SAN JOAQUIN RIVER SPAWNING HABITAT SUITABILITY STUDY

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Abstract: The availability of quality spawning habitat within the San Joaquin River downstream of Friant Dam (Reach 1A) is crucial for successful reintroduction and sustained population of Chinook salmon. Several uncertainties exist as to the suitability of existing spawning habitat within Reach 1A and how sediment transport may affect efforts aimed at improving spawning and incubation habitat. Multiple studies are currently underway or have been completed to help identify the quality of the hyporheic environment as it relates to successful spawning and fry emergence, including evaluations of water quality within the hyporheic zone (DO, water temperature, fine sediment accumulation), egg survival, mesohabitat, bed material size and mobility, scour and deposition, and channel morphology changes associated with alteration to the flow regime. In addition, bedload and suspended load monitoring have been conducted within the reach since 2010.

Critical to identification of potential spawning areas are the bed material and hydraulic conditions within the reach during probable spawning periods of spring-run and fall-run Chinook salmon. This current study combines bed material characterization efforts with two-dimensional hydraulic modeling results to identify areas considered potentially suitable spawning habitat based upon depth and velocity requirements. The suitability of the potential spawning habitat is evaluated with GIS parameterization of substrate and hydraulic conditions, and correlation of surveyed redds, substrate, and hydraulic conditions are examined and quantified.

INTRODUCTION

The San Joaquin River Restoration Program (SJRRP) aims to "restore and maintain fish populations in good condition in the main stem of the San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally-reproducing and self-sustaining populations of salmon and other fish." The SJRRP Fisheries Management Plan identifies spawning and incubation as a life stage to be supported for successful completion of the salmon life cycle.

SJRRP's current understanding of the system is that sufficient availability and quality of spawning habitat within Reach 1A of the San Joaquin River is imperative to sustaining a population of Chinook salmon (*Oncorhynchus tshawytscha*). Multiple studies are currently underway or have been completed to help identify the quality of the surface water and hyporheic environments as they relate to successful spawning and fry emergence (current efforts summarized in Section 3.2 of 2014 Monitoring and Analysis Plan; SJRRP, 2013a). These include efforts to evaluate water quality within the hyporheic zone (DO [Reclamation, 2012a], water temperature effects [Reclamation, 2012a], fine sediment accumulation [SJRRP, 2010a; SJRRP, 2013b]), egg survival (SJRRP, 2012), mesohabitat characterization (SJRRP, 2010b), spawning habitat use by transported fall-run Chinook (SJRRP, 2011; SJRRP, 2013c), bed material size and mobility (Tetra Tech, 2012a,b; SJRRP, 2012; SJRRP, 2013d), scour and deposition (SJRRP, 2011), and channel morphology changes associated with alteration to the flow regime (SJRRP, 2011; SJRRP, 2012; SJRRP, 2013e). In addition, bedload and suspended load monitoring have been conducted within the reach since 2010 (Graham, Mathews & Associates, 2012; Reclamation, 2014a). Most recently, spatial characterization of hydraulic conditions within Reach 1A was completed through two-dimensional hydraulic modeling across a wide range of flows (Reclamation, 2014b), and continuous facies mapping of the bed material was completed within the low-flow channel (SJRRP, 2014b).

The purpose of this current study is to initially characterize potential spawning locations within Reach1A of the San Joaquin River from Friant Dam to Highway 99 (HW99) based upon suitable hydraulics, bed material, and surface water temperature (figure 1). These potential areas will then analyzed for patterns of correlation and compared with mapped spawning redds within the reach over the past 2 years. This effort is part of a larger study to characterize suitability of spawning and incubation habitat based on physical, biological, and chemical criteria.

POTENTIAL SPAWNING HABITAT QUANTITY

Requirements for spawning Chinook salmon evaluated in this initial assessment of potential spawning habitat area include hydraulic conditions, substrate, and surface water temperature. Multiple other aspects of spawning habitat quality may impact where a fish chooses to spawn and are only briefly discussed within this paper. However, we recognize the importance of many additional variables influencing spawning habitat quality and ultimately on the incubation habitat provided for successful emergence. These are anticipated to be incorporated into future analyses.

With respect to hydraulic conditions for spawning Chinook, water depth must be sufficient to cover the fish during spawning, and velocity must be adequate to flush finer particles downstream during the process of red construction, but not so great that eggs do not remain in the egg pocket or adults have to expend too much energy holding position in the water column (SJRRP, 2014a). The SJJRP Spawning and Incubation Subgroup reviewed habitat suitability indices (HSI) from studies on the Tuolumne, Stanislaus (Aceituno, 1990, 1993), and Merced (Gard, 1997) Rivers (all tributaries to the San Joaquin River) and suggested the criteria for suitable spawning depths for the San Joaquin River to be between 0.7 and 3.7 feet (ft) and velocities between 0.8 and 3.4 ft/s. These values correspond to the criteria from the Stanislaus River and encompass the ranges for all three rivers, thereby providing the greatest flexibility for evaluation on the San Joaquin River.

Chinook salmon generally select larger substrate to spawn in than other Pacific salmon species. Suitable spawning gravel consists of a mixture of particle sizes from sands to cobbles, with a median diameter (D50) of 2.5 to 5 cm (SJRRP, 2010c). A review of reported spawning substrate in Central Valley System suggests that the preferred substrate size ranges between 2.5 and 10 cm in diameter, and some studies indicate spawning in substrate up to 30 cm in diameter (SJRRP, 2010c). Substrate requirements for spawning are highly correlated to fish size with large fish capable of using larger substrate materials than small fish (SJRRP, 2014a) to build a redd. Moir and Pasternack (2010) found that Chinook often utilize coarser substrate when higher velocities are present. Fine sediment within the system has a large influence on the incubation habitat once the eggs are laid (Tappel and Bjornn, 1983). However, the presence and influence of fine sediment on egg survival is a topic currently under investigation, the results of which will be incorporated into future designation of suitable incubation habitat.

