Chinook Salmon Habitat Quantification Tool

User Guide (Version 1.0)

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1. Introduction

Photo by Carson Jeffres

1.1 Why is habitat quantification necessary?

Central Valley rivers once carried runoff from large winter storms and spring snowmelt onto low-lying floodplains, slowing and spreading water into complex mosaics of riparian forest and wetlands, depositing sediment, and recharging groundwater. Inundation occurred for weeks to months at a time and the slow, highly productive floodplain waters provided excellent conditions for juvenile salmon to feed and grow before migrating to the ocean. Over the last century and a half, however, floodplain habitats have been reduced to about 5% of their historical extent. Valued for their rich soils, most of the Valley's floodplains have been converted to agriculture and have been disconnected from their rivers by levees and dykes (Figure 1). Flow alteration, especially the reduction in high flows, from large upstream dams has also limited the inundation duration and extent of remnant floodplain habitats.

Chinook salmon are ecologically, culturally, and economically important to California. Prior to Euro-American settlement, an estimated 1-2 million Chinook salmon would return to Central Valley rivers each year (Yoshiyama et al. 1998). Conditions varied from river to river and from upstream to downstream, such that large areas of floodplains were inundated for weeks to months during the juvenile salmon rearing period in most years. This flooding was essential for sustaining the historically large populations. Today, each of the four distinct runs of Central Valley Chinook salmon are now considered at risk of extinction by the end of the century if present trends continue (Katz et al. 2013, Moyle et al. 2017). Their decline and the attendant ecological degradation of California's rivers is emblematic of global trends in biodiversity loss, which is particularly acute in freshwater ecosystems (Dudgeon et al. 2006; IPBES 2019).

Floodplain restoration is essential to the recovery of healthy salmon populations within the Central Valley. Effective restoration requires scientific knowledge of physical and biological processes that create and sustain productive off-channel and floodplain habitats (collectively referred to here as floodplain habitats) for fish. It also requires tools that support decision-making for natural resource managers, landowners, and

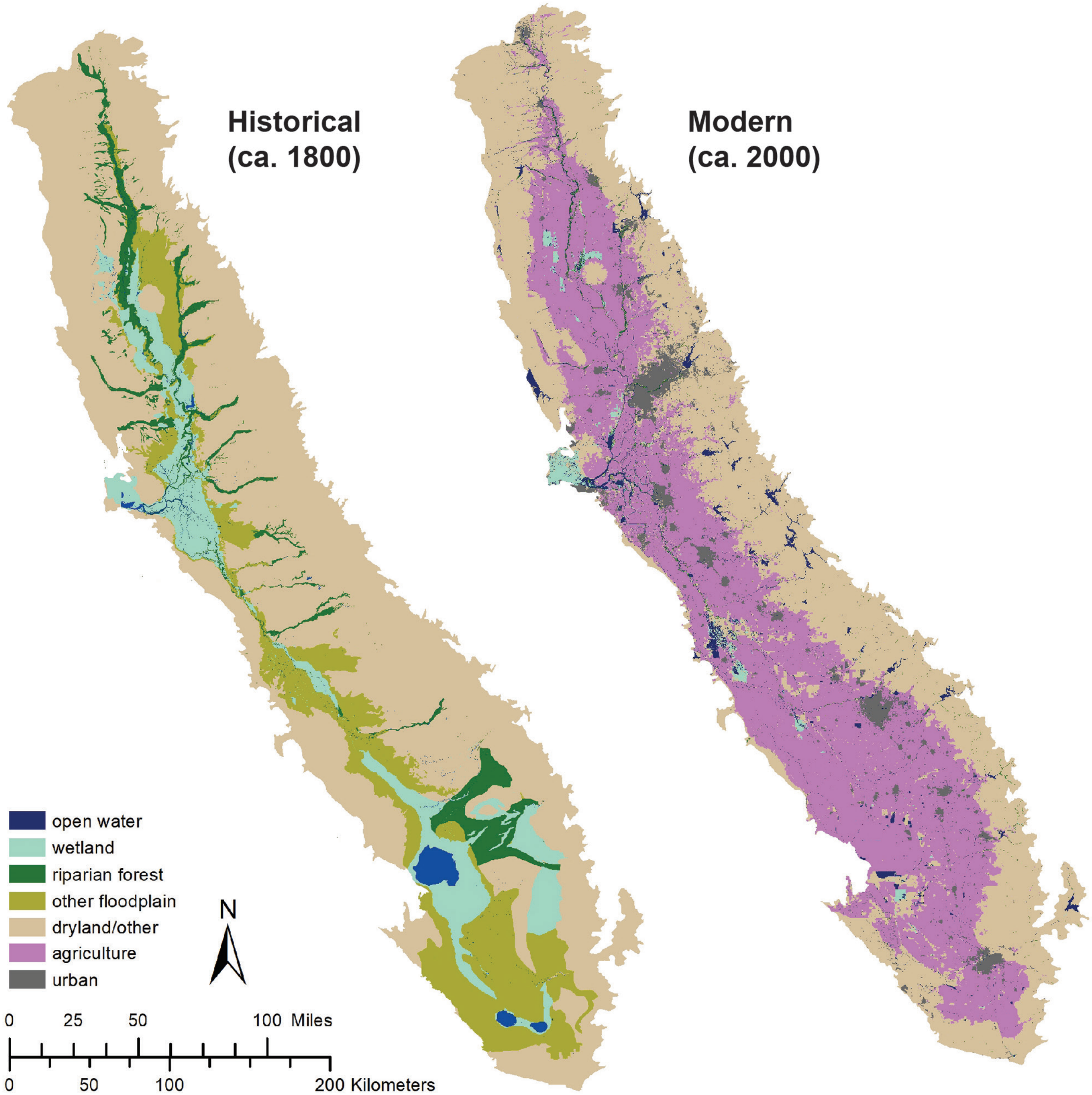


Figure 1. *Floodplain loss in the Central Valley shown by land cover distribution changes between historical (left) and modern conditions (right). Sources: The Bay Institute 1998, USDA 2007, Whipple et al. 2012.*

environmental organizations who are seeking to identify cost-effective solutions for managing floodplains for human and ecological objectives. Specifically, habitat quantification tools provide the means to assess how alternative land management, habitat restoration, and flow manipulation strategies will affect the amount, quality, location, and timing of habitat available for species of management concern, such as Chinook salmon.

1.2 Purpose of the Chinook salmon Habitat Quantification Tool

With increasing attention focused on restoration and conservation of floodplain habitat for rearing juvenile salmon and other ecological functions, there is a need for systematic, transparent, and consistent accounting of the spatial extent, temporal variability, and quality of habitat on the landscape. The Chinook salmon Habitat Quantification Tool (HQT) and the hydrospatial analysis approach it implements, draw from restoration research and practice to establish a science-based framework for quantifying floodplain habitat for rearing juvenile Chinook salmon. The HQT links spatially and temporally variable floodplain inundation – or hydrospatial – patterns to criteria that define high-quality habitat. The HQT includes both modeling and monitoring components designed for use in pre-project design and planning and post-project performance assessment. It is part of the multi-species assessment of the Central Valley Habitat Exchange (CVHE), which is a program for conservation and restoration of wildlife habitat in the Central Valley.

The HQT is intended for use in assessing current available habitat, comparing restoration designs or scenarios during project planning, and evaluating projects post-restoration. It can also be implemented within larger watershed planning frameworks to examine, for example, the effect of environmental flows on floodplain habitat. The HQT can aid resource managers, landowners, and regulators in decision-making and valuation of restoration projects. It may also be useful in research contexts for characterizing physical habitat conditions within floodplains in a standardized and quantitative way. Technical experts involved in project planning, design, and implementation are the expected users of the HQT.

The Chinook salmon HQT consists of:

1. **Landscape context assessment** provides a measure of the habitat potential for a site based on its landscape position within the Central Valley, Chinook salmon presence and abundance, and longitudinal connectivity.
2. **Site evaluation with the hydrospatial analysis approach** estimates daily floodplain inundation patterns based on output from hydrodynamic modeling and a daily flow record, assesses physical parameters, applies habitat suitability criteria, and quantifies suitable habitat over space and time.
3. **Monitoring** assesses conditions affecting habitat quality that are not readily available through modeling (e.g., cover, water quality), as well as conditions useful for model validation. Monitoring plans are project-specific and are thus not discussed in detail here.

This document describes the scientific approach and application of the Chinook salmon HQT, including a step-by-step guide to implementing the site evaluation component of the tool. The background in Section 2 provides scientific foundation for evaluating juvenile salmon habitat within the Central Valley. This is followed by a narrative description of the three primary components of the HQT (Section 3). Detailed steps for implementing the site evaluation component of the HQT are provided in Section 4. Appendices provide additional science rationale for habitat suitability criteria (Appendix A).

1.3 Central Valley Habitat Exchange Multi-species Habitat Quantification Tool

The Chinook salmon Habitat Quantification Tool is part of a Multi-species Habitat Quantification Tool (mHQT), which describes a method for evaluating and quantifying habitat conditions for multiple species native to California's Central Valley. The intent is to establish a means of consistently assessing conditions so that high quality habitat can be managed or maintained to benefit multiple species. By quantifying habitat condition, the tool also allows for a range of applications that support land management, enhancement, restoration, or mitigation. Applications include comparison of relative habitat value at a single location between multiple restoration scenarios or over time to assess improvements or detrimental impacts to habitat condition from past or anticipated actions as well as comparison of relative habitat value between multiple locations.

In addition to Chinook salmon (*Oncorhynchus tshawytscha*), HQTs have been developed for Swainson's hawk (*Buteo swainsoni*), riparian landbirds, Monarch butterfly (*Danaus plexippus*) and giant garter snake (*Thamnophis gigas*). The mHQT is designed for use in the CVHE; however, it has broad applicability for use in habitat mitigation and conservation efforts for the target species in the Central Valley. The mHQT is intended to: 1) provide a quantitative and effective basis for developing credits and debits based on habitat quality for one or multiple target species; 2) to incentivize the development of habitat for target species in locations where it provides maximum benefit; and 3) to inform the suite of potential actions necessary in order to improve habitat conditions and achieve maximum habitat quality.

As the Chinook salmon HQT is applied and tested in a growing range of applications, it is expected to evolve. For example, further development of monitoring guidelines is expected. In its current form, the tool must be applied by technical experts. However, we ultimately aim to adapt the tool to a web-based format that will allow a wider audience to explore the functionality of the tool. Further integration within the multi-species HQT is also in progress, with approaches for evaluating multi-benefit floodplain projects as part of the CVHE.

2. Defining Suitable Habitat in Floodplain Environments

Photo by Alison Whipple

2.1 Floodplain habitat variability

Riverine environments are dynamic and complex, supporting high levels of biodiversity and productivity (Amoros and Bornette 2002; Opperman et al. 2017; Tockner and Stanford 2002). Temporally variable flows interact with the river channel and floodplain to create spatially-heterogeneous and temporally-shifting mosaics of upland, riparian, and aquatic habitat patches. A river's flow regime, with components of magnitude, frequency, timing, duration, and rate of change (Poff et al. 1997), creates variable patterns of hydrologic connectivity within the floodplain, and between the floodplain and river, which in turn, influences nutrient cycling, food web productivity, and biological community composition. A diversity of environmental conditions over space and time creates opportunities for a wide range of species to find habitat needed for feeding, shelter, and/or reproduction (Sparks 1995).

Habitat availability shifts as water levels rise and fall in rivers - water moves out onto floodplains as rivers rise and spreads across the landscape following topographic contours (Figure 2). Areas may pond as water levels fall, only to be reconnected as rivers rise again. Topographic complexity and variable proximity to the river means that different parts of the floodplain have different inundation characteristics at any given flow level. In wet years with large floods, the vast majority of a floodplain may be inundated for extended periods of time, with extreme floods extending into the higher elevation areas of a floodplain for shorter periods. In contrast, dry years may only produce floodplain inundation in small areas immediately adjacent to the river and for short periods of time. The term "hydrospatial regime" is used to describe the dynamic interaction between a river's flood regime and floodplain topography (Whipple 2018).

Patterns of land-water interaction on floodplains in California and globally are now profoundly impacted by human modifications, including changes in landscape form (e.g., from levees, dams, and channel dredging) and changes in river flow regimes (e.g., from diversions, weirs, and dams). The overall effect has been a reduction in the extent and duration of inundation within floodplains and a homogenization of conditions.

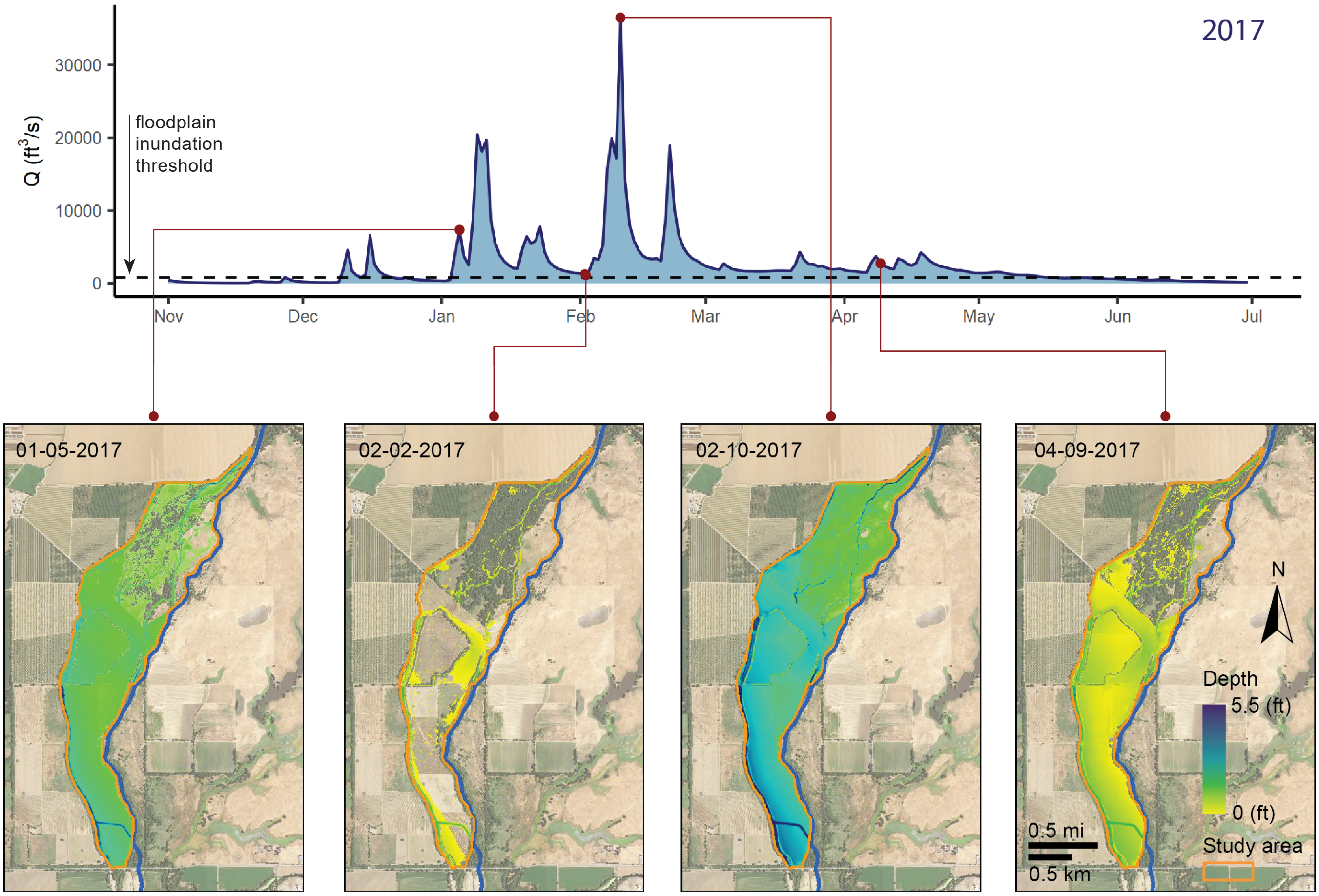


Figure 2. *Extent of inundation and water depth within a floodplain restoration project (orange boundary) along the lower Cosumnes River associated with discharge (Q) for the water year 2017 daily hydrograph at the upstream USGS streamgage (#11335000).*

Supporting diverse and productive freshwater ecosystems requires improving our understanding of how floodplain conditions have been impacted by human activities and the potential for new restoration and management actions that increase habitat quality and quantity.

2.2 Physical habitat quantification

The science and practice of river restoration often involves some form of physical habitat quantification at the site or reach scale. This quantification provides a means for studying ecologically-relevant physical conditions, understanding how and to what degree physical landscape alteration and water management may affect individual species or ecosystem processes, and comparing restoration scenarios. Physical habitat simulation based on either 1D or 2D hydrodynamic modeling has been used for many decades for the purposes of evaluating in-channel fish habitat (Leclerc et al. 1995; Stalnaker 1979). The basic approach is to assign habitat suitability indices based on physical conditions, such as depth or velocity, which are used to compute a weighted usable habitat area that varies with river flow (Figure 3).

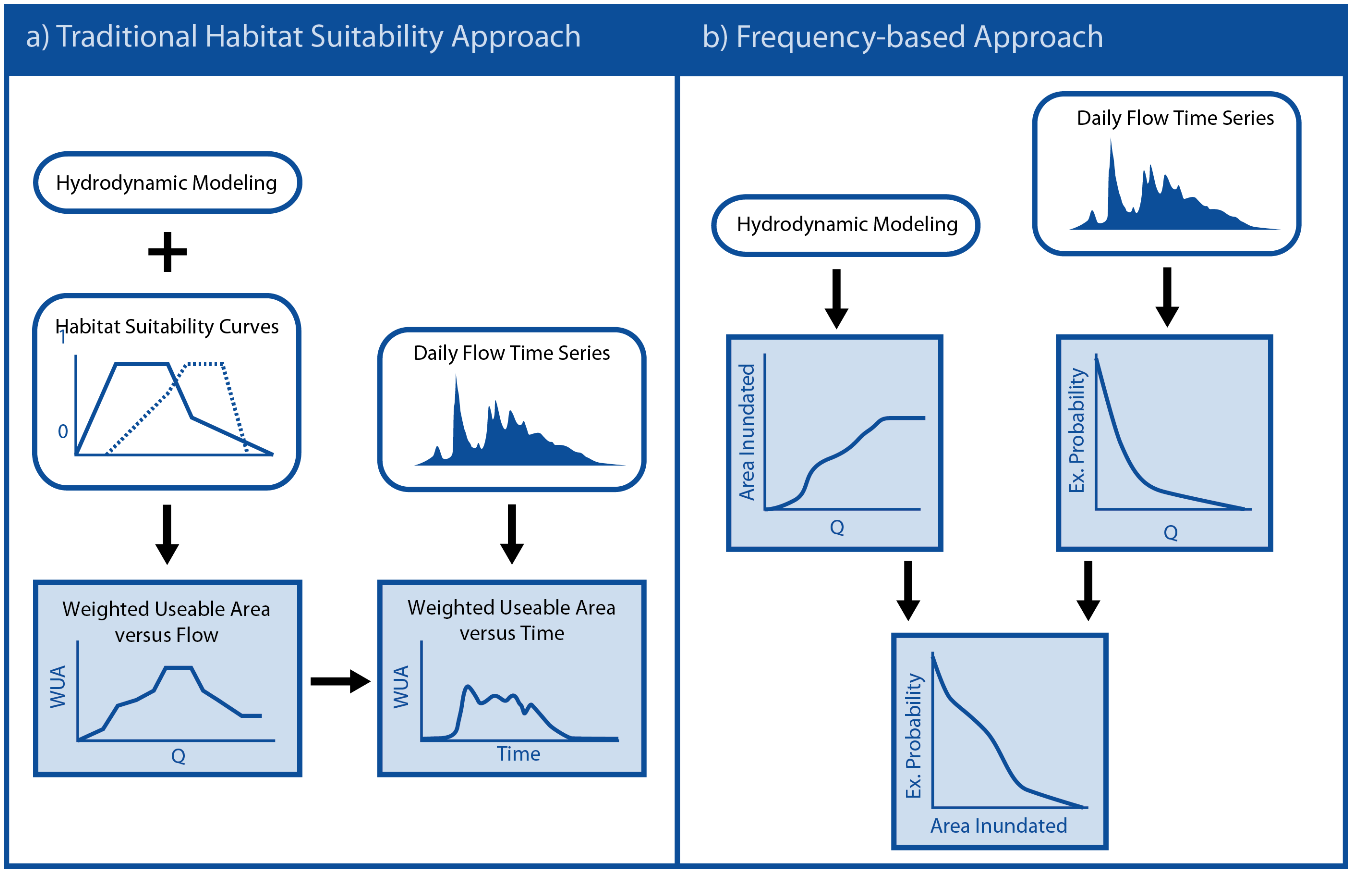


Figure 3. *Commonly applied approaches for quantifying in-channel and floodplain habitat, where hydrodynamic or hydraulic modeling is used to (a) determine weighted useable area (WUA) as a function of flow, which is combined with a daily flow time series, or (b) determine inundated area as a function of flow which can then be combined with frequency analysis of a flow time series.*

Another approach for floodplain habitat quantification based on frequency analysis has been applied recently in Central Valley river restoration and management. The area-duration-frequency and expected annual habitat analysis method of Matella and Jagt (2014) allow for estimating the area, depth, frequency and duration of floodplain inundation. This approach uses flow duration frequency analysis and relationships between inundation area and flow to determine the frequency of inundated area for different flood recurrence intervals. However, this type of analysis assesses annual maximum habitat availability and does not account for spatial variability of habitat availability within a floodplain site or allow the application of suitability criteria in a spatially or temporally resolved way.

The relationship between flow and floodplain habitat area is generally non-linear and not one-to-one, and depends on temporally and spatially variable factors. Efforts to address this complexity have led to the advancement of grid-based habitat suitability modeling (e.g., Benjankar et al. 2015; Carnie et al. 2016; Guse et al. 2015; Stone et al. 2017; Whipple 2018). In this type of analysis, habitat suitability is assessed on a cell-by-cell basis, with each cell assigned a cell suitability index using habitat criteria based on depth and velocity. Depending on how this is implemented, it also allows the application of habitat criteria relating to duration of inundation (conditions at cells can be evaluated across time) and connectivity (conditions can be evaluated across space). The sum of the cell areas weighted by their suitability gives estimated habitat area.

2.3 Physical habitat criteria for juvenile salmon in the Central Valley

The current version of the Chinook salmon HQT is focused on the juvenile life history stage. Subsequent versions may address habitat needs for other life history stages. The focal habitat attributes of the HQT were selected to characterize seasonally inundated habitats along channel margins, outside of the bankfull channel, or off-channel but with some degree of connectivity to the main-channel (collectively referred to here as floodplain habitat). Generally, optimal conditions for juvenile salmonid rearing involve a balance of physical habitat conditions (e.g., temperature, dissolved oxygen, water depth, velocity, suitable cover and substrate); biological habitat conditions (e.g., prey availability, predator density, competition); and extent of available habitat relative to fish territory size and abundance (as a function of fish size, fish density, prey density and habitat structure). The following sections describe physical habitat conditions that are considered within the site-level assessment of the HQT. While different floodplain habitats can provide various levels of habitat quality within these physical and biological conditions, the end goal for juvenile salmonids is the same: maximizing growth from emergence in streams and successful migration to the ocean.

