Floodplains Reimagined: Fish Science Uncertainties and Recommended Data Needs

Memorandum

Provided to the Floodplains Reimagined Program Team

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Introduction

The Floodplains Reimagined Program seeks to restore elements of the ecological function and value of floodplains of the Sacramento Valley, much of which are now part of working agricultural landscapes, to benefit wildlife, fish, wetland and riparian ecosystems, and water quality. Management actions would be guided by a conservation framework based on the nascent concept and practices of reconciliation ecology. Reconciliation ecology, a concept proposed by Rosenzweig (2003), acknowledges that humans are an integral part of ecosystems, and for conservation of biodiversity at large scale to ultimately be effective, we can redesign (and operate) human habitats and working landscapes so that their use is compatible with use by a broad array of other species.

There are multiple challenges to implementing a program like Floodplains Reimagined. First is that we lack specific information on how target species like Chinook Salmon used channel and floodplain habitats prior to large-scale modification of these ecosystems. Thus, our knowledge of the structures and functions that should be targeted for restoration is incomplete. Second, river-floodplain ecosystems are notoriously difficult to study due to their large size, habitat heterogeneity and flow variation at seasonal, inter annual and decadal time scales. Much of the data available to make inferences about restoration actions comes from studies at relatively small spatial and temporal scales and some key information remains unknown. Models and analyses used to explore and evaluate different restoration and management scenarios combine the data that is available with a series of assumptions to begin to make inferences about outcomes. A critical step in the use of models and analyses for any process like Floodplains Reimagined is to explicitly identify the assumptions that are being made and identify the level of uncertainty that exists. This is done to provide context when interpreting model results and to identify and prioritize future data collection that can improve model performance. Here we identify uncertainty and data collection needs that can inform and improve models and analyses used for the FR program and improve understanding of floodplain ecology in the Central Valley in general.

The floodplain landscape template: Flood basins and flood bypasses

The footprint of Floodplains Reimagined Program lies primarily within the flood basins of the Sacramento Valley, which are low-lying areas beyond and parallel to the natural levees of the Sacramento River. Flood basin landforms are unique types of floodplains, a term used broadly by the Floodplains Reimagined Program and within this document. Flood basins are large-scale landscape features and connected at distinct points with the main channel network at intermediate flood levels in contrast to floodplains and terraces immediately adjacent to the bankfull river channel with broad longitudinal river connectivity during flood (Whipple et al. 2012). The Sacramento Valley flood basins reflect the geology, natural physical processes, and geography of the valley. Large-scale depressions formed between alluvial fans extending into the valley and the natural levees built by the Sacramento River since the last glacial period (Atwater 1980). Historically, these basins received, retained, and released peak flood flows of the Sacramento River – at times conveying more water than the main river channel – and also received considerable flow from the many smaller distributary rivers and streams that spread into the valley during the wet season (Gilbert 1917, Bryan 1923). Perennial emergent wetlands dominated the lowest-lying areas of the flood basins, interspersed with sloughs, ponds, and lakes. Along the river side of the wetland margins were the Sacramento River's broad and dense gallery riparian forests. Along the upland margins, perennial wetlands transitioned to complex mosaics of seasonal wetlands, intersected by riparian forest and other habitat types associated with the distributary systems (Whipple et al. 2012).

Flood bypasses and working landscapes are located today in portions of the Sacramento Valley flood basins. The bypasses were constructed as part of engineering efforts to efficiently convey high river flood flows and avoid flooding of other developed urban areas, agricultural land, and flood-vulnerable infrastructure. Dam operations, the flood bypasses, as well as the levees and weirs along the Sacramento River have greatly diminished the extent and duration of inundation within the flood basins and reduced connectivity to the river, within the flood bypasses and most substantially on the dry side of the levees. The structure and management of engineered flood bypasses, along with watershed-scale hydrologic alteration caused by water and drainage management, make them function quite differently from the flood basins of the early 1800s.

Why address uncertainty as part of Floodplains Reimagined?

Consistent with the concept of reconciliation ecology, one key idea being evaluated by Floodplains Reimagined is the potential for re-engineering and re-operating Sacramento Valley weirs and flood bypasses and taking other management actions to provide wildlife, fish, and riparian habitat benefits within the flood basins. While the past flood basin landscapes of the Sacramento Valley almost certainly were part of the waterscape mosaic of habitats that directly and indirectly supported Central Valley salmon populations, improving these ecological functions that may contribute to measurable population-level benefits in the highly modified and managed landscapes of today requires detailed understanding of physical and ecological relationships. There are few examples of successful implementation of large-scale floodplain management to guide such a conservation approach, especially for fish species like the Pacific salmon, which require vast geographic areas of interconnected freshwater and marine habitats, and exhibit highly dynamic use of these habitats affected by their life history requirements and seasonal and long term hydrogeographic patterns (Quinn 2005). Additionally, our understanding of key functional relationships between floodplain dynamics (e.g., spatiotemporal access, floodplain-specific habitat suitability, growth, and survival) and population-level responses of Central Valley salmon runs is rudimentary, at best, requiring several vital assumptions and educated guesses for establishing the simulation models to evaluate feasibility of management actions and potential benefit to the salmon populations and fisheries.

Accordingly, we review, here, the uncertainties underlying key science and modeling tools used to evaluate fisheries benefits of potential measures implemented through Floodplains Reimagined to identify key gaps in data and recommend science activities. By filling in these knowledge gaps, models can be revised to improve understanding of how best to re-establish floodplain-derived benefits for Sacramento River salmon populations without creating unintended harm and consequences. It will be prudent to employ adaptive management frameworks for implementation of cutting-edge conservation actions proposed under Floodplains Reimagined that include well-designed monitoring and focused research elements to address gaps in our understanding of the biology and benefits to salmon of managed floodplain habitats in the Sacramento Valley.

Goals for this technical memorandum

- Elaborate on implications of model assumptions and data limitations affecting comparisons of benefits of Floodplains Reimagined scenarios for Central Valley salmon populations.
- Identify monitoring and research needs that together with purposeful project implementation can address uncertainties in the available data used for modeling to advance scientific understanding and increase probability of desired project outcomes.