Chinook salmon have specific water temperature requirements before and during spawning in order to survive and deposit their eggs (SJRRP, 2014a). Surface water temperatures for successful spawning and incubation are illustrated in table 1. The critical temperature range defines the range over which a fish shows definite signs of thermal stress (Elliot, 1981).

Table 1 Temperature Requirements for Spawning and Incubation (from SJRRP, 2010).

	Spawning	**Incubation and Emergence**
Optimal	≤ 57 °F (13.9 °C)	≤ 55 °F (13 °C)
Critical	60-62.9 °F (15.6-17°C)	58-60 °F (14.4-15.6°C)
Lethal	≥62.6 °F (17 °C)	≥62.6 °F (17 °C)

Two-dimensional Hydraulic Modeling: Two-dimensional hydraulic models of Reach 1A of the San Joaquin River were developed and calibrated using SRH-2D (Reclamation, 2008) to spatially characterize hydraulic conditions throughout the reach as a tool for predicting the availability of spawning habitat (Reclamation, 2014b). For computational efficiency, the reach was modeled in two sections: the first is from Friant Dam (Mile Post (MP) 267) downstream to Highway 41 (HW41) Bridge (MP 255) and is referred to as Reach1A_01, and the second extends from HW41 downstream to Highway 99 (HW99) Bridge (MP 243) and is referred to as Reach1A_02.

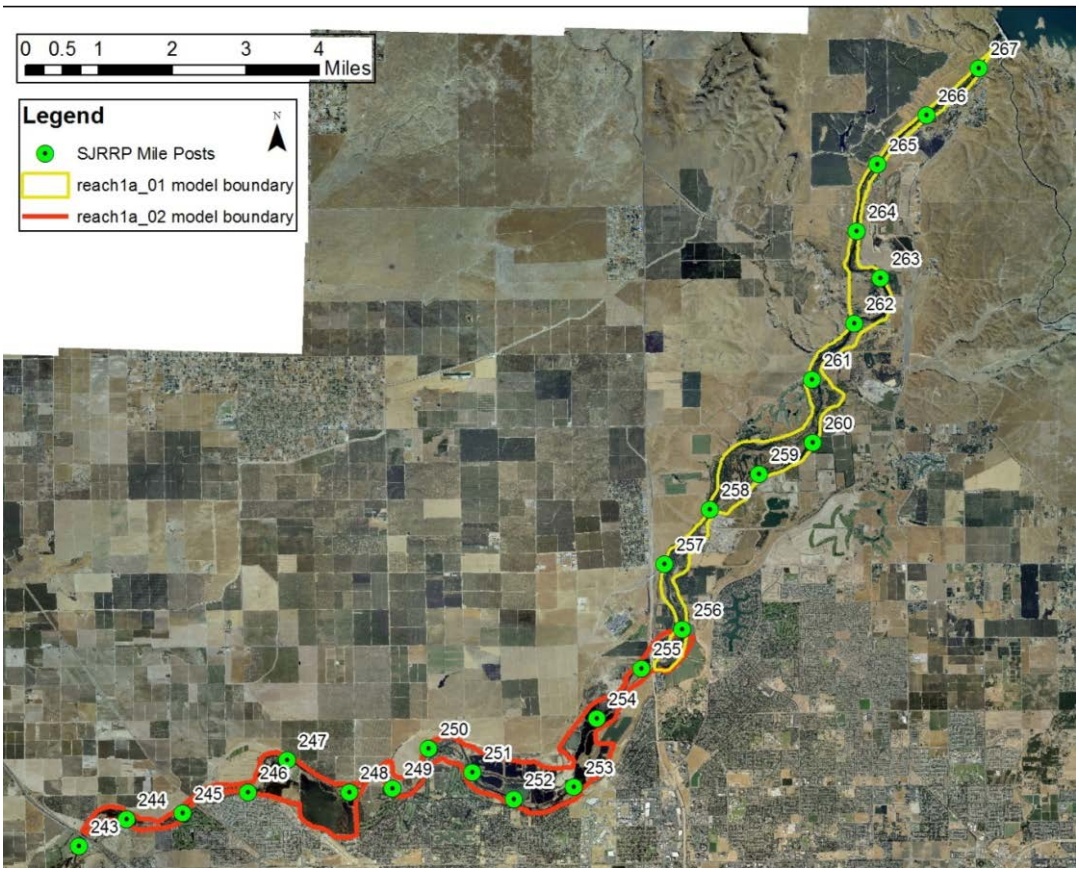

Figure 1 Map of modeled reaches. Reach 1A_01 extends from Friant Dam (MP 267.5 to HW41 (MP 255) and Reach 1A_02 extends from HW41 (MP 255) to HW99 (MP 243) for a total reach length of 24.5 river miles.

The mesh for each subreach generally consisted of rectangular cells to represent the main channel and most side channels and triangular cells to represent the floodplain. Within the channel, rectangular cell sizes ranged between 5-10 ft laterally and 20-30 ft longitudinally. The final grids were comprised of approximately 117,000 cells within the Reach 1A_01 model and 138,000 cells within the Reach 1A_02 model. Terrain data for Reach 1A are a compilation of ground-based survey points and photogrammetry collected in 1998, combined with in-channel bathymetry collected by boat using SONAR in 2009. The final topographic models for each subreach were created in State Plane CA III, NAVD88 ft. Flows modeled to date were based upon the availability of calibration data and range from 270 cfs to 7,650 cfs. Rating curves developed from measured flows and water surface elevations at HW 41 and HW 99 served as the downstream boundary conditions for each model.

