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An Assessment of Lower American River Restoration Projects: Energy, Carbon Emissions and Bed Stresses

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Publication Date
2020-01-04

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LDARCH 227: River Restoration
Final Draft
Fall 2019

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Abstract:

Restoration projects to increase the area of suitable salmon spawning habitat on the Lower American River (LAR) include projects at Sacramento Bar and Sailor Bar. These two projects involved adding suitable sized gravel for fall-run chinook salmon, and constructing side channels with depths, velocities, and substrate suitable for spawning. The Sacramento Bar project was completed in 2016 but washed out in the high flows of early 2017. A similar project at Sailor Bar project completed in October of 2019 incorporated larger sized fill media intending to prevent wash out. Both projects were constructed using heavy equipment such as bulldozers, excavators, loaders, and dump trucks. We calculated that the energy expended by construction equipment was approximately 2,257 megajoules (MJ) to create the modifications to Sacramento bar, and 1,225 MJ to modify Sailor Bar. The 2017 flood that washed out Sacramento Bar had approximately 1,952 MJ of energy per longitudinal unit length of the river reach (i.e. per meter length). Shear stress calculations indicated the 2017 flood exerted shear stresses of up to 95.8 pascals (i.e., N/m^2), and that the gravel placed in the Sacramento Bar project may have been mobile starting at velocities of 1.49 ms^{-1}. Energy calculations indicate that American River possessed a much higher energy during the high flow conditions of early 2017 than the total project energy. We calculated the Sacramento and Sailor Bar's carbon emissions to be 103 and 55 metric tons of carbon dioxide, respectively. Understanding the river's power to move sediment is prerequisite to assessing project longevity. Either new gravel must be continuously placed upstream after floods and letting the river (or body of water) reallocate it, or larger gravel should be initially placed. To prevent spawning gravel from washing out in frequent high flows, larger gravel are necessary to prevent scour. However, for effective salmon spawning, appropriate d_{50} and d_{84} sediment sizes are required; this indicates that other methods aside from increasing gravel size are recommended to prevent washout.

1. Introduction:

The Folsom Dam was constructed in 1952 and is located on the American river northeast of Sacramento, California. The dam starved the river downstream of sediment and blocked upstream access for migratory fish, mainly fall run chinook salmon. A restoration program began in 2007 managed by the Water Forum, which aimed to restore the fish and biological activity lost in the 50s. The Water Forum consists of local governments and business leaders with the goal to restore the Lower American River (downstream of the Folsom Dam) and facilitate the re-introduction of fish to the river as much as possible. This process currently consists of restoring sites downstream of the Folsom Dam by making sites conducive to Chinook Salmon fall run spawning. Restoration projects along the LAR are an ongoing process that is projected to continue for the next 15 years (*Lower American River Anadromous, 2019*). Two recently completed projects along the Lower American River were at Sacramento Bar (in 2016) and at Sailor Bar (in October of 2019). While both projects were similar in their aim to increase Salmon spawning by creating an ecologically favorable side channel, Sailor Bar built upon the lessons learned from the washout at Sacramento Bar in 2017. We examine in the following study the creation of side channels at Sacramento and Sailor bar to evaluate energy, shear stress, and emissions associated with their construction. These findings may be further extrapolated to other gravel projects along the Lower American River.

Our main focus is on the projects' long-term viability, achievement of the primary stated goals, and analysis of the energy input of construction compared to the energy potential of the river itself. At Sacramento Bar, an approximately 330 meter (m) long side channel was constructed across the bar and a 304 m long reach of the main channel was modified to create a more extensive area of shallow gravel-bedded riffle in 2016. The goal was to increase salmon spawning and rearing habitat. The sections planned are shown in Figure C and were taken from the overall plan titled "Environmental Assessment and Proposed Mitigated Negative Declaration Lower American River" (LAR). The site was designed to withstand erosion in flows of up to 5,000 cubic feet per second (cfs), equivalent to 141.58 cubic meters per second (cms). In January and February of 2017, the channel experienced high flows which washed out a number of the project features. Sailor Bar, located upstream of Sacramento Bar (see Figure D) was also restored with the aim of facilitating fish rearing potential. Having been completed in October of 2019, this project serves as a comparison site when looking at the energy inputs required for a project with similar aims and also located on LAR.

This study also compares and correlates the geomorphic impacts of the Sacramento Bar and Sailor Bar projects with others in their ability to support biological processes. We calculated shear stresses and estimated the flow at the threshold of movement at Sacramento Bar. We also quantified the energy available in high flows of the LAR and look at sediment sizes that could be mobilized with the river's own sediment restoration processes. With this we determined requirements of future work to avoid wash out in a similar manner. Additionally, we examined work done on the river using equipment needed to construct the Sacramento Bar restoration project and compared emissions of CO_2 needed to complete large gravel restoration projects.

2. Methods

2.1 Interview and past projects

Historical analysis of past project water depth and river flow data is important in our analysis. We gathered much of our data through our interview with a Scientist from the Water Forum working in the area since 2012. With their help we found plans and specifications on current, past, and future jobs on the LAR, which we used to help make correlations. The long term goals of restoration projects along the American, as well as past failures and future successes are further examined below.

Post interview, we were able to use the information gathered on Sailor and Sacramento Bar's written restoration plan and Sailor Bar's construction plan sheets (included in Appendix A) to conduct our review. Through our investigation of the two plans and specifications we were able to find and interpret geomorphic and construction data as they relate to gravel mobility, energy, and carbon emissions.

2.2 Field Surveying

We conducted field surveys at both Sacramento Bar and Sailor Bar. The survey involved a cross section of the American River at Sacramento Bar, and pebble counts at both the Sacramento and Sailor Bar. We also found out the surface flow velocities at both locations. The survey also included general observations of the current conditions at the two locations. The field surveying involved:

1. Levelling-to determine the cross section of the river.
2. Pebble Count using a Gravelometer.
3. Measuring the velocity of flow by letting organic matter float for a specified distance on the river surface and noting the corresponding time periods.

2.3 Calculations

2.3.1 Potential Energy of River

We calculated the Potential Energy (PE) of the river flow (per unit length of reach) during the flood on 1/11/2017; this flood was responsible for the washout of the Sacramento Bar Project. The equation for PE (per unit length of reach) was calculated using the following formula (Ciotti et al *In Review*) shown below:

$$PE = k * Qa * m * g * h,$$

where PE is Potential Energy per unit length of reach, k is the number of seconds in a year, Qa is the mean annual discharge ($m^3 s^{-1}$), m is the mass of 1 cubic meter of water (kg), g is acceleration due to gravity, and h is the slope of the river bed.

We used the above formula to find an annual PE of the river. We assumed that the formula is valid for PE calculations on a particular day (based on the parameters used in the equation). Thus, we used the same formula for calculating the PE of the river on a particular day (for example, the day of the flood) by using: k= number of seconds in a day, and Qa = flow discharge on a day (m^3s^{-1}). The rest of the formula remained unchanged.

2.3.2 Calculations on CO_2 Emissions and Energy

We calculated the total project emissions of all construction equipment at the recent (September-October, 2019) Sailor Bar gravel project using data from the projects official plan (CBEC, 2016 Basis of Design Report). As a requirement of the California Environmental Quality Act (CEQA) equipment emissions of CO_2, NO_x, PM2.5 and other noxious fumes must be projected in a good faith effort as determined by the governing body. Using the proposed data and other past studies on emissions from commonly used construction equipment, we estimated CO_2 emissions on Sailor Bar's project, and interpolated the estimates to the Sacramento Bar project, and other proposed and poast sites along the American River.

Table C, E and F show the equipment and CO_2 emissions broken down by each type of major equipment at varying past and future jobs along the American River. Major equipment included bulldozers, excavators, loaders, dump trucks, and other miscellaneous haul or water trucks used throughout the Sailor Bar project (Reclamation, 18). We calculated each type of equipment's carbon emissions by finding the mass of carbon per horsepower or per kilowatt per hour, and multiplied by usage as shown below. Additionally, the total energy of each equipment was tabulated simultaneously using the equation below.

$$CO_2\,Emissions\; = \; g\; of\; CO_2\, per\; KW/h\; *\; Equipment\; Hours$$

$$Energy\,[MJ]\; = \; KW/h\; *\; Equipment\; Hours\;\; /\, 1000\; *\; 3.6\, MJ/h.$$

In some cases such data was not made available, such as haul trucks, where data is in terms of mg carbon/time per axle loading and if the truck is full or not. The equation below reflects this calculation.

Due to the equipment type it was assumed 30.58 m^3 (40 cy) haul trucks all have tandem axles and are full one trip and empty the next, thus taking the average of the two loading situations.

The duration of each equipment usage was also taken directly from projected usage requirements from the project plan (Reclamation, 18). A project at Sailor Bar in the summer of 2019 took roughly four weeks of working days according to the project plan. Accounting for 10% extra work as is typical in construction projects (via change order etc.) we used 30 working days as primary usage time for essential equipment (dozers, loaders, excavators), and projected hours per day from the “construction detail” section of the overall American River restoration plan (Environmental Assessment LAR , 2019).