Brief history of floodplain research in general and salmon specifically

Floodplain rivers in North America have been subject to intensive modification associated with human activities. Lateral connectivity between main channels and seasonal habitats has frequently been eliminated or impaired by the construction of levees for flood control and agricultural development. Flow regimes have also been altered by upstream water storage and flood control dams that attenuate peak flows, which further contributes to a lack of lateral hydrologic connectivity between river channels and floodplains.

In the late 20^{th} century, research in unaltered tropical floodplain rivers highlighted the importance of the annual flood cycle for fish in these systems that have adapted to take advantage of high productivity in the aquatic-terrestrial interface during flooding for reproduction and juvenile rearing. These observations were formalized by Junk et al. (1989) as the Flood Pulse Concept (FPC). In temperate systems, Bayley (1991) hypothesized that the greatest productivity would occur when flood pulses coincided with rising temperatures to maximize primary and secondary productivity. This conceptualization of floodplain function for riverine fish triggered new research on heavily modified systems in North America, Europe, and Australia to understand the role of floodplain isolation in declines of riverine fish, and to formulate strategies for restoring these floodplain functions.

In the Central Valley, research on floodplain functionality began in earnest in the mid 1990's within the Yolo Bypass and Sutter Bypass. This work primarily focused on how aquatic habitats within a flood bypass may replicate functions of the historical floodplains for native fishes with a focus on Sacramento Splittail and juvenile Chinook Salmon. Results of a study by Hill and Webber (1999) estimated growth of wild spring run Chinook captured in Butte Creek and recaptured in Sutter Bypass and concluded that the bypass, when flooded, provided growth opportunities. Sommer et al. (2001) suggested that growth of juvenile salmon can be greater in the Yolo Bypass compared to the adjacent Sacramento River channel based on apparent growth rates of coded-wire tagged hatchery fish concurrently released into the bypass and the river channel. Higher growth was attributed to higher abundance of potential prey items combined with warmer temperatures in the bypass, an explanation that was supported by bioenergetic modeling.

These observations suggested that enhanced connectivity with flood bypasses could potentially be beneficial for juvenile salmonids and triggered multiple additional research efforts. Most of these efforts focused on quantifying secondary productivity (primarily zooplankton) and growth of juvenile salmon in the Yolo Bypass (Sommer et al. 2001, Katz et al. 2017), Cosumnes River (Jeffres et al. 2008) and San Joaquin River (Zeug et al. 2019) and largely confirmed the findings of Sommer et al. (2001). While these findings are provocative, much of this work has been done using hatchery fish enclosed in cages or on experimentally flooded agricultural fields rather than with volitionally rearing wild fish during actual flood conditions.

Although much research has been focused on the growth of juvenile salmon in floodplain habitats, if and how the observed growth effect translates to population-level effects has received considerably less attention and remains a subject of conjecture and scientific inquiry. It has frequently been hypothesized that population-level benefits of higher growth are size-mediated (see the conceptual model section below). The thought being, primarily, that larger fish are less susceptible to gape-limited predators[1], and that swimming speed in fishes, generally, increases with size, aiding in evading and avoiding predators. These size-based advantages are then hypothesized to translate into higher rates of survival to the adult spawner stage. However, data on Central Valley salmon to explore this hypothesis are limited and this hypothesis has yet to be rigorously tested.

[1] "Gape-limited" refers to the mouth size of a predator and maximum size of a prey it can capture and ingest.

Sommer et al. (2005) compared recovery rates of coded wire tags from juvenile hatchery-origin salmon released in the Yolo Bypass and Sacramento River and found that survival rates for floodplain rearing fish did not differ from those released in the Sacramento River. An acoustic telemetry study performed in 2019 compared survival rates of fish reared in Yolo Bypass rice fields and in a lab at UC Davis, and then released in the Sacramento River and Yolo Bypass. These data have not yet been peer-reviewed and published, but NMFS' CalFish Track website provides estimates showing that the Yolo Bypass releases survived to Benicia Bridge at a lower rate (0.4 % and 17.6% for the Yolo Bypass release and Sacramento River release, respectively). Use of differences in the geochemistry of river channels and floodplains (e.g., stable sulfur isotopes) is currently being explored as a way to identify a history of floodplain rearing in returning adults and appears to be a promising study technique. However, there remains work to validate observations and better differentiate habitats with similar isotopic signatures (e.g. floodplains and tidal marsh). Additionally, there remains a need to gather quantitative evidence to test hypotheses about population-level effects of differences in geographic areas and habitat use, including use of floodplains, among rearing juvenile salmon.

Conceptual model of floodplain function for juvenile salmonids

Multiple conceptual models describing how floodplains function for fish have been proposed including the Flood Pulse Concept (Junk et al. 1989), Low Flow Recruitment Hypothesis (Humphries et al. 1999), and the Riverine Ecosystem Synthesis (Thorp et al. 2006). Data collected from field studies indicate that functionality for fishes can vary according to fish life history strategy, climatic characteristics and their effect on the flow regime, interannual flow variation within systems (timing and duration of connectivity), and specific habitats within the floodplain mosaic (King et al. 2003, Zeug and Winemiller 2008). In the Central Valley, floodplain functions for juvenile salmon rearing have received the most attention. Potential benefits related to fish size are often referenced but no formal conceptual model has been developed and tested. Here we provide a simple conceptual model that illustrates how fish potentially acquire benefits from rearing on floodplain and how those benefits are hypothesized to propagate through subsequent life stages (Figure 1). This conceptual model does not necessarily represent all the benefits that may accrue for salmon from floodplains nor should it be thought of as a comprehensive depiction of all important ecological linkages between rivers and floodplains that may affect the salmon life cycle. Rather, this is a simple representation of the current working conceptual model for floodplain salmon benefits reflected in projects and published work from the Central Valley that can be used as a framework for organizing actions, data collection and adaptive management within the Floodplains Reimagined program.

