JUNE 2025

Healthy Rivers and Landscapes Science Plan Independent Peer Review

Letters to the Delta Science Program

Delta Science Program

DELTA STEWARDSHIP COUNCIL

Disclaimer

As requested by the California Department of Water Resources, this report combines into one repository document three individually authored peer review letters for the Healthy Rivers and Landscapes Science Plan Peer Review one from each review member. Each letter reflects only the individual author's thoughts, opinions, and suggestions that address the Charge questions that the review member was given for the peer review based on their expertise.

Table of Contents

JUNE 2025

Healthy Rivers and Landscapes Science Plan Independent Peer Review-Mike Runge

A report to the Delta Science Program

Prepared by

Michael C. Runge

Delta Science Program

DELTA STEWARDSHIP COUNCIL

Table of Contents

Executive Summary

The “Healthy Rivers and Landscapes Science Plan” (Science Plan) provides an overarching framework for monitoring and assessment of the Flow and Non-Flow Measures proposed in the Healthy Rivers and Landscapes Program. The Science Plan is lucid, informative, and well-structured. The central strength of the Science Plan is that a carefully conceived and nested set of hypotheses are articulated prior to description of the desired monitoring network, that is, the questions precede the design. Overall, the Science Plan provides constructive guidance for development of step-down science plans at local scales.

In this review, consideration is given to the hypotheses and their construction, the proposed metrics and covariates, the proposed monitoring design, the priority information gaps, and the implementation of adaptive management. For the most part, the comments in the review are minor, as the Science Plan as a whole holds together quite well. But a few substantive suggestions are also included, focused particularly on how to prioritize uncertainties and prepare for adaptive management. The more substantive suggestions are briefly described below.

The hypotheses that form the basis of the Science Plan are stated as one-sided hypotheses with an implied null hypothesis and without specification of a desired effect size. As such, they are valuable hypotheses for scientific inference but may be less effective for management purposes. Specification of desired effect size allows consideration of cost-effectiveness by decision makers, and power analysis by statisticians designing the monitoring.

The metrics proposed for evaluation of the hypotheses are a mixture of natural and proxy scales. Where proxy metrics are proposed, it would be valuable to explain their rationale. As an example, one of the hypotheses associated with fish passage improvements seeks to measure whether entrainment of juvenile salmonids is reduced, but the metric proposed is the observed water velocity at the diversion point. This is clearly a proxy for the desired metric; what is the rationale, and is there evidence this is a reliable proxy?

The monitoring networks and modeling resources needed for evaluation of the hypotheses are generally well described and warranted. In some cases, modeling,

rather than direct monitoring, is suggested as the preferred method for evaluation of a hypotheses; it would be helpful to explain this rationale.

The Science Plan identifies a small number of high-priority uncertainties (“high-level gaps”). This is an important feature of the Science Plan and can provide insight about which monitoring and research activities are most important if resources are constrained. But the methods by which these priorities were identified are not described. There are value-of-information methods from the field of decision analysis that are specifically designed to evaluate the relevance, *to a decision maker*, of different sources of uncertainty. This Science Plan is not an ivory tower exercise in scientific curiosity; it is designed in service to decision makers interested in achieving specific management outcomes. Value-of-information methods could help ground the prioritization of research in the needs of the decision maker.

Finally, one of the stated purposes of the Science Plan is “to provide recommendations on adjusting management actions”, that is, to provide the basis for adaptive management. The underlying notion of adaptive management implied in the Science Plan, however, leaves some critical steps to the future. The hypotheses are designed to test whether the proposed Flow and Non-Flow Measures work as intended (at least in direction, if not in magnitude), and if they are not successful, to diagnose where in the causal chain failure has occurred. But the Science Plan is not designed to identify what alternative measures should be taken in the event of failure. A full-fledged adaptive management program can indicate in advance what alternative steps to take no matter which way the targeted uncertainty resolves. This is not a failure of the Science Plan, but a missed opportunity perhaps; it leaves identification of “recommendations on adjusting management actions” to a future, unspecified process.

The development of this Science Plan was clearly an extraordinary effort by a knowledgeable and astute panel of experts. It is clever, comprehensive, and workable. The suggestions in this review are offered as gentle suggestions to enhance the already excellent work, with particular attention on anticipating the challenges the Science Committee will face in the later years of the HRL Program.

Overview and Strengths

The "Healthy Rivers and Landscapes Science Plan" (Final Draft, dated September 6, 2024; hereinafter "Science Plan") provides an overarching framework for monitoring and assessment of the Flow and Non-Flow Measures proposed for implementation in the Healthy Rivers and Landscapes Program (HRL Program). The Science Plan is structured around a tiered set of hypotheses that describe the causal assumptions about how Flow and Non-Flow Measures are expected to ultimately achieve the objectives of the HRL Program; these hypotheses trace the causal steps from local effects to tributary and Delta effects to population-level effects. Each hypothesis is associated with one or more metrics, which provide measurable attributes that can be the focus of monitoring and research, as well as relevant covariates and baseline conditions. After articulating the underlying hypotheses of interest, the Science Plan then describes, in general terms, the monitoring activities required to assess these hypotheses, the status of suitable monitoring programs that are already in place, and what new monitoring programs would be needed. Finally, the Science Plan describes how the Science Committee would oversee assessment and reporting, data management, and evaluation for the purposes of adaptive management.

Notable Strengths of the Science Plan

The Science Plan is lucid, informative, and well-structured. There are several features that I found particularly strong:

- I greatly appreciated that the set of hypotheses preceded the monitoring design, providing the basis for the monitoring need and motivating the specific details of the monitoring plan. The articulation of *a priori* hypotheses is a foundational element of sound monitoring design.
- The hypotheses are carefully linked to investigate the underlying causal mechanisms that motivate the proposed Flow and Non-Flow Measures, and, as such, they are well designed to assess any breakdown in these causal assumptions. For example, the hypotheses associated with Non-Flow Measures designed to provide spawning habitat for Chinook salmon (*Oncorhynchus tshawytscha*) trace whether the spawning habitat was created (hypothesis H_{S1}), whether the habitat was suitable (H_{S2}), and whether salmon actually produced redds in the habitat (H_{S3}). While the ultimate test of the Non-Flow Measures is whether the number of redds increased,

inclusion of the intermediate hypotheses allows diagnosis in the event of failure.

- The tiered structure of the hypotheses (local, tributary or Delta, population) provides a higher level of causal nesting that both reveals the underlying assumptions of the Flow and Non-Flow Measures and provides the mechanisms of diagnosis and assessment in the event that the HRL Program does not achieve its objectives.
- The Science Plan describes four high-level functions for the Science Program (Section 1.1). One of these functions, "To track and report progress relative to the metrics described in Section 2 of this document", is particularly well served by the Science Plan. The others are discussed later in this report.

Response to Charge

In the following sections, I address the questions contained in the charge for the peer review. I've chosen to address these in a different order than presented in the charge, both to emphasize what I think are the more important issues that need to be addressed and to align with the areas about which I have more expertise.

At the outset, I have some questions about the initial framing. The Science Plan (Section 1.1) describes four high-level functions of the Science Program:

1. "To inform decision-making by the Systemwide Governance Committee, Tributary and Delta Governance Entities, and parties"
2. "To track and report progress relative to the metrics described in Section 2 of this document"
3. "To reduce management-related uncertainty"
4. "To provide recommendations on adjusting management actions to the Systemwide Governance Committee, Tributary/Delta Governances Entities and Parties"

These are described as functions of the Science Program and responsibilities of the Science Committee, but it is not clear if these are all meant to be specifically addressed in the Science Plan. If they are, it is not entirely clear where some of these functions are addressed. Function 2 ("track and report progress") is clearly associated with Sections 2 and 3 of the Science Plan, and in general, is addressed clearly. Function 3 ("reduce management-related uncertainty") appears to be related to information gaps, so I think it is associated with Section 3.4; I'll evaluate this in the section below on "Information Gaps". Function 4 ("to provide recommendations") addresses adaptation that arises out of monitoring and research, so I think it is associated with Section 4.4 of the Science Plan; I'll address it under the "Adaptive Management" topic below. Finally, I struggled with how to understand Function 1 ("to inform decision-making") in the context of this Science Plan. One purpose of monitoring is "state-dependent decision making" (Lyons et al. 2008), that is, monitoring of key variables that are used to inform which actions to implement. Is this what is intended by Function 1? If so, the monitoring variables that are required for state-dependent decisions are not described in the Science Plan. If, instead, Function 1 is meant to describe an overarching advisory function of the Science Program, and not a specific monitoring need, then that should be clarified.

Informing Adaptive Management

There are many different understandings of the concept of "adaptive management". McFadden et al. (2011) provided the beginnings of a classification of the types of adaptive management, by distinguishing the "Decision-Theoretic" and "Resilience-Experimentalist" schools; I think there are many other informal understandings of the concept. The "Decision-Theoretic" school arises out of the seminal work of Walters (1986), with an emphasis on *a priori* articulation of uncertainty, and monitoring designed to reduce that uncertainty. The Science Plan references Walters (1986) and seems to be embracing a related version of adaptive management, but what is described does not fully align with Walters' vision.

The hypotheses and monitoring guidance in the Science Plan are designed to test whether a Non-Flow Measure (and to a lesser extent, a Flow Measure) worked as intended, and if it did not, to diagnose at what stage of the causal chain it failed. As noted above, the articulation of the hypotheses and monitoring designed to test them are a real strength of the Science Plan. But the Science Plan does not provide any guidance for the *adaptation step*, because alternative measures are not articulated. If a proposed Measure fails, what course of action is then recommended? Presumably, the Science Committee, working with others, would evaluate the data, understand at what stage the Measure failed, then invent some proposal about what modifications could be made, or what alternative actions could be taken, to better achieve the objectives. In a stronger form of adaptive management (the form that Walters originally envisioned), those alternatives would be articulated up front, and the resolution of uncertainty would point toward which alternative would be better to pursue. That is, the Science Plan is well designed to evaluate whether a Measure worked as intended, and if it did not, to suggest why it failed, but it is not designed to say what action should be taken instead. This focus applies to the measures in aggregate, as well as individually. In Section 4.4.1 of the Science Plan, one of the purposes of the Year 7 Synthesis Report is to examine "whether continuation of the Healthy Rivers and Landscapes Program beyond Year 8 would help improve species abundance, ecosystem conditions, and contribute to meeting the Narrative Objectives." If the evaluation shows that continuation of the HRL Program would not improve outcomes, then what happens? This focus on assessment, but not adaptation, is not necessarily a fault of the Science Plan, but I would view it as a missed opportunity.

There does appear to be a recognition that full adaptive management arises out of decision-making processes where the effect of uncertainty on alternative actions is considered. In Section 4.4.2, the Science Plan notes that "Recommendations from the Science Committee will be the outcome of structured decision-making processes, as appropriate." As described, the role of the research and monitoring in the Science Plan seems to be to provide information to subsequent structured decision-making (SDM) processes. But the hypotheses have been generated and the monitoring designed prior to the initiation of these SDM processes, so it's possible that the information generated will not be as relevant to the processes as it could be. The full-fledged version of adaptive management proposed by Walters (1986) places the SDM process *prior to* the design of the research and monitoring, so that the uncertainties addressed are specifically the ones that impeded the choice of alternative in the decision analysis.

The Science Plan (Section 4.4.3) describes a number of decision-support models (DSMs) that could be used by the Science Committee at later stages to inform recommendations for adaptive management. In general, I find this an important recognition that such tools, which can be used to predict the degree to which management actions will achieve a decision-maker's objectives, are a critical part of both SDM and adaptive management processes. I think it would be helpful to be quite clear that the selection and design of DSMs is most fruitful when it emerges from an SDM process, that is, when the decision framework is used to specify the inputs (alternative actions) and outputs (fundamental objectives) of the DSM. It would also be helpful to note more clearly that DSMs can be used to evaluate the relevance of uncertainty, and indeed, could be used *prior to* monitoring design.

What could strengthen this Science Plan, with regard to its ability to contribute to adaptive management, in a concept from decision analysis called "value of information" (VOI; Bolam et al. 2019, Runge et al. 2011). A value-of-information analysis is a particular kind of decision analysis that looks at the effect of uncertainty on the choice of alternative actions, and measures how much the expected outcome could be improved if the uncertainty were reduced prior to commitment to action. This concept is the foundation of the Decision-Theoretic school of adaptive management: the uncertainty that should be reduced is the uncertainty that has the highest value of information, and the monitoring should be designed to reduce that uncertainty with high power. A special form of VOI known as the "expected value of partial information" can be particularly powerful in prioritizing sources of uncertainty (Canessa et al. 2015, Runge et al. 2011). A full VOI analysis may not be possible for the Science Plan at this point, given where it is in its development—VOI analyses require specification of the full decision context, articulation of objectives, and development of alternative measures under consideration, along with specification of sources of uncertainty. But the concept of VOI could be integrated into the Science Plan, and it's possible that a recently developed short-cut method (constructed value of information, Runge et al. 2023) could be used to provide an initial prioritization of sources of uncertainty.

Information Gaps and the Value of Information

In Section 3.4, the Science Plan identifies a set of information gaps that it describes as "high-level gaps" that have "implications for the ability of the Science Program to draw broad inferences." I think this is an important exercise at this stage—to identify particularly important uncertainties whose resolution will improve understanding and management—especially when the comprehensive monitoring design (Section 3) is so vast that it is hard to know what pieces are most important. I do not have the region- or subject-matter-specific expertise to comment on whether these particular gaps are the most important; I will leave that to other reviewers.

The concept of value-of-information, however, is highly relevant here. To claim that a source of uncertainty is an important information gap in a management setting is to say that it has a high value of information, that resolution of the uncertainty will lead to better choice of management action, and hence better achievement of the fundamental objectives. The narrative in Section 3.4 describes well why these sources of uncertainty are impediments to inference but does not describe why (or indeed whether) they have a high value of information to the decision maker. Several additional considerations would be helpful: (1) what is the current level of knowledge about the information gap, and (2) how would resolution of the information gap lead to a different choice of action?

As an example, consider the first identified information gap, the ability to differentiate natural- and hatchery-origin adults for each tributary. First, what are current estimates for the fraction of natural-origin adults (in any given tributary), and how precise is this estimate? I assume there is some existing knowledge on this fraction, and that the uncertainty interval is considerably narrower than 0.0 to 1.0. What are those estimates currently, and what are they expected to be under the proposed Measures? Second, how does this estimate affect the evaluation of the Measures and the choice of alternative action? Suppose, for sake of argument (and forgive me if the specific numbers don't make sense in context), that a decision analysis reveals that if the fraction of adults of natural-origin is greater than 0.55, then the population is being sustained and the implemented Measure is successful. Suppose further that there is considerable uncertainty about what the fraction will be when the Measure is implemented, and the confidence interval is 0.62-0.91. In this example, while there is considerable scientific uncertainty, there is not any management uncertainty (the Measure is successful and can continue). That is, there is a low value-of-information for reducing the uncertainty about the fraction of adults of natural origin. How do we know that the information gaps described are not just of scientific interest, but are also of management relevance, considering the current state of knowledge, and the options available to the decision maker?

Hypotheses

As noted above, there are three notable strengths of the Science Plan regarding the set of hypotheses articulated in Section 2: first, the hypotheses that drive monitoring design are stated; second, the hypotheses address sequential steps in the putative causal chain linking Measures to desired outcomes; and third, the tiered structure of the hypotheses addresses the complexity of how the Measures are meant to produce effects that emerge from the local scale to the population scale.

My expertise is not in the species, habitats, and processes of this system, so I do not feel equipped to comment on the specific hypotheses and whether they are comprehensive or redundant. I trust that the other peer reviewers have this expertise. I do, however, have some comments from the perspective of an outsider, with expertise in quantitative ecology.

The hypotheses are all stated as one-sided hypotheses, with an implied null hypothesis, and without specification of a desired effect size. This is a typical way that hypotheses are stated in scientific contexts, particularly when a frequentist statistical approach is being used. But in a management setting (as opposed to a purely scientific setting), it isn't just the detection of a significant directional effect that is important, but the size of that effect. A couple of concepts are relevant here: cost-effectiveness and statistical power. Regarding cost-effectiveness, it is possible that the results of the Non-Flow Measures associated with salmon spawning produce confirming results for hypotheses H_{S1}, H_{S2}, and H_{S3}, that is, the measures may increase the habitat acreage, produce suitable habitat, and increase the density of reeds, but what if the magnitude of those effects (especially the final one) are quite small relative to the cost of the Measures? The decision makers are going to want to know not only whether the Measures worked as intended, but whether they produced a strong enough effect to warrant continued implementation (compared to other options). Second, the design of monitoring should be preceded by a power analysis, to determine the sample size and other aspects of the design that are required to detect a desired effect size. Otherwise, there could be an over- or under-investment in monitoring effort. I would make two recommendations based on these considerations:

- It would be valuable for the Science Plan to state desired effect sizes for each of the hypotheses, or if that is too difficult because of the specifics of each tributary, etc., then the Science Plan should provide guidance to the developers of the step-down Science Plans about how to specify desired effects sizes at the tributary or Delta level.
- The step-down Science Plans should conduct power analyses in the process of designing their specific monitoring plans, and this Science Plan should state that this is an expectation, and should provide guidance about how to go about that process.

The hypotheses are also stated without reference to the current state of knowledge, with the implication that they are all equally uncertain. The Scientific Basis Report that underpins the HRL Program (SWRCB 2023) summarizes the current state of knowledge and, indeed, makes predictions about the anticipated effects of the Measures (Chapter 6). The scientific basis for the hypotheses does not need to be fully recapitulated in the Science Plan, but could a brief summary of the current state of knowledge for each hypothesis be included, and would that help convey which hypotheses are least certain?

The following is a series of smaller questions about some of the individual hypotheses:

- H_{R1}: does the description of this habitat also include whether it is accessible? If some side-channel habitat meets the depth, velocity, and cover criteria, but there is an impediment to the fish reaching this habitat, then does it still count has having been increased?
- $H_{TribFP4}$: it is conceivable that juvenile salmonid presence or density could be higher in floodplain habitats because they are attracted to it, but that does not necessarily mean it is providing benefit. Is the intent of this hypothesis just to document utilization, not benefit, with the following hypothesis documenting the benefit?
- $H_{TribFP6}$: the suggested methods for measuring this hypothesis seem under-developed to me. If the metric is the number of fish sampled in isolated pools, how do you correct for effort, detection probability, predation, and other sources of bias?
- $H_{TribFP7}$: similarly, while the desired inference is to the prevalence of juvenile native fishes, the metric is catch frequency. How will effort, gear, environmental conditions, field crew skill, and other factors be accounted for in this estimate? Is catch frequency a reliable proxy for prevalence or density?
- H_{Pass1}: the desired inference is the rate of entrainment, but the metric is observed water velocity (clearly, a proxy metric). How reliable is this proxy?
- $H_{BypassFP1}$ through $H_{BypassFP3}$: in Section 2.2.3, it is stated that the goal of the flooded agricultural fields is “to provide a growth benefit to juvenile salmon rearing in the mainstem.” If I understand correctly, this outcome is not assessed, rather, only components of it are. The three hypotheses, if all positive, would show that the agricultural fields produce food for salmon and the juvenile salmon eat it (showing an isotopic signal), but not that it produced a significant increase in growth. How would this question be addressed?
- $H_{BypassFP1}$: it isn’t just the area that is inundated that matters, but also the length of time it is inundated. I assume that the Corline et al. (2017) reference describes specifically how to handle duration, but it might be useful to at least briefly describe it here.
- $H_{BypassFP4}$: how is the duration of inundation handled in this metric?

- $H_{BypassFP6}$: the metric for this hypothesis is somewhat confusing, because three separate metrics are proposed—duration of hydrologic connectivity, presence of juvenile salmon, and fish density. It seems to me that juvenile density is the desired metric, and the other two are proxies that might need to be used. If that's the case, it should be clarified.
- H_{TW1}: does this metric only consider water depth?
- H_{TW2}: is habitat suitability only measured by water quality metrics (which ones?) or does it also include the presence of suitable vegetation?
- H_{TW4}: this hypothesis and the metric do not seem well connected to me. The stated metric is the community composition of the diets of native fishes, but the hypothesis is about beneficial taxa in the diet, not the full community composition. There is a suggestion to compare the diet to the zooplankton and invertebrate communities in the environment, but a difference would only suggest that native fish are selective in what they eat. So, it's not clear to me that the proposed metric and basis of comparison can provide any inference that's relevant to the hypothesis. I may be missing something; if so, a clearer explanation would be warranted.
- H_{TW6}: I think the hypothesis and metric should be stated as fish density, not presence. Presence is binary, relatively uninformative, and sensitive to sampling methods. Density is a more direct measure of the objective. Note that the baseline is stated in terms of density, which I think reveals the intent for the hypothesis.
- $H_{TribWide4}$: are timing and body size a direct measure of the life-history diversity of interest, or merely proxies? It isn't clear to me how the metric is connected to the goal of the hypothesis.

Metrics and Covariates

I found it easier to address the hypotheses, metrics, and covariates all at once; please see the bulleted list in the previous section for comments on some specific metrics and covariates.

As an overarching consideration, it might be useful to identify when the proposed metric is a natural metric for the outcome of interest, and when it is a proxy metric. When it is a proxy metric, the rationale for the proxy might be clearly explained.

The lists of covariates come across in the Science Plan as a very large wish list, without guidance on how to prioritize them. The step-down monitoring plans will need to be a lot more specific about which covariates are important and how they will be used. The Science Plan should provide guidance for the step-down plans about how to choose covariates, given that there are likely to be resource limitations.