2.3.3 Bed Shear Stress

Bed shear stress is a measure quantifying the force per unit area produced by flowing water that can mobilize sediment downstream. Bed shear stress was calculated for both Sacramento Bar and Sailor Bar based on flows and field surveys done on 11/10/2019, and on flow data obtained from the USGS for the flood on 1/11/2017. We calculated bed shear stress following the guidance provided in the 2016 Basis of Design Report: *Lower American River Salmonid Gravel Augmentation and Side Channel Habitat Establishment Program*. The equation was also utilized by Brown and Pasternack (2008) and Lisle, et al (2000), and is defined as:

$$\tau_b = \rho_w \left(\frac{\bar{u}}{5.75 \log\left(\frac{12.2H}{2D_{90}}\right)} \right)^2$$

Where, τ_b is the bed shear stress in pascal (Pa), ρ_w is the density of the water (kg/m^3), $\bar{u}$ is the average velocity (ms^{-1}), H is the water depth (m), and D_{90} is the size of sediment with 90% passing. The equation above assumes steady flow—meaning with changing time all conditions in the river remain the same. The measurements at the inlet of the constructed side channel displayed a steady flow velocity after considering our various measurements.

On our field visit, we measured velocity both near the bank at Sacramento Bar (approximately 12.19 meters away from the bank), as well as in the middle of the river (approximately 42.67 meters). We estimated velocity using a stopwatch with multiple timed trials at different points transverse to river flow, including the points where the inlet for the constructed channel would have been in early 2017. From this we determined average surface velocity. We obtained the flow velocities for the flood on January 11th, 2017 flood from the USGS monitoring station located at American R A Fair Oaks. The USGS meter station is located at Sailor Bar identified in Figure E. The velocity at Sacramento Bar was calculated by applying a ratio empirically derived during our field velocity measurements on November 11th, 2019.

We determined the water depth in the main channel of the American at Sacramento bar based on the channel cross section we created during the fieldwork, at a distance of 12.19 meters from the bank. The D_{90} sediment size used in calculations is based on pebble counts we conducted where the inlet location would have previously been upon completion of the channel in late 2016.

2.3.4 Shields Stress

The Shields stress value allows us to determine with some certainty if the sediment will move based on the bed shear force (tb) and median size of sediment material, and is defined as:

$$\tau^* = \frac{\tau_b}{(\gamma_s - \gamma_f)D_{50}}$$

where, τ^* is Shields stress (non-dimensional), y_s is the specific weight of the sediment (Nm^{-3}), y_f is the specific weight of water in (Nm^{-3}), and D_{50} is the median sediment size that was observed during the pebble counts.

For the specific weight of sediment we estimated values based on previous research done in river and reservoir systems (Bureau of Reclamation, 2016; Jon and Ponce, SDSU). The estimates were based on sediment size and composition (gravel and sand mixtures).

The Shields stress non-dimensional values can be attributed to relative bed mobility, where values of: 0.00 to 0.01 indicate no transport; 0.01 to 0.03 indicate intermittent, localized transport; 0.03 to 0.06 indicate partial movement, relative to the exposure of bed surface; 0.06 to 0.1 indicate full bed mobilization of the top layer of sediment (about 1-2 D_{90} thick); and greater than 0.1 indicates "channel-altering conditions" (Brown and Panckerton, 2008; Lisle, et al 2000; Design Report, 2016).

2.3.5 Volumetric Bed Load Transport Rate

The volumetric bed load transport rate is the amount of sediment that would move due to the bed shear force. The rate is based on the values obtained for bed shear stress and Shields stress, as well as the mean sediment size obtained from the pebble counts taken at where inlet of the channel was previously.

We calculated the volumetric bed load transport rate based on the relation by Meyer-Peter and Mueller derived from laboratory experiments on sand and gravel transport in steady flow environments (discussed in the chapter by Mrokowska and Rowiński, 2018). The relationship is defined as:

$$q^* = 8(\tau^* - {\tau^*}_C)^{1.5},$$
$$\text{where } q^* = \frac{q}{D_m\sqrt{grD_m}}.$$

In the above formulae, q^* is the bed load transport rate (dimensionless), g is the gravitational acceleration (m^2s^{-1}), r is the submerged specific gravity of sediment—i.e. the sediment density minus the water density, all divided by the water density—, is Shields stress (dimensionless), is the critical Shields stress for initial motion (equal to 0.047), D_m is the mean sediment diameter (m), and q is the volumetric bed load transport rate (m^2s^{-1}). Upon combining and reorganizing the two formulae presented here, we can obtain "q," the volumetric bed load transport rate.

2.3.6 Recommended Sediment Size

Considering the bed shear stress and bed loads, possible recommended sediment sizes were calculated to prevent bed mobilization based on the high flow measured during the flood event on January 11th, 2017. To obtain a representative range of sediment size, the gravel composition in the bed and the degree of bed mobilization were both taken into account. Gravel composition was determined using the D_{90} of the gravel based on the pebble counts done on January 11th, 2017. Shields Stress values of 0.03 and 0.06 were applied for bed mobilization, both of which minimize sediment movement. While increasing sediment size can aid in minimizing bed mobilization, it is important to also factor in the appropriate size for fish nesting. Using the D_{90} obtained prior to the completion of the 2017 project gives us a more realistic sediment distribution to also meet the goal of fish habitat restoration.

3. Results

3.1 Cross Section

The cross sectional cut near Sacramento bar is shown in Figure A, as field surveyed by our team. We observed that the maximum depth of the river is approximately 1.2 m and the length of the river is approximately 100 m. The river bed seems to be largely uniform with little undulations.

3.2 Pebble Counts

Pebble counts at Sacramento Bar were taken at the previous inlet and outlet of the channel constructed in 2016 (Figure C). Additionally, we also conducted pebble counts next to the river channel and further up on the bar and floodplain (Figure G). The pebble counts were conducted further away from the river to better understand the distribution of gravel at both the inlet and outlet locations. We found the D_{50} to be 32 mm and the D_{90} as 64 mm.

3.3 Potential Energy of Flow

The USGS data gives us the value of flow discharge adjacent to Sailor Bar (USGS, 2017). We determined flow velocities at Sacramento and Sailor Bar sites as previously mentioned. Completing multiple iterations of this process and averaging them yielded Sacramento Bar and Sailor Bar flow velocities to be 1.55 ms^{-1} and 1.14 ms^{-1} respectively. Site plans from Sailor Bar's constructed site, included in Appendix A, were used to estimate the river bed slope at Sacramento Bar using the known slope at Sailor Bar (0.1%). The slope is determined to be 0.13%.

The USGS data revealed the flow discharge on 1/11/17 to be 62,600 ft^3s^{-1} or 1,772.21 m^3s^{-1}. Using the PE formula mentioned in the methods section, we determined the PE per unit length of river reach at the Sacramento Bar to be 1,952 MJ (MegaJoules). For the same discharge, we calculated the PE per unit length of reach at Sailor Bar as 1,502 MJ.

3.4 CO_2 and Energy

Total CO_2 emitted and energy calculations are outlined in Table C, E and F. By scaling the projects based on the size of gravel at the construction site, Sacramento Bar project emitted approximately 103 metric tons of CO_2. The total estimated CO_2 emissions produced at Sailor Bar was approximately 55 metric tons. Additionally, Table D reflects the total energy of machinery required during construction for both Sacramento and Sailor Bar, with energy approximated to be 2,257 and 1,225 MJ respectively. Also included in Table E and F are estimated CO_2 totals for past and future project along the American.

If this data is extrapolated to other sites both past and historic using the same simple gravel scaling method another proposed approximately 10,000 MJ (MegaJoules) of energy will be needed to construct future projects, with over 6,000 MJ already spent on previous restoration projects in the past 10 years. We also found the energy associated with constructing the side channel at Sacramento Bar to be 6.8 MJ if we divide the total length of the channel by the energy required by equipment during construction.

3.5 Bed Shear Stress and Bed Mobilization

The bed shear stress (Pa), Shields stress (dimensionless) and volumetric bed load rate (m^2s^{-1}) for both Sacramento Bar and Sailor Bar are shown in Table 3. Calculations were done based on: 1) field data collected on November 11th, 2019 (with average river velocities of 1.55 ms^{-1} at Sacramento Bar and 1.14 ms^{-1} at Sailor Bar); and 2) measurements taken at monitoring station located at American R A Fair Oaks during the flood event on January 11th, 2017 (with average river velocities of 3.35 ms^{-1} for Sacramento Bar and 2.45 ms^{-1} for Sailor Bar). The ratio we applied to determine the flow velocity at Sacramento Bar for the flood event was 1.37.

Table H reflects calculated gravel sizes based on the D_{90} at Sacramento Bar, for Shields Stress values of either 0.03 or 0.06, and prioritizing the minimization of sediment movement for flow velocities ranging up to 1,772.63 m^3s^{-1}.

For Sacramento Bar, the sediment sizes that could be mobilized ranged from 428.27 to 1,364.69 mm for a Shields stress of 0.03, and from 214.13 to 682.34 mm for a Shields stress of 0.06. For Sailor Bar, the sediment sizes ranged from 284.33 to 1,093.12 mm for a Shields stress of 0.03, and from 142.16 to 547.56 mm for a Shields stress of 0.06.

