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Floodplains Reimagined: Zooplankton production and export potential suitability criteria and application to baseline conditions

Memorandum

Provided to the Floodplains Reimagined Program Team
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Overview

The loss of functional floodplain habitat in California's Central Valley has substantially contributed to species declines and ecosystem change. Through voluntary collaborative partnerships with private landowners, sovereign tribal entities, government, and non-government representatives, the Floodplains Reimagined Program ("Program" herein) seeks to increase connectivity of flood bypasses and agricultural fields with the Sacramento River to affect certain floodplain conditions such as frequency and duration of shallow inundation. The intention is to improve ecological floodplain functions in support of juvenile rearing Chinook salmon and Pacific Flyway birds, while also considering flood benefits, agriculture, recreation, and indigenous cultural values. The first phase of the Program included the establishment of priorities and objectives for the Program and the related methods, criteria, and metrics used to quantify the objectives. This memorandum presents zooplankton production and export potential suitability criteria selected to evaluate the objective focused on increasing inundation to stimulate production of zooplankton for rearing juvenile salmon. Though juvenile salmon eat a variety of invertebrates, the criteria address zooplankton production as it is a common floodplain food for rearing juvenile salmon particularly on managed floodplains, more is known regarding suitable conditions for production compared to other invertebrate groups, and production is driven by floodplain flooding and drying processes. To address the objective, two sets of criteria were established. One examines the potential for in situ zooplankton production, or where and when zooplankton production is likely higher or lower. The second evaluates whether that production could be exported from its location of origin, or where and when productive water is likely to move away from where it is produced.

The suitability criteria are applied within a modeling context and therefore are approximations of potential benefits and do not measure actual zooplankton levels or export volumes. The criteria are intended to be used to compare relative change as a result of hydrologic and hydrodynamic changes due to one or more proposed actions to increase connectivity and inundation within the highly managed landscape of the Program's footprint. They do not represent an absolute measure of zooplankton productivity as the modeling and evaluation effort is limited to those factors that can be readily evaluated using hydrodynamic modeling output. Furthermore, the ultimate fate of the zooplankton (i.e., whether it is transported to the river channel), the ability of fish to access the zooplankton, and whether fish would benefit from it are not a part of these evaluation criteria. As the criteria only apply to zooplankton production and not to other invertebrates eaten by juvenile salmon, evaluations therefore do not capture the full range of food production for juvenile salmon. The criteria in this memo thus represent an initial step, where future work is expected to include additional considerations to better evaluate ecological benefits of production in managed floodplain environments.

Rationale

Floodplains are some of the most productive and biodiverse systems in the world, characterized by high spatial and temporal variability (Amoros and Bornette, 2002; Tockner and Stanford, 2002; Ward et al., 1999). The periodic inundation and flood disturbances generate highly complex and temporally dynamic habitat mosaics, which support high species diversity and biological productivity (Junk et al., 1989). The slower moving and shallow water, periodic hydrologic connectivity, and high levels of organic matter and nutrients within floodplain environments allow for high primary and secondary productivity (Baranyi et al., 2002; Górski et al., 2013; Grosholz and Gallo, 2006; Opperman et al., 2017). Floodplains are important to the health of the larger riverine ecosystem, as nutrients, organic matter, and food resources are exported from floodplains, fueling the food web downstream (Ahearn et al., 2006; Sturrock et al., 2022). Floodplains provide important habitat as well as food resources to wildlife, including rearing juvenile salmon, which eat invertebrates including zooplankton. The quality of floodplain habitat for rearing juvenile fish is related to floodplain heterogeneity generating diverse local food webs (Bellmore et al., 2013). Though many confounding factors exist including whether food availability is limiting fish populations (Bellmore et al., 2012), greater food availability to fish is generally understood to confer greater growth, which may translate to improved survival and spawning return rates (Jeffres et al., 2008; Pratt et al., 2023; Sommer et al., 2005). Recent research, particularly from studies in the flood basins of Central Valley, suggests that the highly altered and managed bypasses and agricultural land can generate highly productive inundated habitats (Corline et al., 2017; Jeffres et al., 2020; Sommer et al., 2001). Estimates of how management actions within floodplain environments affect zooplankton production and its export can offer insight into the potential for those actions to impact potential food availability for juvenile fish.

Criteria Development Process

The criteria recommendations presented in this memo were established through an iterative process involving literature review, expert consultation, and model testing. Initial steps involved identifying physical criteria representing key driving factors affecting productivity, determining potential values associated with those criteria, and considering what analysis approach might be reasonable given the modeling context and in alignment with approaches used for analyzing other criteria (e.g., juvenile salmon rearing, birds). After initial criteria were selected, and early in the development process, a set of sensitivity tests using modeling output across several possible criteria helped refine the set of appropriate values and an appropriate approach for evaluating the criteria. Several discussions were held with subject matter experts as well as the Program technical team at key points in the process to consider options and further refine criteria (Holmes, 2023; Jeffres, 2023; Serup, 2023). The draft criteria were presented to the Advisory Committee on August 11, 2023 and revisions made based on feedback. Revisions primarily consisted of addressing and clearly stating assumptions and caveats. The criteria were brought to and approved by the Steering Committee on August 23, 2023.

Zooplankton Production Suitability Criteria

The Program recommends the criteria listed in Table 1 to quantify zooplankton productivity within the context of Program goals, assumptions, and limitations. For zooplankton production, these include depth, velocity, duration, and land cover. While additional factors affect zooplankton production (e.g., temperature, turbidity), criteria were selected based on whether the physical habitat criteria could be evaluated from the hydrodynamic modeling output, were relevant for comparing different scenarios, and were considered to be most limiting. The criteria, their conditions, and associated suitability values were kept as simple as possible for a number of reasons, including that simplicity would facilitate the interpretation of results, not add specificity beyond what is needed or appropriate given scientific understanding and model uncertainty, and reflect the use of the criteria in a screening tool to evaluate overall relative benefits across different management or land use scenarios. Suitability values associated with each of the criteria were limited to just three values: 1 (good condition), 0.66 (suboptimal), or 0 (not suitable). These therefore represent general bins of quality and should not be interpreted as meaning that a given condition with a suitability score of 1 is exactly 50% better than one with a score of 0.66.