2.3.1 Timing of inundation

The timing and duration of inundation determines the benefits that floodplain habitat may provide to juvenile Chinook salmon. To qualify as suitable floodplain habitat, the period of inundation must overlap within the timing of occurrence of juvenile salmon in the project area. The timing of the spawning and duration of incubation and freshwater rearing vary among runs of Chinook salmon due to heritable genetic traits, environmental conditions, and other factors (Healey 1991). As a result, juveniles from one or more runs may be rearing and emigrating in the Central Valley at any time during the year (NMFS 2014, Williams 2006). However, the relative abundance of juvenile Chinook salmon in Central Valley habitats for all runs combined is generally considered highest in late winter and spring and lowest in summer and early fall. **The HQT defines November 1 to June 30 as the period in which floodplain inundation can potentially provide habitat benefits to juvenile salmon** (Table 1). This time period can be modified by the user of the HQT if more precise information of salmon run timing in a project area is available.

2.3.2 Duration of inundation

The quality of floodplain habitats is also influenced by the duration of inundation. Floods of short-term duration (< 1 week) can provide feeding fish access to terrestrial invertebrates found in submerged soil and vegetation (Langhans 2006). Longer

Table 1. *Generalized life history timing of rearing Chinook salmon in the Central Valley, with blue indicating the period of maximal overlap and largest numbers of juvenile rearing fish across all four runs. The "X's" represent months when inundation events can be considered to be providing habitat for each run.*

Chinook Salmon Run	Fall			Winter			Spring			Summer			Notes/References
	(Sep-Nov)			(Dec-Feb)			(Mar-May)			(Jun-Aug)			
Central Valley spring-run[a]			X	X	X	X	X	X	X	X			[a] Snider and Titus (2000a, b), CDFG (1998), Myers et al. (1998), McReynolds et al. (2005), Lindley et al. (2004), NMFS (2014). [b] Williams (2006) - timing differs somewhat between the Sacramento and San Joaquin basins; Yoshiyama et al. (1998) [c] Snider and Titus (2000a, b), Martin et al. (2001), Poytress and Carillo (2010, 2011, 2012), NMFS (2014)
Central Valley fall-run[b]					X	X	X	X	X	X			
Central Valley late fall-run[b]			X	X	X	X	X	X	X	X			
Central Valley winter-run[c]			X	X	X	X	X	X					

inundation periods and extended solar exposure stimulate autochthonous primary and secondary production that can drive high prey densities and fish growth (Sommer et al. 2001, Sommer et al. 2004, Grosholz and Gallo 2006). Research from the Cosumnes River floodplain showed that secondary productivity reached peak levels at approximately 21 days, after which productivity levels stabilized or declined (Grosholz and Gallo 2006, Katz, unpubl. data). Grosholz and Gallo (2006) recommend repeated flood pulses at intervals of 2- to 3-weeks to best support native fish. In the HQT, **Valley Lowland floodplains (Figure 4) that are inundated between 1 and 18 days are considered potentially suitable habitat. Areas inundated from 18 to 24 days are considered optimal habitat. For floodplains within the Valley Foothill region, shorter duration inundation (between 1 and 9 days) is considered optimal** (see Section 3.1). Inundation meeting water depth and velocity criteria are counted toward duration.

2.3.3 Water depth and velocity

The HQT also considers the quality of floodplain habitats based on the depth and velocity of the inundated areas. For juvenile salmonids, water velocity affects energy expenditures and interacts with temperature, dissolved oxygen, and prey availability to control metabolism and ultimately growth rates. Suitable depths are also needed to support foraging behavior and predator avoidance (Gregory 1993) and contribute to favorable primary production conditions. Juvenile Chinook salmon habitat suitability models for depth and velocity have been developed previously for numerous rivers and off-channel habitats in the Central Valley and elsewhere (Aceituno 1990) and have been applied to floodplain habitat estimates for the San Joaquin River (SJRRP 2012). For the HQT, **suitable floodplain habitat is defined by water depth values between 1 and 3.28 ft (0.3–1 m) and velocity between 0 and 1.5 ft/sec (0–0.46 m/sec).** Areas of the floodplain that have depths and velocities that fall outside of either of these ranges are considered unsuitable. The HQT also requires that **the area meeting these criteria must exceed one acre for at least one day during a flood event**.

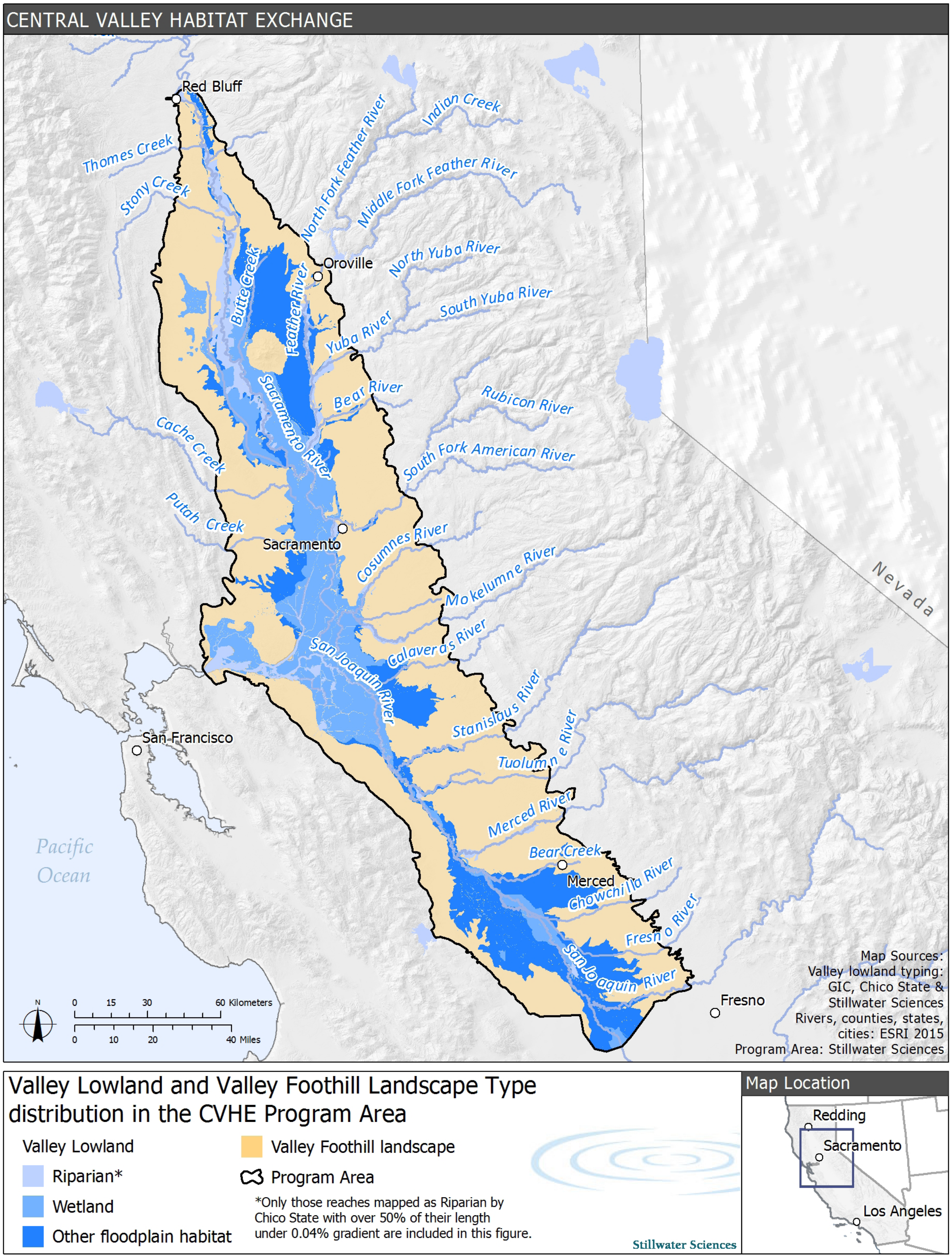


Figure 4. *Distribution of Valley Lowland (three shades of blue) vs. Valley Foothill (light orange) landscape types within the Central Valley Habitat Exchange program area based on historical (pre-1900) wetland and riparian forest distribution.*

2.3.4 Hydraulic connectivity

To realize the potential benefits of floodplain habitat, juvenile Chinook salmon must be able to access the floodplain and return to the river prior to the drawdown of inundated waters. Habitat conditions within the area that connects the river to the floodplain (natural or artificial) must also be supportive of juvenile Chinook salmon. In the HQT, **inundated areas are considered suitable if they are hydraulically connected to the river channel or, if an inundated feature becomes ponded, it must become re-connected to the river channel within seven days of disconnection.** In the case of more managed systems, where volitional ingress and/or egress to inundated floodplains is not possible (requiring methods such as trap and haul), habitat may be suitable but is considered less beneficial (see Appendix A). The hydraulic connectivity of sites managed by human activities requires a separate assessment that requires further development before it is implemented within the HQT.

2.3.5 Water quality and cover

Other environmental attributes that influence habitat quality for juvenile salmonids include cover and structure, as well as water quality parameters. Both cover and structure have been correlated with juvenile salmonid density (McMahon and Hartman 1989). Physical elements that provide cover and/or structural benefits include emergent or submerged vegetation, undercut banks, boulders, live or dead wood, and turbidity. **To qualify as suitable habitat, the inundated floodplain must have >75% cover of combined structural elements or exceed 20 NTUs (assessed on a daily basis).** These parameters must be evaluated through environmental monitoring (see Section 3.3).

Among water quality parameters, temperature and dissolved oxygen are particularly important for juvenile salmonids. High-water temperatures increase metabolic rates and can exceed physiological thresholds, leading to decreased growth and mortality of juvenile salmonids. High water temperatures can also increase infection risk among migrating salmonids (Noga 1996, USEPA 2003). Adequate concentrations of dissolved oxygen in water are also critical for salmon survival. In freshwater streams, low dissolved oxygen levels can impact the growth and development of salmon, as well as the swimming, feeding, and physiological ability of juveniles. If salmonids are exposed to such conditions for too long, mortality will result (Carter 2005). For the HQT, **floodplain habitat is only considered suitable when mean daily water temperatures are below 20°C and dissolved oxygen above 8 mg/L.** These parameters must be evaluated through environmental monitoring (see Section 3.3).

These suitability criteria are summarized in Table 2 and additional information on the scientific justification for the habitat criteria used in the HQT are provided in Appendix A.

Table 2. *Physical habitat criteria used in the Habitat Quantification Tool to define suitable floodplain habitat for rearing juvenile Chinook salmon. Duration criteria listed apply to Valley Lowland landscape type. The Valley Foothill type only includes two periods: 1) ≤ 9 days (suitability weight of 1.0) and, 2) > 9 days (suitabiltiy weight of 0.66). Duration is determined based on areas meeting depth and velocity criteria (e.g. depth and velocity criteria must be met to count toward duration).*

Criteria	Definition	Assessment Method
Timing	November 1 - June 30	Hydrospatial analysis approach
Duration	< 18 days (suitability weight of 0.66) 18-24 days (suitability weight of 1.0) > 24 days (suitability weight of 0.66)	
Depth	1-3.28 ft (0.3-1 m)	
Velocity	≤ 1.5 ft/s (≤ 0.46 m/s)	
Area	≥ 1 acre of inundated area meeting depth and velocity requirements for at least 1 day	
Cover	> 75% cover of structural elements or > 20 NTU (assessed on a daily basis)	Monitoring
Temperature	< 20°C (mean daily)	
Dissolved oxygen	> 8 mg/L (mean daily)	

3. Components of the Chinook Salmon HQT

Photo by Alison Whipple

Within the Chinook salmon HQT, assessing the potential of a site to provide suitable floodplain rearing habitat for Chinook salmon consists of three primary components: landscape context, hydrospatial analysis of the project site, and monitoring (Figure 5).

3.1 Assessing landscape context

Landscape characteristics affect the potential for juvenile Chinook salmon to utilize suitable habitat present at individual sites. Accounting for the landscape context of a site helps address the fact that the relative value of available suitable habitat at various sites within the Central Valley will depend on conditions outside of the project area. The main characteristics for assessing landscape context currently considered within the HQT include, 1) whether a site is located within a lower Central Valley floodplain ("Valley Lowlands") or along rivers upstream ("Valley Foothills"), 2) how many runs of salmon may be present at the site and their extent and distribution upstream of the site, and 3) longitudinal connectivity along migration corridors.

Currently, the landscape context is considered separately from the other components of the HQT. The landscape context assessment, including additional landscape characteristics, how landscape context is evaluated, and whether a landscape index (or indices) should be combined with quantified suitable habitat at the site-scale remains under development. In every case, the rationale behind landscape-scale priority decisions should be documented and reported along with the site-level assessments (via the project site evaluations of hydrospatial analysis and monitoring components). This should include information on the continuity, quality, and timing of the associated migration corridor, as well as the relative importance, locally, of protecting and restoring Valley Foothill vs. Valley lowland habitat, and should be brought directly into consideration in assessing the overall value of a site relative to other areas.

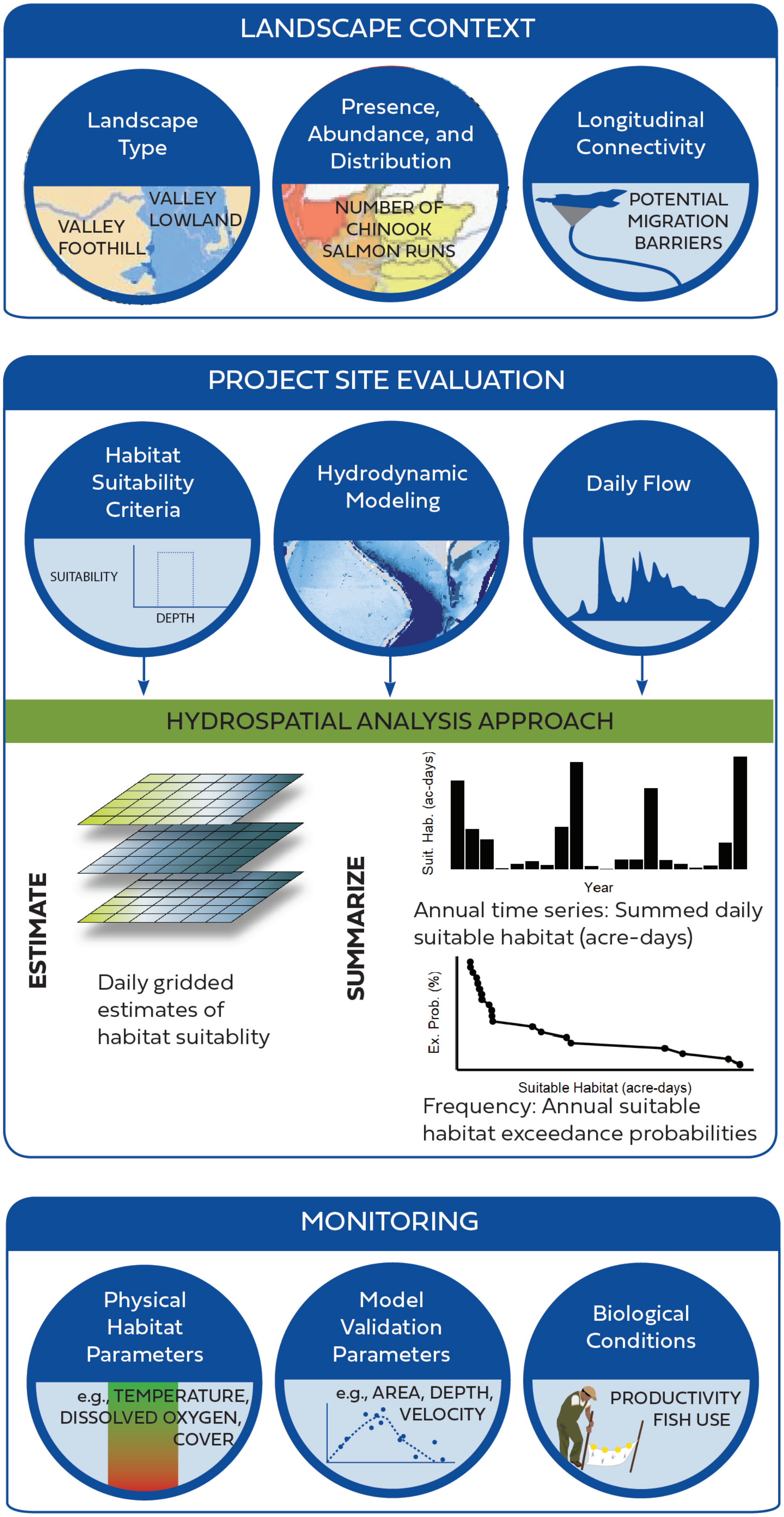


Figure 5. *Illustrative framework of the Chinook salmon Habitat Quantification Tool.*

3.1.1 Landscape type

Both upstream and downstream juvenile Chinook salmon rearing habitat is necessary to support healthy populations. Areas below the elevation threshold of 300 ft (91.4 m) for the CVHE area are classified as occurring within Valley Lowland or Valley Foothill landscape types (see Figure 4). These landscape types have different levels of off-channel habitat quality and are characterized by different geomorphic features and hydrologic processes that influence conservation and restoration potential for a given site (see Appendix A for explanation of these differences and the delineation of their areas). The purpose of the landscape type attribute is to: 1) support prioritization of off-channel habitats in the different landscape types; 2) allow for future refinements in physical habitat criteria that could reflect different response patterns and/or optimal values for the two landscape types; and 3) provide incentives to restore landscape-appropriate floodplain and off-channel habitat by encouraging restoration or acquisition of long-duration inundation sites in the Valley Lowlands and shorter duration off-channel habitat in the Valley Foothills. Currently, whether a site is located within the Valley Lowlands or Valley Foothills affects the duration of inundation that is considered optimal (see Section 2.3) and is addressed via the duration suitability criteria that are applied to a project site in the hydrospatial analysis component of the HQT.

Overall, the relative importance of floodplain habitat in these landscape types cannot be simplified to a single measure. Rather, the needs specific to a salmon run, watershed, and region must be considered holistically, with all available information taken into consideration and incorporated into a well-documented rationale for any programmatic and/or site-specific decision to prioritize one watershed or landscape type over another.

3.1.2 Chinook salmon presence, abundance and distribution

The presence, abundance, and distribution of Chinook salmon are directly correlated to the potential conservation value of a given project or land area in the Central Valley. To assess these, the existing population distributions of the spring-, fall-, late fall-, and winter-run Chinook salmon and the contributing watershed area are considered. Project sites must be located within the known distribution, or likely occurrence, of Chinook salmon to have conservation benefits and to qualify as Chinook salmon habitat within the HQT. Information on the spatial overlap of Chinook salmon runs is used to determine the number of runs that can benefit from a project. Greater value is attributed to projects that can support a greater diversity of runs, which is an indication of the spatial and temporal variability of out-migrant timing the habitat supports. The runs present also allow for assessment of potential benefits for specific runs and offer a way to compare the relative potential benefit associated with a specific project area.

The number of Chinook salmon runs potentially accessing a site is assessed based on presence of runs within the watershed of the project (assessed via the PISCES spatial database at the HUC12 level; Figure 6). This number is divided by four (the maximum number possible) to produce an index between 0 and 1. Projects with no current or

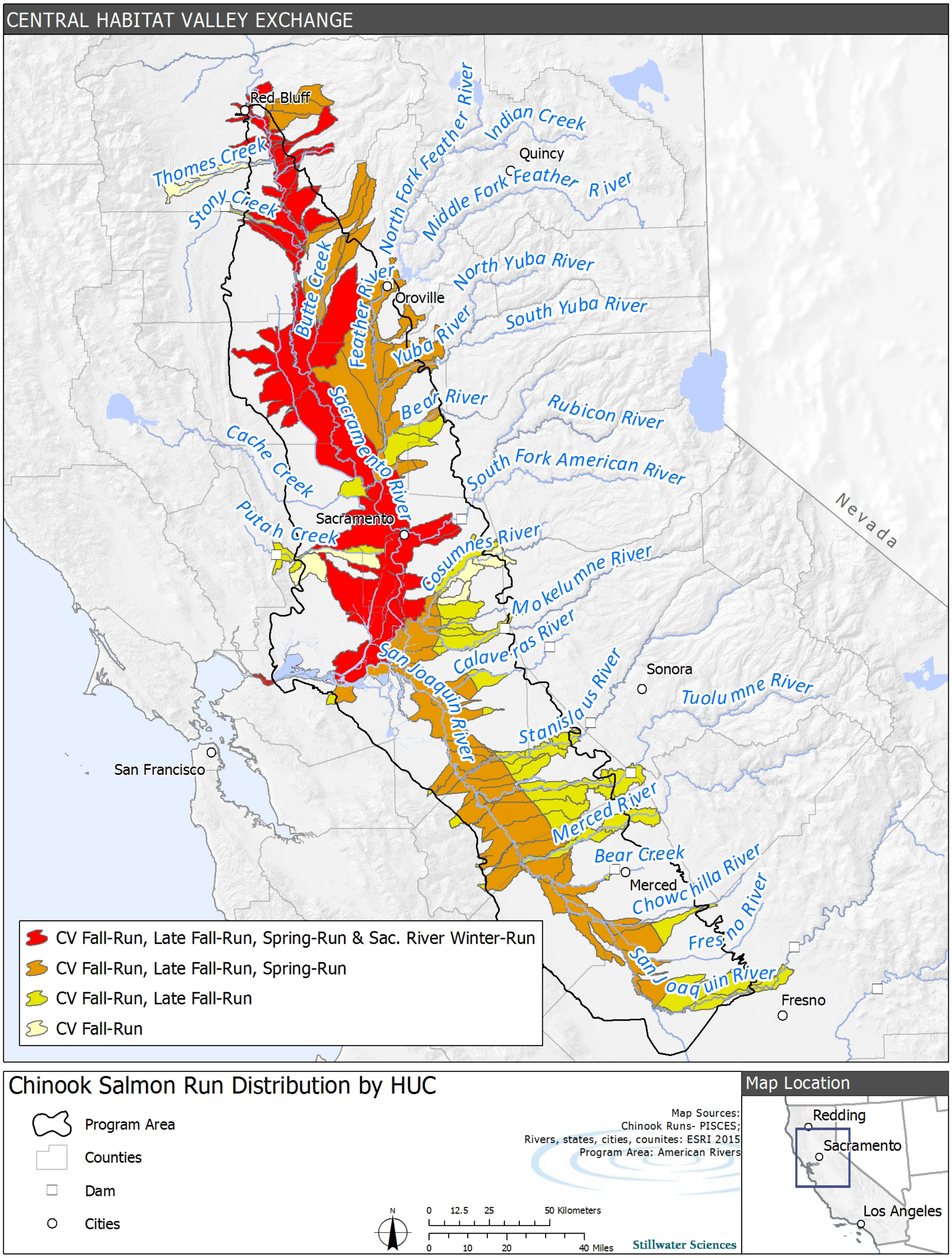


Figure 6. *Distribution of Central Valley Chinook salmon distribution by watershed (USGS HUC-12), based upon PISCES, from UC Davis (https://pisces.ucdavis.edu/).*

expected future overlap in any of the runs receive an index value of 0 and cannot be considered as providing Chinook salmon habitat.

Areas with high current use or high relative abundance of one or multiple Chinook salmon runs are recognized as supporting a larger part of the overall Central Valley Chinook salmon population and are considered to be of greater importance than areas with lower use. Relative abundance is correlated with the potential conservation value of a project site and the contributing watershed. For the HQT, the number of contributing watersheds (HUC 12 watersheds) for each run potentially present at a project location (as defined by the PISCES spatial database) is used as a measure of relative abundance of Chinook salmon expected at the project location. Each run is assigned an index value between 0 and 1, with five or more contributing watersheds receiving the maximum of 1, with linear scaling between one and five watersheds (e.g., two upstream watersheds would receive an index value of 0.4). The sum of the index values for each run is then divided by the number of runs potential present (or a maximum index value of 1). The index value for this landscape characteristic is defined as the product of this watershed index and the index for the number of Chinook salmon runs. Combined with the timing of each run (see Section 2.3, Table 1), this index could be set on a monthly scale and applied within the hydrospatial analysis component of the HQT. Currently, however, this is evaluated and reported separately from the site-scale assessment of potential habitat covered by the hydrospatial approach and monitoring.

