



# Numerical Modeling in Support of Reclamation Delta Smelt Summer/Fall Habitat Analysis

Calanoid Copepod Analysis Addendum

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## INTRODUCTION

The primary goal of flow augmentation actions in the North Delta is to increase food resources for Delta Smelt and other species in the summer and fall. The two actions studied were the North Delta Flow Action (NDFA) in which flow into the Toe Drain is augmented in late August through late September, and the Deepwater Ship Channel (DWSC) Action in which flow from the Sacramento River into the DWSC is present in July. The North Delta Flow Action has occurred in several years and was accompanied by field studies that observed evidence of export of primary productivity and also high growth rate of *P. forbesi* in the productive water associated with the flow pulse in some years. The water associated with the initial flow pulse was found to have elevated calanoid copepod abundance and elevated chlorophyll in some years. The proposed DWSC flow augmentation has not happened historically but elevated calanoid copepod concentration has been observed in the DWSC. Effects of the SMSCG action on copepod distribution was not estimated because Sommer et al. (2020) did not note changes to observed copepod distribution from the SMSCG action in 2018.

The goal of this analysis is to provide a food web metric relevant to Delta Smelt. The analysis was limited to calanoid copepods which are a primary prey item of Delta Smelt in summer and fall (Slater and Baxter 2014). Estimates of biomass density were used by USBR in bioenergetic calculations and could perhaps be included as a component of a Habitat Suitability Index. To be consistent with the abiotic habitat suitability analysis, we report biomass density at a monthly time interval on a 10 m resolution raster. Since effects of the food subsidy actions are expected to be spatially limited, the results shown here are intended as potential upper bounds of management effects.

Our approach incorporated observed calanoid copepod catch per unit effort (CPUE) data, conservative tracer simulations and a simplified representation of copepod growth to estimate time and spatially variable calanoid copepod biomass per unit effort (BPUE) in the water volumes tagged with concentration of 1 in the tracer simulations. Because this water was associated with elevated biomass and was the water tracked by the tracer, it is referred to as “source water” here. The overall calanoid copepod BPUE was then estimated as a weighted average of the “source water” BPUE from the simulation and ambient (observed) BPUE based on observations. The weighting was based on the tracer concentration which represents the proportion of water present at a point in time and space that is “source water”.

## Observed Biomass Density

We estimated monthly calanoid copepod biomass density for June through October of 2018 and 2019 using monitoring data collected by the California Department of Fish and Wildlife, California Department of Water Resources and US Bureau of Reclamation using mesozooplankton nets. The specific data sources included the Environmental Monitoring Program (EMP) Zooplankton Study, the 20-mm Survey (20mm), the Fall Midwater Trawl (FMWT), the Summer Towntnet Survey (STN), the Fish Restoration Program (FRP) and Yolo Bypass monitoring (YOLO). The stations associated with these monitoring programs are shown in Figure 1. Additional information on these surveys and datasets is provided in Kayfetz et al. (2021). Data from these sources was accessed using the Zooplankton Data Synthesizer (<https://deltascience.shinyapps.io/ZoopSynth/>; Bashevkin et al. 2020). This tool

standardizes taxonomic names. However, the different programs do have differing taxonomic resolution with some identifying more individual species than others.

The catch per unit effort (CPUE) for taxa reported in the Zooplankton Data Synthesizer were converted to biomass per unit effort (BPUE) using dry carbon weights reported in Table 1. Only juvenile (copepodites) and adult life stages were included in this analysis because nauplii constitute a small portion of juvenile and adult delta smelt diet (Slater and Baxter 2014). A single carbon weight is used for each though it should be noted that actual carbon weight can vary greatly among different stages of juvenile copepods (Kimmerer et al. 2018).

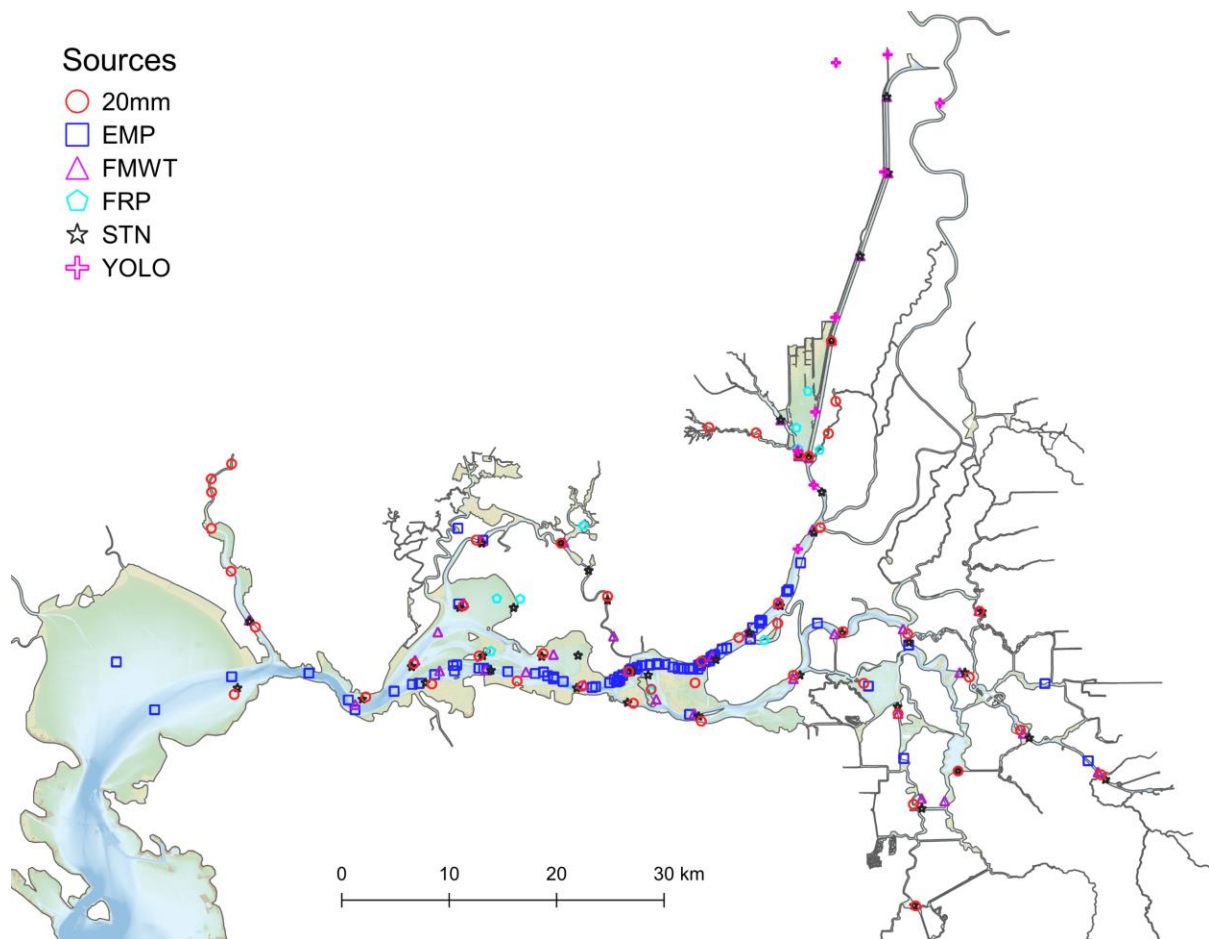


Figure 1 Stations associated with each source of data (survey program) used in calanoid copepod BPUE estimates

