SALMONID HABITAT ANALYSIS ON THE UPPER MOKELUMNE RIVER

Assessing the potential for Chinook salmon reintroduction above Pardee Dam

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EXECUTIVE SUMMARY

The Long-term goal of the Salmonid Restoration Team (SRT) is to *reestablish a successfully reproducing population of fall-run Chinook salmon and or central valley steelhead in the upper Mokelumne River*. To realize this goal, the SRT has developed interim, short-term goals and developed a pilot project to reintroduce small numbers of fall run Chinook salmon into the upper watershed to determine feasibility of transportation, reproduction and survival. Reintroduction of fall-run Chinook salmon to the Upper Mokelumne River offers an opportunity to provide access to over 27km (~17 miles) of historic habitat. The reintroduction of salmon to historical habitats may have profound cultural, economic and ecological benefits. Salmon are an integral part of West Coast culture, primarily with the native peoples of the Pacific Northwest and California and more recently, with hundreds of salmon festivals taking place each fall. Reintroducing salmon to historic habitats can potentially link cultures to lost traditions in the watershed. Since salmon attract people for viewing or fishing there could also be economic benefits related to ecotourism. Lastly, reintroducing salmon could have positive ecosystem-level impacts. Salmon are considered ecosystem engineers because their spawning activities can have profound impacts on everything from sediment distributions, intergravel permeability, and nutrient dynamics, to macroinvertebrate community structure. Salmon carcasses could provide a long-lost source of nutrients, including marine-derived nitrogen, to the upper watershed. In addition, salmon carcasses would also provide a high-calorie food source for local predators and scavengers including otters, bald eagles and black bears.

In this study we assessed the potential for the Upper Mokelumne River to support the SRT's short-term goal of implementing a fall-run reintroduction pilot study. The overarching goal of this study was to determine if available habitat within the study reaches, at the time of this study, could support key freshwater life stages of fall-run Chinook salmon needed for a successfully reproducing population. We assessed this broad goal by providing a qualitative assessment of adult spawning and juvenile rearing habitat present in the study reaches using a combination of remote sensing analysis and field data collection and analysis.

Overall, 4 out of the 6 study reaches (~22km) were found to have potential to support both adult and juvenile Chinook salmon. The Middle and North forks could provide some habitat but are outside the range of gradient commonly associated with Chinook salmon and geomorphic features needed for spawning. In two of the four suitable reaches, habitat quality was considered marginal to poor due to gravel deficiencies. However, enhancement opportunities exist to offset these deficiencies.

INTRODUCTION

Pacific salmon and trout (*Oncorhynchus* spp) have important economic, cultural and ecological value, and have historically supported robust fisheries on the Western United States. However, in the California Central Valley Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*) are at the southernmost extent of their North American range and have undergone significant decline in the past 180 years (Moyle et al. 2008). These declines are linked to a variety of anthropogenic impacts, including over-harvest, drastic reduction in habitat due to gold mining, logging, water diversion, hydropower and watershed development, flood control, water quality degradation, and species invasions (Yoshiyama et al. 1998, 2001, Williams 2006, Israel et al. 2011, Katz et al. 2012, Moyle and Mount 2007). Dam construction has prevented passage to important staging and spawning areas with greater impacts to spring-run Chinook Salmon (and *O. mykiss*) populations that historically made extensive use of higher elevation habitats (Moyle 2002, May and Brown 2002). In response to societal shifts in valuing salmonids, and concerns over climatic change, stakeholders have been considering whether passage above dams could improve salmonid populations (Lindley et al. 2007).

The Upper Mokelumne Salmonid Restoration Team (SRT) seeks to determine the feasibility of introducing native anadromous salmonids (e.g., fall-run Chinook salmon and steelhead) from below Camanche Dam to above Pardee Reservoir in an identified section of the Upper Mokelumne River with an initial focus on fall-run Chinook salmon (Figure 1). The area selected for reintroduction spans the head of Lake Pardee at Middle Bar Bridge (Figure 1) as a downstream boundary, and the historical natural limits of anadromy for salmon as the upstream boundary.

Before such actions are taken, the group wishes to understand the potential for the Upper Mokelumne River, in its present state, to support life stages of fall-run Chinook salmon expected to use this historic range. This will allow the SRT to determine the value of moving anadromous salmonids from below impassable Camanche and Pardee dams into the upper watershed in terms of spawning and rearing capacity and juvenile production. This assessment will help the SRT assess the viability of returning Chinook salmon (and anadromous *O. mykiss*) to the Upper Mokelumne River (Figure 1).

The overarching goal of this study was to determine if available habitat within the study reaches, at the time of this study, could support key freshwater life stages of fall-run Chinook salmon needed for a successfully reproducing population.

Specific study objectives were to:

1. Evaluate the intrinsic potential of each study reach for adult and juvenile fall-run Chinook salmon using available remotely sensed data
2. Use available aerial imagery to map the distribution of habitat units in the study segment
3. Verify and refine habitat units during a reconnaissance survey
4. Map geomorphic features such as gradient, channel and valley width
5. Collect physical data (depth, velocity, substrate, dissolved oxygen, temperature, cover type) at transects within each study reach
6. Note potential barriers to upstream adult migration during the field reconnaissance

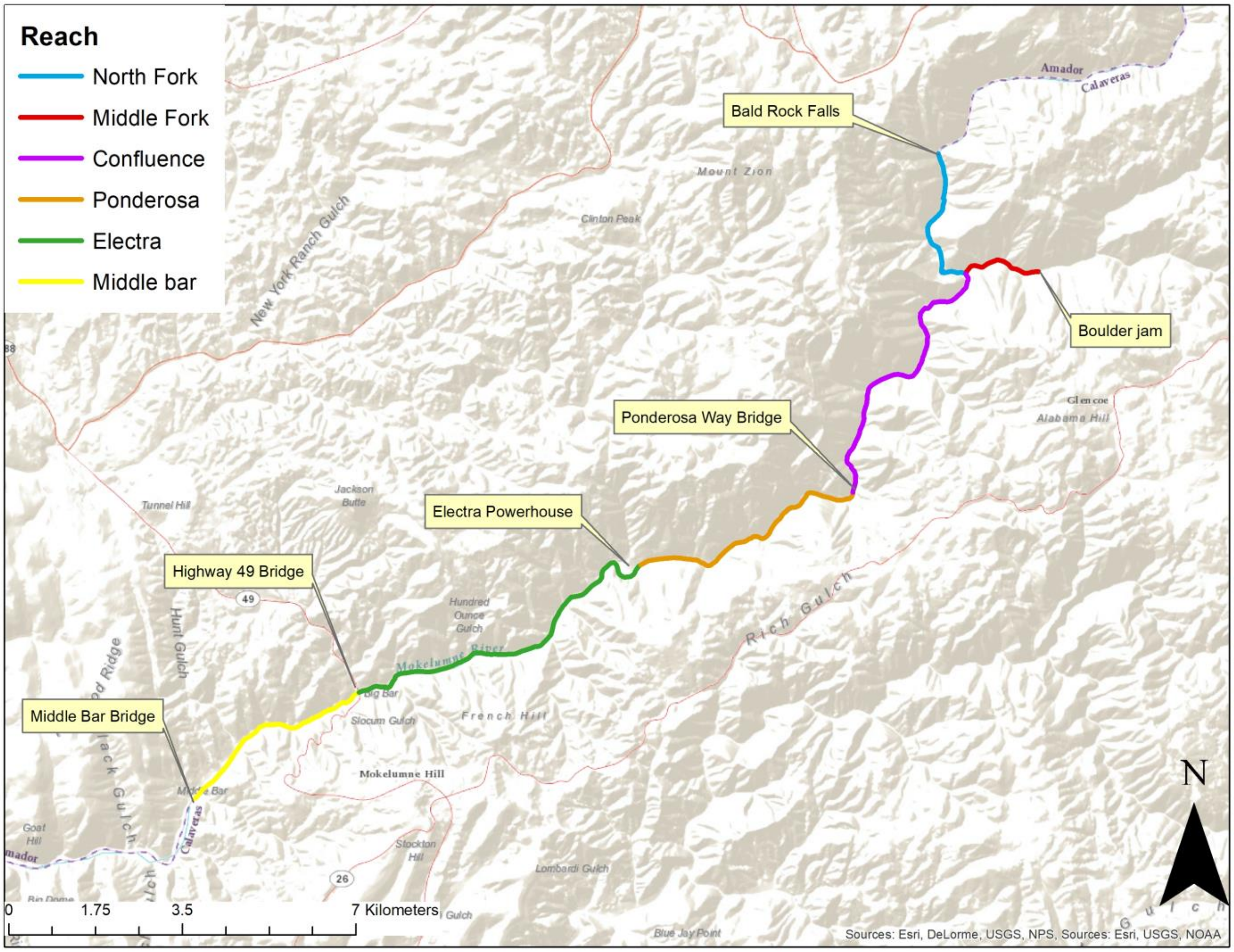

Figure 1. Study reaches within the reintroduction segment of the Upper Mokelumne River.

BACKGROUND

In this section we provide a background and literature review for the watershed setting, the fall-run Chinook salmon life cycle, and assessing salmon habitat. The purpose is to provide general background and context for those reading this report. A more extensive overview of the Upper Mokelumne River watershed can be found in RMC (2007).

Watershed setting

The Mokelumne River drains 5,550 sq. km (2,140 sq. mi) of the Sierra Nevada and California's Central Valley into the San Francisco Delta. The river is approximately 153 km long from its headwaters down to its confluence with the Delta. It is common to refer to the Lower Mokelumne River for sections below Camanche Dam, while the sections above Pardee Dam are referred to as the Upper Mokelumne River. The Upper Mokelumne River watershed branches into three primary forks: the North Fork and the Middle Fork, which branches and includes the South Fork. The North Fork begins at an elevation of approximately 2,616 m, while the Middle Fork begins at roughly 2100 m.

Basin geology within the study area consists primarily of four geologic units ranging from Mesozoic granitic and volcanic rocks, Jurassic marine rocks, and Paleozoic marine rocks. The study reaches predominantly pass through Paleozoic marine rocks; with Jurassic marine rocks and Mesozoic volcanic rocks being constrained to the lower half of the Middle Bar reach. Portions of the Electra, Ponderosa and Middle Fork reaches pass through Mesozoic granitic rocks. The entire North Fork and Confluence reaches both pass through Paleozoic marine rocks. Dominant vegetation biomes within the study reaches consist of oak woodlands in the lower reaches and mixed conifers in the upper reaches.

Basin hydrology is dominated by a Mediterranean climate, orographic effects of the Sierra Nevada and water infrastructure. Natural flows are generally low in the fall, followed by winter precipitation in the form of rain in lower elevations and snowfall at higher elevations. As in many Sierra Nevada Rivers and streams the spring snowmelt component on the hydrograph can lead to sustained high flows that last into early summer. The basin supports a variety of water uses including agricultural, urban, power generation, and recreational. The North Fork has two major reservoirs, Salt Springs Reservoir and Tiger Creek Afterbay Reservoir. The Middle fork has Schaads Reservoir, and the South Fork has no major reservoirs. At the top of the Electra Reach is the Electra Powerhouse that generates power by fluctuating flows with water supplied by Lake Tabeaud. Water supply and power generation in the upper watershed are discussed in RMC (2007).

It is important to note that much of the Mokelumne watershed has been in some state of alteration since at least the mid-1800's, decades before flow regulation and infrastructure were implemented (BLM 2007). Therefore, while the current potential for habitat to support each salmon life stage can be evaluated, large scale impacts beyond barriers should be evaluated as to their potential to reduce the availability of habitat in the future if reintroduction was deemed appropriate.

Focal Species

Fall-run Chinook salmon lifecycle

Central Valley (CV) fall-run Chinook salmon are anadromous and therefore spend most of their life cycle in the coastal ocean waters of the Pacific United States but must return to freshwater to reproduce. In general, distinct life stages, including migration into and out of specific habitats occur during specific time periods (Figure 2).

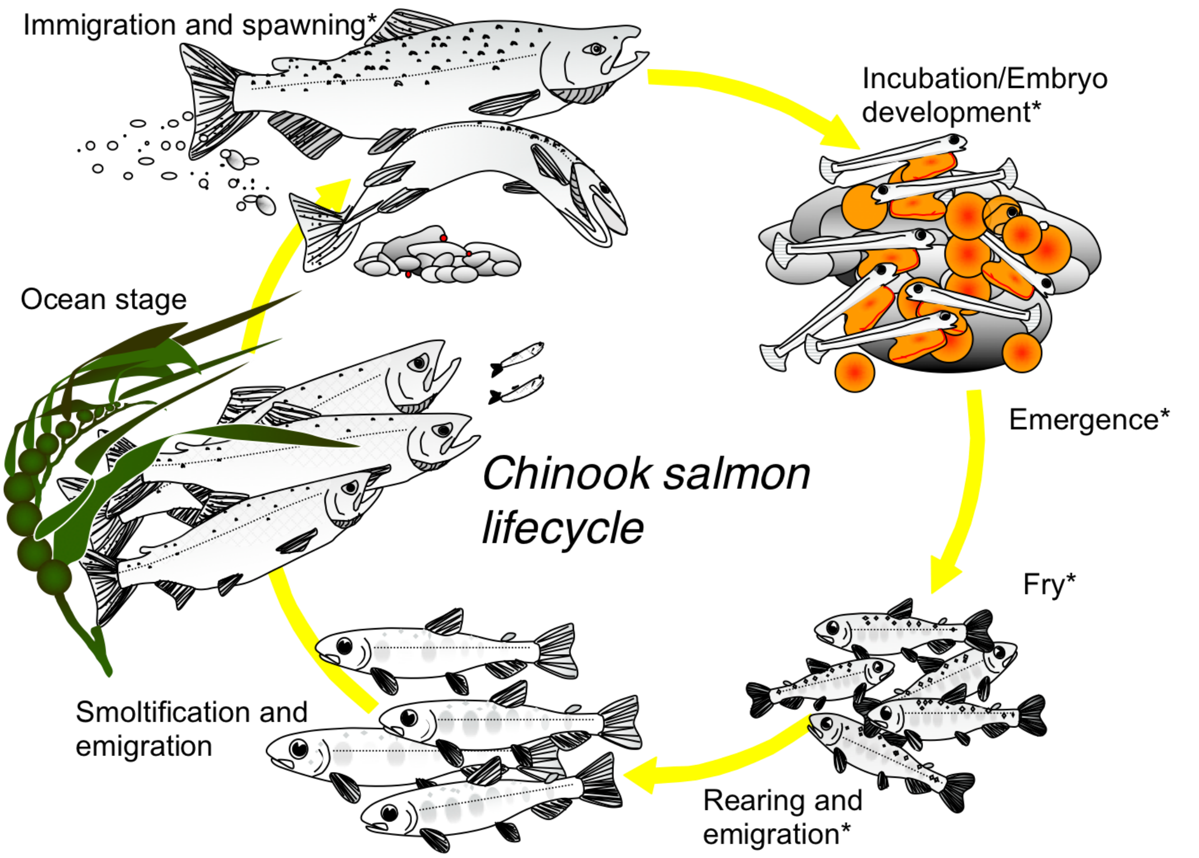

Figure 2. Generalized lifecycle of Central Valley fall-run Chinook salmon. *Indicates key lifestages expected to be supported in the Upper Mokelumne River watershed. Modified from Merz et al. (2015).

Comprehensive descriptions of CV Chinook salmon life stages are given by Moyle (2002) and Williams (2006). Here we summarize the general fall-run Chinook salmon lifecycle for Central Valley Rivers (Figure 3).

