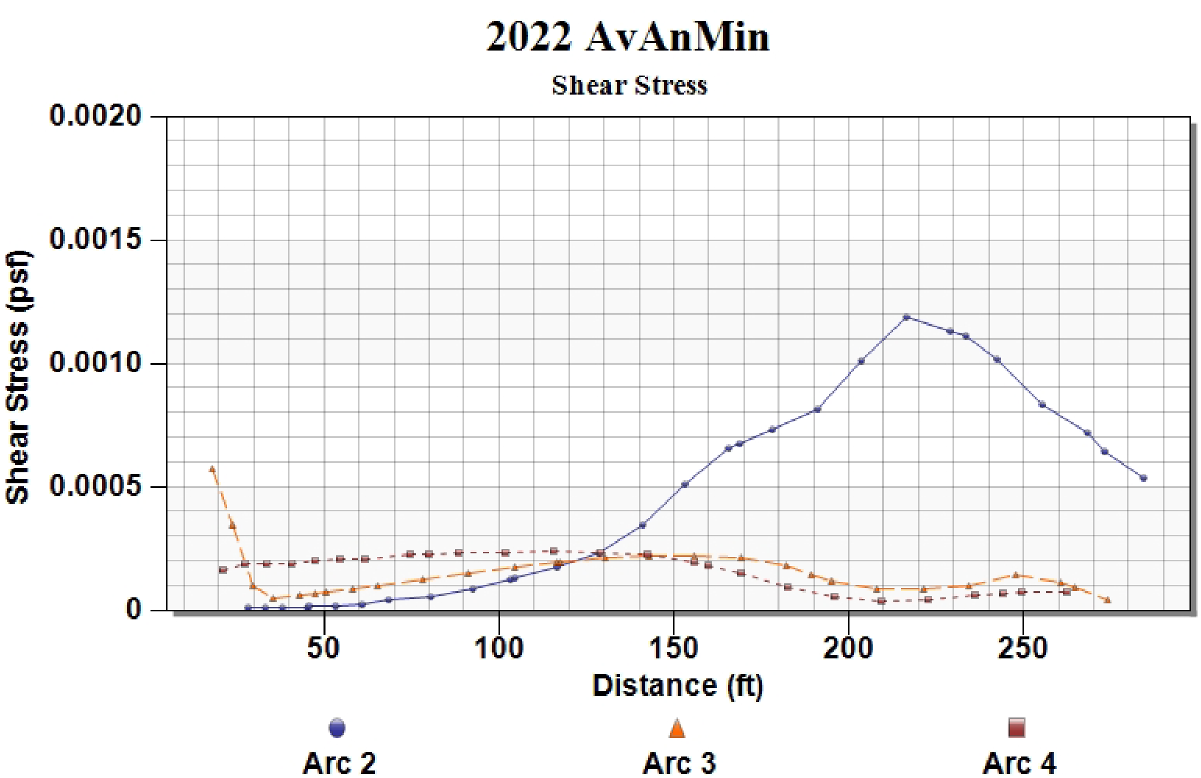

Figure 36. Bed shear stress for transects in Figure 35.

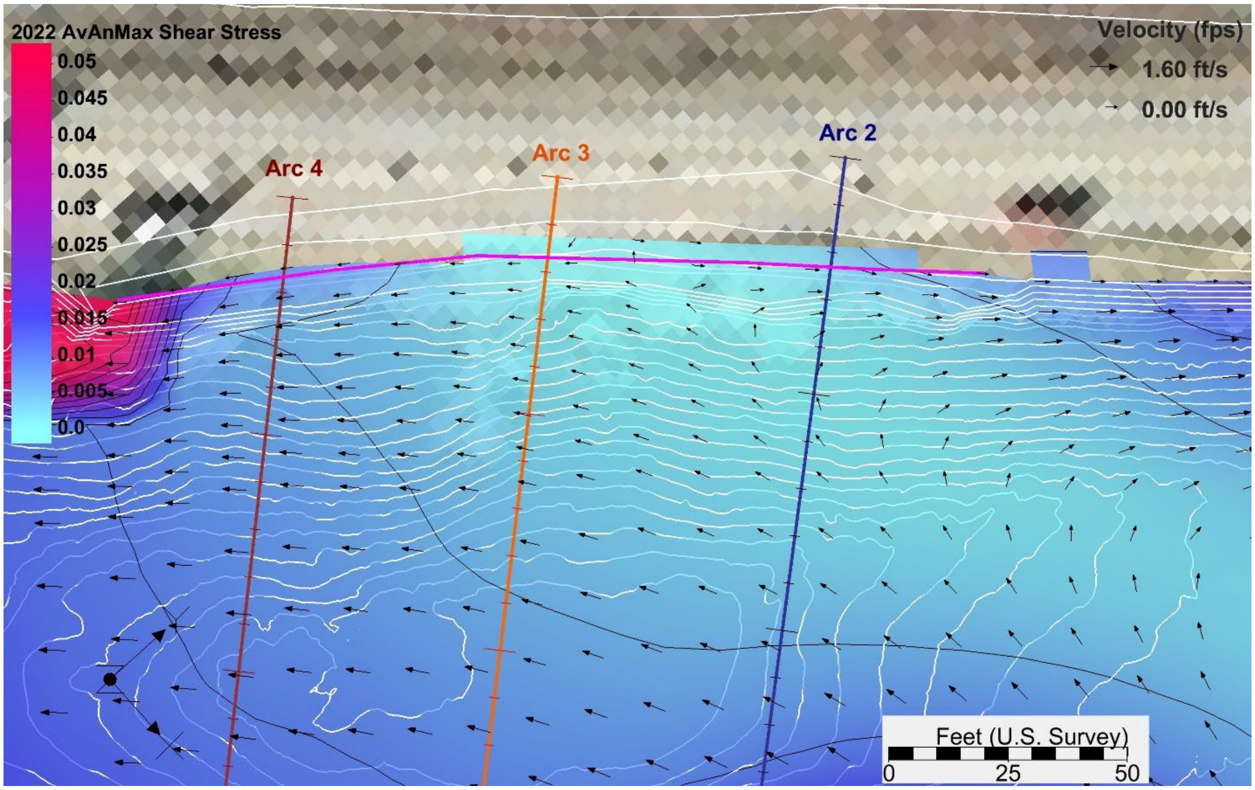

Figure 37. Post-construction bank shear stress for the AvAnMax scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