Hydraulic roughness (Manning's *n*) is defined at each cell in a computational mesh. Initial roughness values were delineated based on zones of vegetation density and land use from 2007 aerial photographs (MEI, 2000; DWR, 2010). Roughness zones were modified in some areas to better reflect current conditions based upon 2011 aerial photos and to improve calibration with initial model results. Final computational meshes for model Reach 1A_01 and Reach 1A_02 consist of 8 roughness categories (table 2).

Model calibration was conducted for both subreaches using available water surface elevation and flow measurements. In-channel calibration was performed first to define roughness within the channel, and then a subsequent calibration effort was conducted to define roughness within the floodplain. Calibration was performed by varying roughness in model simulations to determine the best match to measured water surface elevations (table 2). The goal of the model calibration was to predict water surface elevations with a root mean squared error (RMSE) of less than 0.5 ft.

Table 2 Calibrated roughness values for SRH-2D hydraulic simulations.

Land Use Type	**Reach1A_01**	**Reach1A_02**
Channel Bed	0.04	0.04
Off-Channel Open Water	0.04	0.045
In-channel Riffles/Rough areas	0.065	0.065
Open /Bare Ground/ Scattered Brush	0.045	0.068
Scattered Trees	0.06	0.09
Medium Density Trees/Brush	0.08	0.12
Dense Trees/ Brush	0.1	0.15
Agriculture	0.045	0.055

Depth and velocity data were processed for 350 cfs in each reach to determine areas meeting spawning habitat hydraulic criteria. This discharge was selected as representative of the flow present during Spring-run and Fall-run Chinook spawning based upon the flow release schedule from Friant Dam into Reach 1A as specified in the Stipulation of Settlement (NRDC v. Rodgers, 2006). The spawning habitat hydraulic criteria were provided by the San Joaquin River Spawning and Incubation Subgroup and represent the depth and velocity ranges considered suitable on the Stanislaus River. Areas meeting the criteria for depths ranging between 0.7 and 3.7 feet and velocities ranging between 0.8 and 3.4 ft/s were delineated as polygons within GIS and determined as potentially suitable for spawning based on hydraulic conditions.

Bed Material Characterization: Bed material sampling has been conducted throughout Reach 1A of the San Joaquin River numerous times over the last 20 years using multiple sampling techniques to meet a variety of project goals. To most efficiently evaluate bed material for spawning habitat, a spatially continuous map of bed material was necessary. Facies maps provide an opportunity to capture spatial variability of the sediment comprising a channel bed through delineation of boundaries between notably different areas of bed material. Facies mapping was initially completed within Reach 1A in 2002, but only encompassed the first 12.3 miles downstream from Friant Dam (Stillwater Sciences, 2003), and several locations may have experienced local areas of change within the last 10 years. As such, during the summer of 2013, an effort was undertaken to update and expand upon the initial facies mapping to reflect current conditions of the river bed and to help characterize areas with suitable bed material for Chinook spawning.

In both the 2002 and 2013 mapping efforts, the Buffington and Montgomery (1999) mapping technique was adapted with slight variations between the two years. This is a hierarchical classification system of each facies according to the three most prevalent gain classes (i.e. silt, sand, gravel, cobble, and boulder) and sub-divided according to a classification based on phi-size class (very fine, fine, medium, coarse, very coarse). For example, 'sandy gravel' indicates that the most prevalent grain class is gravel but there are significant amounts of sand. Facies mapping was conducted by floating the river by kayak, delineating areas of bed material change, and visually identifying the facies classification. Simultaneously, pebble counts were performed in areas where no previous volumetric or pebble count samples had been collected. The maps and all sediment data were transferred to GIS.

An analysis was completed to associate a range of gradations with each facies category based upon pebble count data collected over the last 20 years. However, the results indicated that the pebble count data alone were not sufficient to differentiate between the coarse-scale facies categories. In addition, the pebble count data alone were incapable of differentiating between spawnable and non-spawnable facies categories because the resulting range of gradations for each facies where pebble counts were performed covered the preferred range of diameters for spawning. In other words, the results suggested that every facies category with one or multiple pebble counts contained suitable substrate for spawning. Another complication was that many facies categories, such as those over bedrock or in silt, contained no pebble count data.

Surface Water Temperature: The SJRRP has determined that water temperature is likely a limiting factor for each life history stage of Chinook salmon in the San Joaquin River, particularly in the warmest and driest years

(CDFW, 2012). As part of the SJRRP, a water temperature monitoring system was developed to better understand the longitudinal distribution of water temperature and aid in successful management of flow releases during critical salmon life-stages. With respect to salmon spawning, surface water temperature is a key factor influencing adult salmon behavior and survival during late summer and fall (August through December). Twenty water temperature monitoring locations are present within Reach 1 to help identify the spatial distribution of the potential spawning areas based upon known temperature limitations for Chinook salmon. Data collected at these sites within the last several years suggest that in general, the closer the site is to Friant Dam, the more suitable the water temperatures are during the critical spawning period. In 2011 it was observed that the closer the site was to the dam, the greater the number of days temperatures were below critical (14.4 °C) and lethal (15.6 °C) temperature thresholds for spawning and incubation; however, due to releases from the dam (>13°C) being greater than the optimal temperature (13°C) and cooler air temperature in late fall, more days met optimal temperature conditions further downstream than just below the dam (figure 2).

