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AUGUST 2017

SCIENTIFIC FRAMEWORK FOR ASSESSING FACTORS INFLUENCING ENDANGERED SACRAMENTO RIVER WINTER-RUN CHINOOK SALMON (*Oncorhynchus tshawytscha*) ACROSS THE LIFE CYCLE

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

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Scientific framework for assessing factors influencing endangered Sacramento River winter-run Chinook salmon (*Oncorhynchus tshawytscha*) **across the life cycle**

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Executive Summary

California's Central Valley Interagency Ecology Program (IEP) formed multi-agency Salmon and Sturgeon Assessment of Indicators by Life Stage (SAIL) synthesis teams to develop a scientific framework for evaluating existing information on endangered Sacramento River winter-run Chinook salmon (SRWRC; *Oncorhynchus tshawytscha*), green sturgeon (*Acipenser medirostris*), and white sturgeon (*A. transmontanus*) and provide recommendations to improve the management value of life stage monitoring. Developing the SAIL framework for SRWRC and sturgeon followed parallel approaches that included three steps. First, existing conceptual models (CMs) were reviewed and modified to characterize specific environmental and management factors that drive SRWRC responses within discrete geographic domains and life stages. Second, the existing monitoring network was compared to fish demographic responses in the CMs to identify deficiencies. The deficiencies were interpreted as gaps in the existing network that prevent annual, quantitative, population-level metrics from being developed that are needed to support water management actions, assess population viability, and prioritize population recovery actions among geographic domains across the freshwater landscape. Lastly, identified absences were used to develop recommendations on ways to improve the scientific and management value of the current monitoring network. This document comprises the first of these steps for the SRWRC portion of the SAIL projects. It consolidates all the CMs developed by the SAIL synthesis team and their associated narratives.

The SAIL effort utilized much of the same structure of the IEP Delta Smelt Management, Analysis, and Synthesis Team [MAST] CM to promote consistency and foster ease in use and recognition for the Central Valley (CV) watershed science and decision-making community (IEP MAST 2015). The SAIL CM was partitioned by geographic region rather than seasonality. The partitioning resulted in the identification of five geographic regions, and was adopted due to the large geographic range of SRWRC and the tight coupling between seasonality and location by life stage. The SAIL CM goes beyond previous CV anadromous fish CMs by providing additional detail on the proposed mechanistic pathways and environmental factors specific to each geographic region and life stage, and how the pathways and factors are thought to influence SRWRC abundance, timing, and, in some cases, condition.

The overall SAIL CM for SRWRC is comprised of seven separate CMs. The seven CMs are organized among the five geographic regions by the following life stages: Egg to Fry Emergence, Rearing Juvenile to Outmigrating Juvenile, Ocean Juvenile to Ocean Adult, Migrating Adults to Holding Adults, and Holding Adults to Spawning Adults. Each life stage is associated with its respective geographic regions, which were identified based on significant changes in the ecosystem in conjunction with locations of key monitoring points. The five geographic regions are identified as follows: Upper Sacramento River, Middle Sacramento River, Bay-Delta, and Ocean. Within each CM the following hierarchical tiers were created to illustrate the environmental pathways that affect each life-stage and region: Landscape Attributes (Tier 1), Environmental Drivers (Tier 2), Habitat Attributes (Tier 3), and Fish Responses (Tier 4). A star is used within each CM figure to denote which factors have potential control through management actions that can ultimately influence fish responses within and among tiers. Each

CM also has a narrative detailing the geographic extent and life stage biology of that model and a list of the hypothesized mechanistic pathways of the various environmental factors and habitat attributes that affect a life stage within a certain region.

The SAIL team used the seven updated SRWRC CMs to develop recommendations for establishing a core monitoring program for basic management metrics (e.g., abundance, timing, and condition) at each life stage and associated geographic region, and identify studies needed to test the mechanisms underlying large changes in life stage abundances within each region (Johnson et al. In press). The SRWRC CMs are also intended to serve as a tool to guide, inform, and develop future research and adaptive management efforts within the greater CV watershed science community and have already been used and cited in California's Salmon Resiliency Strategy (California Natural Resources Agency 2016).

Acknowledgments

We thank the Interagency Ecological Program and the IEP Directors specifically for prioritizing staff resources towards supporting the SAIL effort. We also thank the many scientists whose research and work contributed towards the information used in this endeavor to inform our conceptual models. We thank Melissa Stefanec, Project Assistant at Anchor AEQ, LLC for her meticulous editing assistance while finalizing the manuscript. And lastly, we thank the California Sea Grant program for providing the opportunity for one of their fellows to work alongside the accomplished scientists who coauthored this document.

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Introduction

Conceptual Models (CMs) are simplified depictions of portions of an ecosystem and are commonly used by scientists to organize and illustrate hypotheses on ecosystem function or, more specifically, how a species or life stage is influenced by its surrounding environment (Williams 2010, Vogel 2011, IEP MAST 2015). Through CMs, various ecological mechanisms and pathways can be identified and summarized with graphical illustrations and narrative text to provide a broader picture of how a system is hypothesized to function. Complex concepts with multiple components are distilled into an accessible format that can be used to discuss ecosystem functions with a broad range of audiences (e.g., scientists, managers, stakeholders, and the public). CMs are also the foundation for quantitative models used to make predictions of ecosystem function, components, or relationships that can be compared to empirical data (Hendrix et al. 2014). CMs can help to prioritize management actions, identify monitoring and research needs, highlight scientific uncertainties, and determine key indicators of project performance to monitor (Johnson et al. In press). Importantly, CMs provide managers with an easily accessible tool to help guide the planning and implementing of ecological research, adaptive management, restoration, and recovery efforts (California Natural Resources Agency 2016).

The Interagency Ecological Program (IEP), a multi-agency research collaborative based in the California Central Valley, prioritized developing a scientific framework for evaluating existing information on Sacramento River winter-run Chinook salmon (SRWRC; *Oncorhynchus tshawytscha*), green sturgeon (*Acipenser medirostris*), and white sturgeon (*A. transmontanus*). Two synthesis teams known as the Salmon and Sturgeon Assessment of Indicators by Life Stage (SAIL) developed CMs for each species, undergoing similar processes that included the following three steps: First, previous CMs concerning salmonids and sturgeon were reviewed and expanded upon to illustrate specific environmental and management factors that drive fish responses at particular life stages and geographic regions. Second, the existing monitoring network was reviewed against the new CMs to determine deficiencies and gaps at key life stages and geographic regions that would assist in quantifying population-level metrics, and therefore support water management, assess population viability, and prioritize population recovery actions (Johnson et al. In press). Lastly, recommendations were developed to improve the current monitoring network based off the identified deficiencies (Johnson et al. In press).

The SAIL CM for SRWRC drew from two previous CMs focused on Central Valley Chinook salmon and mechanisms and indicators that affect this species at different life stages (Vogel 2011 and Williams 2010). The structure and framework behind the SAIL CMs stemmed from the development and successful application of the Delta Smelt (*Hypomesus transpacificus*) CM developed by the IEP Management, Analysis, and Synthesis Team (MAST; IEP MAST 2015, Conrad et al., in review), which was created to provide current hypotheses of how environmental factors affect Delta Smelt. It consists of a tiered framework that illustrates the predicted mechanistic pathways impacting the species throughout the lifecycle. The tiered structure allowed more complex relationships to be accounted for compared to previous CMs, including

environmental drivers, habitat attributes, and Delta Smelt responses. The objective of the MAST model was to provide the scientific community with a common framework for developing hypotheses and guiding research, and a tool for managers to use when communicating and evaluating difficult policy decisions and trade-offs associated with protecting this species. The value of this tool is evident by its use in generating predictions regarding how Delta Smelt may have been impacted during a recent drought (2012–2016) and providing a foundation for testing the predictions with monitoring data, guiding additional data synthesis efforts, and the development of a Delta Smelt resiliency strategy (Conrad et al. in review, California Natural Resources Agency 2016).

Vogel 2011 identifies important environmental stressors that affect the survival of anadromous fishes within the Sacramento River basin at each life stage and the associated geographic region. However, the model is not species-specific, but rather, it provides broad generalizations of the most common stressors affecting each life stage. Vogel 2011 was designed to illustrate the importance of how multiple environmental stressors affect each life stage, and that this changes throughout the salmonid lifecycle. The model also provides support for shifting the focus from studying the impact of individual stressors toward understanding the relative importance of multiple stressors within the context of the lifecycle. The model depicts primary environmental factors commonly recognized as affecting the survival of anadromous fish, but does not describe in detail the hypothetical mechanistic pathways that underlie the relationships between environmental stressors and salmonid survival.

Williams 2010 is more detailed than Vogel 2011 and provides sub-models for each life stage that include short mechanistic pathways for major environmental factors. Each sub-model also hypothesizes whether the environmental factor has a positive or negative affect on a particular life stage. However, the model does not specify differences between geographic regions for each life stage or how management actions in different regions may affect environmental drivers or habitat attributes that influence fish responses.

SAIL Conceptual Model Framework. The SAIL effort utilized much of the same structure of the IEP Delta Smelt MAST CM to promote consistency and foster ease in use and recognition for the Central Valley (CV) watershed science and decision-making community (IEP MAST 2015). The SAIL CM was partitioned by geographic region rather than seasonality. The partitioning resulted in the identification of five geographic regions, and was adopted due to the large geographic range of SRWRC and the tight coupling between seasonality and location by life stage**.** The SRWRC SAIL CM also expands on Vogel 2011 and Williams 2010 by providing additional detail on the proposed mechanistic pathways and the environmental factors specific to each geographic region and life stage, and how the pathways and factors influence abundance, timing, and, in some cases, condition. The SAIL team used the updated SRWRC CMs to develop recommendations for establishing a core monitoring program for basic fish demographic metrics (e.g., abundance, timing, and condition) at each life stage and associated geographic region, and identify studies needed to test the mechanisms underlying large changes in life stage abundances within each region. A map depicting the current monitoring locations and demographic metrics measured and for SRWRC salmon is shown in Figure 1. The SAIL CM for SRWRC is

comprised of seven CMs by life stage and geographic region and is summarized in Figure 2 to illustrate how the CMs relate to each other chronologically and geographically.

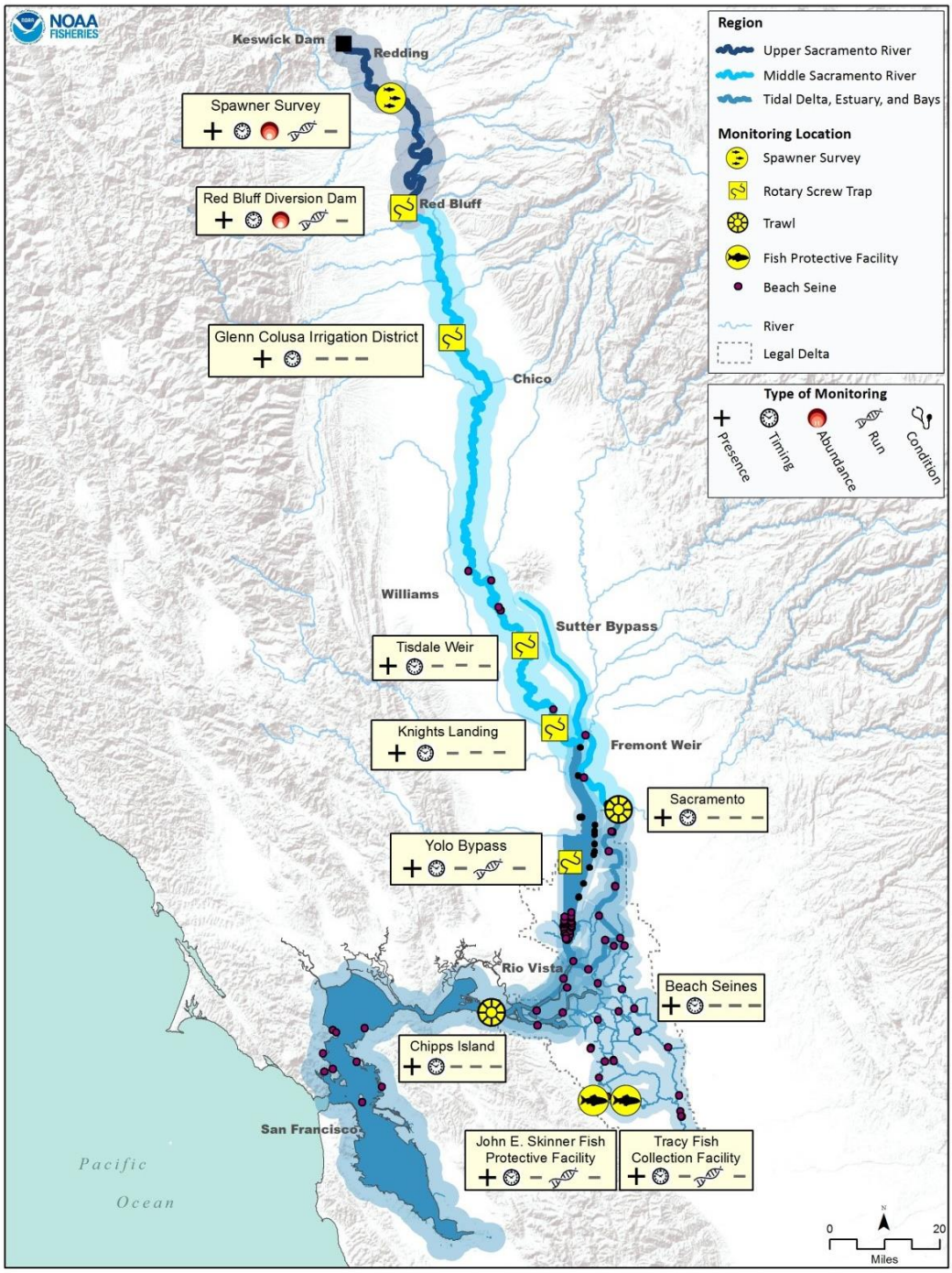

Figure 1. Map of the Central Valley with key Sacramento River winter-run Chinook salmon (SRWRC) monitoring locations identified by geographic domain in the Upper (dark blue) and Middle (bright blue) Sacramento River, and Sacramento-San Joaquin Delta (tidal Delta, Yolo Bypass, Estuary, and Bays; blue). Summary of the extent to which the core monitoring network measures key demographic indicators such as presence, timing, abundance, run, and condition by life stage is displayed. Metrics that are not monitored and interpreted as data gaps are denoted by (-). Modified from Johnson et al In Press.