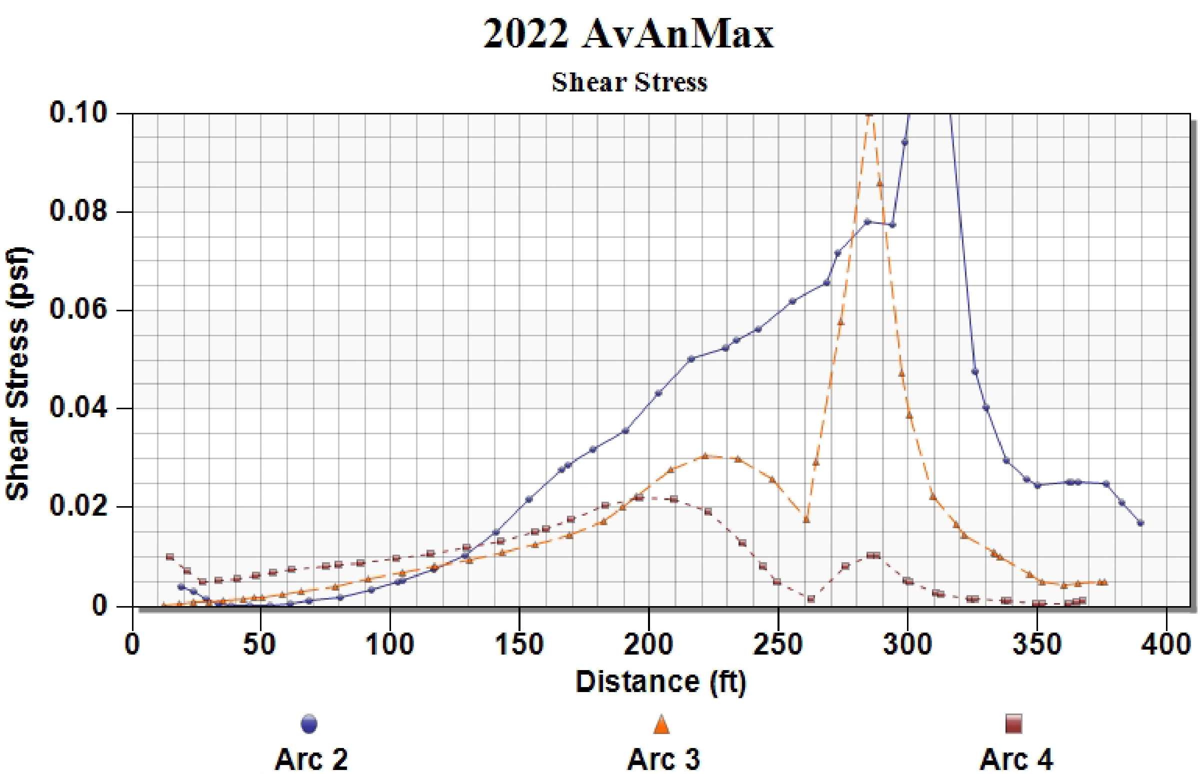

Figure 38. Bed shear stress for transects in Figure 37.

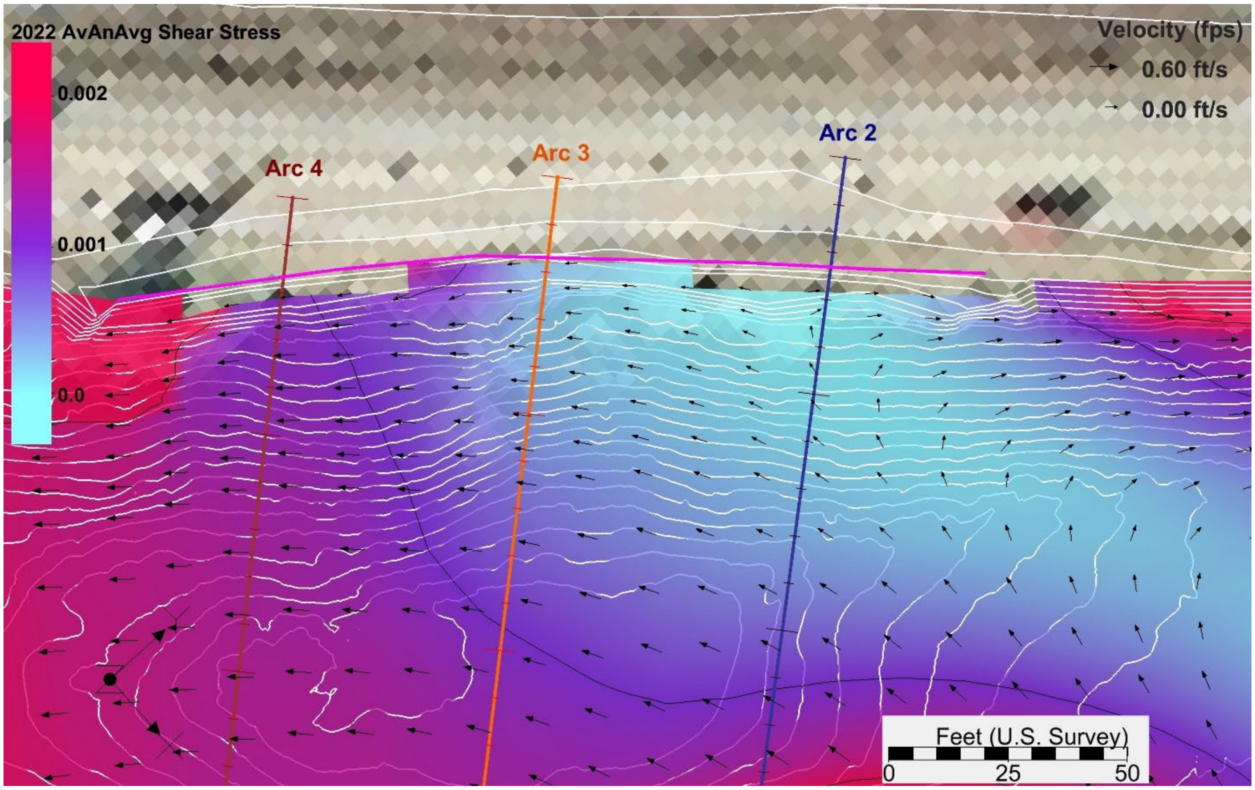

Figure 39. Post-construction bank shear stress for the AvAnAvg scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