The conceptual model in Figure 1 describes life stages, transitions between life stages, and how they interact within the Sacramento River and the Butte Basin/Sutter Bypass (BBSB). Transition "A" represents life stages that are moving down river looking for rearing habitat prior to smoltification (fry and parr). When they arrive at one of flood control weirs and that weir is actively spilling, they may remain in the river channel or move over weir and into floodplain habitats of the BBSB. It is hypothesized that increases in the duration and magnitude of connectivity will result in greater numbers of juvenile salmon accessing the BBSB. In life stage "B" fish are actively rearing in the main channel or floodplain in preparation for smoltification and migration toward the ocean. Fish can grow more rapidly in floodplain habitat relative to channel habitat when food resources are abundant and temperatures are, within narrow limits, relatively warmer than that occurring in the river channel. Although it remains unknown if suitable habitat is currently limiting within the bypasses, it is hypothesized that increasing the availability of suitable inundated habitat can increase the benefits acquired by fish rearing in floodplain habitat. Larger size is associated with reducing risk of predation mortality. Thus, the higher growth of fish on the floodplain is hypothesized to increase survival when fish initiate migration through the Delta and San Francisco Bay (Transition "C") resulting in a greater per-capita survival rate. It is further hypothesized that this growth benefit similarly advantages floodplain reared fish during their early ocean residence (Transition "D"). The final result is hypothesized to be expressed at the spawner life stage (State "E"), where the size benefits to survival are realized in a greater number of fish returning (population-level effect).

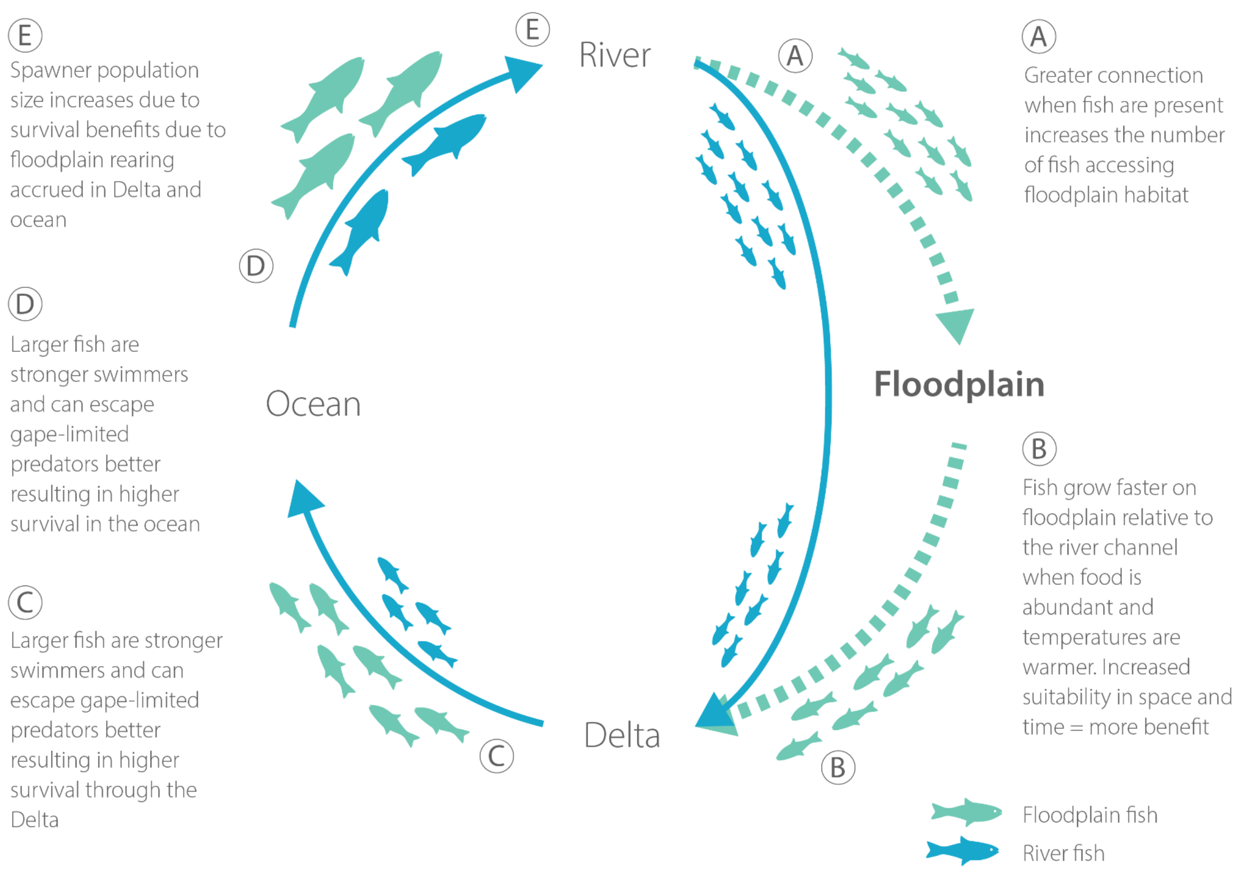

Figure 1. Conceptual model describing use of the Butte Basin/Sutter Bypass by juvenile Chinook salmon and how benefits from floodplain growth translate through subsequent life stages to generate a population-level effect.

Approaches for describing juvenile salmon use of floodplains and habitat availability applied in Floodplains Reimagined

Habitat Suitability

Commonly applied in studies of riverine habitat for fish, evaluating availability of suitable juvenile rearing habitat is a method for measuring physical habitat factors that are key to salmon growth and survival. Notably, the assessments are not direct estimates of salmon growth and survival and are made within a modeling context and are therefore indirect approximations of potential benefits to juvenile salmon. However, as one of several approaches for evaluating salmon benefits by the Floodplains Reimagined Program, it offers a relatively straightforward approach to examine relative habitat impacts of potential alternatives and management actions under the Floodplains Reimagined Program.