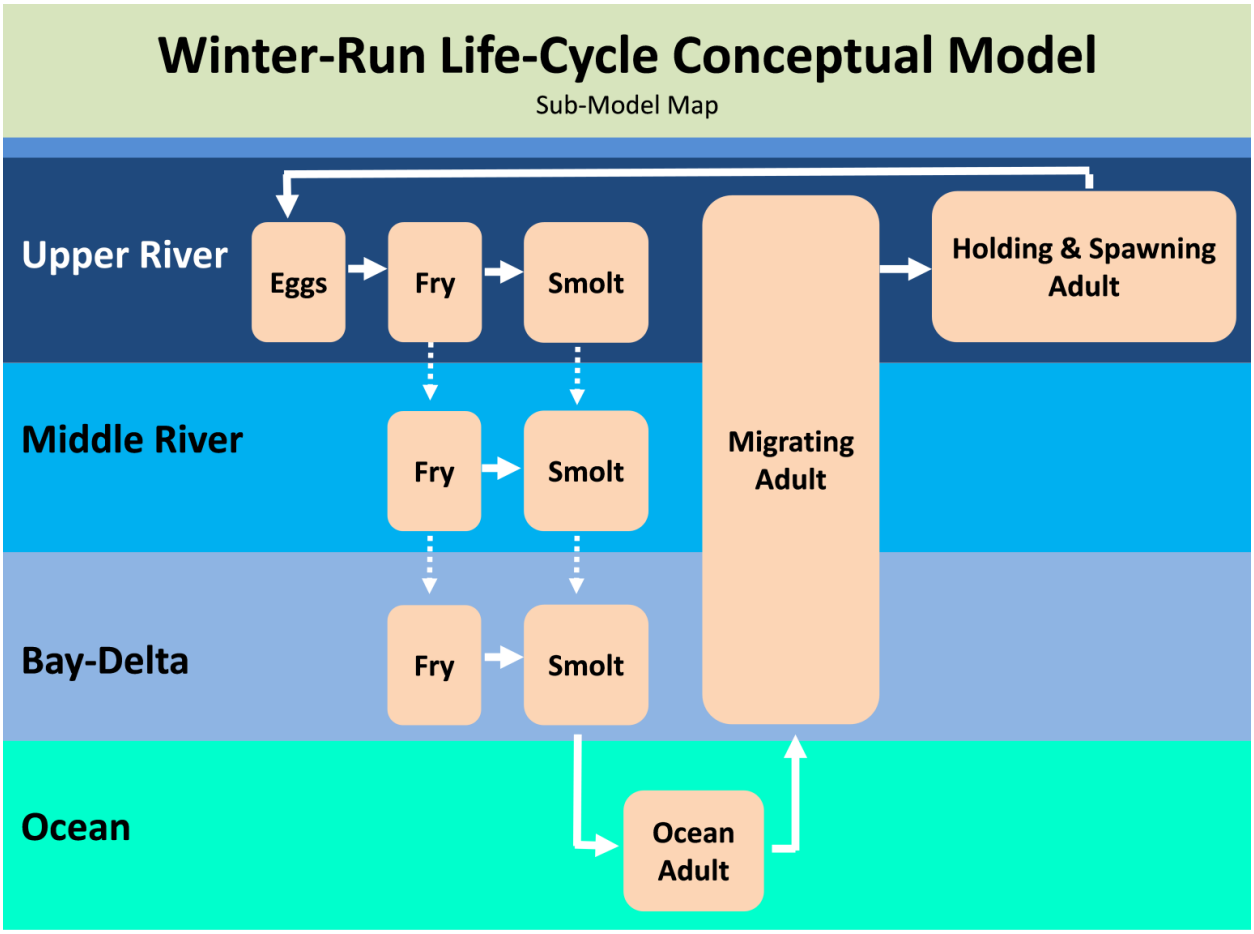

Figure 2. Sacramento River Winter Run Chinook salmon depiction of the different life stage and geographic domains developed into conceptual models (CMs). Figure modified from Johnson et al. In Press.

Life Stages. The SAIL CMs are organized among five geographic regions by the following life stages (Figure 3-9):

- Egg to fry emergence
- Rearing juvenile to outmigrating juvenile
- Ocean juvenile to ocean adult
- Migrating adults to holding adults
- Holding adults to spawning adults

Geographic Regions. Each life stage is associated with its respective geographic regions, which were identified based on significant changes in the ecosystem in conjunction with locations of key monitoring points (Figure 1). These geographic regions are as follows:

- **Upper Sacramento River.** Keswick Dam to Red Bluff Diversion Dam (RBDD).
- **Middle Sacramento River.** RBDD to the I Street Bridge in the city of Sacramento including the Sutter and Yolo Bypasses. Sacramento City is the delineation between the lower bounds of the Middle Sacramento River and the beginning of the lower Sacramento River that is tidally influenced (Tidal Delta).
- **Bay-Delta (Tidal Delta, Estuary, and Bays).** Sacramento-San Joaquin Delta bounded by the City of Sacramento to the north, the confluence of the San Joaquin and Stanislaus rivers to the south, approximate alignment of Highway 5 to the east, and the Golden Gate Bridge, including tidal marshes to the west. Where appropriate, this region is separated into two areas (i.e., Delta and Bay) at the approximate confluence of the San Joaquin and Sacramento rivers at Chipps Island near Antioch, California.
- **Coastal Ocean.** Marine waters west of the Golden Gate Bridge.

Hierarchical Tiers. The seven SAIL CMs included the following hierarchical tiers and symbol to denote which factors have management control within those tiers:

- **Tier 1 - Landscape Attributes.** Local to system-wide features that change slowly over long periods of time, and directly influence environmental drivers (Tier 2)
- **Tier 2 - Environmental Drivers.** Features that occur over a broad range of temporal and spatial scales and occur within the geographic range of the species. Environmental drivers directly influence habitat attributes (Tier 3).
- **Tier 3 - Habitat Attributes.** Features that also have a broad range of spatial and temporal scale, but directly affect the species' demographic responses (Tier 4).
- **Tier 4- Fish Responses.** Factors associated with the transition to a subsequent life stage (i.e., life stage input, survival, timing and migration, and condition and growth). Fish Responses are directly influenced by habitat attributes.
- **Management Actions.** Management actions are noted with a yellow star within CMs. These items are under direct management control and can act on factors in any of the tiers to influence fish responses.

The SWRC SAIL CM framework documents various hypotheses and management actions that influence SRWRC abundance, survival, growth, condition, and life history diversity. The arrows depicted in Figures 3-9 represent linkages between or within tiers and do not indicate directional interaction (positive or negative) or relative importance compared to other factors within the CM. In some cases, the directional impact and relative importance is identified as being a hypothesis (e.g., $\mathbf{H_1}$, $\mathbf{H_2}$). Factors within each of the seven CMs that are directly manipulated by

management actions are denoted with a star, highlighting key pathways that can immediately be influenced. Not every possible environmental factor and interaction could be represented within the CMs because of the complexity of the lifecycle, and number of environmental conditions salmon experience and habitats they occupy. The framework does not prioritize the relative importance or scientific support for the individual hypotheses presented, which would be a useful next-step in the development and use of the framework. Below, each CM is described in greater detail, including the applicable geographic region, affected biology and habitat attributes, and a discussion of the hypotheses developed for each CM.

Sacramento River Winter-run Chinook Salmon Conceptual Models by Life Stage and Geographic Regions

CM1: Egg to Fry Emergence

Geographic Extent. SRWRC spawn in the Upper Sacramento River, extending from just below Keswick Dam to approximately 60 miles downstream to RBDD, though most spawning occurs within the first 10 miles below Keswick Dam.

Biology of Life Stage. Female SRWRC deposit their eggs into redds (i.e., gravel nests) in the summer, where they are fertilized by male salmon and subsequently buried by the female. Peak spawning occurs in June–July and eggs incubate below the bed of the stream within the hyporheic zone for 40–60 days, where permeable sands and gravels exchange water and nutrients with the stream above (Williams 2006, CDFW 2006). Embryos develop and hatch into alevins, a larval stage reliant on yolk for nutrition, and remain in redds until the yolk is completely consumed for an additional 30–40 days (Bams 1969, Fisher 1994). Alevins then emerge from redds as fry at approximately 30–40 millimeters (mm) in length. Alevin size and survival are influenced by the size of the original egg and surrounding environmental conditions. Mortality rates of eggs and alevins are generally high, but also highly variable, with an average egg to fry survival of 26.4 percent (coefficient of variation = 37.9 percent) for brood years 2002–2012 measured at RBDD (Poytress et al. 2014).

Hypothesis for Habitat Attributes that Affect Egg Survival, Timing, and Condition

H_1: In-river fishery and trampling
H_2: Toxicity and contaminants
H_3: Redd quality
H_4: Stranding and dewatering
H_5: Dissolved oxygen
H_6: Pathogens
H_7: Water temperature
H_8: Sedimentation and gravel quantity
H_9: Predation risk

The survival of eggs into emerging fry depends largely on the quality of the redd and the quantity of gravel of appropriate sizes (**H3**, **H8**). Redd quality is affected by gravel size and composition, flow, temperature, dissolved oxygen (DO), contaminants, sedimentation, and pathogens and diseases. If water releases from Keswick Dam decrease substantially after adult spawning has occurred, redds face the risk of stranding (when the surface of the redd is above the surface of the water and the redds become disconnected from the main channel) and dewatering (when the water surface drops below the redd; **H4**). Since 1997, a total of 213,000 tons of gravel have been placed from 300 yards to 1.5 miles downstream of Keswick Dam to increase the availability of suitable spawning habitat (**H8**). There is a positive relationship between the number of female spawners and the number of juveniles estimated at RBDD from 1997–2014, suggesting SRWRC are not currently limited by spawning habitat quantity, perhaps due to their low abundance (CDFW 2006, Poytress 2016).

Water temperature affects the rate of development of embryos and alevins (**H7**; Rombough 1988, Beacham and Murray 1990) and temperature should not exceed 56 °F (13.3 °C) to avoid egg mortality (Slater 1963, Myrick and Cech 2004). The amount of cold water available to achieve optimal temperature for this life stage varies as a function of the amount of cumulative precipitation, reservoir stratification, and previous Shasta Reservoir water operations. Water temperature also affects the saturation concentration of DO within the stream and has been positively correlated with Chinook salmon larval growth up to a concentration of approximately 11 milligrams of oxygen per liter. However, DO concentrations in the Sacramento River are typically less than this level, potentially resulting in embryo and alevin development being stunted (**H5**; Mesick 2001). The deposition of fine sediment (**H8**) can also affect egg survival, compromising an embryo's ability to acquire oxygen and dispose of metabolic waste, potentially resulting in stunted embryo and alevin development. Pathogens, disease, and contaminants affect the survival of eggs and the condition of emerging fry and can be exacerbated by increased water temperature and reductions in flow (**H6**, **H2**; McCullough 1999, Scholz et al. 2000). Water temperature can also impact the predation rate on eggs, embryos, and fry because predator metabolic demands increase with temperature (**H9**).

In general, this portion of the river supports large populations of native fishes such as Sacramento Pikeminnow (*Ptychocheilus grandis)* and Steelhead (*O. mykiss)* that have been observed feeding on salmon eggs during spawning (**H9**). Non-native predators such as Striped Bass (*Morone saxatilis*) are also present. Human activity, such as recreational fishing, could also negatively impair redds due to disturbances such as trampling (**H1**).

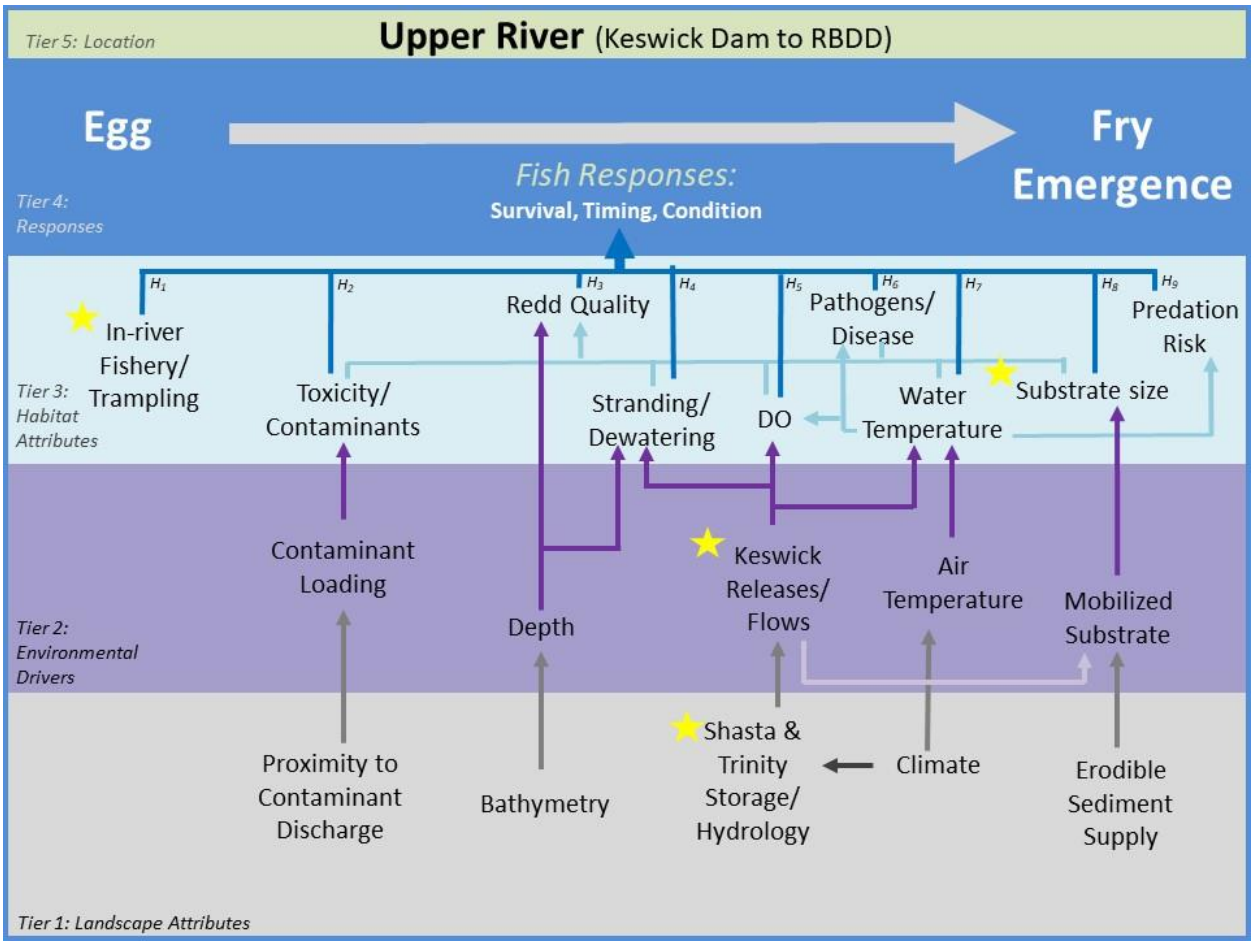

Figure 3. Conceptual model of drivers affecting the transition of SRWRC from egg to fry emergence in the Upper Sacramento River. Hypotheses referenced by the "H-number" are identified in the conceptual model 1 (CM1) narrative. Management actions are denoted by stars and are described in Table 1.