Table 1. *Zooplankton production suitability criteria recommended for comparing scenario outcomes for the Floodplains Reimagined Program.*

Criteria	Source	Condition	Value
Depth		Wetted (depth > 0)	1
		Dry	0
Velocity (water age)	Sommer et al. (2004); Opperman (2008); used model to refine	0.33 ft/s (0 - 0.1 m/s)	1
		>0.33 ft/s (0.1 m/s)	0
Duration (water age): applied after velocity (high velocity event resets duration), also resets after drying	Baranyi et al. (2002); Opperman (2008); Grosholz & Gallo (2006); Keckeis et al (2003)	1-9 days	0.66
		>10 days	1
Land Cover	Catlin et al. (2016); Górski et al.	Wetlands / Rice	1

	(2013); Corline et al. (2021)	Grassland / Other Agriculture / Shrub / Forest	0.66

The approach to apply these criteria is consistent with the science-based hydrospatial analysis approach used by the Program across the suitability criteria analyses. This approach has precedence in prior floodplain habitat evaluation and restoration efforts (e.g., DWR and USBR, 2012; KSN, Inc., 2021), and it follows the hydrospatial analysis approach developed by Whipple (2018) and adapted for the Central Valley Habitat Exchange Chinook salmon habitat quantification tool (Whipple et al., 2019). It estimates habitat suitability based on physical criteria that are applied in a spatially- and temporally-resolved way, such that suitable habitat can be evaluated over space and time and summed to a total available floodplain habitat measured as suitable "acre-days" (area summed over time). Additionally, when calculating across multiple years or other divisions such as flood types, variability in conditions can be assessed (e.g., variability related to wet and dry years or small versus large flood events). When applied to restoration, management, or climate change scenarios, for example, the hydrospatial analysis approach allows users to determine the relative impact of such changes on expected habitat in a temporally- and spatially-explicit way.

The approach uses concepts typical for evaluating suitable habitat from hydrodynamic modeling, which includes the use of habitat suitability criteria to assign index scores to estimates of physical parameters from hydrodynamic modeling outputs (e.g., depth). In this approach, these criteria are applied on a cell-by-cell basis on a daily time step. The index scores or habitat suitability index (HSI) for each parameter are then combined together for a global HSA value (gHSI). For a single cell on one day, this calculation can be generalized to:

$$HSI_{global} = (criteria_1 HSI) * (criteria_2 HSI) * \ldots$$

Grids of cell suitability can then be summarized over the model domain or specified areas for total WUA on day *t* (units of area):

$$WUA_t = (raster\ cell\ area) * \sum_{n=1}^{n} gHSI_n$$

where *n* is the total number of cells. To summarize over time, the sum of daily WUA for a period of time is calculated (units of acre-days):

$$WUA_{days} = \sum_{t=1}^{t} WUA_t$$

where *t* is the total number of days in the analysis period.

Depth

An essential factor for zooplankton growth and reproduction is the presence of inundation. The depth criterion is a simple check as to whether the floodplain area is inundated or not (suitability values of 0 for dry and 1 for wet). Although the lack of light availability becomes limiting at deeper depths for the production of phytoplankton, a food for zooplankton, detrital sources may be a primary driver of floodplain food webs (Jeffres et al., 2020) and the presence of deep water is not considered to be limiting for zooplankton. Depth is also used as part of the duration criteria, where an area transitioning from wet to dry signifies the end of an inundation event and resets the duration counter (i.e., the next inundated day will start at a duration of 1).

Velocity

Water age, or the length of time since a parcel of water entered a given area (e.g., entered a floodplain from the river channel) and roughly analogous to residence time, is a primary factor determining zooplankton community assemblages and population levels (Baranyi et al., 2002; Corline et al., 2021). Velocity and duration are used as proxies for water age in this analysis, as water age cannot be directly evaluated from the hydrodynamic modeling. Slow moving water is an indication of older water or longer residence times, which is necessary for the cycle of primary and secondary (zooplankton) production to occur. Greater and lesser production occurs along a gradient from slow to fast-moving water. Additionally, few studies have focused on determining relationships between velocity and zooplankton production levels, though some reference typical floodplain velocities or velocities likely limiting zooplankton production (e.g., Sommer et al., 2004). This threshold should therefore be considered as a general approximation. For this analysis, the threshold of 0.33 ft/s is used, where velocities below the threshold are given a suitability value of 1 and values above are given a value of 0.

As with depth, velocity is also used to reset duration. When water velocities exceed the velocity threshold (0.33 ft/s), the inundation event duration resets to zero such that the next day with velocities below 0.33 ft/s start with a duration of 1. Appropriate velocity ranges were initially determined based on the literature, and then the threshold value was fine-tuned using sensitivity testing with the hydrodynamic modeling outputs to assess thresholds that best divided periods of inundation into meaningful flood events (e.g., examining how frequently export occurred across a range of different fields within the study area for the wet year of 2019). The threshold needed to be high enough to capture productive slow-moving water, but also low enough to reset flood events. For example, a threshold set too high would mean that event durations would last much of the season, when, in fact, multiple flood pulses had come through the system and likely reset zooplankton production. Alternatively, a threshold set too low would result in much shorter flood event durations and many days and floodplain locations assessed as unsuitable.

Duration

Inundation duration, used as a proxy for water age like velocity, is directly related to zooplankton production as adequate time is needed for the cycle of primary and secondary production to occur. Phytoplankton growth occurs in the initial days after inundation begins and zooplankton subsequently feed on phytoplankton, after which their populations respond. This process is well-researched and though substantial evidence exists, setting criteria values is still an approximation, as many factors can confound the relationship, including the important role of detrital sources of carbon supporting zooplankton production (Jeffres et al., 2020). Sources suggest that anywhere from a week to three weeks allow for the development of high prey densities (Baranyi et al., 2002; Górski et al., 2013;

Grosholz and Gallo, 2006; Keckeis et al., 2003; Opperman, 2008). Overall, a threshold of 10 days appears most consistent with the literature (Baranyi et al., 2002; Keckeis et al., 2003). To reflect this, a suitability value of 1 is given to inundation duration of 10 days or greater, and shorter durations are assigned values of 0.66 (as it is assumed that some production washes in from the river). Though some studies suggest a slight drop in production at longer durations (e.g., after three weeks), many do not suggest this pattern (Baranyi et al., 2002; Grosholz and Gallo, 2006; Opperman, 2008). Therefore, no upper threshold is included. For the purposes of the planning-level use of these criteria, this effort focused on a simple set of values which captures the dominant relationship between inundation duration and zooplankton production levels.

Land cover

The cover criteria assign either good condition or sub-optimal values to all land cover types. The criteria make the basic distinction between wetland and other land cover types to give a higher weight, a value of 1, to wetland types. Seasonal wetland environments of floodplains are where the processes play out to support zooplankton production. Within natural cover types, cover types associated with greater heterogeneity tend to have higher quality food (larger bodied zooplankton), though this research is less focused on overall production magnitude (Bellmore et al., 2013; Catlin et al., 2016; Górski et al., 2013). Rice, a wetland crop, can also be managed such that it can generate high densities of zooplankton (Corline et al., 2021), though it is understood to take some additional time to reach production levels of natural wetlands (though this is not considered to be substantial enough to warrant additional division of classes). Within rice, some research suggests that different management strategies for cover characteristics post-harvest may not be a significant determinant of productivity (Holmes, 2023). A divergence of Advisory Committee member viewpoints was evident when questions were raised around the choice to weight rice and wetland cover types equally. The equal weights were retained, given the evidence of high productivity within rice fields, even though no studies have been found that directly compare the production potential of the two land cover types. Other land cover types are given a value of 0.66, because while less suitable, with appropriate residence times, most cover types would support some zooplankton production. However, this may be highly variable, as field observations have also suggested that riparian forest or shrub may serve as productivity sinks (Holmes, 2023). Also, as these criteria focus on zooplankton, it is not considering that other types of food resources for rearing salmon (e.g., macroinvertebrates) may be more supported in the other cover types, such as riparian forest and shrub. These land cover criteria are slightly different from those of juvenile rearing salmon as the complexity associated with natural cover types is considered to be more of a factor for juvenile rearing.