Monitoring Networks and Modeling Resources

The Science Plan (Section 3) does an excellent job of reviewing the existing monitoring methods and networks and identifying additional monitoring that would be needed to evaluate the hypotheses described in Section 2. From an outside perspective, the existing monitoring networks appear to be extensive and detailed, with the potential to be integrated to address the questions in the Science Plan.

In a couple of places, a modeling approach, rather than a monitoring approach, is suggested for evaluation of a hypothesis. In these cases, it would be helpful to explain why direct monitoring is not possible, practical, or cost-effective, and therefore why a modeling approach is recommended instead.

The following is a small set of questions about specific aspects of Section 3:

- Section 3.1.1.3: in describing monitoring for juvenile salmonid habitat use, several methods (e.g., snorkeling, seining) are mentioned, but without much detail (about, for instance, how to control for effort, detectability, etc.). Are these methods well known and commonly used, or should published methods be cited here to point the reader to the necessary details?
- Section 3.1.2.1: why does evaluating changes in the acreage of floodplain habitat provided by bypasses require hydrologic and hydraulic modeling? Are there not sampling or remote sensing methods that can be used to directly monitor these changes?
- Section 3.1.3.1: why does estimation of the total area of tidal wetland habitat require multi-dimensional modeling? Are there not sampling or remote sensing methods that can be used for direct monitoring?
- Section 3.2.2.4: regarding the monitoring of cyanoHABs, "visual assessments" carried out as part of other surveys are suggested. Are these "semi-

quantitative" methods robust? Will these suffice for the purposes of evaluated the hypothesis in the Science Plan, or will the emerging methods discussed in the fourth paragraph of this section be needed to evaluate these hypotheses?

References

Bolam FC, Grainger MJ, Mengersen KL, Stewart GB, Sutherland WJ, Runge MC, McGowan PJ. 2019. Using the Value of Information to improve conservation decision making. Biological Reviews 94:629-647.

Canessa S, Guillera-Arroita G, Lahoz-Monfort JJ, Southwell DM, Armstrong DP, Chadès I, Lacy RC, Converse SJ. 2015. When do we need more data? A primer on calculating the value of information for applied ecologists. Methods in Ecology and Evolution 6:1219-1228.

Lyons JE, Runge MC, Laskowski HP, Kendall WL. 2008. Monitoring in the context of structured decision-making and adaptive management. Journal of Wildlife Management 72:1683-1692.

McFadden JE, Hiller TL, Tyre AJ. 2011. Evaluating the efficacy of adaptive management approaches: Is there a formula for success? Journal of Environmental Management 92:1354-1359.

Runge MC, Converse SJ, Lyons JE. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biological Conservation 144:1214-1223.

Runge MC, Rushing CS, Lyons JE, Rubenstein MA. 2023. A simplified method for value of information using constructed scales. Decision Analysis 20:220-230.

[SWRCB] State Water Resources Control Board, California Department of Water Resources, and California Department of Fish and Wildlife. 2023. Final Draft Scientific Basis Report Supplement in Support of Proposed Voluntary Agreements for the Sacramento River, Delta, and Tributaries Update to the San Francisco Bay/Sacramento-San Joaquin Delta Water Quality Control Plan. September. (ICF 103625.0.002.01.004.01.) Sacramento, CA.

Walters CJ. 1986. Adaptive management of renewable resources. New York, New York, USA: Macmillan.

JUNE 2025

Healthy Rivers and Landscapes Science Plan Independent Peer Review-Josh Korman

A report to the Delta Science Program

Prepared by

Josh Korman, Ecometric Research

June 29, 2025

Delta Science Program

DELTA STEWARDSHIP COUNCIL

Executive Summary

I was engaged by the Delta Stewardship Council to provide a review of the Healthy Rivers and Landscapes Science Plan (HRLSP). The plan is designed to evaluate hypotheses for a wide range of flow and non-flow Healthy Rivers and Landscapes (HRL) actions for multiple trophic levels and fish species across a range of habitat types distributed over a large geographic area. Given its wide scope, the authors of the HRLSP have done a great job of condensing critical aspects of hypotheses and evaluation methods to provide a broad understanding of the program. The drawback of the condensed presentation is that supporting evidence for the hypotheses is sometimes limited, as are the discussions about challenges in evaluating them.

My review focuses on HRLSP hypotheses related to Chinook Salmon, *Oncorhynchus tshawytscha,* because it aligns with my area of expertise. I first comment on the HRLSP at a broad level, and then review the substantive challenges for reducing uncertainties about effects of HRL actions. I focus on issues related to experimental design (magnitude, duration, and timing of treatments, confounding factors), the need to evaluate variation in both freshwater and marine survival rates (full life cycle) to interpret HRL effects on the narrative objective (doubling salmon production), and confounding effects of changing hatchery practices on evaluating HRL actions. I discuss challenges for evaluating hypotheses related to flood plains and tidal wetland restoration efforts. I briefly review a multiagency program designed to resolve uncertainties about hypotheses related to the recovery of Chinook Salmon and Steelhead, *Oncorhynchus mykiss,* populations in the Snake River sub-basin of the Columbia River (Plan for Analyzing and Testing Hypotheses (PATH)). A similar retrospective effort could be used to synthesize evidence for population-level hypotheses in the HRLSP.

Making reliable inferences about the effect of various HRL flow and non-flow actions depend on basic elements of experimental design which include: the magnitude of actions and their biological effects; the duration of the assessment period and the frequency of actions within it; the magnitude of confounding factors; and the temporal overlap between actions and confounding factors. The 8-year time frame of the HRLSP is insufficient to provide even a moderate level of inference about hypotheses evaluated based on annual data/estimates. The extent

of contrast provided by flow actions, and potential for replication of actions over time, is highly uncertain but likely limited, owing to the complexity of voluntary flow agreements (offramps, hydrologic conditions, multiple decision-makers). I expect that the magnitude of effects of flow and habitat changes will most often result in a low signal-to-noise ratio, making it difficult to discern their effects, especially when replication of actions is limited. There is also considerable potential for confounding factors, such as changing hatchery practices, to substantively complicate the assessment of the effectiveness of HRL actions.

Quantifying variation in marine survival rates of Chinook Salmon as part of the HRLSP is needed to place effects resulting from HRL actions within the context of all factors determining natural-origin adult returns, a key metric of the program. Trends for many Salmon and Steelhead populations on the West Coast of North Ameria have been dominated by variation in marine conditions impacting prey supply and predators, and this dynamic may apply to California Central Valley (CCV) Chinook Salmon populations. The relative importance of freshwater and marine effects on the number of adult Chinook Salmon returning has been a subject of debate in the Columbia River restoration initiative, and some have argued that costly habitat and flow restoration efforts will not meet adult return objectives owing to poor marine survival. Thus, it would be beneficial for the HRLSP to compare estimates of variation in freshwater survival rates resulting from HRL actions and other factors, with variation in smolt-adult survival rates (SAR), as determined by analysis of data from hatchery juveniles with Coded Wire Tags (CWTs), for CCV populations.

Hatcheries producing fall-run Chinook Salmon in the CCV support commercial and recreational fishing. Negative effects of production hatcheries on natural-origin populations resulting from genetic introgression, increased competition, and predator attraction are well documented. I focused on three questions related to hatchery effects in my review that were not adequately addressed in the HRLSP:

1) How will the effects of hatchery-origin juveniles and spawners on natural production of juveniles be separated from effects of HRL actions?
2) How will the abundance of hatchery-origin returning adults and escapement be estimated to calculate metrics of natural-origin returns and escapement?

3) Why are the effects of HRL actions on hatchery-origin fish not included in the science plan?

The number and nature of hatchery releases in the CCV has changed substantially in recent years in response to low adult returns and fisheries closures, and will likely continue to evolve. The HRLSP is deficient in specifying how the program will dis-entangle effects of changing hatchery practices from the effects of HRL flow and non-flow actions.

The number of natural-origin spawners is a metric that will be used to assess many hypotheses in the HRLSP. As most tributaries have substantial numbers of returning fall-run hatchery-origin fish, their abundance must be quantified to calculate natural-origin escapement. However, there are a number of challenges of reliably doing this, some of which were reviewed in the HRLSP. The ability to estimate natural-origin escapement for fall-run Chinook Salmon is poorly defined in the HRLSP. This is a significant limitation given how prominent natural-origin return and escapement metrics are in the plan.

There was no mention in the HRLSP of assessing the effects of flow and non-flow actions on return rates of hatchery-origin fish. Hatchery fish released in tributaries, the mainstem Sacramento River, and perhaps even in the Delta, could have higher growth and survival rates due to HRL actions. This would in turn create benefits for the fishery and result in higher total escapements. Thus, assessing HRL effects on survival rates of hatchery-origin juveniles, and on upstream passage rates of returning adults, seems warranted. Comparison of CWT return rates for hatchery fish released in locations where effects of HRL actions are likely greater (e.g., tributaries and mainstem Sacramento River), with return rates for groups where HRL effects are likely weaker (lower estuary and ocean), could also help evaluate some HRL actions.

A number of hypotheses in the HRLSP focus on evaluating benefits of tributary and Delta/Bypass floodplain restoration efforts. There was only limited discussion of whether such habitats are a net “source” or “sink” for salmonid production due to losses from predation and stranding, even though past studies demonstrate that flooded agricultural areas, and floodplains in dry years, may act as population sinks. The approach to evaluating the “source-sink” hypothesis in the

HRLSP was vague and insufficient given the potential for floodplain restoration efforts to do more harm than good. Studies based on releases of hatchery-origin fish with CWTs in floodplain habitats and adjacent mainstem locations could be included the HRLSP to evaluate this hypothesis.

The Plan for Analyzing and Testing Hypotheses (PATH) was a five-year multiagency program designed to resolve uncertainties about hypotheses related to the recovery of Chinook Salmon and Steelhead populations in the Snake River sub-basin of the Columbia River. Retrospective analyses within PATH were used to evaluate hypotheses based on historical datasets, and prospective analyses incorporated those results into forward simulation models to evaluate consequences of different restoration strategies. I recommend that the HRLSP include a similar retrospective effort for evaluating population-level hypotheses for CCV Chinook Salmon populations.

The most significant limitation of the HRLSP is that it provides an overly optimistic view of how well actions will be evaluated. The plan identifies metrics used for evaluation, and in some cases limitations of the metrics. But the plan falls short with respect to making conclusions about the effects of these limitations on the evaluation of hypotheses. For example, the plan identifies the need to estimate natural-origin escapement for many hypotheses, and the substantial challenges of obtaining reliable estimates. What should the reader conclude? Does the inability to reliably estimate natural-origin escapement mean hypotheses that depend on this metric cannot be evaluated?

The optimistic tone of the HRLSP occurs in other instances. For example, the plan mentions that the 8-year assessment period is too short to evaluate metrics at the life cycle scale of Chinook Salmon. But this period is also too short for assessing hypotheses that depend on annual metrics (e.g., juvenile outmigration abundance) because sufficient replication and contrast across years is still required. The reader is not adequately informed about the challenges of the short period of assessment, and the draft strategic plan makes no mention of extending the 8-year assessment period. Thus, additional commentary on effects of the short duration of the HRLSP is warranted. Is there an unstated assumption in the plan that the assessment period for HRL actions will extend well beyond the stated 8-year period?

Outlining the range of inference strength across hypotheses is fundamental information for making future decisions on investments in HRL actions and assessment programs. The plan does not articulate the magnitude and frequency of HRL flow changes. This is understandable given the nature of the flow agreements. The magnitude of flow increases change with water year type, there are multiple flow increase offramps, and approaches for making decisions on flow increases vary across tributaries. With all this complexity, it is very difficult to determine the magnitude and degree of replication of flow actions over the 8-year assessment period. The HRLSP, or an addendum to it, could use hydrologic modeling to simulate how flow increases from voluntary agreements would alter the hydrograph. In conjunction with existing fish-flow relationships for CCV populations (perhaps developed as part of a PATH-like process), or from other systems, modeling results could be used to predict the range of expected potential biological responses. This could in turn be used to drive statistical power analyses to determine the number of replicated treatments and years to achieve moderate levels of inference about flow change effects.

Table of Contents

1.0 Introduction

I was engaged by the Delta Science Panel to provide a review of the Healthy Rivers and Landscapes Science Plan (HRLSP 2024). As stated in the charge to the peer review team:

"The purpose of the Healthy Rivers and Landscapes Science Plan ("Science Plan") is to provide the framework and specific approach for assessment of the Flow and Non-Flow Measures included in the Program. In the Science Plan, the hypotheses and associated monitoring and analyses are intended to describe a full range of potential approaches for assessing the biological and ecological outcomes of the Healthy Rivers and Landscapes Program."

Three peer reviewers were instructed to provide independent reviews and to focus on hypotheses related to responses to flow and non-flow measures in the HRL program, metrics and covariates to evaluate the hypotheses, monitoring networks and modeling resources, information gaps, and adaptive management.

My review focuses on HRLSP hypotheses related to Chinook Salmon because it aligns with my area of expertise and the majority of Central Valley science projects I have worked on. I first comment on the HRLSP at a broad level, and then review the substantive challenges for reducing uncertainties about effects of flow and non-flow actions. I focus on issues related to experimental design (magnitude, duration, and timing of treatments, confounding factors), the need to evaluate variation in both freshwater and marine survival rates (full life cycle) to interpret HRL effects on the narrative objective (doubling salmon production), and confounding effects of changing hatchery practices on evaluation of HRL actions. I discuss challenges for evaluating the source-sink hypothesis for floodplains and tidal wetland restoration efforts, where there is potential to do more harm than good. I recommend a retrospective analysis of Chinook Salmon data within a multi-agency workshop process to evaluate evidence for population-level hypotheses in the HRLSP. Appendix A provides brief answers to the specific questions posed to the review team, and clarifies the linkage between these questions and content in the main body of this report.

2.0 Overview of the HRLSP

The HRLSP provides a very clear and organized description of hypotheses related to effects of flow and non-flow actions implemented as part of the HRL program. One of the strongest aspects of the science plan is the organization of hypotheses within spatial and temporal hierarchies. Spatially, the plan evaluates actions at site, tributary/Delta, and population-level scales. Temporally, the plan evaluates actions measured over short time scales like days to weeks (e.g., downstream survival rates of chinook in spring under flow pulses), moderate timescales like years (e.g., changes in juvenile outmigration abundance from tributaries), and longer generational timescales (e.g., changes in the cohort replacement rate).

The hierarchical organization of hypotheses in the HRLSP will be helpful to establish cause-effect relationships between actions and response variables. At the lowest level, hypotheses focus on quantities like the amount of new habitat created, or the degree to which physical habitat and water quality are improved due to higher flows. The next level evaluates the effects of actions on vital rates like juvenile growth and survival (i.e., is growth in enhanced in restored habitats, are survival rates during downstream migration higher?). The top of the hierarchy evaluates these effects on the population based on metrics such as natural-origin juvenile abundance and adult returns. This multiple line-of-evidence approach will provide stronger inference about effects of flow or non-flow action on population responses compared to evaluating a single component because it strengthens support for cause-effect relationships.

The strength of inferences about effects of HRL actions will likely decrease in a downstream direction. Effects of flow and non-flow actions on survival rates of Chinook Salmon from spawning through outmigration from tributaries (as quantified by Rotary Screw Trap (RST) data) will be the most reliable because of the availability of relatively long time series of inputs (spawner abundance) and outputs (juvenile outmigrants). Although tributaries can be large, outmigrant abundance estimates from RSTs integrate production from all habitats upstream of the trapping sites. Inferences about flow effects on survival rates of out-migrating juveniles from tributaries to the Delta will also likely be relatively strong given the extensive acoustic tag detection network, high detection probabilities, and numerous studies which have demonstrated that these data can be used to quantify effects of flow on routing and survival rates. Inferences about salmon survival rates will decline between Sacramento and the Golden Gate Bridge due to lower detection probabilities. Quantifying effects of improvements in access to flood plains and their habitat conditions in lower portions of tributaries and the Sacramento River mainstem will be difficult because estimating juvenile mortality due to stranding is very challenging over the large spatial scales of these habitats. Further, the benefits of higher growth rates in floodplains on later survival rates as they migrate through the Delta and nearshore ocean habitat are difficult to quantify. Quantifying the trade-off between growth benefits and survival rates associated with use of restored tidal wetlands will be even more challenging owing to challenges in estimating habitat use and predation losses.

The HRLSP evaluates hypotheses for a wide range of actions for multiple trophic levels and fish species in many different habitat types distributed over a large geographic area. Given this vast scope, the authors of the HRLSP have done a great job of condensing critical aspects of hypotheses and evaluation methods into a reasonably-sized document, facilitating a broad understanding of the program. Many hypotheses and evaluation methods are described in the HRLSP, and long descriptions for all of them would make the science plan unwieldly. The drawback of the condensed presentation is that supporting evidence for the hypotheses is sometimes limited, as are the discussions about challenges in evaluating them. The majority of the comments in my review relate to issues that were only briefly mentioned in the plan or were not considered. They include:

- Significant limitations on inferences about actions due to the 8-year time frame of the HRLSP. This duration is too short for hypotheses evaluated based on data collected at annual (e.g., juvenile outmigrant abundance) and life cycle (adult return) temporal scales. Even processes measured over the course of days or weeks, such as survival rate of out-migrating juveniles, require multiple years of data collection under different conditions to evaluate benefits of higher flows in spring (Section 3.0).

- Failure to consider variation in survival rates over the entire life cycle of Chinook Salmon to provide context for effects of HRL actions and determine the extent to which they contribute to the narrative objective of doubling salmon abundance (Section 4.0).

- Significant challenges related to changes in a variety of Chinook Salmon hatchery practices (stocking rates and locations, clip rates) over time, which potentially confounds interpretation of changes in natural-origin juvenile survival and abundance due to HRL actions, and increases uncertainty in estimates of natural-origin returns and escapement (section 5.0).

- Significant challenges for quantifying stranding and predation losses in floodplains, and habitat use and predation losses in restored tidal wetlands (Section 6.0).

- The need to use a multi-agency workshop process over the 8-year HRLSP assessment period to evaluate population-level hypotheses for Chinook Salmon, following the approach used for the Plan for Analyzing and Testing Hypotheses (PATH) in the Columbia River system (Marmorek and Peters 2001).

3.0 Experimental Design to Evaluate HRL Actions

Reliability of inferences about the effect of various flow and non-flow actions of the HRL program depends on basic elements of experimental design which include:

- The magnitude of the action (e.g., the extent and duration of the flow increase) which in turn may determine the magnitude of the biological response (e.g., extent of survival increase under a spring pulse flow).
- The duration of the assessment period and the frequency of actions within it (e.g., how many spring pulse flows will be implemented between Years 1 and 7?).
- The magnitude of biological effects caused by confounding factors such as changes in flows outside of spring window, and changes in hatchery production and release strategies, that are not formally accounted for in the assessment.
- The temporal overlap between treatments and confounding factors.

To better describe these issues, consider the example of the evaluation of increases in spring flows on survival rates of Chinook Salmon from egg deposition to juvenile outmigration, with the latter quantified using data from a rotary screw trap (RST) trapping site (e.g., $\mathbf{H_{TribWide2}}$). The effect of the flow action could be estimated using the Ricker model,

1) $$\log\left(\frac{R_t}{S_t}\right) = \alpha + \beta \cdot S_t + \gamma \cdot X_t + \varepsilon_t, \quad \varepsilon_t \sim \text{normal}(0,\sigma)$$

where *R* is the estimate of the annual juvenile outmigrant abundance produced from spawners (S) in brood year *t*, α is the maximum productivity (outmigrants/spawner in log space) which occurs when spawning abundance is near zero, β is the density-dependent effect of spawner abundance on outmigrants/spawner, γ is an additive effect (on α) of an environmental covariate X_t (e.g., average flow in March), and ε represents the unexplained error in each year, which is assumed to be a randomly distributed variable from a zero-centered normal distribution with standard deviation σ. With respect to assessing HRL flow actions, X could be an indicator variable taking on values of 1 and 0 in years with and without an enhanced spring flow action. Alternatively, X could be a continuous variable, say the average flows in spring. In this case the effects of the flow action could be backed-out from equation 1 based on the extent of the increase in X from the baseline due to the action. For HRL non-flow actions such as habitat enhancement, X could represent a discrete (before and after restoration) or continuous habitat variable (e.g., area of useable fry habitat).

Equation 1 can be used to highlight a number of experimental design challenges for obtaining strong inferences about effects of HRL actions, as determined by the reliability of the estimate of γ:

Insufficient replication

Optimistically, a minimum of about 10 years of data are required to reliably estimate α and β terms of stock-recruit models in the absence of a covariate effect, with more years needed if covariate effects (e.g., γ) are included (Hilborn and Walters 1992). This period of assessment is considerably longer than the 8-year term identified in the HRLSP. Bradford et al. (2005) concluded that experiment durations of 12 to18 years were needed to provide informative inferences about effects of flow or habitat restoration on freshwater productivity and carrying capacity for salmon populations based on spawner-smolt stock-recruitment relationships.

Insufficient contrast

Reliable estimation of γ, the parameter of interest for assessing HRL actions, depends in part on the extent of contrast in X. Ideally, a wide range of observations of X are available, with some replication at low and high levels. The reliability of γ will be poor if there are few observations at say the high range of X (spurious correlation more likely). It seems unlikely that strong contrasts will occur over the 8-year assessment period given that flow changes under the HRL vary with water year type and are constrained by a number of factors (e.g., meeting water temperature targets at other times of year, HRL 2024).