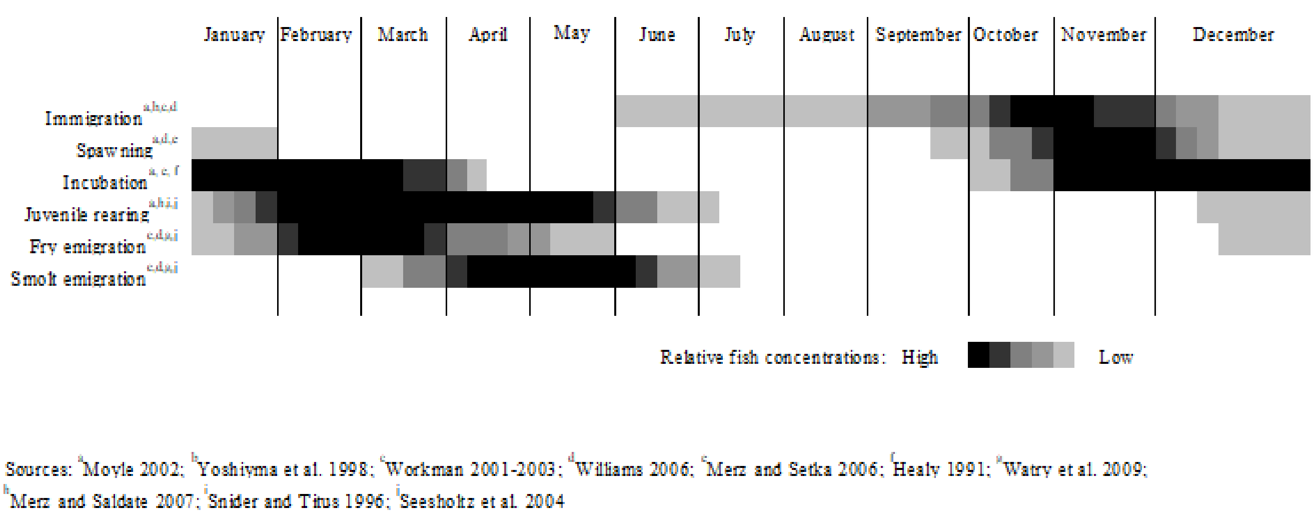

Figure 3. Generalized life-history timing for Central Valley fall-run Chinook salmon (taken from Merz et al. 2015).

Upstream Adults

Although cues that trigger adults to return to spawning grounds are not well understood, it is thought that the ability to find their way is related mainly to long-term olfaction memory (Dittman and Quinn 1996). Homing ability within fresh water also may be aided by vision (Healey 1991), and by celestial and magnetic compass orientation (Quinn 1980) and may be stimulated by changes in streamflow, turbidity, temperature, and oxygen content (Allen and Hassler 1986). Numerous factors, such as predation, harvest, and water quality affect an adult's ability to reach spawning areas and spawn successfully (Hillemeier 1999, Beamesderfer 2000, Goniea et al. 2006). The ability to return to natal watersheds is further affected by anthropogenic effects such as water diversion structures, channel modification, and water quality (Fisher et al. 1991). During immigration, adults stop feeding and subsist on body fat reserves.

Spawning

During spawning, the female constructs an area containing several individual egg pockets called a redd or nest by turning on her side and repeatedly flexing her body to force fine sediment into the water column. This action coarsens the spawning substrate, forming an oval depression with a mound of bed material located immediately downstream (Crisp and Carling 1989). Often, several males will court and fertilize the eggs of a single female. Chinook salmon are semelparous, meaning they spawn once and then die, although individuals may survive for days to weeks after spawning.

In general, Chinook are thought to select spawning locations based primarily upon substrate, channel hydraulics and proximity to cover and resting areas. Substrates required for spawning are river-rounded gravels, with median particle diameter up to about 10% of their body length (Kondolf and Wolman 1993). Newer research has shown linkages between fork length and particle size distribution (Riebe et al 2014). Habitat suitability for spawning adults suggests that velocities ranging from 20 to 100 cm/sec (0.65 – 3.28 feet/sec) and depths ranging from 15 to 35 cm (6 – 14 inches) are most preferable (Bjorn and Reiser 1991). Aquatic vegetation may alter the quality of habitat and subsequent use by spawning females (Merz et al. 2008). Proximity to cover and flow shear zones provides important refuge from predation and resting zones for energy conservation (Merz 2001, Wheaton et al. 2004).

Incubation and Emergence

Female salmon bury fertilized eggs in the redd where the embryos develop in gravel interstices. Incubation generally lasts from 40 to 90 days at water temperatures of 4.4 °C to 12.2 °C (40-54ºF) (Bams 1970, Heming 1982, Bjornn and Reiser 1991, Geist et al. 2006). Alevins, newly hatched salmon, may remain in the gravel for 4 to 6 weeks after hatching, receiving nutrients and energy from their yolk sac before emerging to the water column (Moyle 2002). Incubation is highly dependent on water temperature, dissolved oxygen (DO), and substrate permeability (Merz et al. 2004). Spawning gravel must be sufficiently free of fine sediment to allow permeating water to transport DO to and metabolic wastes away from incubating embryos, while not hindering emergence of fry from the gravel (Tappel and Bjornn 1983 and see discussions in Chevalier et al. 1984 and Groot and Margolis 1991). Other water quality related parameters (e.g., disease, contaminants) can further affect embryo development and survival to emergence (Merz et al. 2006).

Juvenile Rearing

Juvenile salmonids transition through numerous habitats during their rearing development and eventual emigration (Merz et al. 2016). Newly emerged young are often found in shallow, slow-moving water and transition to deeper, faster water as they increase in size (see Cramer and Ackerman 2009). Habitat complexity (e.g., woody debris, overhanging vegetation, seasonally inundated areas) provides juvenile hiding, resting, and feeding habitat, increasing their ability to grow, develop, and survive emigration. Juvenile diets often vary by habitat type, but terrestrial and aquatic invertebrates, and larval fish and eggs are important prey for juvenile salmon upstream of the Delta (Sasaki 1966, Merz and Vanicek 1996, Sommer et al. 2001). Prey size and ingestion rates are affected by juvenile size and water temperature (Merz 2002). At times, floodplains and secondary channels may provide better juvenile rearing opportunities because they often create optimum temperatures, offer habitats rich in prey items and away from salmon predators, and provide refuge from high, relatively cool flows (Sommer et al. 2001, Jeffres et al. 2008, Merz et al. 2016). Habitat availability, water quality, and predation are examples of environmental parameters that can affect successful rearing (Lindley and Mohr 2003).

Edge and bank habitats that support structure such as wood, undercut banks, and young vegetation, provide improved conditions for rearing juvenile salmonids (Beechie et al. 2005, Sellheim et al. 2016). In many salmon-bearing streams, edge and bank habitats support higher densities of rearing salmonids because the prey availability and hydraulic conditions facilitate enhanced growth opportunities and provide refugia from predators (Bartz et al. 2006, Cramer and Ackerman 2009). Here we define edge and bank habitat ('edge habitat' for brevity) as the portion of wetted channel extending from the riverbank to a maximum depth of 0.7m (2.3 ft.) (Beamer and Henderson 1998, Beechie et al. 2005).

Emigration

The timing and stimuli for emigrants to leave a natal stream depends on individual genetics, social cues, and the environmental factors to which individuals are exposed as they emerge, rear, and migrate downstream (Zeug et al. 2014). Within the Central Valley, Chinook salmon emigration size varies widely. For example, juvenile fall-run emigrate as fry (<55 mm fork length [FL]), parr (≥55 mm FL and <75 mm FL), or smolts (≥75 mm FL) (Brandes and McLain 2001, Williams 2001). In some systems, including the lower Mokelumne River, the proportion of salmon leaving as fry, parr, or smolts may shift from year to year (Merz et al. 2015). Though several researchers have questioned if fry migrants make a significant contribution to adult populations (Brandes and McLain 2001, Williams 2001), Miller et al. (2010) empirically demonstrated that Central Valley fry-sized emigrants represent a viable life history strategy. Flow, temperature, water quality, diversion, and predation have been implicated as key parameters that affect successful emigration (Cavallo et al. 2012).

Watershed influence on salmon habitat availability

A fundamental aspect of riverine systems is that they are hierarchical in nature, with smaller objects nested within larger ones (De Boer 1992). Generally, this hierarchy begins at the largest scale of a watershed, and is followed by segments (~10^3 -10^4 mean channel widths), reaches (~10^2 -10^3 mean channel widths), morphologic units (~1 -10 mean channel widths) and microhabitat (<1 mean channel width). Segments may contain multiple reaches, and reaches are comprised of mesohabitat units and so on down the hierarchy. Given the hierarchical nature of geomorphic systems, watershed characteristics influence the types of geomorphic units within reaches and segments, and thus the types of salmonid habitat available (Figure 4).

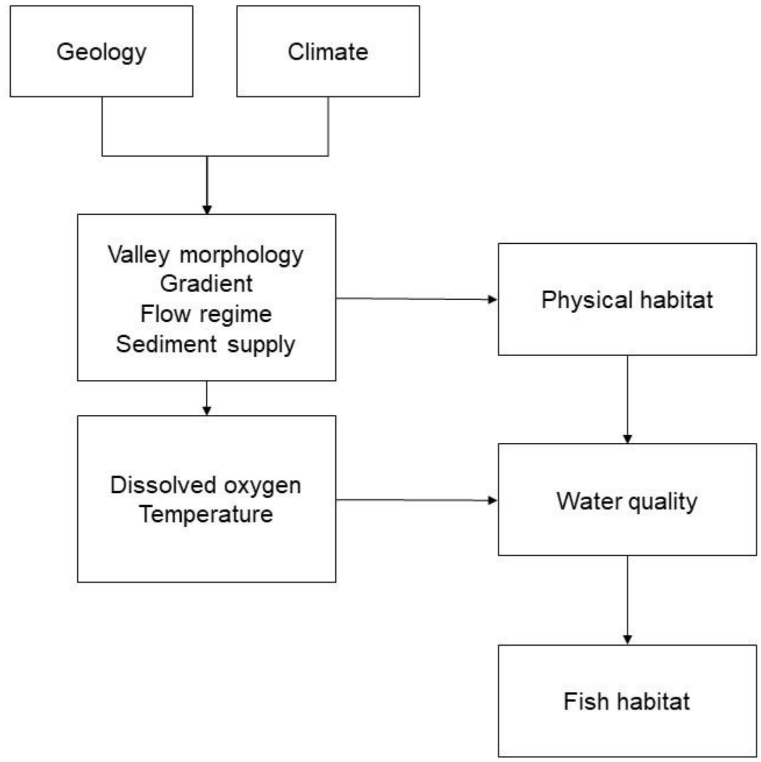

Figure 4. Generalized relationship of natural watershed inputs to channel processes, channel form, habitat characteristics, and salmon. Note that human disturbance can impact any part of the hierarchy and modify habitat.

Watershed characteristics influence river and stream morphology, and this in turn controls the available physical habitat (Montgomery et al. 1999, Buffington et al. 2004, May et al. 2013). Watershed scale geologic and geomorphic forms control the location of salmonid spawning within watersheds, segments and reaches. At the basin scale, geologic controls on the presence of bedrock, channel gradient, lateral confinement, hydrologic regime and sediment supply all interact to produce the physical template for salmonid habitat (Montgomery 2007, Figure 4). For example, it has been demonstrated that stream slope can control both substrate size and depth of scour, thus controlling salmonid species distribution in watersheds (Montgomery et al. 1999, Buffington et al. 2004). Generally, Chinook salmon spawn in reaches with pool-riffle bedforms and gravel substrate where microhabitat is preferential. The literature from fluvial geomorphology places an approximate limit to reach averaged gradient of 2% for riffle-pool reaches (Leopold et al. 1964, Ikeda 1977, Florsheim 1985, Sear 1996, Wohl 2000). Steeper gradients up to ~4% can accommodate these bedforms if sediment supply is relatively high and/or there is also an abundance of woody debris (Massong and Montgomery 2000).

Within segments and reaches, geologic controls such as valley width can influence the storage or transport of alluvium (i.e., unconsolidated sediment), and thus valley and channel morphology, and fish habitat (Grant et al. 1990, Grant and Swanson 1995, McDowell 2001, McKean et al 2008, May et al. 2013). Because spawning and incubating Chinook salmon require predominantly gravel-cobble substrates of ~2-128 mm diameter (~1-5 inches), those substrates' availability and storage within the river are important factors in determining reach-scale habitat suitability. At the reach scale, two primary physical river corridor variables exert strong controls on the storage of spawning gravels. First, channel gradient, or slope, controls the transformation of potential and kinetic energy of flowing water, and thus the amount and size of sediment transported or stored. As a basic example, consider that for all other variables being equal a lower slope river will have finer bed sediments compared to a steeper river.

Second, the amount of lateral space for flowing water to expand (or contract) in a river corridor further modulates sediment transport and storage. Consider the relative impacts of changes in valley width on sediment being transported by flowing water in a river corridor. If the valley widens, or contracts, then there is more, or less area for flow, causing a decrease, or increase, in average flow velocity and thus sediment transport.

While gravel supply is important, it must be organized into meso-scale channel units that can facilitate fluvial forms that provide habitat. Channel and valley morphologic forms such as alluvial bars, riffles and pools are well documented in controlling the spatial distribution of salmonid redds (Geist and Dauble 1998, Dauble and Geist 2000, Hanrahan 2007). Riffle bedforms are thought to be the dominant mesohabitat form associated with spawning salmon. This typically occurs on the upstream side of the riffle, which can be identified as run, glide or pool habitat, depending on stream size and flow stage. For example, Hanrahan (2007) found that 84% of fall-run Chinook salmon redds on the Snake River were associated with riffles. Salmon do not always spawn on the fast portion of the riffle, but usually on the upstream side above where water velocity increases (Hanrahan 2007). Riffle habitat is important because these types of forms can create physical and water quality microhabitat needed for spawning and incubation (Bjorn and Reiser 1991, Geist and Dauble 1998).

Juvenile salmon tend to rear in shallow water habitat, which can take the physical form of stream margins, off-channel habitats, adjacent wetlands and ponds, and floodplains. These habitats are predominantly found in low-gradient river reaches that are unconfined so that flow, sediment and woody material can spread out. Complexity is important in providing energy refugia and escape from predators, as well as providing opportunity to access food and shelter, within any of these habitat types.

Anthropogenic influences on habitat potential

While it is important to identify watershed controls on habitat potential, past and present human activity can disrupt or degrade physical processes that shape and maintain habitat. Human activities such as logging, road construction, gold and gravel mining, dam construction, flow regulation, and urban and agricultural development can all affect watershed processes and degrade habitat. For example, logging of a watershed can reduce the amount of woody material supplied to river corridors. This can in turn reduce channel roughness and sediment storage leading to channel bed incision and a simplification of habitat. Dams are widely known to impact natural processes through alterations to flow and sediment to downstream environs (Moyle and Mount 2007). In California, there have been significant alterations to the timing and magnitude of flow, affecting native fish communities (Brown and Ford 2002, Brown and Bauer 2010, Zimmerman et al. 2017). Another example is gold mining, a prevalent activity in the Sierra Nevada, where vast amounts of alluvium were removed from riverbeds, hillsides and terraces (James 1994). These activities generally denuded landscapes at rates much higher than background geomorphic processes (James 1999). It is not known exactly how much these activities affected anadromous fish. It is likely that erosion in Sierra Nevada Rivers and streams degraded habitat in these areas, and that elevated amounts of sediment likely buried historical spawning beds in lowlands where sediment was temporarily stored. For example, the Lower Yuba River aggraded over 20 m (66 ft.) in some areas from upstream hydraulic mining (James 2009). Human history, especially in California, is ripe with examples of anthropogenic impacts on watershed processes and physical habitat for salmon. Given that most, if not all, watersheds in California have some form of human alteration it is important to view any present-day conditions as possibly affected by historical alterations.

Assessing rivers for suitable salmon physical habitat

Generally, salmonid habitat assessments are done to gage past, present or future potential of a river corridor to support salmonids. This is usually focused on the spawning life stage, since it limits subsequent production in the watershed (e.g. Wheaton et al. 2004). Beyond the spawning life cycle physical habitat for rearing salmonids is commonly assessed by the amount of slow-moving shallow edge habitat as well as off-channel habitat and edge and bank habitats that support structure such as wood, undercut banks, and young vegetation, following that the above requirements have been met for the adult spawning life stage.