CM2: Rearing to Outmigrating Juveniles in Upper Sacramento River

Geographic Extent. The Upper Sacramento River geographic region begins at Keswick Dam and extends downstream approximately 60 miles to the RBDD.

Biology of Life Stage. SRWRC fry begin to emerge from the gravel and start exogenous feeding from July–October (Fisher 1994). Upon emergence from the gravel, fry swim or are displaced downstream. Fry seek streamside habitats containing beneficial aspects such as riparian vegetation, woody debris, and associated substrates that provide aquatic and terrestrial invertebrates for food, predator avoidance cover, and slower water velocities for resting (Healey 1991).

Optimal water temperatures for juvenile Chinook salmon rearing range from 53.6–57.2°F (12–14°C). A daily average water temperature of 60°F (15.5°C) is considered the upper temperature limit for juvenile Chinook salmon growth and rearing (NMFS 1997). Inhibition of Chinook salmon smolt development in the Sacramento River may occur at water temperatures above 63°F (17.2°C; Marine and Cech 2004).

Juvenile migration rates vary considerably, depending on the physiological stage of the juvenile and hydrologic conditions. SRWRC juveniles begin to emigrate from the Upper Sacramento River (past RBDD) as early as mid-July, with peak abundance occurring in September and extending through November; although emigration can continue through May of the next year in dry water years (Vogel and Marine 1991, Martin et al. 2001, Poytress et al. 2014). On average, SRWRC catch in rotary screw traps at RBDD comprises 78 percent fry (less than 46 mm fork length) and 22 percent pre-smolt/smolt size-class fish (greater than or equal to 46 mm fork length, Martin et al. 2001, Poytress et al. 2014). Fry and pre-smolt migration is stimulated by increases in streamflow or turbidity in the upper Sacramento River basin coincident with the first fall or winter storm events (Vogel and Marine 1991, del Rosario et al. 2013, Poytress et al. 2014). Rotary screw trap passage data indicate fry exhibit decreased nocturnal passage levels during and around the full moon phase in the fall (Poytress et al. 2014). Pre-smolt/smolt appear to be less influenced by nighttime light levels and much more influenced by changes in discharge levels (Poytress et al. 2014).

Hypotheses for Habitat Attributes Affecting Survival, Residence Time/Migration, and Growth:

H_1: Toxicity and contaminants
H_2: Predation and competition
H_3: Refuge habitat
H_4: Food availability and quality
H_5: Outmigration cues
H_6: Stranding risk

H_7: Water temperature and DO
H_8: Pathogens and disease
H_9: Entrainment risk

The foremost factor affecting migration, growth, and survival of SRWRC fry is habitat (e.g., substrate, water quality, water temperature, water velocity, shelter, and food; Williams 2006, Williams 2010). Additional factors include disease, predation, and climate variability (NMFS 1997, Williams 2010). Increased instream flow affects many of these factors through dilution (e.g., toxicity and contaminants), reduction in water temperatures (which also affects DO, food availability, predation, pathogens, and disease) and entrainment and stranding risk, and potentially increases in cues to stimulate outmigration. Access to all historical SRWRC rearing habitat was blocked by the construction of Shasta Dam, confining fry to the low-elevation habitats on the Sacramento River that are dependent on cold water releases from Shasta Dam to sustain the remnant population (**H_7**). Levee building and maintenance, bank protection measures, and the disconnection of the river from its historic floodplain have all had negative effects on riparian habitat. However, streamside riparian vegetation along the Sacramento River between the towns of Redding and Red Bluff has not been as severely affected as other parts of the river, with about 45 percent of the original vegetation remaining. However, the channelized, leveed, and riprapped reaches of the Upper Sacramento River typically have low habitat complexity (**H_3**) and low abundance of food organisms (**H_4**), and offer little protection from predators (**H_2**). Juvenile SRWRC are dependent on the function of this habitat for growth and successful survival.

Storage of unimpeded runoff by Shasta and Keswick dams and the use of stored water for irrigation and export have altered the natural hydrograph by which SRWRC base their migrations (**H_5**). Rather than the peak flows occurring following winter rain events, the current hydrology has truncated or eliminated peaks during the winter and spring and has a prolonged period of increased stable flows through the summer dry season. Altered flows have resulted in diminished natural channel formation, altered food web processes, and slower regeneration of riparian vegetation (**H_3**, **H_4**). The changes in flow patterns have reduced bedload movement, caused gravels to become embedded, and decreased channel widths due to channel incision, all of which have decreased the availability and variability of rearing habitat below Keswick Dam (Mount 1995).

Significant flow reductions from Shasta and Keswick dams in the fall present a stranding risk to SRWRC juveniles (**H_6**). The Keswick Dam release schedule has summer high flows of 13,000–15,000 cubic feet per second during June, July, and August to meet water demand, which corresponds to peak SRWRC spawning time. Flows are then reduced to 3,250–5,500 cubic feet per second in September to maximize storage in Shasta Reservoir the following year. As water levels recede, juvenile salmon can become stranded in shallow, isolated habitat that is disconnected from the main channel (Jarrett and Killam 2014). In these isolated pools, they can be exposed to warm, deoxygenated water (**H_7**), as well as increased predation (**H_2**), leading to direct or delayed mortality.

Irrigation and domestic water use influences the amount of water diverted from the Sacramento River for agricultural and municipal purposes. Unscreened or poorly screened water diversions lead to direct entrainment and mortality and can also reduce river flow (**H_9**). Depleted flows contribute to higher temperatures, low DO levels (**H_7**), and decreased recruitment of gravel and large woody material (**H_3**). Water-diversion infrastructures, most notably the RBDD and the Anderson-Cottonwood Irrigation District Dam (ACID), provide in-river structure that support predation on SRWRC fry by native and non-native fishes (**H_2**). SRWRC juveniles passing RBDD are heavily preyed on by Striped Bass and Sacramento Pikeminnow (NMFS 1997). Large concentrations of Sacramento Pikeminnow were observed immediately below the RBDD, when juvenile SRWRC begin outmigration in late summer and early fall prior to the removal of water-control gates at RBDD (Tucker et al. 2003).

The extent of predation (**H_2**) on juvenile Chinook salmon by wild and hatchery reared Steelhead is not known. Steelhead releases by the Coleman National Fish Hatchery (CNFH) may have a high potential for increasing predation on naturally produced Chinook Salmon (CALFED 2000). The CNFH targets releasing 600,000 juvenile steelhead each January at a size of 195 mm fork length (approximately four fish per pound; CALFED 2000). There is also evidence of residualization of CNFH steelhead in the upper Sacramento River, which would compound the effects of annual CNFH steelhead releases on SRWRC.

In February, Livingston Stone National Fish Hatchery (LSNFH) releases up to 250,000 pre-smolt SRWRC at 85 to 90 mm fork length, a larger size than their wild counterparts. LSNFH SRWRC appear to leave the upper Sacramento River en masse and may precipitate the outmigration of remaining wild SRWRC they encounter through a "pied piper effect." It is unclear the extent to which this may positively or negatively impact the survival or natural-origin outmigrants. It is possible, that under these conditions, a smaller wild fish may leave before its development triggers an outmigration response and result in it competing poorly for refugia and prey, or it may be afforded protection by traveling amid a larger number of fish (**H_2**; NMFS 1997).

Urban and agricultural land use and flood-control activities have cleared, degraded, and fragmented riparian forests and increased urban stormwater and agricultural runoff. This decreases rearing habitat, food production (**H_4**), and refuge from predators (**H_3**), but results in increased sedimentation, toxicity (**H_1**), and water temperatures (**H_7**) for SRWRC fry. Fine sediments constitute nearly half of the material introduced to the river from non-point sources (NMFS 1997). Sedimentation of these smaller sized particles can clog or abrade gill surfaces, reduce primary productivity and photosynthesis activity in the water column, and affect water temperature and DO levels. Urban stormwater and agricultural runoff may be contaminated with pesticides, herbicides, oil, grease, heavy metals, polycyclic aromatic hydrocarbons, and other organics and nutrients that potentially have direct lethal and sub-lethal physiological and behavioral effects on SRWRC fry and destroy the aquatic life necessary for salmonid growth and survival (**H_1**; NMFS 1997).

Past mining activities on the Sacramento River routinely resulted in the removal of gravels from streams, the straightening and channelization of the stream corridor from dredging activities, and the leaching of toxic effluents into streams from mining operations (**H_1**). Uncontrolled acidic drainage from Iron Mountain Mine located near Shasta Dam was the largest source of surface water pollution in the United States at one time, and could eventually reach the Sacramento River. Remediation and pollution-control activities have reduced the discharge of acidity, copper, cadmium, and zinc by 95 percent. However, acid mine drainage still escapes untreated from waste piles and seepage on the north side of Iron Mountain, which eventually flows into the Sacramento River.

Specific diseases such as C-shasta (*Ceratomyxosis shasta*), columnaris, furunculosis, and infectious hematopoietic necrosis virus, among others, are known to affect juvenile SRWRC survival in the Sacramento River (NMFS 1997). Disease transfer from hatchery fish and immune impairments from warm temperatures can increase susceptibility to natural-origin SRWRC disease. Several factors can influence disease and pathogen exposure, including seasonal changes, reduced flows, handling practices, and climate change (**H_8**).

Observations throughout the last 50 years reveal trends toward warmer water temperature during winter and spring, a smaller fraction of precipitation falling as snow, a decrease in the amount of spring snow accumulation in lower and middle elevation mountain zones, and an advance in snowmelt by 5–30 days in the spring (Knowles et al. 2006). Climate change may influence SRWRC fry growth, survival, and migration timing (**H_5**) in the Upper Sacramento River due to lower flows, higher stream temperatures (**H_7**), loss of lower elevation habitat (**H_3**), and the increased abundance and metabolism of predators (**H_2**).

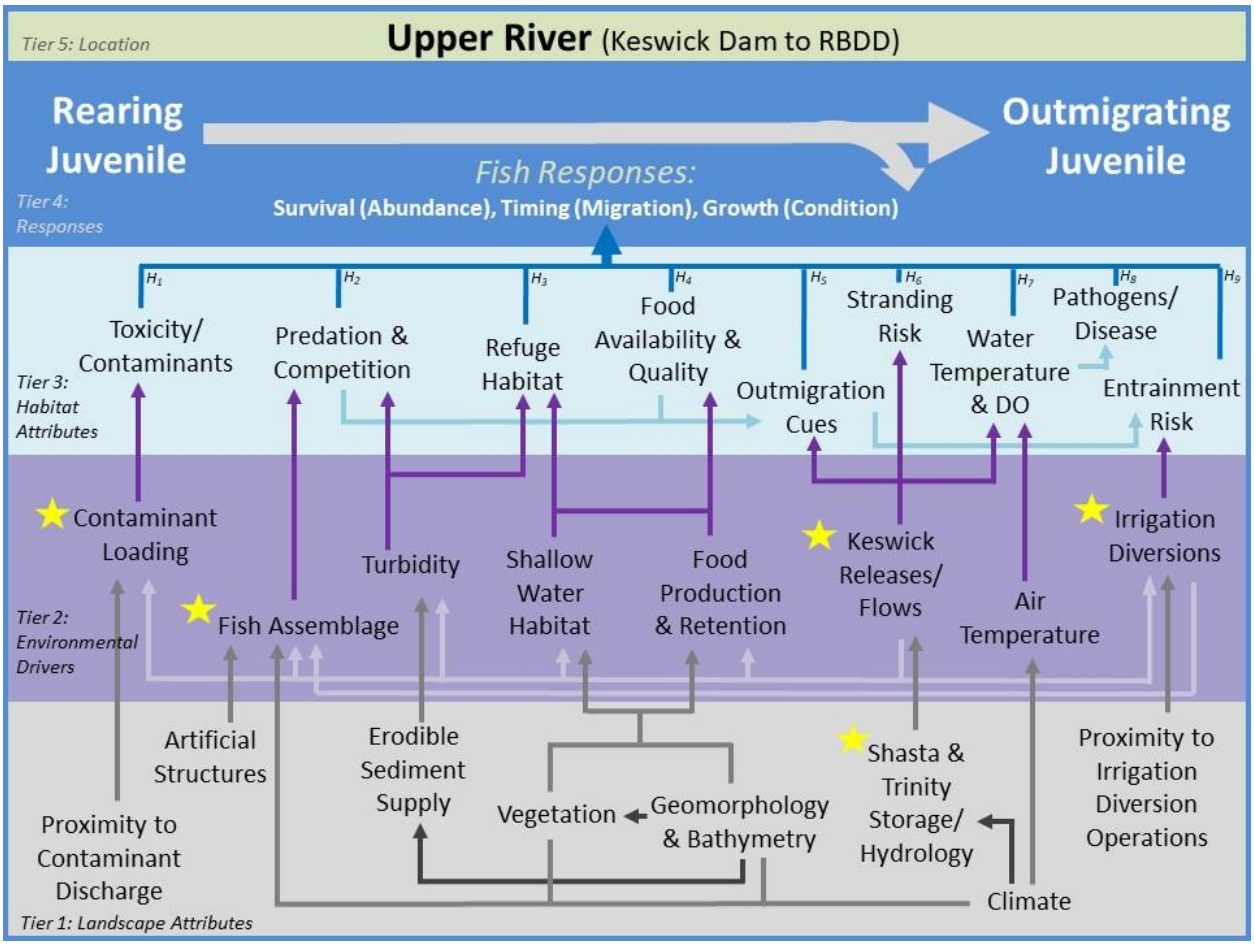

Figure 4. Conceptual model of drivers affecting the transition of SRWRC from rearing juvenile to outmigrating juvenile in the Upper Sacramento River. Hypotheses referenced by the "H-number" are identified in the conceptual model 2 (CM2) narrative. Management actions are denoted by stars and are described in Table 1.