The approach weights inundated habitat area based on suitability criteria related to timing, duration, depth, velocity, connectivity, and land cover and sums that over space and time for a measure of suitable "acre-days". Though it is generally understood that more inundated areas accessible to juvenile salmon for longer periods of time is likely to be beneficial, the suitability criteria approach allows evaluation of relative suitability based on the defined physical criteria. The selection of those criteria and their associated values were set through an iterative process, based on scientific literature, precedence, best professional judgment, and what could be evaluated from the hydrodynamic modeling output. Applied criteria result in approximations of potential benefits to rearing juvenile salmon and are intended for comparing relative differences in benefit across scenarios. For the criteria values and additional description, see the "Juvenile salmon habitat suitability criteria" technical memo.

Benefits of floodplain rearing

The Salmon Benefits Model is a simulation model that was built to assess the potential benefits of floodplain rearing for juvenile Chinook salmon (See SBM tech memo). Simulation models allow various states of a modeled system to be propagated through time and are often useful when system dynamics are highly stochastic, non-linear or both. Additionally, a key advantage of simulation models is that many different sources of data can be used to develop relationships including laboratory experiments, long-term monitoring data, and field studies. An important consideration for using simulation models is that the result should only be used for comparing outcomes of different scenarios evaluated by the models and not for predicting future outcomes as is done with statistical models.

A detailed description of the specific algorithms that comprise the SBM are contained in the tech memo but here we provide a brief overview. Juvenile salmon enter the model at Moulton weir. Their movement and survival rates are applied daily as is the determination of their behavior (rearing versus migrating). Movement onto the floodplain is a function of the proportion of flow going over the weir. Growth, survival and movement rates are different depending on both the location of an individual (floodplain or main channel) and their behavior classification (rearing or migrating). Fish that use the floodplain or remain in the main channel all migrate through the Delta where their survival is a function of flow magnitude. In the ocean, a size-based survival advantage is applied in years of poor ocean productivity but not in years of good ocean productivity. The outputs of the model are reported based on the specific location where fish entered the floodplain (Moulton, Colusa, Tisdale Weirs or Sacramento Slough) and include, 1) the proportion of the juvenile cohort entrained onto the floodplain, 2) the mean size if fish arriving at Chipps Island, and 3) the smolt-to-adult rate for fish using the floodplain relative to that same rate for fish that remained in the river channel (rSAR).

Uncertainties and data needs

How juvenile salmon access the Butte Basin/Sutter Bypass

For a juvenile salmon to use floodplain habitat in the BBSB, a series of things need to occur including,

1. A fish needs to be present at an entry location (weir)
2. The weir must be actively spilling
3. The fish must move over the weir

These three things would be contained within transition "A" of the conceptual model above. All the weirs where salmon can enter BBSB are downstream of natal habitat meaning that fish must be moving downstream to have a chance for access. Fish presence at entry locations is available at a relatively coarse scale from monitoring data. The Red Bluff Diversion Dam juvenile trapping program run by the US Fish and Wildlife Service operates year-round and provides the best information available on the timing and magnitude of fish movement upstream of the flood control weirs. However, there are several issues that introduce uncertainty when attempting to link these data to fish presence at the weirs. First, the trap is located 85 river miles above Moulton Weir. It is unknown if the distribution and magnitude of fish seen at Red Bluff is maintained for this entire distance. A key assumption of the SBM is that fish observed at Red Bluff continue to move downstream at a given rate and do not stop to rear or change their movement rate in those 85 miles. Second, the Red Bluff trapping data indicate the temporal distribution of catch for each run of Chinook salmon can differ between years. Previous analyses of monitoring data in the lower river and estuary have demonstrated that river discharge is a driver of fish movement (Brandes and McLain 2001, del Rosario et al. 2013). In the SBM, a ten-year averaged daily distribution is constructed using the Red Bluff data. This averages out the year-to-year variation in fish timing. These variations can be critical for estimating when fish may have access to the BBSB. However, the data available are not sufficient to estimate the effect of discreet flow events on movement at sub-annual scales. Trapping is often suspended when flows are high, and sampling becomes difficult and dangerous. Large numbers of fish are likely to move on these pulses. Thus, data from the traps may be biased low in relation to flow. Understanding what magnitude flow event is required to change movements of rearing fish would be essential to understand the interaction between fish presence and BBSB access.

The movement of fish from the Sacramento River and over a weir is hypothesized to be a function of the proportion of total flow going over the weir. In the SMB this is represented as a 1:1 ratio (e.g. 30% of total flow over the weir = 30% of fish passing that day go over the weir). No quantitative data on fish movement over these weirs is available. The data that is available to support a proportional flow relationship comes from studies in the tidal Delta where the movement of hatchery-origin smolts at junctions has been modeled using acoustic telemetry data (Cavallo et al. 2015, Perry et al. 2015). There are several key uncertainties about how well the Delta information translates to weir junctions. The Delta studies were performed with large smolts that were actively migrating to the ocean, whereas the focus for this modeling effort are the smaller fry and parr life stages that would be seeking rearing habitat or switching between rearing and migrating behavior as they move downstream. Further, the lateral distribution of fish within the channel could be an important influence on the proportion of fish going over the weir. It is unknown how the physical geometry of the river channel and weir junction interacts with hydrology and channel hydraulics to influence lateral distributions of the fish as they are moving downstream.

Key data needs to understand how fish access habitat in the BBSB include:

1. Quantitative relationships between discrete hydrologic events and fish movement and arrival at junctions
2. Quantitative relationship between fish movement in junction and hydrologic/hydraulic metrics
3. Channel and weir junction characteristics that influence lateral distribution and behavior of migrating fish at junction locations and their potential for entrainment in the bypass.