Productivity Export Potential

To evaluate potential export of productive water, criteria were established to represent conditions depending on the type of connection a given area (cell or field unit) has to the channel network. In order to be available to the larger floodplain and riverine food web, production must be able to move away from where it occurs. Thus, the criteria for export potential focus on connectivity. These connectivity criteria are presented in Table 2. In the context of this effort, considering modeling and analysis limitations, connectivity is narrowly defined as the potential to move away from the area where production is generated (i.e., is it exported from a field), but does not include evaluation of connectivity to a main river channel (see Assumptions and Uncertainties section). Perhaps more than other criteria presented in this memo, establishing these criteria and calculation approach stemmed from understanding the predominant field-based management within the study area and how connectivity could best be evaluated in the hydrodynamic modeling context. The relative productivity export potential also depends on the calculated zooplankton productivity suitability for the area, or field unit, associated with a given connectivity condition.

Table 2. *Zooplankton production export potential criteria and values recommended for comparing scenario outcomes for the Floodplains Reimagined Program.*

Criteria	Value
If berm overtopping occurs (indicating direct connected to channel network)	[ac-ft * productivity suitability] Volume of water per cell exceeding velocity threshold on first Berm Overtopping day * productivity suitability one day prior of those cells
If connected through outlet weir with downstream connection	[ac-ft * productivity suitability] Daily export volume through outlet structures or total field volume on prior day, whichever is lower * area weighted productivity suitability one day prior
Unmanaged areas	[ac-ft * productivity suitability] Daily suitability-weighted volume of cell on previous day when velocity threshold is exceeded
No downstream connection	0

The approach to determine export potential is different from the other hydrospatial analysis applications of criteria used by the Program. While other criteria are applied cell-by-cell, this analysis is about looking at whether a given inundated area has the potential to release its water downstream. Evaluating the nature of the connection is therefore central to the analysis. With the vast majority of the area within the modeling domain managed as separate field units, connectivity to the channel network is also predominantly at the field scale. Therefore, analysis is conducted at the field scale for managed areas (unmanaged areas remain a cell-by-cell analysis, as with other suitability criteria). Two primary connectivity distinctions are recognized in this analysis for managed areas (i.e., agricultural fields or managed wetlands), one where connection is occurring via berm overtopping (e.g., a large flood event causes unmanaged field inundation), and a second where connection is maintained via an outlet structure (e.g., once the flood peak has passed and water levels are below the field berms, water drains slowly from the field via a structure). All other areas are considered unmanaged and connected (i.e., productive water can move out of a given cell), and analysis is applied on a cell-by-cell basis. The values for each of these connectivity conditions are calculated as the volume of water that has the potential to be exported, weighted by the productivity suitability (calculated previously, and presented in the previous section). Finally, when there is no connection to the channel network (fields are being managed at a stable depth), the productivity export potential is given a value of 0.

To apply the criteria, the following calculations are performed for each day of the modeling output. For berm overtopping conditions, the influx of water over a portion or all of a field's berm causes some or all cells within a given field unit to exceed the velocity criteria (set for zooplankton production), which is the portion assumed to be exported. The following calculation is performed for a productivity-weighted berm overtopping export volume on a given day *(t)*:

$$x_{bot,t} = a * \sum_{j=1}^{n_{exd,t}} P_{j,t-1} * d_{j,t-1}$$

where *a* is the cell area, $n_{exd,t}$ is the number of cells exceeding the velocity threshold, $P_{j,t-1}$ is the cell suitability (HSI) for productivity on the prior day, and $d_{j,t-1}$ is the depth of a given cell on the prior day. For conditions when connection is occurring solely via an outlet structure, the calculation for outlet structure export volume at a given day *(t)* is as follows:

$$x_{out,t} = min(V_{out,t} * P_{t-1}, V_{f,t-1})$$

where $V_{out,t}$ is the volume of water exiting the outlet structure on day *t*, P_{t-1} is the field-averaged productivity suitability on the prior day, and $V_{f,t-1}$ is the field productivity-weighted volume on the prior day. The minimum ensures that the field does not export more water than is available to export on the previous day. The analysis assumes that these conditions are mutually exclusive such that berm overtopping cannot occur at the same time as outlet structure flow.

Setting these criteria involved substantial discussion with and feedback from the Advisory Committee. In particular, the relative potential to export productive water between berm overtopping and field outlet structures was questioned. Setting criteria for estimating export potential was highly dependent upon the hydrodynamic modeling. While evaluating the potential for leaving a point of origin was considered feasible, quantifying additional key factors affecting the potential of productive water to support downstream food webs, such as discharge or velocity (other than the threshold velocity criterion), distance to river channel, and the quality and complexity of the within-floodplain channel network, was not. Therefore, the productivity export potential criteria are limited to evaluating whether a given parcel of water can leave the area and do not examine the ultimate fate of that water.

Assumptions and Uncertainties

A number of assumptions and uncertainties are associated with this approach. As emphasized by participants in the Advisory Committee, these are essential to understand alongside the criteria so that results are interpreted accurately. There are overarching assumptions built into the approach as well as uncertainties associated with the criteria and associated values, relating to gaps in scientific understanding as well as how the criteria are evaluated in the modeling results. Many assumptions and uncertainties could be addressed through additional exploration and discussion with advisors in future phases of this Program as well as in new scientific studies and monitoring efforts.

As stated in the Rationale section above, the fundamental underlying assumption is that increased productivity (here, specifically zooplankton production) boosts the food web and increases food availability for fish, translating to improved growth and therefore better outmigration and/or early ocean period survival. While the science is clear on the importance of floodplains for food web benefits, there are many confounding factors that may limit the potential for productivity increases to translate to fisheries benefits. For example, the availability of food does not guarantee that fish will consume it. The distance to the main river channel and the within-floodplain infrastructure may be too far or complex for fish to access or for the productive water to travel. Additionally, there may be factors other than food that are limiting salmon populations. Or, relatedly, fish may simply not be present in the system.

In support of a planning level analysis, the criteria and approach aims to capture high-level differences in key physical conditions related to zooplankton production and the potential for export of productive water from the point of origin. The physical habitat suitability-based approach, with simple index values representing good condition, suboptimal condition, and not suitable, results in assessments that are appropriate for evaluating relative effects of floodplain inundation on secondary (zooplankton) production and potential export. Also, model simplifications introduce uncertainty (e.g., the necessary "hydroflattened" field units for modeling purposes means that much of the small-scale complexity in natural environments that likely affects productivity is lost). In sum, the analysis results do not indicate actual zooplankton densities or biomass. The approach is considered appropriate for relative comparison of management, restoration, or flow scenarios.