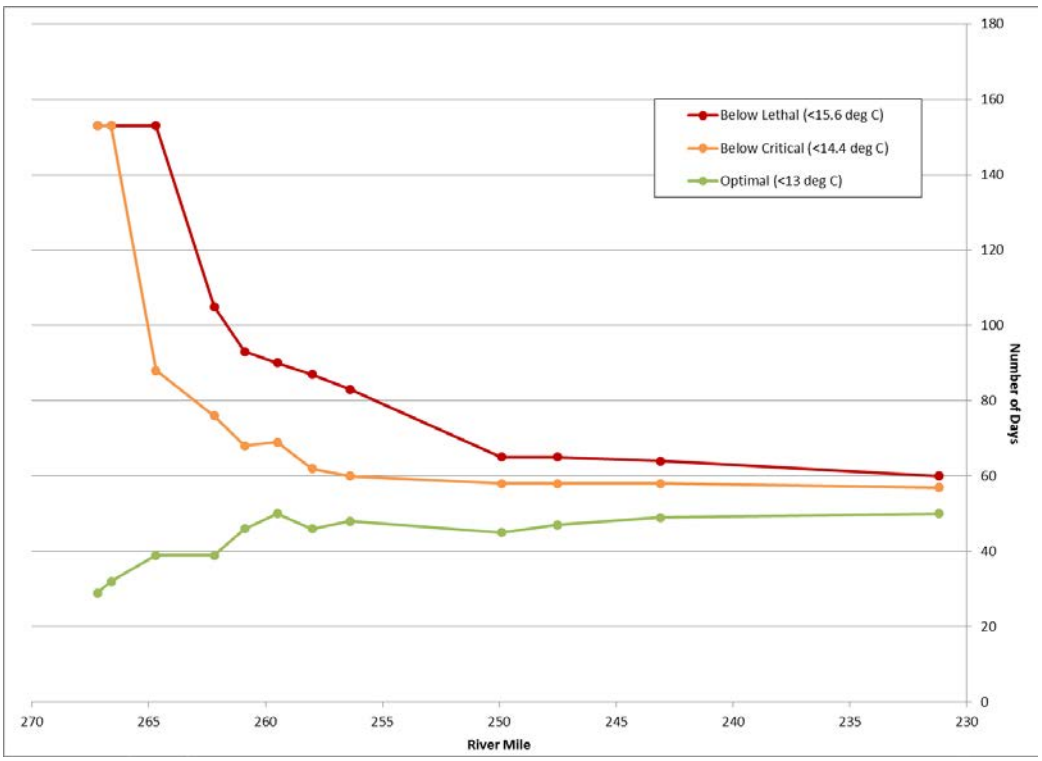

Figure 2 Number of days during expected spawning and incubation period (August through December, 2011) that water temperature was below objectives for incubation and emergence (SJRRP, 2010c).

Spring-run Chinook historically spawned in the San Joaquin River between late August and October, and Fall-run Chinook still spawn within tributaries to the San Joaquin River from October through December, peaking in early to mid-November. Based on this timing, water temperature monitoring indicates that Fall-run Chinook may not be limited by surface water temperatures during spawning within Reach 1A (figure 3). However, Spring-run spawning may be restricted to the first 10 miles downstream from Friant Dam.