4. Discussion

4.1 Pebble Count

The pebble counts showed little variation between the sediment size in the inlet location versus the outlet location. Both grain size distribution curves followed the same pattern and indicated similar D_{50} and D_{90} values. The D_{50} was found to be 32mm; this value was higher than the planned D_{50} by Water Forum at the time of construction which was 25.4mm. The similar gravel distribution observed does implies that the sediment composition at Sacramento Bar was homogenous at both ends of the previous channel at the time of measurement. Onsite visual observations backed the homogeneity of the sediment bed (see pictures in Appendix C).

Upon examination of the gravel distribution based on the distance from the riverbank,we noted some differences. As shown in Figure H for the outlet location, the sediment distributions near and far away from the bank were comparable except at 32 mm. Contrarily, the sediment distributions for the inlet location indicated higher numbers of larger sediment (32 mm or higher) at the closer distance to the riverbank. This distribution may be due to the bed shear force required to move the larger sediment being higher, and less mobilization occurring for specific flow velocities.

4.2 Carbon Emission Effects

Heavy civil construction projects are expensive, and can often result in negative environmental repercussions such as hydraulic fluid leaks, physical damage to the environment, and carbon emissions as previously addressed. As shown in our results for CO_2 emissions, hundreds of tons of CO_2 are at stake when we analyze the impact of continued restoration along the American river. Many of these projects aimed at habitat restoration prior to 2017 were wiped out by floods in January and February of 2017, and reflected in Appendix B.

Putting our results of CO_2 emissions into a common context, a round trip airplane flight from New York to San Francisco creates a warming effect equivalent of 2 to 3 metric tons of carbon dioxide per person (New York Times, Rosenthal). In comparison the entire Sacramento Bar project lasting a projected 60 working days resulted in 102 metric tons of carbon dioxide, which is less than a full airplane flight. The Sailor Bar Project was fortunate that staging grounds were nearby for hauling in gravel and spalls for project use. Rock itself was also used from nearby (Water Forum, Interview) sources to the American. This helped reduce the cycle time for trucks, and per the site plan for Sailor Bar the haul route was only a total of 3.5 miles (Gravel Flyer, 2019). If cycle times were longer or haul routes longer this could also significantly increase carbon and energy totals of a job.

If we take the above considerations into account, the amount of carbon dioxide released by equipment is large, however may not be the low hanging fruit if one's ultimate goal is CO_2 reduction. If a project's goal in general are met, stakeholders may consider the carbon emissions to be worth it. However, the emissions could be saved or reduced by reallocation of resources such as placing gravel downstream of the Folsom Dam and allowing the rivers energy to carry the sediment where it will. We will examine the potential of this in the following sections. Further research should be done on comparable restoration projects to determine mean carbon emissions and better establish the extent of CO_2 that is emitted per project. Having a more thorough understanding of carbon emissions at a larger scale may help determine the cumulative effect of restoration projects, what key factors minimize carbon emissions, and the role that carbon sequestration programs can play when calculating total emissions.

4.3 Potential Energy

We calculated the potential energy per unit length of river reach at Sacramento Bar at the time of the flood event of 1/11/17 to be 1,952 MJ. To put this in context with CO_2 energy emissions, the length of the side channel that was constructed was approximately 330 m. As shown in the results (section 3 of this report), energy associated with the construction of Sacramento Bar per unit length of constructed channel was 6.8 MJ. This energy number is clearly less than the potential energy of the river on the day of the flood event. Overall, about three times less energy was expended in the execution of the restoration project than the energy that washed out the same project. The American possessed enough potential energy that it was able to carry away the gravel riffle and wash out the side channel. This energy was greater than the energy expended in the construction of the above restoration features. Such findings may be predicted in the future by reviewing more advanced hydraulic and sediment models in the design phase.

We also observed a similar trend for Sailor Bar. While the PE of the river flow (per unit length of reach) for the same flood discharge that washed out Sacramento Bar Project was found to be 1,502 MJ, the CO_2 emission associated energy per unit length of construction of channel was found to be 3.141 MJ for a side channel length of approximately 390 m.

The energy expended on construction projects along the river is paltry when compared to the potential kinetic energy needed by the river to return sites to pre-construction conditions. In light of such discrepancies, more in depth and fully flushed out models can be found in the design report of Sailor Bar (Reclamation Managing Water, CBEC). Moving forward, such models appear to be a necessary step to save both manpower and energy. Evaluation of how the river will move sediment is extremely impactful on construction projects. This fact was not lost on the Water Forum planners, as post Sacramento Bar, Sailor Bar did use in depth hydraulic models to more accurately attempt to predict river processes, and should continue to do so on other projects along the American.

In light of the rivers high kinetic energy, it may alternatively be prudent to place gravel upstream (but beneath the dam) and allow the rivers high energy during both normal and flood conditions to do the work of relocating spawning gravel to locations that may be naturally suitable. While downstream gravel is not something that was studied in this paper, it may be worth further research. If gravel suitable for salmon spawning was allowed to simply find its own way down river, it could save energy associated with equipment as well as potential CO_2 emissions. Such alternatives should also be considered by stakeholders in addition to the bed sediment size, as discussed below.

4.4 Bed Shear Stress and Bed Mobilization

Bed shear stress, shields stress, and volumetric bed load rate are all effective indicators of bed mobilization. Shear stress calculations indicated the 2017 flood exerted shear stresses of up to 95.8 pascals. Furthermore, the gravel placed in the Sacramento Bar project may have been mobile starting at flows of approximately 1.49 ms^{-1}.

If we focus on the volumetric bed load rate, we can examine the impact flow has and had at both gravel bars. With the increase in flow to 3.35 ms^{-1} and 2.45 ms^{-1}, the bed load rate increases to 0.027 m^2s^{-1} and 0.014 m^2s^{-1} for Sacramento Bar and Sailor Bar, respectively. At Sacramento Bar, this load rate highlights the energy of the river to reorganize the constructed bed: the river may have had enough power to move approximately 1.62 m^2 in a minute or 97.2 m^2 in an hour of consistent flow. The river's ability to move sediment at such rates can be very effective knowledge when working in rivers; bed load rates can aid with further understanding bed reorganization, how a project may fare in the long run, and/or evaluating the success of alternatives such as upstream gravel placement mentioned previously.

The project design by Water Forum at the Sacramento Bar took into consideration gravel size to impede sediment mobilization. They proposed adding gravel 203.2 mm or larger, based on a D_{90} of

38.1mm and summer flows of approximately 141.58 m^3s^{-1}. To compare, we calculated gravel estimates using the sediment composition observed on November 11th, 2019. Due to the frequency of flood events such as those in 2017, we calculated size recommendations based on flows of 1,772.63 m^3s^{-1}—the velocity of the river flow during the flood event that was attributed to reorganizing the channel. Considering a D_{90} of 38.1 mm, we found that for intermittent to partial transport of sediment (Shields Stress values of 0.03 to 0.06), sediment sizes of 214.13 to 428.27 mm may be effective (further detailed in Table 4). These calculations are for a higher flow velocity and slightly different geomorphic characteristics (measured during field work in 2019 compared to measurements done in 2016-2017), as it may be suggested to design for flood events.

However, adding larger sediment can be detrimental to the project's main goal of increasing fish habitat restoration. Salmonid typically require gravel sizes of D_{50}, D_{84}, and D_{90} to be on the finer side (Kondolf, 2000). Therefore, we suggest also taking into account the appropriate gravel size for fish nesting through study of comparable salmonid habitat at reference sites (gravel size for spawning may vary depending on the site and the life stage in question). Thus, if increasing sediment size to help prevent bed mobilization is considered, we suggest doing so strategically and at key points and integrating this approach with other methods to dissipate the river's energy, such as the incorporation of vegetation and large woody debris. Plans for Sailor Bar upon inspection use a scheme of interlacing spawning gravels with scour resistant cobble. This may protect the gravel from high velocity flows that may result in mobilization, is not yet proven. Further research into the incorporation of both vegetation, increased sediment size, and gravel layout is recommended.

We also recommend further research when determining appropriate bed shear stress calculations and volumetric bed load rates. As bed shear stress tends to be necessary for the calculation of other values, we recommend that further field experiments be done to more fully understand bed roughness. Additionally, investigating bed shear stress for unsteady flow conditions may aid with our understanding of bed mobilization during flood events. Future work should also be done to establish the extent of mobilization that occurs due to river-depth based velocity, as solely surface velocity was measured.

4.5 Goal Achievement

Per our discussion with the Water Forum scientist we interviewed, the Lower Anadromous River restoration program recently began in 2007. As the Water Forum experiences failures and successes, projects will be better adapted and designed to last over time. This is evident in the design for Sailor Bar, which calls for 8" plus (203 mm) scour resistant cobbles (See Appendix A). Sacramento Bar's project specifications mainly designed for non flood flows. Based on shear stress analysis and results in Section 3.5, the bigger cobbles appear better suited to resist high flows on the American. Flow stream gage data from USGS's Fair Oaks station is shown in Appendix B Figure 7 for flow data over the past ten years. Fairly consistent high and low volumes of river discharge can be discernible. Sacramento Bar (2016) was designed with 141.48 m^3s^{-1} as the maximum design flow (CBEC, *2016 Project at Sacramento Bar*). This did not take into account the flood rates which far exceed that (for reference 20,000 ft^3/s is 566 m^3/s) by an order of magnitude in 2017's case. A future project is planned at the same location, but does not have the same significant gravel input and will be designed with these higher flows in mind as to not wash out as easily.