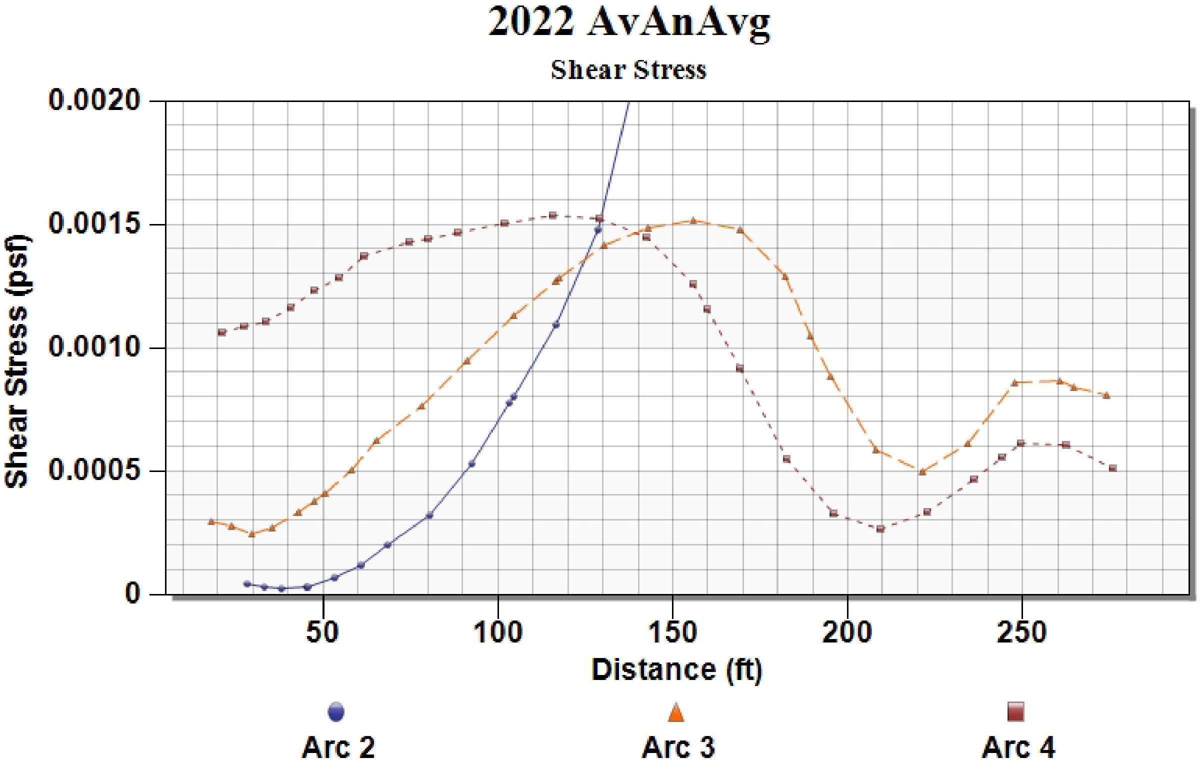

Figure 40. Bed shear stress for transects in Figure 39.

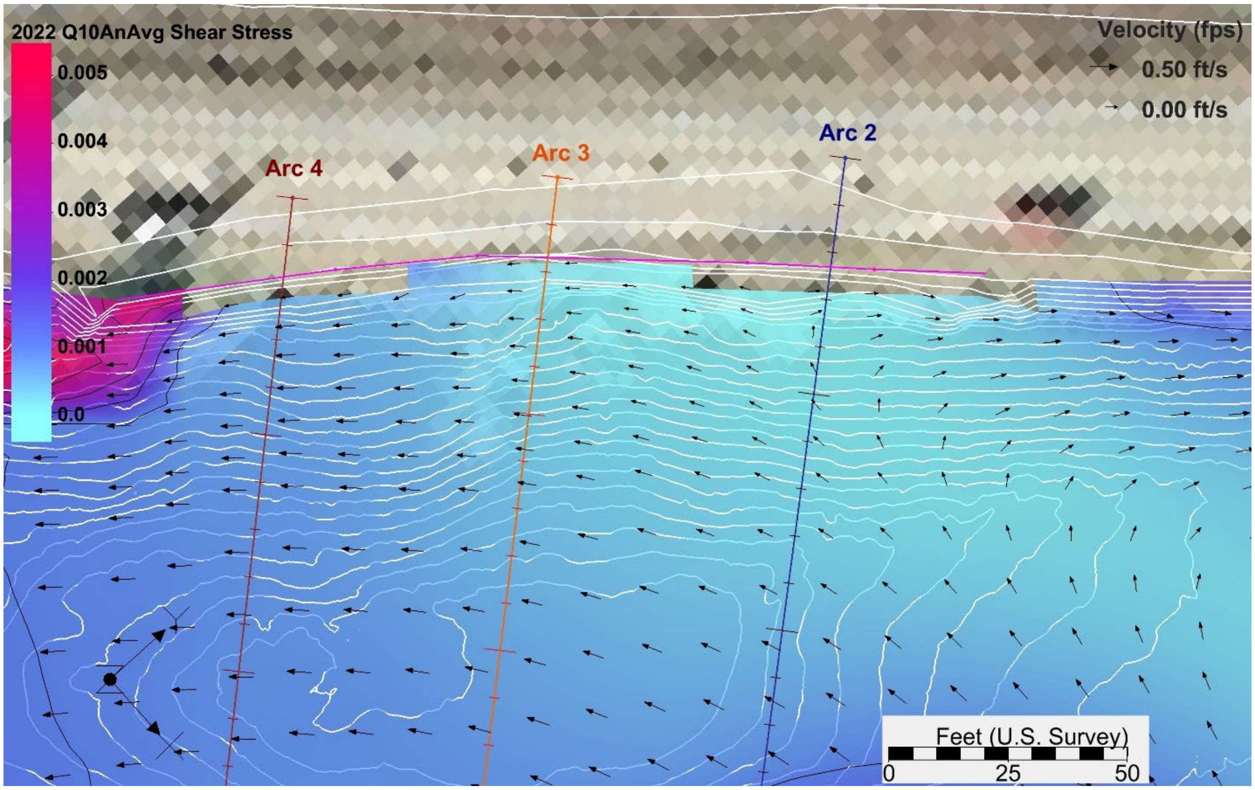

Figure 41. Post-construction bank shear stress for the Q10AnAvg scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