More specific assumptions and uncertainties are provided in the following bullets associated with specific criteria:

- **Duration and velocity as water age:** Water age or water residence time is the primary factor affecting productivity potential, but this measure is not available from the hydrodynamic modeling outputs. It is assumed that duration and velocity can be used together as proxies to represent water age, where longer inundation duration and slower velocities are correlated with greater water age.
- **Maximum velocity:** The velocity threshold is an important variable in this analysis because it is used to identify the start and end of flood events that reset productivity (restart inundation duration) and also to identify water that is moving slow enough for zooplankton production. However, the threshold value used in this analysis is an approximation largely based on selecting a reasonable value from sensitivity testing with the model. This was necessary given the limited published literature to inform what value to select, plus the fact that a clear threshold in nature doesn't actually exist (what is too slow or too fast may depend on other interacting factors).
- **Duration does not vary spatially**: Though longer duration inundation is essential to allow zooplankton growth and reproduction, the actual number of days to reach peak production varies depending on confounding factors, such as source water and antecedent conditions. However, it is not possible to model or analyze conditions at this level of detail. In this analysis, a single representative value of 10 days and above is used as the duration for good suitability for zooplankton production.

- **Other factors not addressed:** A number of factors in addition to those that can be evaluated from the model are important determinants of productivity. These include water temperature, light availability (turbidity), daylength, and antecedence conditions (e.g., soil moisture, periodicity, duration of drying between flood events). The absence of those that are not expected to vary depending on a given management scenario (e.g., daylength), should not affect the objective of relative comparison across scenarios. However, others were simply deemed too complex to represent well in the current approach, though further investigation may identify ways to address these, at least in part.
- **Export potential is narrowly defined:** As stated previously, the evaluation of export potential is limited to evaluating whether water can leave fields and other floodplain areas, but does not consider whether it actually enters a mainstem river channel or what the condition of the path is to get there (e.g., distance, water quality, flow). There exist many nuances and complexities that make it difficult to more fully evaluate within the current scope.
- **Connectivity evaluation for export potential is approximate**: The methods for evaluating export potential via berm overtopping versus outlet structure flow are associated with a number of uncertainties. For example, berm overtopping assumes connectivity of a field to the channel network, where cells that exceed the velocity threshold are considered to exchange their full volume of water. The goal is to capture large-scale patterns of exchange. However, complete exchange for any given cell may not actually occur. Also, spatial variability in velocities within a field may not represent accurate predictions due to terrain simplifications in the modeling. There are also uncertainties introduced by using a productivity HSI weighted volume of water from the prior day as the unit of productivity potentially exported. The approach is very tied to the floodplain configuration and the model representation of that configuration, such that published literature is not very informative. Field observational data comparing the characteristics of water export via these two primary pathways would help refine and validate the approach. Overall, these assumptions and uncertainties mean that there is greater confidence in making relative comparisons between scenarios for each type of potential export (e.g., does a given scenario increase or decrease export potential via berm overtopping relative to baseline conditions). Confidence is considerably lower when comparing between export potential types within a given scenario (e.g., does berm overtopping or outlet structure flow generate more or less export potential).

Baseline Results

Zooplankton Production

Evaluation of baseline hydrodynamic modeling output using zooplankton production suitability criteria resulted in a wide range of mean total annual acre-days of suitable area across the three subregions (Sutter: 1.03 million acre-days, Butte: 15.41 million acre-days, Colusa: 4.95 million acre-days; Figure 1). Across the modeled water years (Figure 2), values are relatively consistent and associated with low coefficients of variation for each of the subregions (Sutter CV: 10.1%, Butte CV: 7.8%, Colusa CV: 8.8%).

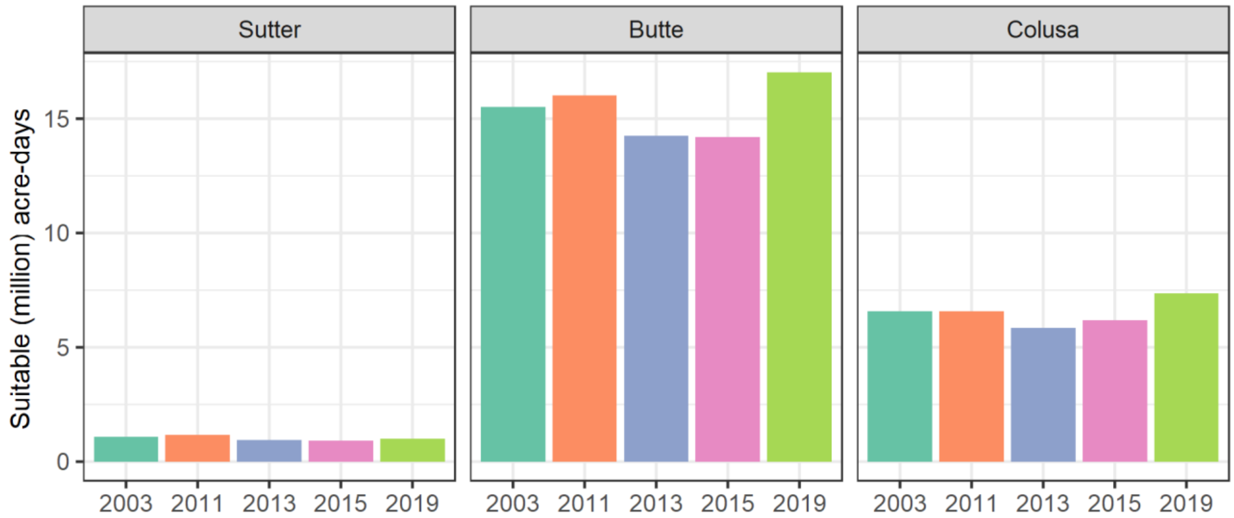

Figure 1. *Suitability-weighted zooplankton production habitat in millions of acre-days (area summed over time) across the three subregions of the study area and for each of the modeled water years.*

This suggests that the zooplankton production criteria are not highly sensitive to wet versus dry year types. However, the wet year of 2019 is associated with the highest acre-days for both Butte and Colusa. The suitability-weighted acre-days for zooplankton production is a high proportion of total wetted area for Butte (85.6% on average) and Colusa (90% on average), but substantially lower for Sutter (51.1% on average). Therefore, Sutter could be considered to have overall lower zooplankton productivity suitability relative to Butte and Colusa. These results are illustrated in Figure 3 by daily estimates of productivity suitability plotted with wetted and connected area. In these plots, Butte and Colusa estimates follow patterns of wetted area, as opposed to connected area, suggesting that the proportionally large wetted (but not connected) areas drive overall estimates of productivity suitability for these subregions. For Sutter, productivity suitability is shown to have an inverse relationship to connected area (likely related to flood peaks that reset productivity).