Goal achievement evaluation is also necessary when weighing the ultimate "cost" of restoration projects. The primary design goals of the many gravel restoration projects are fish spawning. Appendix A Figure 3 shows aerial Redd fish distribution prior to 2016's flood event and afterwards. Due to human involvement in Folsom Dam, lack of appropriate sediment at Sailor bar may be the root cause of the 97% decline in Redd fish at Sailor Bar in 2017. While data post construction at Sailor bar is not available to us, 2018 saw a jump in Redd's at Sailor bar post Upper Sailor Bar project (Water Forum, Interview).

5. Conclusion

The restorative energy of the American River is great, but the amount of work (in energy) required to do restoration projects is even greater. Energy intensive projects may be rendered useless and care must be taken to ensure future fish habitat projects do not become washed away similar to

Sacramento Bar. While high energy is certainly a factor for decision makers, we found CO_2 emissions to be small enough that a projects scope should not be determined by CO_2 emissions alone, but by energy inputs and shear stress evaluations. Current hydrological models should be continually updated and improved prior to construction to avoid energy waste. Further research should be done on comparable restoration projects to better understand mean carbon emissions at a larger scale, the cumulative effect of restoration projects, and the role that carbon sequestration programs may play.

Hydraulic models and sediment size calculations should account for higher flows (especially flood events) and incorporate more diverse design considerations. While adding larger sediment size may help prevent bed mobilization, we suggest doing so strategically, taking into account spawning habitat conditions, and integrating this approach with other methods to dissipate the river's energy, such as the incorporation of vegetation and large woody debris. If measures are taken to dissipate the river's energy and minimize bed mobilization, Sailor Bar and other future projects along the American River have a higher chance of long-term stability. Alternatively, planned re-introduction of spawning gravel placed during winter flows on a semi-regular or bi-yearly basis may accomplish the same end goal as gravel augmentation projects, without the energy and CO_2 cost. Sediment and hydraulic models already developed may help to best predict the success of such ventures. Thorough analysis of shear stress and in relation to bed shear stress should be conducted on a site-by-site basis in order to ensure stability of the site long enough to achieve the project goals and long-term success.

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Tables and Figures

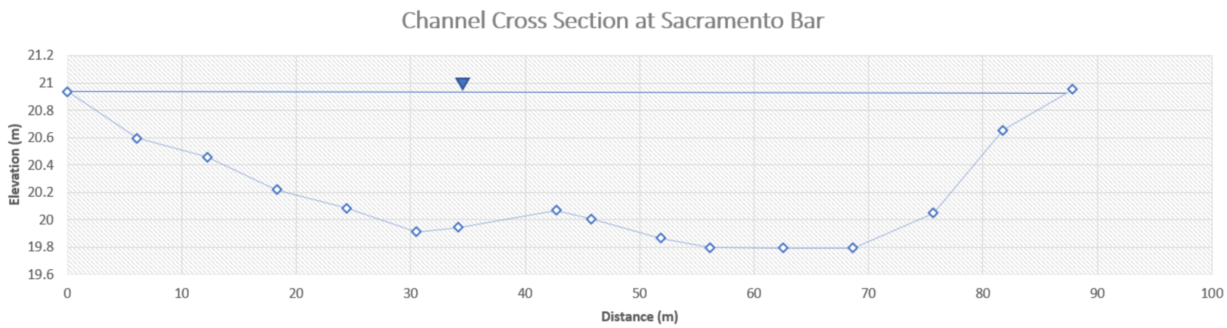


Figure A: Cross sectional cut near Sacramento bar.

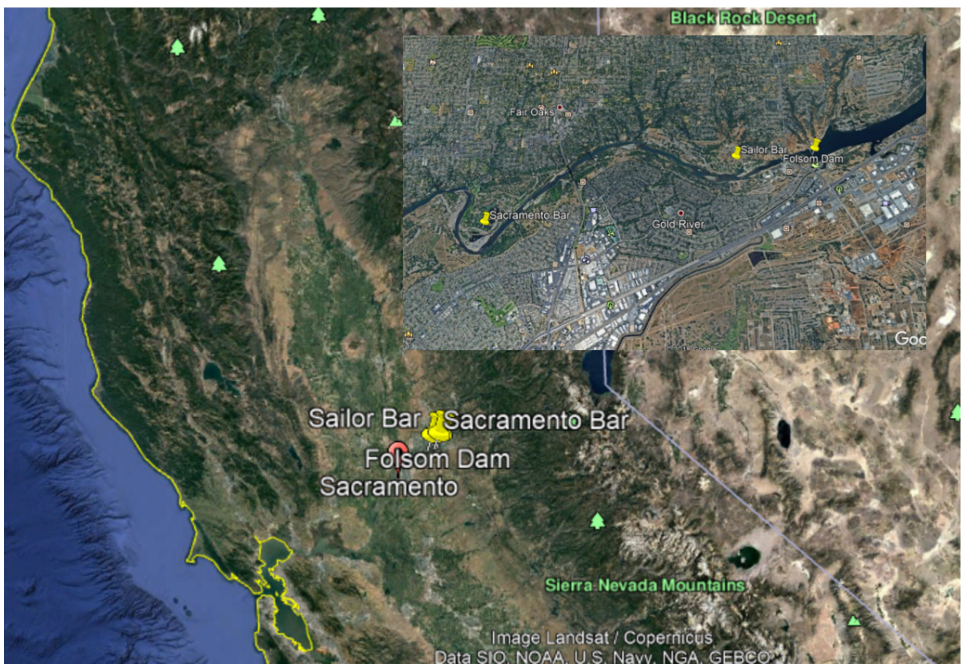


Figure B: Vicinity Map of Sacramento and Sailor Bar

Figure C: Side channel constructed in 2016 at Sacramento Bar that was flooded out in January of 2017. The constructed channel inlet and outlet are shown.

Figure D: Map showing an overview of project sites on the Lower American River. Sacramento Bar and Sailor Bar are both present on the map (CBEC, 2016 Sacramento Bar Design Report).

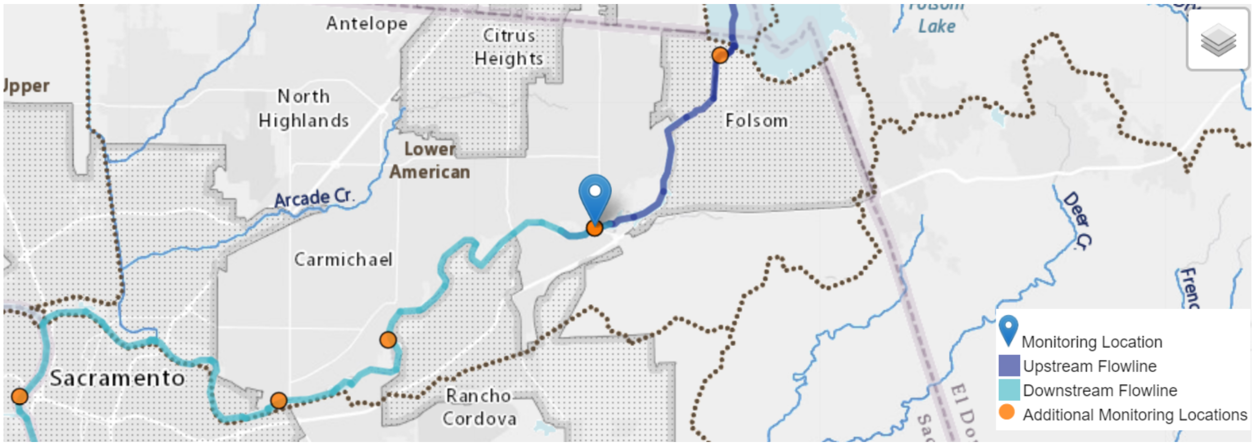


Figure E: Location of USGS monitoring station located at American R A Fair Oaks. The location is upstream of the Sacramento bar, at Sailor bar.

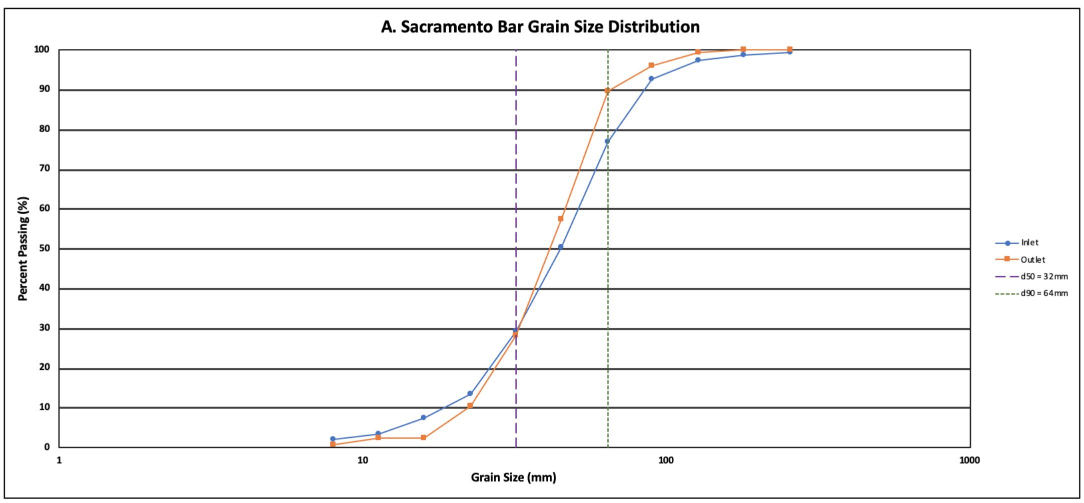


Figure F: Sacramento Bar plot of pebble count as grain size distribution at the outlet and inlet of proposed 2016 side channel of American River.