Low signal to noise ratio

ε_t represents the extent of unexplained variation in in the log of outmigrants per spawner after accounting for spawner abundance effects and a single covariate effect. In order for the flow action to exert a substantive influence on outmigrants/spawner, its additive effect ($\gamma \cdot X_t$) has to be considerably greater than ε_t in some years. In other words, the signal ($\gamma \cdot X_t$) to noise (ε_t) ratio will have to be high for the action to exert a substantive effect on the metric of interest (outmigrants/spawner) and thus allow reliable estimation of the effect size. Given the many factors influencing survival from spawning to outmigration, and limitations on the magnitude and frequency of flow (or habitat) changes under the HRL program, the signal to noise ratio could be low in many cases.

Confounding

Annual unexplained errors are assumed to be randomly distributed through time and with respect to covariate values (X), which may not occur. For example, wetter years may have higher flows during incubation and hence lower water temperatures, but HRL-driven elevated spring flows would be larger and more likely to occur in wetter years (HRL 2024). Such patterns could result in bias in the estimate of the elevated spring flow effect. In this example the benefit of higher incubation survival due to cooler water temperatures would contaminate the estimate of the higher spring flow effect, resulting in a positive bias in γ. This occurs because the ε's are not randomly distributed over years but instead related to the values of X.

Bias in estimated flow effects due to confounding can potentially be addressed by increasing the complexity of the model,

2) $$log(\frac{R_t}{S_t}) = \alpha + \beta \cdot S_t + \gamma \cdot X_t + \delta \cdot I_t + \varepsilon_t,$$

where I is the average water temperature or flow during incubation and δ represents the effect of those conditions on the log of outmigrants/spawner. The challenge of increasing the complexity of models to avoid bias (e.g., equation 2 versus 1) is that they require more replication (years of observations in this case) and an informative design matrix. If these conditions are not available there is a higher chance of identifying a spurious effect. In this example, the ideal design matrix is one where there are a range of incubation temperatures at low, medium and high levels of flow during the spring, and visa-versa. In a laboratory setting the design matrix can be controlled by the investigator, but that is certainly not the case for the real world the HRL program operates in. However, condition-dependent implementation of specific actions could be used to strengthen the design matrix when possible. For example, decision-makers could identify a matrix of desired combinations of conditions (e.g., three years with high spring flows under poor incubation conditions and another three under good conditions). Such a matrix could be achieved if there was flexibility in when HRL actions are implemented. However, this may be very challenging to achieve given the constraints on delivering HRL flows (HRL 2024) and the 8-year duration of the HRLSP.

There is also potential for multiple HRL actions to confound interpretation of individual actions. For example, how will effects of enhancement of spawning habitat in a tributary, or creation of additional side channel habitat for juvenile rearing, be separated from effects of flow increases in the spring? All these actions have the potential to increase egg-smolt survival rates. However, the contribution of each action to a potential increase in outmigrants/spawner cannot be measured without an experimental design intended to separate their effects. The HRLSP proposes to document fish use in enhanced habitats, but it is hard to see how such information can be used to separate effects of habitat enhancement from flow increases on production (outmigrant abundance). The HRLSP needs to consider this issue, and describe if/how it will be solved. In this example, one option would be to hold off on habitat enhancements until the relationship between outmigrants/spawner and flows has been established, and only then begin habitat enhancement. The other option is to give up on the possibility of separating habitat restoration and flow effects, and instead just measure the combined effect. This may be the likely scenario, but the approach substantially limits the utility of information for making future decisions since the relative benefits of habitat restoration and higher flows would not be quantified. Limitations in the experimental design to evaluate HRL actions is likely the greatest impediment to understanding their effects, and applies to all fish species being evaluated within the HRLSP.

4.0 Effects of HRL Actions in Context of the Full Life Cycle of Chinook Salmon and their Contribution to the Narrative Objective

Trends for many Salmon and Steelhead populations on the West Coast of North Ameria have been dominated by variation in marine conditions (Beamish and Bouillon 1993). This has been well documented for Chinook Salmon populations from the Columbia River to Alaska (Sharma et al. 2013; Welch et al. 2000). Marine conditions may also be an important source of variation for California Central Valley (CCV) Chinook Salmon populations (Atlas 2023; Lindley et al. 2007; Satherthwaite and Carlson 2015). The central objective of the HRLSP is to estimate the benefits of flow and non-flow actions on growth and survival rates of Chinook Salmon in freshwater, with the broader objectives of increasing juvenile outmigrant abundance at ocean entry and ultimately adult returns and escapement. Marine survival will be largely independent of HRL actions, but may have substantive effects on the ability of the program to meet the narrative objective of doubling adult salmon returns.

To illustrate this point, consider the following example. Say a tributary produces on average 10,000 smolts from 100 spawners under baseline conditions, and that flow and habitat restoration efforts increase smolt production by 50% to 15,000 smolts. Under the baseline condition paired with a marine survival rate of 1%, 100 spawners would return, resulting in a stable population. Under the restoration scenario, 150 spawners would return resulting in a 1.5-fold increase in the spawning population. In this optimistic example, restoration efforts would achieve the doubling narrative objective for this system in about two life cycles. Now consider the case where the baseline marine survival rate is only 0.5% and flow and habitat restoration still increase smolt production by the optimistic rate of 50%. Due to the lower marine survival, freshwater enhancement would slow the decline of the population but would be insufficient to result in population growth, and thus fail to meet the doubling objective. While it is plausible that HRL actions will increase freshwater survival rates, it is also plausible they will not be great enough to offset poor marine survival rates and therefore meet the narrative objective. It is also possible that variation in freshwater survival rates due to program actions are small relative to interannual variation in marine survival rates and have very little impact on adult returns. Given these possibilities, the HRLSP could include efforts to quantify variation in marine survival to provide context for effects resulting from HRL actions.

The relative importance of freshwater and marine effects on Chinook Salmon trends in the Columbia River restoration initiative has been a subject of much debate (Marmorek and Peters 2001), and some have argued that costly habitat and flow restoration efforts will not meet adult return management objectives owing to poor marine survival (Peters and Marmorek 2001, Welch et al. 2020). There continues to be debate and division on this issue (ISAB 2021). This debate is potentially highly relevant to the Chinook Salmon component of the HRLSP. Michel (2018) concluded that trends in the smolt-adult survival rates (SARs) for CCV hatchery-origin Chinook Salmon with Coded Wire Tags (CWTs) were dominated by trends in outmigration survival in freshwater. He found that river flow was a better predictor of SARs than indices of marine conditions, though his ocean metrics did not include indices of predator abundance. In addition, both Michel (2018) and Lindley et al. (2009) conclude that marine conditions can have infrequent yet drastic impacts on CCV salmon cohorts. Trends for some CCV Chinook Salmon populations show similar declines to those from the Columbia-Snake River systems (Atlas et al. 2023), perhaps suggesting a common and dominant effect of marine survival. Given the possibility that marine survival rates for CCV Chinook Salmon populations have and will continue to be influential on adult return rates, it seems prudent for the HRLSP to incorporate annual- and cohort-specific SAR estimates into the assessment to better understand the extent to which flow and non-flow actions are contributing to changes in adult returns.

Estimation of SAR requires analysis of release and return data from CWT-tagged hatchery-origin Chinook Salmon, as described by Michel (2018). The HRLSP will collate annual estimates of smolt production at RSTs, and these estimates can be routed to the Delta using existing acoustic tag-based survival rates that will also be collated by the program. Each population could be assigned to a hatchery indicator stock, and its CWT-based SAR could then be used to predict the number of adult returns given estimated smolt abundance. Improvements in freshwater survival rates of Chinook Salmon from HRL actions could then be placed in the context of the survival rate for the full life cycle, facilitating a better understanding the contribution of the HRL actions to the narrative objective. This broader context is already used in CCV Chinook Salmon assessments, such as the winter-run Chinook Salmon lifecycle model (http://oceanview.pfeg.noaa.gov/wrlcm/), and is the motivation to develop lifecycle models for other runs and species. Integrating freshwater and marine survival effects into HRL assessments could also be accomplished using a state space model that jointly fits to escapement data, outmigrant estimates at RSTs, and CWT catch in the harvest and escapement (e.g., Walters and Korman 2025). The model could include estimation of HRL effects on egg-RST outmigration survival rates (e.g., equation 1).

5.0 Effects of Hatcheries on Evaluation of HRL Actions

Hatcheries producing fall-run Chinook Salmon in the CCV support commercial and recreational fishing. Negative effects of production hatcheries on natural-origin populations resulting from genetic introgression and increased competition and predation are well documented (e.g., Flagg et al. 2000). Sturrock et al. (2019) summarize an 80-year history of Chinook Salmon stocking in CCV streams and provide a thorough discussion of potential impacts on natural-origin populations. This section of my review focuses on three questions related to hatchery effects, that were not adequately addressed in the HRLSP:

1) How will the effects of hatchery-origin juveniles and spawners on natural production be separated from effects of HRL actions?
2) How will the abundance of hatchery-origin returning adults and escapement be estimated to calculate the many metrics that depend on estimates of natural-origin returns and escapement?
3) Why are the effects HRL actions on hatchery-origin fish not included in the science plan?

5.1 Separating Effects of Hatchery-Origin Fish and HRL Actions on Natural Production

The annual release of millions of hatchery-produced fall-run Chinook Salmon fry and smolts into tributaries, the mainstem Sacramento River, and the Delta, may have significant negative effects on survival rates of natural-origin juveniles. Hatchery- and natural-origin juveniles will compete for prey and habitat, potentially limiting the growth and survival rates of natural-origin fish. Releases of large numbers of smolts that rapidly migrate to the ocean can entrain natural-origin juveniles and change the timing of their outmigration, potentially reducing their survival or altering the timing of their return as adults. Newly released fry and smolts could attract predators and increase predation rates on natural-origin juveniles. It would be ideal if these potential negative hatchery effects could be separated from the effects of HRL actions to guide future decision-making. However, this is unlikely as it would require purposeful changes to the number of fish released, which would impact fisheries and legal obligations. Thus, although not stated in the HRLSP, assessments will quantify the combined effects of hatchery and HRL actions on the production of natural-origin juveniles and adults. This is not a problem if hatchery practices remain relatively constant over the assessment period. However, if practices change, inferences about the effects of HRL actions could be substantially weakened.

There have been some substantive changes in the number, location, and life stage of fall-run Chinook Salmon released from CCV hatcheries due to declining adult returns and fisheries closures. The total number of fall-run juveniles released each year from the five major CCV hatcheries (Coleman, Feather, Nimbus, Mokelumne, Merced) was relatively consistent between 2000-2012, with an average of approximately 30 million fish (Huber and Carlson 2015). Annual releases from California Department of Fish and Wildlife (CDFW) hatcheries (all but the Coleman National Fish Hatchery) averaged about 15 million fish. The number of releases from CDFW hatcheries in 2023 was 23 million fish (https:/wildlife.ca.gov/News/Archive/cdfw-completes-release-of-23-million-fall-run-chinook-salmon) In 2025, CDFW hatcheries released an additional 9.7 million fish above normal production levels, including 3.5 million smolts into the mainstem Sacramento River for the first time (https://www.territorialdispatch.com/2025/05/14/532467/up-stream-from-here). The location of releases has also changed substantially over time, with increasing proportions being released in the San Francisco estuary and in the ocean to avoid high mortality rates in the Delta (Huber and Carlson 2015). These more distant release locations result in higher straying rates of returning adults to tributaries other than the location of broodstock collection. Higher straying rates could have negative effects on natural-origin spawners by increasing competition for spawning habitat. Juveniles produced from straying spawners may be poorly adapted to the tributary they hatch in, which would result in a reduction in the productivity (outmigrants/spawner) metrics being tracked in the HRLSP.

Clearly, the number and nature of hatchery releases in the CCV has changed substantially in recent years, will likely continue to evolve, and has significant potential to influence natural production. The HRLSP is deficient in specifying how the program will be dis-entangle effects of changing hatchery practices from the effects of HRL flow and non-flow actions. While this is understandable as there are no easy remedies for this difficult situation, discussion of this important issue in the HRLSP is warranted, and there may be opportunities for partial remedies. For example, impacts of fall-run release strategies on natural production may vary across fall-run populations or components of a population. Spring-run Chinook Salmon from some the tributaries in the upper Sacramento may be less affected by high straying rates of fall-run fish (e.g., upper Clear Creek). Perhaps the HRLSP could identify populations or run components that experience varying degrees of hatchery effects, thereby providing contrast to perhaps partially separate their effects from those caused by HRL actions. This, however, would require coordinating HRL actions in these different locations to provide an adequate design matrix to separate hatchery and HRL effects, which will likely be very difficult to achieve. At a minimum, the HRLSP could be strengthened by discussing how changing hatchery practices have the potential to substantially confound assessment of HRL flow and non-flow actions. This would provide decision-makers with a more realistic view about the strength of inferences from the HRLSP.

5.2 Estimating Hatchery- and Natural-Origin Spawner Abundance

The ability to reliably estimate natural-origin escapement for fall-run Chinook Salmon is poorly defined in the HRLSP. The number of returning natural-origin adult fish, and natural-origin escapement, are metrics that will be used to assess many hypotheses in the HRLSP (see Table 2 in HRLSP 2024). As most tributaries have substantial numbers of hatchery-origin spawners, their abundance must be quantified to calculate natural-origin escapement. There are a number of challenges for reliably doing this, which is perhaps why this topic is the first in the list in the *Priority monitoring and information gaps* section of the HRLSP:

Currently, relative contributions of natural origin and hatchery-origin Chinook salmon are estimated through the CFM Program where only 25% of hatchery-origin fall-run Chinook salmon are marked (e.g., with fin clips and coded-wire-tags). One of the primary objectives of the CFM Program is to determine the proportions of hatchery-and natural origin salmon in spawner returns to hatcheries and natural areas. To determine the contribution of hatchery-and natural origin salmon, recovered CWT are expanded based on the tagging rate and the proportion of the run sampled to estimate the total number of hatchery salmon in each survey. The contribution of natural origin salmon for each survey can then be determined by subtracting the total number of hatchery salmon from the total escapement estimate (Letvin et al. 2021). However, the abundance of natural origin Chinook salmon cannot be precisely estimated from the CFM Program, particularly when natural origin fish represent a smaller fraction (<25%) of the population. For precise estimates of natural origin abundance, it will be necessary to increase the marking rate and implementing parentage-based tagging for any hatchery production that cannot be marked by adipose fin clip. Until an updated hatchery marking program is implemented, the current CFM program provides rough *estimates, and is supported by baseline data from 2010, the first year of complete CFM tagged returns (e.g., $H_{TribWide2}$, HSWPop1 and HSWPop2*).

....*without the ability to rapidly identify all hatchery origin salmon as such and to their natal tributary system, hypotheses that relate Flow and Non-flow Measures at the individual Tributary scale and Systemwide Scale ($H_{TribPop1}$ – $H_{TribPop3}$, HSWPop1, and HSWPop2, respectively) will be difficult to address.*

This text indicates a number of very significant issues for estimating natural-origin escapement:

- Estimation of natural-origin escapement cannot be done prior to the 2010 return years, which severely limits the baseline period needed to assess HRL actions.
- The CFM approach results in imprecise estimates of natural-origin escapement when their proportions are less than 25% of total escapement, which occurs in many tributaries, and will likely decline due to increases in the number of fish released.

The text did not mention additional issues with the CFM approach:

- High straying rates, which are increasing over time due to more fish being released in their non-natal tributaries, exacerbate problems with the CFM approach for estimating natural-origin escapement.
- Historical CFM rates have varied across hatcheries which is a significant problem when straying rates are high.
- Large numbers of unclipped fry were released in 2025, and this practice may continue in the future. CFM-approaches cannot be used to account for these unmarked releases.

The HRLSP mentions Parental-based tagging (PBT) as one solution to these issues, but few details are provided, such as when this will be implemented at scale, and how feasible it is given the challenge of sampling enough fish in commercial and recreational fisheries and escapements. There is also no mention of how natural-origin escapement will be estimated from the historical data (no PBT available), which forms the baseline.

5.3 Evaluating Effects of HRL Actions on Hatchery-Origin Fish

There was no mention in the HRLSP of assessing the effects of flow and non-flow actions on return rates of hatchery-origin fish. Hatchery fish released in tributaries, the mainstem Sacramento River, and perhaps even in the Delta, could have higher growth and survival rates due to some of the HRL actions. This would in turn create benefits to the fishery and result in higher total escapement. Higher escapement of hatchery-origin fish could result in an increase in the number of natural-origin juveniles, or conversely have negative effects due to increased competition at spawning sites or genetic introgression. Thus, assessing HRL effects on survival rates of hatchery-origin juveniles, and on upstream passage rates of returning adults, seems warranted.

Analyses of CWT return rates for different hatchery release groups could also help evaluate some HRL actions. For example, return rates for fish released near the Golden Gate Bridge could be compared with those released in tributaries. An increase in return rates from tributary releases relative to ocean releases in years with substantive HRL actions (e.g., higher spring flows) would help quantify the net benefits of those actions across tributary, mainstem, and Delta habitats.

6.0 Challenges Evaluating HRL Actions in Floodplains and Tidal Wetlands

A number of hypotheses in the HRLSP focus on evaluating benefits of tributary and Delta/Bypass floodplain restoration efforts, including increased production of prey leading to elevated growth rates for juvenile Chinook Salmon. There is also a brief discussion of whether such habitats are a net "source" or "sink" for salmonid production, due to losses from predation and stranding. Recovery rates of adult returns based on juveniles released in the Yolo Bypass were higher than mainstem releases in two of three years (1998 and 1999), both of which were designated as a wet water year (Sommer et al. 2005). The recovery rate in the one dry year that was evaluated (2000) was lower for fish released in the bypass compared to the mainstem. Differences in recovery rates between habitat types were not significant owing to the limited number of years in the analysis. Later studies of survival rates in flooded agricultural fields showed very low survival rates under drought conditions due to stranding and bird predation (Sommer et al. 2020). Recent analysis of survival rates of out-migrating juvenile spring- and fall-run Chinook Salmon, based on over 11,000 acoustically tagged fish, showed high variation in survival rates across different wet years, which could be caused by variation in losses in floodplain habitats (F. Cordoleani et al., NOAA, unpublished data).

The HRLSP provides limited discussion of the "source-sink" floodplain issue, and the methods proposed to evaluate it are vague:

HtribFP6: *"Over multiple years of collecting data (and utilizing historical data on stranding where possible), it may be possible to model an estimate of the proportion of the juvenile population, across different hydrology conditions, that does not outmigrate from tributaries because of isolation and determine whether this is a significant population impact."*

HBypassFP7: *However, there is no long-running historical record of stranding events on bypass floodplains and stranding numbers are likely to vary across years due to variation in total population sizes and hydrologic conditions. Therefore, this hypothesis may be best evaluated through targeted sampling of floodplain areas at the end of the drainage period.*

Methodologies provided in section 3.1.2.2 of the HRLSP are not described in enough detail to determine if they will provide reliable results. For example, abundance of juveniles exiting a floodplain determined from an RST will be compared to stranding losses in isolated pools determined from beach seine surveys. However, the latter method does not quantify total stranding losses because it doesn't include predation losses or other causes of mortality as water elevations decline prior to when surviving fish concentrate in isolated pools. Further, no details are provided to determine how densities in stranding pools will be expanded to the number stranded over the entire floodplain. There was no mention of using paired CWT releases to compare relative survival rates in floodplain and mainstem habitats, either based on adult returns (as in Sommer et al. 2005), or based on capture of juveniles at a common downstream location (Chipps Island trawl survey). The lack of a rigorous method to determine whether flood plain restoration is doing more good than harm is a significant limitation of the HRLSP. Perhaps enhancement actions in these habitats should not be initiated until a reliable method to evaluate the source-sink hypothesis is described.

To some extent, concerns about limitations for evaluating the source-sink hypothesis in floodplains applies to restoration efforts of tidal wetlands. The HRLSP acknowledges this risk:

HTW6: *Notably, an uncertainty with this hypothesis is the thresholds of predator densities and invasive aquatic vegetation coverage above which survival of native fish species is impaired or at which they will avoid shallow water habitat. Piscivores and invasive aquatic vegetation are prevalent in the Delta and will be present to some extent near shallow-water habitat. It will be beneficial in evaluation of this hypothesis to assess whether increases in predator densities or vegetation coverage result in reduced utilization of the restored habitat or a notable decrease in survival, and these questions will be best addressed through targeted experimental work rather than continuous monitoring efforts (Zeug et al. 2021).*

A review of approaches to evaluate predation risk is provided (section 3.1.3.2, p. 58), and the plan does acknowledge substantive challenges:

Understanding local densities of predators and their behavior in tidal wetlands is a challenging task because of high spatial and temporal complexity over the tidal cycle, requiring tool development to sample predator movements and relate predation risk to microhabitats.

The plan identifies a variety of technologies that could be employed to evaluate predation risk (DIDSON, ARIS, tethering, diet analysis combined with genetic analysis). However, there was no description of how data from these different methods would be used to determine the overall value of tidal wetland restoration for juvenile Chinook Salmon ("source" or "sink"?), let alone harder-to-evaluate species like Longfin Smelt or Delta Smelt. Overall, my impression is that this part of the plan is in a very preliminary stage. Decision-makers could at least be warned that the net benefit of tidal wetland restoration for native fish will likely be very difficult to determine. This warning would also apply to floodplain restoration hypotheses if large-scale CWT releases are not used in the evaluation.

7.0 Plan for Analyzing and Testing Hypotheses (PATH)

The Plan for Analyzing and Testing Hypotheses (PATH) was a five-year (1995-2000) multiagency program designed to resolve uncertainties about hypotheses related to the recovery of Chinook Salmon and Steelhead populations in the Snake River sub-basin of the Columbia River (Marmorek and Peters 2001, Peters and Marmorek 2001, Peters et al. 2001). Retrospective analyses within PATH were used to evaluate hypotheses based on historical datasets, and prospective analyses incorporated those results into forward simulation models to evaluate consequences of different restoration strategies. I recommend that the HRLSP include a similar retrospective effort for evaluating population-level hypotheses for CCV Chinook Salmon populations. The effort would initially be based on data collected before HRL actions are implemented, but could be updated over the duration of the 8-year assessment period to provide a synthesis of outcomes.

