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Automated analysis of lateral river connectivity and fish stranding risks. Part 2: Juvenile Chinook salmon stranding at a river rehabilitation site

Running head: Salmon stranding at rehabilitation site

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Abstract

The dynamics of fish stranding have not been academically investigated within the context of physical adjustments to rivers for habitat enhancement purposes. River projects may aim to help fish populations but instead may function as attractive nuisances reducing populations because of unaccounted-for stranding risk. This study applies a novel algorithm to predict spatially explicit, meter-resolution fish stranding risk at a river rehabilitation site in California to address three scientific questions. Post-project disconnected wetted area predictions were validated against water surface elevation measurements and time lapse photography of flow reductions and stranding events. Comparison of pre-project, final design, and post-project topographies revealed that occurrence and severity of stranding events is highly sensitive to side-channel topographic structure and post-project morphodynamic change. Even with moderate flows, side channel exits tend to close off by bars built across them via bedload transport. Implications for river management practices and river rehabilitation project design are discussed.

Keywords: fish stranding, river restoration, hydraulic connectivity, ecohydraulics, rearing habitat, regulated rivers

1. Introduction

At the global scale, rivers and the ecosystems they support are adversely impacted by anthropogenic disturbances that include flow diversions and alterations, blockage of streams to fish passage, channel geometry simplification, sediment supply modification, and water quality degradation (Meybeck, 2003). In California, as elsewhere in the world, such impacts have caused widespread collapse of freshwater and anadromous fish populations (Moyle et al., 2011). Problem acknowledgement has motivated mitigation, including by restoring, rehabilitating, or enhancing degraded riverine habitats. Such projects have yielded mixed results (Kauffman et al., 1997; Palmer et al., 2010; Morandi et al., 2014), necessitating significant improvements to river restoration project design (Brown et al., 2015; Brown and Pasternack, 2019) and pre- and post-construction design evaluation (Brown and Pasternack, 2009; Schwindt et al., 2020).

1.1. Fish stranding at restoration sites?

In the companion article (Larrieu et al., 2020), a thorough literature review was presented about the scope of fish stranding as an ecological process and river management problem. The topic of fish stranding has not been academically investigated within the context of the burgeoning literature about active and passive physical and vegetative adjustments to rivers for environmental stewardship, whether termed restoration, rewilding, rehabilitation, mitigation, or enhancement. Documented consequences of stranding for individual fish are numerous and wide-ranging, from temporary stress response to mortality (Bauersfeld, 1978; Cushman, 1985; Sabo et al., 1999; Quinn and Buck, 2001; Flodmark et al., 2002; Evans, 2007).

Conceptually, the very areas that are most prone to stranding are often of greatest interest in re-engineering (Rosenfeld et al., 2008; Paillex et al., 2009; Person, 2013; Erwin et al., 2017). Stranding may be interstitial (also called bar stranding or beaching) or pool (also called off-channel stranding, isolation, or trapping) (Hunter, 1992). Large side channels and floodplain habitat features are notorious for increased interstitial and pool stranding risks, yet such areas can also function as ideal habitat with abundant food and cover for rearing juvenile salmonids, resulting in higher growth rates compared to rearing juveniles that do not utilize floodplain habitat (Sommer et al., 2005). It is unknown whether these benefits outweigh detrimental fish stranding.

The relative degree of these effects is expected to be highly dependent on specific physical site characteristics. Factors relevant to fish stranding include topography, ramping rate (rate of water surface elevation change), water temperature, time of day, and wetted history (length of time at sustained discharge before flow reduction occurs) (Bradford, 1997; Halleraker et al., 2003; Irvine et al., 2014; Auer et al., 2017). Historically, fish population resilience hinged on a fecundity-based life strategy, yielding resilience against these physical factors. Today, many fish populations are so small and large fractions of these remaining populations can be so highly attracted to restored sites (e.g., Elkins et al., 2007; Harrison et al., 2019) that such populations may be extremely sensitive to stranding risk. It should also be noted that the majority of stranding studies are concerned with juvenile salmonids, and the influence of physical factors on fish stranding may vary significantly for other species and lifestages.

1.2. Design-phase stranding prediction

Although many scientists report that project monitoring is neglected after river projects are constructed, design (including quantitative design stress testing) is arguably the most neglected project phase (Wheaton et al., 2004; Pasternack and Brown, 2013). Traditionally, baseline characterization and post-project appraisal involve empirical methods that cannot be applied to “virtual” (i.e., on computer only) designs. However, modern mechanistic modeling works equally well on real and virtual cases. The grand challenge of river restoration in the 21st century is to develop and apply comprehensive eco-geomorphic mechanistic models that enable pre-construction design testing, including automated design optimization for different eco-geomorphic objectives (Pasternack, 2020).

A variety of methodologies have been presented in the literature for quantifying stranding risks with hydrodynamic models that could be used in all river project phases (Noack and Schneider, 2009; Richmond and Perkins, 2009; Tuhtan et al., 2012; Noack et al., 2013; Hauer et al., 2014; Vanzo et al., 2016; Juárez et al., 2019). These stranding assessment methodologies have not yet been adopted by the larger scientific and management communities to aid design of environmental flow regimes and river restoration projects. Demonstration of predictive success will be needed to stimulate wider use, as none of the current stranding risk assessment methodologies validate predicted locations and severity of stranding risk using field observations, limiting confidence in their usefulness and interpretability. Such validation can prove quite difficult in practice. While this study achieved good qualitative agreement with predicted and observed stranding events, insufficient data were collected to enable a thorough quantitative validation (e.g. exact numbers of stranded fish and stranding absence were not documented).

1.3. Study purpose

The companion article (Larrieu et al., 2020) presented a novel fish stranding algorithm that could be suitable for use in real river assessment and virtual design testing. In contrast to existing methods, this algorithm employs a graph-theoretic approach to 2D hydrodynamic model outputs to quantify lateral habitat connectivity for any fish species/life stage of interest. The algorithm further produces several metrics relevant to pool stranding for a given downramping scenario, including explicit spatial mapping of disconnection events, discharges at which disconnections occur, disconnection frequency, and more.

This study evaluated the accuracy of that algorithm for a test case and then used findings to answer three fundamental scientific questions about the roles of topography and ramping rate on fish stranding (Table 1). A river rehabilitation project in a regulated river canyon in north central California (Yuba Canyon Project, described later) was selected as the test site. Site features included constructed side channels, riffles, and bars. The site also underwent modest subsequent morphodynamic processes that quickly enhanced stranding risk. Juvenile Chinook salmon was the species and lifestage of interest. This study investigated pool stranding risks for isolating topographic saddles at 0.91 m (3 ft) resolution. Results of stranding risk analyses were compared with field observations to the extent possible to evaluate its efficacy as well as its limitations.

Table 1. Experimental design for answering scientific questions in the case study.

Question	Test methods	Test metrics
Can steady-state 2D hydrodynamic models accurately predict the occurrence of disconnected riverine habitat during flow reductions?	Apply interpolation and path-finding algorithm to incremental steady-state discharge models.	Comparison of predicted disconnecting areas and corresponding discharges with those indicated by gage data and time-lapse video.
How do constructed and natural topographic changes at the test site affect fish stranding risks?	Apply habitat suitability functions to model-derived disconnected areas, link disconnecting discharges to frequency with gage data.	Changes in disconnected habitat area for characteristic flow reduction, disconnection frequency.
How much does ramping rate influence juvenile Chinook stranding risks at the test site?	Quasi-unsteady ramping rate estimation.	Comparison of ramping rate estimates with target values identified in literature.

2. Fish stranding risk algorithm

The companion article (Larrieu et al., 2020) presented a new methodology that characterizes fish stranding risks for a given topography, target species/lifestage, and flow ramping scenario. The concepts detailed in the companion article are briefly summarized here and illustrated with a flowchart (Figure 1). The free, open-source algorithm is implemented as part of River Architect (Schwindt et al., 2020; https://riverarchitect.github.io/).

The methodology requires modern 2D ecohydraulic data inputs and then produces 2D hydraulic disconnection and fish stranding risk maps and associated aggregate metrics. It does not matter what 2D model is used, as long as the digital elevation model

(DEM), water surface elevation (WSE), depth, velocity magnitude, and velocity angle results for each discharge are available as raster data. Users also optionally supply habitat suitability curves, and associated non-hydraulic habitat rasters that present the spatial distributions of conditions such as substrate, cover, and water temperature. There are six user-specified parameters and the user selects the water surface elevation interpolation/extrapolation method.

A wetted area is considered disconnected from the mainstem of the river channel during a flow reduction from Q_{high} to Q_{low} if it is not possible for fish of the species/lifestage of interest to reach the main channel from that area at one or more discharge Q_i. In this study, this definition is applied at the resolution of the hydrodynamic model and underlying DEM. The terms pool stranding and isolation apply, not at the classic morphological unit scale, but at the raster resolution scale. An