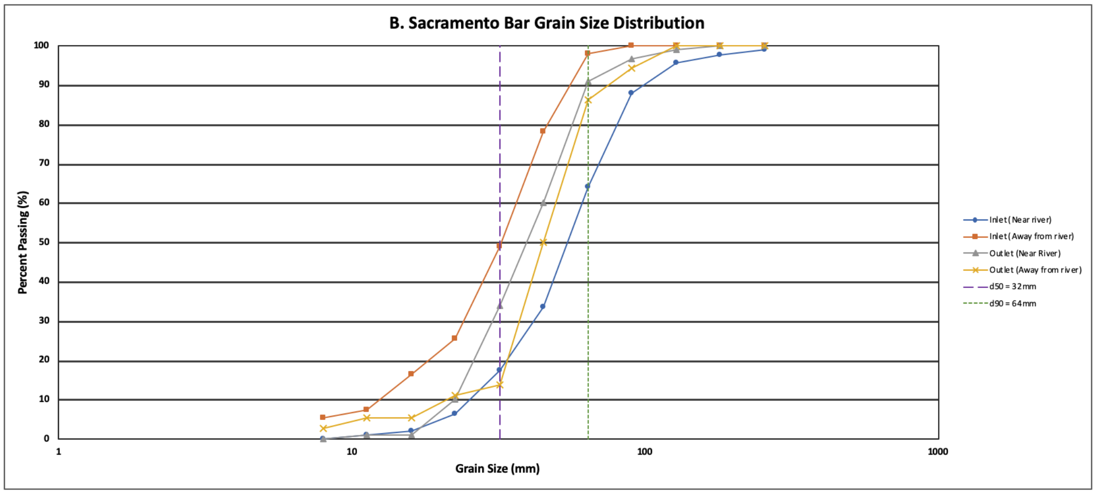


Figure G: Sacramento Bar grain size distribution at the outlet and inlet of 2016 proposed channel, and pebble count up channel from the river reflecting mobility of sediment.

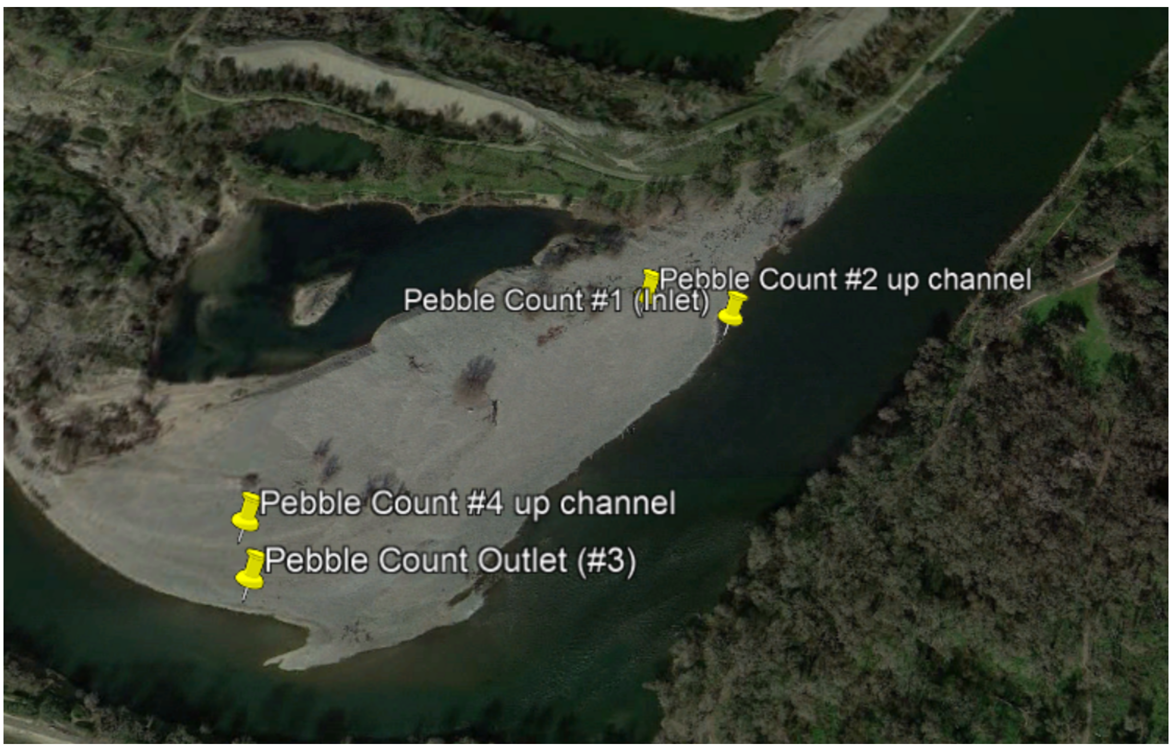


Figure H: Pebble Count Locations

Table A: Pebble Count at Inlet of proposed 2016 side channel at Sacramento Bar

Sac Bar-INLET Pebble Count Gain Size Distribution. Method: Gravelometer.						
Grain Size (mm)	Count	Percent of Total	Percent Retained	Percent Passing		
256	1	1	1	99		
180	1	1	1	99		
128	2	1	3	97		
90	7	5	7	93		
64	23	16	23	77		
45	39	27	50	50		
32	31	21	71	29		
22.6	23	16	86	14		
16	9	6	93	7		
11.3	6	4	97	3		
8	2	1	98	2		
<8	3	2	100	0		

Table B: Pebble Count near the outlet of proposed 2016 side channel at Sacramento Bar

Sac Bar-OUTLET Pebble Count Gain Size Distribution. Method: Gravelometer.						
Grain Size (mm)	Count	Percent of Total	Percent Retained	Percent Passing		
256	0	0	0	100		
180	0	0	0	100		
128	1	1	1	99		
90	4	3	4	96		
64	8	6	10	90		
45	40	32	43	57		
32	36	29	72	28		
22.6	22	18	90	10		
16	10	8	98	2		
11.3	0	0	98	2		
8	2	2	99	1		
<8	1	1	100	0		

Table C: Carbon Emissions at Sailor Bar and Sacramento Bar

Activity	Equipment #	Usage Hours/day	Number of equipment days (Sailor Bar)	Number of equipment days (Sacramento Bar)	Horse Power	Kilowatt / hr		CO2 Emitted Sailor (kg)	CO2 Emitted Sacramento Bar (kg)
Spawning Gravel Augmentation, flood plain, side channel	2	8	30	60	247	184.1879	Bulldozer (Rubber Tired)	11306	20997
	2	8	30	60	158	117.8206	Excavator Komatsu PC 300LC	6051	11238
	2	8	30	60	97	87.6	Front-End Loader	3742	6950
	2	5	30	30	150	111.85	Dump Truck (40 yd, Tandem)	10649	19776
	1	5	15	30	150	111.85	Off-Road water truck	2662	4944
	2	10	30	60	97	87.6	Grader	2812	5222
Site Restoration									
	2	10	20	20	150	111.85	Haul Truck	14198	26368
	1	8	10	20	150	111.85	Water Truck	2840	5274
	1	8	15	30	50	50	Gravel Sorter	720	1337
	1	8	5	10	100	74.57	Hydroseeding Truck	319	593
							TOTAL in metric tons	55	103
Construction Equipment		*Note: All numbers are estimated based on projection and estimated equipment CO2					SUMMED TOTAL (metric tons)	158	

Table D: Energy Output of Construction

Activity	Equipment #	Usage Hours/day	Number of equipment days (Sailor Bar)	Number of equipment days (Sacramento Bar)	Kilowatt / hr	Equipment	Energy Consumed Sailor MJ	Energy Consumed Sacramento Bar MJ
Spawning Gravel Augmentation, flood plain, side channel	2	8	30	60	184.1879	Bulldozer (Rubber Tired)	318	587
	2	8	30	60	117.8206	Excavator Komatsu PC 300LC	204	375
	2	8	30	60	87.6	Front-End Loader	151	279
	2	5	30	30	111.85	Dump Truck (40 yd, Tandem)	121	223
	1	5	15	30	111.85	Off-Road water truck	30	56
	2	10	30	60	87.6	Grader	189	349
Site Restoration							0	
	2	10	20	20	111.85	Haul Truck	161	297
	1	8	10	20	111.85	Water Truck	32	59
	1	4	10	20	50	Gravel Sorter	7	13
	1	8	5	10	74.57	Hydroseeding Truck	11	20
						TOTAL in Megajoules	**1225**	**2257**
Construction Equipment		*Note: All numbers are estimated based on projection and estimated equipment CO2 emissions						

Table E: Future and planned projects along the American River. Included are estimated gravel volumes by the water forum, and our interpolated CO2 and energy consumption.