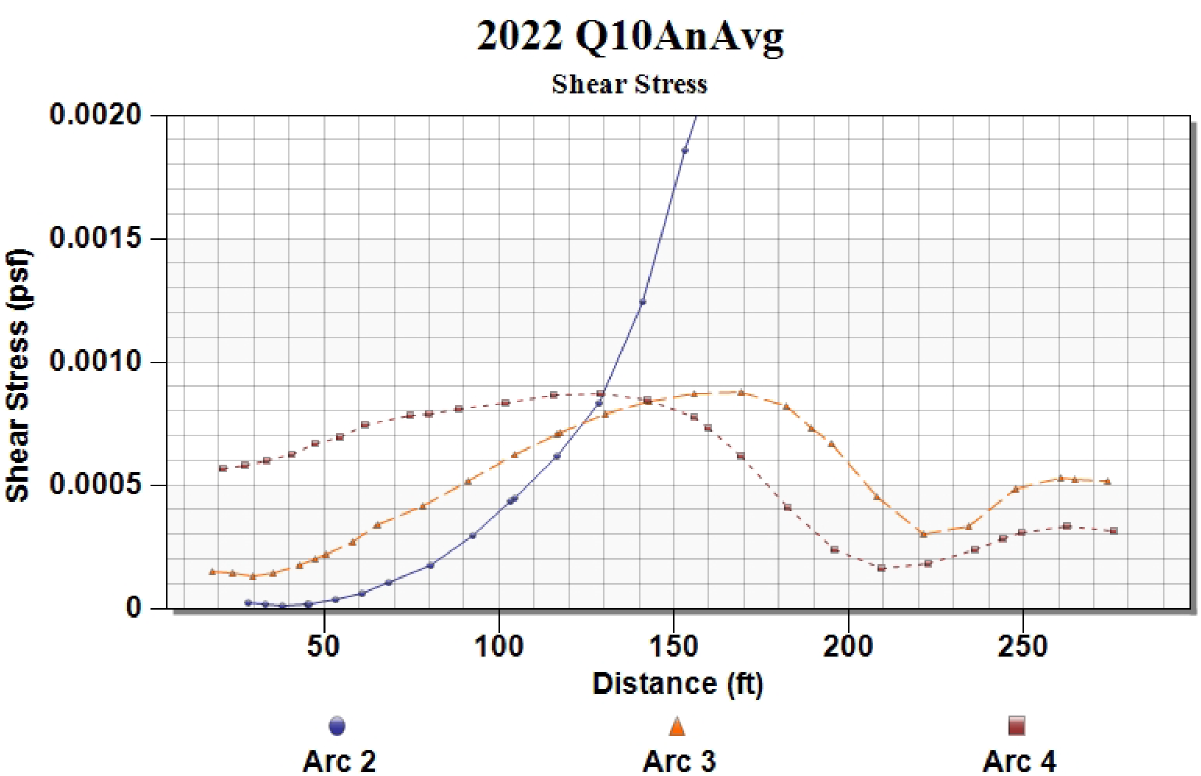

Figure 42. Bed shear stress for transects in Figure 41.

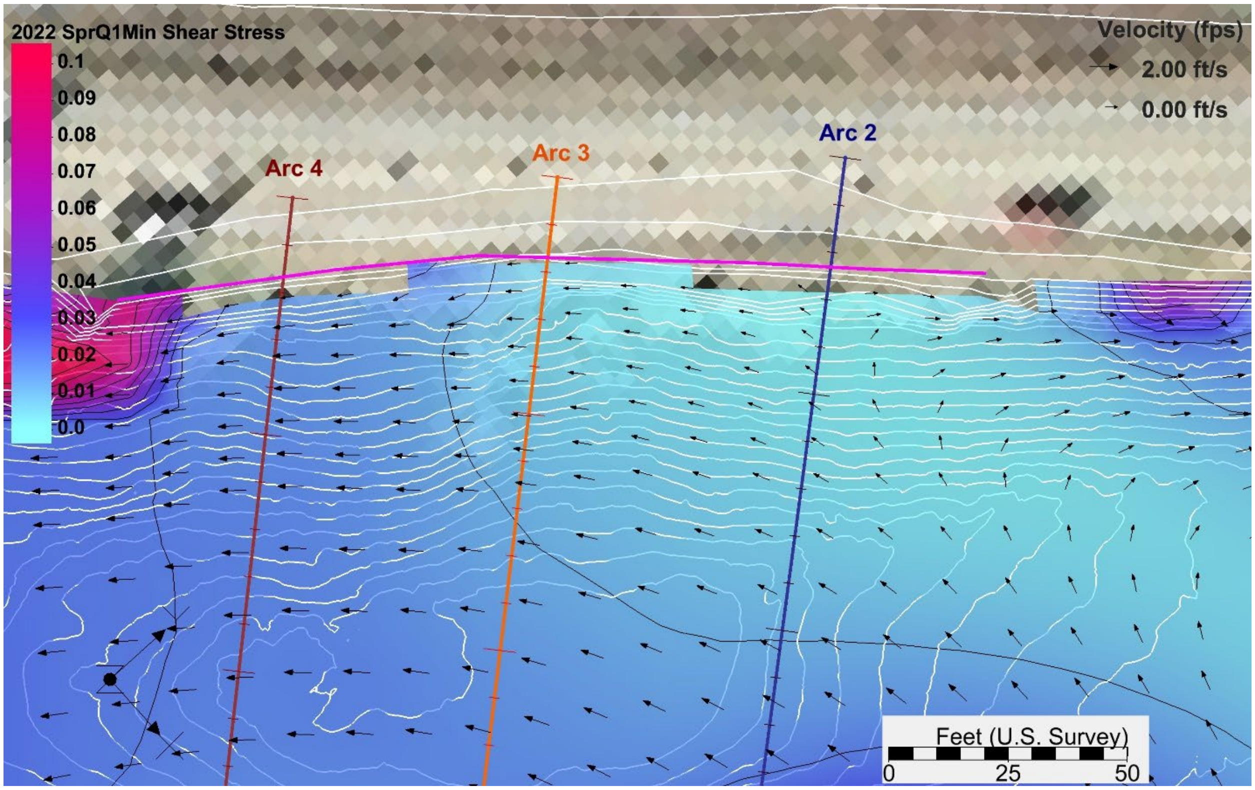

Figure 43. Post-construction bank shear stress for the SprQ1Min scenario. See Table 3 for the flow and water stage information. Coloration legend is shear stress (psf)

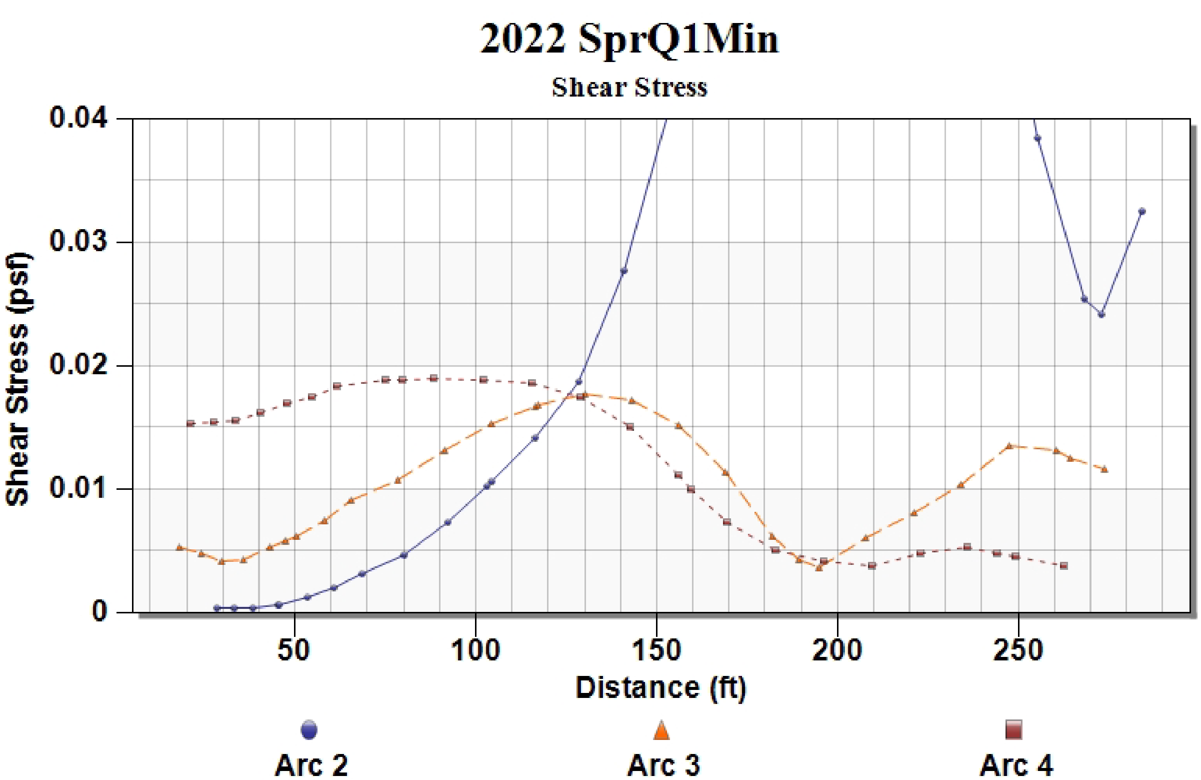

Figure 44. Bed shear stress for transects in Figure 43.