There are a number of different models that could be used for a retrospective CCV PATH-like effort. Freshwater spawner-outmigrant abundance stock-recruit relationships with flow- or temperature-based covariates could be used to evaluate the historical evidence for their effects on egg-smolt survival at the tributary level (see eqn. 1 in Section 3.0). Covariate effects over spawning-incubation, early rearing, and outmigration phases could be evaluated. There are a number of examples where this type of analysis is currently being applied to data from CCV populations: 1) the spring-run Chinook Salmon juvenile population estimate (JPE) model effort (B. Harvey, California Department of Water Resources); 2) fall run Chinook Salmon on the Stanislaus River (Andrea Fuller and Tyler Pilger, FishBio, Stockton, CA); and 3) fall-run Chinook in some tributaries that have voluntary agreements (Laura Twardochleb, California State Water Resources Control Board, and Liz Stebbins FlowWest). A large database of spawner and outmigrant data for the spring-run JPE effort has already been developed, and could be expand to other systems and run types (this is already occurring as part of example 3 above). The R libraries developed as part of the spring run JPE effort include models to estimate annual outmigrant abundance from RST catch and efficiency data (BT-SPAS-X), and to estimate spawner-outmigrant stock-recruit relationships that include covariate effects. In addition, the spring-run JPE effort includes a model that evaluates the effects of flow and other factors on survival rates of outmigrating juvenile Chinook Salmon by fitting to data from historical acoustic telemetry programs. Estimation of historical smolt-adult survival rates from CWT data could also be conducted as part of the CCV-PATH process.

I recommend that these types of modeling efforts be expanded to cover all tributaries with sufficient data that are part of the HRLSP. The PATH-like effort for CCV would require that models and results are reported within a collaborative multi-year facilitated workshop process. This would allow agencies to review results, make recommendations to modify the modelling approaches and inputs, and to come to consensus on the interpretation of results and document disagreements on interpretation. The Snake-Columbia PATH process (e.g., Marmorek and Peters 2001) could be used as a template for a similar CCV effort.

A CCV-PATH effort could substantively improve the HRLSP, provide useful information over the 8-year assessment period, and perhaps be the most useful approach to synthesize results at the end of the period. The modeling efforts would provide quantitative assessments of some population-level hypotheses in the plan based on historical data. As voluntary agreements are implemented and flows are changed, the analysis could be updated based on new data to estimate the effects of the flow changes. Thus, by the end of the 8-year assessment period, CCV-PATH would provide a synthesis of flow effects from HRL actions. Results from this modelling could also be used to drive power analyses (see Section 3.0) to define the required duration of assessment periods and the magnitude and frequency of flow changes to provide stronger inference about HLR actions. The CCV-PATH effort differs from the Structured Decision Making (SDM) Science Integration Team (SIT) project because it would focus on analysis of historical data. In contrast, the SIT SDM effort used a forward simulation model to predict effects of future actions and quantify the preference of decision-makers for predicted outcomes, similar to the prospective analysis in the Snake-Columbia PATH effort (Marmorek and Peters 2001). In the long-run, models and results from the suggested CCV-PATH process could be used to update and improve models like the one used in the SIT SDM effort.

8.0 Conclusions

The HRLSP is comprehensive and succinctly describes a large number of hypotheses and methodologies to evaluate effects of HRL flow and non-flow actions. The authors have done an excellent job distilling considerable amounts of information to produce an intelligible plan. However, there are some very significant limitations of the plan that are going to be difficult to overcome, which include problems with the experimental design of evaluations, and confounding effects of hatchery practices. Some hypotheses are going to be more challenging to evaluate than others, and those related to improvements in floodplain and tidal wetland habitats are perhaps the most problematic.

The most significant limitation of the HRLSP is that it provides an overly optimistic view of how well HRL actions can be evaluated. The plan identifies metrics used for evaluation, and in some cases limitations of the metrics. But the plan falls short with respect to making conclusions about the effects of the limitations of the metrics on the evaluation of hypotheses. For example, the plan identifies the need to estimate natural-origin escapement for many hypotheses, and the substantial challenges of obtaining reliable estimates due to uncertainty in the abundance of hatchery-origin fish. What should the reader conclude? Does the inability to reliably estimate natural-origin escapement mean that hypotheses that depend on this metric cannot be evaluated?

The optimistic tone of the HRLSP is evident in other important instances. For example, the plan identifies that the 8-year assessment period is too short to evaluate metrics at the life cycle scale of Chinook Salmon. But this period is also too short for assessing hypotheses that depend on annual metrics (e.g., juvenile outmigration abundance) because sufficient replication and contrast across years is still required. The reader is not adequately informed about the challenges of the short period of assessment. Perhaps a more articulated conclusion would be that only minor gains in inference about HRL actions will occur over the 8-year period, and it may take a few decades to provide reasonably certain inferences for most of the hypotheses. In some cases, inferences will be weak regardless of the evaluation period owing to confounding factors that the HRL program has no control over, such as hatchery stocking practices. It's not clear whether the HRL program will be extended beyond the 8-year time frame. The description of the program timeline only mentions "the possibility of extension" (section 1.5 of HRL 2024). Thus, there appears to be a disconnect between the stated duration of the HRL program, and what is needed to obtain moderate levels of inference to evaluate action effectiveness.

Finally, the plan does not articulate the details of the timing and magnitude of HRL flow changes. This is understandable given the complexity of the flow agreements (HRL 2024). The strategic plan does specify the volumes of additional water that will be released and how they vary by water year type (HRL 2024). However, the relative change in flow with and without agreements in place was not specified. The strategic plan also mentions offramps for HRL flow releases, and describes different systems for making decisions on flow releases that vary by tributary (Table 7 of HRL 2024). Owing to this complexity, it is very difficult to evaluate the magnitude and repeatability (replication) of HRL flow actions, and hence the likelihood of adequately evaluating their biological effects. The HRLSP, or an addendum to it, could use hydrologic modelling to demonstrate the effects of voluntary agreements on multi-year hydrographs. In conjunction with existing fish-flow relationships for CCV populations (e.g., Michel et al. 2018, Perry et al. 2018), or from other systems (Rosenfeld and Enright 2023), modelling results could be used to predict the range of potential biological responses. This output could in turn be used to drive statistical power analyses to define the number of replicated treatments and years to achieve moderate levels of inference (e.g., Bradford et al. 2005).

I encourage the authors of the HRLSP to include realistic appraisals about the strength of inference on the effectiveness of HRL actions. Outlining the range of inference strength across hypotheses is fundamental information for decision-makers. Some, like those bearing the costs of actions through expenditures or forgone water use, may be reluctant to invest in efforts where the chance of obtaining reasonable inferences about effectiveness is low. Decision-makers focused on improving the status of fish populations, and with a strong a priori belief that HRL actions will be effective, may not be very concerned about the reliability of inferences gained through the HRLSP. Though even for this group, there would be value in determining which actions are most effective. The plan needs to clearly articulate the anticipated strength of inferences over the proposed 8-year assessment period, and ideally subsequent periods, so that decision-makers have a realistic view of what the assessments will tell them in the short- and long-term.

An effort similar to the Plan for Analyzing and Testing Hypotheses (PATH), used to resolve uncertainties about hypotheses related to the recovery of Chinook Salmon and Steelhead populations in the Snake River sub-basin of the Columbia River, could be a useful organizing framework for evaluating population-level hypotheses for CCV Chinook Salmon populations. The effort would initially be based on data collected before HRL actions are implemented, but could be updated over the duration of the 8-year assessment period to provide a synthesis of outcomes. A CCV-PATH effort could substantively improve the HRLSP, provide useful information over the 8-year assessment period, and perhaps be the most useful approach to synthesize results at the end of the period.

9.0 References

Atlas, W.I., Sloat, M.R., Satterthwaite, W.J., Buehrens, T.W., Parken, C.K., Moore, J.W., Mantua, N.J., Hart, J., and A. Potapova. 2023. Trends in Chinook salmon spawner abundance and total run size highlight linkages between life history, geography and decline. Fish and Fisheries 24:595–617.

Beamish, R.J., and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences 50 (5). https://doi.org/10.1139/f93-11

Bradford, M.J., Korman, J., and P.S. Higgins. 2005. Using confidence intervals to estimate the response of salmon poulations (Oncorhynchus spp.) to experimental habitat alterations. Canadian Journal of Fisheries and Aquatic Sciences 62:2716-2726.

Flagg, T. A., B. A. Berejikian, J. Colt, W. W. Dickhoff, L. W. Harrell, D. J. Maynard, C. E. Nash, M. S. Strom, R. N. Iwamoto, and C. V. W. Mahnken. 2000. Ecological and behavioral impacts of artificial production strategies on the abundance of wild salmon populations: a review of practices in the Pacific Northwest. NOAA Technical Memorandum NMFS-NWFSC-XX. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, WA. https://repository.library.noaa.gov/view/noaa/3134

HRLSP. 2024. Healthy rivers and landscapes science plan. Final draft, September 6, 2024. 93 pp.

HRL. 2024. Draft strategic plan for the proposed agreements to support Healthy Rivers and Landscapes. October 2024. 240 pp.

Hilborn, R. and C.J. Walters 1992. Quantitative fisheries stock assessment. Routledge, Chapman and Hall Inc. 570 pp.

Huber, E.R., and S.M. Carlson. 2015. Temporal trends in hatchery releases of fall-run Chinook Salmon in California’s Central Valley. San Francisco Estuary and Watershed Science 13(2).

ISAB. 2021. Review of the coast-wide analysis of Chinook Salmon smolt to adult returns (SARs) by Welch et al. Report prepared by the Independent Scientific Advisory Board for the Northwest Power and Conservation Council. https://www.nwcouncil.org/sites/default/files/ISAB%202021-3%20ReviewOfWelchEtAl2020CoastWideSARs_29June.pdf

Lindley, S.T., Schick, R.S., Ethan, M., et al. 2007. Framework for Assessing Viability of Threatened and Endangered Chinook Salmon and Steelhead in the Sacramento–San Joaquin Basin. San Francisco Estuary and Watershed Science 5(1).

Marmorek, D., and C.N. Peters. 2001. Finding a PATH toward scientific collaboration: Insights from the Columbia River Basin. Conservation Ecology: *5*(2).

Michel, C.J., 2019. Decoupling outmigration from marine survival indicates outsized influence of streamflow on cohort success for California's Chinook salmon populations. Canadian Journal of Fisheries and Aquatic Sciences 76: 1398-1410. https://cdnsciencepub.com/doi/10.1139/cjfas-2018-0140

Perry, R.W., Pope, A.C., Romine, J.G., Brandes, P.L., Burau, J.R., Blake, A.R., Amman, A.J., and C.J. Michel. 2018. Flow-mediated effects on travel time, routing, and survival of juvenile Chinook Salmon in a spatially complex, tidally-forced river delta. Canadian Journal of Fisheries and Aquatic Sciences 75(11). https://doi.org/10.1139/cjfas-2017-0310

Peters, C.N., Marmorek, D.R., and R.B. Deriso. 2001. Application of decision analysis to evaluate recovery actions for threatened Snake River fall summer chinook salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences 58: 2447-2458.

Peters, C.N., and D.R. Marmorek. 2001. Application of decision analysis to evaluate recovery actions for threatened Snake River spring and summer chinook salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences 58:2431-2446.

Rosenfeld, J.S., and D. Enright. 2025. Developing generalized flow ecology relationships for stream salmonids: Providing a clearer empirical basis for minimum flow regulations. Transactions of the American Fisheries Society 154:162-178.

Satherwaite, W.H., and S.M. Carlson. 2015. Weakening portfolio effect strength in a hatchery-supplemented Chinook salmon population complex. Can. J. Fish. Aquat. Sci. 72: 1860–1875. dx.doi.org/10.1139/cjfas-2015-0169.

Sharma, R., L.A. Vélez-Espino, A.C. Wertheimer, N.J. Mantua, and R.C. Francis. 2013. Relating spatial and temporal scales of climate and ocean variability to survival of Pacific Northwest Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 22:14-31.

Sommer, T., Schreier B., Louise, C.J., Takata, L, Bjarni, S., Titus, R., Carson, J., Holmes, E., and J. Katz. 2020. Farm to Fish: Lessons from a multi-year study on agricultural floodplain habitat. San Francisco Estuary and Watershed Science 18 (3).

Sommer, T.R., Harrell, W.C., and M.L. Nobriga. 2005. Habitat use and stranding risk of juvenile Chinook Salmon on a seasonal Floodplain North American Journal of Fisheries Management 25: 1493-1504.

Sturrock, A., Satterthwaite, W.., Cervantes-Yoshida, K., Huber, R.R., Sturrock, H.J.W., Nussle, S., and S. M. Carlson. 2019. Eight decades of hatchery salmon releases in the California Central Valley: Factors influencing straying rate and resilience. Fisheries Magazine 44 (9):433-444. https://doi.org/10.1002/fsh.10267

Walters, C.J., and J. Korman. 2025. A life cycle model for Chinook Salmon population Dynamics. Canadian Contractor Report of Hydrography and Ocean sciences 65. 60 pp. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/41250564.pdf.

Welch, D.W., A.D. Porter, and E.L. Rechisky. 2020. A synthesis of the coast-wide decline in survival of West Coast Chinook Salmon (*Oncorhynchus tshawytscha,* Salmonidae). Fish and Fisheries 22: 194-211. https://doi+/10.1111/faf.12514

Appendix A. Specific Responses to Review Questions and Linkages to Main Body of Review

The intent of this appendix is to clarify the linkages between the content of my review (sections 3-8) and the specific questions provided to reviewers in the charge. Review questions are identified below by bold text, and brief answers to the questions are provided in non-bolded text. The sections of the report that support the answers and provide additional background and are identified.

1. Hypotheses

a. Do hypotheses cover key uncertainties in potential ecological outcomes of the Program actions? Are any uncertainties not addressed?

Yes, for the most part the hypotheses cover key uncertainties about ecological outcomes of HRL actions, with a few critical exceptions.

Uncertainties related to effects of marine survival on adult returns of Chinook Salmon (see Section 4.0), and effects of changes in hatchery release strategies, on evaluation of HRL actions (see Section 5.1), were not addressed in the plan.

The plan also did not consider effects of HRL actions on hatchery-origin returns and escapement, which is a significant omission given potential benefits to fisheries and potential positive or negative effects on natural production of juveniles (see Section 5.3).

b. Are there hypotheses that can be removed because we already have sufficient knowledge/data on the subject, and they therefore do not address uncertainties?

Not to my knowledge, but I do not have a complete understanding of all relevant science.

c. Are identified baselines for individual hypotheses appropriate for the intended reporting purposes of the Science Plan and suitable for the corresponding areas of uncertainty? Are there alternative baselines for specific hypotheses that should be considered to better advance learning?

No for all hypotheses that depend on data or estimates collected at annual and life-cycle scales for Chinook Salmon (see Section 3.0).

Baselines for marine survival rates (based on CWT recoveries) were not identified in the plan, but are needed as part of the evaluation of HRL actions that depend on natural-origin returns and escapement metrics (see Section 4.0).

Baselines for natural-origin adult returns and escapements are corrupted by poorly determined hatchery-origin abundance estimates (see Section 5.2).

2. Metrics and covariates

a. Are the identified metrics and covariates appropriate for the hypotheses?

Yes, for the most part, but not for metrics that depend on natural-origin adult returns and escapement. These metrics depend on survival rates in both freshwater and in the ocean (see Sections 4.0 and 5.2), but only the former are partially controlled by HRL actions. Thus, a smolt-adult survival metric is required to interpret causes for changes in natural-origin adult and escapement metrics.

Hatchery-origin spawners have the potential to reduce egg-smolt productivity (outmigrants/spawner) due to competition and genetic introgression (see Section 5.1). Thus, metrics based on outmigration abundance are potentially corrupted by changing hatchery practices, making evaluation of HLR actions more difficult.

Metrics that quantify differences in survival in bypass floodplains relative to the Sacramento River mainstem, based on recaptures of hatchery-origin fish with coded wire tags (at the Chipps Island Trawl survey location, or as adult returns) were not included in the HRLSP. These metrics represent the most robust way of evaluating the source-sink hypothesis (see Section 6.0).

Proposed metrics to evaluate habitat use and the overall benefit of restored tidal wetlands for juvenile Chinook Salmon and other species (growth, survival) were only vaguely defined in the plan (see Section 6.0).

b. Are there proxies and/or indices that could be used in lieu of a metric/covariate that align with best practices that could be included?

Yes. See response to question 2a. For example, return rates of hatchery fish with coded wire tags would be a proxy/index of survival rates in the Delta-ocean or ocean (depending on location of release) for natural-origin fish (see Section 5.3).

c. Are the identified metrics and covariates in this framework specific enough that individual science plans will be consistent to perform syntheses at the scales relevant to individual hypotheses (local, sub-basin, population, as described in Figure 2 of the Science Plan) and beyond the scale of individual projects and tributaries? Are there metrics and covariates suggested in the Science Plan that are too broad to the point that they may cause inconsistencies?

Yes.

d. Are there additional analytical frameworks or emerging methods for managing inconsistencies (with baseline data and/or across space/specific systems) that should be considered?

Yes, to a limited extent.

Problems for evaluating HLR actions related to experimental design can only be rectified by increasing the duration of the assessment period combined with increasing the magnitude and frequency of HRL actions, and careful planning on when actions are implemented (see Section 3.0). Power analysis can be used to quantify the required study period duration and magnitude and frequency of HRL actions to provide stronger inferences about their effects. A CCV-PATH analysis (see Section 7.0) could provide estimates of potential biological effects of HRL actions to drive the power analysis.

Effects of variation in marine survival rates on natural-origin adult return and escapement metrics could be addressed by analysis of CWT data from hatchery-origin fish (see Sections 4.0 and 5.3).

Parental-Based Tagging (PBT) is an emerging method (briefly mentioned in the HLRSP) that could be used to increase the reliability of estimates of adult returns and escapement of hatchery-origin fish, which would in turn would lead to more reliable estimates for natural-origin adult returns and escapement (see Section 5.2). However, it may take a number of years to implement this approach at the very large scale that is required. PBT would need to be applied to broodstock from all five major fall-run hatcheries, catches in commercial and recreational fisheries, and to escapements in all tributaries. Implementing PBT at the required scales may not occur until a number of years into the HRL 8-year assessment period. In addition, the PBT approach cannot be applied to the historical data. Thus, it seems unlikely that PBT will substantively contribute to the reliability of natural-origin adult return/escapement metrics for baseline and 8-year assessment periods.

3. Monitoring Networks and Modeling Resources

a. Does the Science Plan's review of monitoring networks and modeling resources sufficiently cover what would be needed to address key uncertainties in potential ecological outcomes of the Program actions?

Yes, for the most part but with a few exceptions.

The plan also does not include modelling of changes in flow resulting from the voluntary agreements. These model outputs could be used to determine how much contrast and replication will be provided by the program to evaluate the hypotheses (see Section 3.0).

The plan does not include modelling of the effects of marine survival on natural-origin adult returns and escapement, which impacts the reliability of evaluations of hypotheses that depend on these metrics (see Section 4.0).

A retrospective PATH-like process could be used in the HRLSP to describe the effects of HRL actions, and document the extent of consensus and disagreement on the interpretation of results among agencies (see Section 7.0).

4. Information Gaps

a. Does Section 3.4 of the Science Plan describe the information gaps that are the most important for informing decisions and Healthy Rivers and Landscapes Program Evaluation? Are there additional, major information gaps that should be included?

To a limited extent.

The plan is deficient in identifying substantive limitations in assessing HRL actions due to an assessment period that is too short, variation in flow change magnitudes and frequencies which are likely not great enough to provide sufficient contrast and replication (see Section 3.0), and challenges in estimating natural-origin adult returns and escapement (see Section 5.2).

The plan is also deficient in identifying how the effects of changes in hatchery practices will be accounted for when evaluating effects of HRL actions (see Section 5.1).

5. Informing Adaptive Management

a. What additional components (decision support tools, decision process, recommendation development) are needed to describe how reporting products (Triennial Synthesis Report, Ecological Outcomes Analysis Report) of the Science Plan will be developed to inform adaptive management? Primary Program areas subject to adaptive management both during Program implementation and to inform the shape of the Program post Year 8 will include prioritization for investment in habitat restoration, the timing, shape, and magnitude of environmental flows, and science investments to maximize learning in areas of major uncertainty.

A retrospective PATH-like process could be used in the HRLSP to communicate and discuss results from the program (see Section 7.0). Results from the synthesis reports and a potential PATH effort will contribute to decisions on future investments.

b. What additional content in the Science Plan would be helpful for maximizing the probability that the Science Committee can provide recommendations for adaptive management of the Program?

Power analysis could be used to define the duration of the assessment period, and the magnitude and frequency of flow and habitat actions, to provide reliable inferences (see Sections 3.0 and 8.0).

The plan needs to include a more thorough discussion of challenges for reliably evaluating HRL hypotheses (caused by a weak experimental design and confounding effects of changing hatchery practices). This addition would provide decision-makers with a more realistic expectation of how well the effects of HRL actions will be evaluated over the 8-year assessment period (see Sections 3.0, 7.0, and 8.0). By not discussing the substantive limitations, the plan provides an overly optimistic view of how well HRL actions will be evaluated.

c. What recommendations do you have for approaches or tools for prioritizing hypotheses, metrics and covariates, monitoring and modeling resources to optimize information benefits at the full tributary and delta and population tiers?