*Table 1 Dry carbon weights of calanoid copepod taxa*

<b>Taxon Name</b>	<b>Life Stage</b>	<b>Carbon Weight (<math>\mu\text{g}</math>)</b>
Acartiella sinensis	Adult	2.81
Acartia spp.	Adult	3.14
Diaptomidae	Adult	3.36
Eurytemora affinis	Adult	3.48
Other Calanoid adults	Adult	3
Pseudodiaptomus forbesi	Adult	3.265
Pseudodiaptomus marinus	Adult	4.9
Sinocalanus doerrii	Adult	3.413
Tortanus spp.	Adult	15.895
Acartiella sinensis	Juvenile	1.162
Acartia spp.	Juvenile	1.301
Diaptomidae	Juvenile	2
Eurytemora affinis	Juvenile	1.443
Other Calanoid juvenile	Juvenile	1.5
Pseudodiaptomus spp	Juvenile	1.246
Sinocalanus doerrii juvenile	Juvenile	1.811
Tortanus spp.	Juvenile	7.948

The spatial distribution of BPUE was estimated from values at individual stations. Prior to interpolation, the monthly BPUE estimate at each station was log transformed. It was then interpolated using a diffusion solution on the model grid and antilog transformed. The diffusion solution approach to interpolate and smooth the BPUE field accounted for hydraulic connectivity such that, for example, an estimated copepod BPUE in the Toe Drain had little influence on estimated BPUE in a geographically nearby point in the Deepwater Ship Channel because the diffusion approach interpolated and smoothed the BPUE field with distance along water, not distance across land. Regions further than approximately 10 km distance from any station were assigned a "no data" value for copepod density.

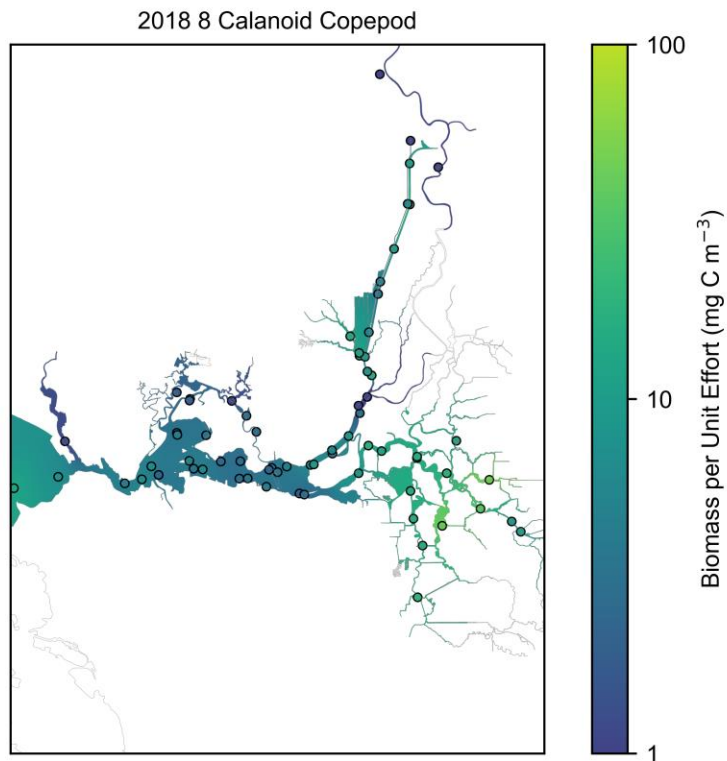


Figure 2. Observed calanoid copepod BPUE in August 2018. Circles indicate BPUE at individual stations and the continuous field is the interpolated BPUE distribution based upon the station data.

Calanoid copepod BPUE for historical conditions were estimated from CPUE observations for 2018 and 2019 (Figure 2), the two historical years used in our study with the most available zooplankton abundance data. Note that NDFA actions did occur in September of 2018 and 2019 and may have influenced the observed calanoid copepod distribution in those periods. However, we will use the term “Ambient” BPUE and “No Action” BPUE to refer to the observed conditions. During these periods there was no obvious indication of elevated observed calanoid copepod BPUE. Therefore, our NDFA alternatives are hypothetical cases in which incoming calanoid copepod BPUE associated with the NDFA was higher than during the historical conditions. The spatial coverage of zooplankton data in 2005 and 2009 was too limited to allow estimates of calanoid copepod distribution. The observed fields for 2018 and 2019 were used in the modeling approach described below with hydrodynamic results from each of 4 water year types (Wet, Above Normal, Below Normal, Dry) and 2 actions (NDFA and DWSC). Estimated BPUE from 2018 (Below Normal) was applied for both Dry and Below Normal water years and BPUE from 2019 (Wet) was applied for both Above Normal and Wet water year type simulations. The water year types and the years associated with different input data are provided in Table 2.

*Table 2 Periods associated with calanoid copepod analysis inputs. Calanoid copepod BPUE was estimated both for the DWSC action and the NDFA action for each of the listed water year types. Model inputs for atmospheric forcing and other hydrodynamic model boundary conditions were applied from the Historical Year, boundary inflows were provided from CalSim II for the CalSim Year and copepod data was applied for the Copepod Data Year.*

<i>Water Year Type</i>	<i>Historical Year</i>	<i>CalSim Year</i>	<i>Copepod Data Year</i>
Dry	2009	1930	2018
Above Normal	2005	1940	2019
Below Normal	2018	1979	2018
Wet	2019	1986	2019

## Biomass Density Modeling Approach

Simulations which predict tracer concentration and associated age are useful to visualize the distribution of a tagged water volume through time as it is advected by net flows and mixed by dispersive processes. The “source water” was tagged with a concentration of one and age zero either as it enters the domain or in some region of the domain at a point in time. Predictions from the water age simulation approach were compared with field observation-based estimates of age in Gross et al. (2019).