In addition to topographic survey (bathymetry), velocity magnitude and direction were observed during the 2021 field visit by UNH CCOM. The processed data was output on a 15-meter grid with magnitude and direction. Unfortunately, concurrent flow and WSEL during the survey is unknown, though a generic comparison to one of the modeled scenarios may be made. Most annual surveys observed a WSEL at the site slightly above 1,245’, and the 2021 bathymetric survey was conducted in April – a wetter month – so it may be safe to assume that flows are a bit higher than average. With this in mind, the Q10AnAvg run has an annual FDC flow value with an exceedance probability of 10% (higher than normal), and an average controlling WSEL above elevation 1,245’ (1245.87’). Assuming normal spring conditions and operations, this scenario may best imitate the river hydrologic and hydraulic conditions during the 2021 survey. The scenario results for both pre- and post-construction models are shown in Figures 45 and 46. In general, the vector directions align well within the main channel, especially at the location of the ELJ. Tangential channels and eddies tend to have larger variability between observed and modeled vectors, though the overall picture painted in these locations agree that flows are not in-line with those of the main channel. Obviously, not having specific flow and WSEL makes it difficult to directly compare the model to observations and is likely one source of the difference to the modeled results. It is also highly likely that the meshing of the modeled surfaces and accounting for roughness in a conceptual fashion rather than the real-world undulations and intricacies (like submerged trees) likely contribute to a much higher degree of natural variability compared to modeled. Note that in both scenarios, velocity magnitudes (the relative size of the arrows) are at different scales to the observed.

In Figures 45 and 46 there are three transects (arcs) that extend from the ELJ to the other side of the river. These are the same transects found in the odd-numbered figures from Figure 25 to Figure 43. Along these transects the bathymetric data was plotted against distance (Figures 47 to 50). Figure 47 displays the three full cross section looking upstream (ELJ is on the right side at approximately horizontal station with its vertical face at stations: Arc 2, (23 to 26 feet); Arc 3 (16 to 18 feet); Arc 4 (17 to 19 feet). Figures 48 through 50 magnify the ELJ stream bank from pre-construction to post-construction. Data from 2021 was not included due to the silt fence being in place at the time of the survey.

In the two pre-construction surveys, the bank retreat is clearly evident at the waterline from 2019 to 2020. The bank erosion rate is about 2 feet/year, which is double the rate identified in Table 1. Table 1 values are derived from point estimates using erosion pins whereas the figures demonstrate the totality of the erosion along the streambank. It should be noted that the streambank slopes below the waterline in Figures 48 to 50 average 36 degrees which is at the very upper limit of the angle of repose for sands. These lower elevation slopes do not demonstrate significant lateral movement over the monitoring period. Streambanks on the outside of meander bends, such as at the ELJ site, typically demonstrate erosion at the toe of the streambank which then results in bank undercutting and then bank failure.

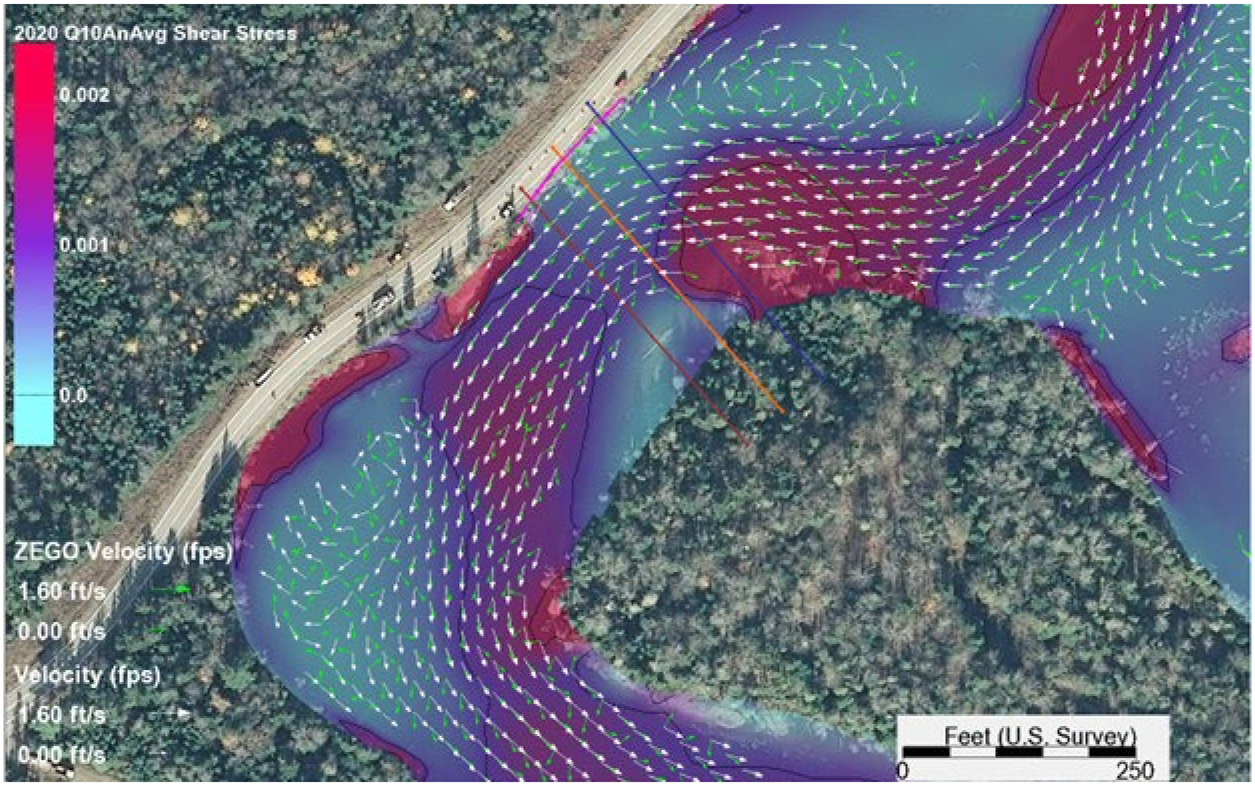

Figure 45. Pre-construction (2020) velocity vectors (black arrows) compared to 2020 ZEGO observed (green arrows). Coloration legend is shear stress (psf)