CM3: Rearing to Outmigrating Juveniles in Middle Sacramento River

Geographic Extent. The Middle Sacramento River is defined as the geographic area between RBDD and the location where tidal forces cause reverse flows to occur during the daily tidal cycle. Although this location varies with Sacramento River outflow and the stage of the spring-neap tidal cycle, it typically occurs between Freeport Bridge Crossing and Georgiana Slough on the mainstem Sacramento River, except during high-flow events that can push the location of reverse flows downstream of the town of Rio Vista. Within the CMs, the I Street Bridge in Sacramento City is used as the landmark denoting the lower end of the Middle Sacramento River. When off-channel habitat such as the Yolo and Sutter Bypasses are connected to the mainstem Sacramento River by flooding, this habitat is also considered part of the Middle Sacramento River.

Biology of Life Stage. Juvenile SRWRC spend a varying duration of time rearing in the Upper River following emergence (CM 2) and before migrating past RBDD into the Middle Sacramento River. Juveniles use the Middle Sacramento River as a rearing habitat and a migratory corridor to the tidal Delta (CM 4). The majority of SRWRC-sized juveniles migrate past RBDD from August–December (Poytress et al. 2014) and past Knights Landing at the downstream end of the Middle Sacramento River between October–April (del Rosario et al. 2013). Increased migrant densities past these points are typically associated with flow and turbidity increases, and the timing of peak migration is associated with the earliest occurrence of threshold flow events during each migration season.

The average duration of time juveniles spend in the Middle Sacramento River varies widely among years. Israel et al. (2015) found that between water years 2007 and 2014, average rearing time was between 65 and 164 days, based on calculating the elapsed time between the median catch of naturally-spawned SRWRC-sized juveniles at RBDD and Knights Landing rotary screw traps. During reduced flows under drought conditions in 2013, juvenile SRWRC experienced a more prolonged entry period and a longer residence time within the Middle Sacramento River, and a more contracted timing of Delta entry (Israel et al. 2015). Acoustically tagged hatchery-origin SRWRC spent an average of 45, 20, and 9 days to transit the Sacramento River in 2013, 2014, and 2015 respectively (Ammann, NMFS, personal communication). These six release groups of acoustically-tagged fish comprised individuals at the upper end of the size distribution of natural-origin SRWRC upon entering the Middle Sacramento River at RBDD. Therefore, migration rates measured using acoustic telemetry may overestimate migration rates of smaller individuals in the naturally spawned population because the migration rate of juvenile Chinook salmon increases with size and developmental stage (Giorgi et al. 1997).

The size distribution of juveniles entering and exiting the Middle Sacramento River also varies among years (del Rosario 2013, Poytress et al. 2014). Rotary screw trapping indicates naturally-spawned juvenile SRWRC generally enter the Middle Sacramento River predominantly as fry (less than 46 mm; Poytress et al. 2014) and exit the Middle Sacramento River to the Delta predominantly as parr or smolt (greater than 46 mm; del Rosario et al. 2013). Differences in size

distributions upon entry and exit are associated with migration timing, which in turn is associated with the timing and magnitude of peak flow events. For example, larger proportions of fry migrants occur in samples taken at entry and exit locations to the Middle Sacramento River in years with exceptionally high and early threshold flow events (del Rosario et al. 2013).

It is difficult to estimate survival of natural-origin SRWRC juveniles once they migrate downstream of RBDD. However, survival of hatchery-origin SRWRC has been estimated from 2013 to 2015. The survival of acoustically-tagged hatchery release groups ranged from 0.161–0.641 during passage along the Middle Sacramento River in 2013 to 2015, respectively (Ammann, personal communication). Due to the relatively large size of hatchery fish that are acoustically tagged and released later in the season compared to the peak of the natural-origin fry outmigrants at RBDD, it is unclear the extent to which they represent adequate surrogates for the naturally spawned population.

Hypotheses of Habitat Attributes Affecting Survival, Residence Time and Migration, and Condition

H_1: Toxicity and contaminants
H_2: Predation and competition
H_3: Refuge habitat
H_4: Food availability and quality
H_5: Stranding risk
H_6: Outmigration cues
H_7: Water temperature and DO
H_8: Pathogens and disease
H_9: Entrainment risk

Residence Time (Emigration Timing from Middle Sacramento River). Residence time in the Middle Sacramento River (and therefore the emigration timing from the Middle Sacramento River) is a function of the physical ability of water flow to advect juvenile salmon downstream and the biological response of juvenile salmon to those advective forces. For example, juvenile salmon may swim with flow in high velocity areas of the channel, or they may resist advection by swimming against flow and by seeking channel areas with low velocity. The response of juvenile salmon to rear rather than emigrate is likely influenced by a host of potential physical and biological cues (**H_5**), including the occurrence of threshold flows, turbidity, water temperature (**H_7**), habitat availability, individual growth rate (food supply), fish densities, and an individual's ability to secure a territory. How an individual juvenile SRWRC responds to these potential cues is in turn affected by the timing, size, condition, and developmental stage upon entry and exit from the Middle Sacramento River. In addition to advection, which serves to speed juvenile migration along the Middle Sacramento River corridor, higher flows activate accessible floodplains and secondary channels, expanding the availability of low-velocity refuge habitat (**H_3**). In addition to activated off-channel habitat, habitat features within the channel such as large wood may serve as low-velocity refuge habitat.

The role of growth rate as a migration cue (**H5**) is complicated, and its implications for juvenile migration rate in the Middle Sacramento River are uncertain. Higher growth rate is associated with earlier smoltification and faster downstream migration (Beckman et al. 1998, Beckman and Dickhoff 1998). However, the inability of a juvenile in a particular habitat to supply its metabolic demand and achieve some threshold growth rate may also serve as a strong cue to leave that habitat and migrate downstream, and a satisfactory food supply (**H4**) may induce a juvenile to remain in the habitat for a longer duration of time to rear. In Central Valley Steelhead, growth rate at a particular developmental window is thought to influence the extent to which individuals migrate to the ocean or remain resident in rivers, and thus may play a similarly important role in the timing of salmon migration (Satterthwaite et al. 2010). Growth rate is essentially an outcome of constraints on maximum potential growth rate and of the balance between juvenile metabolic demand (energy expended) and metabolic supply (energy consumed, food; **H4**). Therefore, the residence time of an individual juvenile in the Middle Sacramento River may be affected by anything that affects an individual's maximum potential growth rate (e.g. intrinsic individual growth rate, water temperature; **H7**), metabolic demand (e.g. water temperature (**H7**), predator-competitor avoidance (**H2**), water velocity (**H6**)), or metabolic supply (e.g. food production, food quality (**H4**), and competition [**H2**]).

***Growth and Condition in the Middle Sacramento River*.** Juvenile size is associated with predation risk (**H2**) because many predators of juvenile salmon are gape limited. Juvenile salmon are themselves gape limited, constraining their ability to obtain food (**H4**). For this reason, growth rate is important for juvenile survival during middle Sacramento River passage and for future juvenile survival in the ocean (Woodson et al. 2013), particularly in years with poor oceanographic conditions for growth where larger juveniles can consume a larger range of available prey.

Fundamental constraints on an individual's realized growth rate are maximum potential growth rate, metabolic energy expenditure, and energy consumption. A component of an individual's maximum potential growth rate is likely genetically determined. External factors such as water temperature (**H7**) below the optimal temperature for growth, and possibly environmental conditions affecting growth rate during early development (in the Upper Sacramento River), serve as external constraints on maximum potential growth rate. For example, sub-lethal water temperatures and exposure to contaminants (**H1**) can affect realized growth rate by increasing metabolic costs, and affect hormone balance or suppress appetite, respectively. Similarly, immune response to pathogens and disease (**H8**) can reduce growth rate by increasing basal metabolic demand. Parasitic pathogens further reduce growth rate by siphoning off consumed energy. Habitats that provide refuge (**H3**) from high water velocity or predators, without depleting food supply (**H4**), function to increase growth rates by reducing energy demand to obtain a given food supply. However, the extent to which fish density results in competition (**H2**) for refuge habitat or food can reduce growth rates by increasing metabolic demands to obtain a given level of food intake.

Inundated floodplains in the Central Valley have proven a particularly successful habitat for fish growth (Sommer et al. 2001, Limm and Marchetti 2009). This success has been attributed to optimum water temperature (**H_7**), lower water velocity, and higher food quality and density relative to the main channel. However, reduced predator and competitor density also likely contribute to high growth rates observed for juvenile salmon rearing in floodplains.

***Survival During Middle Sacramento River Passage*.** Piscivore and avian predation (**H_2**) is probably the most common proximate cause of juvenile mortality in the Middle Sacramento River. Therefore, anything that has a substantial influence on predation risk will also substantially influence survival rate, including factors such as predator density, alternative prey, residence time, and refuge habitat availability (**H_3**). Direct mortality caused by pathogens and disease (**H_8**), contaminants (**H_1**), lethal water temperature (**H_7**), or inadequate food availability (**H_4**) are also potentially important sources of mortality in the Middle Sacramento River. Entrainment (**H_9**) at unscreened or ineffectively screened water diversions or stranding (**H_6**) in disconnected off-channel habitat also influences salmon survival. However, indirect processes may also play a substantial role in salmon survival. For example, the cumulative and sub-lethal effects of multiple stressors can influence juvenile behavior, condition, and growth rate, which all influence vulnerability to predation (**H_2**). Similarly, the timing, size, and condition of juvenile immigrants from the Upper Sacramento River into the Middle Sacramento River likely can influence residence time and vulnerability to predation as juveniles rear and migrate in the Middle Sacramento River.

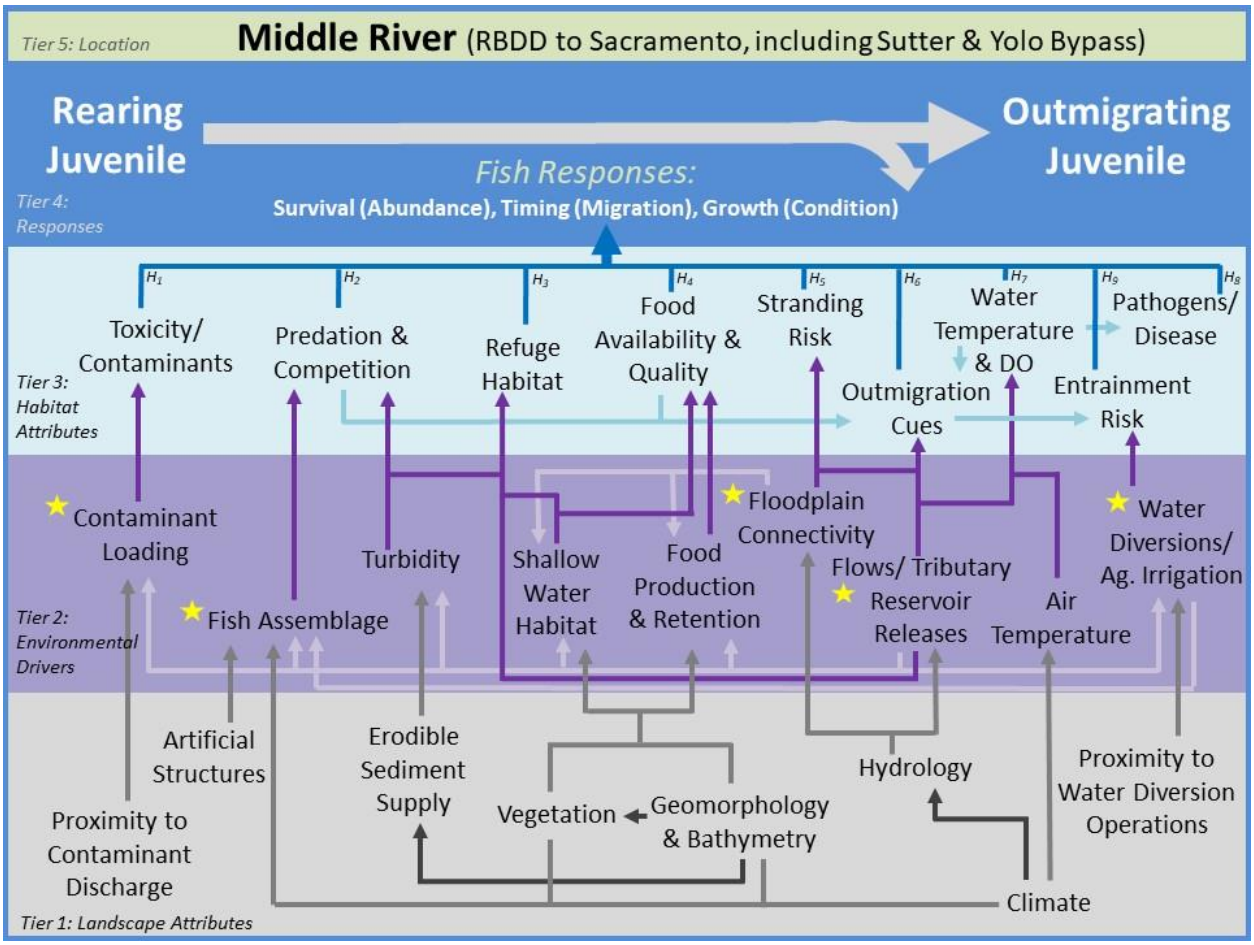

Figure 5. Conceptual model of drivers affecting the transition of SRWRC from rearing juvenile to outmigrating juvenile in the Middle Sacramento River. Hypotheses referenced by the "H-number" are identified in the conceptual model 3 (CM3) narrative. Management actions are denoted by stars and are described in Table 1.