3.1.3 Longitudinal connectivity

An additional landscape consideration that has substantial influence on the value of a particular site is longitudinal connectivity along the migration corridor. Longitudinal connectivity may be severed by physical passage barriers, reaches and periods when water temperatures and/or DO are lethal to Chinook salmon, lack of flow during migration periods, reaches with heavy predation, and long reaches with little to no foraging area. For example, along the Lower Tuolumne River, there is high quality spawning and rearing habitat for fall-run Chinook in the 10 to 12 miles below LaGrange Dam, but out migrant survival (i.e., the fraction of juveniles/smolts that make it to the confluence with the San Joaquin River and beyond) is poor, primarily due to predation by non-native piscivores, mainly largemouth bass, smallmouth bass, and striped bass (Stillwater Sciences 2013). In another example, physical barriers between Friant Dam and the confluence with the Merced River along the San Joaquin River block migration of spring-run Chinook (to be reintroduced in the future) to relatively good habitat for both upstream adult spawners and block downstream passage by juveniles and smolts (SJRRP 2012a). Without taking physical and biological barriers to migration into consideration, the potential benefits of restoring floodplains may be overestimated. While not currently evaluated as a part of the HQT, an assessment of limiting factors to migration is necessary to understand the potential habitat value of a project site and relative value across sites.

3.2 Project site evaluation with the hydrospatial analysis approach

The hydrospatial analysis approach implemented within the Chinook salmon HQT allows for explicit accounting of spatially and temporally variable habitat conditions found in floodplain environments and is used to quantify suitable habitat area at a project site. Aside from different duration weighting depending on landscape type, the landscape context assessment (see Section 3.1) is considered separately from this site-scale assessment. The hydrospatial approach was presented in Whipple (2018) as a method for characterizing floodplain inundation patterns in space and time. It uses four-dimensional data: the x- and y- spatial information, time, and physical parameters of interest (e.g., depth, duration). Similar procedures have been used by others to assess spatially-resolved physical conditions based on 2D hydrodynamic modeling and a flow time series (Stone et al. 2017). The process for conducting hydrospatial analysis within the HQT involves several core components. Detailed explanation of the steps is provided in Section 4.

3.2.1 Inputs for hydrospatial analysis

A primary input for the hydrospatial analysis component of the HQT is a set of gridded (raster) estimates of depth and velocity at known flows across the floodplain site, derived from 2D hydrodynamic modeling. The hydrodynamic model is run for a range of flows, extending from below floodplain inundation threshold flow to the highest flow in the period of record to be examined. Also required is a user-defined floodplain inundation threshold flow (flow at which the site begins to inundate). The explanation herein assumes that a 2D hydrodynamic model for the floodplain site in question has been previously established. The permitting and design process for restoration projects typically involve the development of 2D hydrodynamic models, and generating the needed input for the HQT from such existing models requires limited additional effort.

The second primary input is a daily streamflow time series for the period of record to be analyzed that corresponds to the range of flows represented by the 2D hydrodynamic modeling. The HQT requires at least 20 years of record in order to capture variation in flood magnitude, timing, frequency, and duration that occurs at the site and year-to-year variability. The daily streamflow time series may be representative of current water management operations and flow regimes and/or future conditions (e.g., under environmental flow standards or hydroclimatic change). The daily flow time series can be historical observed flows (e.g., USGS streamgage) or derived from models. This time series is pre-processed to identify flood days and events using the floodplain inundation threshold flow (see Section 4.3).

3.2.2 Analysis overview

The hydrospatial analysis involves two primary components. The first is to estimate daily gridded water depth and velocity. This uses spatially-resolved flow-depth and flow-velocity relationships based on the hydrodynamic model output. These are

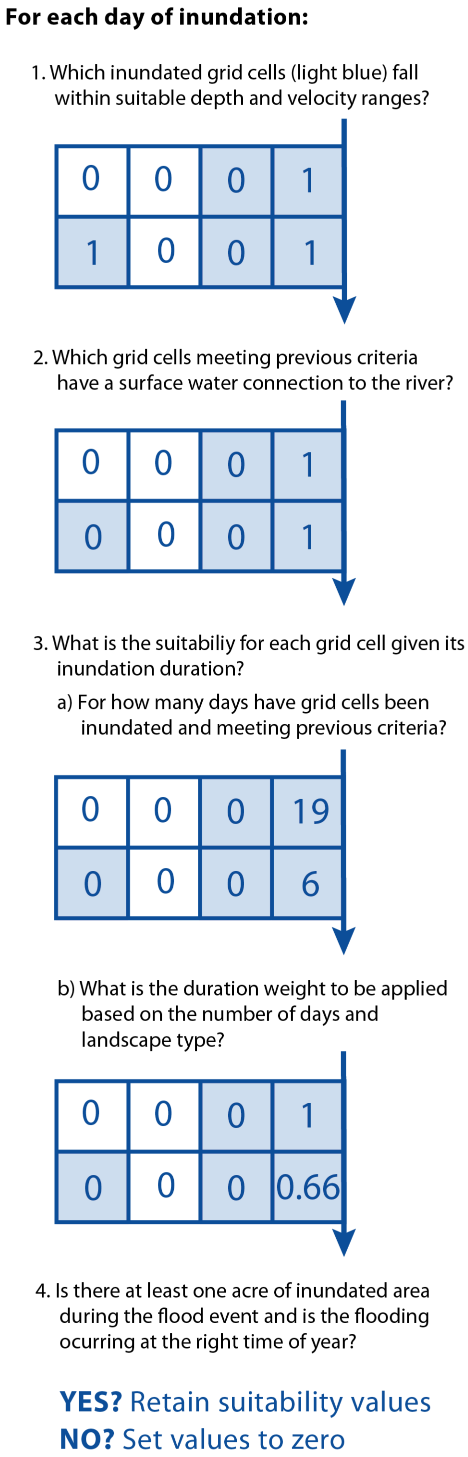


Figure 7. *Conceptual illustration of the step-wise and grid-based application of habitat suitability criteria at the daily scale using the hydrospatial approach. Note that this example applies duration criteria and weights associated with Valley Lowlands. Other landscape context considerations and habitat criteria assessed via monitoring are addressed separately.*

then used to calculate daily gridded estimates of depth and velocity for each day of the input daily flow time series, via spatially-resolved (cell-by-cell) piecewise linear interpolation (see Section 4.4.1).

The second analysis component uses the daily gridded estimates of depth and velocity to evaluate whether habitat suitability criteria are met on a daily gridded scale. First, physical parameters other than the directly interpolated depth and velocity rasters, including duration of inundation and hydraulic connectivity to the river, are determined on a cell-by-cell basis by evaluating the depth rasters. For connectivity, grid cells on each day are evaluated as to whether they are inundated and connected or disconnected from the river channel via a surface water connection, as represented by inundated grid cells. Connectivity is assessed without considering suitability of depth and velocity. For example, if an area of suitable depth is connected via an area that is below the minimum suitable depth, the area of suitable depth would be considered hydraulically connected. Inundation duration is assessed on a cell-by-cell basis as the number of days a cell has been inundated for. For example, a low lying area directly adjacent to a river channel on a given day may be associated with a duration of multiple weeks while a higher elevation location within the floodplain may only be inundated for several days of high flow. For areas that are isolated (disconnected from the river, but inundated) on the falling limb of a hydrograph, additional steps are applied to determine whether those grid cells reconnect to the river within seven days (an assumed period before ponded water evaporates or infiltrates) in order to count them toward inundation duration.

Physical habitat criteria assessed within the hydrospatial analysis component of the HQT relate to physical parameters of depth, velocity, connectivity, duration, timing, and minimum area (see Section 2.3, see Table 2). They are applied to each of the grid cells of the physical parameters for each day, with resulting grid cell values ranging from 0 (unsuitable) to 1 (maximum suitability; Figure 7). If any one criterion is not met, then that grid cell receives a value of 0. In addition, only days within the given timing window are considered and the minimum inundated area threshold must also be met, which involves determining if the threshold has been exceeded for at least one day over the course of a flood event. After criteria have been applied, the resulting output is a set of rasters representing habitat suitability for each flood day.

Daily estimates of suitable habitat area are computed by summing all of the areas (grid cells), weighted by their suitability. These daily values of suitable habitat area are subsequently summed for each water year assessed, as units of acre-days. Annual acre-days of suitable habitat is defined as the daily acreage (weighted by suitability) of inundated area meeting habitat suitability criteria summed across all days in a year. With a sufficiently long period of record (approximately 20 years or more), this can be used to establish average conditions and variability depending on wet and dry years. From the annual time series, summary statistics (e.g., mean, median, min and max) are calculated to assess average and extreme conditions expected for the floodplain site. Additionally, an empirical exceedance probability curve is established for assessing the expected frequencies with which given annual acre-days are expected to be exceeded (Figure 8). This can show, for example, whether most years are much higher than the minimum habitat or if high levels of suitable habitat area only occur in the extreme wet years. It can also illustrate, in instances where restoration scenarios are being compared, whether the differences between scenarios are consistent across years. Interpretation of results is facilitated by the fact that the summary is derived from spatially- and temporally-resolved estimates. For example, the gridded estimates of habitat suitability can be summed over a year to develop a map of total annual suitability that illustrates what areas of a floodplain site contributed more or less to the annual acre-day total (see Figure 8).

There are several limitations to the hydrospatial analysis approach. It does not account for some characteristics of flood events, including flood wave propagation, antecedent conditions, and flow rate of change. It also does not account for evapotranspiration and infiltration on the floodplain. Further, as this analysis is based on the mean daily flow record, it does not account for conditions at peak flows occurring at a sub-daily scale.

3.3 Monitoring

Monitoring is an essential component of the Chinook salmon HQT. Direct observations of the quality and quantity of floodplain habitat is required to assess the condition of habitat parameters that cannot be modeled as part of the hydrospatial approach (see Section 3.2), such as water quality and cover. Monitoring may also be designed for hydrodynamic model validation of inundation area, water depths and velocities. Monitoring is also required to evaluate how floodplain habitat conditions change over time, for example, with changes in vegetation cover, structure, sediment transport, and land use. Finally, monitoring can be helpful for refining the habitat criteria that define suitable habitat for the species of interest. For example, monitoring may show that fish are utilizing a wider or narrower range of habitats than assumed by the existing habitat criteria, resulting in under- or over-prediction of suitable floodplain habitat, respectively. The design of a monitoring program will vary by the questions the monitoring needs to answer, project size, physical complexity of the site, and the

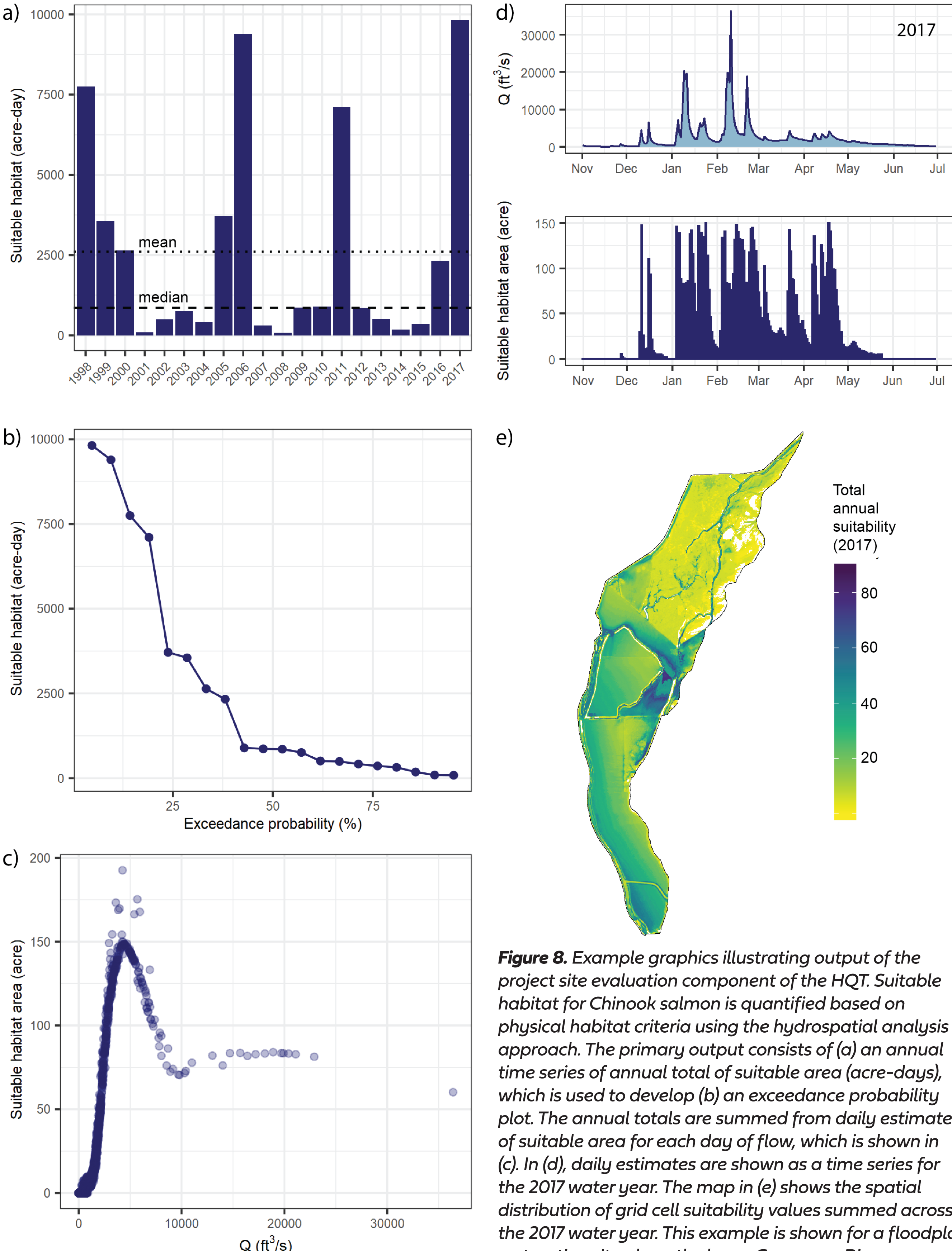


Figure 8. *Example graphics illustrating output of the project site evaluation component of the HQT. Suitable habitat for Chinook salmon is quantified based on physical habitat criteria using the hydrospatial analysis approach. The primary output consists of (a) an annual time series of annual total of suitable area (acre-days), which is used to develop (b) an exceedance probability plot. The annual totals are summed from daily estimates of suitable area for each day of flow, which is shown in (c). In (d), daily estimates are shown as a time series for the 2017 water year. The map in (e) shows the spatial distribution of grid cell suitability values summed across the 2017 water year. This example is shown for a floodplain restoration site along the lower Cosumnes River.*

project budget. Therefore, we only provide general guidelines for monitoring floodplain habitat as part of the HQT.

Key considerations for any monitoring program include: spatial scale and resolution (the extent of monitoring area and the number/density of locations sampled); the temporal scale and resolution (the total time period and frequency of sampling); focal features (the specific habitat elements to be assessed); and methods by which focal features will be measured. Monitoring can include synoptic field measurements, which provide a "snapshot" of conditions at a particular place and time, or continuous measurements, which typically involve deployment of data loggers equipped with sensors to measure environmental parameters, such as water level, temperature, light, and dissolved oxygen. Continuous monitoring provides a direct way to assess whether suitable conditions are met throughout a flood event and can be used to inform relationships between environmental variables and habitat. Environmental monitoring programs can also take advantage of remotely-sensed imagery collected by drones, airplanes, or satellites.

Monitoring for the Chinook salmon HQT should, at a minimum, evaluate the physical habitat criteria that are not represented in the hydrospatial approach. These elements include: water temperature, dissolved oxygen, turbidity, and cover. They should be assessed for both the rearing habitat as well as the areas providing passage between the river and floodplain rearing habitat. Water temperature is most commonly measured at point locations using hand-held devices or through deployment of low-cost underwater continuous temperature data loggers. In instances where a river temperature model or in-channel temperature monitoring exists, this could be coupled with floodplain temperature monitoring to develop relationships between river and floodplain water temperature and potentially allow river temperature to become a proxy for floodplain temperature Dissolved oxygen can also be measured using hand-held instruments and continuous data loggers. Turbidity is an optical property of water that relates to its clarity or murkiness. It can be measured in the field using a secchi disk or tube or with more sophisticated electronic turbidity sensors that detect light scatter from suspended particles in the water in the water column. Floodplain habitat cover for fish can be provided by a wide variety of structural elements, including boulders and artificial structures such as concrete pilings, live and dead wood, submerged and emergent vegetation, and overhanging canopy from plants rooted in riparian and terrestrial habitats. In some cases, cover can be estimated from aerial imagery, although the age and seasonal timing of images should be taken into account. Direct assessment of cover using visual estimates or ground surveys will likely be needed.

Where feasible, monitoring should also include collection of data to validate hydrodynamic model predictions of inundated area, velocity, and depths that are used in the hydrospatial approach. Remotely sensed imagery (from drones or aircraft) or direct measurements from ground surveys can be used to map inundation extent at known flows and compared with predictions of the hydrodynamic model. Depths and velocities should be sampled at point locations over the range of conditions observed at the sites using a handheld velocity meter. Continuous measurements of depth can also be collected by water stage loggers deployed on the floodplain and in the river channel. If the floodplain topography has been observed to change in response to flood events and/or vegetation recruitment, then it may be necessary to re-survey the land surface topography and re-calibrate the hydrodynamic models used in the hydrospatial approach.

When feasible, we recommend that measurements of physical habitat be coupled with monitoring of biological conditions, including the distribution, density, and condition of juvenile salmon as well as the distribution, composition, and quality of food resources on the floodplain. These data can help improve understanding of floodplain habitat use by juvenile salmon and potentially refine the habitat criteria specified in the HQT. Rather than attempting to conduct this type of monitoring at all restored sites, it would likely be most cost-effective to focus on at least several of the larger, well-funded restoration projects where adequate resources are available to implement a well-designed, robust monitoring program. Once sufficient data is available from several restoration projects, results can be used to modify the HQT and improve the design of future restoration projects.

4. Steps for Implementing Project Site Evaluation

Photo by Carson Jeffres

Conducting hydrospatial analysis to evaluate habitat suitability using the Chinook salmon Habitat Quantification Tool (HQT) involves pre-processing input files established from hydrodynamic modeling and from a daily flow time series, running the analysis, and summarizing and visualizing results (Figure 9). The HQT uses the *R* software environment (R Core Team 2019). The following steps describe how to set up and run the HQT. A pilot example is presented in Appendix B.

4.1 System requirements

The HQT requires a computer with *R* installed (*RStudio* is also recommended) that ideally has >24 GB of RAM, though it will run with less. As the analysis is grid-based, a large amount of hard disk space is required. The total amount of space required is highly dependent on the study area size, grid cell resolution, and the total number of years (and flood days within those years) to be analyzed. Typically, a study area of approximately 500 acres, a cell resolution of 10 ft, and a 20-year record will require on the order of 500 GB.

4.2 Installation

The 'hydrospatial' *R* package can be installed using the 'devtools' *R* package, with:

```
devtools::install_github("sfei/hydrospatial")
```

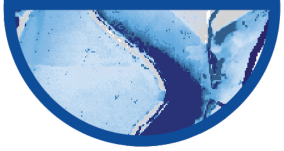
This will also install, if not already installed, package dependencies: 'raster,' 'igraph,' and 'doParallel.' The main hydrospatial analysis functions rely the 'raster' package. Many functions also take advantage of the multi-core processing capacity of the 'raster' package, made possible via the 'doParallel' package. Users may find that the 'snow' and 'rlang' packages must be installed separately. Other packages used include 'dplyr,' 'lubridate,' 'rgeos', 'stringr,' and 'ggplot2.'

Note that this is a development package and improvements and testing are ongoing. Checking for new versions regularly is recommended.

PROJECT SITE EVALUATION

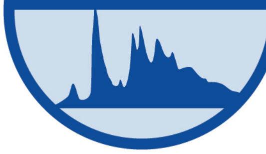
INPUTS

Hydrodynamic Modeling



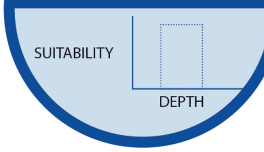
- Determine inundation threshold flow at project site
- Select flows for modeling to capture flooding behavior at the the site
- Run model
- Format model output rasters of depth and velocity

Daily Flow



- Format daily flow time series (>20 years)
- Identify flood days and events
- Set the flow days for raster estimation based on inundation threshold flow

Habitat Suitability Criteria

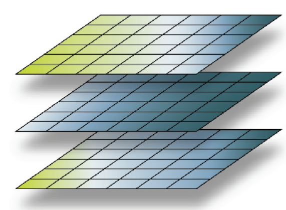


- Identify suitability index values for physical parameters including depth, velocity, connectivity, inundation duration, and timing

HYDROSPATIAL ANALYSIS

Estimate daily gridded depth and velocity

- Set processing directories
- Load hydrodynamic modeling output files and pre-process
- Generate the inundation threshold flow raster
- Estimate daily depth and velocity rasters via cell-by-cell piecewise linear interpolation for selected flood days from the flow time series



Assess physical parameters and apply suitability criteria

- Set processing directory
- Set habitat suitability criteria variables
- Sequentially analyze inundation extent by applying depth and velocity criteria, area threshold, hydraulic connectivity, duration, and timing to generate rasters of daily spatially-distributed habitat suitability ranging from not suitable (0) to maximum suitability (1)
- Write the results to file

RESULTS SUMMARY

- Set processing directories and load files
- Format results tables for plotting
- Generate exceedance probability and annual timer series plots
- Generate daily results plots
- Generate time series plots for a given year
- Generate map of total annual suitability for a given year

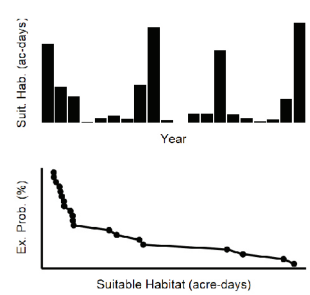


Figure 9. *Technical processing elements for project site evaluation within the HQT, which implements the hydrospatial analysis approach to quantify suitable habitat.*

4.3 Inputs: Requirements and formatting

There are three primary data inputs for the HQT: 1) 2D hydrodynamic modeling output of gridded **depth and velocity at known flows,** and 2) **daily flow time series** of a period of record for which to estimate the area of suitable habitat, and 3) **habitat suitability values** for physical parameters. Additional supporting information is also required. A **floodplain inundation threshold flow** is needed to specify the flow at which the study area begins to inundate. This will be used to limit the analysis process to only the days where inundation is expected. Also, shapefiles of the **study area boundary** and **connectivity areas** designating the parts or boundaries of the study area that are considered connected to the river channel are needed for the analysis. The first two primary inputs and formatting requirements are described in the following sections. See Section 2.3 and Appendix A for habitat suitability criteria, which users assign depending on whether the site is located within the Valley Lowland or Valley Foothill landscape type.

4.3.1 Two-dimensional hydrodynamic modeling

The HQT uses gridded (raster) estimates of **depth and velocity at known flows**, as obtained from output of 2D hydrodynamic modeling. These are obtained via four steps: 1) Determine floodplain inundation threshold flow, 2) Select flows for modeling, 3) Run model, 4) Format model output (Figure 10). This description assumes that a calibrated model exists for the study site in question and that it is possible to generate raster output of depth and velocity (e.g., .tif) from the model.

To obtain the modeling output required for the HQT:

1. **Determine floodplain inundation threshold flow.** The model is used to determine the floodplain inundation threshold flow, or the flow at which the study area begins to inundate. This can also be informed via field-based monitoring. Note that the flows used in the modeling must correspond (either directly or via a known relationship) to the daily flow time series used in the analysis.