Since the 1990s there have been numerous habitat unit classifications developed to assess aquatic habitat, especially for salmonids. Bisson et al (1992) and Hawkins et al (1996) developed a tiered classification system for assessing habitat for salmonids in low water conditions. The system has three levels, where level one is discriminated based on water speed, level two based on flow characteristics, and level three consisting of 18 different units. The California Department of Fish and Wildlife uses this approach in their habitat inventory methods (CDFW 1998). Rosgen (1996) developed a coded classification system that while gaining popularity amongst practitioners, has also been criticized in the peer-reviewed literature for not being based on fundamental processes that create and shape rivers and streams (Simon et al. 2007). Grant et al (1990) developed and applied a hierarchical classification for steep mountain streams. Their classification included pool, riffle, rapid, cascade, and step morphologic units. They found that the presence of different units was related to watershed setting and processes that control the supply and storage of sediment. Further, each unit had associations with channel gradient. Montgomery and Buffington (1997) developed a reach scale classification system for mountain rivers. Under this classification system there are dune-ripple, plane bed, riffle-pool, step-pool and cascade reach types. Each of these types generally organized following a longitudinal gradient of decreased relative transport capacity with decreasing average bed slope. This means that steeper reaches are generally coarser grained because the supply of sediment is relatively low, but the transport of sediment is relatively high, whereas for lower reaches the opposite is generally true.

The common method to map habitat units was to delineate unit start and end points by field survey, recognizing that clear boundaries do not always exist. More recently, advances in the collection of remotely sensed data such as aerial imagery and LiDAR (Light detection and ranging) have facilitated mapping approaches based on imagery (Winterbottom and Gilvear 1997, Harby et al. 2007, Demarchi 2016), 2D numerical models (Wyrick et al. 2014), topography or combinations thereof.

Gradient, valley width, and drainage area have been used to model spawning gravel availability (Buffington et al. 2004, Wilkins and Snyder 2011, Pfeiffer and Finnegan 2016). Valley width and confinement also has been used to study and delineate channel morphology and salmon habitat (Grant et al. 1990, Grant and Swanson 1995, McDowell 2001, May et al. 2013). Similar work has followed, using the concept of "intrinsic potential" for other salmonid life stages such as juvenile rearing (Burnett et al. 2007). Intrinsic potential modeling uses landscape scale variables to assess the viability of salmon utilizing a river reach. Intrinsic potential modeling has been performed for Chinook salmon spawning and rearing on the Western United States (Agrawal et al. 2005, Busch et al. 2011). Three basic variables are used in this approach including reach gradient, channel width and a confinement ratio (valley width divided by channel width). For gradient, almost all literature for fall-run Chinook salmon suggests they preferentially spawn in gradients less than 2%. However, spawning in steeper reaches is possible but the suitability approaches zero at approximately 4%, which is considered the upper limit of forced-pool morphology. Channel width suitability under intrinsic potential is expressed simply as being 0 for channels less than 4 m (13 ft.), and greater than 1 for channels 20 m (65 ft.) or wider ((Busch et al 2011). Channel confinement is thought to represent complexity of habitat, as in wider areas of a river corridor have more space for a diversity of lateral habitat units. The intrinsic potential suitability for confinement is that values equal to 1 have a value of 0.25, while values greater than 8 have a value of 1 (Busch et al, 2011). Intrinsic potential suitability curves represent probable suitability and shouldn't be used as "hard" thresholds. For example, Dauble and Geist (2000) show that fall-run Chinook salmon spawn in confined canyon reaches, but at lower densities compared to unconfined reaches. Similarly, Montgomery et al (1999) report Chinook spawning in reaches that have gradients above 2%, but in lower densities compared to lower gradient reaches.

STUDY AREA

The study area is a segment (e.g. multiple reaches) of the Upper Mokelumne River beginning at the Middle Bar Bridge and extending upstream to the North and Middle forks, totaling ~27.2 km (~17 miles) (Figure 1). The Middle Bar Bridge is the downstream limit because it represents the head of Lake Pardee. Further, it is currently assumed that any reintroduction efforts would release adult fish and collect juvenile fish in this general area. The upstream limits of the study segment were determined by the presence of natural barriers for adult Chinook salmon. Boyd (2014) suggests that Bald Rock Falls is the upstream limit on the North Fork, while a boulder jam is the upstream limit on the Middle Fork.

Within this study segment of the Upper Mokelumne River, six reaches were delineated by the SRT as defined below. River kilometer stationing used here begins at the Middle Bar Bridge and extends upstream through the North Fork, while the stationing for the Middle Fork starts again at zero at the confluence.

The Middle Bar Reach extends from the Middle Bar Bridge (~rKm 0) to the Highway 49 bridge (~rKm 4.2), covering approximately 4.2km (2.6 miles).

The Electra Reach extends from the Highway 49 Bridge upstream 7.15 km (4.4 miles) to the Electra Powerhouse (~rKm 11.35).

The Ponderosa Reach extends from the Electra Powerhouse upstream ~5.1 km (3 miles) the Ponderosa Way Bridge (~rKm 16.45), which is now defunct and previously connected Ponderosa Way to the northern side of the river.

The Confluence Reach extends from Ponderosa Way Bridge upstream ~6 km (3.7 miles) to the confluence with the North and Middle forks (~rKm 22.45). Show on map?

The North Fork Reach extends from the Confluence with the Middle Fork upstream approximately 3.15 km (~2 miles) to Bald Rock Falls (~rKm 25.6), considered the upstream limit to anadromy (see Boyd 2014).

The Middle Fork Reach extends from the Confluence with the North Fork upstream approximately 1.7 km (~1 mile) to a boulder jam (~rKm 1.7), considered the upstream limit to anadromy (see Boyd 2014).

STUDY APPROACH

The overarching question for this study was if available habitat in the study segment could support key freshwater life stages of fall-run Chinook salmon needed for a successfully reproducing population, as measured at the time of the study. The two key life stages are adult spawning, and juvenile rearing and emigration, so the study approach focused on evaluating the study segment for the potential to support both adult and juvenile fish. To answer the overall study question we developed three general criteria (Figure 5). We assumed that it was feasible that adult fish could be successfully transported to the Middle Bar Bridge area, and that juvenile fish could be collected in the same location. Assumptions related to successful trap and haul of either adults or juveniles are not considered here.

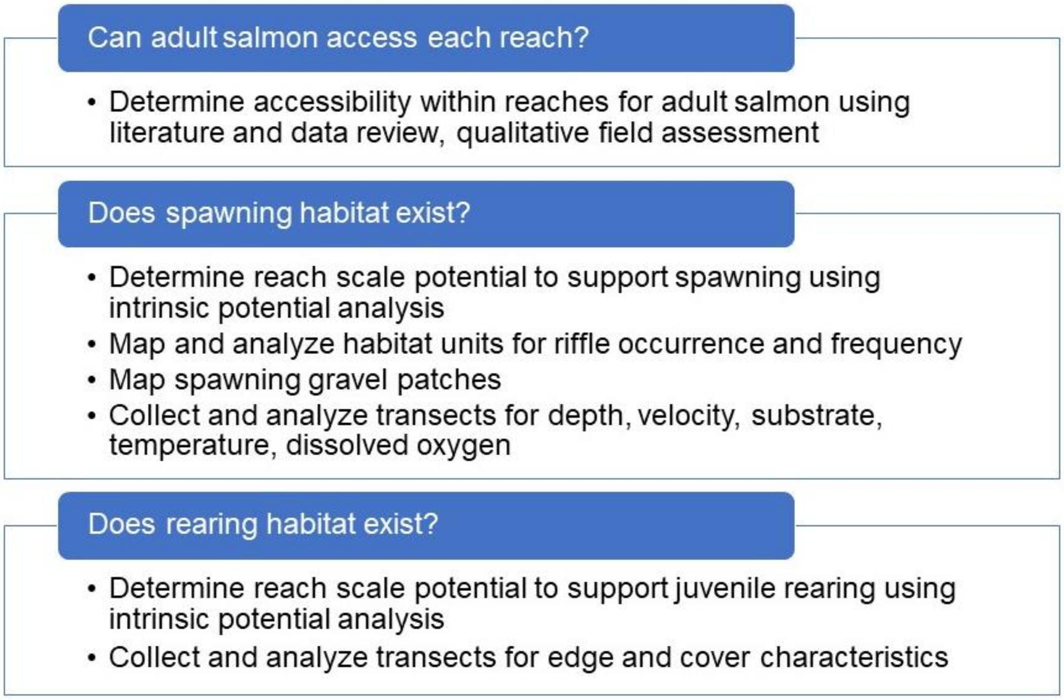

Figure 5. Criterion and approach used to answer overall study question

First we reasoned that for a population to successfully reproduce fish must have access to habitat that supports each life stage. However, it is also important to note that although an individual life stage may not have the capabilities to access a required habitat, a previous life stage may facilitate this access (e.g., adult salmon negotiating a waterfall that subsequent juveniles could not). Although the upstream study limits are thought to coincide with the historical limits of anadromy, we mapped any features thought to constitute a potential barrier to upstream migration. This included consultation of a state database for fish barriers (http://www.calfish.org/pad) and noting potential barriers to upstream adult migration using professional judgment during field surveys.

If fish can access reaches, those reaches need to contain the types of habitat features required to support spawning and rearing life stages. For both spawning and rearing habitat, we used the concept of intrinsic potential to evaluate reach scale habitat suitability. As discussed above in the background section. This type of modeling uses simplified curves of habitat suitability for landform characteristics such as gradient and confinement. This approach is prudent because it relates physical characteristics of a watershed to the potential for a reach to support a given species or life stage. Intrinsic potential analyses are appropriate for reach scale evaluations, but do not explain local variation. To account for this, we delineated habitat units and collected transect data at the head of riffle, rapid and cascade units.

To assess spawning habitat potential, habitat units were collected to analyze riffle abundance and frequency within reaches and throughout the study area, since adult salmon use these types of reaches primarily for spawning. During field surveys we also noted and mapped patches of suitable gravel that were greater than the average redd size for Chinook salmon. This was done to note potential areas of suitable substrate that did not coincide with transect locations. Transect data were used to provide snapshots of local micro habitat that could not be gleaned from aerial photography and publicly available digital elevation models. Parameters collected at transects to evaluate spawning habitat included depth, velocity, substrate, temperature and dissolved oxygen. Depth, velocity, and substrate are three physical parameters known to influence redd site selection, while temperature and dissolved oxygen are important parameters that affect the ability of a fish to successfully spawn.

To determine if rearing habitat is present we also used intrinsic potential modeling to evaluate reach scale suitability for juvenile Chinook salmon. In addition to the parameters above we collected edge-to-cover information to evaluate areas upstream of transects for juvenile rearing habitat.

To evaluate each criterion, a tiered approach using a combination of remote sensing, field data collection, and desktop analysis was used that we could complete in a relatively short period (~3 months). First, a literature review was conducted related to habitat mapping, salmonid habitat suitability, intrinsic potential curves for Chinook salmon and the Mokelumne River watershed above Pardee Reservoir. Next, available remotely sensed data such as digital elevation models (DEMs) and aerial photography were used to classify habitat unit types and estimate channel and valley width. Following this, field studies were performed to verify habitat units along with more detailed transect measurements of relevant parameters. Finally, all data were compiled and analyzed.

METHODS

Determine potential accessible limits of adult Chinook salmon

While overall limits of anadromy were determined by Boyd (2014) we also visually identified other potential barriers within the study segment. First, we consulted the California Passage Assessment Database (http://www.calfish.org/pad) and noted any features within the limits of the study area. Second, our biologist noted drops over cascade and rapid habitat units that could possibly prevent upstream passage during survey conditions. Where possible, we photographed such features with a stadia rod for context. Safety conditions and available time precluded measurements of drop height and pool depth.

Determine if reaches could support adult spawning and juvenile rearing using intrinsic potential

For accessible reaches, we evaluated whether adult fish could spawn using intrinsic potential modeling of gradient, channel width and confinement. We also calculated the intrinsic potential of each reach for juvenile salmon rearing using gradient and confinement. If a reach had a medium-to-high potential for both spawning and juvenile rearing, we considered the reach to have intrinsic potential to support salmonids. If a reach had intrinsic potential for rearing but was located above a reach suitable for spawning, it was not considered suitable. This is because juvenile fall-run Chinook salmon do not commonly migrate upstream into more energetically demanding habitats if adequate habitat exists where they emerge.

Using reach-averaged physical variables such as gradient, channel width and the confinement ratio (described below) we used two intrinsic potential models for Chinook salmon to evaluate reach scale habitat suitability. For adult Chinook salmon we used the curves of Busch et al. (2011), which uses all three variables. For juvenile Chinook salmon we used the curves of Agrawal et al. (2005), which only uses gradient and confinement. Once a score was developed for each variable for each reach we computed the geometric mean. Habitat suitability was assessed using three bins: 0 – 0.3 low, 0.31 to 0.7 medium, and >0.7 high.

Channel and valley width mapping

Initially we used an image classification approach to classify wetted versus non-wetted areas of the image. Due to shadows in confined regions, as well as glare, it was impossible to use this method without user input. The 2016 PG&E imagery did not have significant canyon shade or glare, so that data set was used as an initial polygon for inundation. Using these data as a starting point we manually adjusted the inundation extents to match the 2010 PG&E imagery. To provide an estimate of high flow inundation we manually digitized wetted extents using Google Earth imagery from 28 June 2017. Flow data for the study reaches was available only for Electra and Middle Bar. For the other reaches we visually confirmed that flow was higher for the June 2017 imagery than any other available images. While the exact flow value was not known, it was considered "high" based on available imagery and flow data. A coarse analysis of annual flow data for the North Fork, Middle Fork and Mokelumne River at Highway 49 suggests these flows had recurrence intervals ranging from 1.4 to 3 years. Thus, the "high flow" width series was used as a surrogate for bankfull width. To generate a valley width extent through the river corridor, we tried several GIS toolboxes that automate valley corridor delineation using a digital elevation model (DEM). Unfortunately, none of the automated tools performed well enough to generate a valley width. Therefore, we delineated the valley width based on field data, visual inspection of the 10m DEM as well as features in the aerial photographs. Once valley wall limits were defined a valley width polygon was created. Using the centerline, cross sections of 500 ft. long station lines were created and clipped to the inundation limits for the 2010 PG&E imagery, which was our base flow condition, and June 2017 Google Earth imagery, our surrogate for bankfull conditions, and the valley walls. Using these data, basic statistics for channel and valley widths were calculated as well as a confinement ratio, which is the ratio of valley to base flow width.

Gradient

We estimated reach-averaged gradient using three different data sets. First, we manually recorded the elevation in Google Earth at each of the reach breaks, calculating gradient as the change in elevation over the change in distance. Next, using a 10-m digital elevation model (DEM) from the national elevation dataset (NED), elevation was extracted along each centerline at ~60 m interval. Lastly, we spatially referenced GPS-derived elevations from the habitat typing in the field. While the absolute elevation of any one point may not be correct, it is assumed that the error is distributed evenly across all points. For the last two methods, gradient was calculated by fitting a linear trend to each reach. Ultimately, we used the field-based estimates of gradient instead of DEM based estimates since the latter tends to underestimate gradient. This is because steeper channels tend to have vertical drops that are much smaller than the resolution of a 10 m DEM.

Map and analyze habitat units to determine if spawning habitat exists

Habitat unit classification system

Numerous habitat unit classification systems exist for stream assessments. For this study, it is important that the classification system used be applicable to both low-gradient and high-gradient rivers. Further, the classification system used should have enough fidelity to discern habitat units used by Chinook salmon, but not more than what can be categorized based on remotely sensed data and limited field observations. Therefore, mesohabitat units were selected to 1) provide an assessment of the potential habitat types for fall-run Chinook salmon, and 2) to provide context for the geomorphic landscape setting of each reach. We defined five primary habitat units for this study including pools, flatwater, riffles, , rapids and cascades. Below is a description of each habitat type.