In order to estimate copepod density for proposed flow actions, we applied a simple copepod model focused on transport of calanoid copepods from a source region through the model domain and uptake of phytoplankton by the calanoid copepods. The tracers used in the tracer concentration and age simulations represented the source of potentially elevated copepod abundance. For the NDFA, this “source water” was the water entering the model domain at the Toe Drain boundary near 180 because this water has been observed to have elevated copepod abundance in some years (Owens et al. 2019). For the DWSC action, the “source” was water initially present in the DWSC where elevated copepod abundance is sometimes observed. The tracer transport simulations estimated the spatial distribution of this source water through this model domain for the simulation period.

In addition to estimating the spatial distribution of the source water, we also estimated the age of that water using a constituent-based water age approach (Deleersnijder et al. 2001). For the NDFA, the predicted tracer age varied spatially because “new” (age 0) water entered at the boundary as long as flow in the Toe Drain was directed downstream (seaward). In contrast, the DWSC source water represented water initially in the DWSC, not water entering the DWSC. This was a deliberate choice because the observed copepod abundance in the Sacramento River adjacent to the upper part of the DWSC typically has lower copepod abundance than the DWSC. The source water age for the DWSC scenarios was spatially uniform because it was all initialized to zero at the beginning of the action and no “new” (age=0) tracer was introduced at any later point in time. Therefore, the

tracer age for the DWSC action at any point in time was the time elapsed since the beginning of the action.

As the source water containing elevated copepod and chlorophyll abundance was transported in the model domain, we allowed the predicted copepod BPUE associated with this water to change in time. The method for estimating the copepod density in the source water has been applied by Wang et al. (2019) to estimate evolving chlorophyll concentration in a source water as it is advected seaward. Following this approach, a simplified governing equation for the biomass density or BPUE is

$$\frac{\partial D_s}{\partial t} + \nabla \cdot (\mathbf{u}D_s) = \mu_{net}B \quad (1)$$

where  $D_s$  is biomass density ( $\text{mg C m}^{-3}$ ) and  $\mu_{net}$  ( $\text{day}^{-1}$ ) is the net growth rate accounting for all growth and loss processes. An upper bound of  $\mu_{net}$  of  $0.4 \text{ day}^{-1}$  from Owens et al. (2019) was used.

In a Lagrangian frame of reference this equation is equivalent to

$$\frac{dD_s}{da} = \mu_{net}D_s \quad (2)$$

where  $a$  (day) is the water age calculated by the constituent-based water age approach of Deleersnijder et al. (2001) to provide predictions of age throughout the model domain and simulation period. Given a known initial and boundary concentration, the biomass density inside source water present at all points in the model domain through time was estimated by the analytical equation

$$D_s(x, t) = \min(D_{s,max}, D_s(x_{in}, t - a)e^{\mu_{net}a}) \quad (3)$$

where  $D_s(x_{in}, t - a)$  is the concentration associated with incoming water. In the case of the NDFA,  $D_s(x_{in}, t - a)$  was the calanoid copepod biomass density incoming to the Toe Drain during the flow pulse. Because unbounded growth could lead to unrealistic copepod biomass density estimates, we bounded the prediction of biomass density in the source water by  $D_{s,max}$ .  $D_{s,max}$  was estimated by assuming that a portion of available phytoplankton biomass was converted to calanoid copepod biomass.

$$D_{s,max} = D_s(x_{in}, t - a) + D_{s,uptake} \quad (4)$$

where  $D_{s,uptake}$  is the maximum copepod biomass generated by uptake of phytoplankton biomass since entering the domain.

$$D_{s,uptake} = C_r C_g C_c Chla_s \quad (5)$$

where  $Chla_s$  is chlorophyll concentration ( $\text{mg m}^{-3}$ ) in the source water,  $C_r$  is the C/Chla ratio,  $C_g$  is the growth yield representing the portion of phytoplankton biomass that becomes zooplankton biomass, and  $C_c$  is a competition factor accounting for uptake of phytoplankton by species other than calanoid copepods or could also represent the portion of phytoplankton mass that is not available for uptake by calanoid copepods.  $C_r$  was set to 23 following Kimmerer and Thompson (2014).  $C_g$  was set to 0.35, roughly consistent with the 0.33 value used in Cloern (2007).  $C_c$  is uncertain and was set to 0.5 as a possible upper bound value. Note that part of the competition for phytoplankton would be exerted by clams in addition to other zooplankton species other than calanoid copepods.

A large advantage of this simple model was that it could be run offline efficiently after the tracer simulations were complete. Any elements of the formulation, including parameter values, could be readily changed and new predictions generated.

At each point in time (2-hour interval) and space (grid node) during the simulation, the concentration associated with the source water was calculated by Equation 3. However, because the source water made up only a portion, often a small portion, of the water present at a given location, the overall biomass density was estimated as a weighted average of the source water biomass density and the ambient (observed) biomass density

$$D(x, t) = C_s(x, t)D_s(x, t) + (1 - C_s(x, t))D_{ambient}(x, t) \quad (6)$$

where  $D(x, t)$  is the predicted calanoid copepod biomass density at a point in time and space,  $C_s(x, t)$  is the tracer concentration indicating the proportion of water at  $(x, t)$  that is source water (e.g. from the NDFA flow pulse).  $D_{ambient}(x, t)$  is the ambient biomass density estimated based on observations. Note that during September of 2018 and 2019 the ambient BPUE may have been influenced by the NDFA actions that occurred. However, since an observed effect was not apparent, we refer to the historical conditions as “No Action” estimates.

## Biomass Density Estimates

Using the historical estimates of calanoid copepod BPUE and the simple model of copepod growth described above, we estimated calanoid copepod BPUE for flow action scenarios. Our intention was to estimate a likely upper bound of the management effect of the flow augmentations in the Toe Drain and the Sacramento DWSC on copepod abundance. We acknowledge that larger effects of flow actions could occur due to more complex food web dynamics than those considered here. For example, if the flow actions result in a large algal bloom in downstream regions, that could potentially lead to larger effects on calanoid copepod abundance than those estimated here.