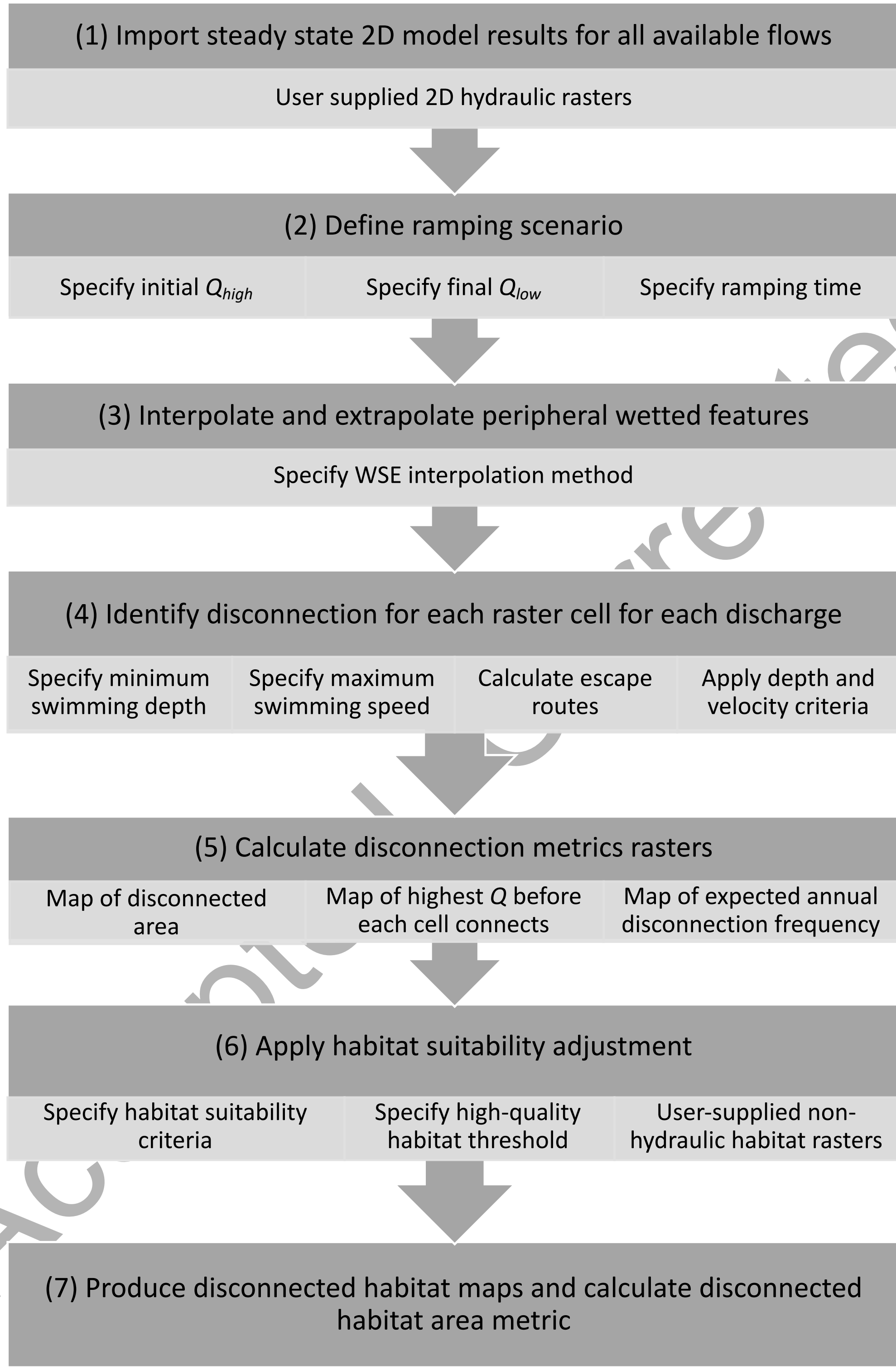


Figure 1. Fish stranding algorithm workflow phases, including required user inputs, key steps, and outputs.

area may be considered disconnected not only in the case of physically separate wetted areas, but also if low depth or high velocity barriers are present preventing individuals from moving into the main channel.

For the purpose of identifying disconnected areas, the main channel is defined as the largest continuous wetted area deeper than the minimum swimming depth threshold at the final, low discharge. This definition implies that if a fish reaches the main channel, it will not become stranded within that area (for the applied downramping scenario). Graph representation of river navigability from any initial wetted cell to the main channel was achieved using Dijkstra's path-finding algorithm, which enables characterization of fish movement options (Dijkstra, 1959; McElroy et al., 2012; Etherington, 2016). Nodes for which no path exists back into the main channel at a given discharge are considered disconnected. Outputs include a disconnected area map for each discharge, a map of the highest discharge at which each cell disconnects, and a map of the average number of times per year that flows drop below the disconnection discharge in each cell. Results may be subset to a seasonal window to align with ecological timing.

Disconnection discharge and frequency rasters are helpful in identifying areas with potential stranding risks, but actual stranding also necessitates fish presence. Habitat suitability modeling (Pasternack, 2019) serves as a proxy for fish presence likelihood and abundance in an area preceding a disconnection event. Computed combined habitat suitability index rasters are used to weight disconnected area to produce a "disconnected habitat" raster. In addition to a spatially explicit map of disconnected habitat for the applied downramping scenario, a summary metric herein referred to as disconnected habitat area (DHA) is computed to indicate the total amount of high-quality fish habitat disconnected by flow reduction (see Larrieu et al., 2020).

3. Study setting

3.1. Yuba River

The Yuba River catchment drains 3,490 km^2 of the western Sierra Nevada mountains (Figure 2). Salmon were once so abundant that Native Americans would spear them "by the hundred" (Chamberlain and Wells, 1879). During California's gold rush miners diverted the river to blast gold-laden hillsides. Released mercury-contaminated sediments filled the valley 6-24 m high (Yoshiyama et al., 1998). This prompted dam construction, including 79-m high Englebright Dam that marks the upstream limit of anadromous salmonid migration. Though salmon have lost access to 73% of their historical Yuba habitat area, Englebright Dam holds back ~ 22 million m^3 of sediment, preventing further harmful sediment fluxes and enabling ecogeomorphic recovery downstream (Snyder et al., 2004; Pasternack et al., 2010).

The ~ 37.5-km long gravel-cobble lower Yuba River (LYR) spans from Englebright Dam to the confluence with the Feather River. It constitutes the remaining area of accessible Chinook salmon and steelhead habitat. It is inhabited by federally threatened spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and Central Valley steelhead (*Oncorhynchus mykiss*). It is designated as critical habitat for both species. Current management includes systemic, repeated mapping, monitoring, and mechanistic modeling that supports habitat enhancement projects throughout the LYR.

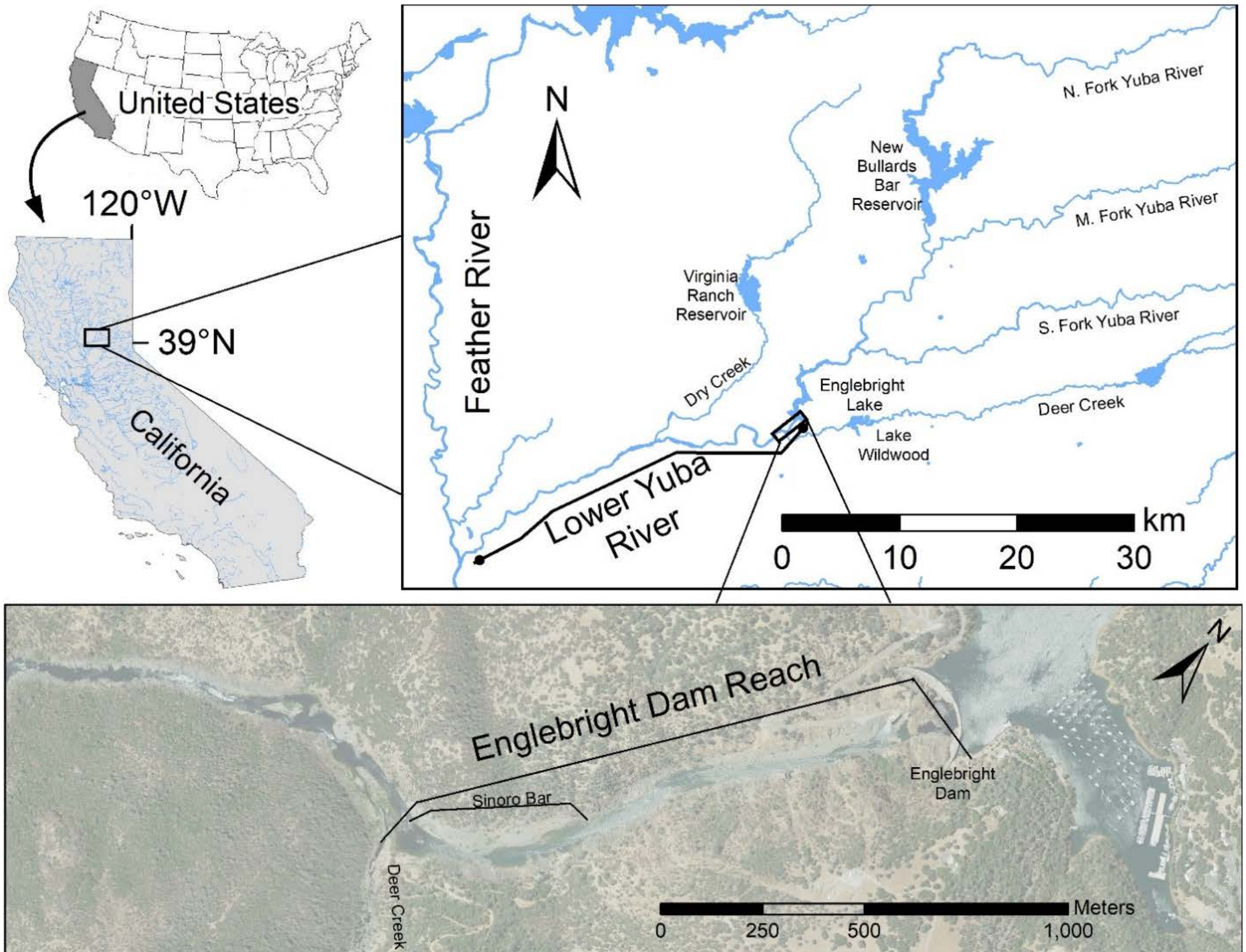


Figure 2. Englebright Dam Reach of the lower Yuba River. The Yuba Canyon Project is located at Sinoro Bar.

3.2. Flow operations

Flow regulations include monthly minimum flow requirements by water year type and specified rate of flow changes when flows are within the controllable range of $\lesssim$116 m^3/s (4,100 cfs). In addition to constraints on daily flow changes, proposed regulatory conditions require that the rate of flow increase not exceed 14.2 m^3/s per hour (500 cfs/hr), whereas the rate of flow decrease must not exceed 5.66 m^3/s per hour (200 cfs/hr) during the fry and juvenile rearing season (FERC, 2019).

To further address the concern of juvenile fish stranding, operators maintain an objective of 2.83 m^3/s per hour (100 cfs/hr) reductions under normal conditions, and 5.66 m^3/s per hour (200 cfs/hr) when passing storm flows. The target rate of 2.83 m^3/s per hour is technically maintained when observed at an hourly timescale. However, 15-minute resolution gage data in addition to 1-minute resolution time-lapse camera observations made as part of this study indicate that the implementation of 2.83 m^3/s flow reductions typically occur during intervals of 20-30 minutes followed by constant flows for the remainder of the hour, corresponding to a maximum instantaneous rate of change in the range of 5.66-8.50 m^3/s per hour (200-300 cfs/hr) (see supplementary materials for examples). Thus, a downramping rate of 7.08 m^3/s per hour (250 cfs/hr) was determined to be representative of the greatest ramping experienced under current operating procedures in regards to stranding risks, at least in the uppermost reaches where hydraulic controls have not significantly attenuated the hydrograph wave.