2. **Select flows for modeling.** This step involves the selection of a set of flows that range from below the floodplain inundation threshold flow to the highest flow in the period of record to be examined. Selecting the specific flow levels to evaluate in the hydrodynamic model requires some understanding of the flood behavior of the site. Based on exploration of the flood behavior at the site (how inundation extent, depth, and velocity varies with flow), the user selects flows that reasonably capture this behavior, such that interpolating conditions between these flows will not miss large changes (typically on the order of 10 to 50 distinct flow levels). Smaller intervals between flows should be used where conditions change rapidly with river stage. For example, if the majority of a given study area inundates between 1,000 and 2,000 cfs, then 100 cfs increments may be warranted. In contrast, if extent changes minimally and depth and velocity change roughly linearly between 2,000 and 10,000 cfs, then 1,000 or 2,000 cfs increments may be warranted. The goal is to minimize the number of flows that need to be modeled to minimize computation time and cost, while still capturing key characteristics of the site.

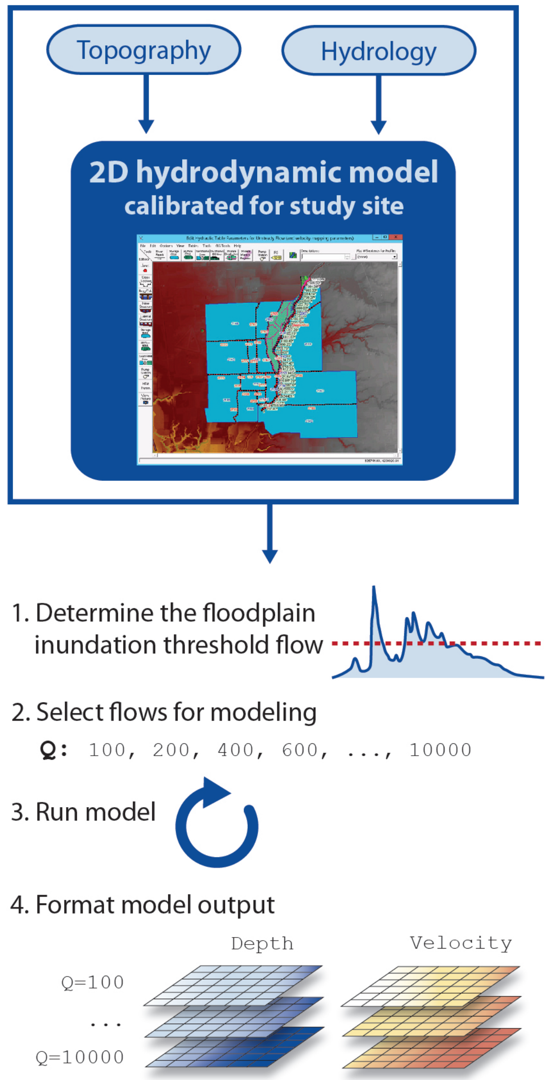


Figure 10. *Illustrated steps for preparing hydrodynamic modeling output for use in hydrospatial analysis.*

3. **Run model.** Once the flows have been set, the model should be run using a continuous, stepped-hydrograph approach, where each step is a selected flow that progressively increases. This means that at each of these steps, the floodplain inundation extent, depth, and velocity can be taken as representative of the flow at that step. This implies that though unsteady flow simulation is performed, the conditions at each step represent quasi-steady state conditions (e.g., velocity is not responding to a rate of change in flow). If inundation extent differs substantially depending on whether a given flow is on the rising or falling limb of a hydrograph (i.e., ponding occurs as flood waters recede), then it is recommended that the selected flows on both a rising and falling limb be modeled. The HQT can be used with or without ponding considered. Details for setting the input hydrograph for the model and running the model are specific to the model being used and site-specific conditions, and are thus not discussed here.

4. **Format model output.** For each of the selected flows (on both the rising and falling limbs of the hydrograph, if used), raster output of depth and velocity need to be generated from the output of the model run. Commonly used formats are acceptable (e.g., .tif, .img, .grd). The grid cell resolution of the rasters should be at a resolution that adequately captures the spatial variability at the site (typically 3 to 10 ft resolution). The model output needs to be clipped to the study area. Along with the rasters of depth and velocity, a table needs to be generated of the flows that each raster represents (each row corresponding to one of the rasters). This is “flws_rasterinterp.csv” in the example files. If both the rising and falling limbs are being used, then both are included in the table, with a ‘limb’ column indicating the rising (‘r’) or falling (‘f’) limb.

4.3.2 Daily flow time series

The HQT uses a time series of mean daily streamflow to create the time series of daily gridded estimated depth and velocity from which to determine habitat suitability. Over 20 years of record is recommended for capturing variation in flood magnitude, timing, frequency, and duration that occurs at the site and year-to-year variability. The daily streamflow time series may be representative of current water management operations and flow regimes and/or future conditions (e.g., under environmental flow standards or hydroclimatic change). The daily flow time series can be historical observed flows or derived from models. The flows in this time series must correspond to the known flows represented by the hydrodynamic model output (e.g., the HQT assumes that a raster of depth at 200 cfs in the model represents conditions at 200 cfs in the daily flow time series).

Prior to being used in the hydrospatial analysis, three steps must be followed to prepare the dataset: 1) Format the daily flow time series, 2) Identify flood days and events, 3) Set the flow days for daily raster estimation. In step 2, based on the user-defined floodplain inundation threshold flow, flood days and events are identified in the tool, with days of continuous flows meeting or exceeding the threshold grouped as individual flood events (following Whipple et al. 2017). Functions from the 'hydrospatial' *R* package are used to establish the input files. Functions referred to herein are from the 'hydrospatial' *R* package unless otherwise specified. These are implemented via the example *R* script, "HQT_1_FlowsPrep.R".

To format and process the daily flow time series:

1. **Format the daily flow time series.** The *utils_flowformat* function from the 'hydrospatial' *R* package takes an input flow time series data frame with a date ('dt', in month-day-year format) and flow ('flw', either in cfs or m^3/s) column. This function adds the following columns based on the flow and date: water year, water year day, cumulative flow, annual flow, high flow (gives the highest flow within the last seven days), and limb (rising ('r') or falling ('f') depending on whether a given flow is higher than flow in the previous seven days). Further details can be found in the function documentation.

2. **Identify flood days and events.** Using the *utils_floodid* function, flood days are identified using the floodplain inundation flow threshold provided as a variable input (described in Section 4.3.1) and the formatted daily flow time series (based on the 'flw' column). This function establishes a subset of the daily flow time series with additional columns for a unique id of the flood event number and flood event day (which is the third item in a list returned by the function). It also characterizes flood events for a variety of metrics (see Whipple et al. 2017), though these are not currently used in the HQT.

3. **Set the flow days for raster estimation.** Via the *utils_flowstopredict* function, both the formatted daily flow time series and the data frame of identified flood days are then used to export a formatted file ("flows_topred_full.csv") used for the first primary step of running the analysis. Aside from formatting the file, the main purpose of this step is to add a post-flood period (default set to seven days) to the flood days time series such that the analysis will consider the seven

days after flow falls below the given floodplain inundation flow threshold to allow for potential ponding (and potential reconnection in the event that flow rises again within the set period and reconnects to the ponded area).

4.4 Running the hydrospatial analysis

Conducting the hydrospatial analysis involves two primary components, each involving a number of steps. The first component is **estimating daily gridded depth and velocity** and the second is **assessing physical parameters and applying habitat suitability criteria**. Each relies on a set of functions within the 'hydrospatial' *R* package. The technical processing steps for each are described below, with graphics from an example run provided.

4.4.1 Estimating daily gridded depth and velocity

For each day in the formatted and processed daily flow time series, rasters of depth and velocity are estimated using the processed 2D hydrodynamic model output. This is implemented within the HQT using the set of functions with the prefix "predrast."

To estimate depth and velocity rasters:

1. **Set processing directories.** It is highly recommended that a dedicated directory with adequate hard disk space for the analysis (discussed earlier) be established for the various files generated over the course of the analysis. Within the working directory for the project, the following directory and subdirectory structure is recommended: ".../predictrasters/forpredicting", ".../predictrasters/predicted/Depth", and ".../predictrasters/predicted/Velocity". If multiple projects or scenarios are being run, then directories with the project name can be added within the "predictrasters" directory. Also, it is recommended that the RTEMP location be changed from its default location using the 'raster' package *rasterOptions* function, as temporary rasters are written to file for some of the processing steps if objects are too large to be stored memory (see the 'raster' package documentation for further information).

2. **Load files.** Both sets of model output rasters, for depth and velocity, and the table of flows that each of those rasters represent should be loaded into the environment. It is essential for processing that the position (index) of each raster in the raster stack of modeled output correspond to row number (index) of each flow the rasters represent.

    a. **Aggregate rasters (optional).** If the cell resolution is higher than necessary, the model output rasters can be aggregated, using the aggregate function from the 'raster' package. Doing so will reduce processing time, but must be considered carefully to insure that the aggregation doesn't smooth over important spatial variability in depth or velocity. For example, aggregating from a ~3 ft to a ~10 ft resolution may be reasonable while a ~3 ft to ~30 ft resolution may not.

3. **Generate the inundation threshold flow raster.** Before the daily rasters are estimated, an inundation threshold flow raster should be created (required if ponding on the falling limb of the hydrograph is being considered in the analysis; Figure 11). This is implemented with the *predrast_thresholds* function. From the set (stack) of model output rasters for depth, this function assigns to each cell the maximum flow before it becomes inundated. For example, if a particular cell is not inundated in the model output raster representing 100 cfs, but is in the model output raster representing 200 cfs, then the value assigned to that cell will be 100.

4. **Estimate daily depth and velocity rasters.** Using the *predrast_interp* function, this step conducts spatially-resolved piece-wise linear interpolation for each of the flows in the table of flow days for raster estimation ("flows_topred_full.csv"). It outputs one raster for each day in the time series provided, appending to the filename the scenario or project name provided, the variable in question ("Depth" or "Velocity"), and the date (Figure 12). This should be run once for estimating depth and again for velocity. Note that though input raster format can vary (see the 'raster' package documentation), the rasters generated in the processing and analysis use the default native format of ".grd."

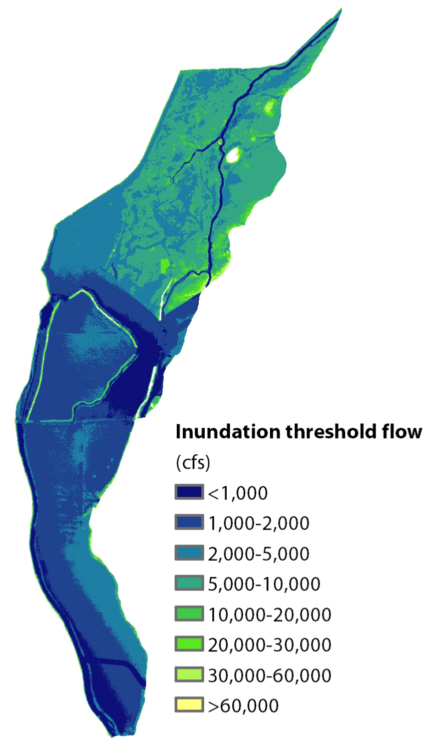


Figure 11. *Map of inundation threshold flows, which shows the spatial distribution of the magnitude of flow at which inundation occurs on a cell-by-cell basis. This map is from the lower Cosumnes River restoration project example.*

4.4.2 Assessing physical parameters and applying suitability criteria

The depth and velocity rasters for each water year are processed sequentially to determine physical parameters in addition to depth and velocity (e.g., connectivity, duration) and apply the physical habitat suitability criteria, performed on a day-by-day and cell-by-cell basis. This is implemented within the HQT using the set of functions with the prefix "hsa." These steps are provided in the example *R* script, "HQT_3_HydrospatialAnalysis.R".

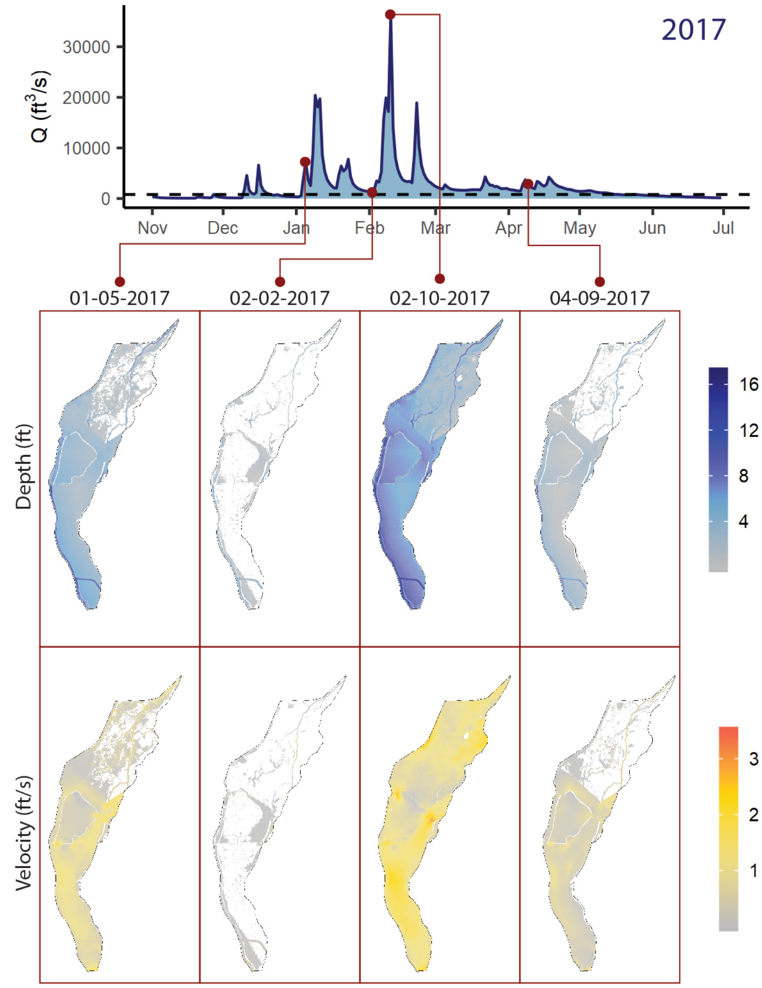


***Figure 12.** Interpolated gridded values of depth and velocity for daily flow, shown as they relate to a range of flow magnitude in the water year 2017 hydrograph. Example shown is from the lower Cosumnes River restoration project.*

To assess physical parameters and apply suitability criteria:

1. **Set processing directories.** Within the working directory for the project, it is recommended that a "rworkingfiles" directory is created. If multiple projects or scenarios are being run, then directories with the project name can be added within the "rworkingfiles" directory. Subdirectories within this directory will be created by the hydrospatial analysis functions. Also, it is recommended that the RTEMP location be changed from its default location using the 'raster' package *rasterOptions* function, as temporary rasters are written to file for some of the processing steps if objects are too large to be stored memory (see the 'raster' package documentation for further information; Hijmans 2019).

2. **Set habitat suitability criteria variables.** Hydrospatial analysis within the HQT uses physical habitat suitability criteria relating to depth, velocity, connectivity, duration, minimum inundated area, and timing. The habitat criteria are set based on the criteria discussed in Section 2.3 (see Table 2), which users assign depending on whether the site is located within the Valley Lowland or Valley Foothill landscape type.

3. **Unit conversion.** It is essential that the user pay careful attention to the units of various inputs and outputs. All input should either be in metric or US customary units (e.g., m^3/s, m, and ha for metric and cfs, ft, and acres for US customary units). A conversion from metric to US customary units can be made at this point. The hydrospatial analysis functions use a cell resolution variable (in square units) and an area conversion factor to handle this conversion.

4. **Prepare flows data frames.** Using the *utils_hsaflws* and *utils_hsaflowsevts* functions, the table of flow days for raster estimation ("flows_topred_full.csv") is formatted into a daily flows data frame and a flood events data frame, which are prepared with additional fields to be filled in by the hydrospatial analysis functions.

5. **Set to process rasters annually.** Each water year in the period of record is analyzed sequentially, where the depth and velocity rasters for a given particular water year are loaded and then physical parameters are assessed, habitat suitability criteria are applied and daily suitable area determined. Attempting to analyze all years together (i.e., more than several hundred rasters at a time) would likely reach computational limits. For each water year, the water year variable is assigned, indices from the daily flows and flood events tables for the water year in question are set, and a flood event grouping index is set for each day to be analyzed in the given water year.

6. **Analyze inundation extent with suitable depth and velocity.** The depth and velocity rasters for a given water year are loaded and the *hsa_extent* function is applied. This function accepts depth and velocity rasters, the associated flows data frame for a given water year, the depth and velocity suitability criteria thresholds, as well as several additional variables. Three sets of rasters are written to file in the output directory specified: one indicating whether cells are inundated (1) or not (0) with the prefix "rsti0…", and two indicating whether cells are inundated and meet both the depth and velocity criteria (one with non-suitable cells set to 0 (prefix of "rsi0…" and another where non-suitable cells are set to NA (prefix of "rsi…"). Total inundated area, inundated area meeting depth and velocity criteria, and percent of study area that meets depth and velocity criteria are calculated for each raster, and values are filled into the flows data frame. Example output is shown in Figure 13.

7. **Apply area threshold.** The *hsa_areathreshold* function is used to determine whether at least one day in a flood event exceeds the minimum inundated area requirement. This is evaluated from the inundated area meeting depth and velocity criteria computed in the previous step.

8. **Analyze inundation frequency.** Using the rasters that designate whether cells are inundated and meeting the depth and velocity criteria or not ("rsi0…"), the *hsa_freq* function is applied. On a cell-by-cell basis, this function assigns unique values for each grouping of consecutively inundated days. For example, if a cell is inundated for three days and then dry for two and then wet again for four,

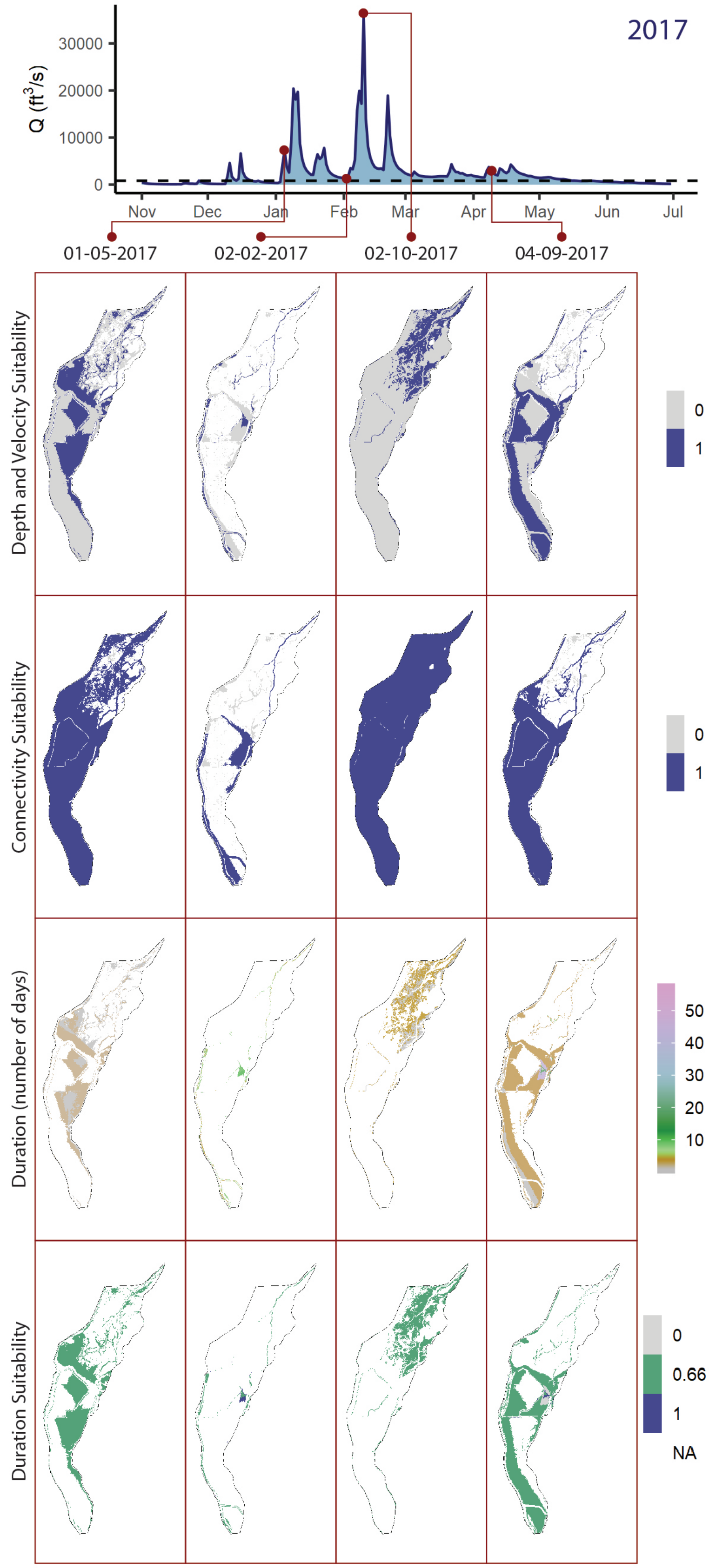


Figure 13. *Example outcomes of primary hydrospatial analysis steps taken from the lower Cosumnes River restoration project.*

the cell would be assigned the following values: 1, 1, 1, NA, NA, 2, 2, 2, 2. These rasters are written to file with the prefix "rsnoinun…".

9. **Analyze hydraulic connectivity.** This step uses the rasters designating inundation ("rsi0…) within the *hsa_connectivity* function. The approach takes all inundated grid cells (meeting depth and velocity criteria) and lumps them into unique patches based on cell adjacency (patch analysis). All grid cells within patches that touch the river channel are identified as connected. Inundated grid cells that have a surface water connection to the river (represented by the connectivity areas shapefile mentioned in Section 4.3) are assigned a value of 1. Disconnected (but inundated) cells are also identified. Connectivity and disconnectivity rasters are written to file with the prefix "rsc…" and "rsdc…". Connected and disconnected area is computed and added to the flows data frame. See example output in Figure 13.

10. **Analyze duration.** Duration of inundation is determined on a cell-by-cell basis, using the function *hsa_duration*. It uses four different sets of previously calculated rasters: inundated area that meets depth and velocity criteria ("rsi.."), inundated area that is connected ("rsc…"), inundated area that is disconnected ("rsdc…"), and inundated area consecutive inundation groupings ("rsnoinun…"). A number of rasters and flood event metrics are generated and written to file (e.g., inundation duration rasters for each flood event). The primary output for subsequent application of suitability criteria is the determination, on a daily basis, the number of sequential days of inundation (meeting depth and velocity criteria) of each cell. If an inundated cell becomes disconnected but is reconnected within seven days (an assumed period before ponded water evaporates or infiltrates), those inundated days prior to reconnection are counted toward duration. As an example, an area that was connected to the river for two days, then disconnected but inundated for three days, and then reconnected on the following day by high river flows would receive an inundation duration of six days on the first day of reconnection (assuming all days met depth and velocity criteria). Four sets of duration rasters are written to file: inundated duration for each flood event ("rsdur0…"), connected inundation duration for each flood event ("rscdur0…"), disconnected inundation duration for each flood event ("rsdcdur0…"), and the day of inundation rasters ("rsdayinun0…"). The flood events data frame with filled out fields is also returned. See example output in Figure 13.