The calanoid copepod BPUE associated with source water was specified based on observed data. For the NDFA all zooplankton data collected by DWR (Frantzich et al. 2018) in the Toe Drain from July through September was considered. This location and time period correspond to conditions that can be present at the time of a North Delta Flow Action. The stations in this region were RD22, I80, LIS, and STTD. The 75<sup>th</sup> percentile calanoid copepod BPUE at these stations in the July through September period for 2016 through 2019 was 5.4 mg C m<sup>-3</sup>. A similar approach was applied to all stations in the DWSC for June and July, the period prior to and during an anticipated action, to estimate a 75<sup>th</sup> percentile BPUE of 19.5 mg C m<sup>-3</sup>. A similar approach was applied to estimate the 75<sup>th</sup> percentile of chlorophyll for each scenario resulting in values of 23.0 mg m<sup>-3</sup> for the NDFA and 2.1 mg m<sup>-3</sup> for the DWSC action.

Several assumptions and approximations are inherent in our approach. Some are general to the approach and some are specific to the representation of the effects of individual actions.

- General
  - The observed calanoid copepod CPUE at stations was representative of actual calanoid copepod abundance
    - This may not be true if copepods had demersal behavior during the daytime (when sampling occurs) or tidal migration behavior

- A single carbon weight was used for each gross life stage of calanoid copepods
  - This is particularly inaccurate for copepodites
- Unidentified species had an assumed carbon weight in a representative range for calanoid copepods
  - This may introduce some sensitivity to the different taxonomic resolution of different surveys
- Several model parameter values described above are approximate
  - In particular the competition parameter is unknown
- Calanoid copepods are transported passively
  - Tidal migration and day-night patterns including demersal behavior during the day have been observed for calanoid copepods
- The growth rate of calanoid copepods corresponded to roughly the highest observed rate for *P. forbesi* of 0.4 day<sup>-1</sup> from Owens et al. (2019).
  - Actual growth could be particularly lower as chlorophyll levels drop
- After the chlorophyll in the “source water” was taken up, growth and loss processes were in balance for calanoid copepods
  - Actual loss processes such as clam grazing can vary temporally and spatially
- Observed ambient (No Action) BPUE is static during the month
  - We estimated a dynamic (2-hour interval) source water BPUE but only a monthly interval “ambient” BPUE because that is based upon observed data typically collected at a monthly interval
- Historical calanoid copepod BPUE during September of 2018 and 2019 was not significantly influenced by historical NDFA actions
  - In contrast our scenarios estimate the effect of a high level of incoming calanoid copepod BPUE and chlorophyll during the NDFA actions
- North Delta Flow Action
  - Calanoid copepod BPUE and chlorophyll concentration incoming at I80 remain fixed during the flow action
    - Actual concentrations are observed to drop
  - The range of age of source water is simplified to the “mean age” estimated using the constituent-based age approach (Deleersnijder et al. 2001)
    - For a non-linear process such as copepod growth this introduces error
- DWSC
  - Uniform initial calanoid copepod BPUE and chlorophyll concentration in the DWSC

Several of these assumptions and approximations are known to be inaccurate but are retained for simplicity in some cases and to provide an upper bound estimate in other cases. For example, calanoid copepods are known to not be transported passively (Kimmerer et al. 2014) but since accounting for the effect of behavior on transport would require a more complex approach, this assumption is applied for simplicity. An inaccurate approximation used as an upper bound for the NDFA was that calanoid copepod BPUE and chlorophyll concentration incoming at I80 were constant in the simulation. Observations indicate that these concentrations actually dropped rapidly during historical North Delta Flow Actions (Owens et al. 2019; Frantzich et al. in progress).

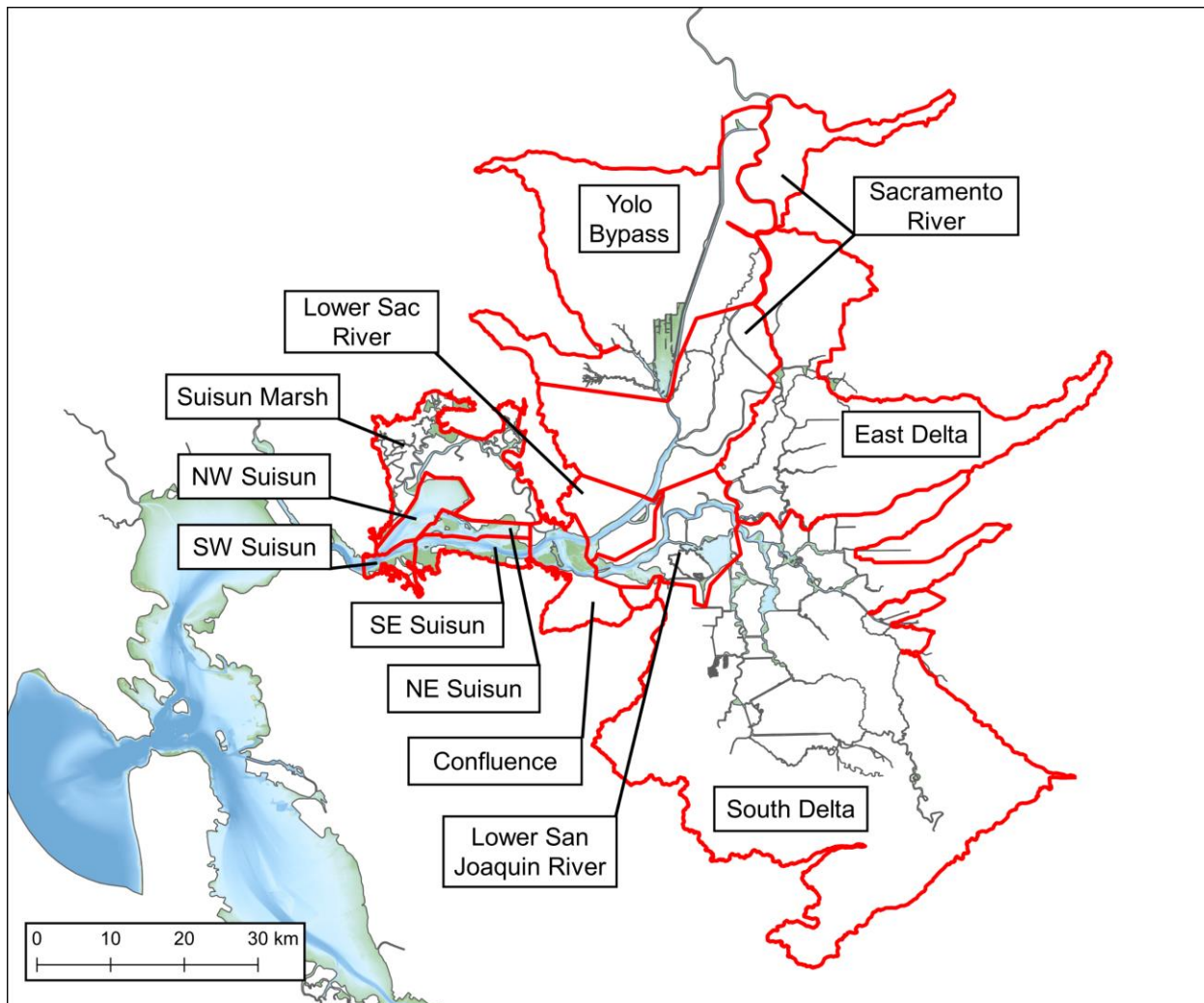


Figure 3 Regions used in the delta smelt IBM and for tabulation of calanoid copepod BPUE in this study.