3.3. Test site

The test site (Figure 2, Sinoro Bar) began 200 m downstream of the Narrows 1 powerhouse in the geomorphically delineated Englebright Dam Reach (EDR) and ended 400 m downstream of the onset of the Deer Creek confluence. The confined bedrock canyon has low sinuosity, an average bankfull width of 59 m, and a mean slope of 0.31%. Beginning in 2007, gravel/cobble augmentation has been regularly implemented by the U.S. Army Corps of Engineers below Englebright Dam to ensure availability of gravel substrate suitable for salmonid spawning (Pasternack et al., 2010). As a result, substrate includes pre-existing bedrock, boulders, and angular shot rock plus injected gravel and cobble.

To increase spring-run Chinook salmon habitat, the U.S. Fish and Wildlife Service's Anadromous Fish Restoration Program and its contractors designed and built a habitat enhancement project called the "Yuba River Canyon Salmon Habitat Restoration Project" (Yuba Canyon Project hereafter), completed summer 2018. An oversized cobble point bar ("Sinoro Bar", a remnant from hydraulic mining sediment) was terraformed to create two new large side channel features to serve as habitat for rearing juvenile Chinook salmon. Excess bar sediment was pushed into the baseflow channel to create spawning riffle habitat. Shortly thereafter in December 2018 side channels were disconnecting from the mainstem. Fish biology experts reported the stranding of an estimated 1,000 Chinook salmon juveniles on one occasion alone (PSMFC, 2019). Stranding has been observed during subsequent disconnections.

4. Methods

4.1. Experimental design

This study was initiated after the site was built in response to disconnections and fish stranding. Therefore, while monitoring of disconnection events and stranding was conducted for the post-project condition, this was not possible for the pre-project condition, and the virtual design was not observable. Further, the timing of real flow ramping could not be controlled, as it hinged on rapidly-changing weather and reservoir inflow. The Yuba Canyon site is remote and only accessible by hiking downcanyon. It is ~ 2.5 hours from campus to field site, not counting prep time. This meant rapid response to sudden downramping was impossible, except by fortuitous occurrence during a site visit. Given this situation, the primary approach to address question 1 (Table 1) involved matching time lapse photography showing disconnections with 2D hydrodynamic model visualizations of the same discharges.

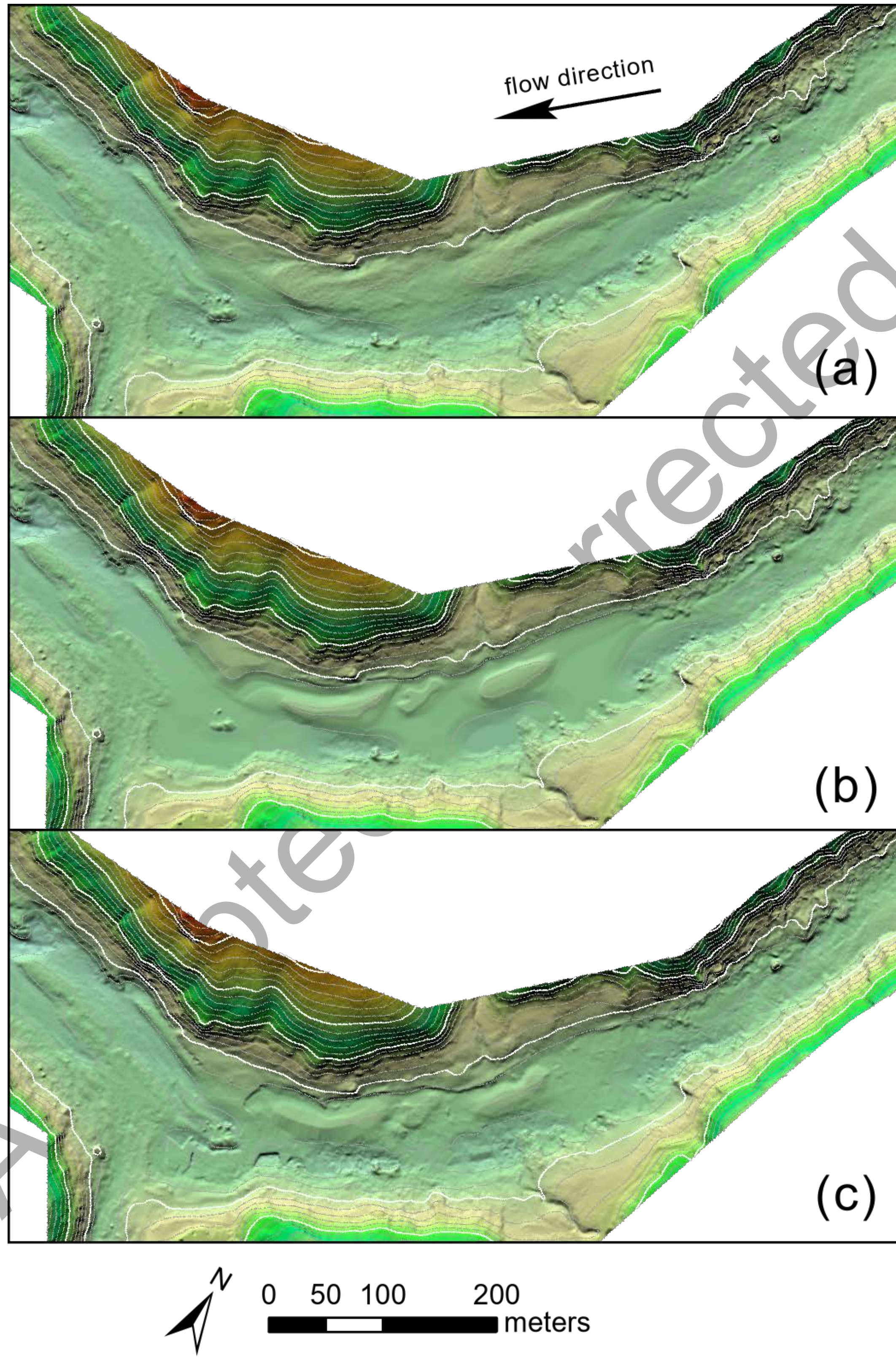
The experimental design consisted of implementing the River Architect stranding risk module for a constant setup in all aspects, except having three topographic scenarios to address question 2 (Table 1). The assessment aimed to determine how topographic modifications made as part of river rehabilitation measures (e.g., the introduction of side channels) affect stranding risks for juvenile Chinook salmon. Key metrics for evaluating changes in stranding risk between topographic conditions included (i) the total amount of area disconnected under a characteristic ramping scenario, (ii) the amount of disconnected habitat area for juvenile Chinook salmon, (iii) the discharge at which potential stranding events occur, and (iv) the expected frequency of such events during vulnerable lifestage periods.

4.2. Digital elevation models

Meter-resolution DEMs were made for 2017 pre-project, final virtual design, and 2019 post-project conditions (Figure 3). The pre-project DEM was made from a combination of near-infrared lidar, green lidar, and sonar data collected in late summer 2017 (Silva and Pasternack, 2018). The final virtual design DEM used for the Yuba Canyon Project had been created by modifying the 2017 DEM to grade the main channel and create two side channel features running through the point bar. The post-project DEM was created by combining new sonar and RTK GPS data collected during late summer 2019, a year after construction. The data from these 2019 surveys cover most of the main channel, as well as the entire Yuba Canyon Project site domain.

4.3. Discharge data and ramping scenario

Discharge time series data were acquired to identify relevant ramping scenarios, set model boundary conditions, and calculate rasters of the expected annual frequency of



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277 Figure 3: Digital elevation models of (a) pre-project, (b) final design, and (c) post-project
278 topography. Contour lines shown for 3.05-m (10-ft) elevation differences.

disconnection. Discharge data for the LYR near Smartsville was obtained from Department of Water Resources' California Data Exchange Center (YRS gage). Deer Creek inflow data was obtained from USGS gage #11418500.

This study's ramping scenario assessed stranding risks for a flow reduction from 56.6 to 14.2 m^3/s (2,000 to 500 cfs) over 6 hours. It was representative of the typical downramp during juvenile spring-run Chinook salmon rearing. Site stranding events exhibit this scenario. The duration was chosen such that the rate of flow decrease (7.08 m^3/s per hour, or 250 cfs/hr) is characteristic of those typically observed during the most rapid regulated flow reductions on the LYR, as discussed in section 3.2.

4.4. Yuba Canyon project 2D model

Steady-state SRH-2D v. 2.2 (Lai, 2008) 2D hydrodynamic models were applied for each topography with the same computational mesh (0.91-m (3-ft) node spacing), model parameters (eddy viscosity coefficient of 0.1; spatially constant Manning's n of 0.055), and downstream boundary conditions (see supplementary materials) used in the Yuba Canyon Project. Models were run for 14 LYR discharges from 14.2 to 56.6 m^3/s (500 to 2,000 cfs). The supplementary materials provide further details regarding model boundary conditions, hydrodynamic model validation, accuracy of River Architect's water surface extrapolation methods, and example downramping hydrographs in the study reach.

4.5. Biological data

Moniz et al. (2019) developed and bioverified observation-based LYR habitat suitability criteria functions for two size classes of rearing Chinook salmon and steelhead. This study used their juvenile Chinook salmon functions to calculate combined (geometric mean) depth and velocity habitat suitability indices in River Architect. Though it is important (Moniz et al., 2019), cover was not accounted for in this analysis mindfully to isolate the influence of altered morphology on stranding risks. Little vegetative or streamwood cover exists in the recontoured terrain to make cover a factor differentiating project stages.

Applied thresholds for minimum swimming depth and maximum swimming speed were 6.1 cm (0.2 ft) and 58 cm/s (1.9 ft/s), respectively. These were estimated from fish passage references (Bell, 1991; Katopodis and Gervais, 2016; CDFW, 2017). The season of interest applied to compute the expected annual frequency of disconnection was February 1 to June 15 (typical LYR Chinook salmon juvenile rearing period).