Productivity Export Potential

Results from applying productivity export potential criteria to baseline hydrodynamic modeling output suggest highest absolute export (measured as suitability-weighted acre-feet) from the Butte subregion, with lower and quite similar export potential from the Sutter and Colusa subregions (Figure 4). For Butte, average export potential across the five modeled water years was a weighted volume of 0.43 million acre-ft, with Colusa and Sutter averaging 0.12 and 0.11 million acre-ft, respectively. Relative to the zooplankton productivity suitability results, export potential is much more variable, aligning with water year type (Sutter CV: 55.7%, Butte CV: 36.3%, Colusa CV: 38.8%), where the wet year of 2019 was associated with the highest suitability across all three subregions. Relative to total wetted area over time, Sutter has the greatest export potential, followed by Butte, and then Colusa. This is primarily related to the fact that Sutter has a higher proportion of connected wetted area compared to the other subregions. Daily estimates of export potential, shown in Figure 5, show high peaks associated with peak river flows (see Figure 2) that rapidly fall close to zero. Maximum daily export potential is shown to be higher for the Sutter than for Butte subregion, despite Butte being a larger area.

Next Steps

The criteria presented in this memo are recommended for use in comparing management scenarios going forward in future phases of the Floodplains Reimagined Program. Given divergence of viewpoints around several areas of key uncertainties, particularly velocity, land cover, and export potential, the program team and participants in the Advisory Committee recommend considering refinement and expansion of the export potential evaluation as well as careful presentation and interpretation of results. Additional research and monitoring would help address underlying scientific uncertainties, refine criteria, and validate results. The following text describes next steps in terms of further criteria refinement or expansion and in terms of scientific research and monitoring opportunities.

Advisory Committee members recommend that future phases of the Floodplains Reimagined Program include alignment with other ongoing work in the region to evaluate floodplain connectivity and export potential (e.g., distance to a river channel via floodplain canals from a given floodplain location) as well as further discussion with advisors on the question of how to best evaluate movement of zooplankton to salmon. If the nature of the river connection – whether the path is short or long, or interrupted by extensive floodplain infrastructure – can be included in the export potential criteria, this will allow for more meaningful interpretation of results, as it will get farther toward estimating the chances of productive water actually reaching fish. It is also expected that field-based research to validate

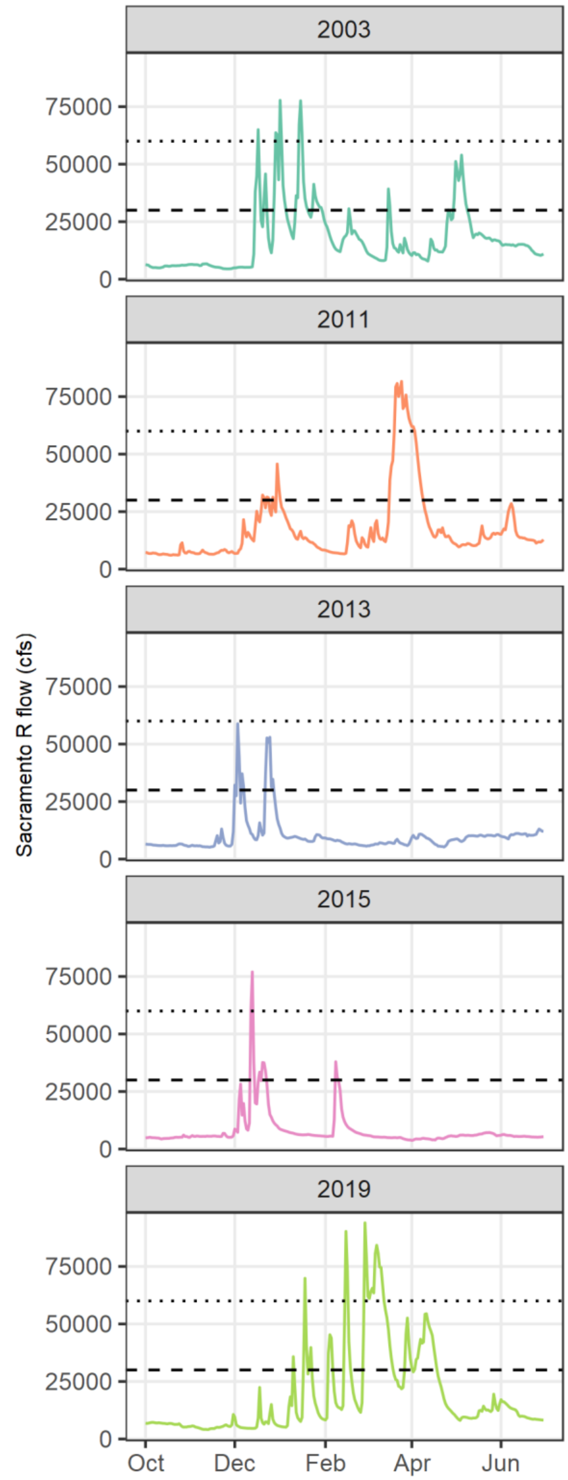

Figure 2. *Daily hydrograph for the each of the five modeled water years. Flow (cfs) is modeled flow near the Butte City streamgage. Horizontal lines represent Moulton weir activation (dotted line, ~60,000 cfs) and Colusa weir activation (dashed line, ~30,000 cfs).*