Site Name	River Mile	Gravel Volume (cy)	Gravel Volume (cubic meter)	CO2 Produced (metric tons)	Energy for Construction (MJ) Projected
Nimbus Basin	23.1	4000	3058.219	15.92	349.91
Upper Sailor Bar	22.5	14000	10703.7665	55.73	1224.67
Lower Sailor Bar	21.8	5500	4205.051125	21.89	481.12
Lower Sailor Bar	21.3	550	420.5051125	2.19	48.11
Lower Sailor Bar	21.1	13000	9939.21175	51.75	1137.20
Sunrise	20.1	13500	10321.48913	53.74	1180.93
Lower Sunrise	19.6	3000	2293.66425	11.94	262.43
Sacramento Bar	19	6000	4587.3285	23.88	524.86
El Manto	18.3	13500	10321.48913	53.74	1180.93
Ancil Hoffman	16.3	11500	8792.379625	45.78	1005.98
Upper River Bend	15.3	13000	9939.21175	51.75	1137.20
Upper River Bend	15	0	0	0.00	0.00
Upper River Bend	14.5	11000	8410.10225	43.79	962.24
River Bend	13.5	4500	3440.496375	17.91	393.64
Total		113050		450.01	9889.22

Table F: List of past restoration projects along American river, gravel volumes reported by the Water Forum, and our interpolated CO2 consumption.

Year	Site name	Gravel Volume (cy)	Gravel Volume (cubic meter)	CO2 Produced (metric tons)	Energy for Construciton (MJ) Estimated
2008	Upper Sailor Bar	4087	3125	16.27	357.52
2009	Upper Sailor Bar	4856	3713	19.33	424.79
2010	Upper Sailor Bar	7055	5394	28.08	617.15
2011	Upper Sailor Bar	7266	5555	28.92	635.60
2012	Upper Sailor Bar	8500	6499	33.84	743.55
2013	River Bend	4750	3632	18.91	415.51
2014	Nimbus Bar	8500	6499	33.84	743.55
2016	Sacramento Bar	25800	19726	102.70	2256.89
Total		70814		281.88	6194.56

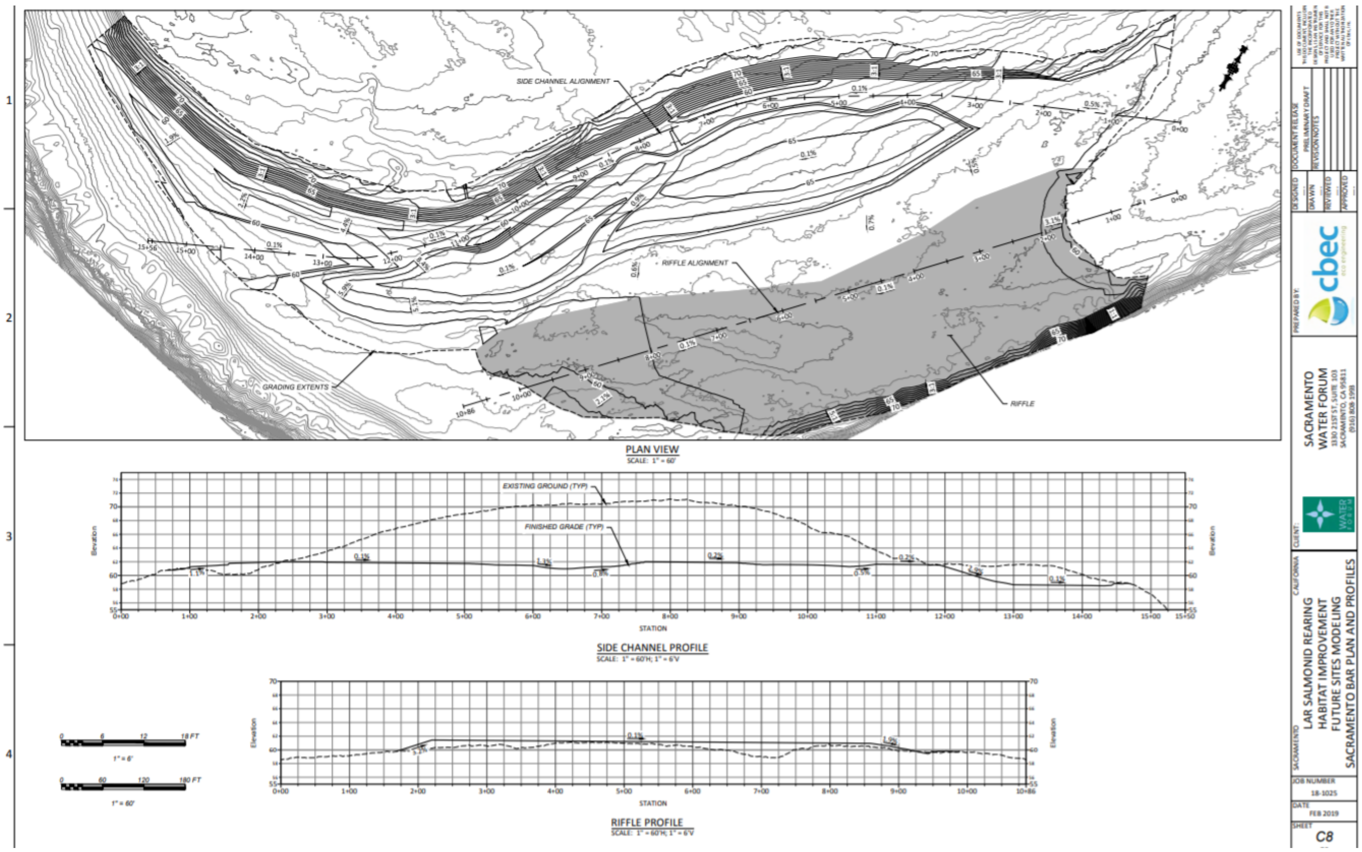
Table G: Bed shear stress (Pa), Shields stress (dimensionless) and volumetric bed load rate (m^2s^{-1}) for both the Sacramento Bar and Sailor Bar.

Site and Date		Bed Shear Stress (Pa)	Shields Stress (Dimensionless)	Volumetric Bed Load Rate (m^2s^{-1})
Sacramento Bar	November 11th, 2019	26.48	0.11	0.0031
	January 11th, 2017 (Flood Event)	95.84	0.51	0.027
Sailor Bar	November 11th, 2019	13.78	0.073	0.00036
	January 11th, 2017 (Flood Event)	63.62	0.34	0.014

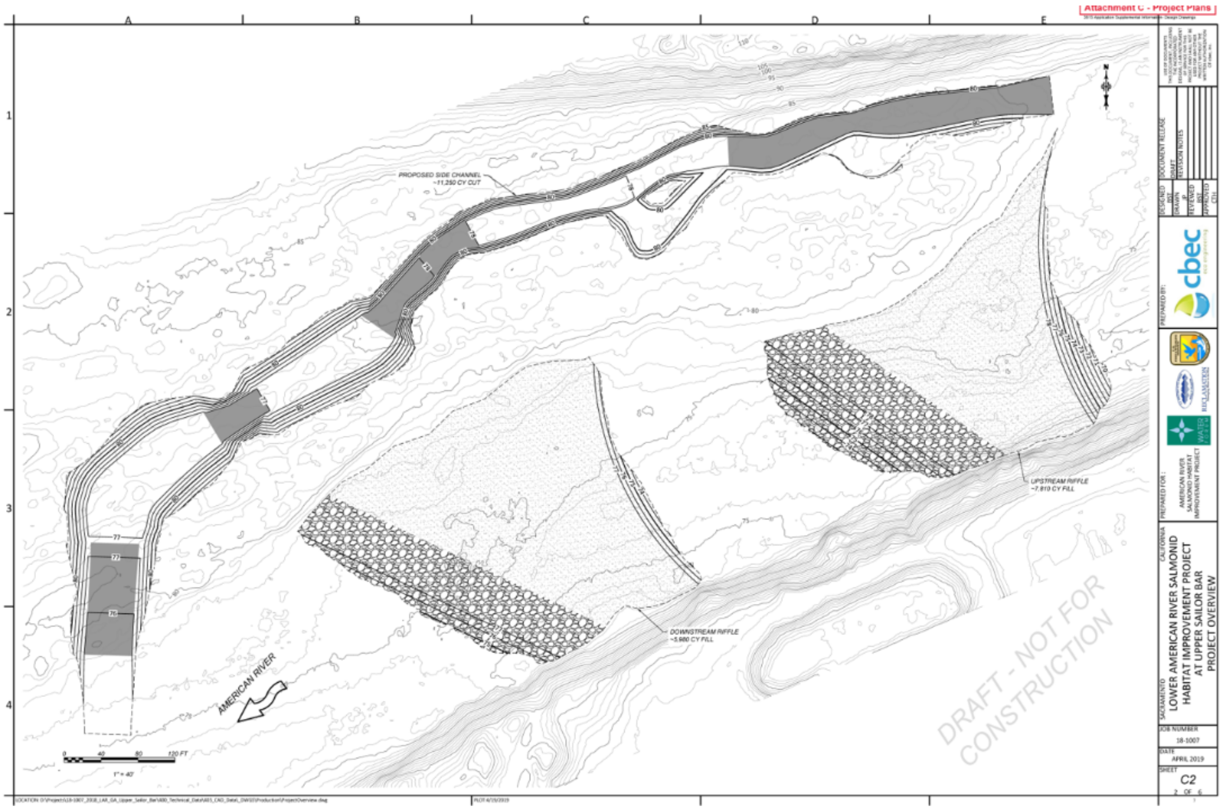
Table H**:** Recommended gravel sizes for flow velocities ranging up to 1,772.63 m^3s^{-1}.