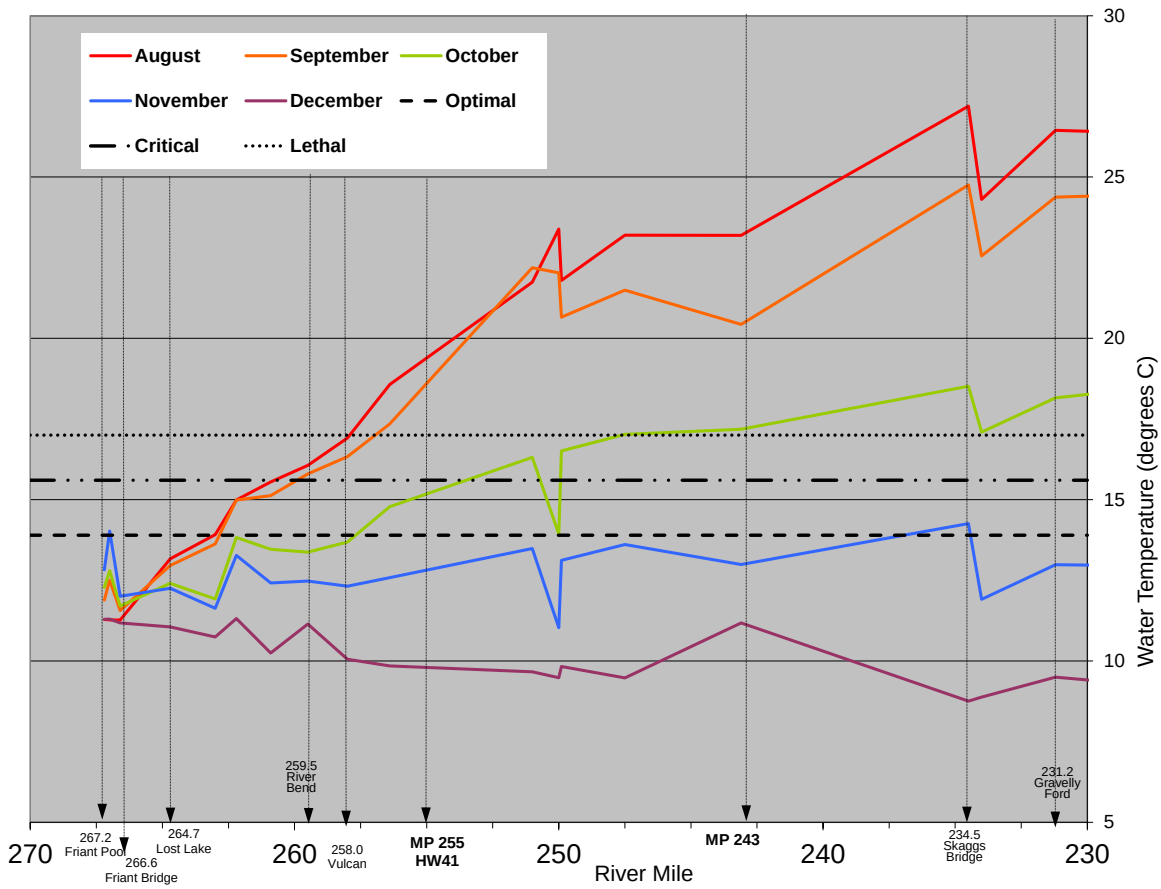

Figure 3 Monthly average stream temperatures for the period of record along with the optimal, critical, and lethal temperature ranges for spawning. The period of record differs slightly for each gage and therefore some points may represent longer time frames than others.

RESULTS OF ANALYSIS

The total modeled area encompassed over 12,000 acres (ac) (table 3). At a discharge of 350 cfs, 1,090 ac of the channel were inundated with depths greater than 0.1 feet. However, only 80 ac were determined to be potentially suitable for spawning based upon hydraulic conditions (0.7 to 3.7 ft depth and 0.8 and 3.4 ft/s velocities), indicating that only 7.4% of the total inundated area was determined to be suitable for spawning based upon hydraulic conditions alone. Inundated areas and areas of suitable hydraulic conditions were also compared with facies mapping to determine the existence of correlations between hydraulics and substrate. An example illustration of the delineation of mapped features is shown in figure 4. Inundated areas with facies designations were evaluated by dominant substrate type (figure 5). The majority of inundated area (excluding gravel pits, side channels, overbank areas, and channel margins) was comprised of sand (59%), while gravel and cobble represented a combined 36% of inundated area. The area deemed suitable based upon hydraulic conditions within each dominant substrate type is depicted in figure 6. Hydraulically suitable conditions were most common in gravel and cobble-dominated substrate, representing a total of 78% of the area (58.3 acres) identified as suitable. Twenty percent of the area with suitable hydraulic conditions was within substrate dominated by sand based upon the facies mapping.

Table 3 Modeled and inundated areas based on two-dimensional modeling results compared with the area meeting the depth and velocity criteria for spawning for each reach and also combined. Results presented are in acres.

	Area (Acres)		
	Reach1A_01	**Reach 1A_02**	**Total Combined**
Modeled Area	5,375	6,627	12,002
Inundated Area	293	797	1,090
Area Meeting Depth and Velocity Criteria for Spawning	44	36	80

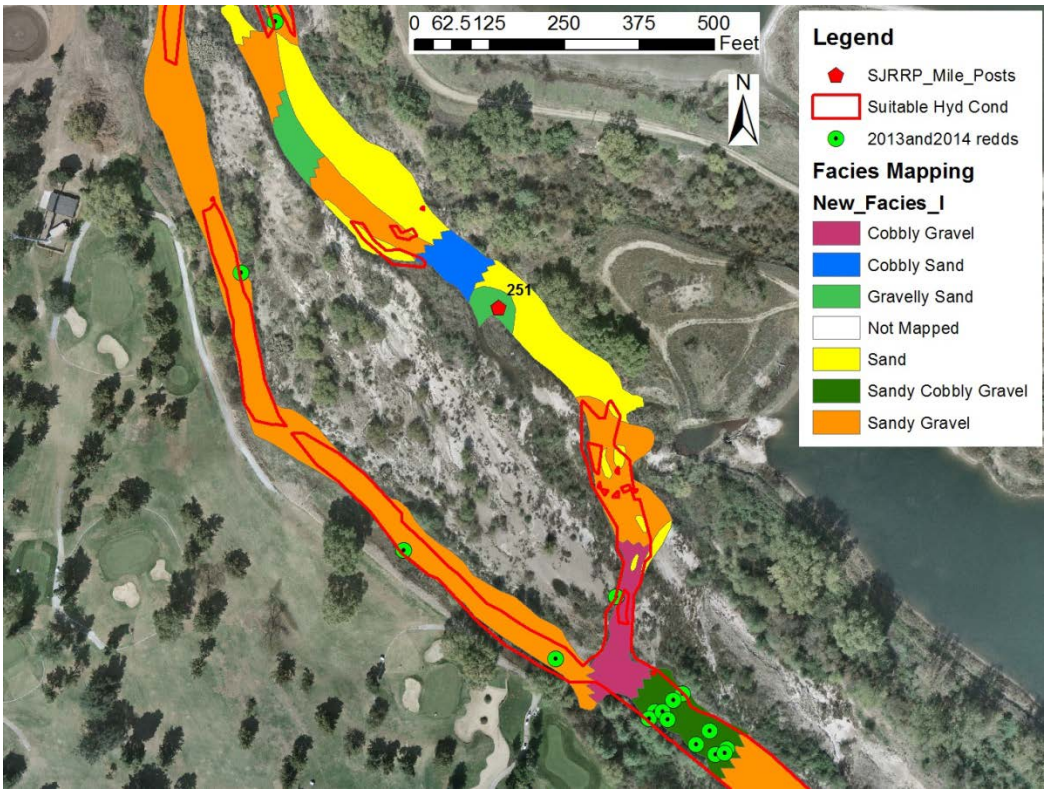

Figure 4 Example map of the delineation of redd locations, suitable hydraulic condition polygons, and facies categories near MP 251.