Structured decision making (SDM) has already been identified as a potential tool in the HRLSP. SDM can be used to prioritize objectives, which in turn can be used to prioritize hypotheses related to the objectives. Most metrics are tied to specific hypotheses, so their prioritization depends on the prioritization of hypotheses. However, metrics that support multiple important hypotheses would be prioritized, especially if they can be reliably quantified. Prioritization of covariates depends on the extent of scientific support for their effects, and the challenges and costs of measuring them.

The PATH analysis for the Snake-Columbia River restoration effort is a highly relevant example of an SDM approach that could be implemented as part of the HRLSP (Marmorek and Peters 2001, Peters and Marmorek 2001, Peters et al. 2001, see Section 7.0).

JUNE 2025

Healthy Rivers and Landscapes Science Plan Independent Peer Review- Stephen B. Brandt

A report to the Delta Science Program

Prepared by

Dr. Stephen B. Brandt
Brandt Scientific Consultants, LLC
and
Professor Emeritus, Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University

Delta Science Program

DELTA STEWARDSHIP COUNCIL

Table of Contents

Executive Summary

The Healthy Rivers and Landscapes (HRL) Program has proposed additional flows, habitat restoration, landscape reactivation, improved fish passage and predator management actions (termed Flow Measures and Non-Flow Measures) to benefit native species in the California Delta as part of the effort to update and implement the San Francisco Bay/Sacrament-San Joaquin Delta Water Quality Control Plan. A Draft Science Plan has been developed to provide the framework for evaluating the success of this program and is the subject of this review.

The Science Plan is a comprehensive guide to the development of individual system-specific science plans. The Science Plan lays out 55 hypotheses that span three nested geographic tiers ranging from local level to full tributary and Delta level to fish population level. The use of hypotheses recognizes the uncertainties in our understanding of how flow and other environmental drivers affect native fishes. Each hypothesis has a specific metric of interest and expected direction of change (positive, negative, or neutral) driven by the proposed action. Each hypothesis also includes a list of additional environmental drivers (covariates) that could influence the metric of interest. The Science Plan suggests a reference baseline for comparison for each hypothesis and discusses the monitoring and modeling that could support the program, the primary information gaps, and the adaptive management process to evaluate whether the program will continue or need modifications.

Overall, the Science Plan is a robust, ambitious, and rather unique approach that is based on an extensive review of the science with cognizant recognition of uncertainties in our level understanding of how flows and habitat restoration/ landscape reactivation might impact fishes in the face of other drivers. A key strength of this overall approach is the extensive review of the background science and existing monitoring programs with the goal to use existing monitoring programs if appropriate. The Science Plan also adopts the use of best available science protocols including endorsing the essential need for a comprehensive and accessible database. Other key strengths of the Science Plan include the endorsement of transparency, collaboration, inclusivity, peer review, and a robust

reporting and an adaptive management evaluation using decision support models. The Science Plan also includes learning as a fundamental goal.

There are several opportunities to enhance the value of the overall Science Plan:

1) Enhanced use of conceptual models both within the overall Science Plan as well as the individual system-specific science plans will help envision direct and indirect relationships among metrics and covariates and help design the monitoring program.
2) Greater emphases on the use of fish vital rates (i.e., growth, reproductive and survival/mortality rates) as metrics will highlight the proximate environmental forces directly impacting fish production. Fish growth rate is highly responsive to changes in environmental conditions such as food availability and water temperature and could be used more often since it is easily measured and well modeled. Food web processes and species interactions could also directly affect the magnitude and direction of ecological outcomes and need to be more explicitly addressed.
3) The Science Plan could also be improved through a more detailed and rigorous discussion of the covariates. Covariates are alternative hypotheses to explain biological outcomes. Understanding and modeling the mechanistic relationships among covariates and metrics will improve monitoring power and learning effectiveness.
4) Finally, the Science Plan could better serve as a stand-alone document if it included some material from the Science Committee Charter.

The hypotheses are very comprehensive but vary widely in their achievability. Some hypotheses are structural and measure whether the habitat restoration design has been accomplished. Other hypotheses address biological outcomes. Overall, several of the individual hypotheses would be more complete with some additional metrics or covariates that are discussed in the review. Additional hypotheses and metrics that could be considered relate to adding fish vital rates such as growth rate or growth rate potential, mortality rate, survival rate or predation rate. Eventually, outcomes for specific indicators of ecosystem health or species vitality as defined and measured through a collaborative process incorporating Traditional Ecological Knowledge should be developed. Other metrics could be developed to assess other key components of the HRL program such as transparency or learning goals.

The approach to monitoring outlined in the Science Plan is excellent and uses some of the five best practices recognized for environmental monitoring. The Science Plan does a good job at reviewing existing monitoring programs (and their challenges) particularly for fish assessment. Some additional effort on reviewing and monitoring of covariates seems appropriate. Monitoring protocols could be improved by more directly linking monitoring to modeling (conceptual models or sub models or full-scale models) to better define the connections among environmental drivers and responses and to improve time, space, frequency, and parameters of the monitoring effort. Secondly, the statistical power of the monitoring programs needs to be sufficient to detect changes in a complex and dynamic ecosystem especially since some of the expected changes in ecological outcomes may be low. Some additional suggestions to enhance the power of monitoring protocols are to encourage the use of new technologies (e.g., fixed, or mobile acoustic sensing) that may be more effective at finer space and time scales and have improved parameter resolution. An important challenge will be to balance existing and new monitoring programs. Existing monitoring programs have known behavior, are well established and are cheaper and easier to incorporate into a database management program.

The Science Plan recognizes priority information gaps in the program related to:

1) ability to differentiate natural and hatchery origin adult salmon,
2) consistency of monitoring approaches across tributaries,
3) design of population estimates for non-salmonid species in the Delta,
4) and data availability and centralization to support coordinated analysis and reporting.

I suggest three additional information gaps:

1) Improved mechanistic understanding of how flow and other environmental drivers affect fish vital rates and ultimately production has been a long-recognized need in the California Delta and is particularly important in the context of predicting ecological outcomes for the HRL program.

2) Improved understanding and models of food webs is a critical need as habitat restoration is often expected to produce invertebrate food but whether that food is fully beneficial to target species or competitors is still a major unknown. Predation on native species can be better assessed if species interactions and food webs are better understood.
3) Improved metrics and understanding of habitat suitability is needed because the design and assessment of many of the habitat restoration efforts depend on Habitat Suitability Indices that often do not include biological metrics nor assess exactly how habitat features affect fishes.

An adaptive management framework is proposed to assess the future of the program based on ecological outcomes. Structured decision-making and consensus will be used in this assessment. At present the details of the adaptive management decision criteria are still vague given uncertainty in how the different hypotheses and metrics will be weighed.

In summary, the Science Plan is a well-thought-out guideline that recognizes the inherent uncertainties in our understanding of biological or ecological processes in the California Delta and sets up a series of hypotheses to improve that understanding. Suggestions in this review are intended to help achieve that goal.

Introduction and Background

The Healthy Rivers and Landscapes (HRL) Program has proposed additional Flow and Non-Flow Measures to benefit native species in the California Delta as part of the effort to update and implement the San Francisco Bay/Sacramento-San Joaquin Delta Water Quality Control Plan (October 2024 Draft WQCP Update, https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/2024/drft-sacdelta-bdplan-updates.pdf).

Over the last few years, the HRL program has made significant progress towards this goal by developing agreements and MOUs, a governance structure, funding plan, a strategic plan, a scientific committee, and science committee charter. There have also been several open meetings including a series of 5 workshops that outlined these various components of the plan and provided opportunities for discussion and public comment (see https://resources.ca.gov/Initiatives/Voluntary-Agreements-Page/Science).

The overall program has proposed increases in flow, habitat restoration and landscape reactivations, improved fish passage, and predator management actions to help achieve two overarching 'Narrative Objectives' related to the protection or enhancement of native fish populations.

One existing objective is to provide for *"water quality conditions, together with other measures in the watershed, sufficient to achieve a doubling of natural production of chinook salmon from the average production of 1967-1991, consistent with the provisions of State and federal law (Narrative Salmon Objective);"*

A new Narrative Viability Objective has been designed to further the viability of native fish populations:

"Maintain water quality conditions, including flow conditions in and from tributaries and into the Delta, together with other measures in the watershed, sufficient to support and maintain the natural production of viable native fish populations. Conditions and measures that reasonably contribute toward maintaining viable native fish populations include, but may not be limited to, (1) flows that support native fish species, including the relative magnitude, duration, timing, temperature, and spatial extent of flows, and (2) conditions within water bodies that enhance spawning, rearing, growth, and migration in order to contribute to improved viability. Indicators of viability include population abundance, spatial extent, distribution, structure, genetic and life history diversity, and productivity. Flows provided to meet this objective shall be managed in a manner to avoid causing significant adverse impacts to fish and wildlife beneficial uses at other times of the year".
(https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/2024/drft-sacdelta-bdplan-updates.pdf)

The HRL program has developed timelines with progress reports (and further review) required at Years 3 and 6 of the program with comprehensive analyses of 'ecological outcomes' at Year 8. At that time, a decision will be made on whether to continue the program, modify the program or end the program.

As part of the overall HRL program, a Draft Science Plan has been developed *"to provide the framework and specific approach for evaluating the biological and ecological outcomes of the Flow and Non-Flow Measures and for addressing several important and broad-scale ecosystem management questions".* The Science Plan is designed to be an overall guide for scientific assessment of the impacts of these management actions and is the subject of this review.

Charge to the Panel

A panel of three reviewers was set up to conduct an independent peer review of the Science Plan. Our overall charge was *to "review the framework, hypotheses, identified needs for monitoring and evaluation, identified priority information gaps, and plans for data management and decision-making tools of the Science Plan."*

We were given a series of detailed questions to guide our feedback and help to *"improve the Science Plan as a guiding framework for system-specific science plans and improving information availability on key system-wide uncertainties." (https://deltacouncil.ca.gov/delta-science-program/healthy-rivers-and-landscapes-science-plan-independent-peer-review)*

The detailed questions within five main topics are listed below.

Hypotheses

a. Do hypotheses cover key uncertainties in potential ecological outcomes of the Program actions? Are any uncertainties not addressed?
b. Are there hypotheses that can be removed because we already have sufficient knowledge/data on the subject, and they therefore do not address uncertainties?
c. Are identified baselines for individual hypotheses appropriate for the intended reporting purposes of the Science Plan and suitable for the

corresponding areas of uncertainty? Are there alternative baselines for specific hypotheses that should be considered to better advance learning?

Metrics and Covariates

a. Are the identified metrics and covariates appropriate for the hypotheses?
b. Are there proxies and/or indices that could be used in lieu of a metric/covariate that align with best practices that could be included?
c. Are the identified metrics and covariates in this framework specific enough that individual science plans will be consistent to perform syntheses at the scales relevant to individual hypotheses (local, sub-basin, population, as described in Figure 2 of the Science Plan) and beyond the scale of individual projects and tributaries? Are there metrics and covariates suggested in the Science Plan that are too broad to the point that they may cause inconsistencies?

Monitoring Networks and Modeling Resources

a. Does the Science Plan's review of monitoring networks and modeling resources sufficiently cover what would be needed to address key uncertainties in potential ecological outcomes of the Program actions?

Information Gaps

a. Does Section 3.4 of the Science Plan describe the information gaps that are the most important for informing decisions and Healthy Rivers and Landscapes Program Evaluation? Are there additional, major information gaps that should be included?

Informing Adaptive Management

a. What additional components (decision support tools, decision process, recommendation development) are needed to describe how reporting products (Triennial Synthesis Report, Ecological Outcomes Analysis Report) of the Science Plan will be developed to inform adaptive management? Primary Program areas subject to adaptive management both during Program implementation and to inform the shape of the Program post Year 8 will include prioritization for investment in habitat restoration, the timing, shape, and magnitude of environmental flows, and science investments to maximize learning in areas of major uncertainty.

b. What additional content in the Science Plan would be helpful for maximizing the probability that the Science Committee can provide recommendations for adaptive management of the Program?
c. What recommendations do you have for approaches or tools for prioritizing hypotheses, metrics and covariates, monitoring, and modeling resources to optimize information benefits at the full tributary and delta and population tiers?

Review Methods and Layout of the Report

We were asked to review the September 6, 2024, draft version the **Healthy Rivers and Landscapes Science Plan** (https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Voluntary-Watershed-Agreements/Draft_VA_Science_Plan.pdf). My review is based on the information provided in the Science Plan and supplemental material spread across 10 documents, and 3 recorded workshops (https://deltacouncil.ca.gov/delta-science-program/healthy-rivers-and-landscapes-science-plan-independent-peer-review), a briefing by the Delta Science Program, and a second briefing by Science Committee. My review is also based on information in other reports and scientific publications, as well my own experience in fish ecology and management, food webs, monitoring, and quantitative measures of fish habitat quality, spanning large aquatic ecosystems such as the Great Lakes, Chesapeake Bay, Gulf of Mexico, Adriatic Sea, South Pacific, Western Atlantic, and the California Delta. I also based my review on my experience serving for ten years each on the Delta Independent Science Board of the Delta Stewardship Council (https://deltacouncil.ca.gov/delta-isb/), and on the Oregon Watershed Enhancement Board (https://www.oregon.gov/oweb/Pages/index.aspx) which provides grants for watershed restoration and protection throughout Oregon.

This letter review was done independently without consultation with other panelists.

My review emphasizes the biological impacts. I did not comment on the governance, policy, or feasibility of the actions. Also, this review is not intended to be an exhaustive review of the scientific background with detailed citations nor a re-evaluation of the scientific basis report upon which much of the Science Plan is based. Rather, I use that information to make higher-level suggestions intended to improve the Science Plan guidance to individual system-specific science plans and to help ensure that results are robust and useful to the adaptive management process. It is anticipated that actual projects completed under the umbrella of this Science Plan would delve into more details on the individual species, monitoring design, space and time scales, and level of scientific understanding within the context of the geography site with appropriate citations.

My review begins with some overarching comments on some of the strengths of the Science Plan and key opportunities to improve the content, messaging, and clarity of the document. Other considerations are discussed within the five topics that span our detailed questions (i.e., hypotheses, metrics and covariates, monitoring networks and modeling resources, information gaps, and informing adaptive management). These topics are highly interconnected and many of the key considerations are equally applicable to other sections.

General Overview and Strengths of the Science Plan

The Science Plan is largely designed to be a guidance document for more system-specific, targeted science plans and to help improve information for system-wide uncertainties. Specifically, the Science Plan states, *"this document is intended to provide guidance to the Science Committee as it develops recommendations for priority areas of focus for additional monitoring, active experiments, decision support modeling, and data analyses needed to fill knowledge gaps, assess the outcomes of the suite of Program measures, and inform ongoing and future* *decision making".* A major goal of the Science Plan is to also use this framework as a learning process to improve our understanding of how environmental drivers affect fish populations and ecosystem responses within the California Delta.

The Science Plan is a robust, ambitious, and rather unique approach that is based on an extensive review of the science with cognizant recognition that there are uncertainties in our level of understanding of how flow and habitat restoration or landscape reactivation might impact fishes in the face of other environmental drivers.

The Science Plan is structured around four spatially nested 'Big Questions' and a series of fifty-five hypotheses designed to evaluate how additional flows (Flow Measures) and Non-Flow Measures (Habitat restoration, landscape reactivation, improved fish passage and predator management) might improve biological outcomes for native fishes at Local-Level, Full Tributary/Delta-Level and Population-Level Tiers. The tiered spatial structure of the big questions and hypotheses fully recognizes that there are increasing challenges in predicting and measuring biological outcomes at the broader spatial and presumably longer temporal scale because of the expanding levels of environmental drivers at the larger scales.

The hypotheses are comprehensive, logical, and clearly organized in the report across the tiered structure. Each hypotheses includes a target metric and prediction of the direction (increase, decrease, or no change) of the expected change in that metric caused by the actions. Each hypothesis also includes a reference basis for comparison as well as a list of specific environmental drivers (covariates) that could also influence the metric of interest.

The use of hypotheses for specific actions is an excellent approach for this program especially if actively treated as hypotheses. The value of this approach is that it:

- Highlights known uncertainties and lays out a science structure to reduce them,
- Directly tethers science to specific management actions,
- Demonstrates the use of science and monitoring to evaluate the hypotheses,
- Provides a process to learn from the experience and assessments.

Some additional strengths of the Science Plan are:

- The Science Plan is based on a Draft Scientific Basis Report (https://waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/2023/staff-report/app-g2.pdf) that describes the latest scientific information on our current understanding of the processes affecting native fishes in the Delta. The scientific basis report is comprehensive, well reviewed, and cognizant of unknowns, ecosystem variance, dynamics, and uncertainties. This scientific basis report has undergone various peer reviews by the Delta Independent Science Board (https://deltacouncil.ca.gov/pdf/isb/products/2023-03-08-isb-voluntary%20agreements-review.pdf) and others (https://waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/2024/2024.02.21-peer-review-package.pdf). Of note, the report and reviews consistently point out the high degree of uncertainty in understanding the mechanistic relationships and relative strengths of environmental drivers and ecological outcomes, the challenges inherent in current monitoring programs, and the lack of sufficient quantitative models. Indeed, the primary reason for framing the Science Plan around hypotheses is to help fill the gap in our understanding.

- The Science Plan builds on and leverages the vast amount of monitoring that has been conducted and is continuing in the California Delta.

- There is an inherent recognition (that could be more explicitly stated) that the Flow and Non-Flow Measures may not be the key drivers in biological outcomes nor address the key bottleneck to a species production or viability. The listing of the covariates as other environmental drivers that could affect outcomes is an excellent approach to illustrate complexities and help understand environmental drivers and ecosystem processes within the California Delta.

- The identification of specific metrics and reference baselines for comparison provides excellent guidance (although flexibility and risk taking should be encouraged in individual system-specific science plans) and serve as concrete reference points and indicators for tracking performance and outcomes for measures.

- The adoption and definition of best available science enhances the program credibility, reliability, and rigor (e.g., National Research Council 2004, Sullivan et al. 2006, Anchor 2009, Ryder et al. 2010).

- The Science Plan recognizes and endorses the need for a central database that is standardized (e.g., FAIR and CARE data principals) and accessible (Wilkinson et al. 2016, Carroll et al. 2020). This will inform rigorous analyses and comparability across regions and provide a basis for required syntheses.

- The Science Plan explicitly supports Adaptive Management as a guiding principle (Wiens et al. 2021) particularly at set times in the overall 8-year program.

- The Science Plan supports a culture of learning and a 'safe to fail' approach which encourages flexibility when needed.

- The Science Plan strongly endorses transparency, collaboration, and inclusivity (i.e., Indigenous Knowledge), peer review, and robust reporting and evaluation. These are key ingredients and supported by the supplemental documents. Efforts to engage diverse perspectives and knowledge certainly enriches the scientific process and acceptance of results. Setting up a solid peer review process improves quality, rigor, objectivity, and trust in the scientific findings. Robust dialog on the synthesis reports and analyses of ecological outcomes will be critical to evaluate the program's success and informed decision making.

- The Science Plan recognizes that collaborations and teamwork will be key to the success of this program and will be a continuing but important challenge.

- The Science Plan recognizes the difficulties inherent in making population-level assessments because of the challenges to measure population abundances as well as to sort out the myriad of interacting environmental drivers of those abundances. This is especially true for species that spend part of their life in marine waters.

- Decision support models (DSM) are highlighted as valuable tools for integrating information, predicting outcomes, filling knowledge gaps, and informing decisions within an adaptive management framework. While this is important, it is of equal value to use these models upfront for program design. See discussion below.

Key Considerations

Below I outline three considerations to improve the overall Science Plan as a robust guide to the science and monitoring programs.

Need for Conceptual Models

One of the key elements required for the system-specific science plans as outlined in Appendix B of the Science Committee Charter is the inclusion of **"***Conceptual descriptions of the links between applicable Flow and Non-flow Measures and their anticipated biological and environmental effects"*. The value of conceptual models to the design of environmental science and monitoring programs is well recognized (e.g., Margoluis et al. 2009, Reynolds et al. 2016, Sherman et al. 2017, DISB 2022). Such conceptual diagrams are critical for understanding observations, setting appropriate monitoring protocols, identifying direct and indirect interactions among metrics and covariates, and amplifying learning opportunities from the process. The arrows in these diagrams also help to highlight mechanistic processes and knowns and unknowns. The Science Plan should consider including examples or even an overarching template of such as a model, particularly for biological outcomes with full inclusion of covariates. Good examples of these types of diagrams are Figure 2 (*A conceptual model of changes in the species composition and abundances (the species pool) on an ecosystem, leading to multiple consequences*) in the DISB (2021) review of Non-Native species in the Delta and Figure 2 (*Simplified diagram of how flows affect fishes populations directly and indirectly, interacting with other drivers*) in the DISB (2015) review of fish and flows in the Delta.

Put Greater Emphasis on Fish Vital Rates and Food Webs

The narrative objectives, as well as the four big questions, focus on improving or maintaining production of native fish species via improvements in habitat. Fish production depends directly on a fish's vital rates: growth rate, reproductive rate, and survival/mortality rate. As such, these are first order effects of environmental drivers, and they need to be more fully considered as a direct metric or as a covariate. Changes in these rates will have a direct impact on a fish's viability in the system. In simplest terms, any increases in habitat size, availability, or quality can only affect fish densities through changes in vital rates or through relocation of fish populations to the areas of interest.