Pools are usually easily identified as a low-flow depression, having relatively high-water depths, low velocities and water surface gradient (Leopold et al. 1964, Keller 1971, Grant et al. 1990). In some cases, such as bedrock or forced pools, conditions can exist where water velocity and water surface gradient is still relatively high at lower flows. Pool spacing in streams generally is within 5-7 average bankfull channel widths (Keller and Melhorn 1978). This range can be the result of random obstructions such as large wood, boulders or bedrock (e.g. forced pools, Buffington et al. 2002, Thompson 2001), or as an expression of freely formed, semi-rhythmic riffle-pool topography (e.g. free pools, Leopold et al. 1964, Keller 1971).

In terms of depth criteria for pool depth, Montgomery et al. (1995) defined a pool as having a depth much greater than the median particle size, and a residual pool depth of at least 25% the average bankfull depth. Usually, bankfull depth is not known a priori in field studies, so a general depth limit is usually assumed. Lisle and Hilton (1992) use the following criteria: a nearly horizontal water surface (slope < 0.00005) during low flows, occupies the main part of the channel, and has a maximum residual depth equal to at least twice the water depth at the downstream riffle crest during low flow. Pools are important holding habitats for adult Chinook salmon, and if sufficient bank and cover characteristic are present juvenile Chinook salmon can utilize pool margins for rearing (Bjorn and Reiser, 1991).

Flatwaters consist of runs or glides and are areas of relatively uniform width and depth, and have average water depths and velocities. They can have a relatively featureless channel bed but may include isolated boulder roughness elements (Wohl et al., 1993, Halwas and Church, 2002, Sear and Newson, 2004, Thompson, 2013). They are differentiated in that glides commonly have uniform and average depths with no turbulent flow, while runs having slightly greater velocities and minor turbulence and surface wave undulations. If sufficient bank and cover characteristic are present juvenile Chinook salmon can utilize flatwater margins for rearing. Similarly, adult Chinook salmon can hold in flatwaters, provided cover is present.

Riffles are defined as relatively shallow and fast zones associated usually with relatively high bed topography. They are constrained to bed slopes ranging up to 1-2%. Riffles are generally spaced 5-7 bankfull channel widths, although the reported range can be between 3 and 11 (Harvey 1975, Leopold et al. 1964, Keller and Melhorn 1978). As flow moves longitudinally over the head of the riffle it transitions from subcritical to supercritical[1]. The water surface is usually rippled, although a small amount (e.g. 5-15%) can exhibit whitewater and standing waves. Bed material is usually cobble and gravel, although intermittent boulders can be present. Adult Chinook salmon generally spawn in the transition from pools to riffles. Juvenile salmon can utilize riffles for feeding and rearing.

Rapids are slightly steeper than riffles and have a greater area that has supercritical flow and whitewater (e.g. 15-50%; Grant et al. 1990). They are generally found in reaches with bed slopes ranging from 2-5%. Cobbles and boulders can be arranged as ribs that span the channel orthogonal or transverse to the channel bed. Between ribs can be pocket pools or runs that span 0.5-1 average channel width. Rapids are not usually associated with salmonid habitat, although they are at least an area of migration for adults.

Cascades are steep, turbulent lengths of channel bed topography containing multiple nested steep drops, sometimes vertical (Grant et al. 1990). Cascade reaches generally have bed slopes greater than 3%, with individual cascades being up to 10%. The substrate is often bedrock, boulder or cobble. The amount of supercritical flow and whitewater is extensive (e.g. > 50%) with flow being dominated by hydraulic jumps. Intermediate pools or pockets are usually less than 0.5 average channel widths, so that most of the unit is very fast and highly turbulent. Like rapids, cascades are not usually directly associated with Chinook salmon habitat.

Habitat unit analysis

Habitat units were first delineated using aerial imagery provided by Foothill Conservancy as well as other publicly available sources of imagery. Since several imagery data sets were available for this study, we first had to determine the data set that was most relevant.

Determining relevant imagery

Imagery from October of 2010 and June 2016 were made available from prior studies on the river (PG&E 2011, Quantum Spatial 2016). Further Google Earth has good quality imagery from 2010 through 2016. Since the imagery is from different years and times of the year we estimated the flow using existing gages operated by the United States Geological Survey (USGS) in the watershed. First, we determined what gage(s) were appropriate to estimate flow for each reach (Table 1). Next, we tabulated monthly averages for each reach (Figure 6). Lastly, we determined the approximate flow per reach for each set of imagery (Table 2).

Table 1. Flow gage data available to estimate flow for each study reach

Reach	Flow gage(s)	Start date	End date
North Fork	11316700	1985-09-30	2016-09-30
Middle Fork	11317000	1911-10-01	2016-10-30
	11318500	1933-10-01	2016-09-30
Confluence and Ponderosa	sum of 11316700, 11317000, 11318500		See above
Electra and Middle Bar	11319500	1927-10-01	2016-09-30

[1] Subcritical flow is dominated by gravitational forces and is relatively slow and non-accelerating. Supercritical flow occurs when inertial forces dominate, and flow is relatively fast moving and unstable.

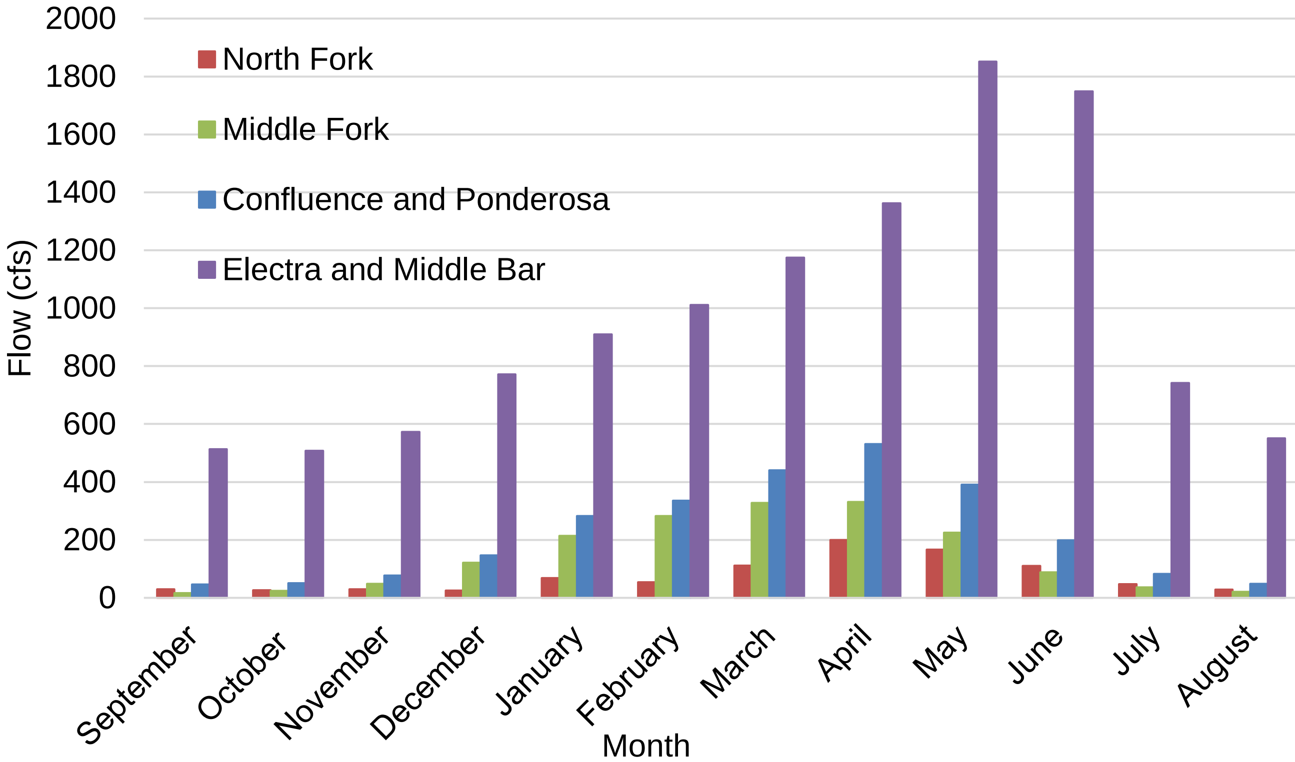

Figure 6. Mean monthly flow for each study reach using the gages shown in Table 1. Note that units are cubic feet per second (cfs). The conversion is 1 ft^3/s is equal to ~ 0.0283 m^3/s.

Table 2. Available imagery, resolution and flow for each study reach. Below are mean and standard deviations of monthly average flow for the month of October. Note that units are cubic feet per second (cfs).

			Flow (cfs)			
Source	**Date**	**Resolution**	**North Fork**	**Middle Fork**	**Confluence and Ponderosa**	**Electra and Middle Bar**
2010 ERC	10/1/2010	0.3333 m x 0.3333 m	*35*	*14.1*	*49*	*342/624*
2016 PGE	6/6/2016	0.3048 m x 0.3048 m	1,390	*34*	1,424	2100
2016 NAIP	6/20/2016	0.6 m x 0.6 m	300	*33*	333	944
Google Earth*	6/5/2009	Varying	605	62	667	1440
	9/15/2010	Varying	*35*	*12.7*	*48*	134
	6/10/2012	Varying	104	38	142	691
	5/26/2014	Varying	316	*16.8*	333	709
	7/24/2014	Varying	50	4	*54*	*426*
	9/19/2015	Varying (BW)	46	2	*48*	*222*
	5/31/2016	Varying	698	45	743	1490
	6/28/2017	Varying	>1400	>62	>1462	>3000
		Mean October flow (cfs)	26	24	50	508
		Standard deviation	14	16	29	170
		Average range (cfs)	13-40	14-40	21-79	338-678

Based on the available information (Table 2) the imagery that corresponded to flows within the average October range was the 2010 ERC imagery. Therefore, this imagery was used to assess habitat units in the study reaches. Habitat units were mapped to a stream centerline for each reach so that the number and percent length of habitat units could be determined.

Field mapping of habitat units

To verify image-based estimates of habitat units, field observations were made during several field surveys in October and early November of 2017. Field surveys involved a team consisting of a biologist, several biological technicians and a fluvial geomorphologist surveying study reaches by hiking, wading and/or floating. Starting at the top of each reach habitat units were mapped using a global positioning system (GPS) handheld unit (Trimble GeoXT™). GPS points were recorded at the start of each habitat unit and the type of unit denoted. In addition to habitat units, geomorphic features were also mapped, including gravel deposits. Location data were downloaded and post-processed using GPS Pathfinder Office™.

Habitat unit analysis

After field data collection, habitat units were refined using field observations. Once a table of habitat unit, length, stationing and reach was developed, the data were analyzed by reach and for the entire segment, excluding the Middle Fork. We omitted the Middle Fork because it consists entirely of pool and cascade units. For each included reach, we determined the percent length and occurrence for each habitat unit. For the entire segment, we also analyzed the cumulative distribution of habitat units.

As discussed in the background section, river reaches with riffle-pool morphology tend to have greater densities of spawning salmon. The spacing of riffle-pool units has been used as an additional proxy for spawning habitat (Montgomery et al. 1999, Hanrahan 2007). Since the study segment is bedrock confined in many areas, pool spacing would not be a good indication of potential spawning habitat. Instead, we used riffle frequency and spacing to evaluate habitat unit suitability. Riffle spacing was calculated by taking the difference in distance between riffles in each reach and then dividing by the average high flow width (e.g. as in Keller and Melhorn 1978).

Collect and analyze transects for spawning and rearing habitat

Transect sampling

As discussed above, field observations were made during several field surveys in October and early November 2017. Along with mapping habitat units we also collected transect data in each reach. In each reach we attempted to collect at least four transects. We were able to do this in all reaches except the North and Middle forks due to time constraints on access. In the North Fork one transect was collected, and in the Middle Fork two were collected.

Transect locations were selected at pool or flatwater transitions above riffle or cascade habitat units. We did this for several reasons. First, we assumed that the salmon reintroduction process would consist of transporting ripe, adult fish to the lowest section of the reintroduction reach. Therefore, habitat that supported spawning would be the primary focus. Second, time constraints dictated approximately four transects per reach. Therefore, we selected sample sites that visually appeared suitable for spawning through the entire study area. The criteria for transect site selection was to locate areas within habitat units that met adult spawning habitat criteria in the literature. This included pool or flatwater transitions into cascades, rapids or riffles, and areas where depths were suitable for spawning (e.g.> 0.15 m) and substrate was within the cobble-gravel range when available.

Transects locations were mapped using a global positioning system (GPS) handheld unit (Trimble GeoXT™). GPS points were recorded at the start of each habitat unit and the type of unit denoted. In addition to habitat units, geomorphic features were also mapped, including gravel deposits. Location data were downloaded and post-processed using GPS Pathfinder Office™.

Each sample location for transects and sediment observations were named using the following notation: The first letter of the reach was used, followed by the transect or site number, going in order for each reach from upstream to downstream, as the data were collected. Lastly, since we collected sediment photographs in addition to transects we differentiated the two by "xs" for transects and "sed" for sediment observations. For example, site "c_4_xs" would refer to a transect within the Confluence Reach that was the fourth site sampled.

Depth, velocity and substrate

A Marsh-McBirney flow meter was used to assess depth and velocity across each transect, generally following United States Geological Survey (USGS) protocols (Turnipseed and Sauer 2010). For one reach, Ponderosa, the flowmeter did not function, and surface velocity measurements were taken using the "float method." The float method measures the distance and time an object travels on the water surface. In the field we did three float method measurements for each transect in the Ponderosa Reach (Turnipseed and Sauer 2010). To summarize hydraulic data, we calculated averaged values of depth and velocity for each transect. We also determined the percent of observations that were within the range of both depth and velocity used by spawning Chinook salmon. The suitable range was taken from habitat suitability curves for the Mokelumne River (CDFW 2001), conservatively defining suitable habitat as having a suitability greater than 0.2. This equated to a velocity range between 0.3 - 1.2 m/s, and depth between 0.24 - 1 m.

At each point along a transect the substrate was visually estimated as fine, gravel, cobble, or boulder. Where there was not a clear dominant class type, two classes were recorded. The class breaks for this classification were as follows: fines < 2 mm (0.08 inches), gravel > 2 mm and < 64 mm (2.5 inches), cobble > 64 mm and < 256 mm (10 inches), and boulder > 256 mm (AGU 1947). To place substrate size in the context of fish that would be potentially reintroduced, we obtained fork length data for the Lower Mokelumne River at the hatchery below Camanche Dam. Five years of recent fork length data were provided by EBMUD for 2012 through 2016. We then estimated the average sediment size a fish could move by assuming that movable rock size was proportional to 10% of fork length (Kondolf and Wolman 1993).

If a transect point had depth > 0.2 m, velocity > 0.3 and <1.2 m/s, and > 50% gravel-cobble substrate it was classified as suitable.

Water quality

Dissolved oxygen (DO) and temperature were measured at each transect location using a YSI probe. To supplement transect temperature data we deployed six water temperature loggers throughout the study reaches. Two were placed in the North Fork. None were placed in the Middle Fork or Confluence reaches because access limited our ability to retrieve them from these reaches. The remaining locations for individual loggers were: at the end of the Ponderosa Reach (above Electra Power House), below the Electra Power House near the attenuation structure, under the Highway 49 Bridge and under the Middle Bar Bridge. Loggers were left for at least one week to capture diel fluctuations. Two of the six loggers, in the North Fork and under the Highway 49 Bridge were not relocated. Temperature and DO data were analyzed relative to suitable ranges identified for spawning Chinook salmon (Bjorn and Reiser 1991). Since data was collected during the fall, it was not used to assess juvenile fish habitat.

Spawning habitat

A coarse attempt was made to map potential spawning habitat within the study segment. We mapped patches of gravel encountered that were at least as large as the average adult redd size of 9 m^2 (Nielsen and Banford 1983; Workman and Bilski 2018), were at least 0.24 m deep and had some current (e.g. >0.1 m/s). Given this was a rapid assessment we qualitatively assessed the suitability of velocity. For each patch we took photographs and GPS'd the perimeter where possible. Data were then overlaid on the 2010 ERC imagery and combined with transect data to create a shapefile of potential spawning habitat (Figure 7). To place aerial estimates in context, we report values as a percentage of the low-flow area for the reach.