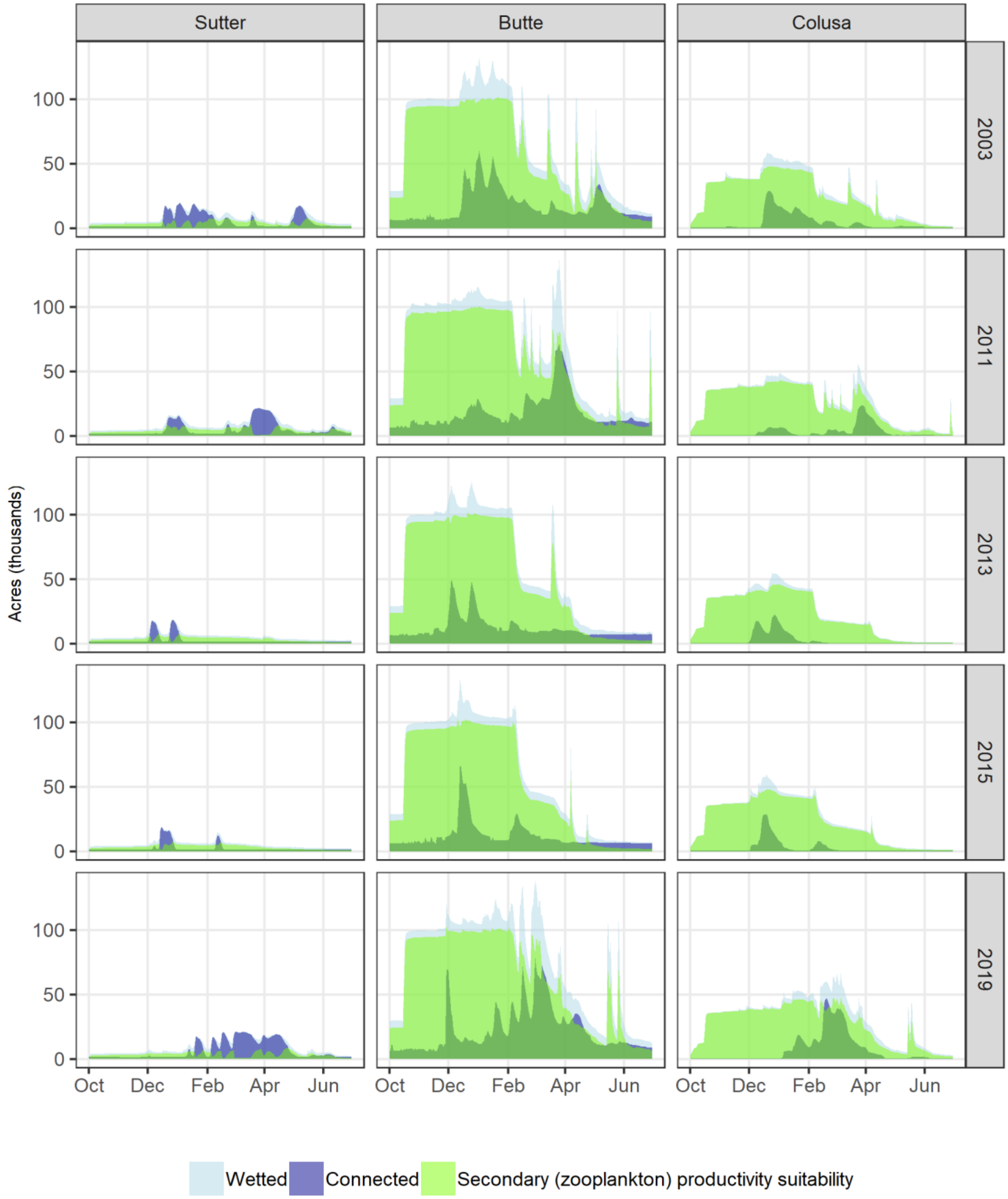

Figure 3. *Daily time series of suitability-weighted secondary (zooplankton) productivity area (orange) relative to connected wetted (dark blue) and total wetted (light blue) area, shown for the wet season of the five modeled water years.*

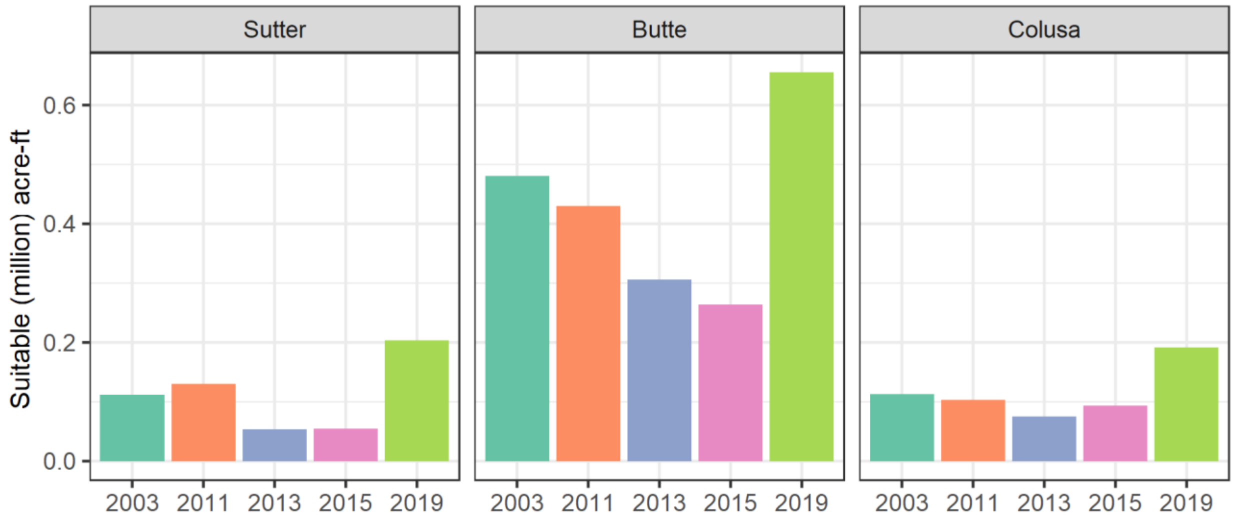

Figure 4. *Suitability-weighted productivity export potential estimates as millions of acre-ft for each subregion of the study area and for each of the modeled water years.*

desktop and modeling approaches would improve confidence in the power of these analyses. Ultimately, these efforts would support the goal of determining what and where floodplain actions may have the greatest positive impact on salmon populations.

Establishing the criteria for this approach relied upon published literature and expert opinion. For future phases of the Program, further exploration of criteria values and how they are expressed within the model is warranted. Additional field-based research that is directed at establishing relationships between zooplankton production and physical habitat criteria, such as those used for this analysis (namely velocity, duration, and land cover), would help refine the criteria, reduce uncertainty, and build greater trust in the process overall. For example, field-based studies could focus on comparison of zooplankton densities over time in rice fields versus natural cover types versus other disturbed land (e.g., other crops) under different inundation conditions. Also, comparing productivity across a spectrum of unmanaged and managed inundation (e.g., for rice, for duck clubs) would also inform evaluation criteria as well as the determination of beneficial management actions. An area of potential model expansion or another field-based study would be to explore improved estimation of water age, whether that be investigations into the capacity to actually model water age (as opposed to estimate via duration and velocity) or to validate the use of duration and velocity to approximate water age through a targeted field-based (or, potentially, model-based) study. As another factor to consider including in the analysis, research has suggested that turbidity (or light availability) could be a key driver of productivity. The role of turbidity and how it might be approximated in the modeling would be informative for this approach and help reduce uncertainty.