4.6. Time lapse photography

To aid assessment of disconnected area prediction, Browning Dark Ops Pro XD Dual Lens 24 megapixel trail cameras were set to record time-lapse photography and deployed to view each side channel's outlet. Downramping events evident in real-time flow gages indicated potential periods of disconnection. When a disconnection was manually found in an event photoset, time stamps enabled linking with the flow record to estimate disconnection discharges. Photo time series were produced into videos.

5. Results

Methodological performance of interpolated and extrapolated peripheral wetted features is reported in the supplementary materials. Testing the relative sensitivity of stranding predictions to the depth and velocity criteria found that the velocity criterion is expected to have little effect on restriction of juvenile Chinook movement in the study area. This result was not surprising considering the relative swimming strength of juvenile salmonids and that flow velocities were typically low in the side channel features and shallow, low-grade areas most prone to disconnection. Nonetheless, sensitivity to the velocity criterion may be greater in other areas with steeper slopes and higher velocities near disconnecting areas.

Video comparison of both side channels disconnecting with modeled disconnection events can be viewed at https://vimeo.com/user120675722.

5.1. Disconnected areas

Disconnected habitat maps for the three topographic conditions illustrate a significant difference between pre-project and post-project stranding risks (Figure 4). While the constructed side channels in the post-project condition are of high habitat quality, they are also the primary sources of disconnected habitat area within the model domain for the applied downramping scenario.

Increases in disconnected area occur from the pre-project condition to project design (7.7%) and from project design to post-project (26%) (Table 2, Figure 5). Notably, the disconnected area is very fragmented with small patches in the pre-project condition, but highly spatial coherent as large patches in the upper designed side channel. They are even more abundant as large patches in the post-project condition.

Yet disconnected area does not tell the whole risk story, because DHA shows a different result. For DHA, there is an 8.8% decrease from pre-project to design, suggesting that the river might have had less stranding afterwards, even if it were more concentrated in the side channel. However, construction resulted in a 207% increase in DHA between design and post-project conditions. Put another way, doing the restoration project tripled the amount of high-quality habitat area that becomes disconnected during the applied flow reduction. This difference is primarily due to the

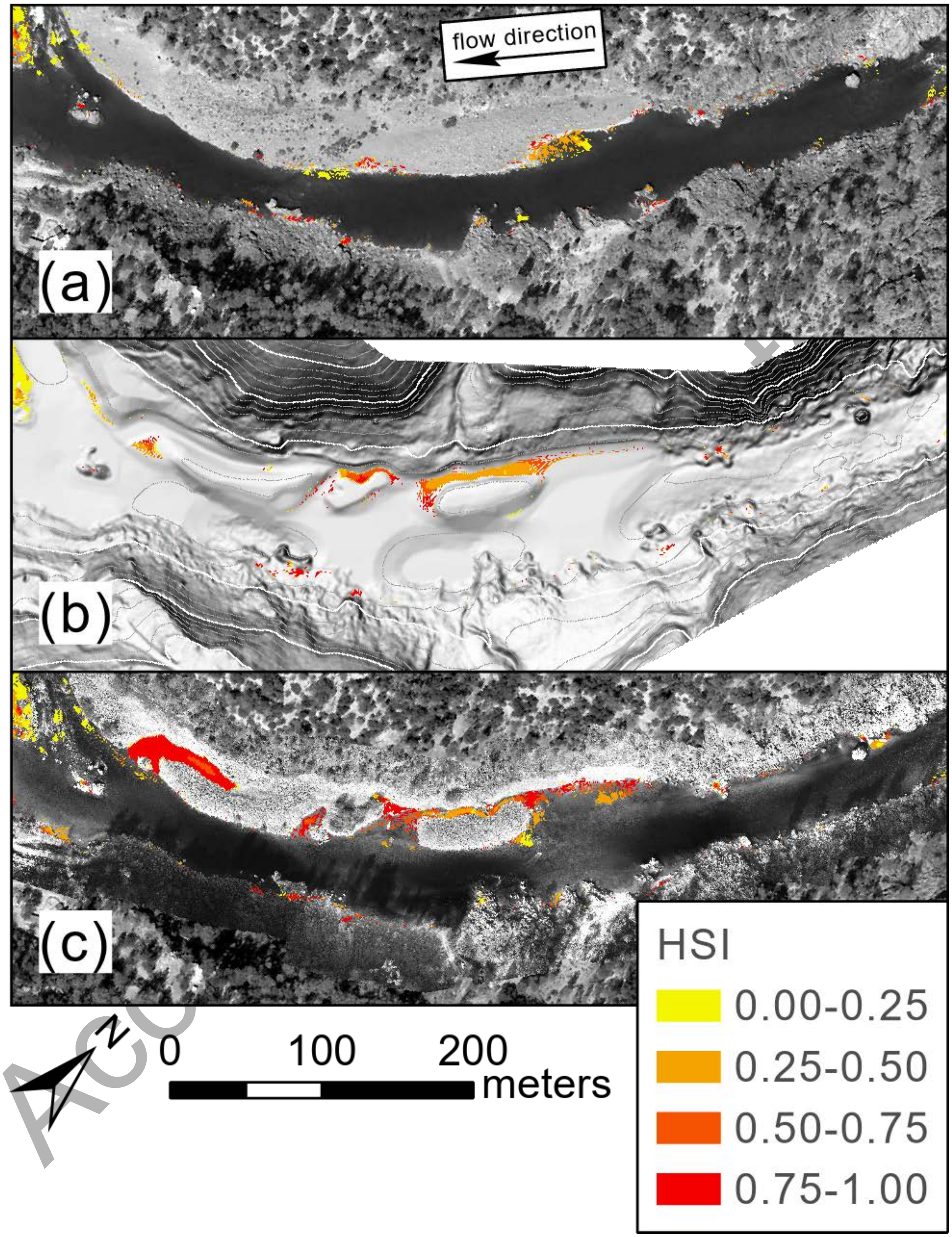

Figure 4. Disconnected area weighted by juvenile Chinook salmon combined habitat suitability indices for a flow reduction from 56.6 to 14.2 m^3/s. Topographic conditions are (a) pre-project, (b) project design, and (c) post-project.

Table 2. Total disconnected area and disconnected habitat area for each of the topographic conditions investigated.

Condition	Disconnected Area (m^2)	DHA (m^2)
Pre-project	4,321	642
Project design	4,656	585
Post-project	5,870	1,798

disconnection of the lower side channel (at the downstream end of Sinoro Bar) that occurs for the post-project topography but was not predicted to occur for the project design topography. In contrast, disconnection of the upper side channel was predicted for the design topography. However, the upper side channel was not included in DHA for the design topography as it was of moderate habitat suitability (0.25-0.75). In all cases, DHA accounted for less than one third of the total disconnected area, indicating that the majority of disconnected area does not fall within the highest habitat suitability range of 0.75-1.

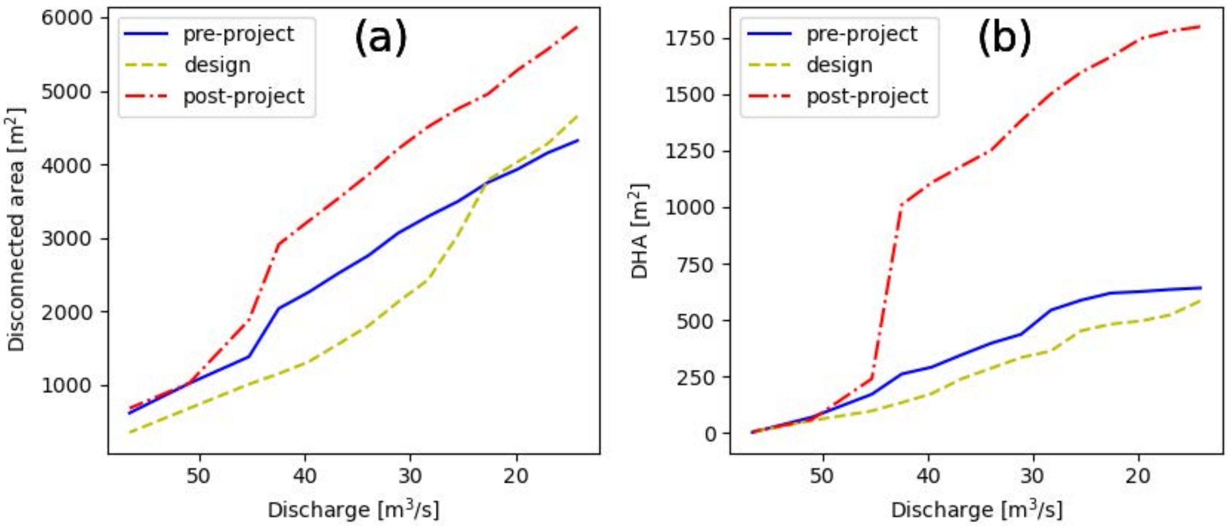

Figure 5. (a) Total disconnected area and (b) DHA for the applied flow reduction. Note discharge decreases along the horizontal axis.

A large portion of the baseline disconnected area for the pre-project condition is on a mid-channel bar downstream of the Deer Creek confluence. This disconnected area was persistent across all topographic scenarios. However, due to its location, it is more difficult to make definitive statements about its patterns of disconnections due to its location and resultant dependence on both Yuba River and Deer Creek flows. This landform has been subjected to many anthropogenic disturbances and modifications by instream gold miners and regulatory agencies. While the disconnecting area of this landform is included in Table 2, this area is not pictured in Figure 4 to focus visualization on the changes within the Yuba Canyon Project area.