The primary outputs of this analysis are 10-meter resolution maps of estimated monthly-averaged calanoid copepod BPUE and tabulated values for discrete regions. An example of these mapped model results is Figure 4, which shows the average predicted copepod abundance in October during the Wet water year type predicted for the NDFA flow action which extended from August 28 to September 23. The pattern of elevated biomass near to the confluence of Prosect Slough into the Liberty Island area is reflective of the NDFA action transporting copepods and their food resources into those areas.

The spatial difference between the ambient (“No Action”) calanoid copepod distributions and the modeled distributions with the NDFA flow action can be seen in Figure 5. These predicted fields through time are available as animations. The snapshot in Figure 5, corresponding to 116 hours after the start of the NDFA flow action, shows that predicted BPUE increased relative to ambient BPUE, indicating that the copepod density in the source water is higher than the ambient (observed) copepod density. At this point in the simulation, the difference in BPUE in areas of concentrated NDFA action “source” water exceeded  $10 \text{ mg C m}^{-3}$ .

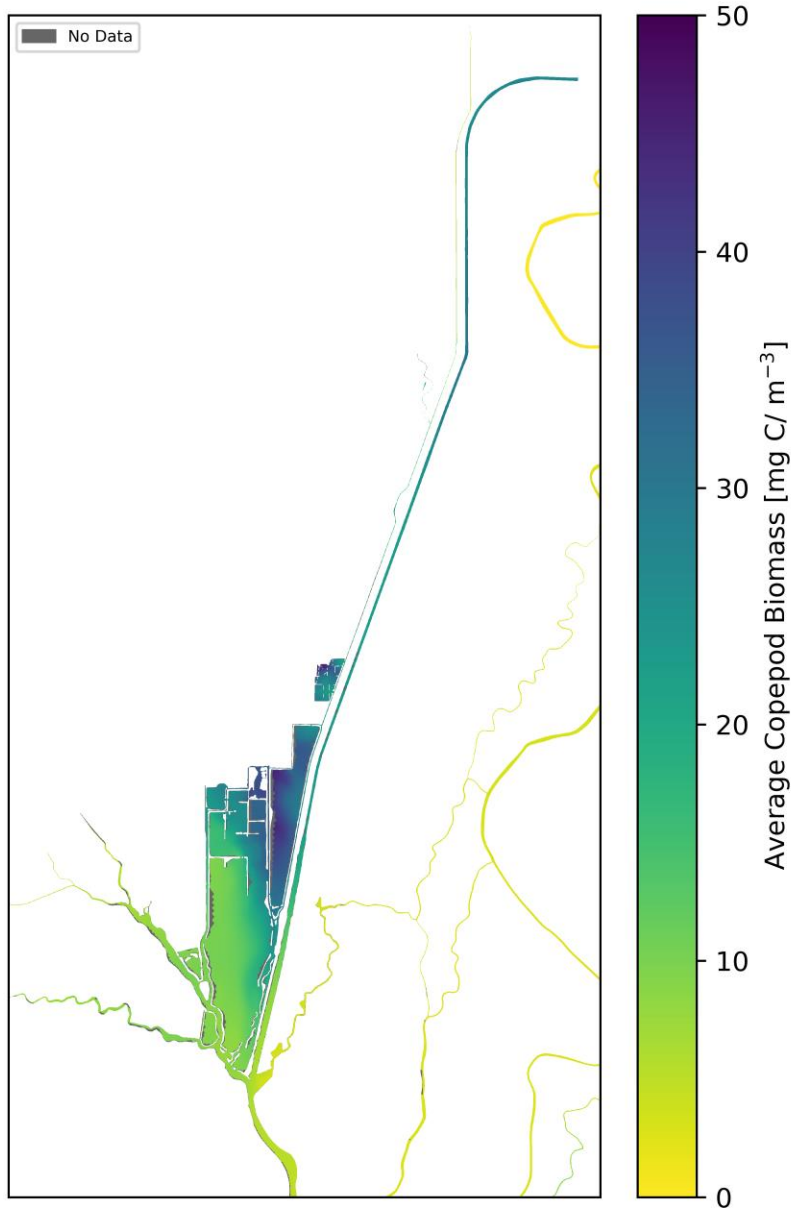


Figure 4 Predicted average monthly calanoid copepod biomass with NDFA action during Above Normal water year (1940 CalSim year).