CM4: Rearing to Outmigrating Juveniles in Bay-Delta

Geographic Extent. Juvenile rearing and migration in the Tidal Estuary and bays (tidal Sacramento River downstream of the I Street Bridge in Sacramento City, the Sacramento-San Joaquin Delta, and the Suisun, San Pablo and San Francisco Bays).

Biology of Life Stage. The use of the Sacramento-San Joaquin Delta and San Pablo and San Francisco bays by juvenile SRWRC is highly variable among years and even between downstream migrant groups during a single year. Natural-origin SRWRC juveniles can migrate into the Delta as early as September (Schaffter 1980) and have been observed leaving the Delta at Chipps Island in the January to April period (Dekar et al. 2013), although some may reside into May. In years with large precipitation storms and subsequent flow events on the Sacramento River in the late fall, a bimodal pulse of downstream migrants occurs (del Rosario et al. 2013). The initial pulse typically follows the first large storm in November or December, with a second pulse in the February–March period when those rearing upstream of the Delta are cued to migrate downstream and into the San Francisco Bay (Dekar et al. 2013, Israel et al. 2015). In years lacking early season precipitation events, the pulse tends to be unimodal, with the majority of Bay-Delta entry occurring in the late winter and early spring months (Israel et al. 2015).

Hatchery- and natural-origin SRWRC utilize side channel and inundated floodplain habitat in the tidal shoreline of the Delta for foraging and growth. The tidal habitat of the Delta also serves the critical role as a physiological transition zone before saltwater entry, with juvenile SRWRC residing in the Delta for an average of 3 months (del Rosario et al. 2013). However, only a small fraction of the wetland rearing habitat is still accessible to fish, and much of the modern Delta and bays have been converted to serve agriculture and human population growth (SFEI-ASC 2014). Information regarding juvenile SRWRC use of Delta and bay habitats is limited. This is because routine sampling by the California Department of Fish and Wildlife (CDFW) occurs once a month and the capture of juvenile Chinook salmon during U.S. Fish and Wildlife Service (USFWS) beach seining is generally restricted to years with high outflow.

Differences in Federal Endangered Species Act listing status among Central Valley Chinook salmon populations has resulted in classifying juveniles of each run type based on a length-at-date (LAD) criteria (River LAD, Fisher 1992; Delta LAD, Harvey et al. 2014). However, spatial and temporal variability in growth rates makes size-based assessments of juvenile Chinook salmon run unreliable (Pyper et al. 2013, Harvey et al. 2014). The four Central Valley salmon runs spawn at different times of year or in different habitats, but the growth of the juveniles varies depending on rearing location. As the juveniles migrate downstream, the size of juveniles on a particular date overlap, thus making it difficult to determine the timing and relative abundance of juveniles from the various runs without genetic sampling.
Pyper (et al. 2013) and Harvey (et al. 2014) found that SRWRC and spring-run Chinook salmon juvenile abundance was overestimated at Chipps Island and at water export facilities based on river or Delta LAD criteria, while fall and late-fall run Chinook salmon abundance was underestimated. Although size-based run identification methods are still broadly used in the

Tidal Estuary, run-specific timing and abundance information derived from LAD criteria to catch data in monitoring surveys must be interpreted with caution.

Hypotheses of Habitat Attributes Affecting Survival, Residence Time and Migration, and Condition

H_1: Toxicity and contaminants
H_2: Predation and competition
H_3: Refuge habitat
H_4: Food availability and quality
H_5: Outmigration cues
H_6: Stranding risk
H_7: Water temperature and DO
H_8: Pathogens and disease
H_9: Entrainment risk

In this CM, every term in the habitat attributes tier (Tier 3, Figure 4) is connected to survival, timing, and growth in the response tier (Tier 4), because habitat attributes may act together to produce additive stressors or negate a habitat benefit or energetic cost. For example, the availability and quantity of salmon prey, the physicochemical conditions that maintain prey communities, and temperatures that promote high metabolic efficiency are all aspects of the capacity of habitat to support juvenile Chinook salmon (Simenstad and Cordell 2000). Simulations suggest that a juvenile salmon thermal tolerance is constrained by size, feeding rate, prey quality, and water temperature (Beauchamp 2009). For example, if more food is available or a fish is smaller, it may benefit from higher metabolic efficiency associated with higher temperature conditions. However, if less prey is available, the thermal tolerance for higher temperatures (>56°F/13.3°C) will likely diminish. This tradeoff between prey quality and temperature thresholds is also affected by competition and predation risk acting together to influence habitat capacity (**H_2, H_4, H_7**).

Increased toxicity negatively affects the survival, migration, and condition of juvenile salmon within the Tidal Estuary (**H_1**). Toxicity from contaminants (e.g., algae, metals, and insecticides) can affect condition and survival (Finlayson and Verrue 1985, Spromberg and Meador 2005), suppress salmon immune systems (Arkoosh et al. 1994, Arkoosh et al. 1998, Arkoosh et al. 2001, Milston et al. 2003), reduce somatic growth (Finlayson and Verrue 1985), and alter behavior (Scott and Sloman 2004). Indirectly, contaminants can cause alterations in fish behavior that increase risk to predation and inter- and intra-specific competition by limiting food availability and reductions in the ability to detect prey or predators (Day and Kaushik 1987, Scott and Sloman 2004; **H_2, H_4**). In addition, contaminants may influence the migration of Chinook salmon by affecting their olfactory systems (Stein et al. 1995, Scholz et al. 2000; **H_5**). It is also hypothesized that pathogens and disease may negatively affect juvenile SRWRC in the Tidal Estuary (**H_8**). Negative effects of pathogens have been demonstrated in the Sacramento and San

Joaquin rivers and Coleman National Fish Hatchery and Feather River Fish Hatcheries (Kelley et al. 2007, Bendorf et al. 2007).

Habitat attributes affect fish access to the habitat, such as flooding, geomorphic features important to connectivity or entrainment, proximity to disturbance and refugia areas, and the strength of cues (e.g., habitat opportunity; Simenstad and Cordell 2000). The presence or lack of accessible refugia from extreme temperatures, predators, and anthropogenic structures and diversions can decrease or increase risk of thermal stress, predation, stranding, and entrainment, thereby providing or depriving juvenile Chinook salmon an opportunity to use and benefit from rearing and migratory habitats within the Lower Sacramento River, Delta, and bays (**H_2, H_3, H_6, H_7, H_9**). For example, thermal heterogeneity may create the opportunity for salmon to thermoregulate behaviorally and take advantage of the trophic resources in environments with temperatures that are less metabolically efficient (Armstrong et al. 2013). Further, fishes may use local cover (e.g., aquatic vegetation, woody debris, or coarse sediment) to avoid contact with or detection by predators, which minimizes mortality risk (Werner et al. 1983, Harvey and Stewart 1991, Rahel and Stein 1998). Bathymetric heterogeneity can also provide refugia and has been shown to increase residence time in a restored marsh by providing appropriate water depths for juvenile Chinook salmon throughout the tidal cycle (Hering et al. 2010).

Salmon occur across a landscape, and effects on previous life stages can contribute to measurable salmon responses in later life stages. This cumulative landscape effect complicates evaluations of the relationships between population level management goals and site-specific assessments. A primary influence on juvenile salmon survival is habitat capacity (**H_2, H_4, H_7**). In addition, survival in the Lower Sacramento River, Delta, and bays is influenced by predator densities in migration corridors and rearing habitats (**H_2**). The Sacramento-San Joaquin Delta hosts large populations of introduced Striped Bass and Largemouth Bass (*Micropterus salmoides*), as well as the native piscivore Sacramento Pikeminnow (Grossman et al. 2013), all of which consume Chinook Salmon (Schreier, unpublished data). Indeed, bioenergetic modeling work for Striped Bass has shown that even if this species consumed every Chinook Salmon in the system, the salmon population could not support the energetic demand of the Striped Bass population (Loboschefsky et al. 2012). Additionally, in the CM, predation and competition are linked to refuge. In some habitats, predation risk may be increased when the access to refugia habitat is low. For example, in leveed river channels, predator density may be high with few or no areas with cover or low velocity. In contrast, shallow, vegetated, tidal wetland areas may host predators, but predation risk may be lower because juvenile salmon may have access to refugia (Kilgore et al. 1989, Grimaldo et al. 2000; **H_3**). Salmon densities (determined in part by hatchery releases) also influence predation rate by determining the level of competition for refugia habitat and the degree of predator attraction to salmon rearing and migration areas. Furthermore, the condition of individual salmon can affect mortality risks and will be affected by prior and current exposure to toxins (**H_1**), temperature and DO (**H_7**), and food availability and quality (**H_4**) in the surrounding environment.

Salmon survival rates are also influenced by habitat opportunity attributes. Migration corridors and rearing habitats near water diversions increase the risk of entrainment-related mortality (**H_9**). Juvenile salmon arriving in the southern end of the Delta are at risk of entrainment in the Central Valley Project and State Water Project water intakes. Each of these pumping plants has a fish salvage facility, and recent research suggests that once juvenile salmon enter the southern Delta, survival can be higher for fish captured in the Central Valley Project salvage facility and re-released more seaward (Buchanan et al. 2013). This reflects the extremely poor survival rate in the South Delta, which is hypothesized to result from poor rearing conditions (such as low refuge habitat and food availability) and high predation risk. In addition, juvenile salmon may experience a diminished ability to navigate out of the South Delta toward the ocean due to confusing navigational cues from altered hydrology, changes in channel network configuration and water quality gradients, and impairments to sensory systems from contaminants. Elsewhere in the tidal river Delta, a myriad of water diversions exists for local agriculture, most of which are un-screened (Moyle and Israel 2005), and mortality from these diversions may be significant during some seasons. Additionally, anthropogenic structures may increase stranding risk (**H_6**), which is substantial in stilling basins or deep areas of weirs that are full of water after floodwaters recede (Sommer et al. 2005). Stranding can also occur after flooding of large floodplain areas (e.g., the Yolo Bypass) and riparian areas as the hydrograph recedes (**H_6**; Nagrodski et al. 2011).

Juvenile salmon growth in the Tidal Estuary is influenced by water temperature, food availability, and inter- and intra-specific competition (**H_2, H_4, H_7**). Juvenile salmon metabolic rates are influenced chiefly by water temperature (Bradford and Geen 1992, Beakes et al. 2014). In the Lower Sacramento River and Delta, water temperature varies with air temperature, flow, and habitat type (Wagner et al. 2011). Shallow tidal wetland and floodplain habitats are generally warmer than leveed river channels (Sommer et al. 2001). Warmer water temperatures and longer water residence times in these areas boost productivity and retention of zooplankton and aquatic insect prey (Schemel et al. 2003) and results in faster growth rates in juvenile salmonids compared to steep, armored river channels (Sommer et al. 2001, Jeffries et al. 2008). Juvenile salmon densities and intra-guild competitor densities influence food availability. Therefore, high densities of hatchery salmon can have a negative impact on natural-origin juveniles, which has been shown to occur during years of poor ocean conditions (Levin et al. 2001).

Juvenile salmon migration timing is influenced by hydrology as well as habitat opportunity and capacity in the Lower Sacramento River system, Delta, and bays (**H_2, H_3, H_4, H_5, H_7**). Connectivity within the tidal wetland network also affects migration route selection and timing for juvenile Chinook salmon. Artificial structures can delay migrants and result in a mismatch of environmental cues and migration-timing adaptations (Schaller et al. 2014). SRWRC follow flow cues to initiate migration downstream (e.g. past Knights Landing), with large migratory pulses occurring coincident with the first large storm event of the winter season (del Rosario et al. 2013). However, their residence period within the tidal system before moving to the bays (e.g., past Chipps Island) varies, with residence time within the Delta ranging from 41 to 117 days (del Rosario et al. 2013). Additional variation in migration timing may result from temporal variability in habitat opportunity. For example, when large floodplain areas are available in

periods of high flow, such as when the Fremont Weir overtops and juvenile salmon can access floodplain areas in the Yolo Bypass, SRWRC residence time may increase. Delta residence times also depend on size when entering the Delta (del Rosario et al. 2013). However, delayed migration in the mainstem channels of the Delta has also been observed (Michel et al. 2012). Human modification of the Delta has resulted in a channel network that no longer operates across predictable gradients for native fish and provides unnatural cues and routes for migration (SFEI-ASC 2014). In the interior Delta, longer travel times and lower survival have been documented (Brandes and McLain 2001, Newman and Brandes 2010, Perry et al. 2010). In one study, survival probabilities were negatively associated with water exports, suggesting that water exports affect migration by increasing the risk of entrainment, although the authors note that many more years of data would be needed to precisely estimate the export effect (Newman and Brandes 2010). In the CV, there is evidence for diverse juvenile migratory phenotypes contributing to the adult population (Miller et al. 2010, Sturrock et al. 2015). However, studies also show that biocomplexity among adult returns has been severely reduced such that annual return rates have become highly correlated in recent years, thus reducing basin-wide population stability and leaving CV salmon populations more vulnerable to extreme events (Carlson and Satterthwaite 2011). An important contributor to reduced biocomplexity of adult returns has been the homogenization of juvenile out-migration timing promoted by hatchery and other management practices (Lindley et al. 2009). Planned wetland restoration is expected to diversify rearing habitat in the Delta and increase variation in out-migrant timing and population stability.