Growth, survival, and movement behavior

Growth of juvenile salmon is by far the most studied aspect of juvenile Chinook salmon ecology on Central Valley floodplains. The SBM growth function relies on coded wire tag release and recovery data (see SBM Tech memo for details) and fish in the river and floodplain experience their respective growth rates (mean and distribution) each day. A key assumption of this function is that growth rates are constant in space and time and that the coded wire tagged fish are representative of all fish that use river and floodplain habitat. Studies in the BBSB have found that growth of caged salmonids can be highly variable in space and time (Cordoleani et al. 2023). In the wettest year, when all weirs were spilling, there was less variation in growth of caged fish within channel and floodplain habitats. The greatest differences in growth of caged fish in the two habitats tended to occur under hydrologic conditions occurring in drier water year types, which exhibit less frequent and lower magnitude hydraulic connections between rivers and bypasses (and, consequently, less access opportunity and potential benefit for juvenile salmon) than in wetter water years under current hydrologic and operational conditions.

Other floodplain growth studies have been performed in the Yolo Bypass (Sommer et al 2001, Katz et al. 2017, Jeffres et al. 2020), Butte Basin/Sutter Bypass (Cordoleani et al. 2023), Cosumnes River (Jeffres et al. 2008, and San Joaquin River (Zeug et al. 2019). In all but the Sommer et al. (2001) study, fish were confined to discrete locations within cages, net pens or experimentally flooded plots. Those studies have largely affirmed that growth rates in floodplains can be greater. However, under certain conditions growth in the river channel can be higher or equal to that of floodplain habitat suggesting that the magnitude of growth benefits may change in space and time (Zeug et al. 2019, Cordoleani et al. 2023). Additionally, the caging of fish is likely to have a greater effect on fish in the river channel relative to the floodplain because fish are more restricted from accessing more of the water column and potentially access to the most energetically favorable habitat in a river channel. Cordoleani et al. (2023) reported growth of volitionally migrating fish in the river channel were higher than caged fish in that same habitat, and more similar to fish reared in off channel cages, suggesting a cage effect that may influence observed differences in fish growth between habitat types. Similarly, evidence from stable isotopes of carbon and sulfur studies of juvenile salmon rearing and feeding histories indicate substantial differences in feeding behavior, opportunity, or prey types and availability between caged fish and free-swimming fish in the Sacramento River main channel (Bell-Tilcock et al. 2021a).

Currently there is little quantitative information on the comparative survival of fish rearing on the flood bypasses, the river channel, estuary, or other non-natal habitats. In the SBM, survival during rearing is applied daily but in floodplain habitats, that rate is a function of flood magnitude based on a theoretical relationship (see SBM Tech Memo). Both the relationship with flood magnitude and the daily survival rates do not currently have a quantitative basis and represent a major assumption of the model. The increased growth of fish on floodplains could lose its potential benefit if survival rates are lower in floodplain habitat. The theoretical relationship is based on aquatic predator encounter rates; however, the shallow habitat on floodplains may increase susceptibility to avian predators, and concentration of fish moving off the bypass floodplains through drainage outfalls and outlets may create a predation bottleneck. There also may be certain time periods, floodplain habitats or salmon life stages, across which survival varies and understanding these relationships would be essential for planning restoration and management strategies.

Movement and behavior in the BBSB is only represented as residence time and is a function of flood duration. This relationship was developed from data collected in the Yolo Bypass and scaled for use in the BBSB (See SBM Tech memo). There is currently no information about how fish distribute among habitat patches within the BBSB, how they move among patches, how they move through canals and structures during egress or what triggers their movement and habitat selection. Getting better information on habitat use and selection would help guide targeted approaches to restoration to maximize potential benefits. Similarly, this information is lacking in the main channel. In wet years, greater fractions of fish arrive in the Delta and Bay suggesting that habitat capacity is unlikely to be the primary driver of behavior. Thus, engaging in rearing vs. migrating behavior is controlled by factors we do not understand. Getting better information on this would provide insight into how flow and habitat may be managed to produce the greatest benefit for rearing salmon while minimizing risks.

Key data needs

1. Growth of freely moving and migrating juvenile salmon during the hydrologic conditions of interest in both the main channel and floodplain
2. Habitat-specific estimates of survival for rearing juvenile salmon in habitats, and under hydrologic conditions of interest
3. Survival during egress through bypass outlets (e.g., Sacramento Slough)
4. Survival during egress/migration under extended rearing scenarios
5. Spatial distribution of rearing juvenile salmon in the BBSB
6. Patterns and factors associated with movements onto, within, and off the floodplain and back into the main river channel.

Floodplain habitat suitability

The adoption of a habitat suitability evaluation approach for the Floodplains Reimagined Program enables a reasonably direct estimation of the relative impact of different management actions on floodplain conditions that may affect juvenile rearing salmon. However, by focusing on habitat conditions, the approach does not extend to utilization of the habitat and directly estimate salmon benefits. More specifically, the evaluation does not address whether there will be fish present to take advantage of the available habitat and whether growth and survival will improve if more habitat is available. Therefore, an overarching assumption when using this approach, and of the Floodplains Reimagined Program in general, is that floodplain habitat availability is a limiting factor for the growth and survival of juvenile salmon. While, as noted earlier, extensive literature from floodplain systems globally establishes the critical ecological role of floodplains, including for fishes (e.g., Bayley 1991, Pratt et al. 2023), and Central Valley studies also point to benefits of floodplain rearing (e.g., Sommer et al. 2001, Jeffres et al. 2008), definitively attributing a specific quantified fish benefit to a given habitat area at a given point in time is inherently an imprecise process.

Habitat preferences of rearing juvenile salmon in floodplain environments are influenced by many interacting physical and biological factors and are made even more complicated in highly managed systems like Central Valley floodplains. However, adoption of simplified relationships between physical factors and habitat suitability is required to apply physical habitat suitability criteria to hydrodynamic modeling output using the hydrospatial analysis approach taken within the Floodplains Reimagined Program. Representing the relationships in associated criteria and applying the criteria are confounded both by imperfect knowledge of those relationships and inability to represent the relationships exactly in a modeling environment. The following text highlights several key areas of uncertainty relating to these challenges and further details are offered in the “Juvenile salmon habitat suitability criteria” technical memo.