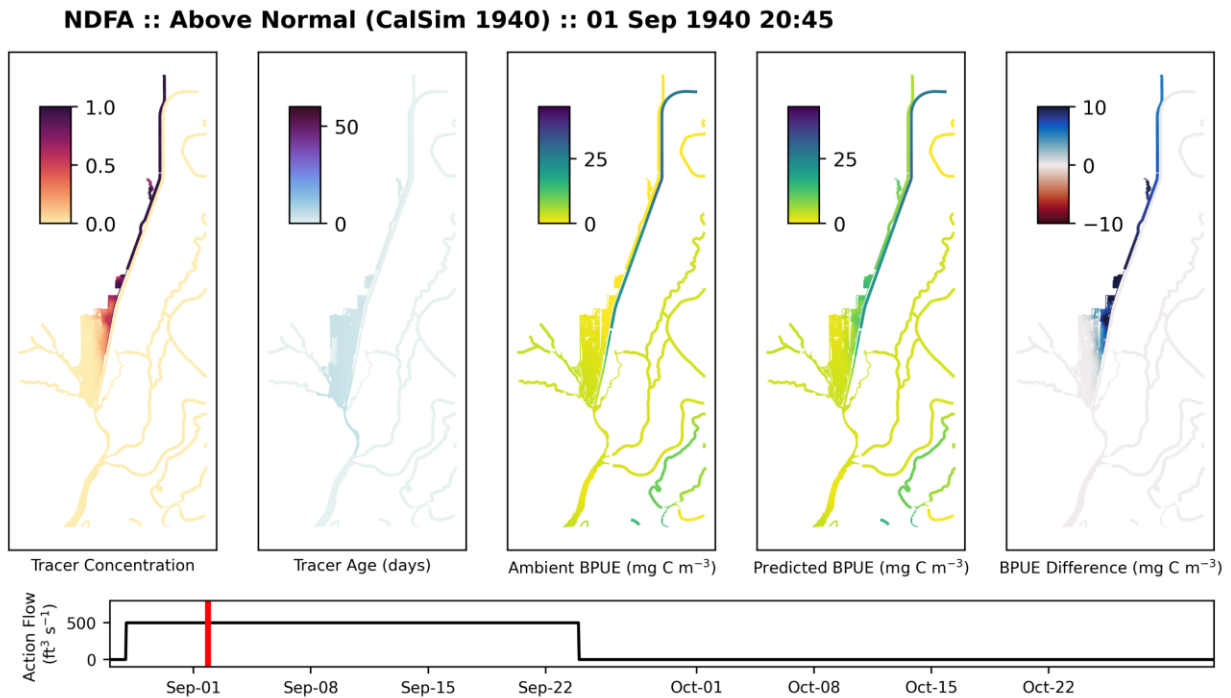


Figure 5 Snapshot of calanoid copepod and tracer results for the NDFA, during an Above Normal water year (CalSim year 1940). Predicted BPUE is a function of the concentration of the flow action water (tracer concentration), the age of this water (tracer age), and calculated initial calanoid copepod and food resource (chlorophyll) concentrations in the flow action source water. The difference between predicted and ambient (interpolated from observations) BPUE at this time in the simulation indicates greater calanoid copepod BPUE localized near to the flow action.

A similar snapshot demonstrates simulation progression for the DWSC flow action in Figure 6. 140 hours after the start of the flow action, much of the flow action source water was still in the Deepwater Ship Channel, due to its high volume relative to the action flow rate, and a high initial source water calanoid copepod BPUE. Some source water mixed into southern Liberty Island causing a slight increase in the predicted copepod BPUE there.

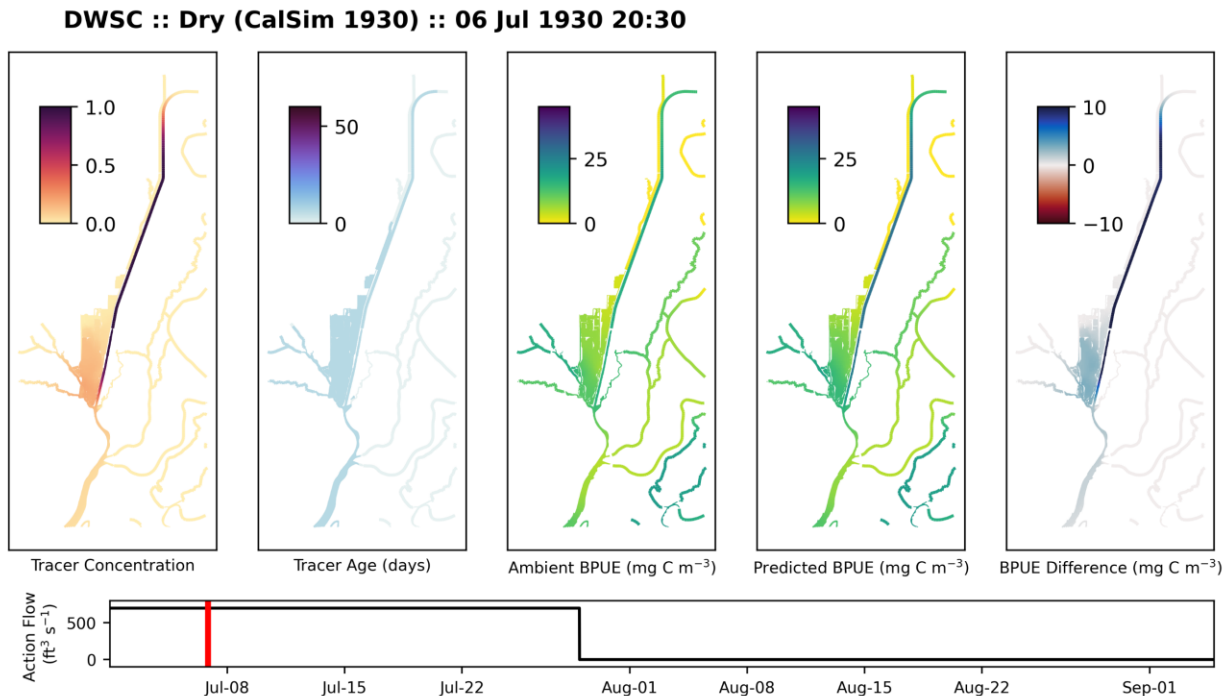


Figure 6 Snapshot of calanoid copepod and tracer results for the DWSC flow action, during a Dry water year (CalSim year 1930). Predicted BPUE is a function of the concentration of the “source” water (tracer concentration) corresponding to water initially in the DWSC, the age of this water (tracer age) since initiation of the flow action, and calculated initial calanoid copepod and food resource (chlorophyll) concentrations in the flow action source water. The difference between predicted and ambient (interpolated from observations) BPUE at this time in the simulation indicates greater calanoid copepod BPUE in and near the DWSC.

GeoTIFF data files indicating the spatially-variable difference between interpolated ambient and predicted monthly-averaged calanoid copepod BPUE are also available. These differences represent a likely upper bound of monthly-averaged changes in calanoid copepod biomass possible from flow actions. The NDFA action ended in September, and predicted calanoid copepod BPUE increased by 15 mg C m<sup>-3</sup> above ambient over a large portion of Liberty Island (Figure 7 for Above Normal water year). This estimated effect persisted into October decreased as the NDFA water was diluted by mixing with ambient water.

Monthly-averaged BPUE difference plots show a smaller increase in copepod BPUE for the DWSC action during July, when the DWSC flow action took place (Figure 8) relative to the estimated NDFA flow action effect (Figure 7). The smaller estimated effect was partially due to hydrodynamics, with DWSC action source water (water in the DWSC at the beginning of the simulation) never reaching the high concentrations of NDFA source water in Liberty Island, but was mostly due to the specified calanoid copepod BPUE of the source water. Measured copepod concentrations were high in the DWSC, but food resources (chlorophyll) were low, therefore predicted copepod results are reflective of a generally poor growth environment. Therefore, DWSC action predicted BPUE were mostly a function of transport and dilution of initial DWSC BPUE rather than growth.