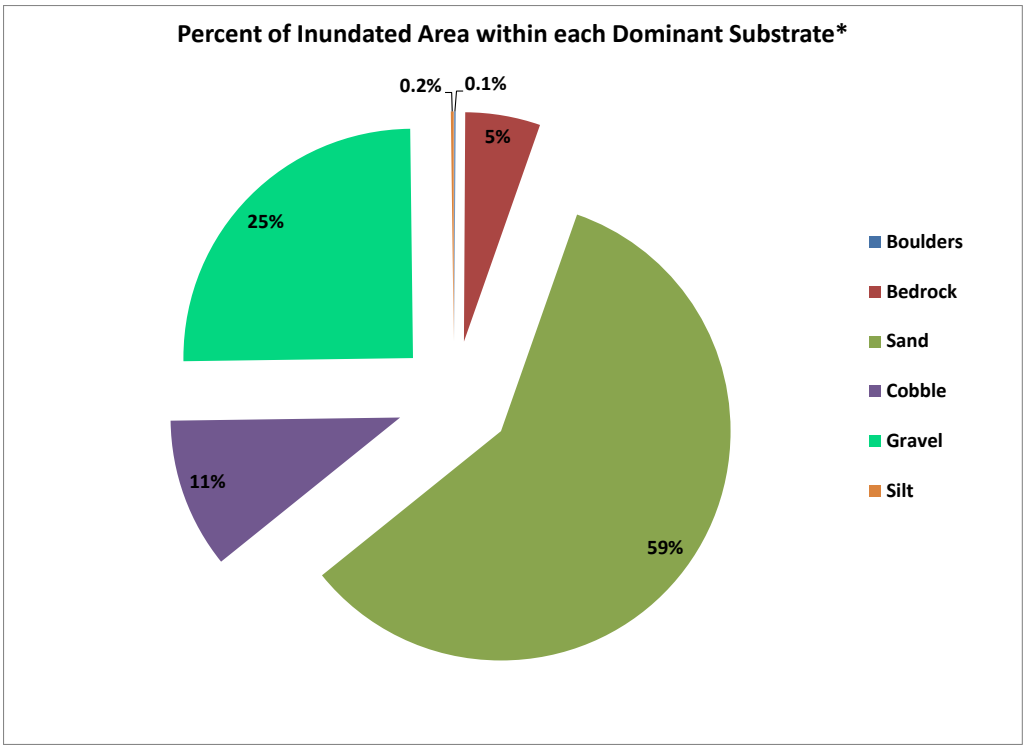

Figure 5 Percent of inundated area within each dominant substrate. *This analysis excludes inundated areas that did not have facies characterization, such as gravel pits, side channels, and channel margins.

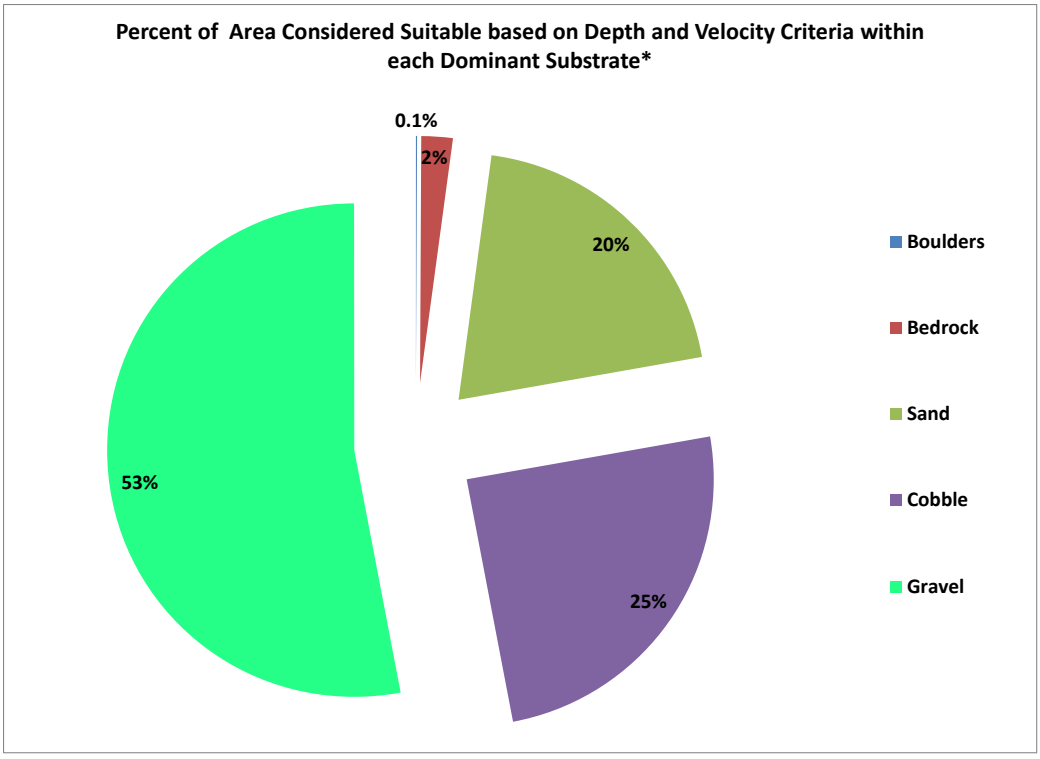

Figure 6 Percent of area with suitable hydraulic conditions within each dominant substrate type. *This analysis excludes suitable areas that did not overlap with facies characterizations, such as those in side channels and along channel margins.