5.2. Disconnecting discharges and disconnection frequency

Most disconnections were predicted to occur in the range of 42.45 m^3/s (1,500 cfs) down to 28.31 m^3/s (1,000 cfs), with relatively little area disconnecting over the rest of the modeled flow range (Figure 6). The lower side channel is estimated to become disconnected for juvenile Chinook salmon at ~ 42.45 m^3/s causing a large increase in DHA (Figure 5), while the upper side channel is expected to split into parts which disconnect over a range of flows from 36.79 m^3/s (1,300 cfs) to 28.31 m^3/s. A few other small pools and alcoves that become

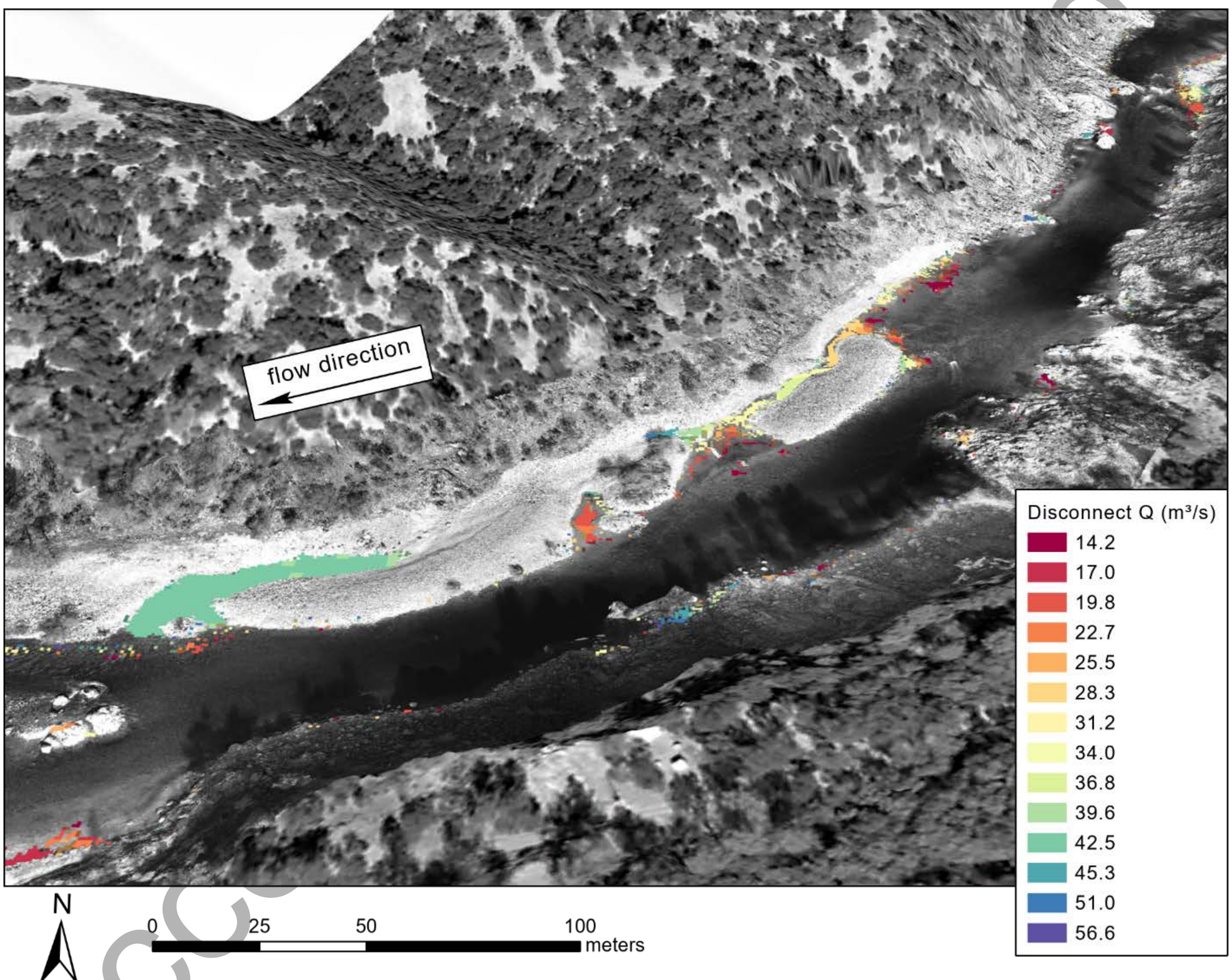

Figure 6. Disconnecting discharges for each area disconnected by a flow reduction from 56.6 to 14.2 m^3/s. Aerial imagery courtesy of Duane Massa.

disconnected are delineated between the two side channels as well as upstream of the Yuba Canyon site.

Disconnection frequencies ranged from < 1 to ~9 disconnections per year during the juvenile rearing season (Figure 7). Notably, the lower side channel is both the largest source of DHA and predicted to have one of the highest disconnection frequencies. A general trend exists between disconnecting discharge and disconnection

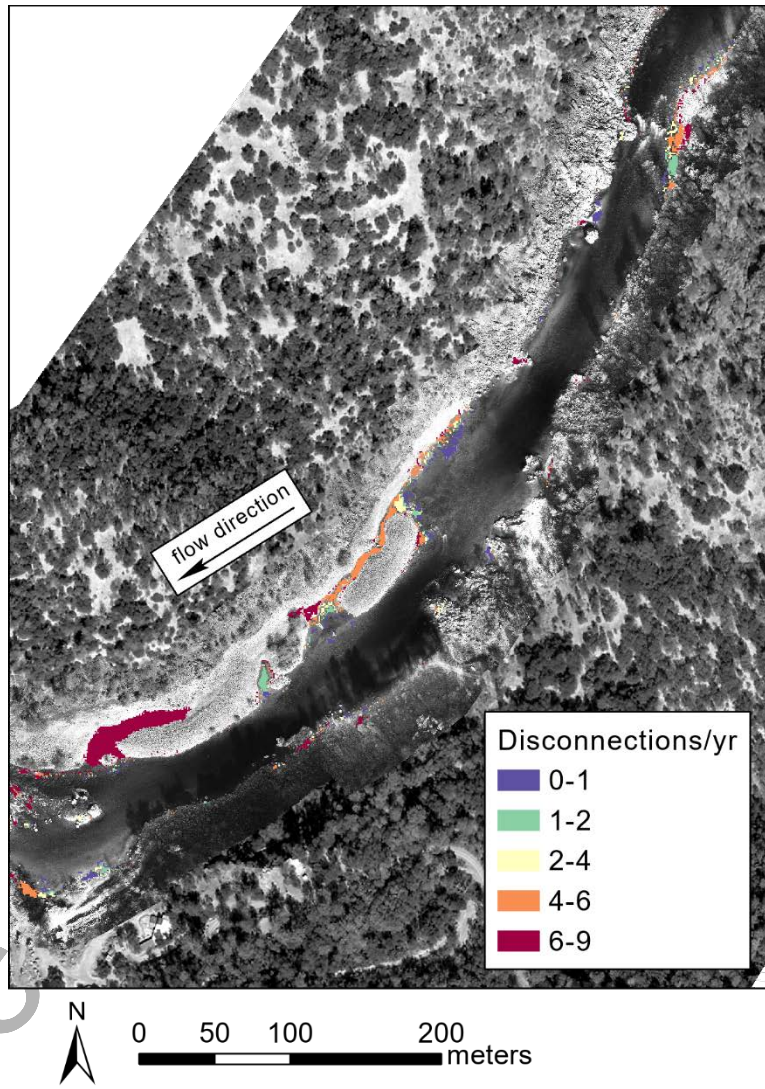

Figure 7. Disconnection frequency for the areas disconnected by a flow reduction from 56.6 to 14.2 m^3/s. This calculation only considers disconnections occurring during the applied season for juvenile Chinook rearing of Feb 1 - June 15.

frequency, with features disconnecting at lower discharges (Figure 6) also having lower disconnection frequencies (Figure 7).

5.3. Ramping rate estimates

Ramping rate estimates range from 0-20 cm/hr, with the majority of disconnected area at the Yuba Canyon site falling within the range of 5-15 cm/hr (2-5.9 in/hr) (Figure 8). For reference, using the stage-discharge relation for the applied downramping scenario yields an average ramping rate of 11.26 cm/hr (4.43 in/hr), roughly corresponding to the mid-range of the ramping rate estimates within disconnected areas.

5.4. Disconnecting discharge prediction accuracy

The lower side channel was observed to disconnect at a flow of ~ 42.45 m^3/s (1,500 cfs) (Figure 9), the corresponding flow for which the side channel was predicted to become effectively disconnected (Figure 6). While some hydraulically connected interstitial areas were observed at 42.45 m^3/s, the water depth was below the minimum swimming depth for juvenile Chinook salmon. Four subsequent visits were made to monitor the site from late fall to spring 2019 when flows were below 42.45 m^3/s. On every such occasion, the lower side channel was observed to be disconnected, while dozens of juvenile salmon were observed to be trapped in the side channel.

The upper side channel was predicted to disconnect in stages (Figure 6). At 56.6 m^3/s (2,000 cfs), it maintained connectivity at the inlet and outlet. Then, it was predicted to separate at the midpoint into one section with a downstream connection and another section with an upstream connection. Upon further flow recession, the lower half was predicted to disconnect at ~ 36.79 m^3/s (1,300 cfs) followed by the upper half disconnecting at ~ 28.32 m^3/s. Field observations at a flow of ~ 38.20 m^3/s (1,350 cfs) illustrated conditions in agreement with this predicted sequence of events (Figure 10).

Dozens of juvenile salmon were also observed in this side channel during visits made as part of this study, in addition to the stranded juveniles observed in both side channels in December 2018 (PSMFC, 2019).

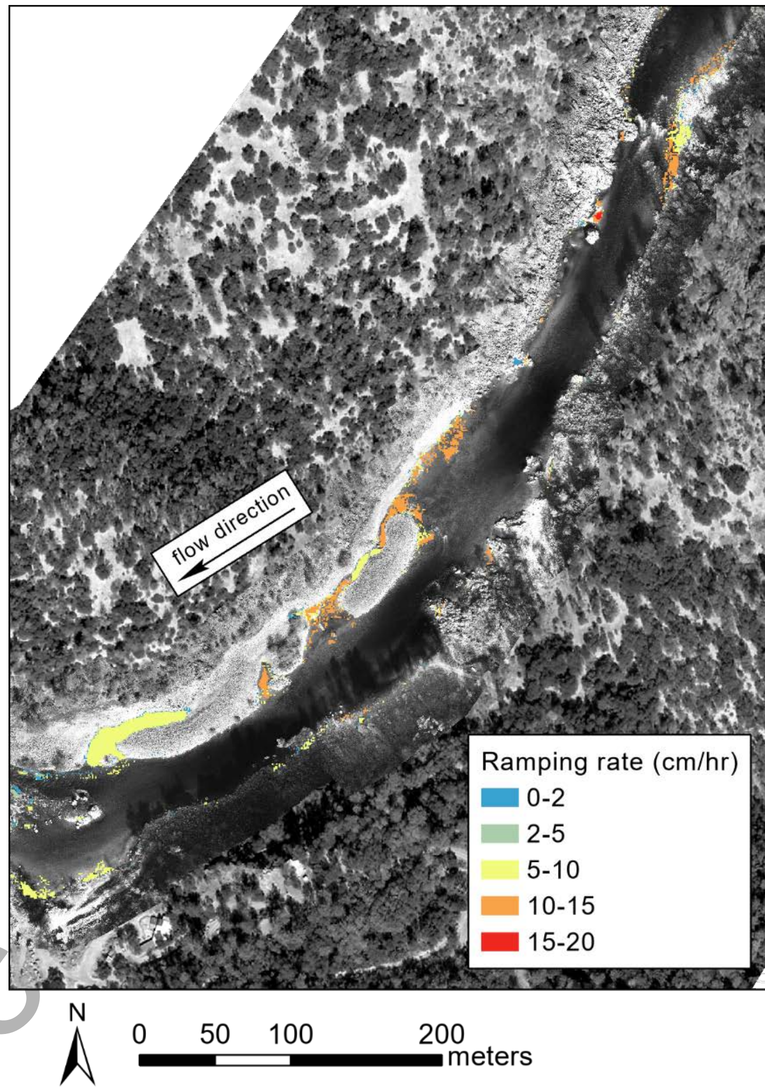

Figure 8. Ramping rate estimates for the areas disconnected by a flow reduction from 56.6 to 14.2 m^3/s over 6 hours.