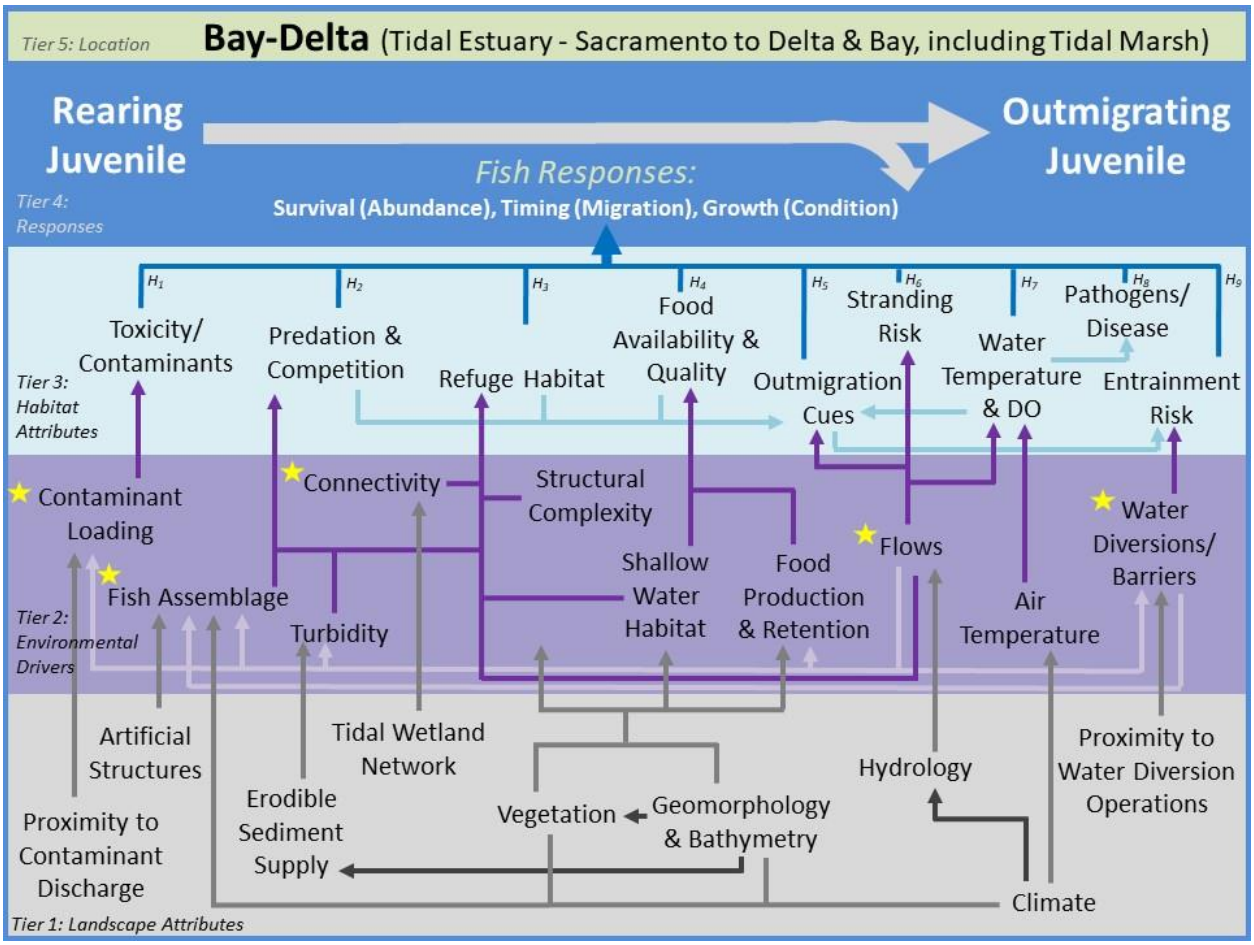

Figure 6. Conceptual model of drivers affecting the transition of SRWRC from rearing juvenile to outmigrating juvenile in the Bay-Delta. Hypotheses referenced by the "H-number" are identified in the conceptual model 4 (CM4) narrative. Management actions are denoted by stars and are described in Table 1.

CM5: Ocean Juvenile to Ocean Adult

Geographic Extent. The northeast region of the Pacific Ocean, west of the coast of the United States and Canada.

Biology of Life Stage. The ocean is a critical environment for SRWRC, and is where these fish spend most their lives and put on most of their growth and weight. The length of juvenile Chinook Salmon at the time of seawater entry is highly variable and ranges from 75 to 250 mm (Williams 2006). Outmigrating juveniles leave San Francisco Bay generally between January and March and initially enter the Gulf of the Farallones, a relatively shallow, protected area, with high prey abundance (Santora et al. 2012). Once in the nearshore marine environment, their diet consists largely of larval and juvenile fishes and plankton such as euphausiids (Healey 1991, MacFarlane and Norton 2002, Wells et al. 2012). Juveniles initially reside in eddies on either side of the Golden Gate Bridge, and then move north and south within a range extending from Monterey Bay to the Columbian River (Williams 2010). Generally, SRWRC ocean residency is concentrated off the California central coast (Satterthwaite et al. 2013, Johnson et al. 2016).

Mortality during this ocean phase of the lifecycle is highest during the first year and strongly influences their survival to harvest or spawning (Beamish and Mahnken 2001, Quinn 2005, Wells et al. 2012, Woodson et al. 2013). Most CV Chinook Salmon spend approximately 2 years in the ocean, with the majority of that time spent residing on the continental shelf rather than the open ocean. As juveniles transition into adults, it is likely their distribution is influenced by ocean conditions (Williams 2010). Central Valley Chinook salmon typically occupy habitat where the water temperature is between 8 and 12 °C, and move into deeper waters in the winter (greater than 200 meters) and shallower waters in the late spring and early summer (Hinke et al. 2005).

Variation in ocean conditions can influence the abundance of returning adult salmon as much as variation in freshwater conditions (Bradford 1995). Ocean productivity can be largely responsible for the survival and size of returning adult salmon, and the likelihood of survival increases with fish size and condition (MacFarlane 2010, Woodson et al. 2013). Ocean upwelling intensity off Central California's coast influences nutrient availability and primary production, thereby directly influencing the abundance of zooplankton and forage fish abundance (Wells et al. 2008a). Salmon growth and recruitment depends on the availability of these prey items, and juvenile salmon diet composition, condition, and abundance responds positively with upwelling (Wells et al. 2008b, Wells et al. 2012).

Management actions within the Sacramento River and Sacramento-San Joaquin Delta influence the size, timing, and abundance of juveniles emigrating to the ocean, and therefore juvenile survival in the ocean, depending on ocean conditions. If outmigrating juveniles are small when ocean conditions are poor, there is likely increased mortality (Woodson et al. 2013) due to predation (Emmett and Krutzikowsky 2008). If hatchery fish releases are increased to

compensate for perceived poor survival of wild salmon in the ocean, density dependence may occur, increasing mortality on smaller (and likely wild) juveniles (Miller et al. 2013). Contrarily, if wild juveniles are similar in size to hatchery fish, this could create niche overlap and increased competition within the ocean (Daly et al. 2012). Variability in juvenile salmon size and timing when entering the ocean, along with predation, needs to be considered in the context of ocean productivity at the time of entry, which presents a very complex system to manage (Satterthwaite et al. 2013, Fiechter et al. 2015).

Hypotheses for Habitat Attributes that Effect Juvenile and Adult Salmon in the Ocean

H_1: Predation and competition
H_2: Food availability and quality
H_3: SRWRC bycatch in mixed-stock ocean salmon fisheries
H_4: Freshwater migratory cues for returning adults

Three primary factors affect salmon survival during the ocean phase of their lifecycle: 1) predation, 2) food supply, and 3) harvest (Vogel 2011). Juvenile salmon are susceptible to predation and competition when they enter the open ocean, especially during their first year of residence when mortality is highest (**H_1**). Ocean survival of salmon are size- (Woodson et al. 2013) and condition-dependent (Tucker et al. 2013), and juvenile salmon are negatively impacted through competition with the release of hatchery smolts that are larger in size and greater in numbers than wild stocks (Levin et al. 2001). Juveniles also experience high predation upon entering the ocean, and predation pressure may depend upon the availability of alternative forage bases of food (such as sardines) for their predators (LaCroix et al. 2009). Ainley et al. (2014) demonstrates that common murre (*Uria aalge*) and rhinoceros auklet (*Cerorhinca monocerata*), among other piscivorous seabirds, prey on juvenile Chinook salmon. Humans also act as competitors and predators for adult ocean salmon by harvesting forage fish that adult salmon eat (or that have a dietary overlap with juvenile salmon) and harvesting adult salmon directly.

Ocean conditions and productivity influence the availability and quality of food supply, and thus have a significant effect on the survival and growth of salmon residing in the ocean (**H_2**). Diets in the ocean depend on many factors, including what is available given the ocean conditions at that time and location. Therefore, the quantity and quality of available food is likely more important than actual species consumed (Healey 1991, Thayer et al. 2014); it varies temporally and spatially, and therefore influences variation in juvenile and immature adult salmon growth rates at sea and the size and age of returning adult salmon (Wells et al. 2006).

The distribution of salmon stocks in the ocean is heterogeneous (spatially and temporally), but at broader spatial scales salmon are often found in mix-stock aggregations at sea (Weitkamp 2010, Johnson et al. 2016). SRWRC adults are caught incidentally in mixed-stock commercial and recreational fisheries that primarily target fall-run Chinook salmon off the California central

coast (**H_3**; Satterthwaite et al. 2013, Johnson et al. 2016). O'Farrell et al. (2012) estimated that SRWRC spawner abundance was reduced between 11 and 28 percent (average = 20 percent) for brood years 1998 to 2000 as a result of ocean fisheries.

Once adult salmon begin the process of sexual maturation at sea, they undergo three important and complex biological changes during their homeward migration into freshwater: 1) the cessation of feeding, 2) major endocrinological changes associated with maturation, and 3) the physiological transition in osmotic conditions from saltwater to freshwater (Quinn 2005). Salmon cannot assess the appropriate conditions needed in freshwater from the ocean, so migration from the ocean into rivers is strongly controlled by genetic factors and local adaptations, and facilitated through social behaviors (Quinn 2005, Johnson et al. 2016). Once adult salmon begin to approach their natal river, the freshwater source provides critical information for homing and the final stages of the migration from the ocean into rivers (**H_4**), because juvenile salmon imprint on odors while migrating downstream and are attracted to these odors as returning adults (Quinn 2005). Salmon that enter river systems in the fall often do so after freshets by responding to increased flow and turbidity. Thus, freshwater habitat in the form of river flow level, timing and olfactory cues provides migration cues for adult salmon when leaving the coastal ocean environment. Habitat attributes in freshwater can affect these cues and the success of salmon initiating their migration into freshwater during periods that maximize overall population fitness and productivity.

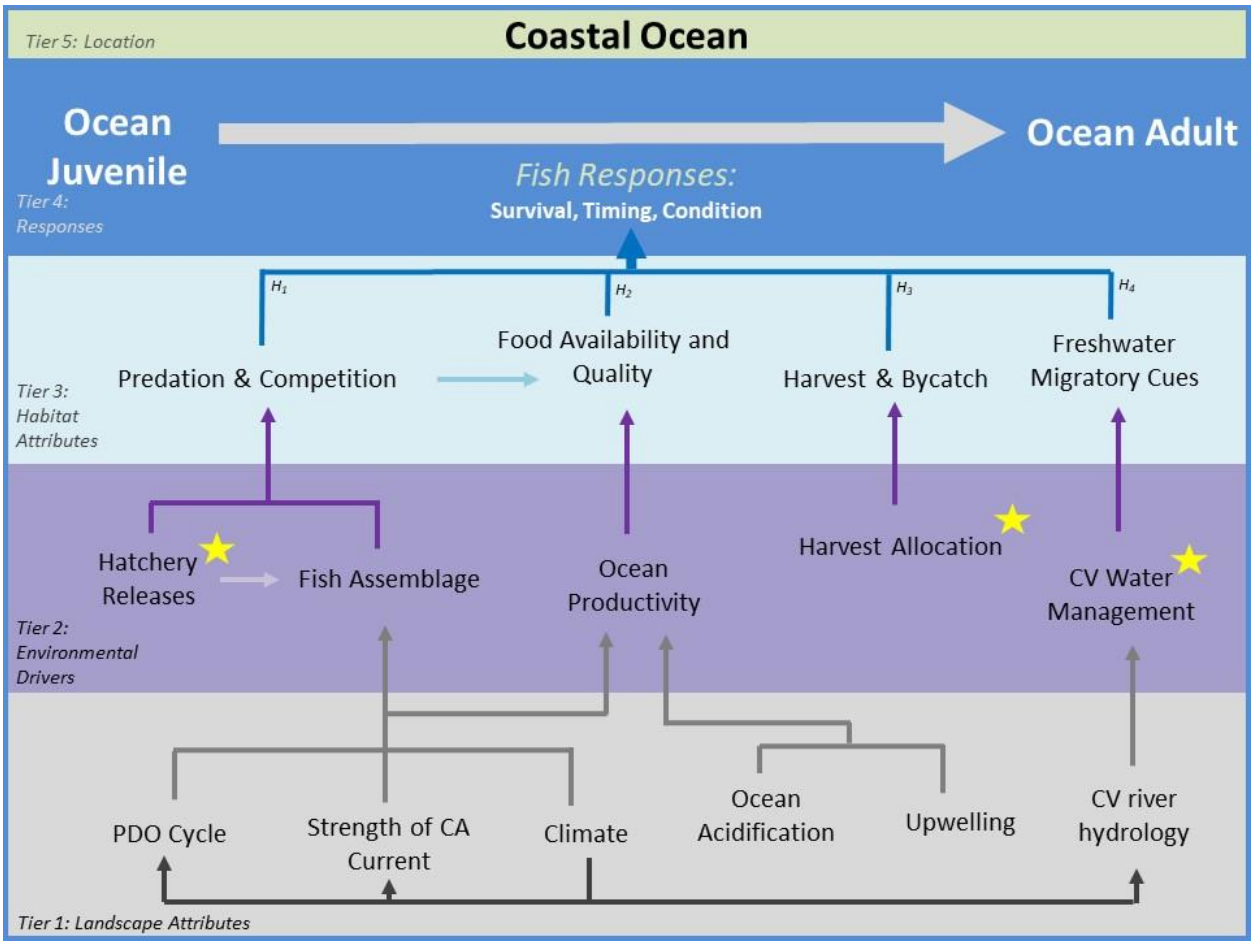

Figure 7. Conceptual model of drivers affecting the transition of SRWRC from ocean juvenile to ocean adult in the Coastal Ocean. Hypotheses referenced by the "H-number" are identified in the conceptual model 5 (CM5) narrative. Management actions are denoted by stars and are described in Table.

CM6: Adult Migration from Ocean to Upper Sacramento River

Geographic Extent. The entire Bay-Delta and Sacramento River system.