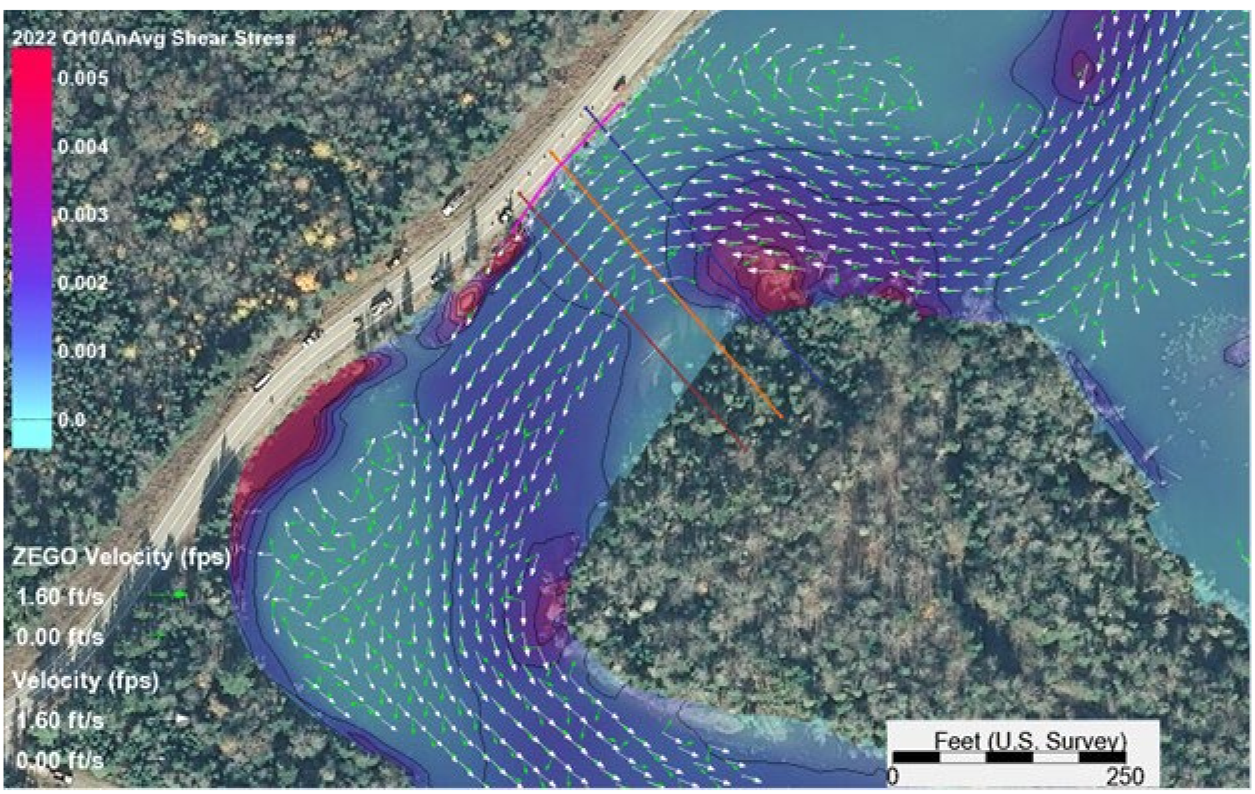

Figure 46. Post-construction (2022) velocity vectors (black arrows) compared to 2020 ZEGO observed (green arrows). Coloration legend is shear stress (psf)

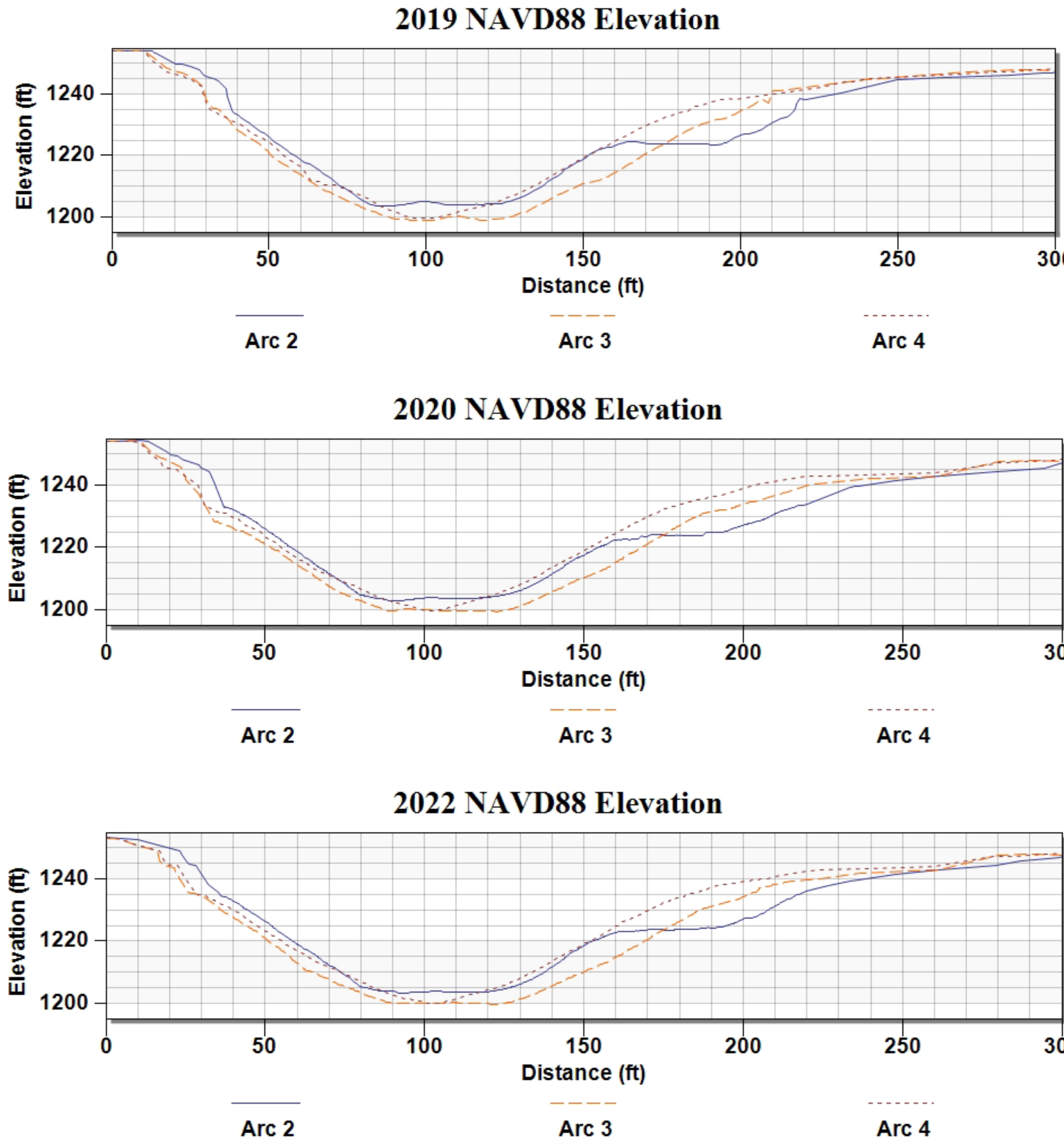

Figure 47. Stream cross sections looking upstream at the three transections delineated in Figures 45 and 46. For each Arc, the ELJ is at Distance: Arc 2, 23.25 ft to 26.25 ft; Arc 3 16.25 ft to 18.25 ft; and Arc 4 16.75 ft to 19.0 ft.