11. **Apply duration weighting.** Using the day of inundation rasters from the duration analysis ("rsdayinun0…") and the duration criteria and weightings, the *hsa_durationwgt* function is applied. This function assigns the duration weights to each cell based on the day of inundation. For example, if a cell has been inundated for 5 days, it receives the short duration weight. If that cell stays inundated for 4 more days, then it will receive a long duration weight on that day because it will have reached a duration of 9 days. The rasters written to file are assigned the prefix "rsdayinun0wgt…". See example output is shown in Figure 13.

12. **Apply the timing criteria and compute daily suitable habitat area.** The final hydrospatial analysis function to be applied in this sequence is the *hsa_timing* function. This function uses the rasters from the previous step ("rsdayinun0wgt..."). Any suitable area that falls outside the given timing window criteria are assigned a value of 0. The resulting suitable area for each raster (each day) is computed as the cell value (suitability weight) multiplied by the cell area, or a weighted usable area approach. A hydraulic habitat suitability ratio is also computed as the weighted usable area divided by the total inundated area. The rasters written to file here represent the final daily rasters designating habitat suitability and are assigned the prefix "rshabsuit...".

13. **Write the results to file.** Once computation is completed for each year and the entire flows data frame and flood events data frames have been filled with computed values, the hydrospatial analysis is complete and these data frames should be written to file to save the results (named "flws_HS" and "flws_e_HS", respectively in the example).

4.5 Summarizing and visualizing results

After completing the hydrospatial analysis, the output flows data frames with computed daily suitable habitat area (a weighted usable area metric) and rasters of each flood day with cell values of habitat suitability can be summarized and visualized in a variety of ways (see Figure 8). The daily values of suitable habitat area are subsequently summed for each water year assessed, with units of acre-days (e.g., area summed over time). From this annual time series, summary statistics (e.g., mean, median, min and max) are examined to assess average and extreme conditions expected for the floodplain site. Additionally, an empirical exceedance probability curve is established for assessing the frequencies with which given annual acre-days of suitable habitat are expected to be exceeded. Using several functions from the 'hydrospatial' package with the prefix 'utils', the files are processed and prepared for plotting via the 'ggplot2' package. These summaries and plots are provided in the example *R* script, "HQT_4_ResultsPlotting.R".

To summarize and plot results:

1. **Set processing directories and load files.** To visualize and plot results, files from the "input" directory, the raster processing directory ("rworkingfiles"), and the shapefiles are needed. This includes the "flows_format" file in the "input" directory, the "flws_HS" file from the "rworkingfiles" directory (rasters will also be used from this directory), and the study area shapefile. Also, it is recommended that a graphics directory also be set for writing plots to file. Also, see Step 3 on Unit Conversion in the previous section as consistency is also key here.

2. **Format results tables for plotting.** To generate a continuous time series (that includes the days of zero available habitat below threshold flows), the *utils_*

rsltsformat_daily function is applied to both the daily results file ("flws_HS.csv") and the formatted input daily flow time series ("flows_format.csv"). To calculate annual summaries in acre-days of suitable habitat (suitable area summed over time for each year), the *utils_areaday* function is applied to the daily results file.

3. **Generate exceedance probability and annual time series plots.** Using the annual time series output of suitable habitat (acre-days) from the *utils_areaday* function, the *utils_rsltsexprob* function calculates exceedance probabilities. A plot showing suitable habitat versus exceedance probability and a time series plot of suitable habitat for each year is produced.

4. **Generate daily results plots.** Several plots for daily results are generated from the output of the *utils_rsltsformat_daily* function. This includes 1) a time series for daily statistics (median with the 10th and 90th percentiles) of suitable habitat area, 2) a graphic showing daily suitable habitat area for the time series with water year on the 'y' axis and water year day on the 'x' axis, 3) a scatter-plot of flow versus suitable habitat area.

5. **Generate time series plots for a given year.** For detailed examination of a given year, a composite time series plot shows results for daily total inundated area, inundated area meeting depth and velocity suitability criteria, hydraulically connected inundated area, and suitable habitat area.

6. **Generate map of total annual suitability for a given year.** To show the spatial distribution of suitability within the project area, the cell-by-cell sum of daily habitat suitability rasters for a given water year is calculated and then plotted using the *geom_raster* function within the 'ggplot2' package.

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Appendix A. HQT Rationale

This document describes the scientific rationale for the development of habitat criteria for the Chinook salmon Habitat Quantification Tool (HQT). It provides an overview of key concepts and supporting documentation (e.g., peer-reviewed literature, gray literature, expert opinion) that guided development of the Chinook salmon HQT and the rationale for focusing on specific habitat attributes.

Chinook Salmon HQT Development Process

The general approach of the HQT was established by the Science Team of the Central Valley Habitat Exchange (Table A.1), based upon work with other salmonid conservation programs in the Central Valley. A broad outline of the structure and content of the HQT was recorded in a memo in 2015. Stillwater Sciences was then enlisted to work with the Science Team to further develop those components into a draft HQT. On September 19, 2016, the Science Team and Stillwater Sciences convened the first meeting of the Chinook salmon Technical Advisory Committee (TAC; Table A.1), attended by experts from a range of institutions. During this first TAC meeting, the Science Team and Stillwater Sciences provided an overview of the CVHE and provided a 'tour' of the draft HQT. Discussion during that meeting on the draft HQT attributes, parameters, and metrics yielded a number of questions and suggestions that were consolidated and reflected back to TAC participants after the meeting. A second meeting was held March 24, 2017 to discuss suggested revisions, consider methods to address additional questions, and to further review the contents in the draft HQT. The third TAC meeting was on September 5, 2017, where additional feedback was received. The first version of the tool was completed by Stillwater Sciences in October 2017. Interest in further developing the spatial and temporal resolution of applying habitat criteria within the HQT via modeling led to work with Alison Whipple and the San Francisco Estuary Institute using the hydrospatial analysis approach of Whipple (2018) for components of the HQT. Initial pilot applications were presented on December 17, 2018. Additional pilot testing and development of the user guide followed, which retained some components of the Stillwater Sciences document (much of which comprise this appendix). A draft was sent to the TAC for review and feedback in August 2019.

Key Scientific Concepts of the HQT

Habitat quality and species performance

Habitat represents a particular combination of resources (e.g., food, shelter, and water) and environmental conditions that support a wildlife population's vital rates—i.e., survival and reproduction (Hall et al. 1997, Morrison et al. 2006). Habitat can vary in quality and therefore its ability to support a population's vital rates over

Name	Organization
Abrams, Jeff	NOAA/NMFS
Ambros, Charlotte	NOAA/NMFS
Blanco, Cesar	USFWS
Boysen, Kristen	Environmental Incentives
Cain, John	River Partners
Campbell, Beth	USFWS
Carlson, Stephanie	UC Berkeley
Carr, Chris	SWRCB
Collins, Alison	Metropolitan Water District
Ellrott, Brian	NOAA/NMFS
Gard, Mark	USFWS
Hackenjos, Bethany	FlowWest
Harris, Michael	CDFW
Harvey, Brett	DWR
Henery, Rene	**Trout Unlimited**
Heyne, Tim	CDFW
Hoobler, Sean	CDFW
Howard, Jeanette	TNC
Jeffres, Carson	UC Davis
Johnson, Matt	CDFW
Johnson, Rachel	NOAA/NMFS
Kaiser, Dan	EDF
Katz, Jacob	**CalTrout**
Keith, AJ	Stillwater Sciences
Kratville, Daniel	CDFW
Lorenzato, Stephanie	**DWR**
Louie, Stephen	CDFW
Merz, Joseph	Cramer Fish Sciences
Nelson, Jonathan	CDFW
Phillis, Corey	Metropolitan Water District
Ratcliff, Donald	USFWS
Riley, Katie	Environmental Incentives
Roberts, Jason	CDFW
Seavy, Nat	**Point Blue**
Setka, Jose	EBMUD
Shaffer, Kevin	CDFW
Shelton, John	CDFW
Siegel, Stuart	Siegel Environmental
Small-Lorenz, Stacy	**Environmental Defense Fund**
Sommer, Ted	DWR
Stauffer-Olsen, Natalie	Trout Unlimited
Tompkins, Mark	FlowWest
Vogel, Dave	Natural Resource Scientists, Northern Water Districts
Wikert, John	USFWS
Workman, Michelle	EBMUD
Wulff, Ryan	NOAA/NMFS
Zimmerman, Julie	TNC

Table A.1. *List of individuals who have been involved in Chinook salmon HQT Technical Advisory Committee (TAC) meetings or document review over the development of the HQT (beginning in 2016). Members of the Central Valley Exchange Science Team are indicated in* ***bold****. Rene Henery serves as the scientific lead for the Chinook salmon HQT TAC.*

time. Simply put, high quality habitat is more likely to sustain resilient populations than poor quality habitat. Improvement of habitat quality can increase carrying capacity, allowing existing habitat area to support a higher species density and greater total population size. Poor habitat quality may lead to low survival and reproduction, lower densities, and eventual extirpation of a population. Marginal habitat may support some amount of occupancy by a species, but may still result in low survival and/or reproduction, which will likely lead to population declines without high levels of immigration. Because of this, the ability to accurately assess habitat quality is vital to managing species' populations. In the HQT, the metrics that make up habitat quality are directly tied to a species' needs and intended to directly support population's vital rates.

Water

Water is a critical component of habitat for many species, including Chinook salmon. Multiple habitat attributes are combined to determine whether an area is suitable in terms of its ability to provide shelter and food resources for a given species. The California Central Valley was once dominated by vast stretches of wetlands and floodplains, flanking the Sacramento River and its tributaries to the north, the San Joaquin River and its tributaries to the south, and extending hundreds of thousands of acres across the valley floor (Figures A.1 and A.2A–D). Because of this unique geography, the historical Central Valley was perhaps the most productive wetland-floodplain complex in North America, supporting a diverse and abundant spectrum of wildlife including the now-threatened Chinook salmon. Winter and spring floodwaters supported vast emergent wetlands and extensive willow and cottonwood gallery forests that were home to many wildlife species. These floodwaters also allowed young salmon and other native fishes

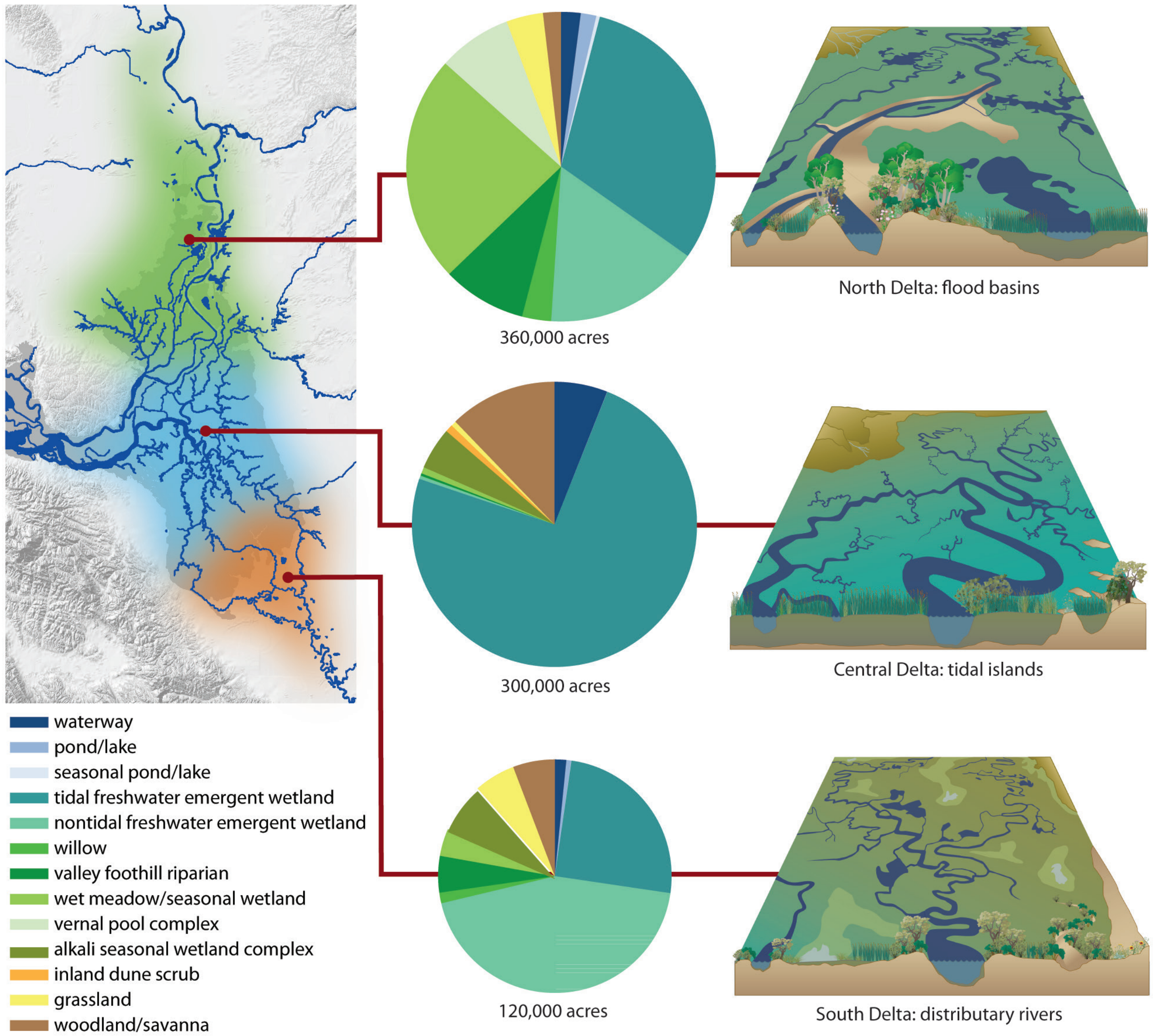
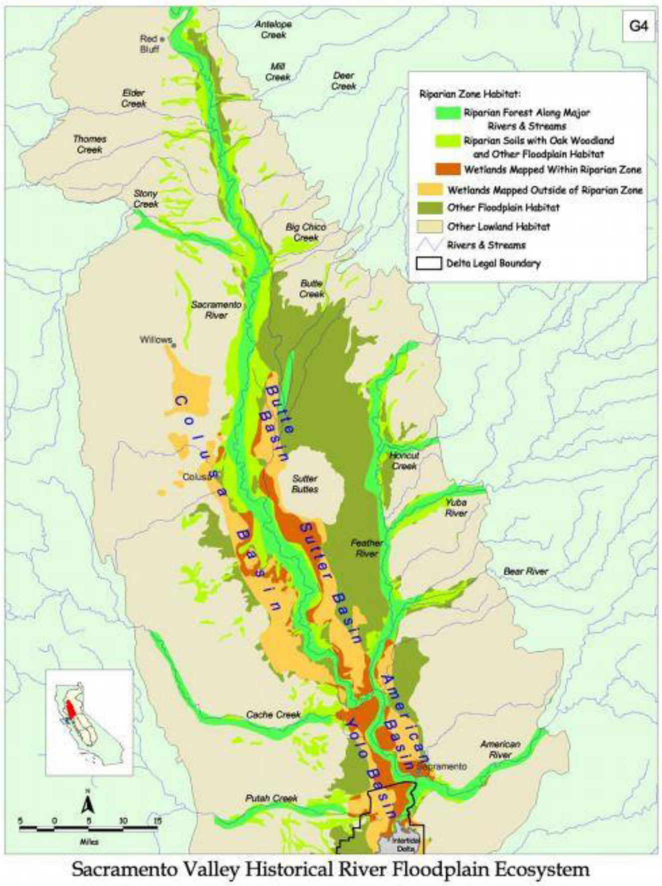


Figure A.1. *Distribution of major vegetation types in the Delta under pre-European settlement conditions (from Whipple et al. 2012).*

to move out of the river channels and into the floodplains and marshes. Protected from the current of the main river and supplied with abundant food resources, these sheltered habitats provided environmental conditions that were optimal for growth as young salmon migrated out to the ocean.

The once hydrologically dynamic central valley landscape has been significantly altered over the last century; its rivers channelized and levied, wetlands drained, and much of its native riparian habitats destroyed. Today, only about five percent of the Central Valley's historical wetland complex still exists (Figures A.2C and A.2D; Bay Institute 1998, Whipple et al. 2012). Native riparian floodplain habitat has been so drastically changed that, without remediation, populations of riparian dependent species, including Chinook salmon, are on the verge of collapse (Katz et al. 2013).



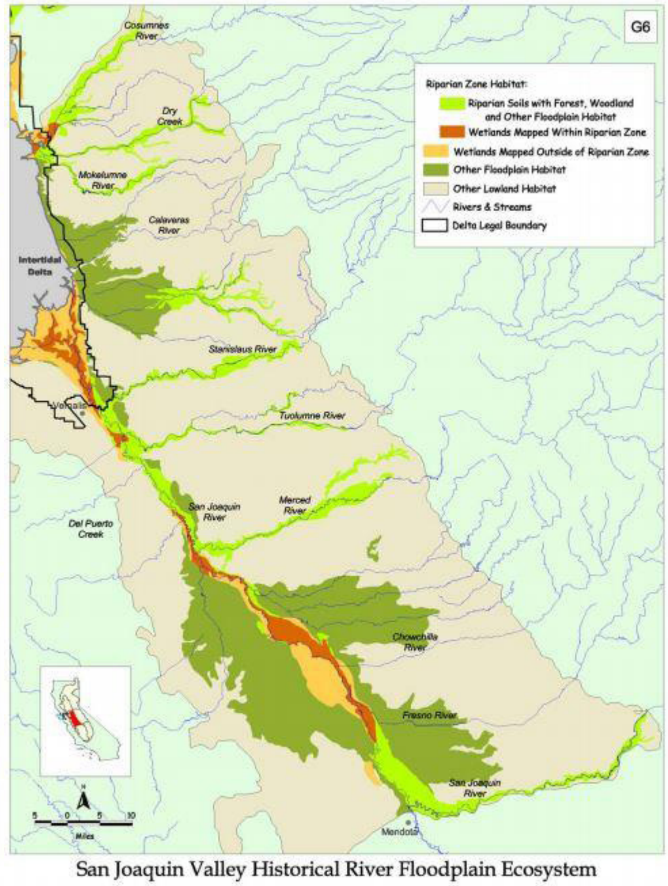
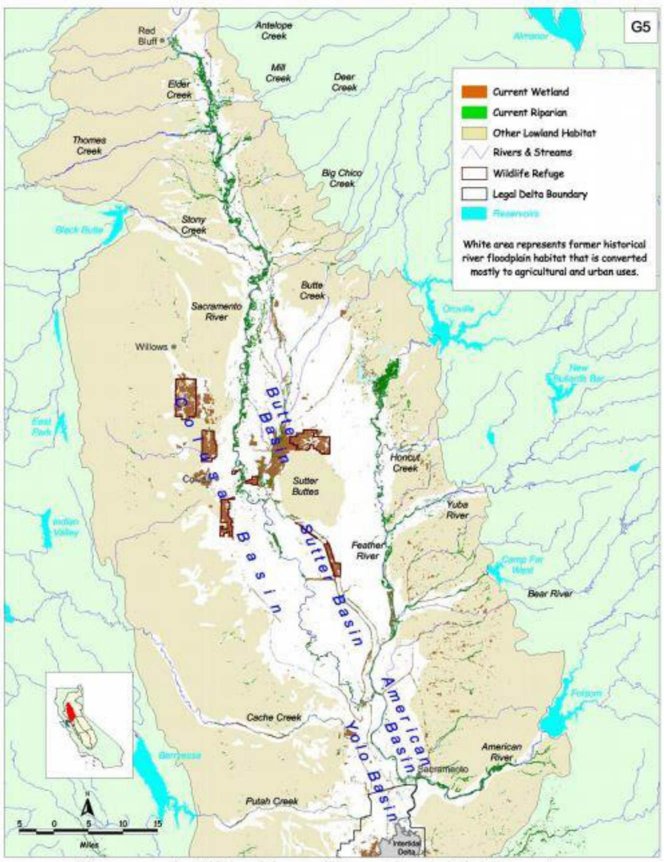


Figure A.2A. *Historical distribution of floodplain and wetland ecosystems in the Sacramento Valley (from Bay Institute 1998).*

Figure A.2B. *Historical distribution of floodplain and wetland ecosystems in the San Joaquin Valley (from Bay Institute 1998).*

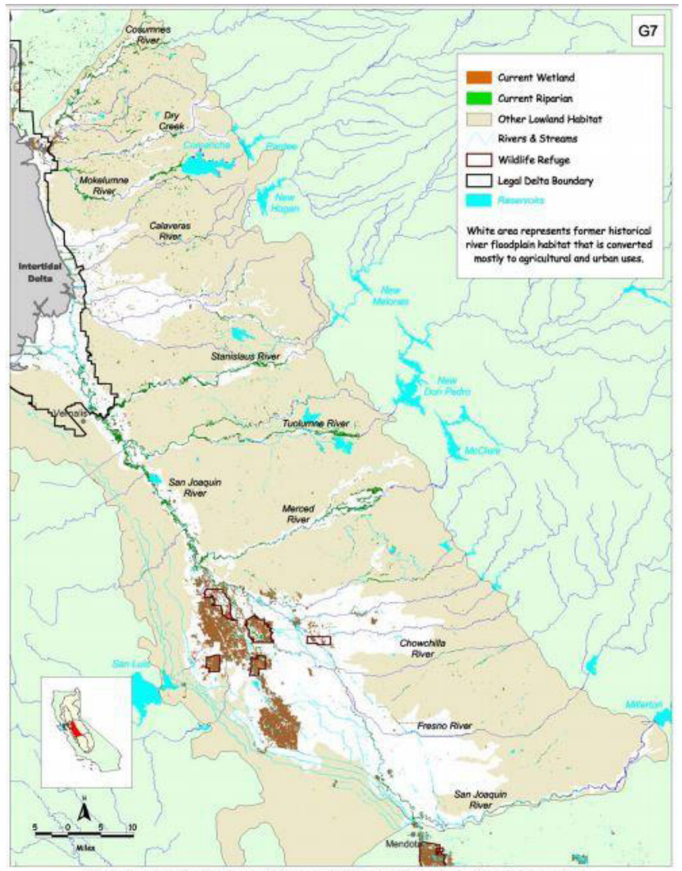
Spatial scale

As with many ecological processes, habitat selection occurs at multiple spatial scales, with individuals choosing to settle in a location by keying in to different features at different scales, determined in part by their ability to move among habitat gradients (Wiens et al. 1987, Morrison et al. 2006). For example, birds are highly mobile and may perceive physical vegetation structure first over a relatively large, landscape scale, then settle across the landscape according to more fine scale vegetation composition, vertical structure, and other factors, such as competitors (Saab 1999). Favorable river reaches or large floodplains, attract congregations of fish capable of swimming hundreds of miles inland from the ocean. Within these larger scale habitats, the distribution of individuals is often determined based upon habitat characteristics or competitive interactions at finer spatial scales. Issues of spatial scale are incorporated into the HQT through metrics and weighting that considers the landscape context and separate metrics and weighting to quantify habitat at finer scales.



Sacramento Valley Current River Floodplain Ecosystem

Figure A.2C. Current distribution of floodplain and wetland ecosystems in the Sacramento Valley (from Bay Institute 1998).



San Joaquin Valley Current River Floodplain Ecosystem

Figure A.2D. Current distribution of floodplain and wetland ecosystems in the San Joaquin Valley (from Bay Institute 1998).

Time scales

Temporal (time) scales also vary among ecological processes, and ecological responses to increasing time scales may not be linear (Wiens et al. 1987). The time required for a riverine system to respond to management practices and for a fish population's vital rates to reflect such changes will vary by ecosystem, geography, area, climate, land use, and species life history. For example, salmon populations have multi-year life history patterns that result in a two- to five-year periodicity for cohort freshwater habitat use. Similarly, salmon populations often exhibit large fluctuations in abundance due to cyclical climate factors that affect marine and freshwater survival (Beamish and Bouillon 1993, Koslow et al. 2002). The HQT attempts to account for these issues of temporal fluctuations at different time scales by requiring reporting of conditions that change over time. For example, hydrologic modeling that combines expected future conditions (e.g., physical modifications to a site and/or climate change) must be performed to estimate future time-dependent conditions for Chinook salmon. Repeated empirical measures of habitat conditions via monitoring during multiple inundation events are used to assess past or existing habitat quality.