Biology of Life Stage. Returning adult salmon have a fixed amount of somatic energy to accomplish a salt-to-freshwater transition, an energetically demanding spawning migration, sexual maturation, and reproduction. Because Chinook Salmon spawn only a single time in their life, lifetime fitness depends on the physiological condition and health during their spawning migration. There is considerable variation in the extent to which the condition of an adult can buffer and defend against susceptibility to deleterious diseases (Cooke et al. 2012). Salmon evolved complex mechanisms to navigate and return to the river where they were spawned (Ueda 2012, Keefer and Caudill 2013). Salmon use different navigation tools at different spatial scales to facilitate successful migration, much like humans may navigate to a distant location using general cardinal directions and switch to road signs and addresses when nearing a destination. There is strong evidence for a combination of geomagnetic and olfactory cues contributing to salmon homing to their natal rivers (Hasler and Wisby 1951, Nordeng 1977, Quinn and Dittman 1990). Berdahl et al. (2014) and Johnson et al. (2016) also found evidence that social interactions and collective behavior may function as additionally important cues. Several factors can function to delay adult migration, make the journey more energetically costly, or prevent adults from reaching their intended destination.

Hypotheses for Habitat Attributes that Effect Adult Survival, Migration Timing, and Condition

H_1: In-river fishery and poaching
H_2: Toxicity from contaminants
H_3: Stranding risk
H_4: Dissolved oxygen
H_5: Pathogens
H_6: Water temperature

The survival of salmon during spawning migrations is subject to multiple endogenous and exogenous, as well as biotic and abiotic factors. Ultimately, salmon must arrive at spawning areas with sufficient reserve energy stores and in sufficient health to cope with pathogen burdens and maintain homeostasis long enough to complete spawning prior to senescence and death. Targeted (poaching) or incidental hooking of SRWRC due to in-river fishing has a direct influence on adult survival during migration and can also function to delay migration (**H_2**). Recreational angling occurs in the San Francisco Bay and throughout the SRWRC migration corridor into the Upper Sacramento River. Thus, fishing regulations for Steelhead and other salmon runs can influence the targeted or incidental hooking of SRWRC adults, resulting in mortality or delay in migration timing. As a response to this potential threat, in 2015 and 2016

CDFW modified resident trout fishing regulations upstream of the Highway 44 bridge in the Upper Sacramento River where SRWRC migrate, hold, and spawn.

Natural and artificial barriers can delay the upstream passage and increase energetic costs to migration for salmon. For example, gates at the RBDD were operated in the open position during portions of SRWRC migration beginning as early as 1989 to reduce migration delays and were permanently removed in 2012 (USFWS 1991, NMFS 2009). Similarly, ACID has two fish ladders at its diversion dam to facilitate upstream passage of SRWRC. ACID places boards across the river to divert water for irrigation and municipal uses, which are modified seasonally to reduce migration delays.

Salmon use olfactory navigation cues to follow source water and migrate to specific spawning grounds. Water operations can influence the routing of Upper Sacramento River-origin water through agricultural fields into drainage canals and can create false attraction cues that cause salmon to deviate from the mainstem Sacramento River migration corridor and become stranded in agricultural fields behind flood bypass weirs (**H_3**). Although the relative contribution of flow reaching migration junctions via alternate routes influences route selection in returning adult salmon, little is known about how water operations may influence navigational cues. However, the need to modify existing flood bypass weirs to reduce migration delays, mortality, and stranding risks has been identified by several agency efforts (CALFED 2000, USFWS 2001, USBR and DWR 2012). In some years, flows through the bypasses likely result in false migration cues and large numbers of adult SRWRC traveling up the Colusa Basin Drain for 40–70 miles before being blocked at weirs preventing successful migration. In 2013, more than 600 stranded adult SRWRC and spring-run Chinook salmon were observed, and 312 were relocated to the mainstem Sacramento River or the Livingston Stone National Fish Hatchery (Killam et al. 2014, Beccio 2016). It is not possible to monitor and rescue all adults that become stranded in the Colusa Basin, and thus, the loss of adults prior to spawning can be demographically costly to the population.

Stranding of adults can influence their migration timing, condition, and fate. For example, stranding in bypasses can expose SRWRC to elevated and lethal water temperatures (**H_6**) and poor water quality factors such as low DO **(H_4),** which can compromise fish condition and the ultimate success of fish rescues into the mainstem Sacramento River. Stranding also increases the exposure of adults to poaching **(H_2)**. There are three hypothesized routes that SRWRC adults use to enter the Colusa Basin Drain: 1) Yolo Bypass via the Knights Landing Ridge Cut; 2) Knights Landing Outfall Gates; and 3) hydrologic connection between the Colusa Basin and the Sacramento River. It is unclear the extent to which stranding behind flood bypass weirs has played a chronic role in limiting SRWRC adult migration success. The 2013 data suggest that in some years stranding effects can be substantial. The ultimate reproductive success of fish intercepted at the bypass weirs and returned to the Sacramento River is unknown.

The condition of migrating adults, as well as water quality and toxicity (**H1**, **H4**, **H6**) can influence their exposure and susceptibility to disease, olfactory navigation cues, and migration success (**H5**). An omnipresent challenge for salmon involves the suite of fungal (e.g., *Saprolegnia sp*.), bacterial (e.g. *Columnaris sp*., *Renibacterium salmoninarum*), myxozoan (e.g., *Parvicapsula spp*.), protozoan (*Loma sp*., *Ichthyophthirius multifiliis, Cryptobia salmositica*), and viral agents to which salmon are exposed to throughout their lifetime (**H5**; Cooke et al. 2012). Recent work coupling telemetry with biomarkers in Sockeye Salmon (*O. nerka*) reveals that early physiological and disease measures of fish in the ocean, mouths of the rivers, and onwards to spawning grounds can predict the rate at which the salmon failed to reach the spawning grounds (Cooke et al. 2006, Crossin et al. 2009).

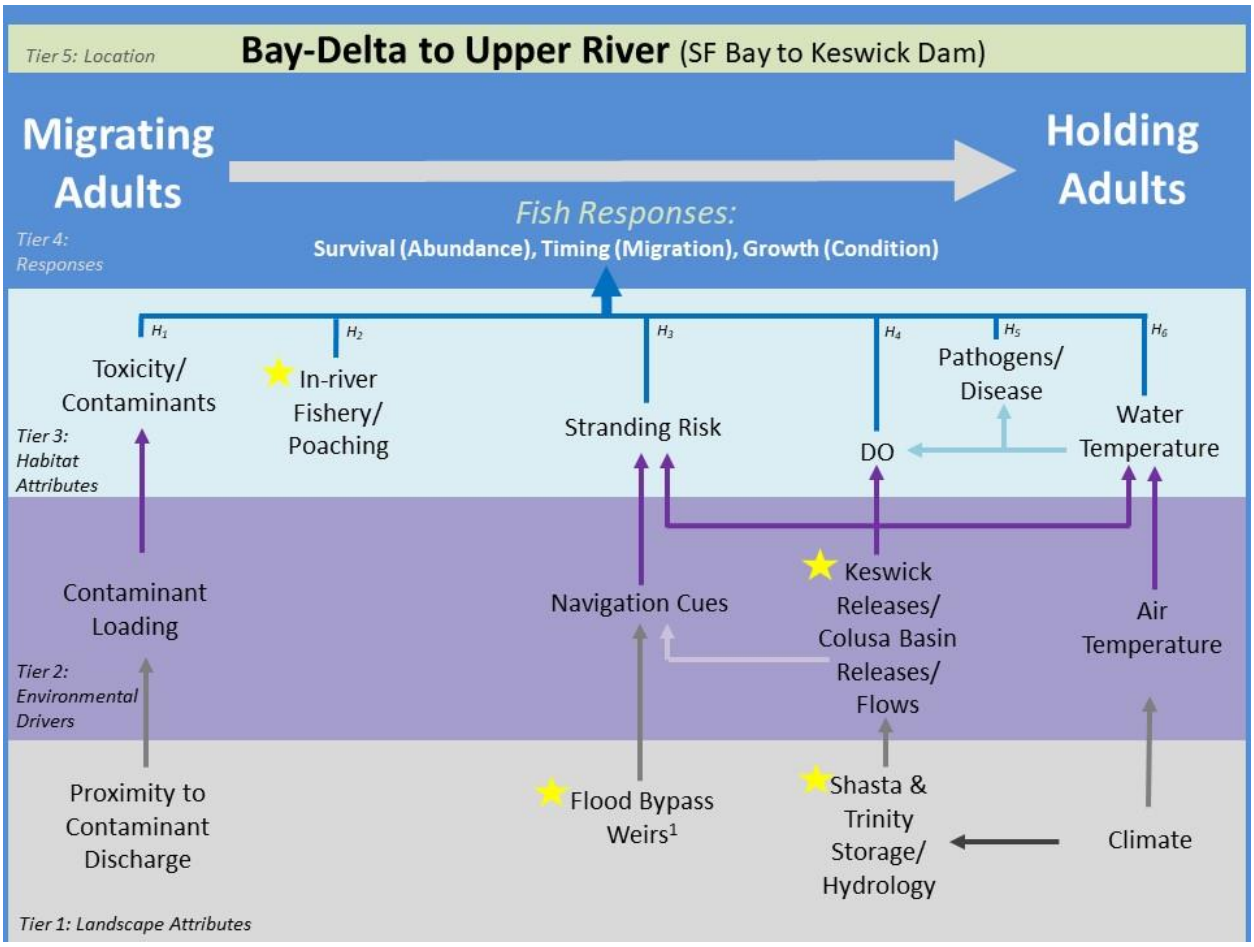

Figure 8. Conceptual model of drivers affecting the transition of SRWRC migrating adults from the Bay-Delta to holding adults in the Upper Sacramento River. Hypotheses referenced by the "H-number" are identified in the conceptual model 6 (CM6) narrative. Management actions are denoted by stars and are described in Table 1.

CM7: Adult Holding in the Upper Sacramento River

Geographic Region. The Upper Sacramento River from Keswick Dam to RBDD approximately 60 miles downstream.

Biology of Life Stage. Adult SRWRC migrate from the ocean into the Sacramento River largely at age 3, with some returning as 2- and 4-year-olds (Hallock and Fisher 1985). They move upstream and can be found holding in the upper 10 to 15 river miles of the Sacramento River below Keswick Dam from December to July (NMFS 2011). Unlike fall-run Chinook Salmon, SRWRC enter the Sacramento River system, usually with gametes not fully developed, and move into the upper Sacramento River where they hold until ready to spawn. Spawning takes place from mid-April through early August, with the peak occurring in June (Killam et al. 2014). Thus, adults could be vulnerable to factors that influence adult mortality or gamete development in the Upper Sacramento River for up to 8 months prior to spawning.

Hypotheses for Habitat Attributes that Affect Holding and Spawning

H_1: Toxicity from contaminants
H_2: Competition, introgression, and broodstock removal
H_3: In-river fishery or poaching
H_4: Spawning habitat
H_5: Dissolved oxygen
H_6: Water temperature
H_7: Pathogens and disease

SRWRC have been excluded from historical spawning habitat since the construction of Shasta and Keswick dams (NMFS 2011). Spawning occurs primarily between Keswick Dam and RBDD, though spawning has taken place as far downstream as Hamilton City (DWR 1988, Crozier et al. in prep). In recent years, water temperatures suitable for critical SRWRC life stages (spawning, egg incubation, and fry emergence) appear to have confined successful reproduction to the upper 10 to 15 river miles below Keswick Dam. Adult Chinook Salmon held at temperatures greater than 60 °F have exhibited poor survival and reduced egg viability (DWR 1988). Laboratory and field studies have shown that when adult fish are exposed to constant or average temperatures above 55.4–60 °F (13–15.6 °C) during holding prior to spawning, there is a detrimental effect on the size, number, or fertility of eggs held in vivo (EPA 2001). Thus, adult holding and spawning distribution may be limited by the temperature-controlled stretch of the Sacramento River.

The physiological condition of SRWRC adults upon arrival to the holding/spawning area can influence the extent to which stressors lead to pre-spawn mortality or reduced fecundity. Physiological stress measured by elevated plasma lactate and cortisol levels caused by migration, and holding stressors, such as incidental fishing, warm water temperatures, and toxins, affect

gamete maturation and viability and susceptibility to disease (DWR 1988, EPA 2001, Cooke et al. 2006). Warm water temperatures (**H_6**) generally decrease DO (**H_5**), increase physiological stress and metabolic rates, and decrease immune responses to pathogens (**H_7**). Contaminant loading of heavy metals from mines such as Iron Mountain Mine, or oil and other toxins from non-point sources such as stormwater runoff, have been identified as stressors that reduce spawning success or cause mortality (**H_1**; McCarthy et al. 2008).

Flow-related stressors can weaken fish during periods of holding prior to spawning. Decreased flows can concentrate fish within a smaller habitat area, and fish densities increase the potential for lateral transmission of disease and pre-spawn mortality becomes higher (**H_7**; USFWS 2002). Increased flows can move weakened fish downstream out of the temperature-controlled section of river, reducing spawning success, or laterally to the stream margins, making them more vulnerable to predation, harassment, or poaching (**H_3**). Human activities (**H_3**) such as poaching and harassment that temporarily or permanently displace fish from holding or spawning areas, can reduce energy reserves needed for survival or successful spawning in preferred habitats (Cooke et al. 2012).

Returning adult hatchery fish can influence natural adult spawners either through competing for spawning habitat or genetic introgression (**H_2**, **H_4**). Spawning of hatchery fish with natural-produced salmon can affect locally adapted gene complexes and reduce fitness in the wild (Ford 2002, Araki et al. 2007, Chilcote et al. 2001). Prior to 2005, the proportion of LSNFH-origin spawners in the river was between 5 and 10 percent, consistent with guidelines from the Hatchery Scientific Review Group for conservation hatcheries (CA HSRG 2012). However, the hatchery proportion has increased since 2005 and reached 20 percent hatchery influence in the most recent generation, placing the population at a moderate risk of extinction (Lindley et al. 2007, Johnson and Lindley 2016). Compared to prior years, the hatchery also produced and released two to nearly three times as many juveniles during the 2013–2014 and 2014–2015 drought years, respectively, to prevent the loss of SRWRC cohorts those years. When mortality is high for natural-origin juveniles (e.g., drought years), increasing hatchery production may elevate the overall extinction risk due to genetic impacts of hatchery introgression due to the return of a disproportionately large number of hatchery adults.