Habitat suitability criteria established for this approach relate to timing, duration, depth, velocity, connectivity, and land cover. Selection of the criteria and their associated values largely drew on precedent and the best professional judgment of the Advisory Committee. Much of the science backing up the suitability relationships (e.g., depth preferences for juvenile salmon) is drawn from in-stream studies or more natural and typical floodplain environments, which therefore raises the question of whether those relationships hold true in highly managed floodplain environments of the Central Valley and can thus be transferred to this application. Particular areas of identified uncertainty with regard to criteria, which led to a divergence of viewpoints on how to set the criteria, included whether to set an upper depth threshold (e.g., around six feet depth) beyond which suitability was assigned a lower value. Though shallower depths for foraging potential (including prey production) and predator avoidance are generally thought to be preferable to juvenile fish and reflected in criteria established for similar approaches (e.g., DWR and USBR 2012), inadequate consensus concerning its relevance in floodplain environments and inconsistency across various precedents meant that no upper depth limit is currently included in the approach. Another specific area of uncertainty with regard to setting criteria was that of cover. As with depth, the science is not definitive, leaving the criteria open to interpretation. Ultimately, the criteria giving higher weight to natural land cover types reflect the general understanding that habitat complexity and availability of refugia on natural land cover types provide higher quality habitat relative to managed agricultural fields, and that managed fields are generally associated with greater risks (e.g., within-field infrastructure, toxins). Focused research addressing these factors within Central Valley floodplain habitats could support refinement of criteria and reduce uncertainty in analysis results.

What the analysis does not evaluate is also important to consider in terms of uncertainty. For the analysis approach and the purpose of comparing relative impact of management actions, factors not represented in the model (e.g., turbidity, temperature, toxins) are assumed to not substantially affect outcomes. Further research describing habitat potential as it relates to such factors could improve interpretation of results and reduce uncertainties. An overarching limitation of the criteria selected is that potentially detrimental conditions, such as those associated with stranding potential or passage requirements for other life stages (e.g., adult migration) are not evaluated. The application of the criteria thus requires the assumption that the benefit of the floodplain rearing habitat is greater than any potential harm. Additional synthesis of existing literature and focused studies to improve scientific understanding of suitability relationships within Central Valley floodplains would offer opportunities for refinement of criteria as well as substantially improve confidence in the analysis results.

Another set of uncertainties are more associated with limitations of representing complex physical and biological processes and relationships in a hydrodynamic modeling context. How hydraulic connectivity to and within the flood basin landscape is handled is a prominent area of uncertainty, as access to available rearing habitat by juvenile fish is necessary for any benefits to accrue. The habitat suitability approach includes connectivity criteria, though evaluation is limited to whether a given area is connected to a near-by channel. A more sophisticated and complex evaluation of the nature of connection to the main river channel as well as field-scale ingress and egress opportunities would instill greater confidence in evaluating habitat suitability as it relates to connectivity. Additionally, improved empirical knowledge of juvenile fish movement on, within, and off Central Valley floodplains would also inform how connectivity criteria might best be applied in a modeling context. Understanding the potential impact on results of other model simplifications, such as reduction of small-scale topographic complexity, would also improve interpretation of results and reduce uncertainty.

Key data needs:

1. Use and/or preferences for depth and cover type of juvenile rearing salmon within floodplain environments, including managed floodplains of the Central Valley.
2. More detailed understanding and representation of connectivity and conveyance features, including managed field operations, and how they affect ingress, egress, movement, and survival within the floodplain and between the floodplain and main river channel.
3. Greater understanding of detrimental impacts and/or trade-offs relative to other life stages (e.g., potential for adult passage via within-floodplain infrastructure).
4. Field-based validation comparing observed juvenile fish use and predicted habitat within Central Valley floodplains.

Benefits subsequent to floodplain rearing

One of the key hypotheses related to floodplain rearing is that higher growth and, thus, larger size, provide a benefit to individuals in subsequent life stages that translates to benefits at the population level. The most frequently cited size-based advantage is that larger fish should have greater protection from gape-limited predators and larger fish are stronger swimmers which would also enhance evasion of predators and other potential hazards. It has also been hypothesized that faster growing fish may migrate earlier when conditions in the migration corridor are more favorable. The combination of these is predicted to result in higher survival during migration through the Delta and during early ocean residence.

Multiple acoustic tagging studies of Chinook salmon smolts within riverine environments in the Central Valley have found a significant positive effect of either fork length or fish condition on survival (Henderson et al. 2018, Zeug et al. 2020a, Hassrick et al 2022). These same data for Chinook salmon in the estuary are lacking and the SBM does not contain a survival function in the estuary that is a function of fish size. One study by Perry et al. (2018) found a significant positive effect of fork length on survival of fish in the estuary. However, that study used yearling late-fall Chinook that are outside the size range of sub-yearling fish being modeled in the SBM. Pope et al. (2021) directly compared survival of smolts migrating through the Yolo Bypass and Sacramento River during flood conditions and found that values were similar. That study did not test for an effect of size. Two unpublished studies performed by UC Davis researchers have released acoustically tagged fish reared in flooded rice fields or a laboratory.

In 2019, these releases were made in the Sacramento River and Yolo Bypass, and in 2023, they were released in the Sutter Bypass and Sacramento River. Reports or publications of these data are not yet available but preliminary estimates of survival to Benecia on the CalFish Track site do not indicate obvious benefits for rice-reared juvenile Chinook salmon.

Currently there is little information on the relationship between growth rate and the timing when migration is initiated in naturally rearing fish. There is evidence that hatchery smolts released earlier in the migration window tend to survive better but timing was related to spawn timing rather than growth rate (Zeug et al. 2020b).

There is evidence that size at ocean entry can have survival benefits for juvenile Chinook salmon. Satterthwaite et al. (2014) reported that size at release had a positive effect on recovery rates of coded wire tagged hatchery Chinook salmon smolts released directly into the estuary. Woodson et al. (2013) used otolith analysis of Chinook salmon captured in the ocean to estimate size at ocean entry. They found that size-selective survival operated in low recruitment but not in high recruitment years, suggesting size effects may not be consistent from year-to-year, but may depend on predicating conditions of ocean productivity and other ecological factors at sea.