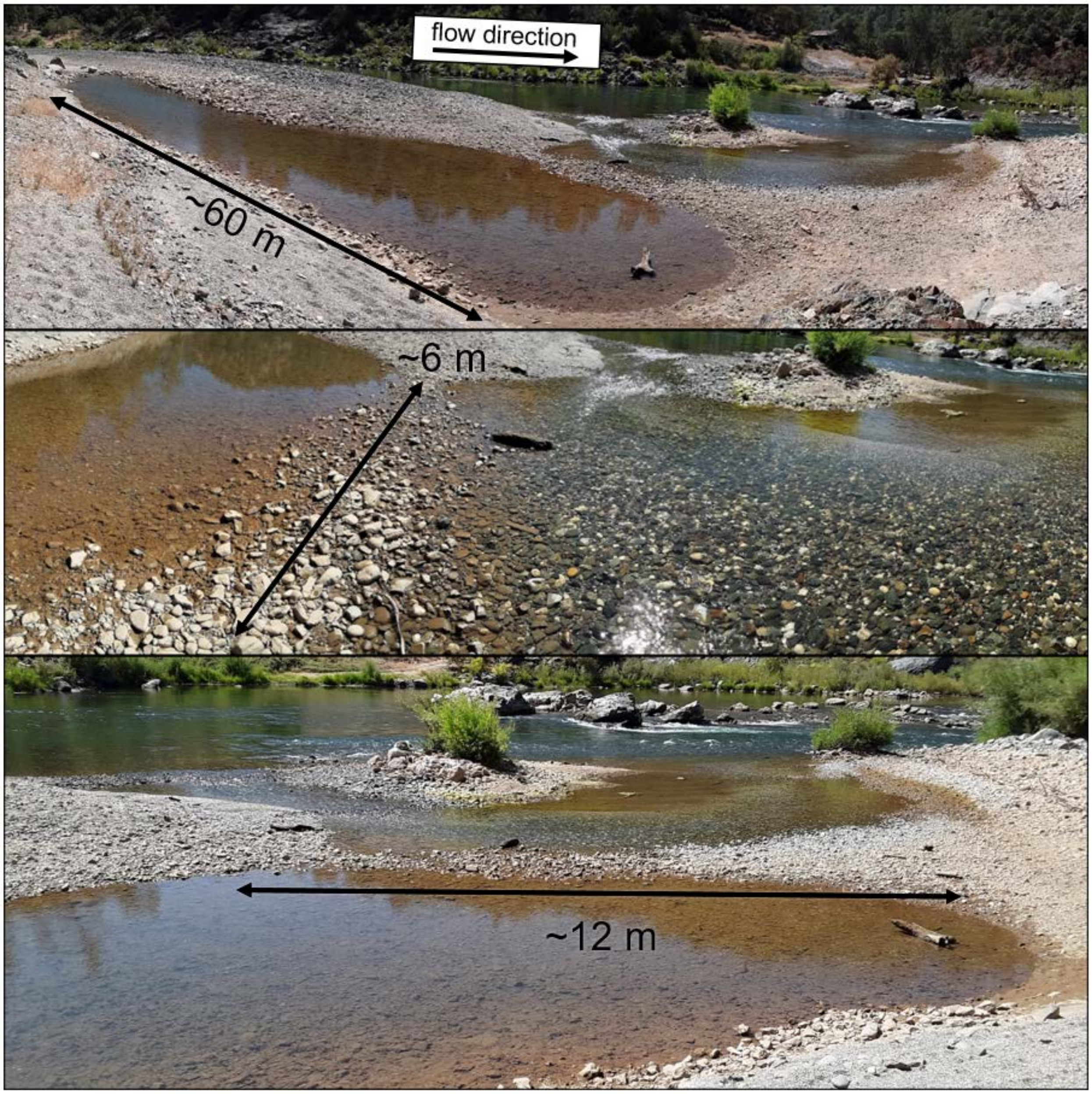

Figure 9. Three perspectives of the lower side channel becoming disconnected from the mainstem at ~ 42.45 m^3/s.

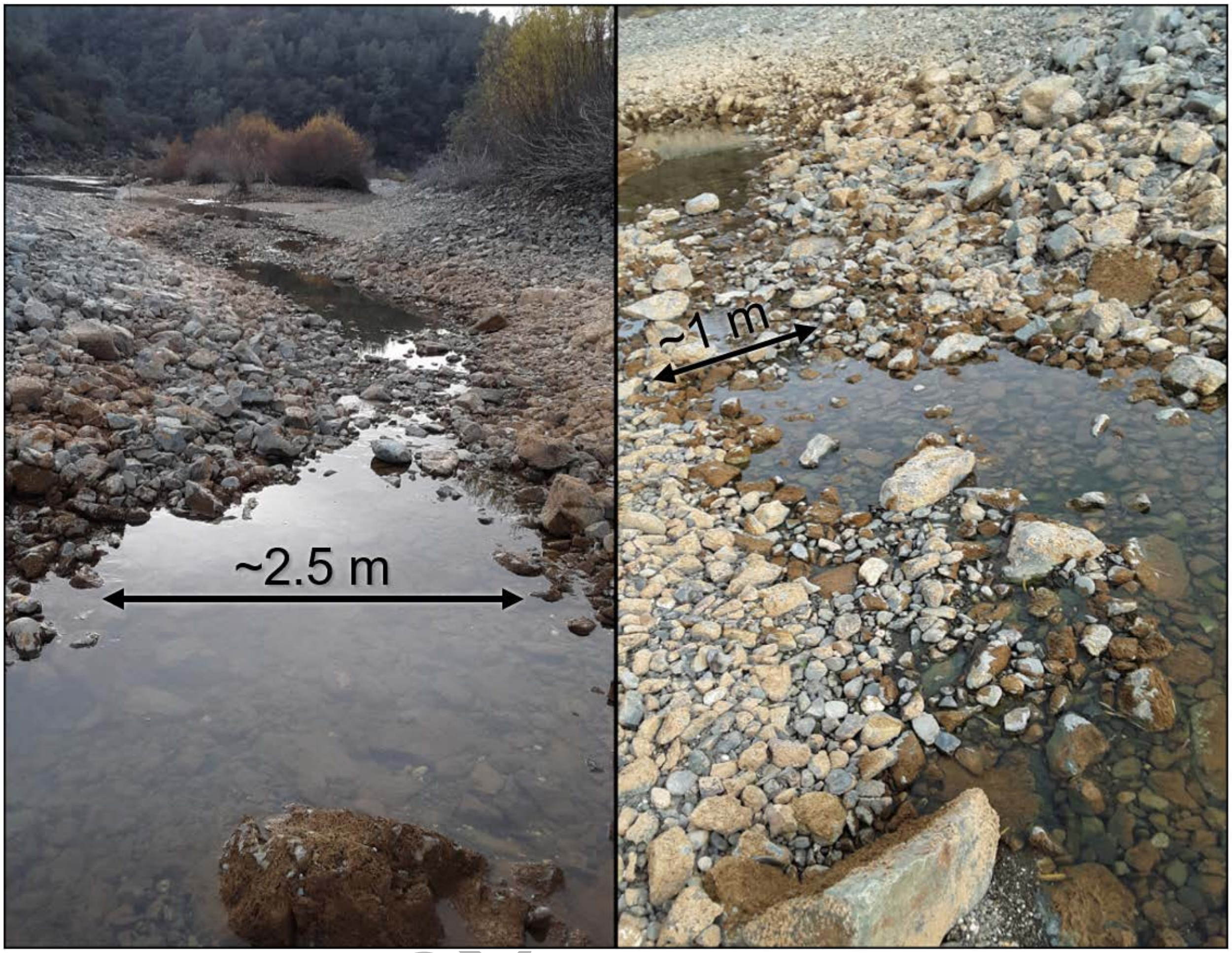

Figure 10. The upper side channel split in half with the lower portion disconnected at ~ 38.20 m^3/s. The side channel is shown from upstream (looking downstream, left image), and close-up at the downstream disconnection (looking upstream, right image).

6. Discussion

Overall, areas identified as high stranding risk correspond to the same locations where the most severe stranding events were observed in the study area. However, exact fish counts were not taken and absence of stranding in other areas was not explicitly documented. Thus, while these results provide encouraging qualitative validation of the stranding risk analysis, future studies could more rigorously document stranding occurrence (and absence) during downramping events to produce a quantitative validation.

Habitat rehabilitation projects have modeled microhabitat (e.g., Koljonen et al., 2013), scour potential (e.g., Elkins et al., 2007; Fischer et al., 2020) and bioenergetics (Wheaton et al., 2018), but thus far not fish stranding risk. Unfortunately, creating shallow landforms inevitably increases redd dewatering and fish stranding risks. If too much of a regulated river's fish population is attracted to rehabilitated sites that are then subjected to dewatering and stranding conditions at the wrong times, then the population may decline, defeating project goals.

Project efforts may focus on discharges for targeted functionality, but ignore other present flows impacting critical functions. This is especially of concern when river rehabilitation projects and environmental flow regimes are designed independently by different entities who are not collaborating. Parties designing projects need to be aware of the entire flow regime, which is unlikely to change because of one rehabilitation project yet could affect the success of that project.