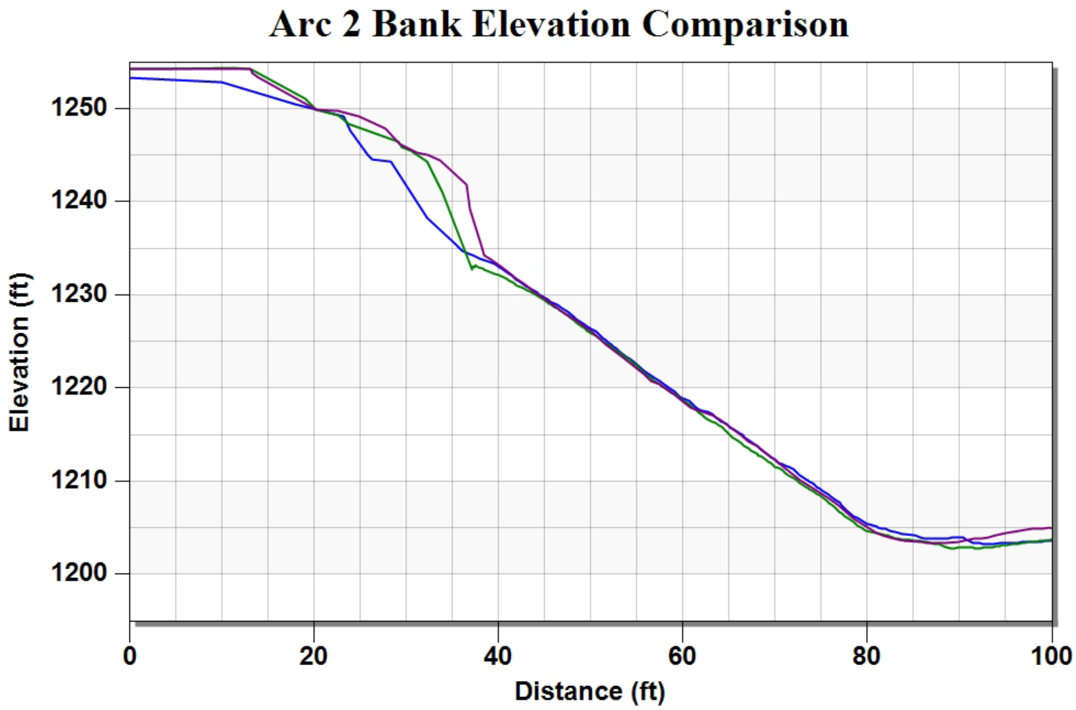

Figure 48. Time series of Arc 2 slope. BLUE colored line is 2022 elevation, the GREEN colored line is 2020, and the PURPLE colored line is 2019. ELJ is at Distance 23.25 ft to 26.25 ft

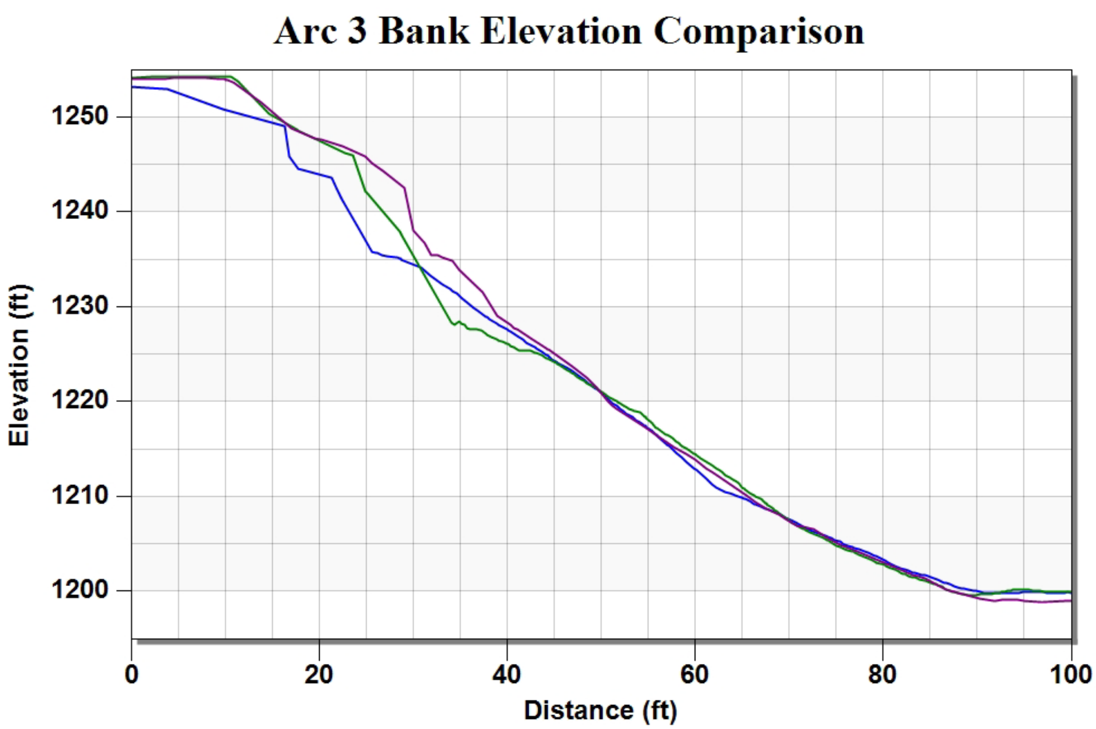

Figure 49. Time series of Arc 3 slope. BLUE colored line is 2022 elevation, the GREEN colored line is 2020, and the PURPLE colored line is 2019. ELJ is at Distance 16.25 ft to 18.25 ft.