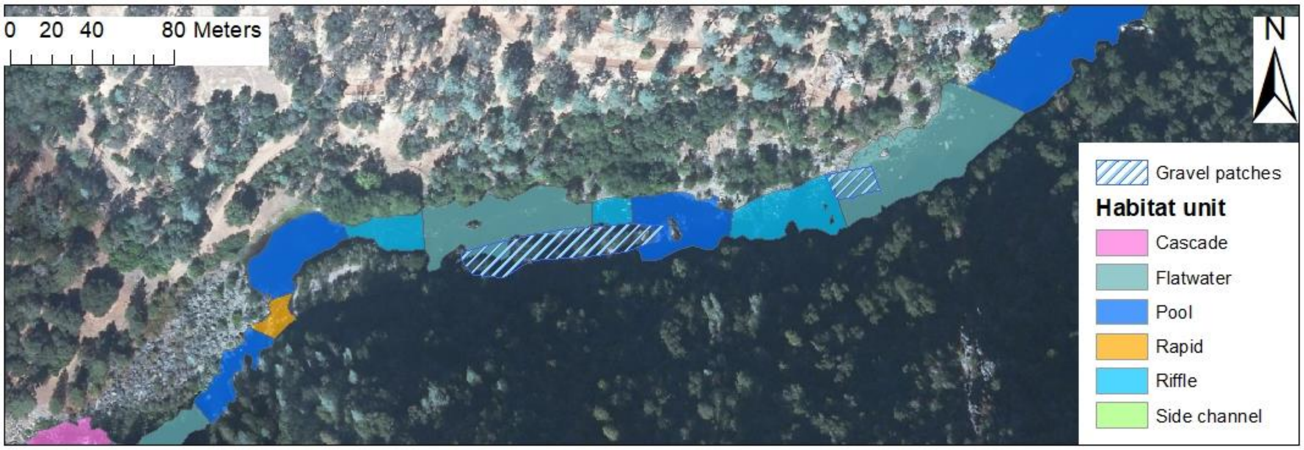

Figure 7. Example of habitat unit and spawning gravel patch polygons for a section of the Confluence Reach.

Rearing habitat edge and cover analysis

For regions above each transect location, we measured the distance from water's edge to a depth of 0.7 m (i.e., edge habitat width) at three locations on river right, and river left (as defined looking in the downstream direction). We also noted the presence, absence, and identification of cover types that are known to influence rearing habitat quality at each location where edge habitat widths were measured. Cover types identified were based on a categorization scheme that has been established for juvenile Chinook salmon (Gard 2006, Beakes et al. 2014).

We estimated the area of edge habitat within a geomorphic habitat unit based on the product of the geomorphic habitat unit's length and the average edge habitat width on the river right and left banks within that unit. We calculated the proportion of edge habitat within a surveyed geomorphic habitat unit by dividing edge habitat area by the total wetted habitat within a surveyed unit. We used the proportion of edge habitat as an index of rearing habitat quality, where geomorphic habitat units containing a relatively high proportion of edge habitat were considered high quality for rearing juvenile salmonids.

RESULTS

Can adult salmon access each reach?

The California Passage Assessment Database had two entries within the study segment. Bald Rock falls was listed as the historical limit of anadromy on the North Fork. The second entry was the attenuation structure below Electra Powerhouse (E1) (Figure 8Figure 9). This entry was listed as being "unassessed." Given that Kokanee salmon (*Oncorhynchus nerka*) were observed spawning just above the structure during our surveys it seems likely that Chinook salmon could also pass upstream.

We encountered several potential barriers to upstream migration during the field surveys, but none of these were considered permanent barriers to adult Chinook salmon (Figure 8Figure 9). On the North Fork we encountered a bedrock step lacking a plunge pool (NF1) that could be a low flow barrier. We also encountered a boulder step with no plunge pool located below Roaring Camp (NF2). At the confluence of the Middle Fork there is a cascade with approximately 4 m in elevation drop over 10 m of stream (MF1). Within the Confluence reach approximately 1000 m downstream of the confluence with the Middle Fork, there is another cascade with approximately 6 m in elevation drop over 16 m of stream

(C1). With higher flows in both reaches, these features may be partially drowned out and less stressful for upstream migration.

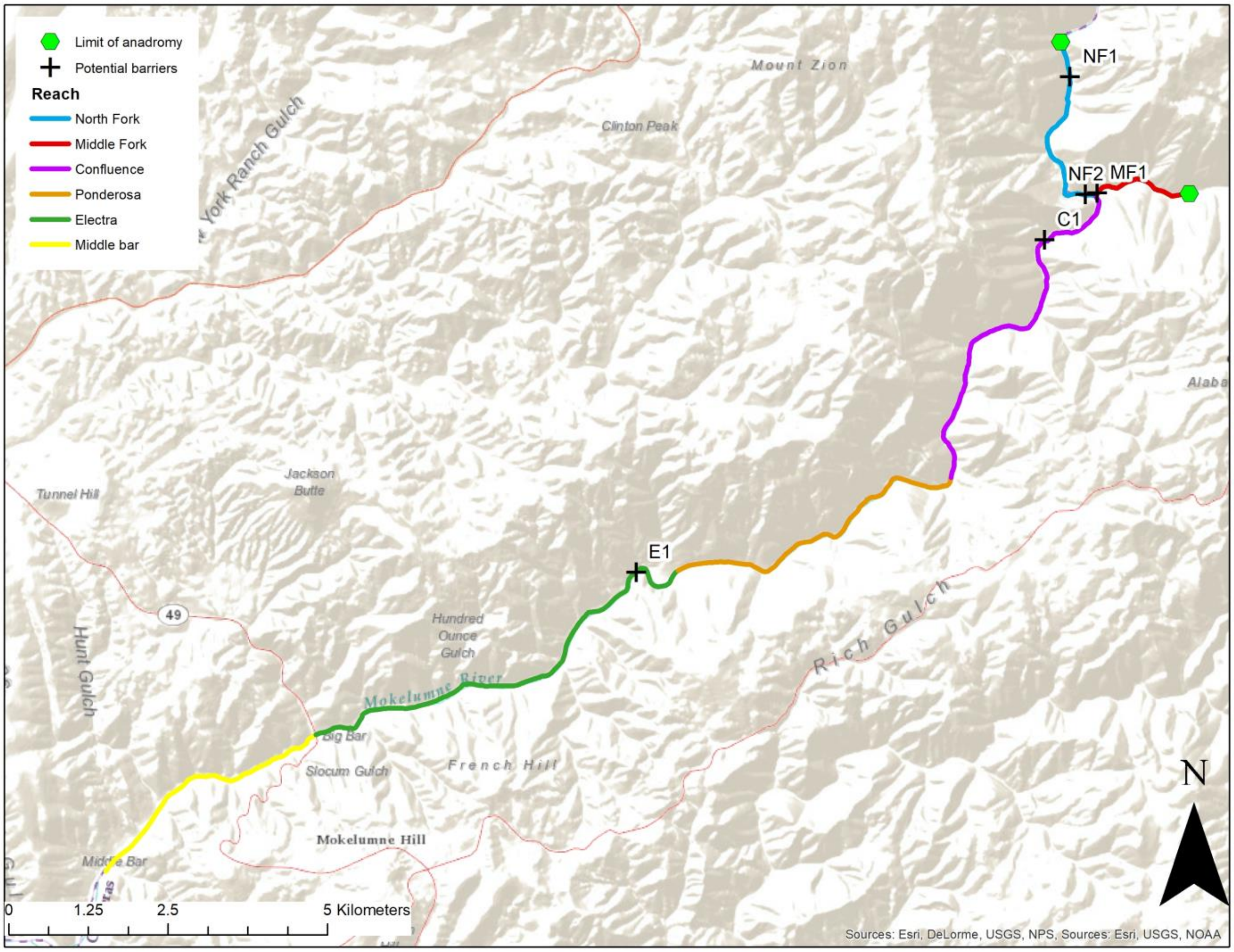

Figure 8. Location map of potential barriers to upstream migration qualitatively evaluated during field surveys. The limits of anadromy were defined by Boyd (2014).

NF1 - Bedrock step with no plunge pool on the North Fork

MF1 - Boulder cascade at Middle Fork confluence

C1 – Bedrock and boulder cascade in Confluence Reach

NF2 – boulder step with no plunge pool on the North Fork

E1 – Attenuation structure below Electra powerhouse

Figure 9. Photographs of potential barriers to upstream migration. All photos taken during field surveys in October of 2017, except "E1" which was found on Google Earth.

Is there spawning habitat?

Intrinsic potential

Intrinsic potential analyses require physical characteristics of each reach. Therefore, we discuss these characteristics first. The average physical characteristics of each reach are shown in (Table 3).

Table 3. Physical attributes of each reach

Reach	Length (m)	Avg. Gradient	Base flow channel width (m)	High flow channel width (m)	Valley width (m)	Confinement	% length bedrock	Dominant substrate
North Fork	3,149	4.89%	26	45	85	3.3	78%	Boulder-bedrock
Middle Fork	1,666	3.94%	12	16	58	4.9	100%	Bedrock-cobble
Confluence	6,012	2.19%	21	40	96	4.5	74%	Boulder-cobble
Ponderosa	5,089	1.75%	24	43	94	4.0	62%	Boulder-cobble
Electra	7,153	0.98%	33	45	114	3.5	11%	Cobble-boulder
Middle Bar	4,197	0.62%	37	51	102	2.8	17%	Cobble-gravel

Each of the reaches shows the typical increase in gradient with upstream distance common to rivers. Generally, Chinook salmon utilize streams that have predominantly pool-riffle bedforms, which occur at gradients less than 2%. Therefore, based on reach average gradient the North Fork and Middle Fork are outside of the expected range of bed slopes for Chinook salmon (Table 3). The Confluence Reach is just above 2%, and Ponderosa is 0.25% below this limit, suggesting these reaches are on the threshold of reach gradient suitability. It is important to note these are average bed slopes. There are locally flatter sections within each reach that could facilitate the development of fluvial forms associated with Chinook salmon habitat. Conversely there are locally steeper areas not captured in an estimate of reach-averaged gradient.

Visual substrate classification from fieldwork and mapping of aerial imagery shows that generally sediment composition becomes finer in the downstream direction (Table 3). The North Fork has a predominantly boulder substrate up to about 1.7 km upstream, where it becomes exclusively bedrock controlled. The Middle Fork is predominantly bedrock controlled, with discrete nested patches of very large boulders, cobble and smaller patches of gravel. The Confluence Reach is predominantly confined by lateral bedrock outcrops that make up 74% of total reach length. Despite the dominance of bedrock there are several boulder and cobble bars. The Ponderosa reach has predominantly bedrock lateral and vertical controls for the upper 1.2 km, but bed substrate is mostly cobble and boulder, although more gravel was present in the lower 1.0 km of the reach near the Electra Power house. Electra and Middle Bar have occasional bedrock outcrops but less so than the upper reaches (Table 3). The dominant substrate in Electra was boulder and cobble, while for Middle Bar cobble and gravel were the dominant substrates.

The intrinsic potential analysis suggests that the four lowermost reaches could provide high quality habitat for adult fish, IP $\geq$ 0.7 (Table 4). It is important to note that this analysis does not directly consider substrate.

Table 4. Intrinsic potential values and ranking for adult Chinook salmon for each study reach.

Reach	Gradient	Channel width	Confinement	Total IP	IP Suitability
North Fork	0.05	1	0.5	0.3	Low
Middle Fork	0.05	0.5	0.6	0.2	Low
Confluence	0.9	1	0.6	0.8	High
Ponderosa	1	1	0.5	0.8	High
Electra	1	1	0.5	0.8	High
Middle Bar	1	1	0.4	0.7	High

Habitat units

Habitat unit occurrence and distributions generally followed the physical template of the surrounding landscape, with higher gradient reaches having a greater number and percent length of cascade and rapid units (Figure 10, Figure 11, Figure 12). The North Fork consisted primarily of rapid, pool, cascade and flatwater habitat types, with a small percentage of riffle. The Middle Fork, which is largely bedrock, consisted almost exclusively of cascade and pool habitats. In terms of percent length, the Confluence had the highest amount of pools at 42%, being 14% greater than the next closest reach. In terms of number of units, the Middle Fork had more discrete pools. The percent length for the Confluence Reach is skewed due to the occurrence of several large bedrock-confined pools. The Ponderosa Reach showed an increase in cascades from the Confluence Reach, but also showed a decrease in rapids. Between the Confluence and Ponderosa Reaches there were 24 and 25% that were either cascade or rapid, respectively. This is not surprising given the similarities in the two units. The Electra Reach was predominantly flatwater, although 40% were either riffle, rapid or cascade. The Middle Bar Reach had the highest percentage of riffles per unit length (28%), and the highest percentage of flatwater (53%), but the lowest percentage of pool (12%).

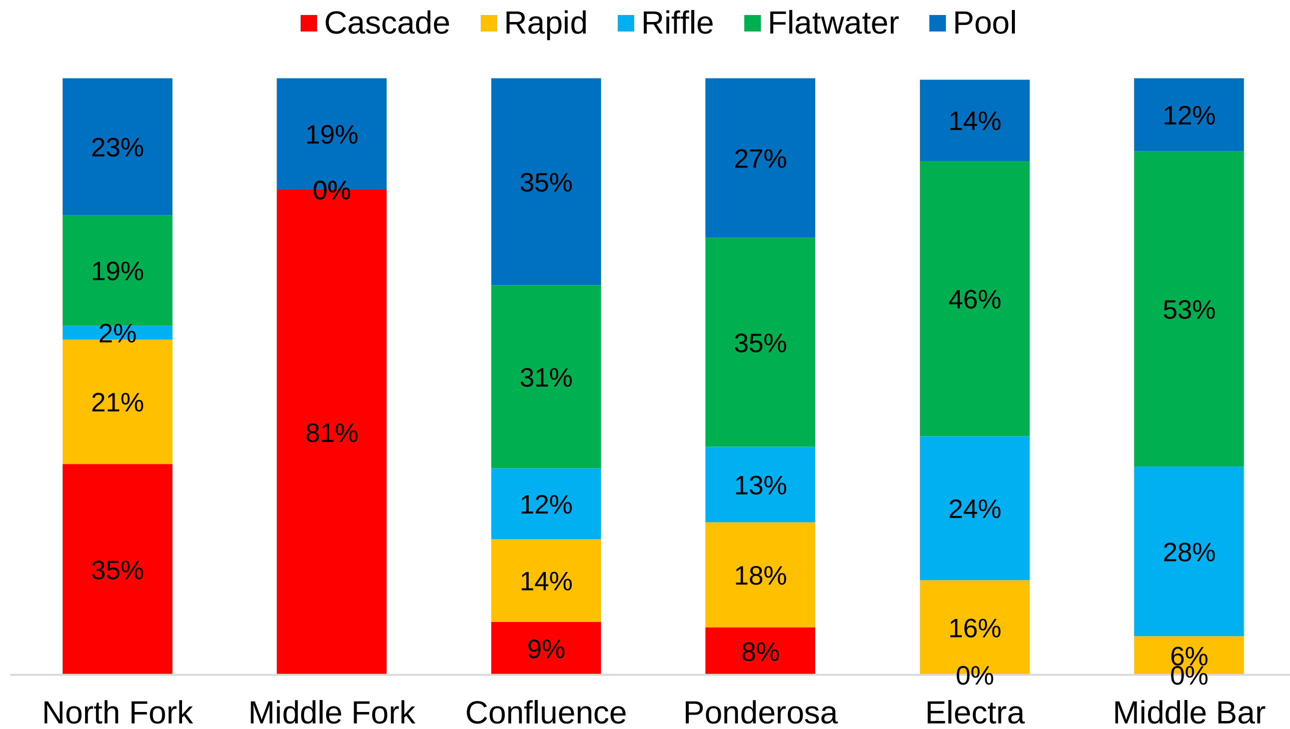

Figure 10. Percent length of habitat units for each reach.