The Science Plan often considers 'fish metrics' as fish abundances or densities, or more precisely, abundance indices. While this is the ultimate measure of success or failure, environmental drivers more directly affect one of the three main vital rates that determine production, and these should be made more explicit. Measuring rates can be challenging in a largely open, dynamic ecosystem. Again, a conceptual model should be included to illustrate these relationships. This was one of the key recommendations made in the Fish and Flows report by the Delta Independent Science Board (DISB 2015). The type of rates that should be considered included egg and larval survival rates, smolt survival (e.g., Michel et al. 2021), growth rates (Takata et al. 2017), and predation rates (Nobriga et al. 2007, Grossman et al. 2013, Grossman 2016). One can ask; what are the direct drivers of these rates in the ecosystem?

Growth rate can be used as an example as a vital metric. Growth rate is a critical factor for fish and directly corresponds to higher survival rates (e.g., increased swimming speeds and abilities to avoid predation) and reproductive capacity. Higher growth rates (measured or predicted) have long been used as a quantitative measure of fish habitat quality (e.g., Mason et al. 1995, Brandt et al. 2023). Growth rate is perhaps one of the more easily understand and measured vital rates and is highly sensitive to changes in environmental drivers. For many of the restoration hypotheses in the Science Plan, improvements in individual growth rates are an implied intermediate level of response between higher food (invertebrate) densities and higher fish density and should be included as an intermediate hypothesis/metric in this process.

Growth rate can easily be measured in several ways (length/weight, condition, caloric density, wet weight to dry weight ratio, bioelectric impedance, otoliths, scales). It is a highly responsive measure that can change quickly to changes in temperatures and food availability or can be tracked over longer time periods. Growth rate can be easily modeled through bioenergetic models which provide increasingly powerful tools to build mechanistic connections to fish populations (Brownscombe et al. 2022). Bioenergetic models exist for key species in the California Delta such as Delta Smelt (Rose et al. 2013a, Rose et al. 2013b), salmon (e.g., Beauchamp 2009) and some of the predators such as striped bass (Brandt et al. 2009), largemouth bass, and many other species (Deslauriers et al. 2017). Bioenergetic models are easier to develop than full life cycle models and can be used to calculate expected changes in food availability required to produce measurable changes in fish body weight or can be used to set targets or expectations (e.g., Rudstam 2024). A bioenergetic model can also be used to calculate growth rate potential (how well would the fish grow if placed in the habitat) as a measure of fish habitat quality based on vital rates (e.g., Mason et al. 1995, Demers et al. 2000, Nislou et al. 2000, Cassandra et al. 2012). Growth rate potential could be a powerful metric for evaluating habitat quality particularly for rare species such as the Delta Smelt and to test if prevailing habitat conditions could support growth.

The metabolic processes that regulate growth in fish are often nonlinear responses to both physical and biological conditions (e.g., striped bass, Brandt et al. 2009). Understanding the nature of these relationships better informs the monitoring metric of the covariate. For example, measures of the onset and duration of warming and daily range may be more meaningful than mean temperature as a covariate.

More attention also needs to be paid to food web processes. Much has been done on specific aspects of the food wed in the Delta (e.g., MacNalley et al. 2010, Durand 2015, Brown et al. 2016, Hammock et al. 2019, Jeffries et al. 2020, Colombano et al.

2021). Ecological connectivity is important in the California Delta and increased productivity and elevated densities of invertebrate taxa and floodplains relative to the mainstream is predicted from Non-Flow Measures. Food web processes and species interactions can amplify or dampen biological effects of environmental drivers and could play a decisive role in setting the level or even direction of an ecological outcome in this program.

Food webs are mentioned often in the Science Plan and supporting documents, but discussions are largely restricted to increasing overall food resources as measured by overall invertebrate densities or production and predation rates on target species. Increases in food resources are largely presumed to benefit target species. Yet the lack of a quantitative understanding of food webs in the California Delta (DISB 2024) restrains our ability to predict how increases in invertebrates will impact an individual species. Higher food resources may just as likely benefit potential competitors or younger life stages of predators with unknown consequences. Invertebrate productivity may also be reduced by top-down processes and the presence of other potential competitors (Kimmerer et al. 2008, 2013, 2014; Corline et al. 2017; Rogers et al. 2024).

Monitoring related to food web processes could be improved. Measures of food availability could be further refined beyond invertebrate densities or benthic macroinvertebrate indices. Fishes tend to have species and life stage specific preferences for prey types and sizes. Thus, invertebrates are not all equal value to target fishes. Invertebrate prey will also differ in their nutritional value. Redefining food resources or availability based on fish selectivity or diets is an important refinement of metrics or covariates. Fish diets can also be a sign of environmental changes (Glaspie et al. 2019). Other approaches are available. For example, a 'foodscape' approach has been applied in rivers to translate the spatiotemporal patterns in food densities to food availability and quality to map growth rate potential for salmon (Quellet et al. 2024, Rossi et al. 2024).

More attention should be paid to the most abundant species in the ecosystem which can have direct benefits from or impact on ecological outcomes. The native species in the system are relatively rare compared to the dominate species which probably play domineering roles in the food web and energy cycling (see DISB 2024). The densities or growth rates of the most abundant or ecologically important fish species should be considered as a covariate in most of the biological metrics as it has for some. More attention also needs to be paid to the density and grazing rates of the invasive benthic clams as a covariate, that can lower production rates of phytoplankton and zooplankton (Kimmerer and Thompson 2014, Kimmerer and Lougee 2015).

Predator densities are considered important in tidal wetland restoration sites. It is also well-recognized that predation risk, which is often a combination of predator density, consumption capability, prey size, and shelter, can influence habitat use (See Figure 1 in DISB 2024 for a conceptual diagram of food web processes). A more innovative approach could be used to assess predator demand (e.g., Hartman and Brandt 2011). Predation rates or consumption are highly dependent on water temperatures as predators can stop feeding at certain high temperatures. Predatory demand for food can be easily calculated and mapped with a bioenergetic model which are well developed for striped bass and largemouth bass (Brandt et al. 2009, Deslauriers et al. 2017).

Overall, the Science Plan could be improved by more explicitly defining how food-web processes (e.g., detritus role, primary producer-zooplankton linkages, secondary productivity, nutritional value of food, and top-down processes) will be monitored and integrated into habitat suitability, use, and biological effectiveness assessments. The effort will help evolve the HRL program from single species concentrations to more of an ecosystem perspective.

More Rigorous Evaluation of Covariates

The Science Plan framework includes identifying and tracking essential covariates that may help explain why predicted outcomes were not achieved. Overall, the Science Plan does a good job at recognizing that the non-flow and flow measures may not be the sole or even primary environmental drivers in the ecosystem. Most of the individual hypotheses have a list of ‘covariates’ which are largely defined as environmental factors that should be tracked since they might influence the success of the program actions and help explain why program actions do not achieve predicted outcomes. The development of covariates is a key strength of the Science Plan. Covariates will be critical for evaluating ecological outcomes in the context of Adaptive Management and structured decision-making and provide the key ingredients for the learning goals of the Science Plan.

A more detailed and rigorous discussion of the definition, role, formation, functional relationships, and use of covariates would provide better overall guidance to system-specific projects. Monitoring of covariates should also be rigorous as changes in covariates need to be quantitatively assessed.

The types of listed covariates cover a wide range environmental factors including flow, temperature (water and air), turbidity, dissolved oxygen, substrate, food resources, predator densities and cover elements (e.g., vegetation, large woody debris). Some of these covariates operate at different time and spatial scales and can evolve through the duration of the project. A deeper dive into the functional relationships of how the covariates might affect the metric of interest would improve the monitoring and learning. Covariates are not just a list of other things that could influence the results but by definition have a suspected mechanistic connection to the metric of interest. The Science Plan suggests that covariate data will be analyzed using statistical models and reported in Science Program products. Perhaps a more useful approach would be to place more emphasis on the nature and expected impact of covariates at the beginning of the sampling and in the design of the monitoring. Statistical correlations are a first order approach and likely will miss nonlinear or threshold level effects which are common for some drivers like water temperature. The better one can describe these mechanisms, the better one can define the appropriate ‘covariate within the covariate’ and the needed spatial and temporal frequency of monitoring that covariate. Covariates are alternative hypotheses and should be described and measured in that context.

Finally, a more thorough description of some of the covariates would be useful. For example, flow is often listed as a driver or covariate but is not well defined. Often flow is considered as a hydrological term and defined as cubic feet per second. However, a more specific definition of flow is needed to assess biological impact.

Fish cannot directly detect cubic feet per second (DISB 2015). Reconsider what is the real driving driver here such as velocity (rates, timing, extremes) or maximum velocity threshold (e.g., swimming speed of fish that cannot overcome) and define what is meant by flow in each of the hypotheses.

More discussion of temperature as a covariate also seems necessary. Temperature is a key driver of biological processes and often has nonlinear and threshold processes (Richter and Kolmes 2005, Armstrong et al. 2021, Michel et al. 2021). Improved descriptions of this metric (e.g., onset, height and duration of warming, daily variations, temperature thresholds for fish vital rates) seems warranted.

Additional Content

The Science Plan is designed as a framework and overall guidance to developers of individual system-specific science plans. As such, the document could be more complete by including some of the key content found in various parts of the supporting documentation.

In particular, some of the requirements for specific science plans that are listed in Appendix A of the HRL Science Committee Charter (https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Support-Healthy-Rivers-and-Landscape/VASciProgramDraftCharter.pdf) that should be restated in the Science Plan are quoted below:

- *Descriptions of the existing or additional monitoring and studies necessary to track progress relative to the Healthy Rivers and Landscapes Program and to address relevant hypotheses, including monitoring and studies that anticipate opportunities for learning based on unique situations.*

- *Identification of existing and new models to be reviewed by the Science Committee, information needs to improve the predictions of these models, and if appropriate and mutually acceptable, used in assessing expected outcomes of implementation of Flow and Non-flow Measures.*

- *Explicit opportunities for coordination with other groups and initiatives.*

- *Procedures for updating the Science Plan as new information becomes available regarding conceptual models, evidence to support or refute current hypotheses, or changes to other major Science Plan components.*

- *Description of and timeline for anticipated Flow and Non-flow Measures.*

It would also be useful to highlight some of the key attributes of best available science (Sullivan et al. 2006) currently listed in Appendix B of the Science Committee Charter including:

- *Well stated objectives*
- *Clear statements of assumptions and limitations*
- *Use of conceptual, mathematical, statistical, or spatial models*
- *Experimental design with standardized methods for data collection*
- *Statistical rigor and sound logic for analysis and interpretation*
- *Clear documentation of methods, results, and conclusions*
- *Sources of data used are cited*
- *Analytical tools used in analyses and syntheses are identified*

In addition, hypotheses are laid out in such a way as to set up monitoring to prove that the management action has an impact. This is appropriate. However, it might be useful for individual projects to evaluate how the null hypothesis, no effect, could be tested for biological results. Would the sampling design be any different?

The Science Plan would also benefit from a precautionary discussion of some important processes such as sublethal effects, indirect effects (e.g., A affects B and B affects the fish), multiple drivers, synergy, cumulative effects, species behavior and how it is related to feeding, predation risk, environmental factors and nonlinear or threshold effects. While these types of processes are challenging to measure within the context of this program, it might be useful to simply discuss them for background and recognize that these factors could affect results but will probably mostly remain in the unknown category.

Finally, some specific definitions (covariate, ecological outcomes, metric, targets) would be useful as would an explanation of when and how the targets would be derived and used. Ecological targets have yet to be developed.

Hypotheses, Metrics, and Covariates

General Overview

A total of fifty-five hypotheses are tabulated and discussed with each hypothesis having a metric of interest, a response prediction (increase, decrease, or no change), and a description of the reference basis for comparison and a list of covariates that could also affect the metric of interest. The hypotheses are arranged in a series of three spatially nested tiers beginning at local level (Non-Flow Measures only) and expanding to full tributary/delta-level, and population-level metrics. Each of these tiers increases in geographic scale and complexity of the driving forces, and thus the degree of difficulty in achieving or even observing results in the time frame allocated. This is well recognized in the Science Plan.

There is also often a dependent connectivity of hypotheses most notably for habitat restoration. A stepwise process is outlined with four different metrics:

1. Create the habitat (acreage).
2. Ensure that the habitat meets habitat suitability criteria for the species of interest.
3. Ensure that the species has access and uses the habitat.
4. Document that the use of that habitat results in some benefit to the vital needs of the species of interest.

This bottom up or stepwise approach is logical and well thought out. The value of this progressive nature of some of the hypotheses could be better highlighted and explained. A conceptual layout of the design of the hypotheses and that one feeds into the other would be useful.

The aptness of the Habitat Suitability Indices and use/effectiveness assessments are critical components of this approach (see discussion below). If the habitat suitability indices are a poor measure of species-specific habitat quality, then positive ecological outcomes are less likely. Results will be quite dependent on the validity of the Habitat Suitability measures as beneficial to fishes. Much work has gone into the development of Habitat Suitability Indices (e.g., Raleigh 1986, Gard 2009, Anchor 2019, Riebe et al. 2014, Mertz et al. 2018, Davies et al. 2022). These indices play a key role in both the design and assessment of habitat restoration. Many of these indices are based on just a few non-biological factors and their functional relationship to fish is largely not considered per se. It is also unclear how different components of a Habitat Suitability Indices are weighed (see discussion on information gaps).

The choice of a baseline will also be critical to the success of this program. Reference baselines for restoration are largely either comparisons to pre-existing conditions or to nearby reference areas. The Science Plan might consider establishing some solid, measurable, criteria for the selection of these types of baselines. Having two baselines would improve the results significantly.

The hypotheses are very comprehensive but vary widely in their degree of "achievability". Some metrics are structural and direct measures of the actions themselves, such as acreage, while others measure direct biological outcomes that range from individuals to populations. Still, others evaluate whether a particular technique is a good technique. Some metrics assess whether food is produced with the assumption that increased food will lead to improvements in growth or production. The biological and ecological outcomes are in essence the true measure of the success of the management actions. Often, these are measured as endpoints such as densities of the target species. Measuring densities of fishes with active sampling is challenged by ineffective sampling techniques that are often dependent on local conditions (e.g., day or night, turbidity), catchability (which is largely unknown), and patchy distributions or can represent an endpoint that can take some time to get evolve. Therefore, measured densities are largely abundance indices. All biological outcomes should be looked at closer to see if vital biological rates could provide a more robust, immediate and be more sensitive metric to local conditions.

Some greater discussion of the timescales involved in each hypothesis would be useful. Some biological responses may take years whereas some biological responses (e.g., growth) could occur over days to weeks. In some cases, responses could be transient as fish move in and out of the area of interest. Habitat suitability (e.g., cover density, substrate size) may change, shift, or evolve during the study.

Potential New Hypotheses and Metrics

There are several measures of fish vital rates and food web processes that could be added to the list of hypotheses and there are several key drivers that are listed as covariates or having an important influence on fish vital rates but are not specifically listed as hypotheses. Listing these as hypotheses or metrics may help to emphasize their importance and begin to develop a more complete picture of ecological outcomes.

Some additional hypotheses or metrics to consider are:

- As discussed above and in the discussions of individual hypotheses below, fish vital rates should be directly added as a metric of interest. This would include survival (or mortality) rates for eggs, larvae, or juveniles (e.g., in response to reduced predators) or growth rate for any native fishes when food supply is a consideration. Growth rate potential might be considered as a specific metric or habitat suitability measure for Delta Smelt or salmon. Metrics refining food resources and a further consideration of dominate species would be valuable.
- Predation rate or predator demand of key non-native predatory fish species should be considered as a metric since habitat restoration is considered a strategy to reduce this stressor.
- The amount of thermal refugia for native fishes could be considered a metric or a covariate since some specific restoration actions (e.g., creating shaded riverine aquatic habitat, restoring riparian vegetation, enhancing floodplain connectivity) may increase the availability and use of thermal refugia.

- Outcomes for specific indicators of ecosystem health or species vitality, as defined and measured through a collaborative process incorporating Traditional Ecological Knowledge (TEK), should be developed.
- Transparency is a key component of the HRL program. One could develop some metrics/measures to encourage site specific work to be inclusive. Performance measures and techniques are well established in the outreach and engagement field (e.g., Fergeson 2016 and references cited therein) and could be incorporated into the monitoring design and indicator selection.
- Learning is also a key goal for the Science Plan. How will this be formally assessed?

Closer Look at Individual Hypotheses, Metrics, and Covariates

Spawning and Rearing Habitats S1-3, R1-4,

The first six hypotheses cover spawning and rearing habitat for salmon. Physical and structural habitat are described as driving forces. Covariates include flow which needs a more specific description (units). The methods for measuring success are number of redds rather than egg or larval survival and densities of juveniles rather than growth rates. Covariates ignore presence of competitors or densities of non-native competitors that could impact biomass density of secondary production or predators that could affecting egg, larval, or juvenile survival.

Tributary Floodplain

The tributary floodplain Hypotheses 1through6 cover salmon and Hypothesis 7 covers some other native species. Covariates should include densities of non-native fishes as potential consumers (TribFP3). Metrics of target densities (TribFP4 and TribFP7) should include density of potential predators as a covariate.

TribFP5 does includes salmon growth rate as a metric as driven by water temperature and food availability (secondary production) and here is where temperatures should reflect the nonlinearity and threshold level of response.

TribFP7 is catch frequency of native fishes. Again, one could include growth rate here as a direct measure of production and covariates could include a definition of flow and presence of competitors, especially the more abundant non-natives species, and predator density or predation risk.

Bypass Floodplain

The BypassFP1 metric (acreage suitable for invertebrate production) is vague. Does this include all invertebrate production or only invertebrates that form the main diet of salmon? It seems that covariates should include temperature, nutrient loading and maybe the presence of other consumers.

BypassFP2 should include those key factors that affect zooplankton densities which could include water temperatures and the densities of major consumers of zooplankton. The word 'beneficial' needs to be better described.

BypassFP3 is very specific in that salmon will bear an isotopic signal of these items in their diet. It seems one could measure fish growth rates again. Does water temperature affect these rates?

BypassFP5 suggests that it will increase availability of habitat suitable for growth survival and/or reproduction. It seems that if that is the case, the metrics should be growth rates, survival rates or reproductive rates as opposed to water quality variables that are suitable for this. Covariates should include water temperature.

Bypass FP7 really talks about increased mortality due to stranding and predation while on the floodplain. The importance of this really needs to be looked at in comparison to the overall benefit in production provided by the floodplain.

Bypass FP9 argues that native fish spawning success will increase, and the metric is going to be the number of juveniles exiting the Yolo pass and the number of adults in the Delta. Is there a direct way to measure spawning success, egg and larval production, or survival? Why are only splittail and blackfish being considered for this hypothesis?

Tidal Wetlands

TW2 addresses habitat suitability for target species defined by water quality. Clearly this is an important criterion and requires more detailed discussion of the habitat suitability within wetlands. Most of the body of the text related to this metric focuses on harmful algal blooms (HABs). Covariates for HABs would include water temperature and degree of stratification as well as nutrient levels.

TW3 does include densities of potential competitors as a covariate to invertebrate production since competitors might impact food availability for target species. As mentioned elsewhere, densities of potential competitors should be included in similar metrics of food availability.

TW4 is a measure of the diet rather than a consequence of actions per se. Clearly as one begins to unravel the relationship of habitat reconstruction (TW1) to invertebrate production (TW3) to growth and condition (TW5) it is important to understand what the fish are eating relative to what is being produced. This set of hypotheses get closer to looking at the food web which is a critical information gap (see below). This hypothesis is of solid value to learning. TW4 also highlights some of the various genetic techniques and other techniques that can be used for these analyses.

TW5 is measure of growth and condition. It is clearly dependent on water temperature in a nonlinear fashion. TW5 is the linchpin of what we're really looking for in terms of an ecological result.

Tributary Flow Pulses

TribFlow 1 and 2 are sound but how do you compare the rates from one year to the next? Is there a way to standardize the increases in rates relative to the time frames of interest to the total migrations rates? Water velocities should be considered as a covariate or driving force and explicit listed.

TribFlow 3 is a measure of salmon survival and a direct measure of a vital rate. Is predation rate a covariate?

Tributary Wide

TribWide 2 is a measure of the relative survival to juvenile stage and should include potential sources of mortality such as predator densities or predation rates as a covariate.

Similarly, Tribwide 3 is a measure of condition and should incorporate growth rate as a metric. Covariates go beyond water temperature and should include some measure of food availability. It is suggested that improvements in primary and secondary production will improve condition of Chinook Salmon *Oncorhynchus tshawytscha*. Metric measures should go beyond Fulton's condition factor (see discussion on vital rates).

TribWide 2 and 4 should provide a better description of what is meant by flow as a covariate.

Delta Outflow

Many of the Delta flow comments are similar to other hypotheses. For covariates it is best to define the proximal drivers and clarify what is meant by outflow, inflow and hydrodynamics or at least require the system-specific science plans to do so.

DeltaFlow 3 hypothesizes that increased spring delta outflows will improve recruitment and result in increased adult and larval longfin smelt. It should be well recognized that inter annual variability in recruitment and adult population size are based on several factors as evidenced by the developing life cycle model for longfin smelt. There are several different covariates that could be listed here (e.g., food abundances, predation rates) and it would be a challenge to specifically relate changes in abundances to an increased spring delta outflow.

DeltaFlow 4 is also a challenge given the low abundances of Delta smelt.

DeltaFlow 5 has two metrics: reduced travel time and increased survival of juvenile salmon.

DeltaFlow 7 deals with white sturgeon and appears to be directly dependent on the spawning population size. Other factors such as survival and mortality rates should be covariates.

The DeltaFlow 9 metric is frequency, magnitude, and severity of Harmful Algal Blooms. Residence time and degree of stratification should also be covariates.

Monitoring Networks and Modeling Resources

Overall Design of Monitoring

Monitoring is fundamental to understanding ecosystem status and responses to environmental and management drivers. The proper design and execution of the monitoring programs within the Science Plan will be foundational to the success of the program. The Science Plan understands this and spends well over one third of the Science Plan discussing the specifics of potential monitoring strategies to measure the responses of metrics to management actions.