There were 130 redds surveyed within the reach between Friant Dam and HW99 (figure 1) during 2013 and 2014 combined. There were an additional 22 redds surveyed just at or downstream from HW99 that were not included in the analysis because they were not located within the longitudinal extent of the mapped facies and two-dimensional modeling boundary. An analysis was done to identify which type of substrate the fish selected to spawn in based upon the facies mapping. The distribution of spawning within dominant substrate is shown in figure 7. Ten of the 130 redds were located outside of the mapped facies areas in areas identified as islands or channel margins above the low flow channel. Of the remaining 120 redds, the salmon overwhelmingly selected to spawn in facies with a gravel- (84 redds, 70%) or cobble-dominated (23 redds, 19%) substrate. However, several still chose to spawn in facies mapped as being dominated by sand or bedrock. This could be due to the presence of patches of gravel and cobble within larger generalized areas of mapped substrate.

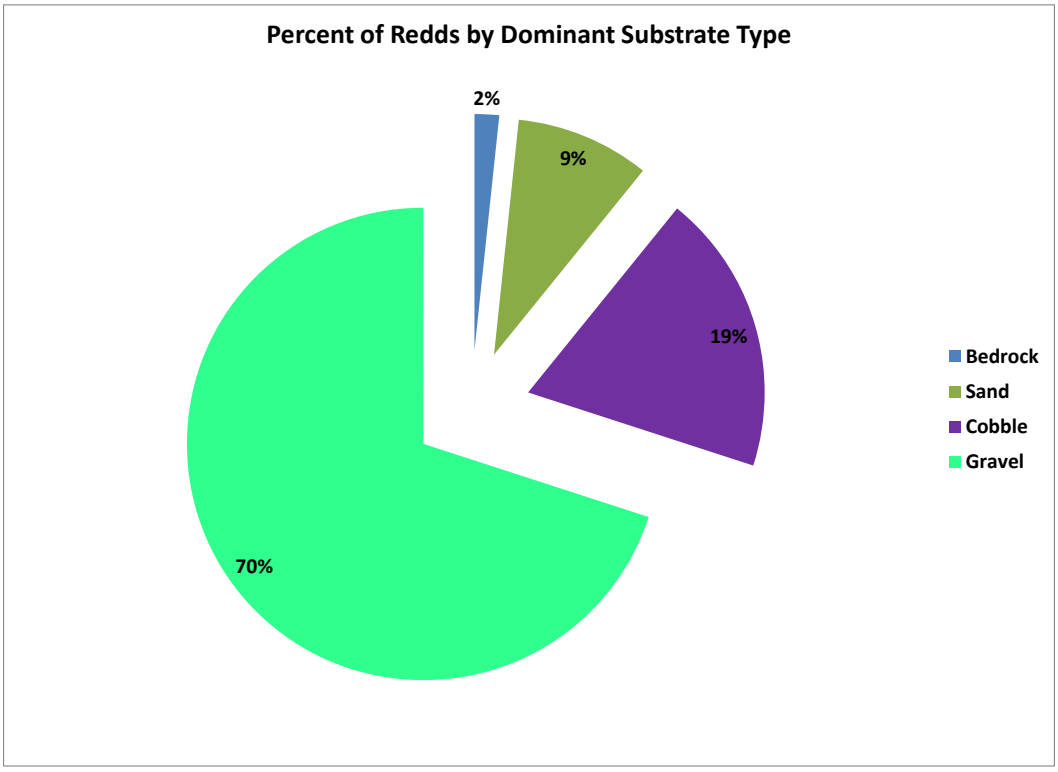

Figure 7 Percent of the occurrence of redds by dominant substrate type out of 120 redds.

Of the 130 redds within the reach, 96 of them (74%) were located within an area with suitable hydraulic conditions based upon two-dimensional modeling results; 123 (95%) were located within 15 feet of an area with suitable hydraulic conditions. It should be recalled that the numerical model grid within the channel was typically comprised of quadrilaterals ranging in size between 5-10 ft by 20-30 ft.

An investigation was completed to determine the association between those 96 redds within suitable hydraulic conditions and the dominant substrate type. Three of the redds were not located in a mapped facies as they were all constructed at the very edge of the low flow channel boundary. The results show little variation from the results of all 130 redds illustrated in figure 7, which is expected because most all the redds were located within the area defined as hydraulically suitable. A final statistical evaluation was performed using Jacob's electivity analysis to determine the preference of salmon to place redds within each dominant substrate type and within hydraulically suitable areas. Jacob's index was measured using the following formula:

$$D = (r - p)/(r + p - 2rp)$$

Where r represents the proportion of habitat used; p represents the proportion of habitat available, and D varies from -1 to 1, indicating a degree of preference for each habitat type (Hamann et al., 2014). A value of -1 indicates strong avoidance; a value of +1 indicates strong preference, and values approaching 0 suggest that the habitat is used in

proportion to its availability in the environment. The results and interpretation of the analysis are presented in table 4 and table 5.

Table 4 Results of electivity analysis indicating the degree of association of redds with hydraulic conditions.

	Jacob's Index	Interpretation
Hydraulically Suitable Area	0.9	Strong Preference
Non-hydraulically Suitable Area	-0.9	Strong Avoidance

Table 5 Results of electivity analysis indicating the degree of association of redds with dominant substrate type.