6.1. Morphological impacts on stranding

Comparison of stranding risks across the three topographic conditions illustrates how the Yuba Canyon Project and subsequent topographic changes affected stranding risks. The most relevant topographic change was the creation of a series of side channels running through the preexisting point bar. However, additional morphodynamic changes occurred following completion of the project that increased stranding risks. Because the flows modeled for this stranding risk analysis were not high enough to initiate sediment transport (as indicated by model-derived Shields stresses, direct observation, and past studies of augmented gravel migration in the reach (Brown and Pasternack, 2014)), these changes are expected to have occurred on the falling limb of much higher flows. Though morphodynamically relevant discharges were not modeled for this study, comparison of stranding risks between fixed topographies still illustrates the importance of morphodynamic processes altering stranding risks.

The lower side channel was originally designed to have a smoothly graded connection to the mainstem at the downstream outlet, with a connection occurring from the upstream end only at flood flows (i.e. > 141.58 m^3/s). Thus, the lower side channel was anticipated to gradually drain during flow reductions without the formation of depressions which could potentially strand fish (Figure 6). Though the design topography did not indicate stranding risk for the lower side channel, accumulation of sediment near the downstream outlet following completion of the Yuba Canyon Project formed a barrier between the side channel outlet and the river mainstem. Because this side channel only had a single connection to the river mainstem, this resulted in complete disconnection of the lower side channel at flows below 42.45 m^3/s. Flow from the main channel is deflected by a vegetated gravel-cobble bar, creating a backflow towards the side channel outlet (Figure 9). The rapid reduction in flow velocity decreases sediment transport capacity, which may have led to the observed accumulation of sediment at the outlet. The side channel's lack of an upstream connection also prevents higher velocity flows from passing through which would promote the sediment transport and scour necessary to keep the side channel open. Flood pulses which allow overflow from upstream and induce scour play an important role in maintaining side channels, and the lack of this scouring capacity can lead to the formation of alluvial plugs (Constantine et al., 2010; Riquier et al., 2017). Once alluvial plugs are established, side channels generally aggrade over time due to suspended sediment deposition (Citterio and Piégay, 2009; Riquier et al., 2017). Furthermore, the flow frequency in side channels has been found to be a strong predictor of side channel sedimentation rates, with more rapid aggradation occurring in less frequently flowing side channels (Citterio and Piégay, 2009; Riquier et al., 2017; van Denderen et al., 2019b).

In contrast with the lower side channel, the upper side channel maintains both an inlet and outlet connection at a discharge of 56.63 m^3/s. Despite this fact, it was still predicted to become disconnected by a flow reduction for both the design and post-project topographies. This disconnection is due to its low gradient, leading to the majority of the side channel having depths less than d_{min} before going dry. In this situation, minute topographic variations cause the formation of pools that effectively trap juvenile fish.

Due to the lack of fine sediments in the EDR, sedimentation dynamics in both side channels are likely driven by bedload transport. For bedload-supplied side channels, evidence suggests that aggradation could be mitigated by increasing the side channel's width-to-depth ratio, as well as by shortening the length of the side channel relative to the length of the main channel (van Denderen et al., 2019a).

Because both side channels were created on the inside of a meander bend, helical flow may also be contributing to aggradation of the side channels. Helical flow caused by river meandering creates a near-bed flow velocity component that is transverse to the depth-averaged flow, leading to a disproportionate routing of sediment at bifurcations. As a result, a greater proportion of sediment is routed towards the bifurcate on the inside of a meander bend (Kleinhans et al., 2008; Hardy et al., 2011; van Dijk et al., 2014). Because this effect is not resolved by the applied 2D hydrodynamic model, the use of hydro-morphodynamic models and/or geomorphological considerations would be necessary to determine the significance of this effect when designing side channels.

Overall, this study illustrated that even if a side channel is designed to drain positively, it may still pose significant stranding risks if it has low gradients or if alluvial plugs form at inlets/outlets. Under a regulated flow regime, stranding risks in side channels might be avoided by ensuring they remain inundated with active inlet and outlet connections at minimum flows. Increased frequency of flow releases that inundate the side channels could also help maintain active connections and prevent the formation of alluvial plugs (Constantine et al., 2010, Riquier et al., 2017). However, these very same measures would also likely diminish the habitat quality for rearing juveniles, as they would be exposed to unsuitably high depths and velocities under such conditions. To an extent, there may be a fundamental tradeoff between the amount of quality rearing habitat and the presence of stranding risks for juvenile fish. The relative impact of both factors should be considered as part of river rehabilitation project design, as well as active management to effectively improve conditions for the target species.

6.2. Ramping rate effects on stranding risk

Ramping rates are not likely to be a dominant driver of juvenile Chinook salmon stranding in the LYR. Because (i) the applied rate of change of discharge corresponds to the highest levels experienced under current flow regulation practices, (ii) the flows investigated are relatively low (where $\frac{\partial h}{\partial Q}$ is generally greatest), and (iii) the methods used to estimate ramping rates do not consider wave attenuation, the estimated values are expected to be upper bounds on the ramping rates experienced on the LYR. These ramping rate estimates are much lower than those experienced in many hydropeaking European rivers, staying near or below the target rates of <10-15 cm/hr suggested in the literature for minimizing the effect of ramping rates on stranding risks (Halleraker et al., 2003, 2007). Consequently, a focus on river topography, especially for recontouring sites, is critical to managing stranding risk.

6.3. Other considerations

Typical water temperatures directly below Englebright Dam range between 7−13 ˚C, coldest around February and warmest around July (RMT, 2010). Because spring-run Chinook fry emergence begins in November, followed by fall-run Chinook salmon and steelhead in the subsequent months, the coldest water temperatures experienced by these juvenile salmonids typically occur during the same time period when fry are smallest and most susceptible to stranding (Hunter, 1992). Additionally, ramping rate has a greater impact on stranding under cold conditions (Bradford, 1997; Saltveit et al., 2001; Halleraker et al., 2003). Consequently, the combination of relatively small juveniles, cold temperatures (~6 ˚C), and moderate ramping rates (~10-15 cm/hr) indicate that disconnecting habitat areas are expected to pose relatively greater stranding risk during the winter in the EDR compared to those present during other seasons or at locations further downstream. In contrast, ramping rates are not expected to significantly impact stranding risks during the summer when waters are warmer and juveniles are larger.

Regulated downramping on the LYR also typically occurs during the daytime, which may elevate stranding risks for wild fish. However, hatchery fish could potentially strand more in nighttime downramping scenarios (Saltveit et al., 2001). Because both wild and hatchery fish are present on the LYR, the effect of time of day on stranding is uncertain.

7. Conclusions

More work is needed to further improve fish stranding prediction, but this study showed promising results from applying a novel algorithm (available in well-documented open-source software on GitHub) to a site known to have disconnections and fish stranding. The algorithm successfully identified discharges at which different areas become disconnected and confirmed the presence of high stranding risks in areas where significant stranding was observed. The occurrence and severity of stranding events were highly sensitive to topography and morphodynamic changes. In especially active rivers, and particularly in artificially constructed features without any active self-maintenance mechanisms, river morphology can change rapidly, in turn rapidly changing stranding risks. Thus, as with most aspects of river science, the lack of understanding of morphodynamic processes limits the applicability of these methods presented to predict future conditions. Accurate characterization of stranding risks with any method are inextricably dependent upon the availability and accuracy of topographic data reflecting the present geomorphology. While the methodology presented herein appears to be effective at delineating present stranding risks, it may not capture the full extent of future stranding risks as morphodynamic changes alter a design topography, as was the case for the lower side channel of the Yuba Canyon Project. While the Yuba Canyon Project did create more spawning and rearing Chinook salmon habitat, side channel disconnection also elevated stranding risks.

Authorship contribution statement

K.G. Larrieu: literature review, conceptualization, methodology, field work, software, data analysis, original draft; G. B. Pasternack: conceptualization, 2D modeling and ecohydraulics theory and practice, articulation about types of stranding, field work, original draft editing, producing draft into journal manuscript, funding acquisition, supervision, project administration.

Declaration of Competing Interest

The first author (Larrieu) declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Larrieu was responsible for selecting model parameters, the downramping flow regime, and conducting all data analysis with scientific independence. The senior author (Pasternack) has had 17 years of science and management involvement helping steward the lower Yuba River, possibly arising a perception of conflict of interest, so disclosure is provided of activities relevant to this section of the river. Pasternack was a UC Davis Principal Investigator on a Cooperative Ecosystem Studies Unit collaboration with AFRP from 2003-2008 in which reports and articles were written about the Englebright Dam reach (EDR). Pasternack was a paid consultant for the multi-stakeholder Yuba Accord River Management Team to help design and implement systemic ecohydraulic and geomorphic analysis of the LYR, including EDR. Pasternack was a paid consultant for and later a UC Davis Principal Investigator in a Cooperative Ecosystem Studies Unit collaboration with the US Army Corps of Engineers to analyze gravel/cobble deficiency in the Englebright Dam Reach, design a long-term gravel augmentation plan, and help implement the plan in its early years. Pasternack was separately a paid consultant hired to undertake planning level assessment of the number of spring-run Chinook salmon that could be supported by river rehabilitation in the lower half of Englebright Dam Reach and in the Narrows Reach. That consulting was funded by California Department of Water Resources and Pacific Gas & Electric for their Habitat Expansion Agreement for Central Valley Spring Run Chinook Salmon and California Central Valley Stealhead via subconsultancy through ICF International, unrelated to and predating the AFRP project in this same area. Pasternack was once again a UC Davis Principal Investigator on a Cooperative Ecosystem Studies Unit collaboration with AFRP only during their early planning phase for the Yuba Canyon Project, with the work limited to sharing public data with AFRP consultants and having early planning discussions with AFRP consultants. Pasternack had no involvement in the AFRP project thereafter (e.g., not in any AFRP pre-project characterization, project design, or project implementation). Pasternack was a paid consultant for Yuba Water Agency before and during this study to help apply scientific research in Yuba River management broadly. YWA sought advice and analysis as to the stranding events occurring at the Yuba Canyon project site. Consulting was done independently of academic research following UC Davis policies and procedures.

Supplementary materials

Supplementary material associated with this article can be found on the journal's website.