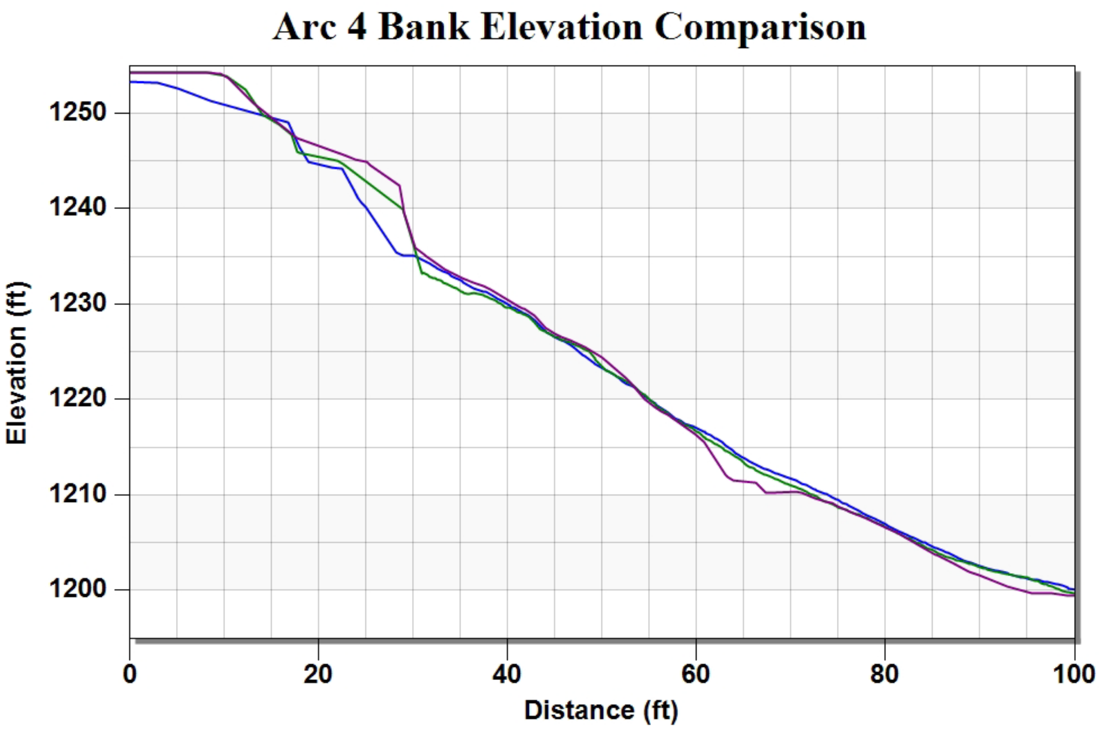

Figure 50. Time series of Arc 4 slope. BLUE colored line is 2022 elevation, the GREEN colored line is 2020, and the PURPLE colored line is 2019. ELJ is at Distance 16.75 ft to 19.0 ft.

Riparian Wildlife

In an effort to understand riparian wildlife, for approximately 2 months each year (June and July) game cameras were positioned along the streambank prior to ELJ construction and across the river during and after construction. Little to no observable wildlife was detected by the game cameras prior to construction. There was evidence of burrowing animals at the steep eroded bank faces. In addition, along the bank margins where native vegetation could establish, insects were observed. Along the shoreline, ducks were observed floating by. Because of the steep slope, the lack of vegetation, the Jersey barriers, and the proximity to traffic, the pre-construction streambank (Figure 34) was relatively inhospitable to most wildlife. In addition, this particular streambank created a riparian corridor disconnect along this side of Route 16 which made it more convenient for wildlife to cross the road to the other side rather than stay on this side of the road.

Post construction streambank physical attributes included reducing the above-waterline bank angle, moving the road farther away, and planting native vegetation. Some burrowing animals were still present (Figure 35). Although the game cameras did not pick up wildlife along the

ELJ, there was ample evidence of significant riparian wildlife activity including: hoof and footprints, herbivory, and droppings.

Figure 47. Pre-construction streambank geometry.

Figure 48. Burrowing animal evidence along the ELJ.

Aquatic wildlife

Prior to construction and post construction, two Go Pro cameras were deployed below the water line and close to the streambed about 15 feet offshore from the ELJ location. Cameras were deployed on back-to-back days each year in June during daylight periods, for durations of two to ten hours. and shot continuous videos. The videos were then downloaded, and any fish caught in the videos had a still image cropped from the video. The fish in still images were then identified with the aid of USFWS and NHF&G personnel. In general during the pre-construction periods, water clarity was on the order of ten feet for the Go Pros. Prior to construction, dozens of fish were caught on the videos and included: chain pickerel, yellow perch, smallmouth bass, white sucker, and fall fish (Figure 49). During the lone post construction video deployment, the water clarity was poor, with visibility less than one foot. Four perch were detected on the post construction videos.

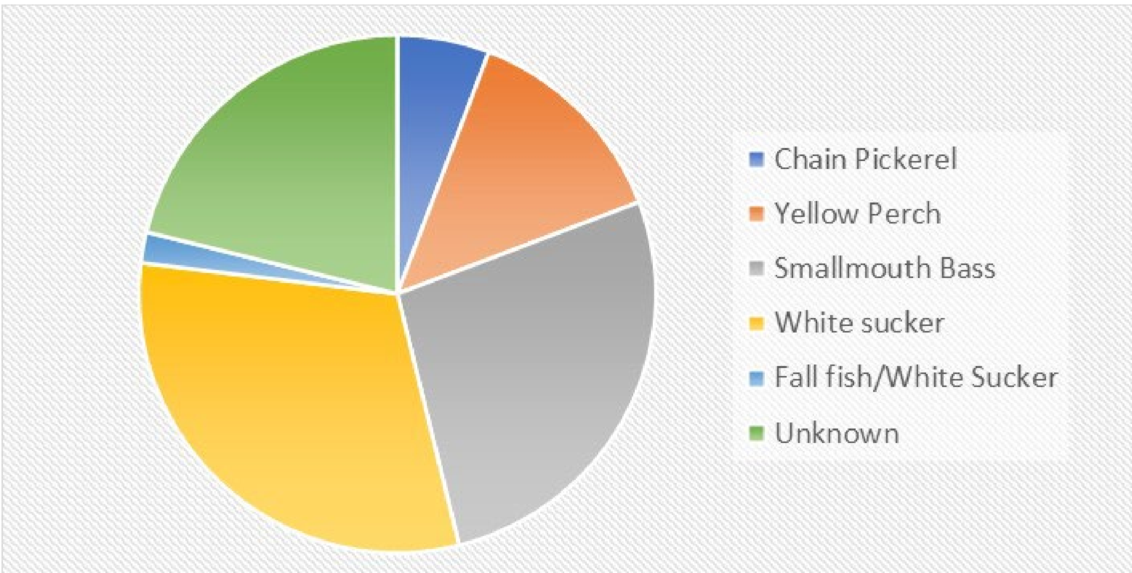

Figure 49. 2020 Observed fish results (n = 52)

Conclusions

The ELJ along the Magalloway River has arrested streambank erosion and greatly improved the terrestrial ecosystem characteristics. There is more numerous wildlife use of the terrestrial part of the streambank post-construction (insect, avian, mammal). The ELJ now creates a wildlife corridor at its location where previously none realistically existed. There is insufficient data to determine if the ELJ had any impact on aquatic resources. The ELJ does not appear to have dramatically altered near bank hydraulics. Episodically the ELJ is an armored feature capable of withstanding the near bank shear stresses that occur at the site. From observations, the ELJ also withstands the increased wave attack from boat wakes.