This pattern of greater increases in monthly-averaged predicted calanoid copepod BPUE from the NDFA flow action, compared to DWSC, held across the four different flow type years for the Yolo

Bypass region (Figure 9). The NDFA flow action differences are generally most visible in the Yolo Bypass, while the DWSC action produces very modest increases in calanoid copepod BPUE downstream into Eastern Suisun Bay and Suisun Marsh.

We stress that these are upper bound estimates of the potential flow action effect on calanoid copepod BPUE and are sensitive to the assumed calanoid copepod BPUE and chlorophyll in source water. Given the computational efficiency of the approach, a suite of such simulations could be performed to explore uncertainty related to these and other model inputs.

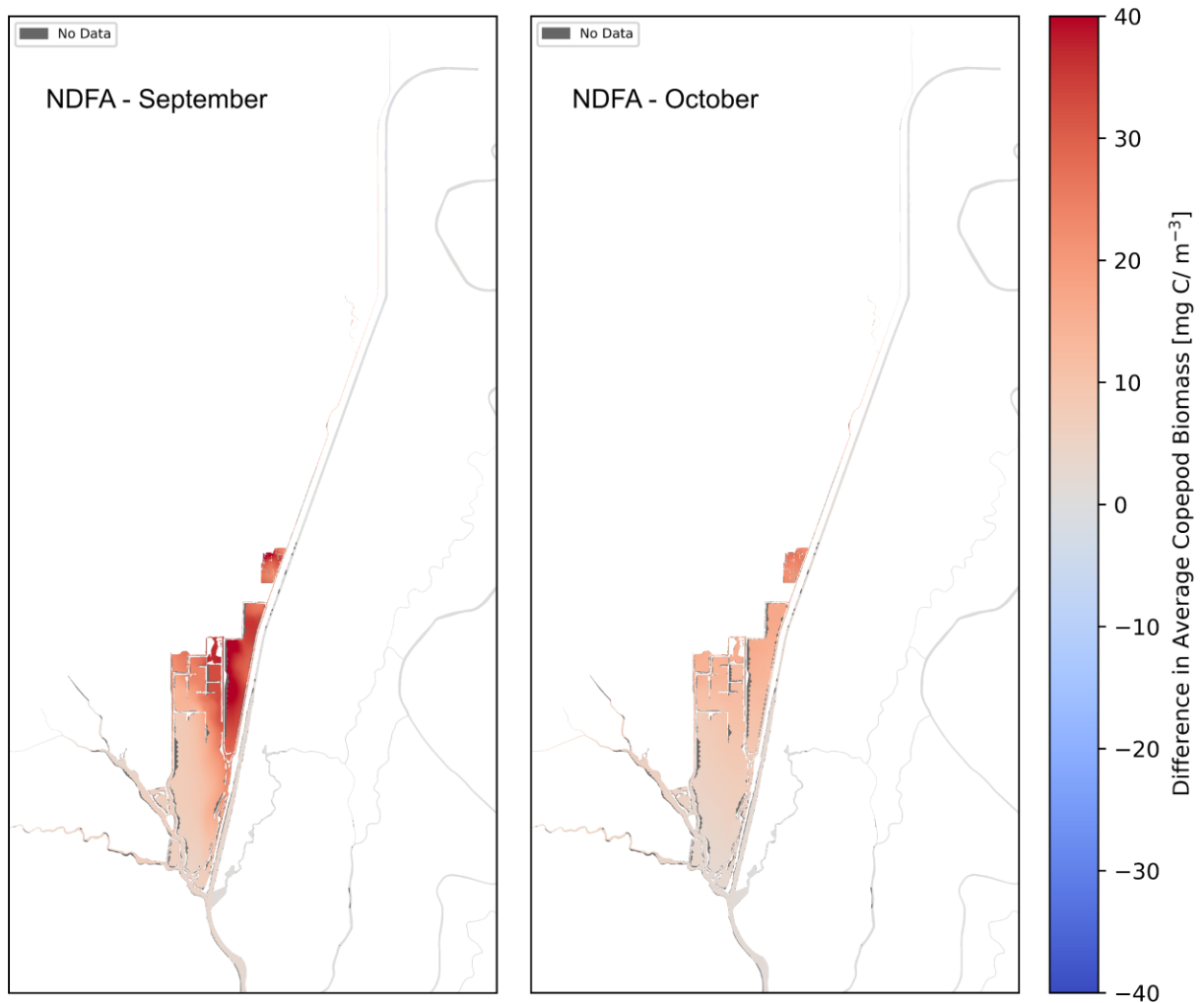


Figure 7 Difference between NDFA and No Action monthly-averaged calanoid copepod BPUE during September (left) and October (right) of the Above Normal water year (CalSim year 1940).