Data Availability Statement

The vast majority of the data used in this study is public domain data held by the United States Fish and Wildlife Service Anadromous Fish Restoration Program. That includes the original topography of the study site in 2017, the final project design topography, and all SRH-2D model files for the AFRP project. We obtained these data by sending an email request to the AFRP staff person assigned to the Yuba River, which changes from time to time. The only data that we generated for this manuscript was a new, post-project topographic map a year after construction (2019), which was then put into the pre-existing SRH-2D models and run. These data are owned by the project sponsor Yuba Water Agency, who determines availability. An email request for that data may be submitted to Yuba Water Agency.

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Automated analysis of river habitat connectivity and fish stranding risks. Part 2: juvenile Chinook salmon stranding at river rehabilitation site

Supplementary Materials

1 Floodplain interpolation accuracy

Extrapolation accuracy was tested on 2D model WSE results for the lower Yuba River (Hopkins and Pasternack, 2017). WSE values in the main channel were used as training data, while side channels, backwaters, and other ponded areas were used for testing. The choice of training and testing data was made to be more representative of typical WSE extrapolation than randomized cross-validation. A randomized cross-validation was also performed, which yielded lower errors than those presented herein due to generally greater geographic proximity of training and testing points. Overall, the extrapolated wetted areas exhibited a qualitatively good match to the original data (**Table 1**), considering that the median error is comparable to uncertainty in WSE prediction from 2D modeling of the 37-km lower Yuba River segment as a whole. Specifically, in comparing 2.1 million airborne LiDAR observed vs 2D model predicted WSEs at a summer baseflow, 69% were within ±6.1 cm, which is very good performance for meter-resolution modeling of such a long domain.

Table 1: Median signed and unsigned errors for each interpolation method tested.

Method	Median signed error (cm)	Median unsigned error (cm)
Nearest Neighbor	-5.89	9.41
Inverse Distance Weighted	-3.74	7.68
Ordinary Kriging	-5.23	8.35
Empirical Bayesian Kriging	-2.67	8.16

2 Yuba Canyon model details

2.1 Model boundary conditions

The Yuba Canyon Project's stage-discharge rating curve was developed using WSE values collected from a pressure transducer and discharge values taken as a time-lagged sum of YRS and DCS gage readings. WSE was then fitted as a function of discharge for flows up to 226.40 m^3/s (8,000 cfs) using a fourth order polynomial. This function was adapted to set boundary conditions for all model simulations. A constant inflow of 1.22 m^3/s (43 cfs) was included at the Deer Creek tributary. This value was chosen as the median recorded flow at the DCS gage since the beginning of Deer Creek regulation and during the season of interest for juvenile Chinook salmon rearing (Feb 1 - June 15).

Table 2: Inlet discharges and outlet water surface elevations used to set boundary conditions for the SRH-2D models.

Yuba River Inflow (cfs)	Deer Creek Inflow (cfs)	Outlet WSE (ft)
500	43	270.167
600	43	270.354
700	43	270.534
800	43	270.708
900	43	270.876
1000	43	271.038
1100	43	271.194
1200	43	271.345
1300	43	271.491
1400	43	271.632
1500	43	271.768
1600	43	271.899
1800	43	272.149
2000	43	272.383

2.2 2D model validation

Extensive SRH-2D hydraulic validation has been done in EDR (Brown and Pasternack, 2012, 2013) to evaluate mass conservation, WSE (15,135 observations), velocity magnitude (2,141 observations), and velocity direction (1,743 observations). For example, the coefficient of variation between predicted and observed velocity magnitudes was 0.76 and 0.85 for the 2012 and 2013 studies, respectively. A thorough analysis of recirculating eddy prediction was also reported. All validation results were at or above peer-reviewed journal article standards for 2D modeling. Furthermore, model accuracy was vetted through bioverification of Chinook salmon spawning habitat predictions against observed spawning locations with an excellent outcome.

Because this study used the same model in the same resolution for similar flows as previous validation was done, extensive validation work was not necessary. Nevertheless, WSE was particularly important because it controls disconnection. Post-project WSE measurements taken near the water's edge at the Yuba Canyon site showed a small mean absolute error of 3.1 cm (0.1 ft).

Survey points were also taken with a Trimble R8 real-time kinematic global positioning system unit at the water's edge when side channels were disconnected. This data was compared with corresponding interpolated depth rasters. Wetted areas delineated by the IDW interpolation showed agreement within one pixel for nearly all such points collected.

3 Flow downramping

Fifteen-minute resolution Yuba-Smartsville (YRS) gage readings were analyzed in order to characterize relevant downramping scenarios during juvenile spring-run Chinook salmon rearing on the lower Yuba River. Figures 1 and 2 illustrate characteristic flow reductions used to determine a characteristic downramping rate of 7.07 cms/hr (250 cfs/hr).

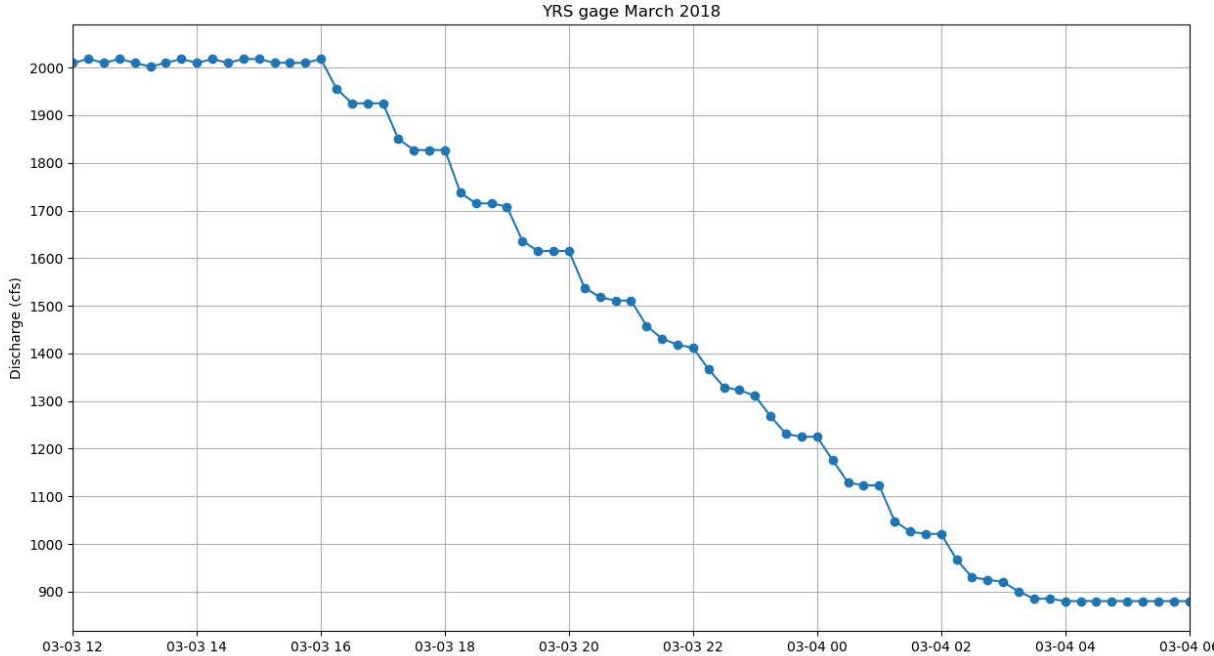

Figure 1: A flow reduction during March 2018. All points correspond to measurements recorded 15 minutes apart. Note that each hour consists of a ~100 cfs flow reduction over 30 minutes, followed by 30 minutes of constant flows.

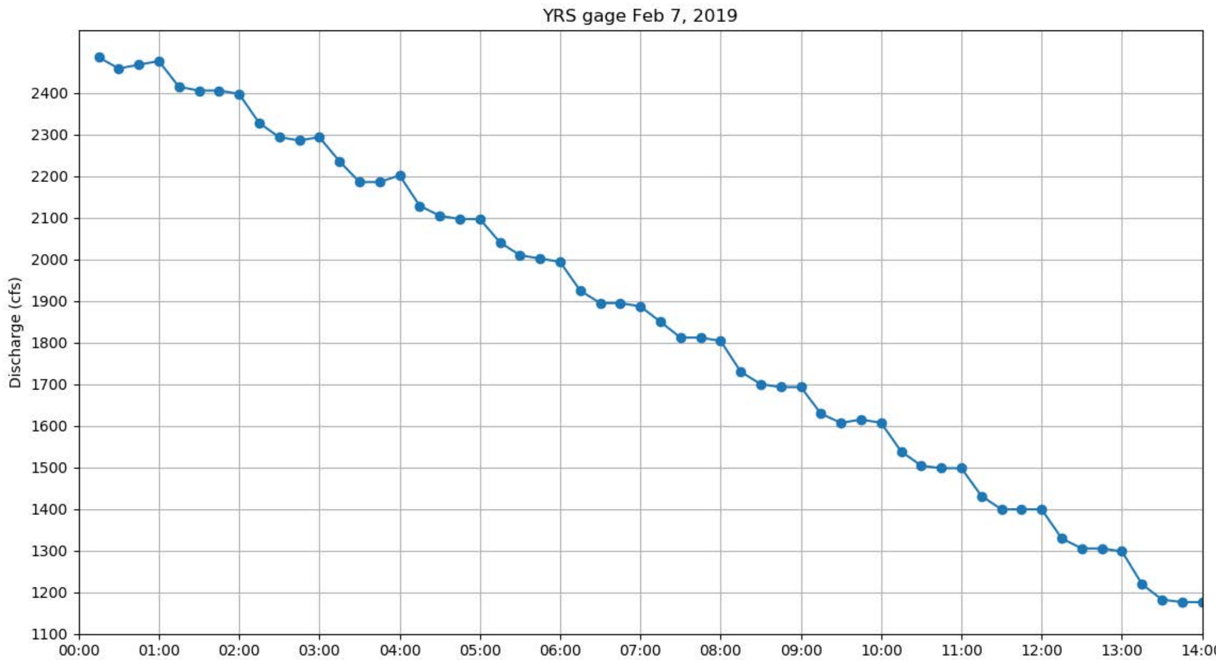

Figure 2: Another flow reduction during February 2019. Again, note that each hour consists of a 100 cfs flow reduction within 30 minutes, followed by 30 minutes of constant flows.

4 References

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