The Science Plan monitoring program is highly responsive to the five best practices for monitoring outlined in the Delta Independent Science Board comprehensive review of the Delta Monitoring enterprise (DISB 2022) and recognized elsewhere (e.g., Reynolds et al. 2026; Fancy et al. 2009). Generally, those five best practices are:

1. Formally tie monitoring to questions, goals, and objectives.
2. Be informed by stakeholders' needs and capability and include alternative forms of data and knowledge.
3. Adapt as new information and technology becomes available.
4. Include data management, analysis, and synthesis.
5. Ensure data are accessible.

These best practices are largely adopted by the Science Plan as a whole and the Science Plan should encourage their use for system-specific science plans.

The DISB (2022) also laid out a detailed adaptive monitoring framework (also see Lindenmayer and Likens 2009; Lindenmayer et al. 2011) for designing an individual monitoring program that sketches out (among other things), the need for a conceptual model, the need to set the time and space scope of the project, and the need to specify how, where, when, frequency and duration of measures. Individual monitoring programs in system-specific science plans should also be encouraged to review the DISB (2022) and references cited therein for this guidance.

The Science Plan monitoring is designed to test whether the Flow Measures and/or Non-Flow Measures have their intended outcomes. Metrics are quite varied and range from implementation evaluation (e.g., acreage), to validation (e.g., evaluating certain techniques) to assessing the biological consequences of management actions. The problems being addressed are well framed using hypotheses, metrics, and covariates.

The Science Plan does a good job of reviewing the existing monitoring programs and assessing how the programs currently align with the metrics needed to evaluate the hypotheses. This will provide a solid starting point for the development of monitoring programs for specific projects. Overall, a more thorough review of existing or historic monitoring programs should be done for each project and greater emphasis should be placed on the monitoring of covariates as these are essential to assessing the outcomes (see discussions above). Nelitz et al. (2020) provides a comprehensive inventory of the monitoring enterprise of the Delta that includes discussions of the size and geographic scope of monitoring programs across federal, statewide, regional, local, agency, and private entities. The inventory includes 120 unique monitoring activities spanning over 1500 sampling locations within the Delta and Suisan Marsh. The inventory includes detailed tables of which entities are doing the monitoring as well as the years sampled, and specific parameters being measured. There is also an analysis of interactions among agencies doing the monitoring.

The Science Plan regularly points out some of the inherent uncertainties or limitations to existing monitoring programs and the challenges with biological data including unknown fish catchability, a focus on larval and juveniles rather than adult pelagic species, lack of enough information on marine mammal or bird predation, and lack of databases for major areas such as fish diets. Several reviews on monitoring programs in the California Delta should be considered by system-specific projects since they further illustrate the strengths and challenges with existing monitoring programs. For example, the IEP Technical Report #96

https://cadwr.app.box.com/s/5y13dz3wg04t5abkprvjfj9lmwz29a96

reviews three of the main bottom and midwater trawls surveys and points out their value and limitations in assessing relative fish abundance in the context of evolving objectives over the past fifty years. During 2020-22 the Collaborative Science and Adaptive Management Program (CSAMP) reviewed five monitoring reviews (Melwani et al. 2021):

https://csamp.baydeltalive.com/docs/25921

1. The Delta Independent Science Board monitoring enterprise review 2018-2022.
2. Historical IEP Monitoring Program Reviews 2004-2019.
3. IEP Long-term monitoring Review Pilot Effort 2020.
4. 6-agency monitoring redesign 2020-2022.
5. Salmon and Sturgeon Assessment of Indicators by Life Stage (SAIL) 2015-2016.

More focused reviews at the species, project, or methodology scale are available in Interagency Ecological Program annual and technical reports (https://iep.ca.gov/Publications/Library). There are also several scientific publications that look at specific issues relative to monitoring. For example, Johnson et al. (2017) argue for system-wide actions on winter-run salmon that include genetic run identification, real-time fish survival and movement monitoring, and collecting more data on fish growth and condition.

Below I point out several opportunities to improve overall monitoring efforts across the Science Plan.

Linking Monitoring to Modeling and Learning

Ultimately, the purpose and value of any monitoring program depends on the level of scientific understanding of the ecosystem being monitored, as well as the specific management purpose. As mentioned earlier, the use of a conceptual model at the outset was a part of the requirements of project submissions outlined in the Science Committee Charter as well as a key recommendation for the development of effective monitoring programs (Margoluis et al. 2009, Reynolds et al. 2016, DISB 2022).

Monitoring and modeling need to be better and more explicitly and formerly linked in the Science Plan. The availability and value of biological/ecological models to restoration and management should be more thoroughly reviewed (e.g., Swannack et al. 2012, Rose et al 2015, DeMutsert et al. 2016, Gruss et al. 2017, Geary et al. 2020, Peterson and Durante 2020). This will improve the power of the monitoring by focusing effort on key metrics and covariates and will guide learning.

Models should be developed at the outset of a project to help develop monitoring programs and better define direct and indirect relations that may not be apparent with a simple listing of covariates. Tighter linkages between monitoring and modeling may better quantify sensitive parameters and identify gaps. There are several existing models that could be used. Existing models span a host of complexity ranging from simple models that outline the expected driving forces and responses (e.g., plus or minus) to models that can focus on the specific metric of interest such as growth rate (a bioenergetic model) or egg survival rate to more complex models that have been used to link hydrodynamic processes to growth and survival (e.g., Rose et al. 2013a, 2013b).

Full life cycles models may not be needed for most metrics. Life cycle models have been developed for Delta smelt and salmon and are under development for longfin smelt. These models will apparently form part of the Structured Decision-Making process. It is unclear whether these decision-support models are being used to help design sampling programs or only applied in Year 8 as a retrospective analysis.

Improving the Power of Monitoring

Perhaps the fundamental challenge of the monitoring program is to ensure that the monitoring has sufficient (statistical) power to detect the level of changes anticipated. For some of the metrics such as acreage, this is not an issue. But it is clearly an issue for most of the biological outcomes which have a high degree of variability in estimates due to patchy distributions, unknown and variable catchability, and ecological dynamics. The current Science Plan largely just requires sufficient sampling power to detect an increase or a decrease rather than to detect progress toward a specific target. However, many of the expected biological outcomes are predicted to be small and may even take time/years to evolve. For example, some of the anticipated outcomes illustrated in Chapter 6 of the Scientific Basis Report are on the order of a few percentage points. Can this level of change be detected? Individual system-specific science plans should discuss the degree of power of their sampling program in this context using prior sampling information and experience. Quantitative modeling can also help here. A similar argument needs to be made when sampling the covariates; is monitoring sufficient to detect significant variations?

A better sense of the level of expected changes in metrics **and covariates** would help to ensure that the sampling has sufficient power to be able to detect that change (Zuur et al. 2010, Southwell et al. 2019, Rogers et al. 2022). There are some numbers available in the scientific basis report but as a minimum it should be required that specific projects have these estimates in mind and that the sampling protocol is sufficient to detect any differences. A quantitative power analysis should be encouraged.

A better understanding of the functional relationship of covariates to metrics would also improve monitoring power since the more relevant parameter and time scales would be assessed (see discussion in covariates above). Understanding the time and space scales of responses as well as the nonlinearities and thresholds in the functional relationships will improve the power of the monitoring as well as the suitability of parameters being measured.

Ultimately, sampling designs should be done in a way so that the null hypothesis, no effect, can be refuted with confidence. Variances that are too high to detect differences would merely lead to the conclusion that more data are needed.

Balancing Existing and New Monitoring Efforts

There will be a need to balance the use of existing monitoring programs and new efforts, and this will be challenging.

A stated purpose for monitoring in the Science Plan is to take advantage of existing monitoring efforts and to help ensure that any new monitoring is comparable to existing monitoring efforts. The monitoring enterprise in the California Delta is large, comprehensive, and is being done by a host of different entities and agencies. Nelitz et al. (2020) provide a comprehensive inventory of the monitoring programs across the Delta. The advantages of using existing monitoring as the framework for hypothesis testing are many. Consistency in metrics and data collection methods is essential to enable syntheses across tributaries and to evaluate the aggregated effects of the actions. Many of these monitoring programs have undergone extensive review and their strengths and limitations are well known. The use of existing monitoring programs will also be less costly, and the data generated will likely be more suitable for database inclusion.

Monitoring programs in the California Delta have been developed for a variety of different reasons and may not have the statistical power or spatial/temporal resolution to test hypotheses particularly at the local or full tributary scales. Some new technologies are mentioned throughout the monitoring discussion. These technologies may be critical, especially for looking at finer-scale space and time resolution. They often can provide more quantitative measures. Some of these new technologies include: advanced genetic techniques (parentage-based tagging, otolith microchemistry, genetic diet analysis), environmental DNA (eDNA) and Close-Kin mark-recapture (CKMR), acoustic techniques such as acoustic tagging/telemetry to monitor species movements and mobile or fixed split-beam echo sounding to measure fish densities (Cutter et al. 2017), sonar imagery (Dual Frequency Identification Sonar or Adaptive Resolution Imaging Sonar (ARIS), and linking advanced hydrodynamic and life cycle modeling (Rose et al. 2013a, 2013b). These technologies have proven capabilities and can often provide detailed, spatially explicit information on fish movement, survival, and passage efficiency.

The development of a robust project-specific monitoring plan might begin by following the guidance in the review by the Delta Independent Science Board (DISB 2022) to explicitly identify the hypothesis, develop a conceptual model, and then design the monitoring program at the appropriate time and space scales using the most appropriate technologies and sufficient sampling power to test/reject the hypothesis. Once this exercise has been completed, existing monitoring programs could be reviewed for applicability. This formal exercise would help assess the value of new techniques and allow an evaluation of the limitations or consequences of using existing sampling programs.

Information Gaps

Introduction

Section 3.4 of the Science Plan discusses four high-level priority information gaps that will need more attention because they have “implications for the ability of the Science Program to draw broad inferences about the effects of the Flow and Non-Flow Measures in support of Narrative Objectives.” These information gaps are relevant to several hypotheses. The information gaps identified are:

1. Ability to differentiate natural origin and hatchery-origin adults for each tributary.

Clearly, the ability to identify natural origin salmon is critical to achieve the narrative objective of double the natural production of Chinook Salmon. Marking all stocked fish would resolve this issue. The Science Plan also mentions that otolith growth patterns and microchemistry (Barnett-Johnson et al. 2007; Barnett-Johnson et al. 2008) might also be a useful approach but is labor intensive. One could make the case that improved salmon habitats could, by inference, be beneficial to all salmon.

2. Consistency of monitoring approaches across tributaries to support system level analysis.

This is clearly an important goal as one moves up the analyses to delta-wide and population-wide assessment. This section could further elaborate on the comparisons of production of benthic invertebrates and zooplankton. It seems the zooplankton and phytoplankton sampling are not fully accounted for in Table 4 and that there are several other invertebrate sampling programs conducted alongside the fish monitoring and other water quality program monitoring. Secondly, not all invertebrates are equal. As discussed above, fish are often highly selective in the size and type of prey they eat. Although there has been a lot of diet work on fishes in the Delta (DISB 2024), these data do not have a centralized database nor are zooplankton sampling categorized by species-specific food requirements.

3. Design of population estimates for non-salmonid target species in the Delta.

This certainly is a major information gap. Although there is a wealth of fish sampling programs in the Delta, most of these programs only provide abundance indices given the unknown gear-type/species type and size selectivity. Sampling is also done at relatively course ,often monthly, schedules which challenges our ability to decipher mechanisms which can operate at shorter time intervals.

The various trawling programs have been examined and reviewed and compared in several different ways (Melwani et al. 2021). Some new approaches could be used to quantify fish population size. For example, pelagic fish are notoriously difficult to catch in midwater trawls during the day and night sampling may be far more effective particularly at site specific locations where the catchability is likely to increase. Similarly, combining midwater trawls with active underwater acoustics has been effective as assessing the fine-scale spatial distributions and absolute abundances of pelagic fishes in other large ecosystems and estuaries (Boswell et al. 2007, 2010, Samedy et al. 2015) and has been applied in the California Delta (Cutter et al. 2017).

4. Data availability and centralization to support coordinated analysis and reporting.

This is clearly a need and has been suggested elsewhere.

Below I describe three additional information gaps that ultimately will be critical for understanding the impacts of proposed management actions and other environmental drivers on fishes. Clearly these gaps will unlikely be filled during the eight-year time frame of this project since they are big issues, but awareness of these gaps would help guide science and prioritize learning opportunities.

Mechanistic Understanding of Environmental Drivers and Fish Production

One information gap is our lack of understanding of the mechanistic responses of a fish's vital rates to flows and other environmental drivers. This mechanistic understanding was identified as a major need in the DISB (2015) review of fish and flows. How exactly do flows affect fish populations and what part(s) of flow are the mechanistic drivers? What are the key bottlenecks to fishes' population vitality?

The Science Plan and supporting documents discuss a host of uncertainties. The primary factors influencing each species abundance need to be synthesized and included in the conceptual model with identification of the unknowns and knowns in this context. This has been done in a lot of the primary literature, but a synthesis document targeted at the specific hypotheses and alternative hypotheses generated by the covariates is needed.

The entire mechanistic connection of fish abundances to flow rates has been the subject of much debate (DISB 2015). Although correlations in annual flows and annual abundance indices of some fish populations have been observed, the primary mechanisms driving this relationship remain unknown. A better understanding of the biological responses to environmental drivers, particularly flow, has been a long-standing question and an important unknown for highly relevant to the HRL program. Developing a quantitative and mechanistic understanding of environmental drivers and the biological responses is a huge, but necessary challenge.

Improved Understanding of Food Webs

A recent review by the Delta Independent Science Board (DISB 2024) highlighted our need for improved understanding of Delta food webs particularly at the upper trophic levels. They recommended developing appropriately scaled and spatially explicit food web models to predict how environmental drivers and management actions affect fish species as well as the need for a centralized database on fish diets. Understanding food web processes is a recognized need in the California Delta and various approaches have been valuable to restoration and management in other large ecosystems (e.g., VanderZanden et al. 2006, Rieman et al. 2015, Demutsert et al. 2016, Gruss et al. 2017, Kaplan et al. 2019, Lewis et al. 2021, Naiman et al. 2022, Zhang et al. 2023).

Nearly all the non-flow measures that relate to habitat restoration rely on the assumptions that these efforts will increase the density and abundance of food for targeted native species. The underlying assumption is that more food in general might mean more food for the target species of interest. However, those food resources will also supply food to potential competitors which are likely far more abundant. Those competitors could reduce that food supply. As discussed above, the real question is where this production goes and who benefits from it. Similarly, predators may be important in setting the overall production rate of native species (e.g., Nobriga et al. 2007, Schreier et al. 2016). Both top-down and bottom processes are evident in the Delta (Rogers et al. 2024) and food web processes directly affect growth, reproduction, and survival and counterintuitive reactions are common in food web dynamics (Naiman et al. 2022). Improved understanding of species interactions and food webs in the Delta will strengthen the ability of management actions to predict outcomes.

Improved Metrics for Fish Habitat Suitability

Habitat Suitability Indices (HSI) are key metrics of the Science Plan used to both design and evaluate the success of habitat restoration and landscape reactivation. The success of this HRL program in general will depend directly on how well HSI captures the essential conditions required for a fish species viability. The limitations of the HSI and challenges in accounting for and evaluating the quality and functionality of restored habitat beyond acreage are recognized in the supporting documents (Appendix F of the HRL Strategic Plan and the Scientific Basis Report) but are still given great significance in the overall Science Plan structure.

The Habitat Suitability Indices used in the Science Plan are non-biological and often only include a few structural features (e.g., salmon spawning habitat) or water quality criteria (salinity, water temperature, turbidity, water depth) that are largely based on simple correlations with observed fish abundances or expert opinion. Key habitat suitability factors like food supply, densities of competitors and predators, refuge, and vegetation were not fully included in suitability criteria due to lack of data.

Habitat suitability essentially defines habitat quality and should be based on the vital needs and differences among species and their life stages. Our level of confidence or understanding of HSI differs broadly across species and life stages. The exact definition of HSI is often left to be developed by the system-specific science plan. This is perhaps best illustrated by Hypothesis Bypass HP5 which has a tabulated metric of water quality for targeted native fish that will be identified “based on best available science for the life stage and species”. The full stated hypothesis is “Bypass floodplain habitat resulting from efforts to increase availability of the habitat to targeted native fishes, will be suitable for their growth, survival, and or reproduction as required by the targeted life stage”. This requires a quantitative functional understanding of habitat needs for growth, survival, and or reproduction which is an information gap for most fish species in the Delta. HSI based purely on correlations will miss the nonlinearities and thresholds inherent in biological responses to environmental drivers. Improvements in the HSI will help better align habitat accounting to habitat use and effectiveness in the context of the Science Plan and ecological outcomes. Further work on functional measures of habitat quality (e.g., Zhang et al. 2014, Brandt et al. 2023) might be valuable here, especially for pelagic fishes.

Informing Adaptive Management

An adaptive management framework is proposed to assess the future of the HRL program based on ecological outcomes. Adaptive management is recognized as an important process linking science to management in the California Delta (Wiens et al. 2017). In the HRL program, there are key times (Year 3, Year 6, Year 8) at which syntheses will be done and ecological outcomes will be reported. Ultimately a decision will be made to continue the program, end the program, or move forward with a modified program. Decision support models will provide valuable tools to evaluate priorities for habitat restoration and, based on ecological outcomes, help identify information gaps and sensitivity to drivers.

Normally an adaptive management program has key decision targets or thresholds (Wiens et al. 2017) to determine whether the program is successful. In the HRL program, decisions will be based on 'ecological outcomes', but the overall decision-making criteria are somewhat vague especially if results are inconclusive or mixed. This raises several questions. How will results across the 55 hypotheses be weighted? The various hypotheses have a mixture of metrics. Some metrics assess whether certain design criteria were achieved. These could be achieved without any biological effect or any detectable biological outcome. How will these compare to the biological measures of increased growth or abundances of target species which is the goal? Would the program move forward if all non-fish metrics were achieved but no changes in fish metrics were detected? If there are no improvements in fish metrics, does the monitoring have sufficient power to eliminant or identify covariates or deficient HSI characterization as the primary cause? The interpretations of the covariates will also be important for adaptive management.

What would happen if there were improvements in biological outcomes but also significant correlations with covariates? Can the roles of environmental drivers be better isolated? Many of the suggestions made is this review to foster more effort on vital rates and food webs, better define functional relationships especially among covariates, improve habitat suitability indices, and link models to project design are intended to strengthen the ability of the science to explain results and thus improve adaptive management.

The adaptive management program must also define how it will deal with changes that occur during the eight-year time frame. The California Delta is dynamic and conditions in the delta are likely to change during the program (e.g., Norgaard et al. 2021). Changes that might be anticipated include:

- An event-level change in the primary drivers such as a flood, a drought (Hartman et al. 2024), or a new species (DISB 2021) such as the golden mussel.
- Advances in sampling technology.
- Significant improvement in our understanding of a process.

Flexibility in the design of the programs or assessments at the annual or triennial stage could be part of a more formal “adaptative science strategy” or an “adaptive monitoring strategy” (Lindenmayer and Likens 2009, Lindenmayer et al. 2011). The Adaptive Management component of the Science Plan should give specific consideration for dealing with these types of major changes in drivers. Expected changes should also be considered in system-specific science plans.

Final Thoughts and Conclusions

The California Delta is a large, complex, dynamic ecosystem that has undergone tremendous changes and continues to undergo those changes (Norgaard et al. 2021). As such, the actions being taken in the Healthy Rivers and Landscapes program could be considered comparatively small relative to past changes, other environmental drivers, and interannual variability. It will take a concerted effort to align any ecological outcomes to specific management actions particularly at the population or ecosystem levels. The Science Plan recognizes the challenges of dealing with multiple stressors and sets up robust hypotheses and monitoring programs to address them. The Science Plan is a novel and scientifically driven way to tether science to management actions and ultimately to improve understanding to allow actual predictions and reasonable target expectations to be set and met. I strongly commend this effort.

The comments made in this review are not to be viewed as criticisms but merely suggestions to improve scientific validity and rigor of the methods proposed so that the biological impacts of management actions can be meaningfully tested.

References

Anchor, Q.E.A., 2019. Conservation Planning Foundation for Restoring Chinook Salmon (Oncorhynchus Tshawytscha) and O. mykiss in the Stanislaus River. 402 pp https://www.noaa.gov/sites/default/files/legacy/document/2020/Oct/07354626617.pdf

Armstrong, J. B., Fullerton, A. H., Jordan, C. E., Ebersole, J. L., Bellmore, J. R., Arismendi, I., Brooke, E. P., and G.H. Reeves, 2021. The importance of warm habitat to the growth regime of cold-water fishes. Nature Climate Change. 11(4): 354–361.

Beauchamp, D. A., 2009. Bioenergetic ontogeny: Linking climate and mass-specific feeding to life-cycle growth and survival of salmon. American Fisheries Society Symposium. 70: 1–19.

Boswell, K. M., M. P. Wilson, and C. A. Wilson, 2007. Hydroacoustics as a tool for assessing fish biomass and size distribution associated with discrete shallow water estuarine habitats in Louisiana. Estuaries and Coasts 30:601-617.

Boswell, K. M., M. P. Wilson, P.D. Macrae, C. A. Wilson, and J. H. Cowan, 2015. Seasonal estimates of fish biomass and length distributions using acoustics and traditional nets to identify estuarine habitat preferences in Barataria Bay, Louisiana. Fisheries Research. 172: 225-233.