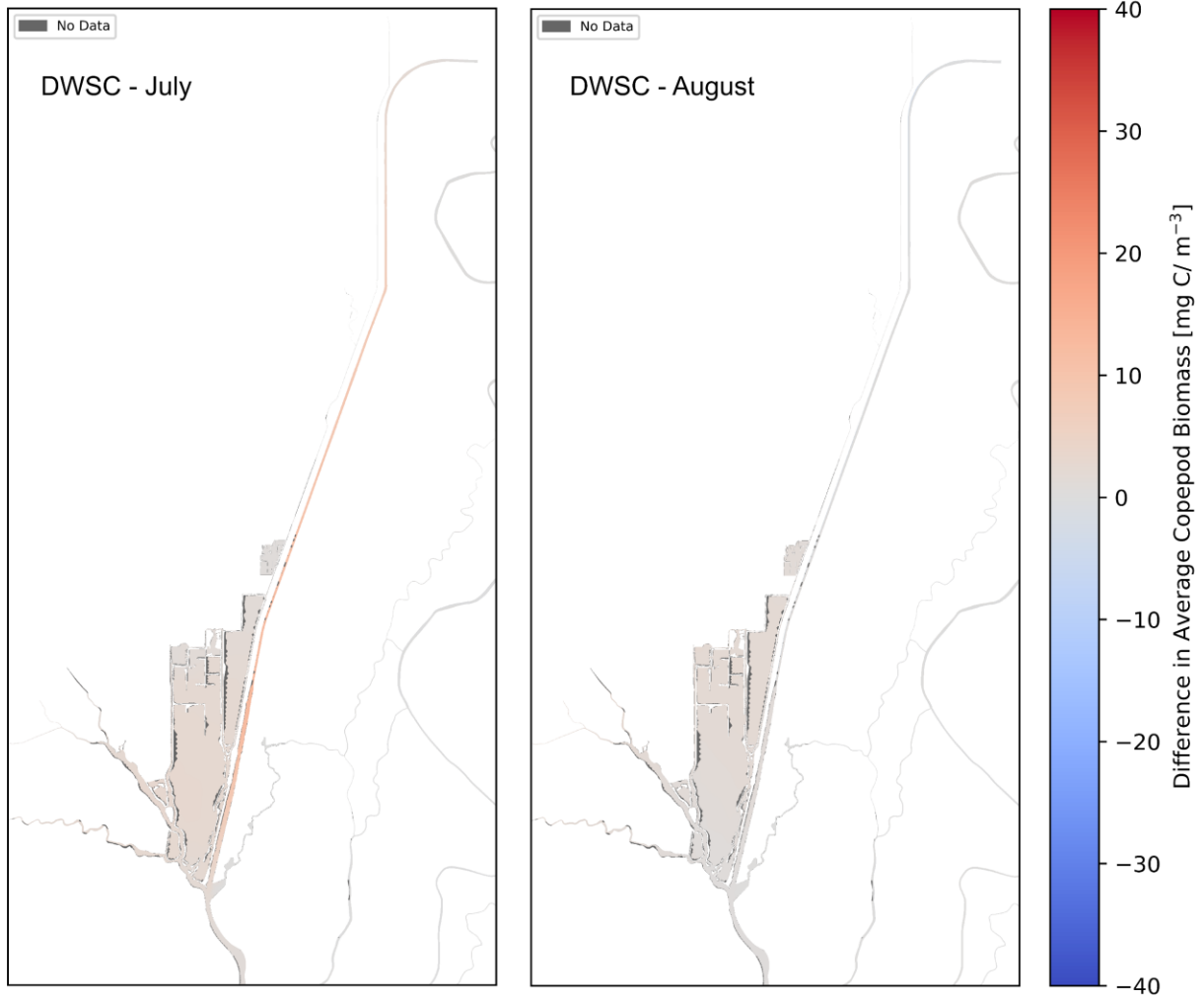


Figure 8 Spatial difference between predicted and ambient monthly average calanoid copepod BPUE for the DWSC flow action, during July (left) and September (right), for Above Normal water year (CalSim year 1940).

Monthly-averaged volume-weighted copepod biomass

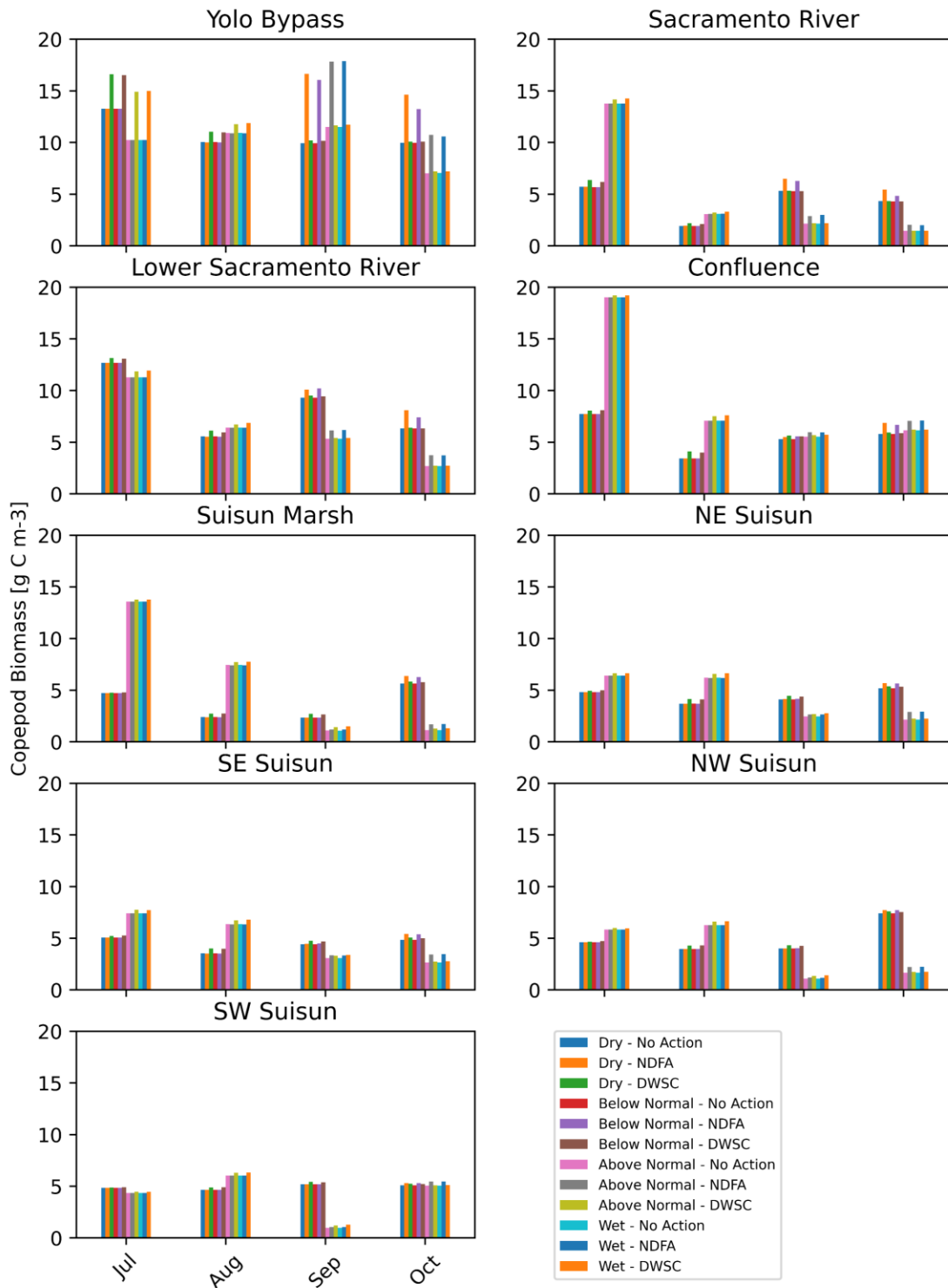


Figure 9 Regionally-averaged monthly calanoid copepod BPUE (Rose et al. 2013 IBM regions), for 4 water years types and 3 different management scenarios.

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