Site	D_{90} Size (mm)	Sediment Size Recommendations (in mm)	
		For Shields Stress of 0.03	For Shields Stress of 0.06
Sacramento Bar	38.1	428.27	214.13
	180	1,040.64	520.32
	256	1,364.69	682.34
Sailor Bar	38.1	284.33	142.16
	180	788.21	394.10
	256	1,093.12	547.56

Appendix A: Maps and Cross Sections



1. Sacramento Bar Channel Profile (existing conditions with plans for future work). From Anadromous fish report.



2. Map of Sailor Bar and Lower American River.

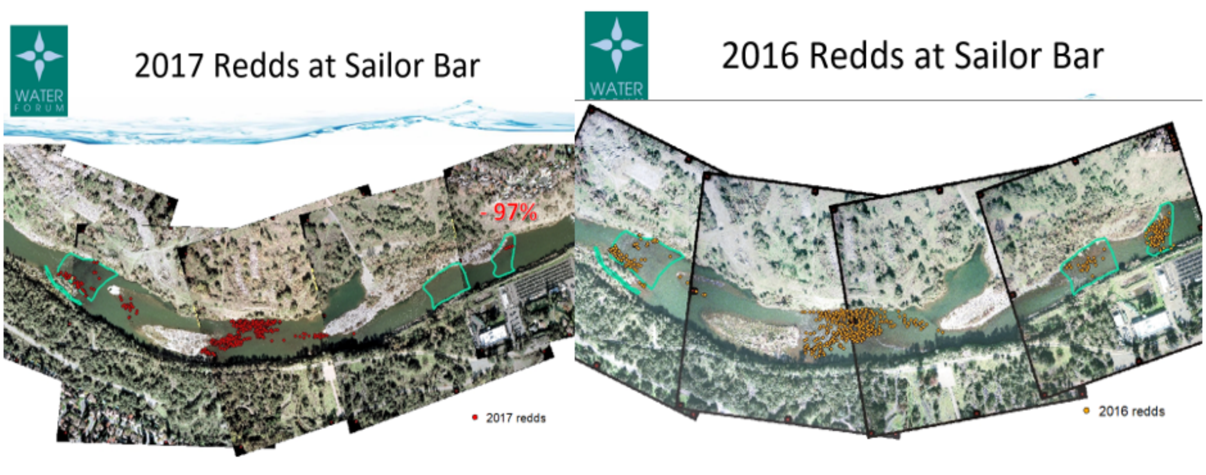
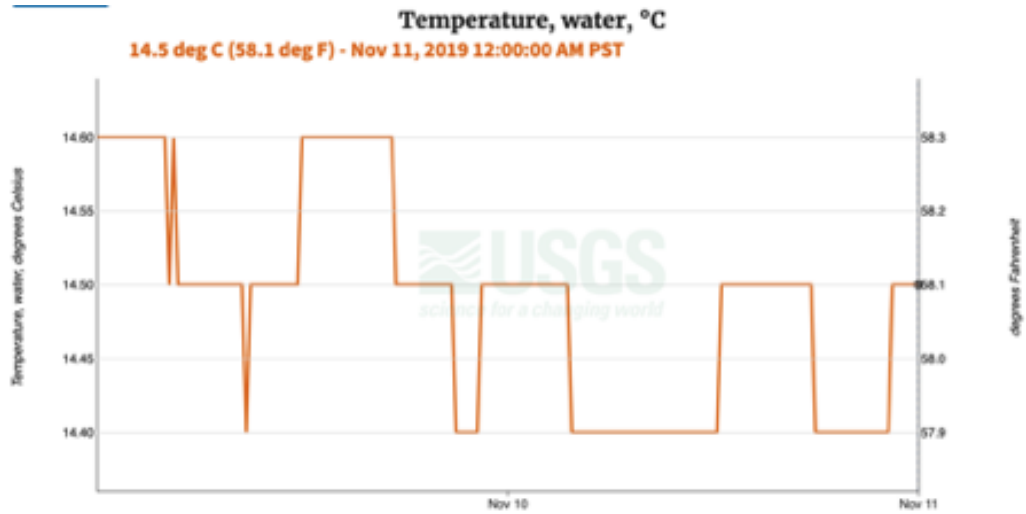
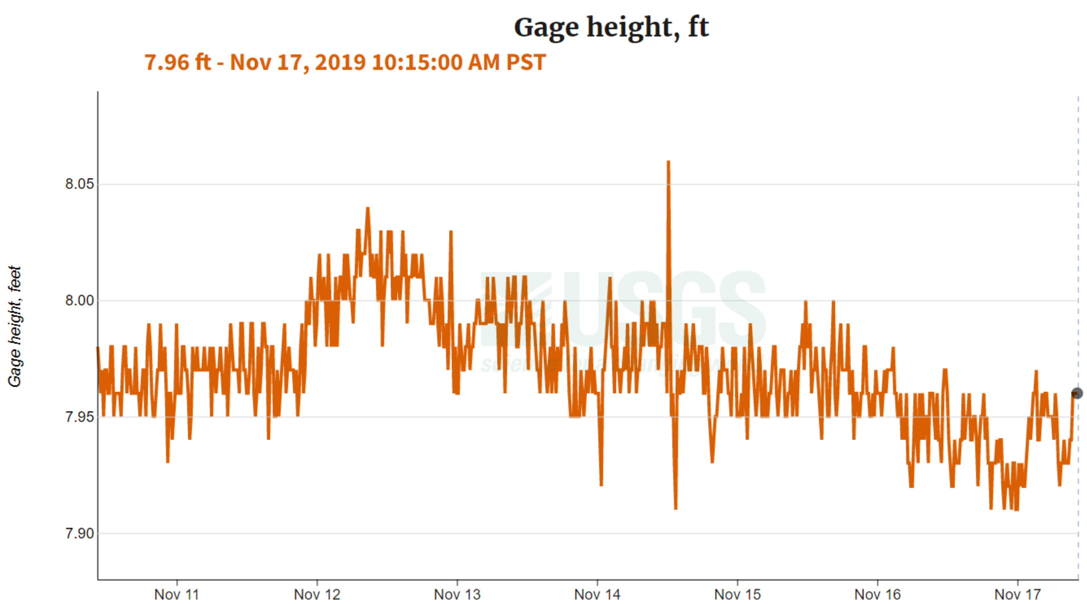


Figure 3: Upper Sailor Bar reflecting 97% decrease in Redd fish in 2017

Appendix B: USGS Data

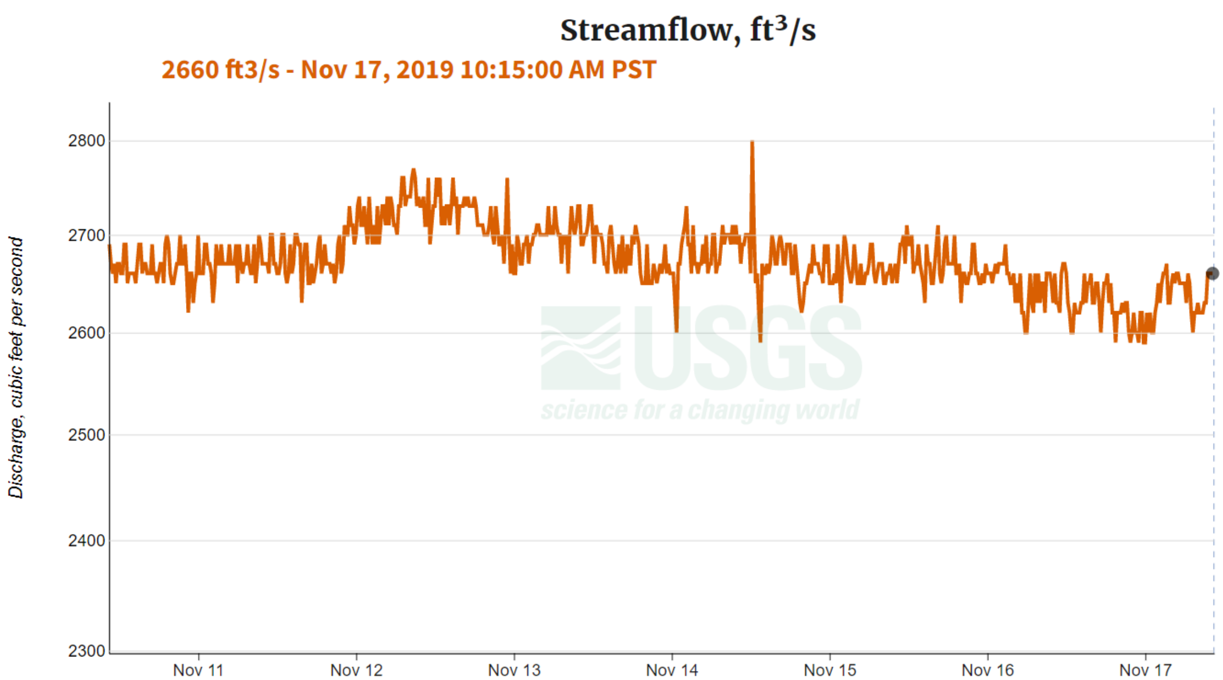


1. Water temperature (in Celcius) on November 10, 2019 from monitoring station located at American R A Fair Oaks.



2. Gage Height (ft) from monitoring station located at American R A Fair Oaks. Date range from November 11, 2019 to November 17, 2019.