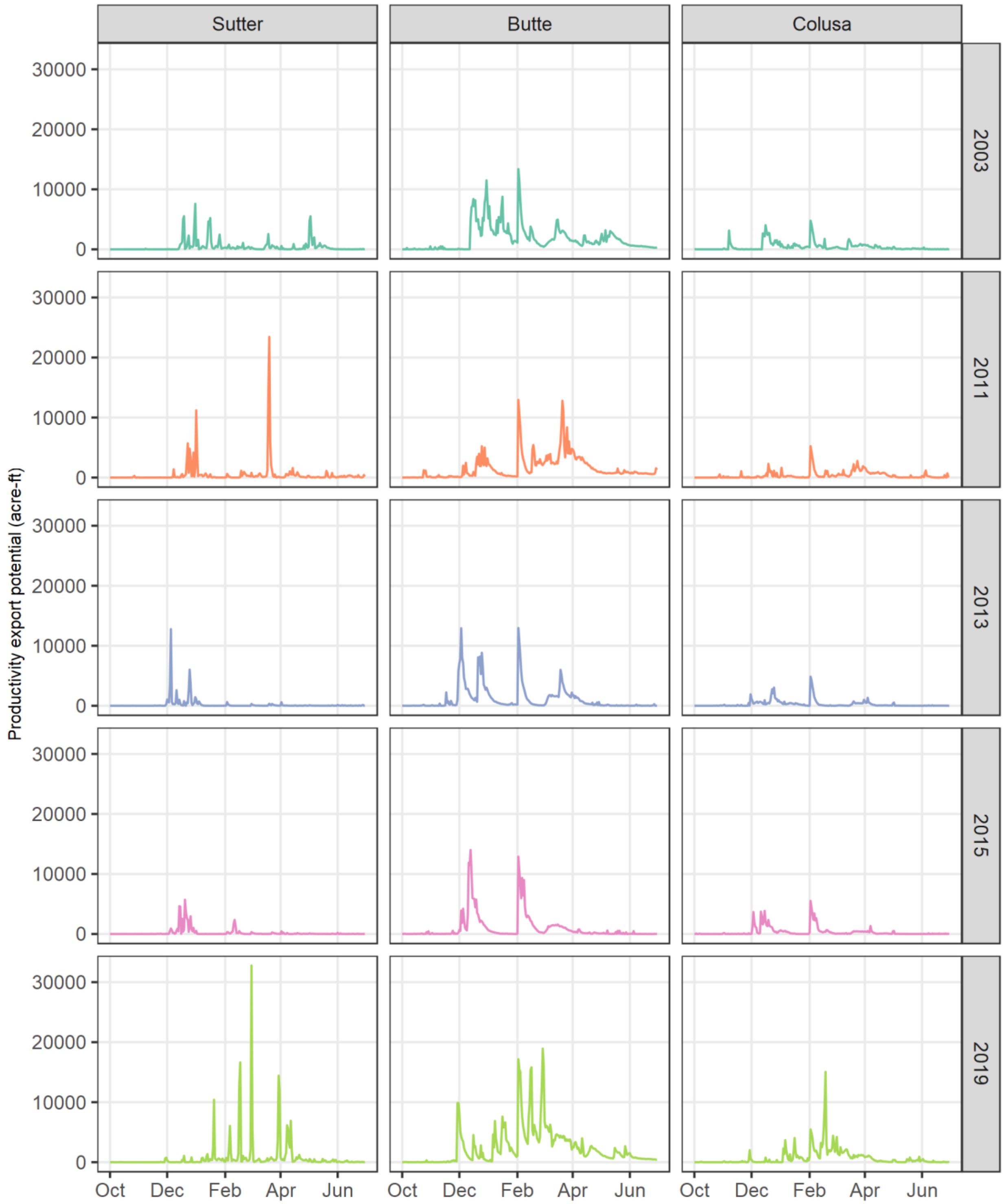

Figure 5. *Daily suitability-weighted productivity export potential estimates as acre-ft for each subregion of the study area and for the wet season of each of the modeled water years.*

Synthesis of existing data and further field-based research and monitoring of productivity and its export to river channels within the study area over time is recommended to help validate the analysis approach. An initial synthesis of existing data relative to validation needs in the model (e.g., where is zooplankton production highest and under what conditions) would be an important first step to identifying data gaps and designing research and monitoring to address the needs.

For reporting results comparing scenarios, the Program team and Advisory Committee members recommend reporting the results from each criteria separately as well as the overall habitat suitability assessment, in order to aid the interpretation of results. This enables one to understand the relative impact of each criterion to the overall result.

Summary

Approach:

- Two sets of criteria are used, where one examines the potential for in situ zooplankton production (i.e., where and when zooplankton production is likely higher or lower), and the other evaluates whether that production could be exported from its location of origin (i.e., where and when productive water likely moves away from where it is produced).
- Weighted suitable habitat area (suitable acre-days) for secondary (zooplankton) production is based on criteria related to depth, velocity, duration, and land cover.
- Productivity export potential is a volume of water (suitable acre-feet) weighted based on conditions related to connectivity. While other criteria are applied cell-by-cell, productivity export potential evaluates whether a given inundated area has the potential to release its water downstream.
- Criteria were established based on a compilation of sources, precedents from prior efforts, best professional judgement, and a desire to keep evaluation and interpretation relatively simple.
- The hydrospatial analysis approach evaluates hydrodynamic modeling output using multiple physical habitat criteria and applies them in a spatially- and temporally-resolved way.
- Applied criteria result in approximations of zooplankton production and potential export and are intended for comparing relative differences in benefit across scenarios.

Assumptions and uncertainties

- While the science is clear on the importance of floodplains for food web benefits, there are many confounding factors that may limit the potential for productivity increases to represent fisheries benefits.
- The suitability criteria are applied within a modeling context and therefore are approximations of potential benefits and do not measure actual zooplankton levels or export volumes.
- The ultimate fate of the production (e.g., whether it is transported to the river channel) and the ability of fish to access the food are not a part of these evaluation criteria.
- Velocity and duration are used as proxies for water age, as water age (a key factor driving productivity) cannot be directly evaluated from the hydrodynamic modeling.

- For land cover criteria, rice and wetland cover types are weighted equally. There was a divergence of viewpoints across Advisory Committee members about this. The weights were retained, given the evidence of high productivity within rice fields (though no studies are known to directly compare the production potential of the two land cover types).
- For productivity export potential, connectivity is narrowly defined as the potential to move away from the area where production is generated (i.e., is it exported from a field), but does not include evaluation of connectivity to a main river channel.
- The velocity threshold value is an approximation largely based on selecting a reasonable value from sensitivity testing with the model, given the limited published literature to inform what value to select, plus the fact that a clear threshold in nature does not actually exist.
- The duration threshold was selected to match what was most evident in the literature, however the actual number of days to reach peak production varies depending on confounding factors, which is beyond the level of detail handled by this approach.
- A number of factors in addition to those that can be evaluated from the model are important determinants of productivity.
- The methods for evaluating export potential via berm overtopping versus outlet structure flow are associated with a number of uncertainties.

Baseline results

- Zooplankton production varies across the three subregions, but does not vary substantially year to year, suggesting low sensitivity to water year type or flow magnitude.
- Relative to total wetted area, zooplankton production is highest for Butte and Colusa subregions.
- For productivity export potential, Butte shows the highest of the three subregions.
- Productivity export potential is more sensitive to water year type and flow magnitude than zooplankton production suitability.
- Sutter has the greatest relative productivity export potential across the three subregions.