The cumulative distribution for the entire study segment (excluding the Middle Fork) shows similar trends. Cascades, rapids and pools tended to be preferentially located upstream, while riffles and flatwater were more prone to downstream. The lack of pool habitat in Electra is shown by the "flatline" of the cumulative distribution between approximately 7000 and 11000 m. Overall, these data suggest that steeper reaches, such as the North and Middle forks tend to have almost no riffle habitats, and instead have higher energy habitat types such as rapids and cascades (Figure 10, Figure 11, Figure 12).

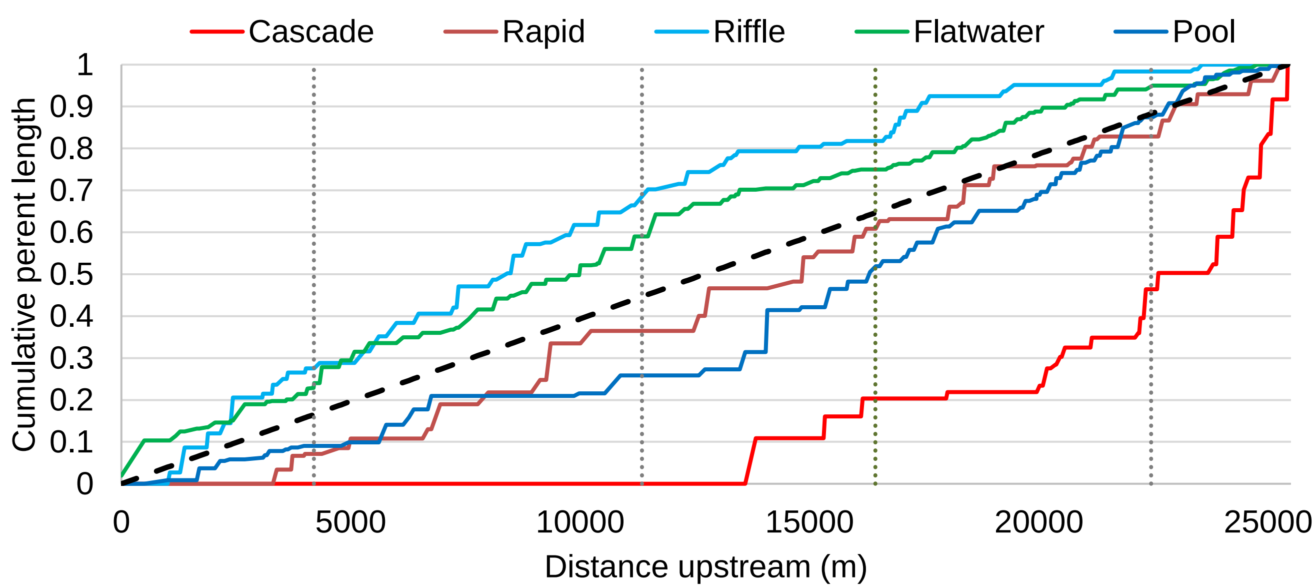

Figure 11. Cumulative distribution functions for habitat units. Vertical dotted grey lines represent reach breaks. The diagonal black dashed line represents uniform distribution.

The percent of riffles (Figure 12), and percent length (not shown) by reach increase with decreasing gradient. Similarly, riffle spacing followed a similar relationship with gradient with steeper reaches having greater spacing in riffles (Table 5). The Middle Fork had no riffles, and the North Fork had one. The Confluence, Ponderosa and Electra reaches all had riffle spacing close to 10. Middle Bar had riffle spacing of 6.6, which is within the commonly cited modal value for alluvial rivers with riffle-pool morphology.

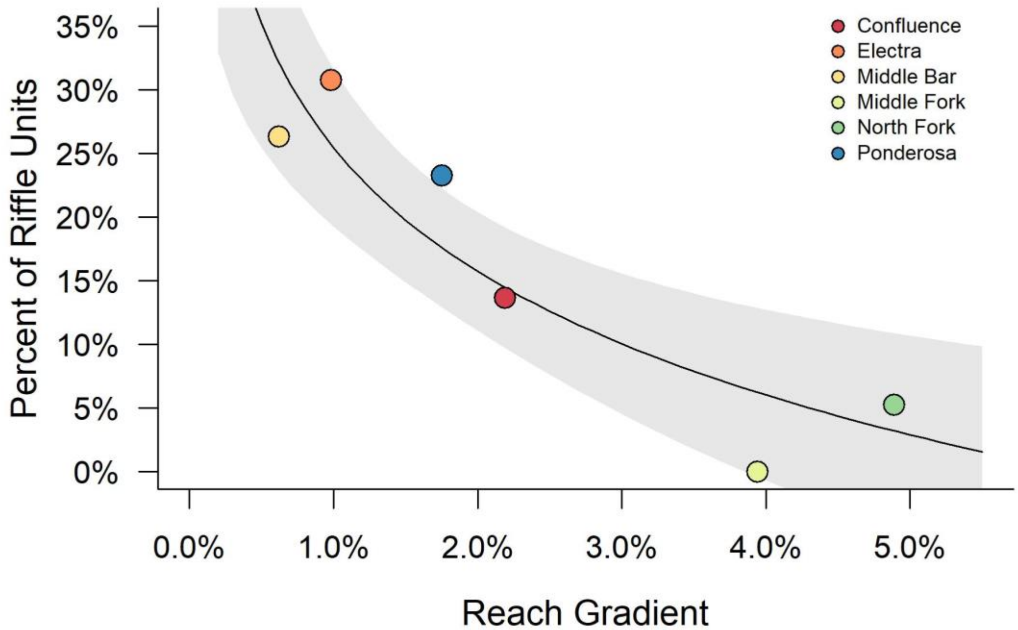

Figure 12. The percent of habitat units classified as riffle and gradient for each reach. The solid line is a logarithmic trend.

Table 5. Riffle spacing and number of riffles for each reach

Reach	Number	Average Spacing (channel widths)
North Fork	2	21.2
Middle Fork	0	NA
Confluence	12	10.8
Ponderosa	10	10.4
Electra	16	9.9
Middle Bar	10	6.6

Transects

Across the 6 reaches 19 transects were collected (Figure 13). Due to time constraints, only one transect was taken in the North Fork and two in the Middle Fork. For the remaining four reaches, four transects were taken.

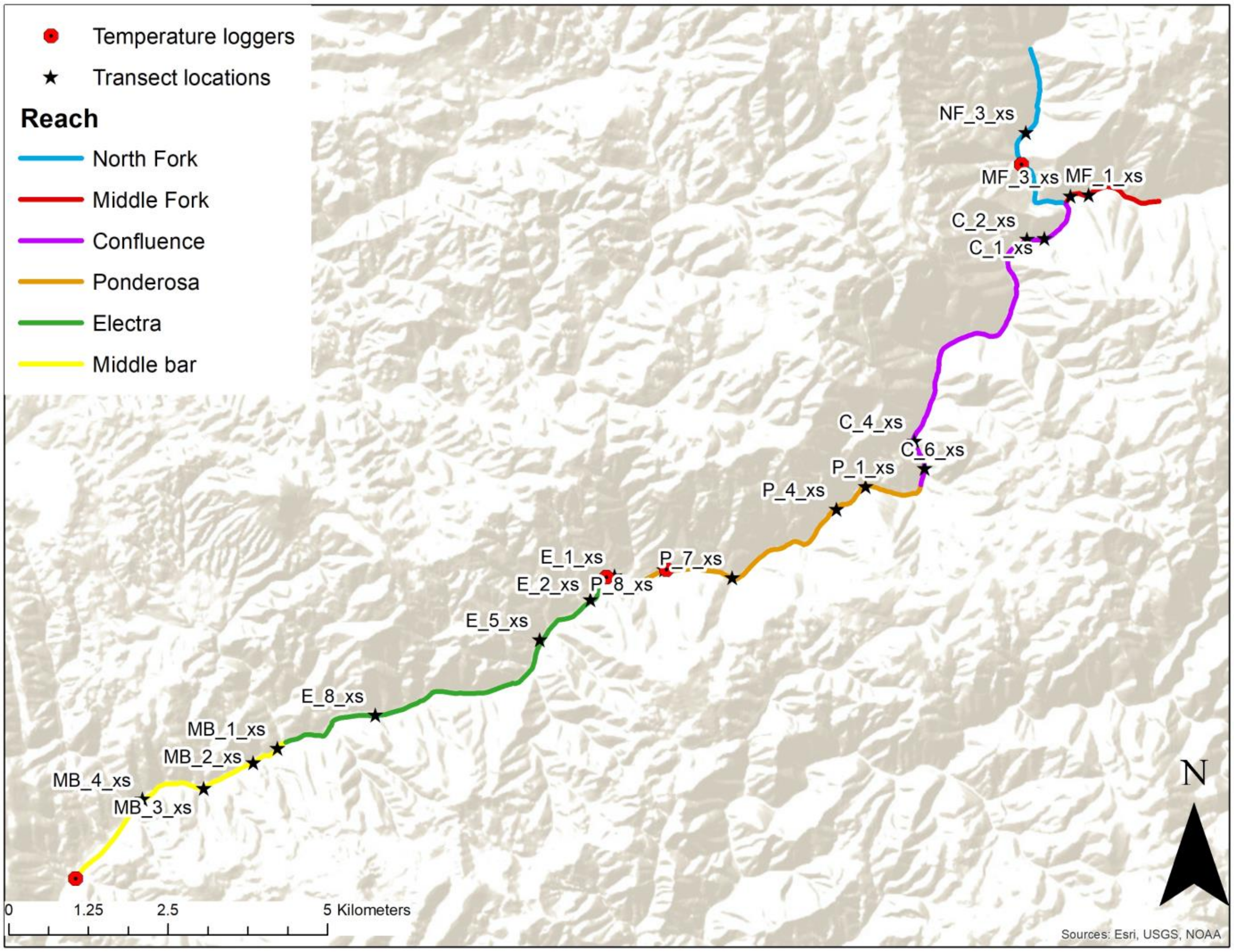

Figure 13. Transect sample and temperature logger locations

Depth, velocity and substrate

It is important with hydraulic transect data that one appreciates the spatial and temporal variability with flow. Mountain rivers commonly have complex flow-hydraulic relationships, where depending on the amount of flow different topographic features can modulate different flow patterns (Brown and Pasternack 2014). However, transect data does provide a glimpse into what potential spawning habitat would look like under the survey conditions.

Overall the transect data shows that all the locations had depths suitable for spawning, while velocity was more variable and less suitable (Table 6). The North Fork transect shows that depths and velocities are suitable, with 50% of the transect meeting both depth and velocity criteria. The Middle Fork data shows that depths are suitable, but velocities were on average lower than what the literature suggests Chinook salmon would prefer. The Confluence Reach generally had suitable hydraulic zones for spawning Chinook salmon. While average velocities were lower for 3 out of the 4 transects, each location had between 27 and 67% meeting both depth and velocity criteria. For the Ponderosa Reach the flow meter malfunctioned. Therefore, we used a “float method” as described in the methods section. This means that the percent of the transect meeting both depth and velocity could not be calculated. At least one transect had suitable average velocities, while 2 others were within 0.03 m/s, so it is likely these locations had some suitable area for spawning. Data for the Electra and Middle Bar reaches are somewhat skewed in that flows during the survey were unusually low for maintenance at the Electra Powerhouse, which was a needed condition for transect measurements. Considering depth was not limiting, it is likely that more flow would increase velocities, potentially increasing the overall hydraulic suitability.

Table 6. Transect data showing cross section averaged depth (D) and velocity (V) and the percentage of each transect in meeting both depth and velocity criteria for spawning Chinook salmon. Visual classification of particle sizes is also included, and the percent of observations along each transect where gravel was observed. Distance upstream is from the Middle Bar Bridge except for the Middle Fork where stations are distance from the confluence with the main river. Transect locations are shown on 2.

SiteID	W(m)	Distance upstream (m)	Average depth (m)	Average velocity (m/s)	% of transect obs. in DV in range	Dominant Substrate (Visual)	% Gravel or Cobble (Visual)	Suitable for spawning?
MB_4_xs	25	1640	0.47	0.24	38%	CO-GR	64%	Y
MB_3_xs	31	2690	0.68	0.16	0%	GR	55%	N
MB_2_xs	21	3570	0.47	0.31	64%	GR	55%	Y
MB_1_xs	24	4030	0.46	0.31	44%	CO	75%	Y
E_8_xs	40	5770	0.80	0.09	0%	GR-CO	65%	N
E_5_xs	36	8910	0.46	0.15	3%	CO	92%	Y
E_2_xs	51	9950	0.26	0.13	12%	GR	82%	Y
E_1_xs	29	10540	0.77	0.12	13%	CO-GR	87%	Y
P_8_xs	35	11630	0.54	0.28	NA	CO-GR	83%	Y
P_7_xs	28.7	12720	0.75	0.27	NA	CO-BO	53%	N
P_5_xs	21	14050	0.64	0.35	NA	BO	38%	N
P_4_xs	23	14840	0.57	0.15	NA	GR-BO	58%	Y
C_6_xs	15.8	16700	0.69	0.33	67%	BO	38%	N
C_4_xs	24.2	17190	0.73	0.20	27%	BO-CO	7%	N
C_2_xs	44	21440	0.29	0.27	58%	BO-CO	38%	Y
C_1_xs	41.4	21720	0.70	0.18	33%	CO-BO	64%	N
NF_3_xs	16.87	24200	0.59	0.25	50%	BO	0%	N
MF_3_xs	18.2	450	0.40	0.11	0%	GR-BR	70%	Y
MF_1_xs	12.1	150	0.41	0.19	22%	GR-BR	44%	Y

Fork length data from 5 years at the Mokelumne River Hatchery provide insight into the biophysical limits of spawning gravel size (Figure 14). Data from almost 58,000 fish shows a wide distribution between 50 and 100 cm. The median fork length size is approximately 70 cm, which using the “10%” rule, would yield a sediment diameter of 70 mm. Considering that most sediment classifications split gravel and cobble at 64 mm, this data also shows that median sediment sizes appropriate for redd construction almost equally encompass gravel and cobble. The 99th percentile fork length is approximately 90 cm, which would equate to a sediment diameter of 90 mm. This suggests that Mokelumne River salmon primarily can spawn in gravels with smaller cobbles up to 90 mm in diameter.

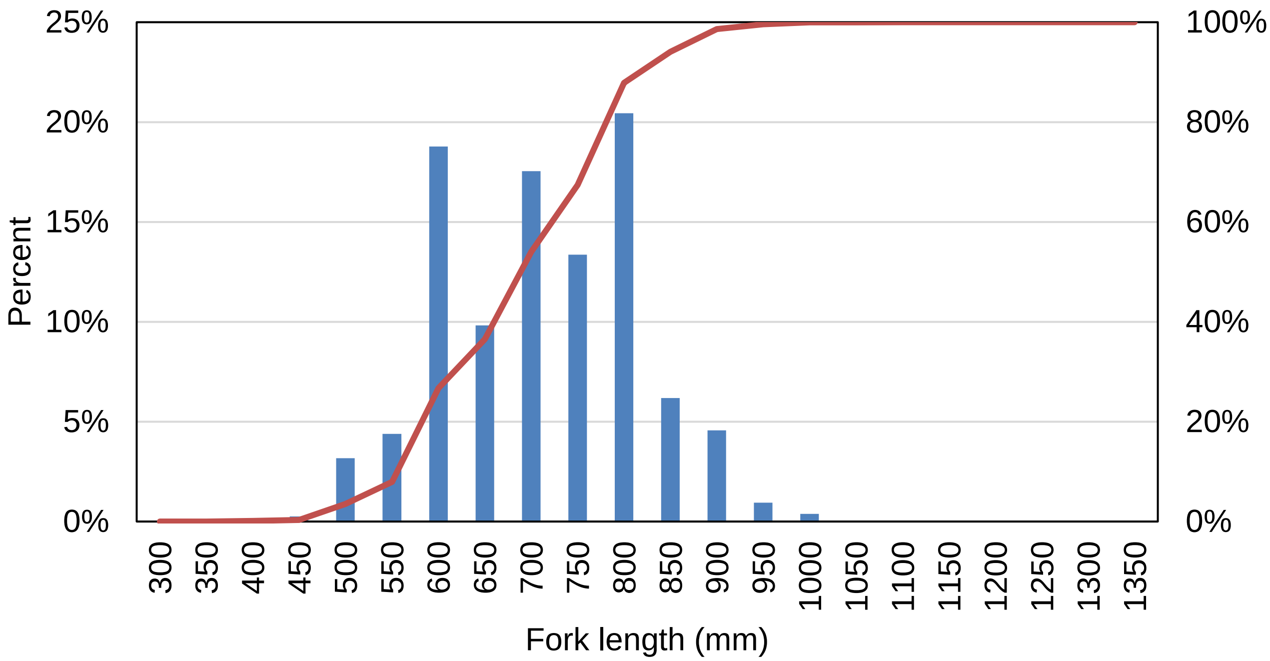

Figure 14. Percentile distribution (columns, left x-axis) and cumulative percent (solid line, right x-axis) of adult Chinook salmon fork lengths based on data from 2012-2016 from the Mokelumne River Hatchery.