Brandt, S.B., M. Gerkin, K. Hartman, and E. Demers, 2009. Effects of hypoxia on food consumption and growth of juvenile striped bass (*Morone saxatilis*). Journal of Experimental Marine Biology and Ecology. 381:143-149.

Brandt, S.B., S.E. Kolesar, C.N. Glaspie, A. Laurent, C.E. Sellinger, J.J. Pierson, M.R. Roman, and W.C. Boicourt, 2023. Functional seascapes: Understanding the consequences of hypoxia and spatial patterning in pelagic ecosystems. Oceanography 36:28–30.

Brown, L.R., Kimmerer, W., Conrad, J.L., Lesmeister, S. and A. Mueller-Solger, 2016. Food webs of the delta, Suisun Bay, and Suisun marsh: An update on current understanding and possibilities for management. San Francisco Estuary and Watershed Science, 14. DOI: 10.15447/sfews.2016v14iss3art4.

Carroll S.R., Garba I., Figueroa-Rodríguez O.L., Holbrook J., Lovett R., Materechera S., Parsons M., Raseroka K., Rodriguez-Lonebear D., Rowe R., Sara R., Walker

J.D., Anderson J., and M. Hudson, 2020. The CARE Principles for Indigenous Data Governance. Data Science Journal. 19(1): 1-12.

Cassandra, J.M., D.D. Aday, R. S. Hale, J.C.S.D. Selinger and E. A. Marschall, 2012. Modeling habitat selection of a top predator: Considering growth and physical environments in a spatial context. Transactions of the American Fisheries Society**.** 141(1): 215-22.

Colombano, D.D., Handley, T.B., O'Rear, T.A., Durand, J.R. and P.B. Moyle, 2021. Complex tidal marsh dynamics structure fish foraging patterns in the San Francisco Estuary. Estuaries and Coasts. 44:1604–1618.

Corline, N. J., T. Sommer, C. A. Jeffres, and J. Katz, 2017. Zooplankton ecology and trophic resources for rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA. Wetlands Ecology and Management 25:533–545.

Cutter, C.R., Jr., S. C. Manugian, J. Renfree, J. Smith, C. Michel, D. Huff, T.S. Sessions, B. E. Elliot, K. Stierhoff, S. Mau, D. Murfin, and D. A. Demer, 2017. Mobile Acoustic Sampling to Map Bathymetry and Quantify the Densities and Distributions of Salmonid Smolt Predators in the San Joaquin River. NOAA Technical Memorandum, NOAA-TM-NMFSSWFSC-575. 134 pp.

Davis B, Bush E, Lehman P, C. Pien 2022. Temperature thresholds for aquatic species in the Sacramento San–Joaquin Delta. version 2. Environmental Data Initiative. https://doi.org/10.6073/pasta/0ffa27c1302fd8f 6197ea5ffd9feff9e

Delta Independent Science Board, 2015. Flows and fishes in the Sacramento-San Joaquin Delta. Research needs in support of adaptive management. 38 pp. https://deltacouncil.ca.gov/pdf/isb/products/2015-09-29-isb-final-fishes-and-flows-in-the-delta.pdf

Delta Independent Science Board, 2021. The science of non-native species in a dynamic. Delta. 84 pp. https://deltacouncil.ca.gov/pdf/isb/products/2021-05-21-isb-non-native-species-review.pdf

Delta Independent Science Board, 2022. Review of the Monitoring Enterprise in the Sacramento-San Joaquin Delta. Report to the Delta Stewardship Council Sacramento, California. 186 pp. https://deltacouncil.ca.gov/pdf/isb/products/2022-03-22-isb-monitoring-enterprise-review.pdf

Delta Independent Science Board, 2024. Advancing Scientific Understanding and Management of the Delta Through a Food Web Perspective. Report to the

Delta Stewardship Council. Sacramento, California. 118 pp. https://deltacouncil.ca.gov/pdf/isb/products/2024-10-02-isb-food-webs-review.pdf

Demers, E., S.B. Brandt, K.L. Barry and J.M. Jech, 2000. Spatially-explicit models of growth rate potential: Linking estuarine fish production to the biological and physical environment. pp 405-426. In: J.E. Hobbie (ed.). Estuarine Science: A Synthetic Approach to Research and Practice. Island Press, Washington, D.C. 539pp.

De Mutsert, K., Steenbeek, J., Lewis, K., Buszowski, J., Cowan, J.H. & Christensen, V., 2016. Exploring effects of hypoxia on fish and fisheries in the northern Gulf of Mexico using a dynamic spatially explicit ecosystem model. Ecological Modelling, 331:142–150.

Deslauriers, D., Chipps, S.R., Breck, J.E., Rice, J.A., and C.P. Madenjian, 2017. Fish Bioenergetics 4.0: An R-Based Modeling Application. Fisheries 42: 586-596.

Durand, J.R., 2015. A conceptual model of the aquatic food web of the upper San Francisco Estuary. San Francisco Estuary and Watershed Science, 13.

Fancy, S., Gross, J. E., and S.L. Carter, 2009. Monitoring the condition of natural resources in the U.S. National Parks. Environmental Monitoring and Assessment, 151, 161–174.

Ferguson, L., 2016. An annotated reference guide for scientific engagement with natural-resource practitioners. Oregon Sea Grant. 20 pp.

Gard, M., 2009. Comparison of spawning habitat predictions of PHABSIM and River2D models*. International Journal of River Basin Management 7: 55–71.

Geary, W. L., M. Bode, T. S. Doherty, E. A. Fulton, D. G. Nimmo, A. I. T. Tulloch, V. J. D. Tulloch, and E. G. Ritchie, 2020. A guide to ecosystem models and their environmental applications. Nature Ecology and Evolution 4:1459–1471.

Glaspie, C.N., Clouse, M., Huebert, K., Ludsin, S.A., Mason, D.M., Pierson, J.J., Roman, M.R. and S.B. Brandt, 2019. Fish diet shifts associated with the northern Gulf of Mexico hypoxic zone. Estuaries and Coasts. 42: 2170–2183.

Grossman, G.D., 2016. Predation on fishes in the Sacramento-San Joaquin Delta: Current knowledge and future directions. San Francisco Estuary and Watershed Science, 14(2) DOI: 10.15447/sfews.2016v14iss2art8.

Grossman, G. D., T. Essington, B. Johnson, J. A. Miller, N. E. Monsen, and T. N. Pearsons. 2013. Effects of fish predation on Salmonids in the Sacramento

River – San Joaquin Delta and associated ecosystems. California Department of Fish and Wildlife. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=73874

Grüss, A., K. A. Rose, J. Simons, C. H. Ainsworth, E. A. Babcock, D. D. Chagaris, K. De Mutsert, J. Froeschke, P. Himchak, I. C. Kaplan, H. O'Farrell, and M. J. Zetina Rejon, 2017. Recommendations on the use of ecosystem modeling for informing ecosystem-based fisheries management and restoration outcomes in the Gulf of Mexico. Marine and Coastal Fisheries 9:281–295.

Hammock, B.G., Hartman, R., Slater, S.B., Hennessy, A., and S.J. Teh, 2019. Tidal wetlands associated with foraging success of Delta smelt. Estuaries and Coasts. 42:857–867.

Hartman, K.J., and S.B. Brandt, 2011. Predatory demand and impact of striped bass, bluefish, and weakfish in the Chesapeake Bay: Applications of bioenergetics models. *Canadian Journal of Fisheries and Aquatic Sciences* 52(8):1,667–1,678.

Hartman, R., Burdi, C., Maguire, A., Bosworth, D., and E. Stumpner, 2024. Dry me a river: Ecological effects of drought in the upper San Francisco Estuary. San Francisco Estuary and Watershed Science. 22(1) 1-28.

Jeffres, C.A., Holmes, E.J., Sommer, T.R. and J.V.E. Katz, 2020. Detrital food web contributes to aquatic ecosystem productivity and rapid salmon growth in a managed floodplain. PLoS ONE 15(9): e0216019. https://doi.org/10.1371/journal.pone.0216019

Johnson, R.C. et al., 2017. Science advancements key to increasing management value of life stage monitoring networks for endangered Sacramento River Winter-Run Chinook Salmon in California San Francisco Estuary and Watershed Science 15 (3):1-43·

Kaplan, I. C., T. B. Francis, A. E. Punt, P. D. Lynch, K. N. Marshall, J. J. Deroba, M. Masi, J. K. T. Brodziak, K. Y. Aydin, K. Holsman, H. Townsend, D. Tommasi, J. A. Smith, S. Koenigstein, M. Weijerman, and J. Link, 2019. A multi-model approach to understanding the role of Pacific sardine in the California Current food web. Marine Ecology – Progress Series, 617: 307–321.

Kimmerer, W.J., Gartside, E. and J. Orsi,1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Marine Ecology Progress Series. 113: 81–93.

Kimmerer, W.J., Brown, L., Culberson, S., Moyle, P.B., Nobriga, M.L. and J. Thompson, 2008. Aquatic ecosystems. In: (edited by M. Healey, M. Dettinger & R. Norgaard). State of Bay - Delta Science, 174 pp.

Kimmerer, W.J., Thompson, J.K., 2014. Phytoplankton growth balanced by clam and zooplankton grazing and net transport into the low-salinity zone of the San Francisco Estuary. Estuaries Coasts 37: 1202-1218.

Kimmerer, W.J. and L. Lougee, 2015. Bivalve grazing causes substantial mortality to an estuarine copepod population. J. Exp. Mar. Biol. Ecol. 473:53-63.

Kimmerer W.J. and K. A. Rose, 2018. Individual-based modeling of delta smelt population dynamics in the Upper San Francisco Estuary III. Effects of entrainment mortality and changes in prey. Transactions of the American Fisheries Society. 147:223–243.

Kimmerer W.J., MacWilliams M.L., and E.S. Gross, 2013. Variation of fish habitat and extent of the low-salinity zone with freshwater flow in the San Francisco Estuary. San Francisco Estuary and Watershed Science. 11:

Lewis, K.A., Rose, K.A., De Mutsert, K., Sable, S., Ainsworth, C., Brady, D.C., and H. Townsend, 2021. Using multiple ecological models to inform environmental decision-making. Frontiers in Marine Science, 8, 625790.

Lindenmayer, D.B. and G.E. Likens, 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends in Ecology & Evolution, 24(9): 482- 486.

Lindenmayer, D.B., Likens, G.E., Haywood, A., and L. Miezis, 2011. Adaptive monitoring in the real world: proof of concept. Trends in Ecology & Evolution, 26(12): 641-646.

Mac Nally, R., Thomson, J.R., Kimmerer, W.J., Feyrer, F., Newman, K.B., Sih, A., Bennett, W.A., Brown, L., Fleishman, E., Culberson, S.D., and G. Castillo, 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). Ecological Applications. 20: 1417–1430.

Margoluis, R., Stem, C., Salafsky, N. and M. Brown, 2009. Using conceptual models as a planning and evaluation tool in conservation. Evaluation and Program Planning. 32: 138– 147.

Mason, D. M., A. Goyke, and S. B. Brandt, 1995. A spatially explicit bioenergetics measure of habitat quality for adult salmonines: Comparison between Lakes

Michigan and Ontario: Canadian Journal of Fisheries and Aquatic Sciences. 52(7): 1572-1583.

Melwani A, Tillotson M, Hobbs JA, Slater SB, Hennessy A, Schreier B, Arend K, McLain J. 2022. Evaluation and Analysis of Five Long-Term Biological Monitoring Studies in the Upper San Francisco Estuary. 2021 Final Report. Available from: https://csamp.baydeltalive.com/docs/25928

Merz, J., Caldwell, L., Beakes, M., Hammersmark, C., and K. Sellheim, 2019. Balancing competing life-stage requirements in salmon habitat rehabilitation: between a rock and a hard place. Restoration Ecology 27(3):661–671.

Michel, C. J., M. J. Henderson, C. M. Loomis, J. M. Smith, N. J. Demetras, I. S. Iglesias, B. M. Lehman, and D. D. Huff. 2020. Fish predation on a landscape scale. Ecosphere 11(6):e03168. 10.1002/ecs2.3168

Michel, C. J., J. J. Notch, F. Cordoleani, A. J. Ammann, and E. M. Danner, 2021. Nonlinear survival of imperiled fish informs managed flows in a highly modified river. Ecosphere. 12:e03498.

Naiman, S.M., White, S.M., Bellmore, J.R., McHugh, P.A., Kaylor, M.J., Baxter, C.V., Danehy, R.J., Naiman, R.J. and A.L. Puls, 2022. Food web perspectives and methods for riverine fish conservation. WIREs Water, 9, 1–21.

National Research Council, Committee on Defining the Best Scientific Information Available for Fisheries Management, 2004. Improving the use of "Best Scientific Information Available" Standard in Fisheries Management. National Academy Press, Washington D.C. Available at http://www.nap.edu/catalog.php?record_id=11045#toc.69.

Nelitz, M., Morton., C., Tamburello, N., Shellenbarger, G., Singh, J., Semmens, C., Koford, E.J., and T. Langerquist, 2020. Monitoring Enterprise Review: Comprehensive Synthesis Report. Report prepared by ESSA Technologies Ltd., CBEC eco engineering, and PAX Environmental, Inc. for the Delta Independent Science Board.

Nislow, K.H., C.L. Folt, and D. L. Parrish, 2000. Spatially Explicit Bioenergetic Analysis of Habitat Quality for Age-0 Atlantic Salmon. Transactions of the American Fisheries Society. 129(5): 1067-1081.

Nobriga, M.L. and F.V. Feyrer, 2007. Shallow-water piscivore-prey dynamics in California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science, 5.

Nobriga ML, Michel CJ, Johnson RC, and J.D. Wikert, 2021. Coldwater fish in a warm water world: Implications for predation of salmon smolts during estuary transit. Ecology and Evolution. 11:10381– 10395.

Norgaard, R.B., Wiens, J.A., Brandt, S.B. and others, 2021. Preparing scientists, policy-makers, and managers for a fast-forward future. San. Fran. Estuary Watershed Sci. 19: 1–22.

Peterson, J., and A. Duarte, 2020. Decision analysis for greater insights into the development and evaluation of Chinook salmon restoration strategies in California's Central Valley. Restoration Ecology 28 (6):1596–1609.

Quellet, V., A. H. Fullerton, et al, 2024. Food for fish: Challenges and opportunities for quantifying foodscapes in river networks. WIREs WATER. 29pp.

Raleigh, R., Miller, W., and P. Nelson, 1986. Habitat Suitability Index Models and Instream Flow Suitability Curves: Chinook Salmon (No. Biological Report 82(10.122)). National Ecology Center, Fish and Wildlife Service, U.S. Department of the Interior.

Reynolds, J. H., M. G. Knutson, K. B. Newman, E. D. Silverman, and W. L. Thompson, 2016. A road map for designing and implementing a biological monitoring program. Environmental Monitoring and Assessment 188(7):399. 25pp.

Richter, A., and S. A. Kolmes, 2005. Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. Reviews in Fisheries Science. 13(1): 23–49.

Riebe, C.S., Sklar, L.S., Overstreet, B.T., Wooster, J.K., 2014. Optimal reproduction in salmon spawning substrates linked to grain size and fish length. Water Resour. Res. 50: 898–918.

Rieman, B.E., Smith, C.L., Naiman, R.J., Ruggerone, G.T., Wood, C.C., Huntly, N., Merrill, E.N., Alldredge, J.R., Bisson, P.A., Congleton, J., Fausch, K.D., Levings, C., Pearcy, W., Scarnecchia, D. and P. Smouse, 2015. A comprehensive approach for habitat restoration in the Columbia Basin. Fisheries, 40: 124-135.

Rogers, M., Selker, J. S., Peterson, J., & Arismendi, I. D. (2022). Identifying and quantifying sources of temporal and spatial uncertainty in assessing salmonid responses to watershed-scale restoration. River Research and Applications. 38(5): 884–894. https://doi.org/10.1002/rra.3956.

Rogers, T.L., Bashevkin, S.M., Burdi, C.E., Colombano, D.D., Dudley, P.N., Mahardja, B., Mitchell, L., Perry, S., and P. Saffarinia, 2024. Evaluating top-down, bottom-up, and environmental drivers of pelagic food web dynamics along an estuarine gradient. Ecology, 105(4) e4274.

Rose, K.A., Kimmerer, W.J., Edwards, K.P., and W.A. Bennett, 2013. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: I. Model description and baseline results. Transactions of the American Fisheries Society, 142: 1238–1259.

Rose, K.A., Kimmerer, W.J., Edwards, K.P., and W.A. Bennett, 2013b. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: II. Alternative baselines and good versus bad years. Transactions of the American Fisheries Society 142: 1260-1272.

Rose, K.A., Sable, S., DeAngelis, D.L., Yurek, S., Trexler, J.C., Graf, W., and D.J. Reed, 2015a. Proposed best modeling practices for assessing the effects of ecosystem restoration on fish. Ecological Modelling, 300: 12–29.

Rossi, G. J., Power, M. E., Pneh, S., Neuswanger, J. R., and T.J. Caldwell, 2021. Foraging modes and movements of Oncorhynchus mykiss as flow and invertebrate drift recede in a California stream. Canadian Journal of Fisheries and Aquatic Sciences, 78(8): 1045–1056.

Rudstam, L. G., Parker-Stetter, S. L., Sullivan, P. J., and D.M. Warner, 2009. Towards a standard operating procedure for fishery acoustic surveys in the Laurentian Great Lakes, North America. ICES Journal of Marine Science, 66(6): 1391–1397.

Rudstam, L. G. 2024. Review of SFHA Monitoring and Science Plan A report to the Delta Science Program 93 pp. https://deltacouncil.ca.gov/pdf/science-program/panel-letters/2024-06-20-sfha-monitoring-and-science-plans-peer-review-panel-final-letters.pdf

Samedy, V., M. Wach, J. Lobry, J. Selleslagh, M. Pierre, E. Josse, and P. Boët, 2015. Hydroacoustics as a relevant tool to monitor fish dynamics in large estuaries. Fisheries Research 172(3B):225-233.

Schreier, B.M., Baerwald, M.R., Conrad, J.L., Schumer, G., and B. May, 2016. Examination of predation on early life stage Delta Smelt in the San Francisco estuary using DNA diet analysis. Transactions of the American Fisheries Society, 145(4): 723-733.

Sherman, S., Hartman R., Contraras D., editors, 2017. Effects of tidal wetland restoration on fish: A suite of conceptual models. Interagency Ecological Program Technical Report 91. Department of Water Resources: Sacramento, CA, USA.

Southwell, D.M., Einoder, L.D., Lahoz-Monfort, J.J., Fisher, A., Gillespie, G.R., and B.A. Wintle, 2019. Spatially explicit power analysis for detecting occupancy trends for multiple species. Ecological Applications, 29(6), e01950.

Sullivan, P. J., Acheson J. M., Angermeier P. L., Faast, T., Flemma, J., Jones, C. M., Knudsen, E. E., Minello, T. J., Secor, D. H., Wunderlich, R., and B.A. Zanetell, 2006. Defining and Implementing Best Available Science for Fisheries and Environmental Science, Policy, and Management. Fisheries 31(9): 460-465.

Swannack, T. M., J. C. Fischenich, and D. J. Tazik, 2012. Ecological Modeling Guide for Ecosystem and Management. Environmental Laboratory, Engineer Research and Development Center ERDC/EL TR-12-18, USACOE, Washington DC Page, Vol. 48.5155

Takata, L., T. R. Sommer, J. Louise Conrad, and B. M. Schreier, 2017. Rearing and migration of juvenile Chinook salmon (Oncorhynchus tshawytscha) in a large river floodplain. Environmental Biology of Fishes 100(9):1105–1120.

Vander Zanden, M. J., Olden, J. D., & Gratton, C. (2006). Food-web approaches in restoration ecology. In D. A. Falk, M. A. Palmer, & J. B. Zedler (Eds.), Foundations of Restoration Ecology (pp. 165–189). Island Press

Wiens, J. et al. 2017. Facilitating Adaptive Management in the California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science, 15 (2): 1- 15.

Wilkinson, M.D., Dumontier, M., Aalbersberg, I., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J-W, da Silva Santos LB, Bourne PE, Bouwman J, Brookes AJ, Clark T, Crosas M, Dillo I, Dumon O, Edmunds S, Evelo CT, Finkers R, Gonzalez-Beltran A, Gray AJG, Groth P, Goble C, Grethe JS, Heringa J, 't Hoen PAC, Hooft R, Kuhn T, Kok R, Kok J, Lusher SJ, Martone ME, Mons A, Packer AL, Persson B, Rocca-Serra P, Roos M, van Schaik R, Sansone S-A, Schultes E, Sengstag T, Slater T, Strawn G, Swertz MA, Thompson M, van der Lei J, van Mulligen E, Velterop J, Waagmeester A, Wittenburg P, Wolstencroft K, Zhao J, and B. Mons, 2016. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data. 2016 Mar 15:3:160018. doi: 10.1038/sdata.2016.18

Zhang, H., S.A. Ludsin, D.M. Mason, S.B. Brandt, C.A. Stow, A.T. Adamack, X. Zhang, D.G. Kimmel, M.R. Roman, and W.C. Boicourt. 2014. Effects of hypoxia on habitat quality of pelagic planktivorous fishes in the northern Gulf of Mexico. Marine Ecology Progress Series 505: 209-226, https://doi.org/10.3354/meps10768.

Zhang, H., D. M. Mason, N. W. Boucher, E. S. Rutherford, D. J. Cannon, J. Kessler, A. Fujisaki-Manome, J. Wang, and E. A. Fulton, 2023. Effects of vertical mixing on the Lake Michigan food web: An application of a linked end-to-end earth system model framework. Ocean Dynamics 73: 545–556.

Zuur, A.F., Leno, E.N. and C.S. Elphick,2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution. 1: 3-14.