Other runs of adult salmon may overlap in space and time with SRWRC adults, eggs, and juveniles. These potential negative interactions are largely unknown. For example, in 2015 114 Feather River spring-run Chinook Salmon were collected at the Keswick Dam fish trap (Rueth, U.S. Fish and Wildlife Service, personal communication 2015), which implies there were spring-run Chinook Salmon within the SRWRC spawning reach. The extent to which competition or predation from hatchery spring-run Chinook Salmon strays are influencing SRWRC has not been studied.

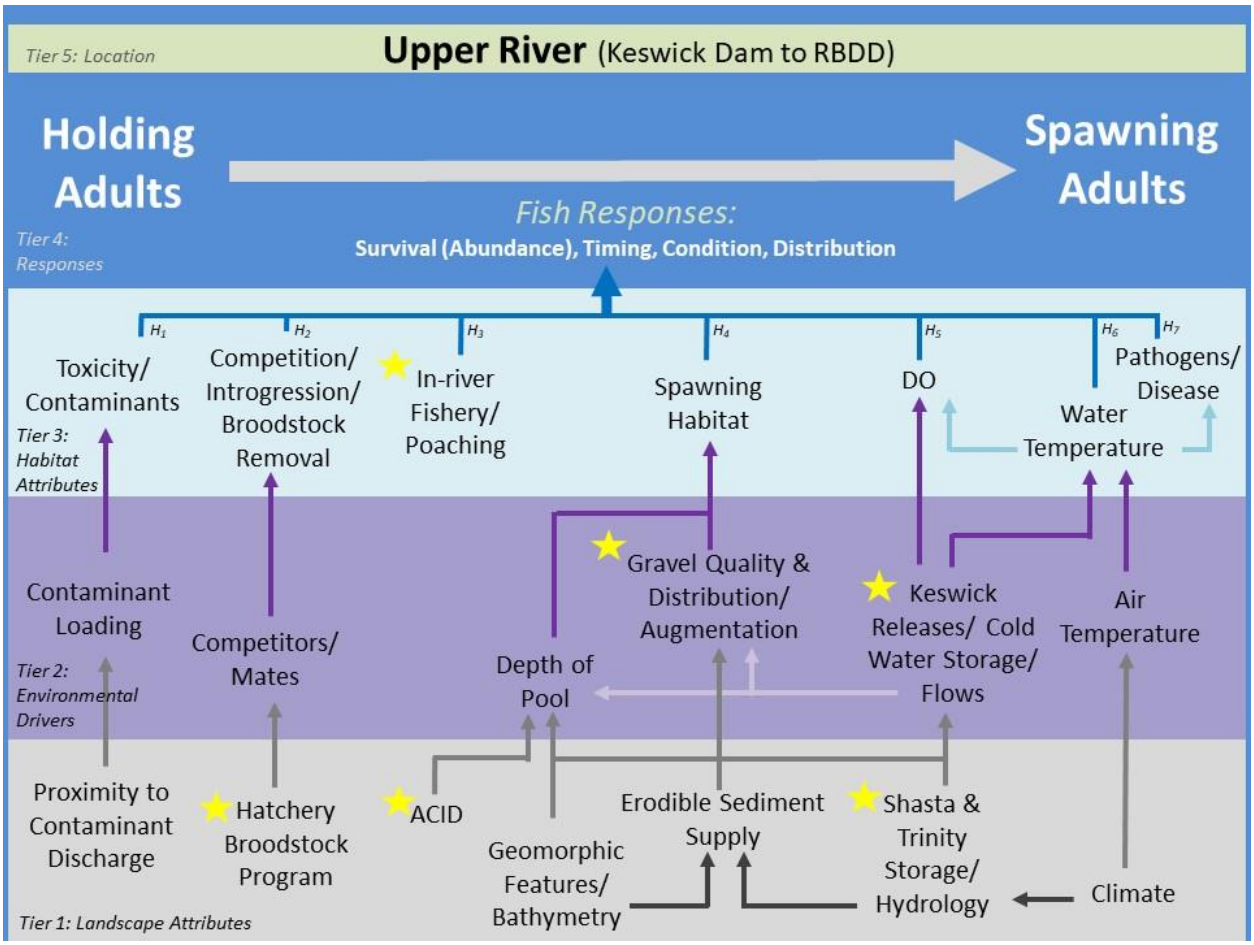

Figure 9. Conceptual model of drivers affecting SRWRC from holding adults to spawning adults in the Upper Sacramento River. Hypotheses referenced by the "H-number" are identified in the conceptual model 7 (CM7) narrative. Management actions are denoted by stars and are described in Table 1.

Management Toolbox

As discussed above, CMs can be used to organize hypotheses on ecosystem function and how a species or life stage is influenced by its surrounding environment and prioritize management actions and key indicators of project performance to monitor. For example, Johnson et al. (In press) used the CMs described here to assess how well the existing core monitoring network for SRWRC provides the metrics necessary to manage SRWRC at key life stages and geographic regions. Johnson et al. (In press) concluded the current monitoring network was insufficient to diagnose when (life stage) and where (geographic domain) chronic or episodic reductions in SRWRC cohorts occur, which precluded making within and among year comparisons. They identified six system-wide recommended actions to strengthen the value of data generated from the existing monitoring network for assessing resource management actions: 1) incorporate genetic run identification, 2) develop juvenile abundance estimates, 3) collect data for life history diversity metrics at multiple life stages, 4) expand and enhance real-time fish survival and movement monitoring, 5) collect fish condition data, and 6) provide timely public access to monitoring data in Open Data formats.

Similarly, examples of key management actions, their implementing authorities, and hypothesized influences on SRWRC were developed based on the seven CMs discussed above (Table 1). By placing the management actions in the context of the habitat attributes or environmental drivers they manipulate (the stars in Figures 3-9), the pathways by which management actions likely influence the presence, timing, abundance, life history diversity, and condition of SRWRC can be identified. Without a robust core monitoring program focused on measuring and reporting key demographic metrics of SRWRC, developing empirical support for the value of different management actions will be challenging.

The CMs discussed above serve as a framework to develop focused studies to directly test the hypothesized factors that influence SRWRC responses to management actions and for developing further actions that can be tested in an adaptively managed program. In addition, the CMs support the development of quantitative models that provide predictions on how various management actions (Table 1) influence different life stages of SRWRC and tools critical for adaptively managing species in an ever-changing aquatic landscape. The core monitoring data derived from implementing the six monitoring improvements identified by Johnson et al. (In press) can also be used to test quantitative model predictions. Thus, for the successful adaptive management of endangered SRWRC, the CMs discussed above are integrally connected with the development of enhanced quantitative tools and the monitoring of fish responses to management. A valuable next step would be to evaluate the scientific support for the individual hypotheses identified in the seven CMs discussed above to prioritize the specific studies needed to reduce relevant scientific uncertainties. Implementing the six recommendations identified in Johnson et al. (In press) will improve the core monitoring for SRWRC, and generate the data necessary to develop and test robust quantitative models needed to achieve better management outcomes for SRWRC.

Table 1. Example tool-box for applying the conceptual models to Sacramento River winter-run Chinook salmon management by life stage and geographic region. Note: The potential management actions outlined here are the actions denoted by stars in the individual CMs (Figures 3-9).

Life stage Conceptual Model (CM)	Potential Management Actions	Hypothesized Responses	Management authorities
Upper River			
Eggs CM1	Reduce in-river fishery	Reduces trampling impacts to redds (H_1)	CDFW fishing regulations[1]
Eggs CM1	Prescribe Keswick releases [temperature and flow]	Provides non-lethal temperatures (H_7), high DO (H_5), reduces risks of dewatering/ stranding (H_4), and mobilizes fine sediments (H_8)	Annual Temperature Management Plan, State Water Resource Control Board Water Rights Order 90-5l; NMFS Biological Opinion 2009[2]
Eggs CM1	Implement multi-year reservoir management	Provides reliable quantity of cold water (H_7)	End of September storage, NMFS Biological Opinion 2009[2]
Eggs CM1	Augment gravel	Increases the quality of redds through optimal gravel sizes facilitating interstitial flows (H_5)	Central Valley Project Improvement Act (CVPIA) 1992 (b)(13)
Juveniles CM2	Maintain/reduce contaminant loading	Reduces chemical exposure [Iron Mountain] and associated impacts to fish physiology, growth and behavior (H_1)	US EPA Clean Water Act, Section 404; Superfund[3]
Juveniles CM2	Optimal hatchery release densities and timing	Minimizes impacts of intra-specific competition with natural origin fish and predator assemblage (H_2). Minimizes likelihood of prey-switching behavior in predators to prevent increased predation rates.	Hatchery Genetic Management Plan; NMFS Biological Opinion 2009[2]
Juveniles CM2	Prescribe Keswick releases [temperature and flow]	Increases availability of shallow water riparian refuge habitat (H_3), decreases predation risk and competition (H_2)	Not Applicable
Juveniles CM2	Screen irrigation diversions and provide adequate riverine flows	Reduces entrainment risk and minimizes impacts of water withdrawls [ACID] on survival rates (H_9)	Anadromous Fish Screen Program, CVPIA 1992
Adults CM7	Reduce in-river fishery	Reduces pre-spawn mortality from catch-release handling (H_3)	CDFW fishing regulations[1]

[1] CDFW modified steelhead fishing regulations in 2015 upstream of the Hwy. 44 bridge where SRWRC migrate, hold, and spawn *https://nrm.**dfg**.ca.gov/FileHandler.ashx?DocumentID=93497*

[2] http://www.westcoast.fisheries.noaa.gov/central_valley/water_operations/

[3] US EPA Region 9; https://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/vwsoalphabetic/Iron+Mountain+Mine?OpenDocument

Adults CM7	Mate only natural-origin genetic SRWRC with most unrelated individuals in hatchery	Maintains locally adapted traits within ESU, reduces inbreeding, maximizes genetic diversity, and reduces domestication selection (H_2)	Hatchery Genetic Management Plan, NMFS Biological Opinion 2009[2]
Adults CM7	Produce and release an optimal number of hatchery juveniles	Prevents extinction if natural mortality is high, minimizes genetic (introgression/ domestication selection) and demographic impacts (competition) to natural spawning adults (H_2)	Hatchery Genetic Management Plan, NMFS Biological Opinion 2009[2]
Adults CM7	Augmentation gravel	Increases the amount of spawning habitat and placement can influences the spatial distribution of spawning (H_4)	Central Valley Project Improvement Act (CVPIA) 1992 (b)(13)
Adults CM7	Prescribe Keswick releases [temperature and flow]	Influence the location and timing of spawning (H_6), vulnerability of eggs to dewatering/ stranding (H_4). Reduces pre-spawn mortality and disease transmission (H_7)	Annual Temperature Management Plan, State Water Resource Control Board Water Rights Order 90-5l; NMFS Biological Opinion 2009[2]
Middle River			
Juveniles CM3	Maintain/reduce contaminant loading	Reduces chemical exposure and associated impacts to fish physiology, growth and behavior (H_1)	US EPA Clean Water Act, Section 404[3]
Juveniles CM3	Release an optimal number of hatchery juveniles over time	Minimizes impacts of intra-specific competition with natural origin fish (H_2). Minimizes likelihood of prey-switching behavior in predators to prevent increased predation rates.	Hatchery Genetic Management Plan, NMFS Biological Opinion 2009[2]
Juveniles CM3	Prescribe Keswick releases and tributary flows to achieve floodplain connectivity	Increases availability of shallow water refuge habitat [Sutter Bypass] (H_3), prey quantity and quality and retention (H_4), decreases predation risk and competition (H_2)	Not Applicable
Juveniles CM3	Screen irrigation diversions and provide adequate riverine flows	Reduces entrainment risk and minimizes impacts of water withdrawals on survival rates (H_9).	Anadromous Fish Screen Program, CVPIA 1992
Tidal Estuary			
Juveniles CM4	Maintain/reduce contaminant loading	Reduces chemical exposure and associated impacts to fish physiology, growth and behavior (H_1)	US EPA Clean Water Act[3]
Juveniles CM4	Release an optimal number of hatchery juveniles over time	Minimizes impacts of intra-specific competition with natural origin fish (H_2). Minimizes likelihood of prey-switching behavior in predators to prevent increased predation rates.	Hatchery Genetic Management Plan, NMFS Biological Opinion 2009[2]
Juveniles CM4	Prescribe Keswick releases and tributary flows to achieve floodplain connectivity	Increases availability of shallow water refuge habitat [Yolo Bypass] (H_3), prey quantity and quality and retention (H_4), decreases predation risk and competition (H_2)	NMFS Biological Opinion 2009[2]

Juveniles CM4	Restore shallow water habitat	Increases amount of juvenile rearing habitat providing prey quantity and quality (H_4), structural complexity for refuge (H_3) from predation (H_2)	NMFS Biological Opinion 2009[2]; EcoRestore, California's Natural Resources Agency[4]
Juveniles CM4	Screen irrigation diversions and provide adequate riverine flows	Reduces entrainment risk, provides adequate outmigration cues (H_5) and minimizes impacts of water withdrawals on survival rates (H_9)	Anadromous Fish Screen Program, CVPIA 1992
Juveniles CM4	Reduce the number of non-native predators in key locations	Modifies fish assemblages and reduces predation on juveniles	NMFS Biological Opinion 2009[2]
Migratory adults CM6	Modify passage barriers in flood bypasses	Allows volitional passage between bypasses and river, reduces migration delay, and stranding risk (H_3)	NMFS Biological Opinion 2009[2]
Migratory adults CM6	Enforce fishing regulations	Reduces poaching and pre-spawn mortality from catch-release handling (H_2)	NMFS Biological Opinion 2009[2]
Migratory adults CM6	Provide adequate mainstem flows during adult migration	Reduces false attraction flows through the bypasses	NMFS Biological Opinion 2009[2]
Ocean			
Adults CM5	Sustainable harvest allocation	Minimizes bycatch of winter run in mixed stock fishery	NMFS Biological Opinion 2009[2]
Adults CM5	Optimal hatchery release densities and timing	Minimizes impacts of intra-specific competition with natural origin fish (H_2)	Hatchery Genetic Management Plan, NMFS Biological Opinion 2009[2]
Adults CM5	Provide adequate mainstem flows during migration	Provides adequate attraction flows and cues to spawning grounds (H_4)	NMFS Biological Opinion [2]

[4] http://resources.ca.gov/ecorestore/

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