Overview of Chinook Salmon Rearing Habitat Attributes

The Chinook salmon HQT is focused on the juvenile life history stage. HQT attributes were specifically selected to characterize seasonally inundated habitats along channel margins, outside of the bank, or off-channel but with some degree of connectivity to the main-channel (collectively referred to as *off-channel*). Generally, optimal conditions for juvenile salmonid rearing involve a balance of: (a) physical habitat conditions (e.g., temperature, dissolved oxygen, water depth, velocity, suitable cover and substrate); (b) biological habitat conditions (e.g., prey availability, predator density, competition); and, (c) extent of available habitat relative to fish territory size and abundance (as a function of fish size, fish density, prey density and habitat structure). While different habitats can provide various levels of habitat quality within these physical and biological conditions, the end goal for juvenile salmonids is the same: sustain metabolic needs and survive while maximizing growth from emergence to ocean entry.

These conditions vary across a range of macro-habitat types within the riverine landscape used by juvenile salmonids (e.g., riffle, pool, run) and are used differently by specific species and life-stages (Roper et al. 1994, Bradford and Higgins 2001, Merz et al. 2015). In general, Chinook salmon fry occupy low-velocity, shallow areas near stream margins, including off-channel habitat, backwater eddies, and areas associated with bank cover such as large woody debris (Lister and Genoe 1970, Everest and Tonina, McCain 1992). As Chinook fry grow, they move into deeper and faster water farther from the banks. Along the Mokelumne River, juvenile Chinook Salmon have been shown to prefer off-channel floodplain habitat for rearing while juvenile Steelhead prefer in-channel riffle habitat (Merz et al. 2015). As an intra-specific example, the same valley floodplain area may be used as a migration pathway by out-migrating juvenile Chinook salmon smolts and as a primary rearing area for Chinook salmon parr. Juvenile Chinook salmon often continue to feed and rear as they migrate downstream towards the ocean and the line between rearing and migratory habitat can be non-distinct. The HQT focuses on rearing habitat under the assumption that an abundance of high quality rearing habitat will provide suitable migratory conditions and, in some cases, benefits to adjacent in-channel migratory habitat. Migratory issues not interlinked with rearing habitat (e.g., diversions that affect upstream adult migration, passage barriers, etc.) are not currently included in the HQT.

Historically in the Central Valley, massive seasonal floodplains, year-round wetlands and other aquatic features supported prolific salmonid populations, in particular Chinook salmon, prior to habitat alteration, dam construction, and the introduction of non-native predatory fish species (NMFS 2014, Mount et al. 2012, Yoshiyama et al. 2001, Whipple et al. 2012). Existing and on-going research continues to emphasize the unique value and importance of habitats inundated during the winter flood and spring snowmelt season since these areas provide exceptional growth opportunities, shelter from high flows, and cover from predators in the form of turbidity and flooded vegetation and debris (Sommer et al. 2001, Sommer et al. 2005, Ahearn et al. 2006, Jeffres et al. 2008, Henery et al. 2010). For a given species, the interaction of different life history stages with different macro-habitats can reinforce cohort- and population-level life history diversity and associated resilience (McClure et al. 2008, Zimmerman et al. 2015). For example, juvenile Chinook salmon rearing on floodplains can experience greater maximum size, diversity in growth, and exposure to environmental pollutants than juvenile salmon reared in the associated river channel (Sommer et al. 2001, Sommer et al. 2005, Jeffres et al. 2008, Henery et al. 2010).

The seasonal inundation of floodplains, sometimes referred to as the 'flood pulse', provides substantial habitat and trophic benefits to river ecosystems as a whole and specifically to resident or migrating native fish (Junk et al. 1989, Junk and Wantzen 2004, Poff et al. 2010). Inundating floods 'activate' the floodplain by making otherwise terrestrial habitat aquatic habitat, mobilizing organic material and nutrients on the soil surface into the water column, and by triggering life history and/or growth responses among various invertebrate species and other food sources residing in or on the fluvial surface (Ahearn et al. 2006, Grosholz and Gallo 2006, Benigno and Sommer 2007). One important component of such highly productive off-channel habitat is the slowing and spreading of water during periods when water temperatures are cool and flows elevated (i.e., autumn, winter, and spring). This allows solar insolation of shallow waters to increase local water temperatures, which helps to fuel intensive primary production of phytoplankton biomass (Schemel et al. 2004, Sommer et al. 2004, Ahearn et al. 2006) and secondary production through zooplankton growth (Müller-Solger et al. 2002, Grosholz and Gallo 2006). Greater frequency of inundation has also been linked to increased drift invertebrate biomass (Sommer et al. 2001; Benigno and Sommer 2007) and higher levels of invertebrate productivity (Boulton and Lloyd 1992, Grosholz and Gallo 2006, Tronstad et al. 2005). Repeated flood pulses also help refresh the water quality and dissolved nutrients on the floodplain, allowing for renewed productivity and movement of floodplain organisms into the river channel, which subsidizes productivity in the main channel and facilitates fish passage to and from the floodplain (Ahearn et al. 2006; Jeffres et al. 2008; Katz, unpubl. data).

Within the Central Valley, off-channel habitats that are inundated year-round provide optimal habitat for non-native piscivorous predators, such as largemouth bass, and can be a population sink for juvenile salmonids. In contrast, seasonal off-channel habitats that dry out during the dry season prevent increased concentration of predatory fish. Even though predation rates have the potential to be high in temporary shallow off-channel habitats, this mortality is more than offset by the increased growth rates and subsequent high rate of ocean survival of fish using such habitats (Sommer et al. 2005).

The timing, frequency, and duration of floodplain inundation events indicate how much Chinook salmon will benefit. Several factors support the current focus on fluvial surface types that provide off-channel rearing habitat with targeted inundation durations. These factors include: (1) the importance of off-channel, seasonal inundation areas as high-quality Chinook salmon rearing habitat; (2) the need for much larger areas of this habitat in the Central Valley; and (3) the relatively straightforward and widely practiced methods required to restore or enhance many of these habitats.

Landscape context

Contextual information on Chinook salmon and landscape-scale characteristics are used to help identify, screen, and prioritize potential project areas. In the HQT, a separate landscape context evaluation is performed for each project area. A great deal of discussion ensued during the Chinook salmon TAC meetings over the wisdom of including the landscape context scores into the HQT, since they do not include a complete picture of the true landscape context for Chinook salmon, and thus could be applied mistakenly as true indicators of the landscape priority of a project area when they are not. Most notably missing from the landscape context attributes are defined metrics for quantifying spatial-temporal continuity along the migration corridor.

The TAC also recognized the importance of both upstream juvenile Chinook rearing habitat, such as is found in the Valley Foothill landscape, and downstream habitat, such as is found in the Valley Lowlands. The relative importance of each of these habitat types cannot be boiled down to a single scoring algorithm across the entire Program Area. Rather the needs specific to a run, watershed, and region must be considered holistically, with all available information taken into consideration and incorporated into a well-documented rationale for any programmatic and/or site-specific decision to prioritize one landscape type over another.

Landscape connectivity

There are many means by which a migration corridor can be broken, including physical passage barriers, reaches and periods when water temperatures and/or DO are lethal to Chinook salmon, lack of flow during migration periods, reaches with heavy predation, and long reaches with little to no foraging area. For example, along the Lower Tuolumne River, there is high quality spawning and rearing habitat for fall-run Chinook in the 10 to 12 miles below LaGrange Dam, but out migrant survival (i.e., the fraction of juveniles/smolts that make it to the confluence with the San Joaquin River and beyond) is poor, primarily due to predation by non-native piscivores, mainly largemouth bass, smallmouth bass, and striped bass (Stillwater Sciences 2013). In another example, physical barriers between Friant Dam and the confluence with the Merced River along the San Joaquin River block migration of spring-run Chinook (to be reintroduced in the future) to relatively good habitat for both upstream adult spawners and block downstream passage by juveniles and smolts (SJRRP 2012a). As part of the San Joaquin River Restoration Project, site-specific restoration projects are being completed or planned to remedy the barriers but full passage is not yet a reality. Another example is the precipitous drop in winter-run numbers reported above vs. below Colusa along the Sacramento River (pers. Com., Daniel Kratville, CDFW with Amy Merrill 9/5/2017). In this case, the factors known to limit survival of out-migrating winter-run juveniles along the reach above Colusa should be a major consideration in prioritizing areas along their entire migration path. Without taking this aspect of the landscape context into consideration, restoration downstream areas may be favored over upstream areas, even though actual use of the upstream areas is greater due to migration barriers to the downstream sites. Without an assessment of what limits

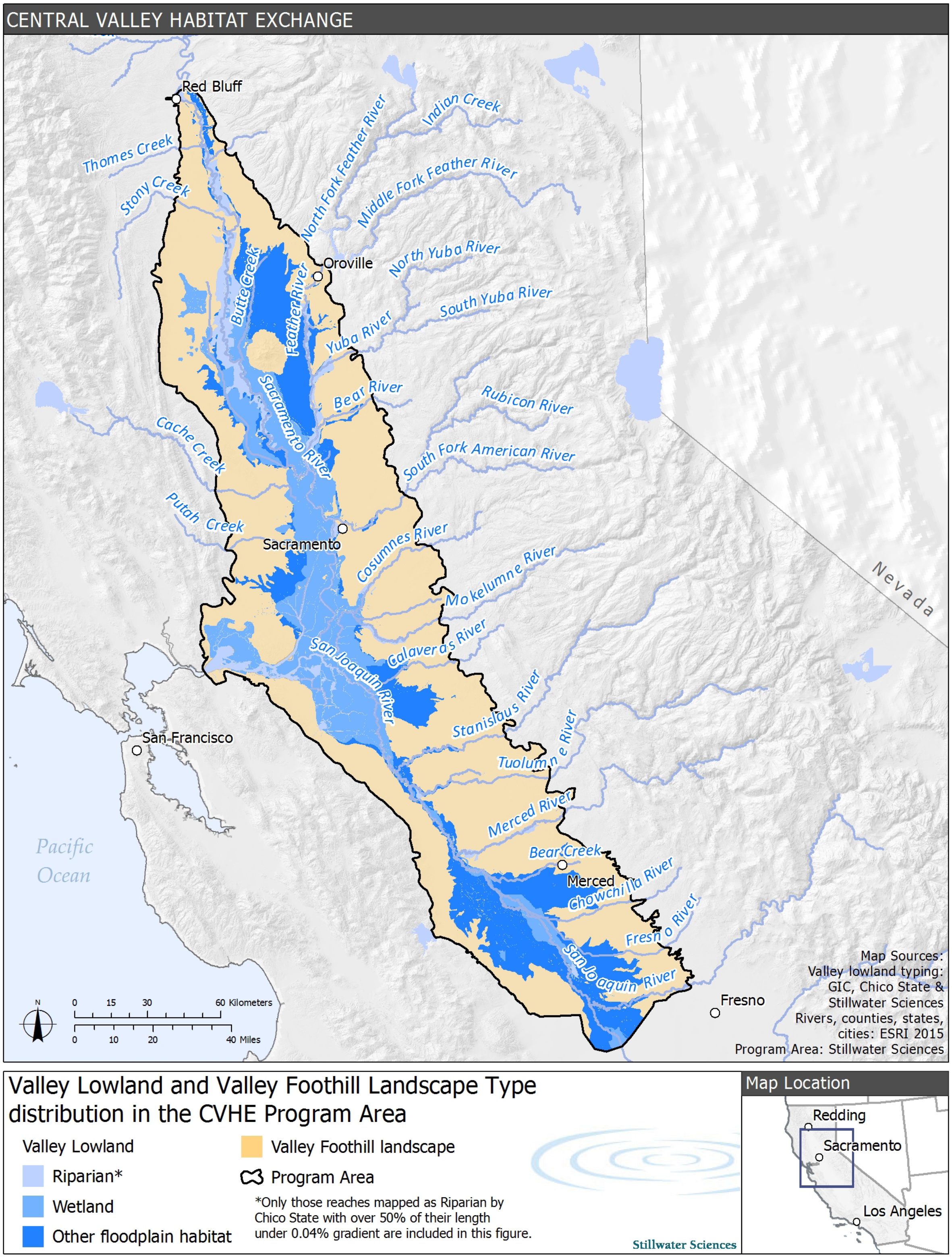


Figure A.3. *Distribution of Valley Lowland (three shades of blue) vs. Valley Foothill (light orange) landscape types within the Exchange Program Area.*

downstream migration, resources could be directed away from issues constraining the population's overall success. Due to this variability and importance of understanding the full range of potential landscape factors limiting salmon presence or use of a stream corridor, the TAC decided against including any quantitative or qualitative scoring for landscape connectivity.

Landscape type: Valley Lowlands versus Valley Foothills

Areas meeting the elevation threshold of < 300 ft (91.4 m) for the Exchange Program Area are classified as occurring within (1) Valley Lowland or (2) Valley Foothill landscape types. These landscape types have different levels of off-channel habitat quality and are characterized by different geomorphic features and hydrologic processes that influence project area conservation and restoration potential (Figure A.3). In the current HQT, the landscape type attribute is used to classify sites to: (1) support prioritization of off-channel habitats in the different landscape types; (2) allow for future refinements in attribute scoring curves that could reflect different response patterns and/or optimal values for the two landscape types; (3) allow for future weightcng of Valley Lowland vs. Valley Foothill sites; and (4) provide incentives to restore landscape-appropriate floodplain and off-channel habitat by encouraging restoration or acquisition of long-duration inundation sites in the Valley Lowlands and shorter duration off-channel habitat in the Valley Foothills.

The Valley Lowland landscape has little topographic relief and large, slow moving rivers that support expansive floodplains with some of the most productive types of rearing habitat. In these habitats, rearing habitat quality is generally supported by long inundation periods and associated extended hydraulic residence times that allow autochthonous primary and secondary productivity to occur. Surfaces characterized by long-duration inundation events typical of the Valley Lowland landscape allow for extended solar exposure that can stimulate autochthonous primary and secondary production that can drive high prey densities and fish production (Grosholz and Gallo 2006). On the Cosumnes River floodplain studied by Grosholz and Gallo (2006), planktonic crustaceans emerged first, followed by insect macroinvertebrates. Importantly, juvenile fish diets tracked the species composition of the emerging invertebrate community on the inundated floodplain. Floodplains in this landscape also provide: (a) rearing habitat for juvenile Chinook salmon; and, (b) a migratory "rest stop" and predator avoidance pathway for juvenile Chinook salmon; although predation can occur on floodplains, this predation risk is off-set by increased survival downstream due to increased growth rates (Sommer et al. 2005).

The Valley Foothill landscape type is characterized by slightly higher elevations with greater topographic relief than the Valley Lowland landscape. This Valley Foothill landscape typically supports narrow inset floodplains, seasonally inundated side channels, and backwaters that are flooded for short periods alongside hillslope-confined channels. Rearing habitat quality in these habitats is generally supported by allochthonous invertebrates that are displaced into the water during inundation and to a lesser extent due to benthic invertebrate drift. This landscape type typically encompasses the lower reaches of Sacramento River and San Joaquin River tributaries (e.g., Merced, Tuolumne, Feather, Yuba, etc.) that flow from the terminal dams to the valley floor, and smaller tributaries to these rivers. While the site-by-site conservation value is lower in the Valley Foothill landscape relative to Valley Lowland landscapes, the aggregate value of the many reaches that support localized rearing congregations of Chinook salmon is high. In addition, off-channel habitat in the Valley Foothill landscape provides important rearing opportunities for juvenile Chinook salmon prior to reaching the Valley Lowlands and Delta, where increased size can improve survival, passage to the sea, improved ocean survival and the ultimate percentage of out-migrants that return to spawn as adults (Yoshiyama et al. 1998, Sommer et al 2001). As in the Valley Lowland landscape, off-channel habitat in the Valley Foothill landscape type can provide a migratory "rest stop" and potential predator avoidance pathway for juvenile Chinook salmon. Temperature ranges are typically similar to that of in-channel habitats since the water residence time is not long enough for extensive solar heating.

Several different approaches to delineating these landscape types in the Program Area were explored during the development of the HQT, including drawing a line ten miles east of the mainstem San Joaquin and Sacramento Rivers, using a threshold elevation and/or channel slope that matched distribution of areas with known flood durations, and the estimated distribution of pre-1900 wetland types in the Program Area. The TAC reviewed maps showing the distribution of pre-1900 wetland types (California State University at Chico 2003) in combination with channel gradient and suggested that a combination of these two sources of information could provide the most reliable estimates on the landscape type distributions in the very large Program Area. Thus, these two bodies of information, with guidance from areas known to have experienced long vs. short-term flooding under pre-1900 conditions, were used to delineate areas estimated to support long duration floods from those that historically flooded only for less than ten days at a time.

Valley Lowlands are mapped as all areas classified as "wetlands" and "other floodplain habitat" in the Central Valley Historical Mapping Project (California State University at Chico 2003) as well as areas classified as "riparian" in which 50% or less of the associated reach channel length is estimated to have under a 0.04% channel gradient. Channels, reach delineations, reach contributing areas, and reach gradients were acquired from NHD-Plus data (EPA/USGS collaboration; developed from 1:100,000 scale stream network and 30 m DEM; https://www.epa.gov/waterdata/nhdplus-national-hydrography-dataset-plus). Small tributaries, with less than a 50 km^2 (19 mi^2) contributing area, were excluded from this Central Valley wide analysis.

Delineation of landscape types relied on Chico State historical mapping project used multiple existing sources to create best estimates of pre-1900 wetland areas, including written observations from early explorers and settlers, historical maps, and soil type distribution. However, areas mapped as historical riparian forests could include areas that flooded for long durations and those that did not, since willows and some other tree and shrub species are tolerant of long term flooding particularly in the spring months. Therefore, we used channel gradient within the mapped historical riparian areas to distinguish between areas likely to have experienced long-term inundation from those that did not. We mapped the distribution of channel gradients, based on segments created through HUC12 designations and confluence points for watersheds with at least 50 km^2 (19 mi^2) contributing areas. Those segments that were within the mapped historical riparian forest polygons and that had at least half of the segment length with less than 0.04% gradient were put in the Valley Lowland areas. This gradient length threshold (=>50% under 0.04%) was selected based on a review of the Program area channels and areas known to experience long inundation events under current conditions. Other landscape clues, such as sinuosity and overall land topography were also used to corroborate these designations. Valley Foothill landscape type occupies the area outside of the delineated Valley Lowland areas up to the 300 ft (91.4 m) elevation boundary of the Exchange program area (see Figure A.3).

Chinook salmon presence, abundance and distribution

The presence, abundance, and distribution of attributes are directly correlated to the potential conservation value of a given project or land area. To assess Chinook salmon presence, abundance, and distribution, the existing population distributions of the spring, fall, late fall, and winter- run Chinook salmon and the contributing watershed area are considered. Project sites must be located within the known distribution, or likely occurrence, of Central Valley Chinook salmon to have conservation benefits. Information on the spatial overlap of Chinook salmon runs is used to determine the number of runs that can benefit from a project. Greater value is attributed to projects that can support a greater diversity of runs (e.g., spring, fall, late fall, winter).

The number of Chinook salmon runs potentially accessing a site is assessed based on presence of runs within the watershed of the project (assessed via the PISCES spatial database at the HUC12 level). Areas with high current use of one or multiple Chinook salmon runs are recognized as supporting a larger part of the overall Central Valley Chinook salmon population(s) and are considered to be of greater importance than areas with lower use. Relative abundance is correlated with the potential conservation value of a project site and the contributing watershed. For the HQT, the number of contributing watersheds (HUC 12 watersheds) for each run potentially present in at a project location (as defined by the PISCES spatial database) is used as a measure of relative abundance of Chinook salmon expected at the project location.

Project site habitat attributes

Inundation regimes

The timing and duration of inundation determines potential benefits that floodplain habitat will provide to juvenile Chinook salmon. The timing of the spawning period and the duration of incubation and freshwater rearing vary among runs of Chinook salmon due to heritable genetic traits, environmental conditions, and other factors (Healey 1991). As a result, juveniles from one or more runs may be rearing and emigrating in the Central Valley and the San Francisco Estuary at any time during the year (NMFS 2014, Williams 2006). Although the timing and period of peak abundance of juvenile rearing and emigration for a given Chinook salmon run varies somewhat by location in the Sacramento River (spring-run, fall-run, late-fall run, and winter-run) and San Joaquin River (fall-run and spring-run), the relative abundance (i.e., likelihood of presence) of juvenile Chinook salmon in Central Valley habitats for all runs combined can generally be considered highest in late winter and spring and lowest in summer and early fall (Table A.2). More constrained rearing times occur for the different runs within specific locations of the Central Valley. Because peak river flows and subsequent inundation of floodplains and off-channel habitats in the Central Valley occur during winter and spring, the period of overlap between habitat inundation and juvenile Chinook salmon occurrence is November 1 through June 30. The period between January 1 and May 31 is when juveniles from most runs are typically rearing and emigrating downstream and when there is the greatest amount of floodplain inundation during spring snowmelt flows.

For rearing habitat benefits to be realized for a given cohort, inundation must occur in at least one out of every two years (assuming a yearling strategy in some percentage of out-migrants), although at least annual inundation over a great portion of the inundation season is more beneficial. For short-duration inundation events, frequency drives habitat availability and prey density since displacement of terrestrial invertebrates serves as a main food source. Duration and frequency are both critical for increasing productivity through long inundation events, since autochthonous production may continue to increase over time during a single long-duration event, as previously discussed (Grosholz and Gallo 2006). Research from both the Yolo Bypass and Cosumnes River floodplains indicates that new flood pulses will reset the productivity cycle once productivity rates have begun to stabilize or decline during a post-flood interval (Grosholz and Gallo 2006, Katz, unpubl. data), which suggests the most productive inundation pattern would be multiple, long-duration inundation events over the full course of the inundation and rearing seasons.