Visual substrate observations show that dominate substrate size decreased downstream (Table 6). It is important to note that all sites were pre-selected for adequate spawning conditions, generally with the presence of at least some gravel. For example, the North and Middle fork transect sites were selected as having the greatest potential habitat, but outside of these areas very little in channel gravel was encountered in contiguous patches (e.g. > ~9 m^2) that could be used by spawning Chinook salmon. The North Fork and Confluence reaches consisted primarily of boulder and cobble. The same can be said for Ponderosa, but gravel did become more abundant towards the lower half of the reach.

Overall, 11 out of 19 transects had some suitable spawning habitat in terms of depth, velocity and substrate. That number could be 13, since two transects in Middle Bar and Electra had low depths and velocity during anomalously low release flows from Electra Powerhouse. Another consideration is that transects were pre-selected to represent the best possible habitat, but more adequate hydraulics could be found nearby. Substrate is likely more of a limiting factor. Considering substrate only 14 transects had area with some gravel -cobble substrate that a female Chinook salmon could use to construct a redd.

Water quality

All the temperature data collected at transects ranged between 10.4 C (50.72 °F) and 14.2 C (57.56 °F) and were within the suitable ranges for spawning Chinook salmon (Table 7). Temperatures generally increased from the Confluence Reach down to the Ponderosa Reach but declined at the Electra Powerhouse. Some variation can of course be attributed to the fact that transects were taken during days with different average temperatures, as well as daily variations. Dissolved oxygen values ranged between 10.6 and 11.9 mg/L, averaging 11.3 mg/L. These values are well above the commonly cited minimum value of 5 mg/L. All but two locations were also within the 5.6 to 13.9 mg/L range cited by Bjorn and Reiser (1991).

Table 7. Water quality data collected at each transect.

Site ID	Station (m)	Temperature (c)	DO mg/l	Suitable for spawning?
MB_4_xs	1,640	12.8	11.86	Y
MB_3_xs	2,690	13.1	11.73	Y
MB_2_xs	3,570	12.8	11.73	Y
MB_1_xs	4,030	12.2	11.91	Y
E_8_xs	5,770	11.7	11.69	Y
E_5_xs	8,910	11.4	11.76	Y
E_2_xs	9,950	11.40	11.58	Y
E_1_xs	10,540	11.5	11.5	Y
P_8_xs	11,630	14.1	11.02	Y
P_7_xs	12,720	14.2	10.95	Y
P_5_xs	14,050	13.8	10.96	Y
P_4_xs	14,840	13.7	11.1	Y
C_6_xs	16,700	12.9	10.6	Y
C_4_xs	17,190	12.5	10.89	Y
C_2_xs	21,440	10.4	11.08	Y
C_1_xs	21,720	10.3	11.12	Y
NF_3_xs	24,200	10.7	10.98	Y
MF_3_xs	150	11.4	10.82	Y
MF_1_xs	450	11	10.91	Y

Recorded temperatures from the retrieved loggers were generally below the lethal limit, except for several hours above and below the Electra Powerhouse (Figure 15, Table 8). The highest average temperatures were recorded above and below the Electra Powerhouse, with the lowest being recorded in the North Fork and at Middle Bar Bridge. Since the Middle Bar Bridge logger was deployed at different times it is not reasonable to compare all profiles. However, using air temperature for context some generalizations can be made. The North Fork water temperature was in many cases lower than average air temperatures. This is likely due to the canyon setting of the North Fork compared to the unconfined location of the Mount Zion weather station. Above and below Electra water temperatures were slightly over average air temperatures, and in most cases below maximum air temperature. In terms of diel variation Middle Bar Bridge had the lowest variation, likely due to thermal buffering provided by the reservoir (Table 8). The greatest variation was found above and below the Electra Powerhouse. We hypothesize this variation is due to mixing of the natural flow with flows released by the powerhouse from Lake Tabeaud. Overall the temperature logger data suggests that water temperatures are generally suitable for Chinook salmon.

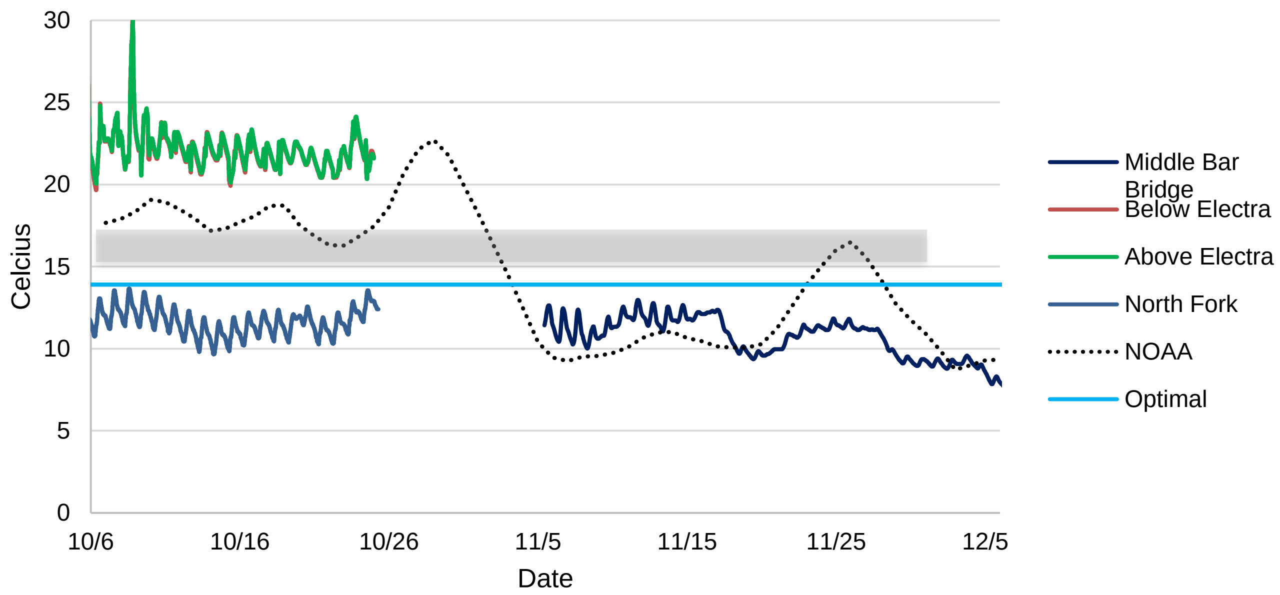

Figure 15. 7 day average temperature profiles for retrieved loggers and a NOAA weather station (USR0000CMTZ) in Mount Zion, CA. The blue line represents optimal spawning temperatures for Chinook salmon, and the grey box indicates the critical temperature range from SJRRP (2011).

Table 8. Approximate diel variation, minimum, average and maximum temperature recorded. Locations are shown on Figure 13.

	Temperature (degrees Celsius)			
	Approximate diel variation	Minimum	Average	Maximum
North Fork	1.6 - 2	9.57	11.79	15.38
Above Electra Powerhouse	1.2 - 2.1	20.04	22.14	30.05
Below Electra Powerhouse	1 - 2.6	19.66	22.07	30.05
Middle Bar Bridge	0.7 - 1.7	6.78	10.20	13.27

Spawning habitat

Spawning habitat availability generally increased in the main channel with distance downstream from both the Middle and North forks.

For the North Fork, we encountered two patches totaling less than 60 m^2. One of these areas was behind a large boulder that was roughly 5 m tall and 5 m wide. The other areas were out of water on the upstream end of a cobble-boulder bar. The Middle Fork had more gravel present than the North Fork, but gravel patches were still relatively small, with both in-water patches less than 50 m^2 in size. Gravel patches surveyed were only 1.2% of the low flow area for the Middle Fork and less than 1% for the North Fork. A relatively large area of gravel was encountered 375 m downstream from the Middle Fork in the Confluence Reach. For roughly 450 m the channel slope was locally flatter than the surrounding river (~< 1%) and locally wider. For reference transects C_1_xs and C_2_xs are located in this area but transects did not cross the entirety of these patches, since the deposits were lateral and oriented downstream. Modest sized patches of gravel were found below this area in the Confluence Reach but yielded only 4.8% of the low flow wetted area. Most of these patches were either on small tributary fans or located in pools out of the main flow path. Lateral sediment storage is a common mechanism in mountain rivers since flow is usually fast and deep in a narrow region of the main channel (Brown and Pasternack 2014). Beyond those patches at the downstream limit of the Ponderosa Reach and upstream limit of Electra Reach were large areas of gravel and cobble. In this area, it is hypothesized that the attenuation structure below Electra Powerhouse slows flows, and in the process, attenuates gravel and sands that might otherwise continue being transported downstream. This is hypothesized to be why the Ponderosa Reach has almost 20% of its low flow wetted area having gravel and cobble, with the largest area being above the powerhouse. Similarly, the Electra Reach had 4.6% of its wetted low flow area as gravel and cobble, but a large amount was skewed upstream due to the attenuation structure. In the Middle Bar reach substrates were generally gravel and cobble, yielding 12.4% of the low flow wetted area.

To place these values in context we conservatively estimated approximately half of the low flow area would provide suitable spawning conditions, and so divided the total low flow area by two to estimate a useable area of 226,000 m^2. Then we divided that area by the average redd size (9 m^2) to estimate the number of redds that could be supported. We then divided that value by 2 adult fish per redd to estimate that 12,555 adult Chinook salmon could reproduce in the study segment (Table 9). This value is well above the minimum population size of 833 fish for species viability suggested by Lindley et al. (2007).

Table 9. Areas of visually defined suitable spawning habitat mapped in the field.

Reach	Area (m^2)	Low flow area (m^2)	Percent low flow area
Middle Fork	142	11,953	1.2%
North Fork	14	49,766	0.0%
Confluence	3,768	78,772	4.8%
Ponderosa	14,628	75,415	19.4%
Electra	6,502	141,594	4.6%
Middle Bar	11,904	95,951	12.4%
Totals	36,958	453,451	8.15%

Is there rearing habitat?

Juvenile rearing intrinsic potential

The intrinsic potential analysis suggests juvenile habitat potential decreases in the upstream direction (Table 10). The Electra and Middle Bar Reaches have high potential for juvenile rearing habitat, while the Confluence and Ponderosa reaches have medium potential due to steeper gradients. Similarly, high gradients in the North and Middle Fork Reaches yielded low potential for juvenile rearing habitat.

Table 10. Intrinsic potential values and ranking for juvenile Chinook salmon for each study reach.

Reach	Gradient	Confinement	Total IP	IP Suitability
North Fork	0.05	0.95	0.2	Low
Middle Fork	0.05	1.00	0.2	Low
Confluence	0.4	1.00	0.7	Medium
Ponderosa	0.6	1.00	0.7	Medium
Electra	0.7	0.97	0.9	High
Middle Bar	0.8	0.92	0.9	High

Rearing habitat edge and cover analysis

The availability of edge and bank rearing habitats within discrete geomorphic habitat units ranged from approximately 103 to 707 m^2 and varied across the surveyed reaches (Table 11). Geomorphic habitat units surveyed within the Confluence reach had the largest average area of edge/bank habitat at 707.46 m^2 (± 607.75 m^2 SD). Middle Fork supported the least edge/bank habitat of the reaches surveyed with an average wetted area of 103.34 m^2 (± 11.26 m^2 SD).

Some form of cover was available on one or both riverbanks in all habitats units surveyed. Cover types ranged from overhanging vegetation and large wood to submerged aquatic vegetation and boulders. In most reaches surveyed the edge and bank habitats were relatively unaltered by anthropogenic activities. Previous research has shown that these unaltered riverbanks can support almost 150% higher densities of rearing juvenile salmon compared to altered riverbanks (Bartz et. al. 2006). As such, it is unlikely that the availability of cover along the river edges and banks is a limiting factor to rearing juvenile salmonids.

Table 11. Summary statistics (mean ± (SD)) for valley and channel widths, local channel confinement ratio, and edge and bank rearing habitat availability in surveyed geomorphic habitat units by reach.

Reach	Valley (m)	Channel (m)	CCR	Wetted (m^2)	Edge/Bank (m^2)	% Edge/Bank
North Fork	64.26 (NA)	16.24 (NA)	3.96 (NA)	1776.51 (NA)	517.75 (NA)	0.29 (NA)
Middle Fork	35.1 (1.67)	10.07 (2.48)	3.63 (0.89)	233.83 (124.58)	103.34 (11.26)	0.55 (0.31)
Confluence	77.35 (15.78)	20.3 (5.99)	3.92 (0.57)	1222.87 (730.42)	707.46 (607.75)	0.51 (0.23)
Ponderosa	87.02 (16.46)	23.95 (8.31)	3.76 (0.51)	1588.1 (1148.57)	688.47 (874.9)	0.35 (0.19)
Electra	101.88 (18.71)	39.21 (5.03)	2.6 (0.43)	2022.07 (165.98)	618.4 (203.02)	0.31 (0.11)
Middle Bar	90.63 (14.65)	24.06 (4.01)	3.8 (0.65)	1116.39 (132.89)	537.98 (370.79)	0.47 (0.28)

We observed a linear relationship between the total wetted area and edge habitat area within a geomorphic unit (Figure 16). The total wetted area of a geomorphic habitat unit explained approximately 60% of the observed variation in edge/ bank habitat area (Figure 16, linear model, *Adjusted*-$R^2 \approx 0.61$, $P < 0.01$). We estimate that increasing the total wetted area of a geomorphic habitat unit by 100 m^2 would result in a ~50 m^2 increase in edge or bank habitat on average (Figure 16). This statistical relationship makes intuitive sense. In areas where the river channel increases in width the areal extent of wetted habitat increases and so does the availability of edge habitat.

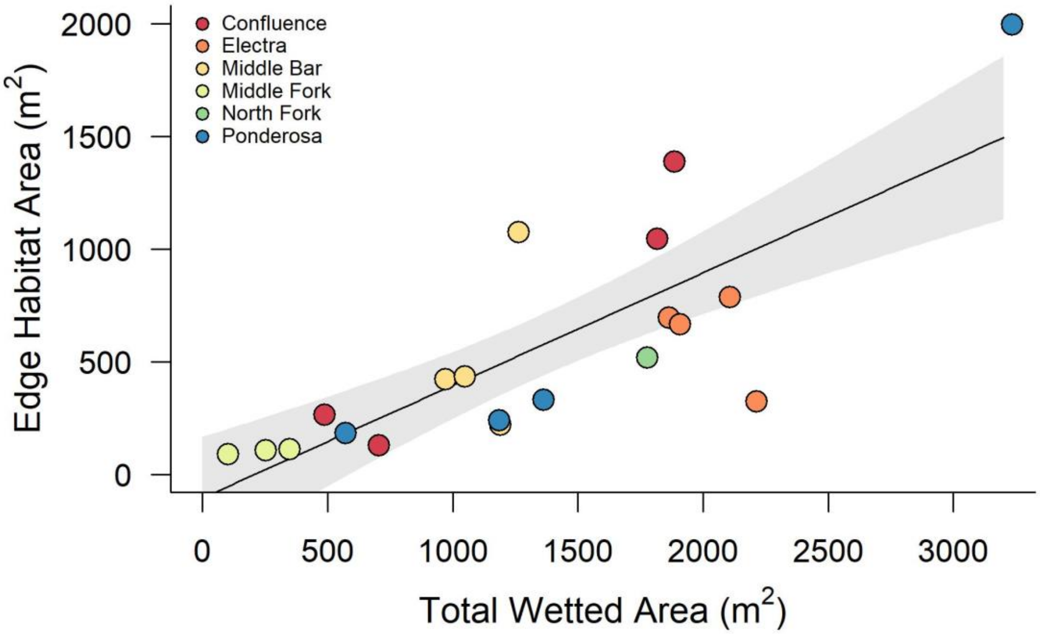

Figure 16. Linear fit between a geomorphic habitat unit's wetted area and corresponding edge habitat area. Grey polygon encompasses the 95% confidence intervals for the linear fit (solid line).