More recently, research has focused on the use of stable isotopes of sulfur in otoliths and eye lenses to attempt to identify floodplain rearing in returning adults (Bell-Tilcock et al. 2021a,b). This technique appears to be promising but remains in the developmental stages with a need for validation and better resolution of isotopic sources in all potential rearing habitats. For example, stable isotope ratios of sulfur in tidal marshes of the Delta are similar to those on floodplains (Young et al. 2021) and juvenile Chinook salmon are known to rear in these habitats, particularly in wet years (Brandes and McClain 2001).

Key data needs

1. Studies that specifically test hypothesized benefits of size during migration through the Delta
2. Studies that specifically test hypothesized benefits of size during early ocean residence
3. Test relationships between growth rate and migration timing.
4. Identification and quantification of other mechanisms of hypothesized benefits
5. Validation of isotopic techniques and better resolution of isotopic sources within potential rearing habitat in the river, floodplain and estuary.

Why Address Scientific Uncertainty in Salmon Benefits Model and Habitat Suitability Criteria?

Landscape-level salmon habitat conservation actions and multi-benefit landscape reconciliation efforts require decisions and choices for investments of public and private resources despite often large amounts of uncertainty in the available information from many sources. This uncertainty can result in risks to habitats and populations from inappropriate management advice (Fogarty et al. 1996, as cited by Steel et al. 2003). Steel et al.'s (2003) admonition reminds us best that, *"Past failures of management (and recovery) plans to prevent population declines and collapse are due in part to the failure to recognize uncertainty in available information and a lack of procedures for including uncertainty in the decision-making process (Wade 2001). Inevitably, decisions will be based on a tapestry of models, estimates, expert opinions, myths, predictions, and data. By identifying, quantifying, and acknowledging the uncertainty in information used for recovery planning, we can increase the likelihood that recovery plans will be successful."*

The role of science and scientists in natural resource management and conservation is to inform the decision-making process with the best available data, analyses, and knowledge. The available empirical data are sometimes insufficient, and models are used to simulate processes, predict potential outcomes, and organize knowledge to identify key understandings and data gaps, for research and management purposes (Beechie et al. 2003). Use of the terms scientific and model uncertainties does not necessarily mean a lack of knowledge but an understanding of the limits of existing knowledge or an expression of the possible range of outcomes based on what is known about the issue at hand (Steel et al. 2009). Uncertainty in models and their outputs comes from 1) variability in natural systems, 2) measurement errors in data used, 3) parameter imprecision, 4) inaccuracy of model representation of natural processes, and 5) mismatched conditions between model structure and the scenario to which it is applied (Steel et al. 2009).

Clear-eyed consideration of model uncertainties between scientists and managers improves the chance of better decision outcomes when uncertainties underlying evaluations and recommendations are transparent, considered, and understood. And, importantly, such explicit consideration of foundational data and model uncertainties should allow managers to avoid or minimize taking undesired risks or obtaining undesired resource conservation outcomes that are misaligned with stakeholders' interests.

Fundamental Uncertainties

In addition to the uncertainties described above for specific life stages and transitions represented in the conceptual model, there are also fundamental uncertainties related to how fish interact with the river-floodplain mosaic as it currently exists that should be considered when planning management and restoration activities. It is important to recognize that floodplains are one part of the larger river-floodplain ecosystem that at a broad scale contains the main river channel, perennial floodplain habitat and seasonal floodplain habitats (Amoros and Bornette 2002). The formation, evolution, and connectivity of these habitats is variable at flood event, seasonal, interannual, and multi-decadal scales (Winemiller et al. 2000, Amoros and Bornette 2002). Fish native to river-floodplain ecosystems have adapted to take advantage of the spatiotemporal heterogeneity that defines these systems. Both floodplain and main channel habitats are important and can be productive at various points in the hydrologic cycle (Humphries et al. 1999, King et al. 2003 Thorp et al. 2006). The life history traits of species interact with hydrology and habitat to determine conditions that are most productive (King et al. 2003, Zeug and Winemiller 2008). Thus, management actions should be undertaken cautiously to ensure the integrity of seasonal and perennial habitats and support the entire native fish assemblage and supporting ecosystem while minimizing the potential for unintended consequences.

The primary floodplain habitats that still exist in the Sacramento River are managed as flood bypasses and working landscapes. There are key differences between the structure of engineered flood bypasses and typical natural floodplain habitats that could impact their ability to provide benefits at the population level. The first challenge is related to fish access and egress. In the BBSB, under all but the most extreme flows, fish can only access floodplain habitat at one of four discrete locations and exit at one location. Historically, access and egress to the flood basin likely occurred at many points along the length of the river-floodplain interface.

Using the entrainment functions in the SBM described above, the analysis of five water years, including two wet years (2011 and 2019), indicate that fewer than 50% of juveniles will be entrained into the BBSB and when fish presence does not align with weir spill, that number goes down quickly. A key question that arises is "What proportion of fish using the floodplain is needed for a detectable population-level effect?" This may be preliminarily achieved using simulation and explicit assumptions about the uncertainties described above.

Similarly, there is a single egress location for fish in the BBSB at Sacramento Slough. This is a relatively narrow channel that enters the Sacramento River just upstream of the confluence with the Feather River. The confluence of these two rivers is a known aggregation point for striped bass and other predators of juvenile salmon and large numbers of fish coming into this location from Sacramento Slough could result in high mortality rates. It is essential to understand the survival dynamics during egress, particularly if future management may result in more fish exiting through this location under low water conditions or during periods when striped bass are seasonally abundant.