3. Gage height Gage Height (ft) from monitoring station located at American R A Fair Oaks. Date range from January 2017 to March 2017.



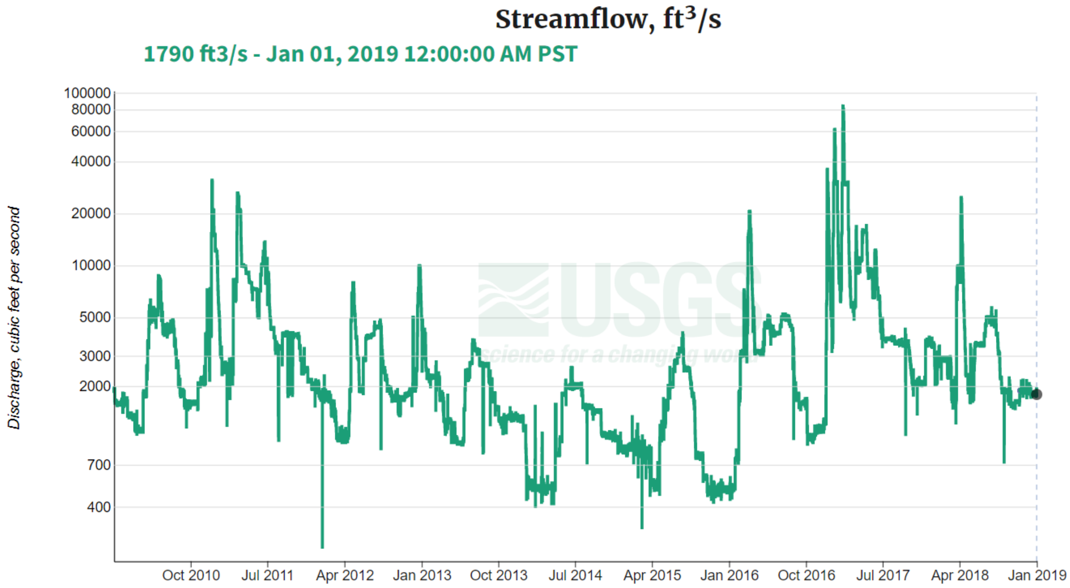
4. Streamflow (cfs) from monitoring station located at American R A Fair Oaks. Date range is from November 11, 2019 to November 17, 2019.

Control	Flow Adjust. Code	Channel Number	Channel Name	Meas. type	Stream flow method	Velocity method	Channel flow (ft3/s)	Channel width (ft)	Channel area (ft2)	Channel vel. (ft/s)	Channel stability
	NONE	1	Imported Channel 1	CRAN	unspe	unkno	117000	701	12800	9.21	UNSP
Unspecifed	NONE	1	Main	CWAY	QSCMM	VPAA	66000	432	8200	8.05	FIRM
	NONE	1	Imported Channel 1	CWAY	unspe	unkno	42800	428	6240	6.86	UNSP
Clear	NONE	1	Imported Channel 1	CWAY	unspe	unkno	34100	420	5530	6.17	UNSP
Clear	NONE	1	Main	MBOT	QADCP	VADCP	34200	408	5800	5.90	FIRM
Clear	NONE	1	Imported Channel 1	CWAY	unspe	unkno	33500	418	5790	5.79	UNSP
Clear	NONE	1	Imported Channel 1	UNSP	QADCP	VADCP	36300	413	5960	6.09	UNSP
DebrisLight	NONE	1	American River at Fair Oaks, CA	MBOT	QADCP	VADCP	30400	391	5220	5.83	FIRM
	NONE	1	Imported	CRAN	unspe	unkno	31600	547	5240	6.02	UNSP

5. Table with channel velocity and streamflow measured from monitoring station located at American R A Fair Oaks on January 11, 2017.

Date / Time	Temper-ature, water, deg C,	Dis-charge, ft3/s,	Gage height, feet,
01/10/2017 21:15 PST	9.2[A]	62,600[A]	20.32[A]
01/11/2017 15:30 PST		62,600[A]	20.32[A]
01/11/2017 15:45 PST		62,500[A]	20.31[A]
01/11/2017 00:30 PST		62,300[A]	20.28[A]
01/10/2017 20:45 PST	9.3[A]	62,200[A]	20.26[A]

6. Table with maximum channel discharge measured from monitoring station located at American R A Fair Oaks on January 11, 2017.



7. Streamflow measurements at the Fair Oaks Gage dating back to 2010

Appendix C: Site Photographs

1. Sacramento Bar. View facing upstream, at the point where the inlet to the channel constructed in 2017 once was. Pebble counts done here indicated relative homogeneity.

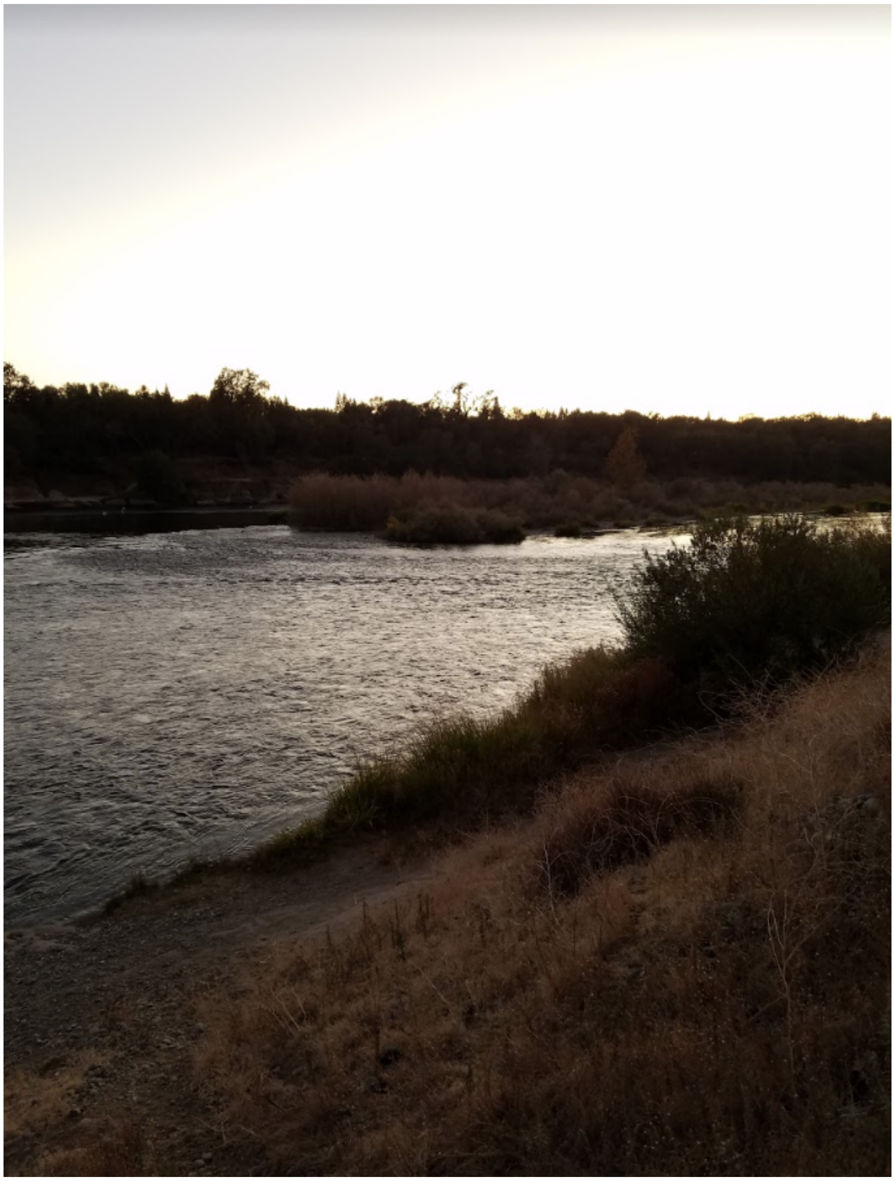
2. Sacramento Bar. View from what was the outlet of the channel constructed in 2017. Facing in the upstream direction. Remains of the channel can still be seen at this point (as seen in the bottom right hand corner of photograph).

3. Sacramento Bar. Photo was taken from middle portion of where channel had been pre-flood in early 2017. River is behind us. The tree in the center of the image is visible on google satellite imagery and was used as a marker for elevation and orientation.

4. Sacramento Bar. Photo was taken near where the channel outlet was pre-flood in early 2017. Vegetation is seen growing in this one area. Remains of the channel are still visible, with stream flow slower and more shallow depth on the bank side of vegetation.

5. Sacramento Bar. Photo taken from tree seen in photo 3. Facing the downstream direction, looking at what once was the middle portion of the channel and the outlet (back, left of the photo). The sign in the middle of the photo read: “River Mile 185.”

6. Sailor Bar. View from bank, facing upstream. Sailor bar lies just below this spot, out of the shot.



7. Sailor Bar. Photo was taken facing downstream, looking at sailor bar and the inlet of the newly constructed channel.