Next steps

- Given divergence of viewpoints around several areas of key uncertainties, particularly velocity, land cover, and export potential, a refinement and expansion of the export potential evaluation as well as careful presentation and interpretation of results is needed.
- Alignment with other ongoing work in the region should support the evaluation of floodplain connectivity and export potential.
- Further exploration of criteria values and how they are expressed within the model is warranted.
- Additional field-based research is needed directed at establishing relationships between zooplankton production and physical habitat criteria.
- Improving estimation of water age should be explored.
- Synthesis of existing data and field-based research and monitoring of productivity and its export to river channels within the study area over time would help validate the analysis approach.

References

Ahearn, D.S., Viers, J.H., Mount, J.F., Dahlgren, R.A., 2006. Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. Freshwater Biology 51, 1417–1433. https://doi.org/10.1111/j.1365-2427.2006.01580.x

Amoros, C., Bornette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47, 761–776. https://doi.org/10.1046/j.1365-2427.2002.00905.x

Baranyi, C., Hein, T., Holarek, C., Keckeis, S., Schiemer, F., 2002. Zooplankton biomass and community structure in a Danube River floodplain system: effects of hydrology. Freshwater Biology 47, 473–482. https://doi.org/10.1046/j.1365-2427.2002.00822.x

Bellmore, J.R., Baxter, C.V., Martens, K., Connolly, P.J., 2013. The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. Ecological Applications 23, 189–207. https://doi.org/10.1890/12-0806.1

Bellmore, J.R., Baxter, C.V., Ray, A.M., Denny, L., Tardy, K., Galloway, E., 2012. Assessing the Potential for Salmon Recovery via Floodplain Restoration: A Multitrophic Level Comparison of Dredge-Mined to Reference Segments. Environmental Management 49, 734–750. https://doi.org/10.1007/s00267-012-9813-x

Catlin, A.K., Collier, K.J., Duggan, I.C., Catlin, A.K., Collier, K.J., Duggan, I.C., 2016. Zooplankton generation following inundation of floodplain soils: effects of vegetation type and riverine connectivity. Mar. Freshwater Res. 68, 76–86. https://doi.org/10.1071/MF15273

Corline, N.J., Peek, R.A., Montgomery, J., Katz, J.V.E., Jeffres, C.A., 2021. Understanding community assembly rules in managed floodplain food webs. Ecosphere 12. https://doi.org/10.1002/ecs2.3330

Corline, N.J., Sommer, T., Jeffres, C.A., Katz, J., 2017. Zooplankton ecology and trophic resources for rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA. Wetlands Ecol Manage 25, 533–545. https://doi.org/10.1007/s11273-017-9534-2

Department of Water Resources (DWR), US Bureau of Reclamation (USBR), 2012. Yolo Bypass Salmonid Habitat Restoration and Fish Passage Implementation Plan, Long-Term Operation of the Central Valley Project and State Water Project Biological Opinion. Reasonable and Prudent Alternative Actions I.6.1 and I.7.

Górski, K., Collier, K.J., Duggan, I.C., Taylor, C.M., Hamilton, D.P., 2013. Connectivity and complexity of floodplain habitats govern zooplankton dynamics in a large temperate river system. Freshwater Biology 58, 1458–1470. https://doi.org/10.1111/fwb.12144

Grosholz, E., Gallo, E., 2006. The influence of flood cycle and fish predation on invertebrate production on a restored California floodplain. Hydrobiologia 568, 91–109. https://doi.org/10.1007/s10750-006-0029-z

Holmes, E., 2023. Personal communication.

Jeffres, C.A., 2023. Personal communication.

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

Jeffres, C.A., Opperman, J.J., Moyle, P.B., 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environ Biol Fish 83, 449–458. https://doi.org/10.1007/s10641-008-9367-1

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106, 110–127.

Keckeis, S., Baranyi, C., Hein, T., Holarek, C., Riedler, P., Schiemer, F., 2003. The significance of zooplankton grazing in a floodplain system of the River Danube. Journal of Plankton Research 25, 243–253. https://doi.org/10.1093/plankt/25.3.243

KSN, Inc., 2021. Evaluation Criteria Technical Memo, Sutter and Tisdale Bypasses Flood & Multi-Benefit Management Plan.

Opperman, J., 2008. Floodplain conceptual model. Sacramento-San Joaquin Delta regional ecosystem restoration implementation plan (DRERIP). Sacramento, CA.

Opperman, J.J., Moyle, P.B., Larsen, E.W., Florsheim, J.L., Manfree, A.D., 2017. Floodplains: Processes and Management for Ecosystem Services. University of California Press.

Pratt, O.P., Beesley, L.S., Pusey, B.J., Gwinn, D.C., Keogh, C.S., Douglas, M.M., 2023. Brief floodplain inundation provides growth and survival benefits to a young-of-year fish in an intermittent river threatened by water development. Sci Rep 13, 17725. https://doi.org/10.1038/s41598-023-45000-x

Serup, B., 2023. Personal communication.

Sommer, T., Harrell, B., Nobriga, M., Brown, R., Moyle, P., Kimmerer, W., Schemel, L., 2001. Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture 26, 11.

Sommer, T.R., Harrell, W.C., Nobriga, M.L., 2005. Habitat Use and Stranding Risk of Juvenile Chinook Salmon on a Seasonal Floodplain. North American Journal of Fisheries Management 25, 1493–1504. https://doi.org/10.1577/M04-208.1

Sommer, T.R., Harrell, W.C., Solger, A.M., Tom, B., Kimmerer, W., 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. Aquatic Conserv: Mar. Freshw. Ecosyst. 14, 247–261. https://doi.org/10.1002/aqc.620

Sturrock, A.M., Ogaz, M., Neal, K., Corline, N.J., Peek, R., Myers, D., Schluep, S., Levinson, M., Johnson, R.C., Jeffres, C.A., 2022. Floodplain trophic subsidies in a modified river network: managed foodscapes of the future? Landsc Ecol 37, 2991–3009. https://doi.org/10.1007/s10980-022-01526-5

Tockner, K., Stanford, J.A., 2002. Riverine flood plains: Present state and future trends. Environmental Conservation 29, 308–330. https://doi.org/10.1017/S037689290200022X

Ward, J.V., Tockner, K., Schiemer, F., 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regulated Rivers: Research & Management 15, 125–139. https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<125::AID-RRR523>3.0.CO;2-E

Whipple, A.A., 2018. Managing Flow Regimes and Landscapes Together: Hydrospatial Analysis for Evaluating Spatiotemporal Floodplain Inundation Patterns with Restoration and Climate Change Implications (Dissertation). University of California, Davis, Davis, CA.

Whipple, A.A., Grantham, T., Desanker, G., Hunt, L., Merrill, A., 2019. Chinook Salmon Habitat Quantification Tool: User Guide (Version 1.0) (No. 953), Prepared for American Rivers. Funded by the Natural Resources Conservation Service Conservation Innovation Grant (#69-3A75-17-40), Water Foundation and Environmental Defense Fund. San Francisco Estuary Institute, Richmond, CA.