The total wetted area of a geomorphic unit was unrelated to the proportion of that geomorphic unit composed of edge or bank habitat (linear model, *Adjusted*-$R^2 < 0.01$, $P > 0.05$). For example, geomorphic habitat units surveyed in the Middle Fork and Confluence reaches had the lowest and highest average total wetted area of the habitats surveyed (Table 11). Yet habitats surveyed in these reaches had the top two highest proportion of edge/ bank habitat. In other words, even though the total amount of wetted habitat may be relatively low (e.g., Middle Fork) the proportion of high-quality edge/ bank rearing habitat may have been relatively high. This finding suggests that there are factors that impact the proportion of edge habitat within geomorphic habitat units other than total wetted area.

We found a log-linear relationship between edge habitat area and valley width (Figure 17). As valley width increases the amount of edge habitat increases geometrically.

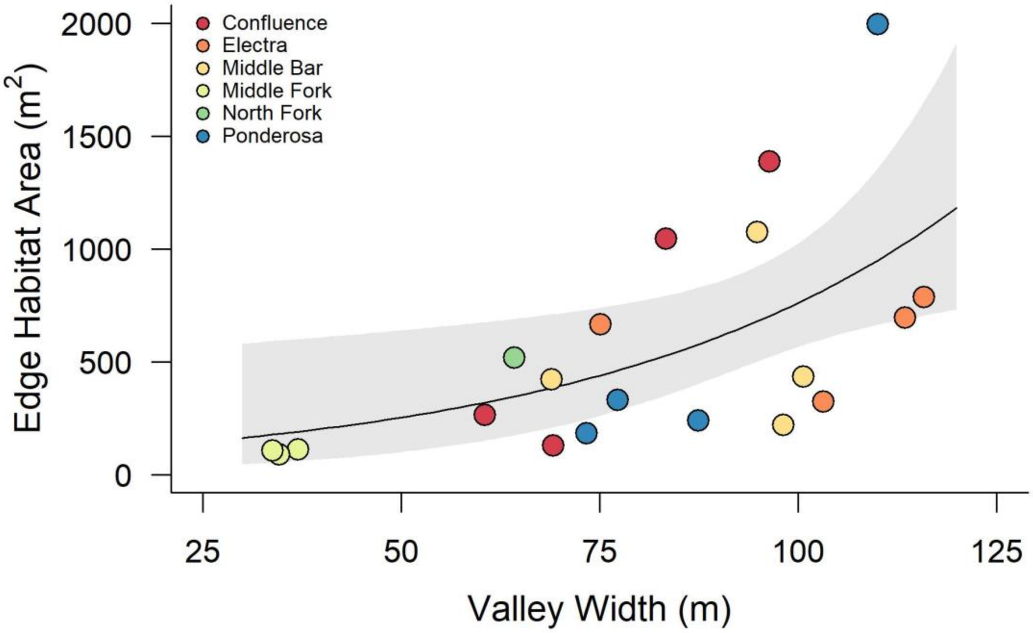

Figure 17. Log-linear fit between the local valley width and edge habitat area in adjacent geomorphic habitat units. Grey polygon encompasses the 95% confidence intervals for the linear fit (solid line).

We also observed a positive trend between proportion of edge habitat and the local channel confinement ratio (Figure 18). Collectively these results indicate that as the valley and wetted channel widen, the total amount of edge habitat increases, and the proportion of edge habitat likewise increases.

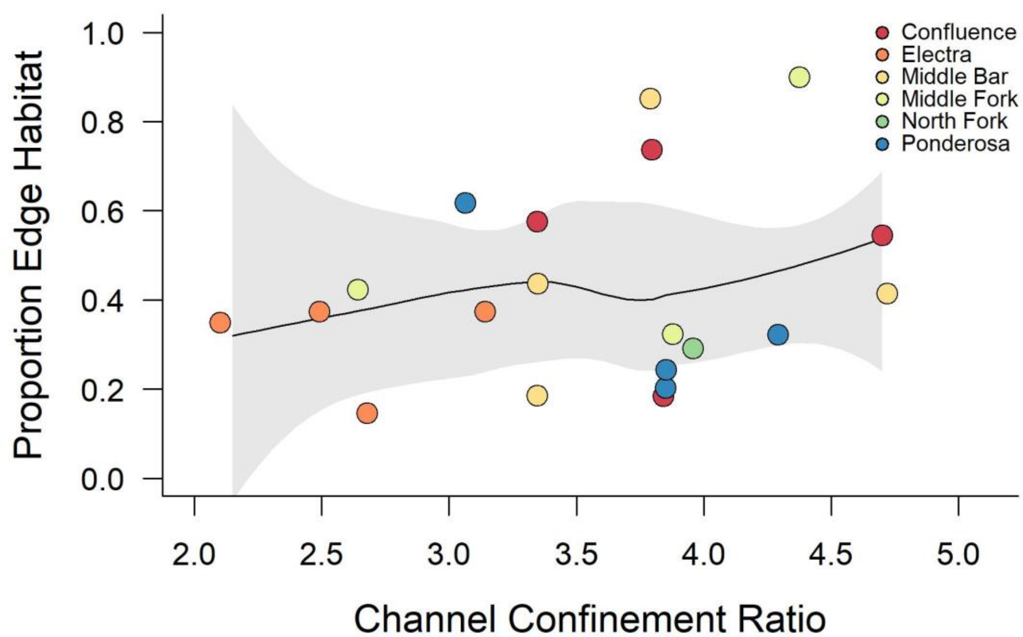

Figure 18. The relationship between local channel confinement ratio (valley width/channel width) and the proportion of edge habitat in adjacent geomorphic habitat unit's trends positive. Grey polygon encompasses the 95% confidence intervals for the locally weighted regression fit (loess, solid line).

DISCUSSION

Can adult salmon access each reach?

Overall, fish can access each of the study reaches provided they are transported to the Middle Bar Bridge. However, we identified several rapids and cascades that may impede adult upstream passage at low flows due to shallow depths and fast water velocities.

Is there spawning habitat?

Intrinsic potential analysis suggests that all reaches other than the North and Middle forks could support high quality habitat (Table 12). It is important to caveat these results in that they do not consider substrate. Habitat typing supports these results with riffle abundance and frequency being low to non-existent for the North and Middle Fork reaches. Riffle spacing was between 6.6 and 10.8 for the lower 4 reaches. Overall, percent length and occurrence of riffle units generally increases with distance downstream, with the Middle Bar Reach having over 20% riffle habitats.

Lastly, within a riffle habitat unit, substrate needs to be within the gravel-cobble size class range. While the Confluence, Ponderosa and Electra Reaches had riffle habitat units, many of these did not have gravel substrate that would allow for adult spawning. Immediately above and below the Electra Powerhouse, but above the attenuation structure, there is a relatively large area of gravel, cobble and sand. During our surveys we observed multiple Kokanee salmon (*Oncorhynchus nerka*) spawning in this general area. Most of the riffles in the Middle Bar reach had gravel-cobble substrate that would support adult Chinook salmon spawning. Understanding whether gravel deficits in upper reaches are associated with the sediment transport capacity of these reaches, or if it is due to anthropogenic impacts, is a critical knowledge gap.

Water quality parameters such as temperature and dissolved oxygen were generally within the suitable range for Chinook salmon. However, we did observe high water temperatures above and below Electra Powerhouse relative to spawning Chinook salmon requirements. Even so, in this same area we observed several Kokanee salmon spawning, suggesting a thermal gradient present in the river that was not captured by temperature loggers. Important to note these data come from only a single season of monitoring where temperatures are not presently managed for Chinook. Further work is needed to discern whether temperatures would prohibit spawning.

Taken together, all the reaches could support adult Chinook salmon in some capacity. However, the overall suitability of the North Fork and Middle fork is likely very low. The results here should not be surprising as historic records demonstrate Chinook accessed the upper watershed up to Bald Rock Falls (Boyd 2014). Even with significant human alteration, Kokanee, Rainbow (*O. mykiss*) and Brown trout (*Salmo trutta*) naturally reproduce in portions of the study area.

Table 12. Summary of reach suitability determined from this study for adult Chinook salmon where Y = yes and N = no. Note that some habitat exists in all reaches, but this table seeks to summarize overall data on a reach basis. DVS refers to depth, velocity and substrate and DO refers dissolved oxygen.

			Transects		
Reach	IP Suitability	Habitat Units	DVS	Temperature	DO
North Fork	N	N	N	Y	Y
Middle Fork	N	N	Y	Y	Y
Confluence	Y	Y	N	Y	Y
Ponderosa	Y	Y	Y	Y	Y
Electra	Y	Y	Y	N	Y
Middle Bar	Y	Y	Y	Y	Y

Is there rearing habitat?

Intrinsic potential results suggest that all reaches except the Middle and North forks could provide high-quality rearing habitat for juvenile salmon (Table 13). The presence of abundant cover features (e.g., large wood, over hanging vegetation), and lack of altered edge/ bank rearing habitats created relatively high-quality rearing habitats. Although not collected during the rearing season, water temperatures were found to be well within the bioenergetic limits for rearing salmonids. Qualitative evaluation of macroinvertebrate production indicated that prey was abundant and is likely not limiting. Collectively these results suggest that the rearing habitat potential was high across the habitats surveyed.

It is important to note that our field survey was conducted during an anomalously high-water year. We suspect that on dry and average water years the volume of flow within the surveyed reaches would be substantially lower. It is also likely that water temperatures would be higher under lower-flow conditions. Collectively, these changes would likely reduce both the availability and quality of edge and bank habitats for rearing.

It is equally important to note that the field survey was conducted during the summer and early fall, which is not the typical rearing season for juvenile Chinook. The availability of edge and bank habitat may be fundamentally different under spring flow conditions when juvenile Chinook have emerged and are starting their freshwater rearing. As such, we suggest results from our evaluation of rearing habitat be interpreted with caution and in context with the period in which the survey was conducted.

Table 13. Summary of reach suitability determined from this study for adult Chinook salmon where Y = yes and N = no. Note that some habitat exists in all reaches, but this table seeks to summarize overall data on a reach basis.

Reach	IP Suitability	Cover
North Fork	N	Y
Middle Fork	N	Y
Confluence	Y	Y
Ponderosa	Y	Y
Electra	Y	Y
Middle Bar	Y	Y

Additional considerations

A key aspect of upstream reaches that do not have abundant riffle habitat or gravel deposits is that these areas can provide a diverse array of habitat that could support a wider gene pool than what is commonly associated with modal habitat. That is, having areas that allow fish to segregate by size and fitness could strengthen the population gene pool, possibly enhancing their overall viability. For example, while the North and Middle fork are unlikely to provide significant spawning habitat areas for most Chinook salmon, smaller fish may be able to utilize pocket gravel areas. Moreover, adults could theoretically migrate upstream and utilize pools for holding before spawning.

Is habitat in the Upper Mokelumne suitable for steelhead?

While not the focus of this study we believe most of the surveyed reaches could support steelhead. There are some similarities in the physical habitat requirements for Chinook and steelhead. For example, both species require gravel sizes within a similar range, which is determined predominantly by fish length. Further, both species have relatively similar rearing habitat requirements. In this context we posit that much of the physical spawning and rearing habitat we identified as suitable for Chinook salmon may also be suitable for steelhead.

Although the physical habitat requirements for both species overlap the timing of their life cycle is markedly different. Therefore, we would suspect the hydraulic conditions and water quality to be dissimilar during adult and juvenile life stages. Juvenile steelhead can also rear in freshwater for multiple years before migrating to the ocean whereas Chinook typically out-migrate within the first year of freshwater rearing. Thus, steelhead would likely require sustained rearing habitat quality year-round. It is currently unclear how water and habitat quality changes in late summer during dry and average water years. Rearing habitat quality may decline under low/normal water years.

Since Steelhead are smaller fish and tend to spawn predominantly in the winter, there could be some adequate spawning habitat in the North and Middle forks. For example, we noted several smaller in channel patches of gravel in both reaches that could support smaller bodied fish spawning. In addition, with higher flows in the winter compared to the fall, lateral gravel deposits could also be used by spawning steelhead.

What management actions could improve habitat suitability for both species?

Several management and restoration actions could potentially improve habitat for Chinook salmon. These include:

- Topographic manipulation – regrading or re-sculpting river bed, banks or adjacent landforms
- Woody material augmentation – passive addition of woody material
- Instream structures – construction of woody debris and/or boulder structures to improve habitat quality
- Flow and temperature management with water and power supply – manage and optimize flow and water temperature for salmon habitat and water and power supply
- Gravel augmentation – addition of rounded gravel for Chinook salmon spawning either passively or directly at designated spawning beds
- Predator management – management of known predators to juvenile Chinook salmon including Brown trout
- Downstream reservoir water quality control during adult and juvenile migration periods.

POTENTIAL NEXT STEPS

We have outlined the following list as potential next steps:

- Determine population goals and carrying capacity analysis
    - Understanding what the desired population goals for upstream re-introduction would provide a baseline for determining if physical habitat is limiting. Estimates of available spawning gravel suggest adequate adult habitat is available to support a viable population but analyses are coarse and could be refined based on specific management goals.
- Ecohydraulic and hydrologic analysis
    - We recommend that a full ecohydrologic analysis be considered to better understand the relevance of flow on habitat types. This would entail a statistical analysis of flows for various portions of the salmonid life cycle.
- LiDAR Mapping of the river corridor
    - LiDAR (light detection and ranging) technology is now relatively affordable and feasible. An accurate meter scale topographic map would allow the Salmon Restoration Team and other stakeholders to map and model current habitat and how restoration and management actions may improve conditions. With such a topographic map one could use modeling to evaluate multiple management and climate scenarios, such as flow modification, and whether this affects salmon.
- Sediment source and potential analysis
    - Habitat from the Ponderosa Reach going upstream could be improved for adult salmon if more rounded gravel was present. The amount of gravel was found to be limiting, with a general trend of downstream fining of bed sediments. This could be the result of several factors. Downstream areas may have a reduced sediment transport capacity associated with lower gradient and higher valley widths compared with upstream areas. This is likely the case for the North Fork and Middle Fork reaches where gradient is ~4-5% on average. In addition, some gravel deficit in the Confluence and Ponderosa Reaches could be due to a reduction of sediment supply from upstream dams. Understanding if gravel is limited because of historic or current anthropogenic activities, or intrinsically limited due to landscape factors is an important management item.
- Upstream limits of anadromy
    - Prior work has suggested that upstream migration on the North Fork is limited to the upstream reach limit at Bald Rock Falls (Boyd 2014). Given the amount of bedrock in this area it is not unlikely that this area could prohibit upstream passage. Similarly, prior work has suggested that a boulder jam located at the upstream limit of the Middle Fork is also a barrier to adults. Due to time constraints neither of these areas were surveyed. Since the hydraulics of these types of features is flow dependent it may be that these are passable under limited flow conditions where water depths provide an adequate tailwater for flow plunging over the drops. Future work should attempt to verify flow conditions and how these features may act as barriers.
- Pilot tagging study
    - Reintroduction of salmon to historical habitats provides a unique opportunity to test our assumptions/hypotheses about habitat preferences for these species. We can learn more about how salmon interact with their ecosystems by taking a BACI-type approach to evaluating changes to the physical and biological elements of the Upper Mokelumne River ecosystem before and after reintroduction.

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