Table A.2. *Generalized life history timing of rearing Chinook salmon in the Central Valley, with blue indicating the period of maximal overlap and largest numbers of juvenile rearing fish across all four runs. The "X's" represent months when inundation events can be considered to beproviding habitat for each run.*

Chinook Salmon Run	Fall			Winter			Spring			Summer			Notes/References
	(Sep-Nov)			(Dec-Feb)			(Mar-May)			(Jun-Aug)			
Central Valley spring-run[a]			X	X	X	X	X	X	X	X			[a] Snider and Titus (2000a, b), CDFG (1998), Myers et al. (1998), McReynolds et al. (2005), Lindley et al. (2004), NMFS (2014). [b] Williams (2006) - timing differs somewhat between the Sacramento and San Joaquin basins; Yoshiyama et al. (1998) [c] Snider and Titus (2000a, b), Martin et al. (2001), Poytress and Carillo (2010, 2011, 2012), NMFS (2014)
Central Valley fall-run[b]					X	X	X	X	X	X			
Central Valley late fall-run[b]			X	X	X	X	X	X	X	X			
Central Valley winter-run[c]			X	X	X	X	X	X					

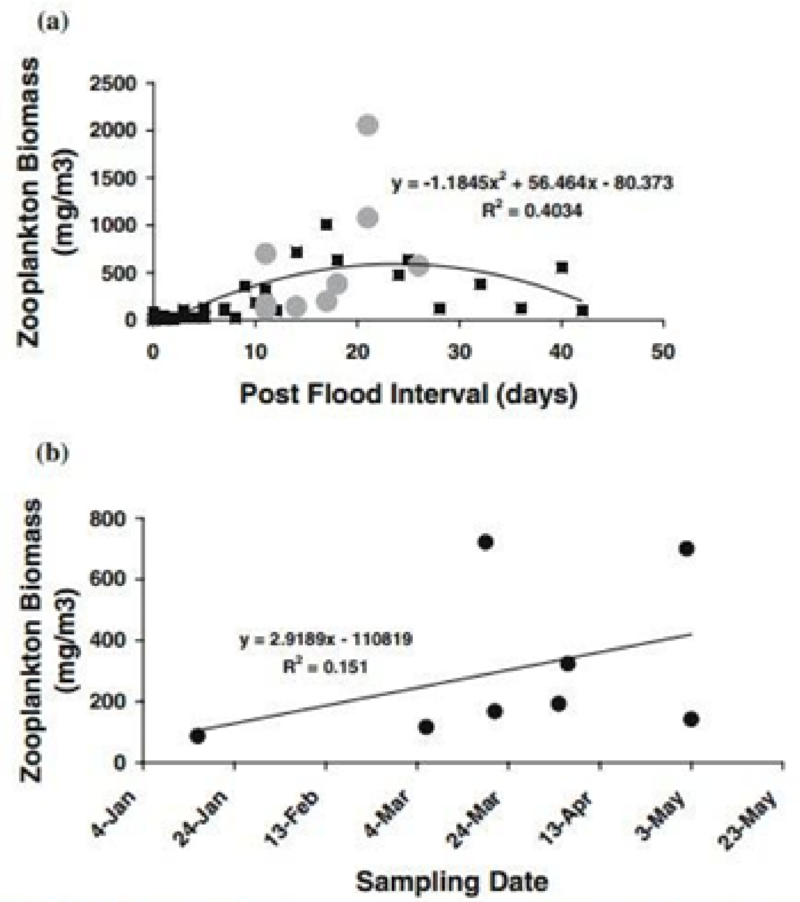


Figure A.4. *a) Zooplankton biomass vs. the time since disconnection from the river channel (post-flood interval); b) maximum zooplankton biomass vs. date of occurrence for eight flood events between 2000–2002 in the Cosumes River floodplain (from Grosholz and Gallo 2006).*

Inundation duration impacts off-channel habitat quality and productivity for rearing juvenile Chinook salmon. As previously discussed, in off-channel habitats, short-duration inundation can displace terrestrial invertebrates from soil and vegetation, and drive terrestrial invertebrate distribution by modifying heterogeneity of organic matter (Langhans 2006). Longer inundation times and extended solar exposure can stimulate autochthonous primary and secondary production that can drive high prey densities and fish production (Sommer et al. 2001, Sommer et al. 2004, Grosholz and Gallo 2006). Research from the Cosumnes River floodplain found that secondary productivity reached peak levels at approximately 14 days (Grosholz and Gallo 2006, Katz, unpubl. data) and that after approximately 3 weeks, productivity levels stabilize or are in decline. Grosholz and Gallo (2006) recommend a 2- to 3-week post-flood interval duration and repeated flood pulses to best support native fish.

The duration of inundation is considered a keystone attribute that creates a fundamental distinction in rearing habitat form, function, food web dynamics, and other ecological processes. A study by Grosholz and Gallo (2006), revealed that when inundation of the floodplain occurs and the flood pulse subsides, there is a delay or incubation period for primary and secondary production that occurs during days 1 through 9 post-flood, on average. Thereafter, the productivity reaches high levels that

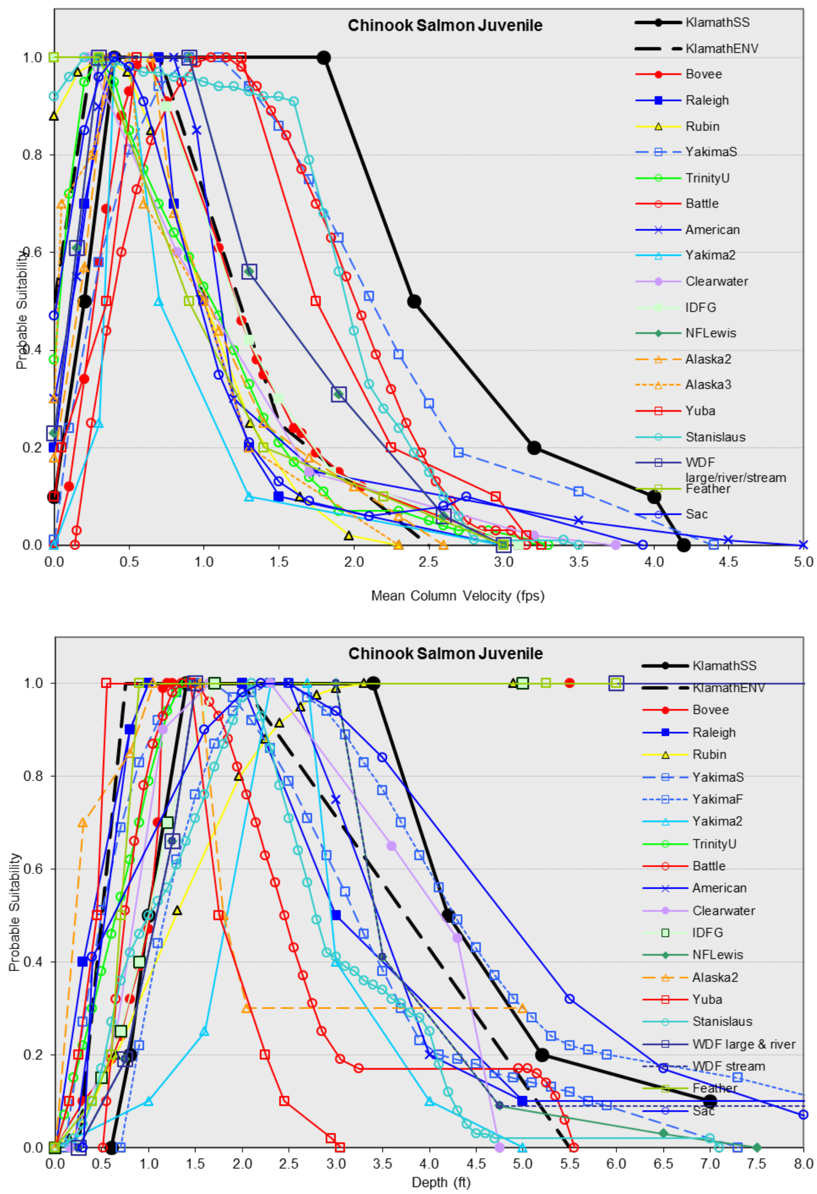


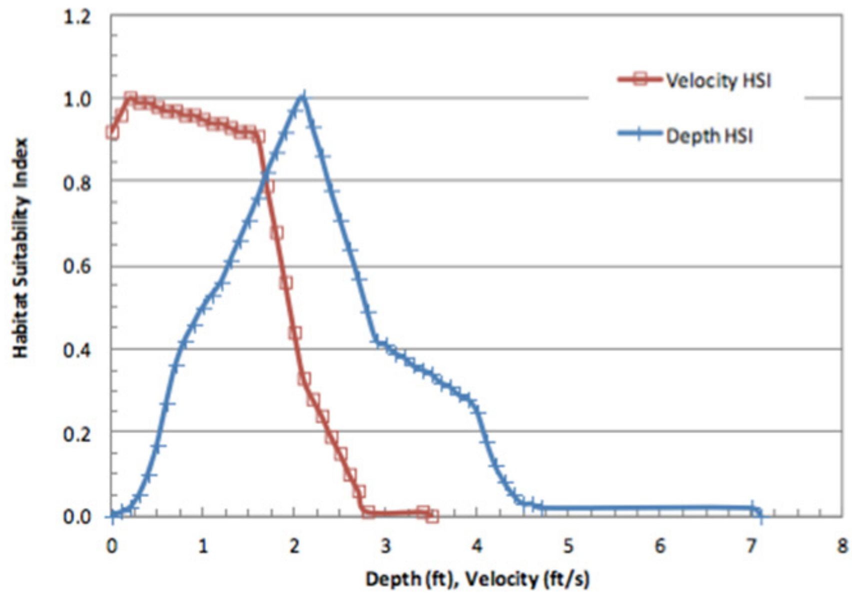
Figure A.5. *Habitat Suitability Index values for velocity and depth, for juvenile Chinook salmon on multiple rivers. Compiled by SJRRP (2012) from multiple published and unpublished empirical (when available) and modeled data sets.*

peak at approximately 21 days of inundation, last through approximately day 25, and subsequently decrease (Figure A.4). Other studies have shown that primary production occurs first, and secondary production follows, including the release of zooplankton that can lie dormant in dry floodplain substrates and soils for approximately two years (Ahearn et al. 2006), with zooplankton being an especially rich food source for juvenile salmonids and other floodplain rearing fish.

Water depth and velocity

Both depth and flow velocity critically affect juvenile salmonid habitat quality since adequate velocity and depth enable salmon to take part in normal and beneficial behavior (SJRRP 2012). Therefore, water depth and water velocity are parameters commonly applied to habitat suitability models for juvenile salmonids. Different

Figure A.6. *Based upon Habitat Suitability Indices, Aceituno (1990) found velocities between 0–0.46 m/s and depths between 0.3–1.0 m provided the best habitat conditions; this graph provides an idealized example of variability and pattern in HSI values for increasing velocity and depth.*



combinations of water velocity and depth can contribute to physical and ecological functions, as well as heterogeneity both within and across habitat types. For juvenile salmonids, water velocity is a key driver of activity level, which interacts with temperature, dissolved oxygen, and prey availability to drive consumption rates and ultimately affect growth rates. Optimal depth and velocity for juvenile salmonids can vary significantly among river systems and for fish of different sizes (Figure A.5) Because the energy required to maintain position within the water column is generally a function of water velocity and body size (Chapman and Bjornn 1969, Everest and Chapman 1972), small fish, such as newly emerged salmonid fry, typically inhabit slower-water habitats, and are often found at the margins of mainstem channels, backwaters, side channels or off-channel habitats.

Suitable depths support foraging behavior and predator avoidance (Gregory 1993) and contribute to favorable primary production conditions. Juvenile Chinook salmon habitat suitability models for depth and velocity have been developed previously for numerous rivers in the Central Valley and elsewhere (Aceituno 1990) and applied to floodplain habitat estimates for the San Joaquin River (SJRRP 2012). These estimates suggest optimal depth values exist between 0.3 and 1 m (1–3.28 ft) in floodplain or off-channel conditions, and these depths are used in accepted HSI (Habitat Suitability Index) models (Figure A.6; Aceituno 1990, SJRRP 2012). The same studies, based on the velocity requirements for juvenile Chinook salmon, assigned optimal velocity values for those habitat types at between 0–0.46 m/sec (0–1.5 ft/sec; Figure A.6; Aceituno 1990).

Suitable water velocities and depths for off-channel habitats can be lower than for in-channel habitats. Research findings on juvenile Chinook salmon rearing on flooded rice fields in the Yolo Bypass showed excellent growth for juvenile Chinook salmon at shallow depths with no flow through and minimal water velocities but with consistently high food levels (Katz, unpubl. data). Heterogeneity in velocity and depth values throughout an off-channel area can provide a rich complex of habitat conditions to serve multiple functions, but even inundated agricultural fields can still provide high quality rearing habitat due to high food availability and favorable growing conditions.

Hydraulic connectivity

Ecologically functional floodplains and other off-channel habitats are connected to the adjacent river or stream channel and thereby allow exchange of water, sediment, nutrients, and organisms (Williams et al. 2009, Opperman et al. 2010). Hydraulic river-floodplain connectivity supports physical and ecological processes throughout the system, providing habitat benefits and productivity to support organisms in the channel and in off-channel areas. In addition to the benefits documented for floodplain-rearing salmonids (Sommer et al. 2001, Jeffres et al. 2008), lateral connectivity between river channels and adjacent floodplains has been shown to be an important control on the timing, composition, and total river invertebrate biomass (Castella et al. 1991), as well as the quantity and quality of riverine phytoplankton (Lehman et al. 2008). Research in the Cosumnes River (Moyle et al. 2005) and Tuolumne River (Stillwater Sciences 2007) suggests that water flow-through on inundated floodplains appears to be among the most important attributes for providing suitable habitat for Chinook salmon and other native fish species. In summary, the degree of hydraulic connectivity is positively related to the strength of linked river/floodplain ecological processes and benefits.

Fish must be able to access the inundation surface, leave the surface with or prior to drawdown of the inundation waters, and conditions across the connected area are supportive for juvenile Chinook salmon. Without these three conditions, fish access to the surface is either not possible or not supportive. Beyond these required conditions, the quality of the habitat is considered higher if the following beneficial conditions are satisfied:

Volitional fish ingress and egress: Native fish sense and respond to changing floodplain conditions and so move on or off a floodplain to enhance their survival (Moyle et al. 2007). The ability to sense and respond by moving on or off a floodplain surface is recognized as an important trait to maintain in natural-origin Chinook salmon populations. While volitional ingress and volitional egress are often the preferred methods for entering and leaving a site, human assisted movement, such as trap and haul to inundated rice fields followed by volitional egress, is among the mechanisms that can result in increased size, and by extension the likelihood of survival, of juvenile salmon compared to those that remain in the channel (Katz et al. 2017). Thus, while neither volitional ingress or volitional egress is necessary, they are both considered beneficial.

Naturally occurring connectivity: Naturally occurring connectivity between a channel or water body and the inundation surface does not require human interventions. This type of connection, such as on a floodplain adjacent to a river, supports the natural flood regimes and associated behaviors with which Central Valley Chinook salmon evolved (Moyle et al. 2007). In contrast, surfaces that require human actions to flood, or to be linked to a channel, are not necessarily tied to the species natural preferences on timing and location. This is not a necessary condition since human assisted connectivity, such as surface inundation via gated irrigation canals or bladder dams, is an important and effective means by which increasingly engineered water systems and cultivated valley lands can accommodate both human and wildlife needs. Examples of human assisted connections include gates on irrigation canals; toe drain gates, bladder dams; and active catch and haul systems that connect fish but not water to the inundated surface.

Cover

The land and vegetation cover of inundated areas influences habitat quality and serves important functions for rearing salmon. Land and vegetation cover attributes are core components of the physical habitat for juvenile salmonids that can interact with other physical habitat attributes (e.g., water velocity) and ecosystem dynamics (e.g., primary and secondary production, predator-prey interactions) to influence habitat use by juvenile salmonids, and the resulting density and survival of fish.

Cover and structure have been correlated with juvenile salmonid density (McMahon and Hartman 1989). As concepts, cover and structure have significant overlap, encompassing a range of common physical elements and differing primarily based on the function they serve for juvenile salmonids. For example, a root wad might be considered “cover” when the function it is serving is to provide juveniles with refuge from predators or high flows, and “structure” when the function it is serving is to create an area of scour and deeper depth, regulate territory size, or provide a surface for invertebrate prey. Thus, the HQT focuses on the role of land and vegetation cover features and characteristics that provide beneficial functions without assigning them to primary functional roles.

Structure is important for creating topographic variability and complexity, as well as cover from predators, although cover from predators can also take the form of non-structural components such as herbaceous vegetation or turbidity (Gregory and Levings 1998, Gregory 1993). Turbidity can provide cover from predators in habitats such as inundated floodplains that have little to no structure. Topographic variability due to larger-scale geomorphic processes as opposed to localized structures can also increase habitat quality in seasonally inundated off-channel areas.

Many studies have examined a range of physical structures definable as “cover” in terms of the extent to which they support suitable habitat for juvenile salmonids (Hampton 1988, Raleigh et al. 1986, Sutton et al. 2006, WDFW and WDOE 2004). Physical structures constituting cover are not addressed consistently across these studies, and suitability scores for common cover types are also not consistent. In 2012, the San Joaquin River Restoration Program developed a summary of habitat suitability for cover from multiple sources for use in modeling suitability of floodplain rearing habitat (SJRRP 2012). Cover categories and values developed in the HQT (Table A.3) were applied as the basis for floodplain rearing habitat cover parameters in combination with the California Department of Fish and Wildlife’s California Salmonid Stream Habitat Restoration Manual (Flosi et al. 2010).

Temperature

Juvenile salmonid growth, life-stage duration, and metabolic efficiency are directly influenced by water temperature (Quinn 2005). For juvenile salmonids that are actively feeding over a certain range of temperatures, growth increases with increasing temperature as long as food is readily available. Increasing temperatures may lead to decreased growth, physiological impairment, or death when food supplies are not sufficient to support increases in metabolic rate. Temperatures ultimately limit growth and survival at thresholds that are species-, population-, and individual-specific (Incipient Upper Lethal Temperatures [IULT]).

Temperatures that can be tolerated by rearing juvenile Chinook salmon depend to a great extent on food availability. USEPA (2003) indicates that, when food supplies are "unlimited" temperatures from 13 to 20°C (constant) may be optimal. Recent studies on Central Valley Chinook salmon rearing on inundated floodplains reveal excellent survival and growth rates at even higher temperatures. Growth and survival for limited periods have been recorded at temperatures as high as approximately 25°C (Katz, unpubl. data; Jeffres, unpubl. data). The increased tolerance for high temperatures in these fish is believed to be related to the high prey densities and food quality available on floodplains, coupled with low activity costs (Sommer et al 2001) and suggests that, when food is not limiting, Chinook salmon can tolerate and even thrive at temperatures approaching the physiological limits observed in the laboratory (i.e., incipient upper lethal temperature, or IULT). As a result, following successful restoration of floodplain habitats (and during periods when juvenile Chinook salmon occupy inundated floodplains), rearing Chinook salmon could survive temperatures approaching 25°C. However, when Chinook salmon are not in habitats that support super-abundant food resources (e.g., in-channel habitats), lower temperatures are required to avoid negative sub-lethal effects.

Temperatures that produce mortality among Pacific salmon depend, to some extent, on acclimation temperatures—higher acclimation temperatures produce a higher IULT (Myrick and Cech 2004). Various sources indicate an IULT for Chinook salmon in the

Table A.3. *Cover type categories, thresholds for presence, and source of threshold valuation.*

Cover Type	Threshold	Source
A. Emergent or submerged vegetation cover	"sufficient submersed vegetation" cover	Flosi et al. 2010
B. Undercut Banks	>0.3 m undercut	Flosi et al. 2010
C. Boulders	>0.25 m diameter	Flosi et al. 2010
D. Large Woody Debris	Large- >0.3 m diameter, >6' long	Flosi et al. 2010
E. Small Woody Debris	Small- <0.3 m diameter	Flosi et al. 2010
F. Riparian Forest	"branches in or near the water"	Flosi et al. 2010
G. Turbidity	> 20 NTU and/or sechhi disk depth <66 cm	Gregory and Levings 1998; Ligon et al., unpubl. data

range of 24–25°C (Myrick and Cech 2004). Baker et al. (1995) found that Central Valley Chinook Salmon had an IULT between approximately 22 to 24°C. Negative sub-lethal effects (those that may increase susceptibility to other mortality mechanisms) begin to occur at temperatures lower than the IULT. In the laboratory, when fish have access to full rations, growth of juvenile salmonids increases with temperature up to fishes' physiological limits; however, when food supply is limited (as it often is under normal field conditions) optimal and sub-optimal growth and even mortality occur at lower temperatures. For example, Mesa et al. (2002) detected increased levels of heat shock proteins (an indicator of stress) after several hours of exposure to 20°C for Columbia River fall-run Chinook salmon.

Temperature specifically can affect growth, parr-smolt transformation, and saltwater survival in juvenile salmon. Chinook salmon have high growth rates at temperatures approaching 19°C. However, in order for them to complete the parr-smolt transformation (i.e., become adapted to life in saltwater), lower temperatures are required. Chinook salmon can smolt at temperatures ranging from 6–20°C; however, salmon that smolt at higher temperatures (>16°C) tend to display impaired smoltification patterns and reduced saltwater survival, while salmon that rear in the 10–17.5°C temperature range are optimally prepared for saltwater survival (Myrick and Cech 2004). Cooler temperatures (<10°C) tend to increase their seawater adaptation. Cooler temperatures also reduce their risk of predation and disease, both of which are enhanced at higher temperatures (Myrick and Cech 2004).

Among juvenile fall-run Chinook salmon from California's Central Valley population, Marine and Cech (2004) found decreased growth, reduced smoltification success, and impaired ability to avoid predation at temperatures above 20°C. They also reported that fish reared at temperatures 17–20°C experienced increased predation relative to fish raised at 13–16°C, although they found no difference in growth rate among fish reared in these two temperature ranges. The finding of decreased performance at temperatures above 17°C is consistent with several studies that suggest, when food supplies are not super-abundant, optimal growth and survival among Chinook salmon occurs at temperatures somewhat lower than 17°C. USEPA (2003) identifies constant temperatures of 10–17°C (and a seven-day average daily maximum [7DADM] less than 18°C) as being optimal conditions for juvenile Chinook salmon when food supplies are limiting. Richter and Kolmes (2005) cite optimal temperatures in the range of 12–17°C from numerous sources.

High water temperatures can lead to direct mortality and indirect loss of fitness for migrating salmon. The IULT may be as low as 21 to 22°C for both adult Chinook salmon and Steelhead during migration (USEPA 1999, 2003; Richter and Kolmes 2005). Swimming performance is reduced at temperatures greater than 20°C (USEPA 2003). High water temperatures also facilitate infection among migrating adult salmonids (Noga 1996); USEPA (2003) identifies an elevated risk of infection at temperatures above 14°C and a high risk of infection at temperatures greater than 18°C. Slightly higher water velocities in short-duration floodplains, combined with generally lower food availability compared to long-duration floodplains, translate to greater metabolic stress on individuals in short-duration floodplains at temperatures above 18°C than on individuals in the slower and richer waters of the long-duration floodplain habitats. Therefore, the Science Team identified a maximum optimal temperature for the short-duration inundation floodplains that is slightly lower (18°C), than for the long-duration floodplains (20°C).

Dissolved oxygen

Adequate concentrations of dissolved oxygen in water are critical for salmon survival. In freshwater streams, low dissolved oxygen levels can impact the growth and development of salmon, as well as the swimming, feeding, and physiological ability of juveniles. If salmonids are exposed to such conditions for too long, mortality will result (Carter 2005). Factors affecting dissolved oxygen levels may vary among sub-habitats used during juvenile rearing and migration. On floodplains, dissolved oxygen levels may be spatially heterogeneous and driven by factors including temperature, mixing, biological oxygen demand (BOD), and biological oxygen production.

While salmon are known to survive periods of low oxygen levels, stress occurs whenever dissolved oxygen is not at an optimal level (Bustard 1983). A low oxygen event of extended duration has the potential to stress juvenile Chinook salmon, leading to physiological effects or behavioral changes. With increased temperatures, higher oxygen levels are needed to maintain optimal physiological performance for Chinook salmon (Raleigh et al. 1986). Salmonids may be able to survive when dissolved oxygen concentrations are low (<5 mg/L); but growth, food conversion efficiency, and swimming performance will be adversely affected (Bjornn and Reiser 1991). Davis (1975) reviewed numerous studies and reported no impairment to rearing salmonids if dissolved oxygen concentrations average 9 mg/L; while at oxygen levels of 6.5 mg/L "the average member of the community will exhibit symptoms of oxygen distress", and at 4 mg/L a large portion of salmonids may be affected. WDOE (2002) concludes that a monthly or weekly average oxygen concentration should be at least 9 mg/L, and a monthly average of the daily minimum concentrations should be at or above 8–8.5 mg/L to have a negligible effect (5% or less) on growth and to support healthy growth rates. USEPA (1986) states that due to the variability inherent in growth studies, reductions in growth rates seen above 6 mg/L are not usually statistically significant, while reductions in growth at dissolved oxygen levels below 4 mg/L are considered severe. WDOE (2002) recommended that dissolved oxygen levels below 5.0–6.0 mg/L should be considered a potential barrier to movement and habitat selection of juvenile salmonids. Based upon these studies, DO levels at or above 8 mg/L are considered supportive habitat conditions.