Dominant Substrate	Jacob's Index in total inundated area with mapped facies	Jacob's Index in hydraulically suitable area	Jacob's Index in non-hydraulically suitable area	Interpretation
Boulders	-1.0	-1.0	-1.0	Strong Avoidance
Bedrock	-0.5	-0.7	-0.2	Avoidance
Sand	-0.9	-0.9	-0.9	Strong Avoidance
Cobble	0.3	0.4	0.2	Mild Preference
Gravel	0.7	0.7	0.8	Preference
Silt	-1.0	-1.0	-1.0	Strong Avoidance
Cobble and Gravel	0.9	0.9	0.9	Strong Preference

CONCLUSIONS

Results of this effort provide supportive evidence for characterizing spawning habitat using hydraulic information gained from two-dimensional modeling and from substrate characterization. Based upon the hydraulic modeling effort, only 7.4% of the total inundated area was determined to be suitable for spawning. However, 74% of the redds surveyed within the last 2 years were located within these areas, and 95% were within 15 feet of these areas. These data suggest a strong correlation between the hydraulic conditions determined to be suitable for spawning using depth and velocity and between locations selected by salmon for redd construction. The results may also indicate that the current grid resolution captures the preferred spawning locations to within +/- 15 feet because the cell sizes within the channel were typically 5-10 ft wide by 20-30 ft long to limit model simulation time. A refined model at select locations may assist in further refining localized spawning preferences. However, the results also point towards the possible use of a buffer zone of approximately 15 feet around areas deemed suitable when a coarser-scale model is necessary to capture long reaches.

Redd data analyses reveal that salmon tend to spawn in gravel and cobble more frequently than other substrate. However, some fish selected to spawn in facies dominated by sand substrate. This may be partially attributed to the detail of the facies mapping. A benefit of the facies mapping is the ability to map long reaches of channel within a relatively short time frame. Patches of gravel and cobble are often present along channel margins or locally within the channel and may not be captured in the facies mapping. Refined mapping within mapped facies dominated by sands may improve the correlation between large substrate and redd construction location. Another possible explanation may be that salmon are less concerned with substrate than other factors when searching for a location to spawn, and the substrate is more important to defining incubation habitat and egg survival. Data from this effort could be used to develop preference curves for substrate for spawning salmon, in which sand and boulder substrate receive lower values than cobble and gravel substrates.

Examination of the dominant substrate within areas determined to be suitable for spawning based upon hydraulic conditions shows that even though gravel and cobble only represent a combined 36% of the total inundated area with mapped facies, 78% of the suitable hydraulic conditions are within gravel- and cobble- dominated substrate.

Similarly, the 96 redds within suitable hydraulic conditions were located in gravel- and cobble-dominated substrate 89% of the time. These data along with Jacob's electivity analysis results demonstrate a strong preference for redd sites to be located in suitable hydraulic conditions and in gravel- and cobble- dominated substrates. Clear correlations exists between substrate and suitable conditions for spawning, between redd sites and hydraulically suitable conditions, and between redd sites and gravel- and cobble-dominated substrate. From a common understanding of physical processes with the respect to the influence of hydraulic conditions on sediment transport and resultant substrate, the data from this exercise suggest that both hydraulic conditions and substrate are important in redd sites selection.

Finally, water temperature was also reviewed in this study to evaluate how it may limit the area considered suitable for spawning. Results suggest that water temperature may not limit spawning for Fall-run Chinook in most years because the temperatures, while not optimal, are below lethal in October, November, and December from Friant Dam downstream to HW 99 (~MP 243). However, the water temperatures may limit Spring-run Chinook spawning to the first 10 miles downstream from Friant Dam. These first 10 miles of the entire 24.5 mile reach encompasses 36.2 acres of suitable spawning habitat based upon depth and velocity, which represents 45% of the total suitable spawning area within Reach 1A.

STUDY DIRECTION

This current study presents a small fraction of the analysis necessary to eventually define the availability and quality of spawning and incubation habitat within Reach 1A. However, this step is important in determining that two-dimensional modeling results and substrate can indeed be used to help quantify available suitable spawning habitat. Additional analyses are planned to determine the applicability of mesohabitat maps in delineating potentially suitable spawning habitat. In addition to the reach-scale two-dimensional hydraulic modeling, finer-scale modeling of several riffles within Reach 1A is planned to identify the sensitivity of model results to refined topographic information and mesh resolution.

The quality of spawning and incubation habitat will be further distinguished through incorporation of findings from studies characterizing the hyporheic environment (DO, toxicity, temperature), vegetation and cover mapping, sediment mobility, substrate permeability, fine sediment accumulation within redds, egg survival, and escapement. One of the greatest challenges anticipated from this effort is the extrapolation of localized findings within one or several redds or riffle to the entire Reach 1A.

The ultimate goal of the larger-scale endeavor is the capability to predict the quantity and location of habitat meeting the needs of Chinook salmon to successfully complete their life cycle through spawning and incubation. Once the abundance or scarcity of suitable spawning and incubation habitat is determined based upon the anticipated fish use of the system, the limiting factors can be identified, and any means necessary to improve those conditions and the locations in need of improvement will be definable.

ACKNOWLEDGEMENTS

The authors of the paper express gratitude to all SJRRP members for their efforts in collecting and analyzing data related to spawning and incubation habitat that was used for this study. Erica Meyers was responsible for maintaining and evaluating the water temperature data as it relates to spawning and incubation, and Andy Shriver significantly contributed to the collection and GIS translation of the facies characterization. We are grateful to the SJRRP for continuing to support spawning habitat investigations, and appreciate the continued input by members of the Spawning and Incubation Subgroup.

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