Since hydrology is a key feature that links habitats and drives biological responses within the river-floodplain system, it will be important to consider how benefits to salmon may be linked through different parts of the system. For example, in high flow years there is often greater connectivity between the main channel and floodplain allowing fish to access off channel habitat. However, higher discharge also is associated with higher survival of fish in the river (Henderson et al. 2018, Hassrick et al. 2022) and Delta (Perry et al. 2018), and turbid conditions during high flows can also enhance survival (Gregory and Levings 1998, Ortega et al. 2020). Since these conditions are autocorrelated, the benefits of each cannot be separated. Thus, there is considerable uncertainty about the magnitude of benefits if floodplain rearing is enhanced in years when riverine conditions during migration are more similar to those observed in drier years (lower discharge and higher clarity).

Summary

River-floodplain ecosystems are large, temporally dynamic, and spatially heterogeneous, which can make it challenging to collect data in these systems. However, restoration and management of highly managed systems like the BBSB for the benefit of juvenile salmon requires additional data both to reduce uncertainty in decision making and validate hypothesized ecological benefits. The conceptual model presented above provides a starting point to understand hypothesized functions of floodplain rearing. Development of models and analyses described above attempt to parameterize those hypothesized relationships with data that are available. The modeling and analyses combined with discussions of other scientists participating in Floodplains Reimagined have revealed key areas of uncertainty that should be addressed. Some of these apply specifically to relationships within the Floodplains Reimagined footprint and others are related to fundamental uncertainties that link floodplain dynamics with the entire life cycle of Chinook salmon and the native fish assemblage as a whole. Table 1 summarizes data needs within both of these categories that should be addressed to increase reliability of model results and reduce uncertainty in restoration and management outcomes.

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Table 1. Summary and recommendations for priority research and monitoring data needs to support the Floodplains Reimagined Program. We recognize that approaches for each need will need greater specificity than what can be provided here. There also may be new technologies or approaches that are in development and could be used to collect these data. The potential approaches should be viewed as suggestive rather than prescriptive.

Scale	Life stage/transition from conceptual model	Relative importance	Data/Science Need	Potential Approach
Within the FR footprint	A	Medium	Quantitative relationship between discrete hydrologic events and the movement of fry/parr from natal habitat to bypass weir locations	Paired sampling in natal habitat and at entry locations during discrete hydrologic events of various magnitude. Mark fish in natal habitat and recapture at entry locations
	A	High	Quantitative relationship between the proportion of fish moving over a weir in relation to hydrologic conditions (e.g. flow proportion)	Mark-recapture and/or telemetry studies of relative abundance of marked fish observed in river channel up- and downstream and within the weir inflow channels
	A	Low	Junction specific properties that that influence entrainment of fish and their lateral distribution with the channel	Bathymetric and 2-D hydraulic models, habitat suitability inventory/characterizations to evaluate potential associations with fish habitat and migration corridor preferences
	B	Medium	Growth of natural-origin free swimming fish in the channel and floodplain habitats of interest under a range of hydrologic conditions	Otolith, body proximate, RNA/DNA ratio analyses of fish captured using an appropriately designed sampling protocol
	B	High	Habitat specific survival estimates for rearing juvenile salmon under the hydrologic conditions of interest	Additional mark-recapture and/or telemetry studies of relative survival of fish acclimated and released simultaneously in river and floodplain habitats.
	B	Medium	More detailed understanding and representation of connectivity and conveyance features, including managed field operations, and how they affect ingress, egress, movement, and survival within the floodplain and between the floodplain and main river channel	Acoustic tagging of fish captured on the floodplain. Tethering studies to estimate relative predation rate.

	B	High	Use and/or preferences for depth and cover type of juvenile rearing salmon	Appropriately designed fish sampling and micro habitat characterization throughout inundated floodplain habitats.
	B	High	Spatial distribution of natural-origin juvenile salmon on the floodplain, including field-based validation comparing observed juvenile fish use and predicted habitat	Appropriately designed fish sampling and micro habitat characterization throughout inundated floodplain habitats across a range of hydrologic conditions, with validation analysis.
	B	Low	Triggers for natural-origin salmon to move among habitat patches and from the floodplain back to the main channel	Serial sampling/monitoring of fish presence among representative habitats along length of bypass with simultaneous physical parameter monitoring (e.g., WQ, habitat suitability criteria, fish size and condition)
	C,D	Medium	Quantitative estimates of size effects on survival in the Delta and during early ocean residence for the size range of natural-origin salmon exiting the floodplain vs. migrating through the river channel	Coordinate/collaborate FR-focused monitoring and research with system wide monitoring programs to extract information on topic.
Broader Geographic Data Needs	NA	NA	Separation of floodplain rearing benefits from other wet-year benefits (e.g. flow-survival, turbidity)	Coordinate/collaborate FR-focused monitoring and research with system wide monitoring programs to extract information on topic.
	NA	NA	Predicting the proportion of fish that need to access floodplain to obtain a measurable population benefit	Simulation
	E	Medium	Experimental validation of isotopic techniques and better resolution of isotopic sources in all rearing locations. Particularly the tidal march	Characterize isotopic values in all potential rearing habitat during hydrologic conditions of interest. Validation studies with fish in matching habitats. Distinguish between rearing in

				floodplain habitat and using floodplain-derived resources.
	NA	NA	Identification of hydrology and habitat needs of other native fishes to reduce unintended impacts	Systematic fish community surveys and simultaneous habitat condition inventories at selected representative sites and under specific hydrologic conditions of interest in the floodplain and riverine habitats. This can be simultaneous with some of the focused salmon monitoring and sampling efforts.
	NA	NA	Assess if available habitat is a limiting factor for juvenile salmon growth and survival in the Central Valley	Coordinate/collaborate FR-focused monitoring and research with system wide monitoring programs to extract information on topic.
	NA	NA	Assess tradeoff between growth benefits and potential survival impacts (e.g. stranding, avian predation)	Coordinate/collaborate FR-focused monitoring and research with system wide monitoring programs to extract information on topic.
	NA	NA	Assess if habitat has negligible impact on other life stages (adults) or other native species.	Coordinate/collaborate FR-focused monitoring and research with system wide monitoring programs to extract information on topic.