Contaminants

Common contaminants including some pesticides and metals are known to adversely affect fish when above a certain concentration threshold. Many studies have tested myriad contaminants and their effects on salmon, but specific thresholds for every contaminant in the Central Valley system are not always readily available, nor are thresholds or studies often available on the synergistic effects of multiple

__Table A.4.__ Hazardous common contaminants in the Central Valley, California.

Contaminant	Source
Diazinon	Scholz et al. (2000)
Chlorpyriphos	Baldwin et al. (2009)
Mercury	Beckvar et al. (2005)
Selenium	Hamilton (2003)
Copper	Hansen et al. (1999)
Ammonia	Harader and Allen (1983)
Dinoseb	Viant et al. (2006)
Esfenvalerate	Viant et al. (2006)

contaminants. Moreover, inclusion of specific contaminant threshold requirements for contaminants could exclude many if not most of the areas in the Central Valley due to the pervasive occurrence of mercury from upstream gold mining extraction, of selenium, a naturally occurring element in many San Joaquin Valley soils, and common pesticide and herbicide derivatives ubiquitous in the Central Valley agricultural lands (Philips et al. 2016). Many of the most common contaminants are listed in Table A.4, along with suggested thresholds of effect based on multiple studies.

Due to the adverse effects of contaminants on salmon growth and survival, optimal habitat conditions include an absence of stressful contaminant levels. However, since many contaminants commonly occur in surface waters and flood flows in the Central Valley (Philips et al. 2016), requiring evidence that all contaminant levels be below specified threshold values could be prohibitive. The TAC discussed what the most appropriate goals should be for ensuring that habitat is not encouraged in areas known to have major contaminant problems, while not excluding the many areas with 'non-extreme' contaminant levels. The TAC discussed the challenge and cost of demonstrating that a site has 'below threshold' contaminant levels, which are expensive to measure and can be highly variable over time. Moreover, contaminant levels in surface and groundwater are often a result of upstream current or historical activities and often not within control of the land owner. The TAC ultimately advised that there were too many uncertainties in collecting and reporting such data, potentially prohibitive costs of demonstrating below threshold levels, and a ubiquitous nature of many of these contaminants in the Central Valley. Members of the TAC discussed how a broad question regarding major contamination issues would be the most appropriate filter for excluding sites with that could be toxic to fish. In this case, "major contaminant issue" refers to areas with extremely high known levels of toxins due to things such as acid mine drainage, local mercury mine tailings, and localized high concentrations of selenium.

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Appendix B. Deer Creek Pilot

Deer Creek Study Site

Deer Creek is one of California's last remaining native spring-run Chinook salmon streams, and also supports populations of fall-run Chinook salmon, steelhead, and Pacific Lamprey. Deer Creek drains approximately 222 mi2. (WBD 2019) from the headwaters in the high mountains near Lassen National Park, through the rugged foothills of the Ishi Wilderness, onto the plains dotted with multi-generational family farms and ranches, and finally joins the Sacramento River in the Central Valley on its way to the Pacific Ocean (Figure B.1). Deer Creek is the lifeblood of dynamic ecosystems and valuable fisheries, a diverse wildlife community, and traditions of sustainable timber harvest and family agriculture dating back over a hundred years. However, loss of habitat and altered physical and ecological processes due to agricultural expansion, levee building and water diversion suggest that restoration efforts along Deer Creek can better support salmon populations and the broader ecosystem.

The Lower Deer Creek Flood and Ecosystem Improvement Project is located along approximately 11 river miles of Deer Creek in the upper Sacramento Valley, near Vina, California. The primary land use within the project area is pasture (both irrigated and non-irrigated), followed by nut orchards and vineyards. Though three diversion dams exist in the downstream reaches, Deer Creek is characterized by a largely natural flow hydrograph. The USGS gage near Vina, CA (gage number 11383500) has a gage record dating back to 1912. To date, the largest flow on record occurred on January 1, 1997 at a magnitude of 24,000 cfs.

Deer Creek Restoration Background

There are three irrigation diversion dams on Lower Deer Creek—the Deer Creek Irrigation Diversion (DCID) Dam, the Cone-Kimball (CK) Dam, and the Stanford Vina Ranch Irrigation Company (SVRIC) Dam. The SVRIC Diversion Dam is the downstream-most diversion structure and the tallest at approximately 10 ft high. The upstream pool is completely filled with gravel and cobble transported from upstream—a condition that has necessitated regular bank protection actions as the creek tries to meander into the left bank just upstream of the dam. Even though it is equipped with two fish ladders, it remains a partial barrier to passage of adult salmonids and Pacific Lamprey migrating upstream (NHC 2019).

In 1949, the US Army Corps of Engineers completed a flood control project on the lower 6 mi of Deer Creek. The flood-control project relies on confining flood flows

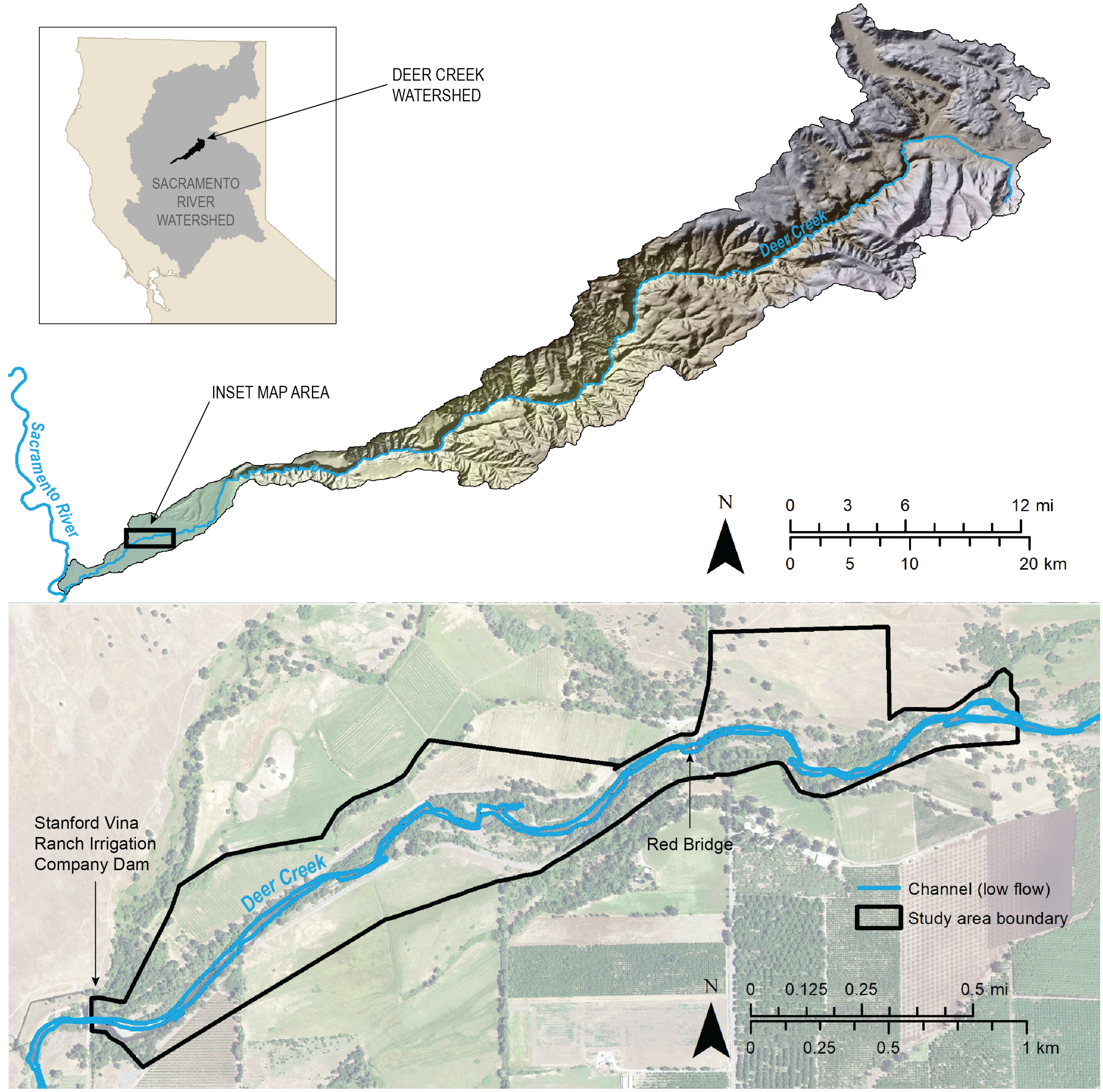

Figure B.1. *Deer Creek study area (~184 acres) for the HQT pilot application with locator maps.*

between levees set close to the channel margin coupled with regular sediment removal and vegetation clearing to maintain channel capacity and design specifications (DCWC 2011). However, multiple levee breaches and flooding have continued to occur in the lower Deer Creek corridor since this project was completed (Tompkins et al 2005). In addition, significant non-project flood and erosion control structures have been installed (e.g., non-project levees, bank armoring and riprap, and rock groins).

Given current conditions, the availability of suitable floodplain habitat for rearing salmonids is limited and what remains continues to be negatively impacted by ongoing maintenance of the flood conveyance and bank protection infrastructure along this reach.

The history of in-channel and floodplain alterations resulted in significant decreases in habitat diversity, complexity, and productivity in the Lower Deer Creek corridor. To address historical and ongoing impacts to the resource as well as continued impacts from bank erosion and flooding, the Deer Creek Watershed Conservancy (DCWC), together with numerous stakeholders and agency personnel, completed the Deer Creek Watershed Management Plan in 1998 (DCWC 1998). The plan outlined strategies that would facilitate continued, responsible resource management in the Deer Creek watershed. Acceptance of the plan prompted the development of the Lower Deer Creek Restoration and Flood Management: Feasibility Study and Conceptual Design Report (DCWC 2011), and most recently, the Deer Creek Flood and Ecosystem Improvement Project.

The environmental planning process for the Deer Creek Flood and Ecosystem Improvement Project is currently underway, but the full set of design alternatives has not been finalized. The current set of project alternatives combine a variety of elements, including levee removals and setbacks, floodplain restoration (including floodplain lowering), fish passage and geomorphic improvements at the Stanford Vina Ranch Irrigation Company (SVRIC) dam, existing levee improvements, and replacement of Red Bridge (https://flowwest.shinyapps.io/deer-creek/). The portion of the project evaluated using the Chinook salmon HQT process focused on the primary levee setback reach between Red Bridge and SVRIC dam. This area includes floodplains along both the right and left bank of Deer Creek extending about 2.4 mi upstream of the SVRIC dam and encompassing 184 acres (see Figure B.1).

Project Site Evaluation Process

To pilot the project site evaluation component of the HQT, the hydrospatial analysis approach (Whipple 2018) was applied to the Deer Creek restoration site. In collaboration with FlowWest, a restoration design scenario was selected and the existing hydrodynamic model was run to generate modeled data used as input for the hydrospatial analysis. The restoration design scenario included levee setbacks, floodplain lowering (approximately 2 ft), increased riparian vegetation, the assumption of a fully operable SVRIC dam (modeled without a dam structure in place), and channel grading to facilitate more natural geomorphic conditions in the vicinity of the dam.

The existing 2D hydrodynamic model developed by FlowWest using HEC-RAS (v 5.0.7) was run with a stepped hydrograph ranging from below the floodplain inundation threshold (~250 cfs) to the flood flow magnitude of record (24,000 cfs). A total of 22 steps were selected, with smaller intervals at the lower flows (100 cfs) and larger intervals at higher flows (3,000 cfs). Both the rising and falling limb of the hydrograph were modeled to capture ponding occurring on the falling limb. A gridded raster dataset representing inundation thresholds across the study area was created from this model output for use in the analysis (Figure B.2). Additionally, a shapefile to evaluate the hydraulic connectivity criteria (whether inundated floodplain cells had a direct surface water connection to the main channel) was created based on buffering the low flow channel boundary by 30 ft. For the daily flow record input, 25 years of the USGS Vina gage (number 11383500) was selected (water years 1994-2018) and flood days were identified as those above the floodplain inundation threshold. This application used the habitat criteria associated with the Valley Lowland landscape context (see Table 2). The criteria assessed with the hydrospatial analysis approach include timing, duration, depth, velocity, and area.

Once input data were formatted, gridded estimates of water depth and velocity at the daily scale were generated using spatially-resolved piecewise linear interpolation based on the hydrodynamic model output and the daily flow record. The subsequent hydrospatial analysis component applied the habitat criteria at the daily grid cell scale and quantified a daily weighted usable area (acres). The daily estimates (acres) were summed at the annual scale to develop a time series of total annual suitable area (acre-days).

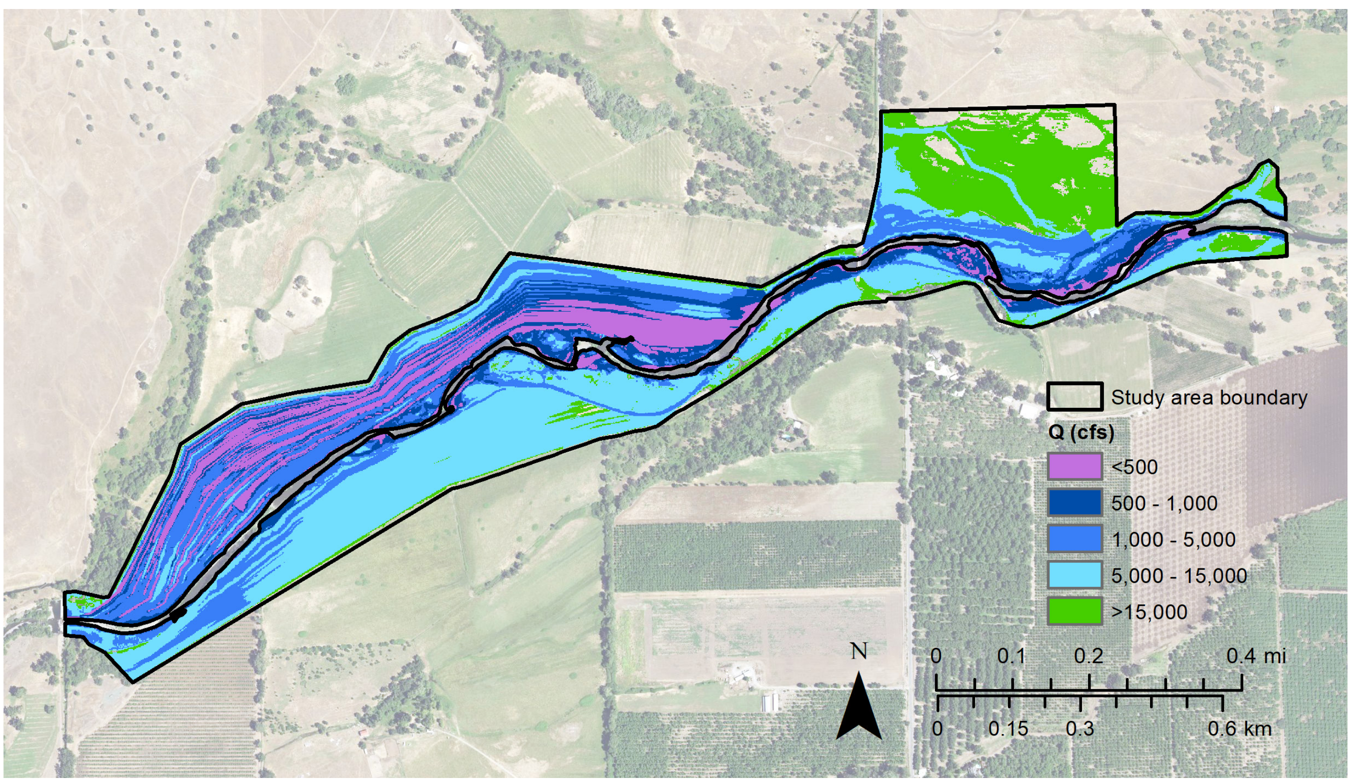

Figure B.2. *Inundation threshold flows determined from 2D hydrodynamic modeling for the Deer Creek study area.*

Results Summary

The project site evaluation results show a mean total suitable habitat of 159 acre-days (median: 161 acre-days) over the 25 years analyzed. Annual habitat is highly variable year-to-year, following the high variability in wet and dry years that is characteristic of California's Mediterranean climate (Figure B.3a). The maximum annual total was 285 acre-days (2017 water year), and the minimum was 43 acre-days (2014 water year). The exceedance probability curve from the total annual habitat time series shows a fairly linear response in habitat as exceedance probability changes (Figure B.3b). This means that at least some habitat is produced for all years and that the lower exceedance probability years (typically wet years) produce greater but not disproportionately greater habitat. In Figure B.3c, daily quantified suitable habitat related to flow shows that suitable habitat area is maximized at about 7,500 cfs, with a secondary peak around 2,000 cfs. Variation in suitable habitat area for given flows is a product of differences between the rising and falling limb of the hydrograph and the application of the duration criteria. To illustrate the temporal and spatial resolution of results, daily suitable habitat area is shown in Figure B.3d and the spatial distribution of total annual suitability (suitability summed over time) is shown in Figure B.3e, both for the 2017 water year. Patterns in the daily time series reflect daily flow variability. It also shows that intermediate flood flows are important for overall total availability. The spatial distribution reveals that small areas of the floodplain study area contribute disproportionately to the total availability, particularly at the center of the reach. Further, large areas of the floodplain do not meet suitability criteria despite being inundated for at least some portion of the year. Further exploration revealed that when large areas were inundated, cells were often either not meeting the depth or not meeting the velocity criteria (e.g., water depth was too shallow when velocities were suitable or velocities were too high when water depth as suitable).

Conclusions and Next Steps

The Deer Creek pilot example demonstrates the utility of the HQT as a tool for quantifying expected habitat at a floodplain restoration site. In collaboration with FlowWest, hydrodynamic modeling results from an existing model established for the site were applied as inputs, suggesting that application of the project site evaluation component of the HQT should be a cost-effective method for restoration planning and evaluation. This pilot illustrates the use of the hydrospatial analysis approach that applies habitat suitability criteria in a spatially and temporality distributed way. As shown here, the resulting quantified habitat can therefore be explored for how it varies within a particular year and where within a floodplain site habitat is maximized across a range of flows. It can also illustrate how the complexity of floodplain site (e.g., topography, configuration of landforms) affects habitat across a range of flows.

Opportunities to further maximize habitat can be revealed through the hydrospatial analysis implemented with the HQT. For example, this analysis revealed that, despite floodplain lowering, large areas of the floodplain were not meeting habitat criteria and

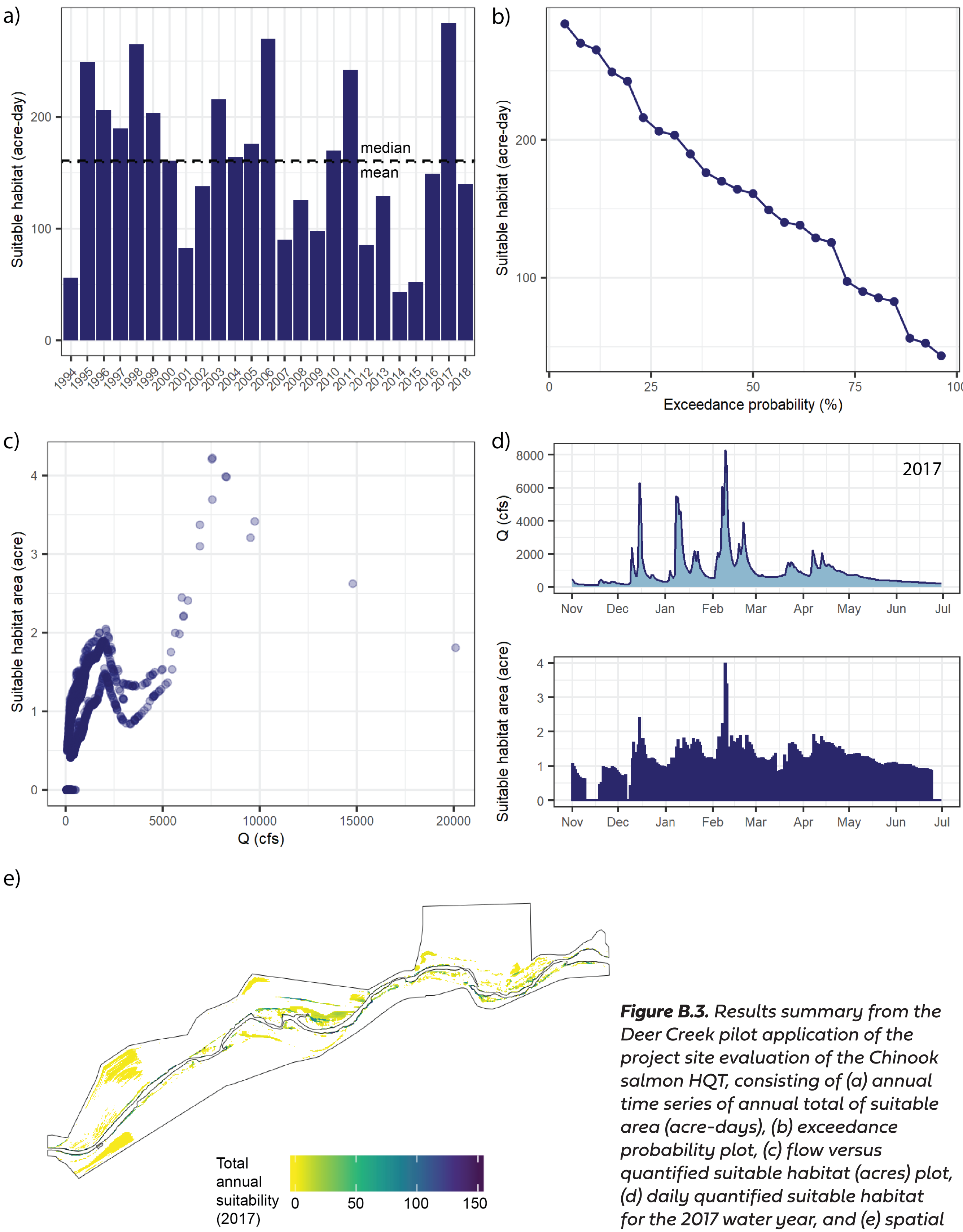

Figure B.3. *Results summary from the Deer Creek pilot application of the project site evaluation of the Chinook salmon HQT, consisting of (a) annual time series of annual total of suitable area (acre-days), (b) exceedance probability plot, (c) flow versus quantified suitable habitat (acres) plot, (d) daily quantified suitable habitat for the 2017 water year, and (e) spatial distribution to total annual suitability (summed) for the 2017 water year.*

thus reducing the overall potential of the site. This issue was a result of velocities often being too high when depths were adequate, and depths being too low when velocity was adequate. This could help in the design of other alternatives that could include features or configurations that would alter these dynamics such that greater inundated area met the habitat criteria.

Further exploration, development, and additional testing of the hydrospatial analysis approach is warranted through examining a wider range of applications. This may include the allowance of user-defined suitability criteria commonly developed for specific watersheds and species. This would allow comparison to traditional habitat quantification methods, helping further demonstrate the utility of the HQT and giving restoration planners and managers more tools to better understand and interpret results. Additionally, the landscape context component of the HQT should be considered in the evaluation of potential projects. For example, the SVRIC dam as currently constructed and operated poses a migration barrier, which makes the habitat area quantified on the project site level less suitable if these issues are not remedied. Further work to better couple the landscape context and project site evaluation components would represent a more complete evaluation of Chinook salmon floodplain habitat value.

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