From:	Hartman, Rosemary@DWR <Rosemary.Hartman@water.ca.gov>
Sent:	Wednesday, February 1, 2023 1:57 PM
To:	Foresman, Erin@Waterboards; Frazier, Scott@Waterboards; Riddle, Diane@Waterboards; Ekdahl, Erik@Waterboards; Leahy, Tina@Waterboards; Heinrich, Dana@Waterboards; Holland, Matthew@Waterboards; Louie, Stephen@Waterboards
Cc:	Hinojosa, Tracy@DWR; Reeves, Ryan@DWR; Grimaldo, Lenny@DWR; Jones, Kristopher@DWR; White, Molly@DWR; Yarbrough, John@DWR; McQuirk, Jacob@DWR; Hunt, Thaddeus@Waterboards; Louie, Stephen@Waterboards
Subject:	2022 TUCO drought impacts report
Attachments:	Drought Short-term white paper draft_2023Jan31.pdf
Follow Up Flag:	Follow up
Flag Status:	Flagged

EXTERNAL:

Dear Mr. Ekdahl,

Attached is a report on the impact of drought conditions and drought actions in the Delta as required by Condition 7 of the of the 2022 TUCP, “conduct modeling, monitoring, analysis, and reporting and prepare other technical information necessary to inform operational decisions and assess drought emergency actions authorized by this Order and any subsequent temporary urgency change orders in combination with other drought actions”, including completion of the Drought Synthesis element of the IEP workplan.

Any questions or comments can be addressed to me, Rosemary.Hartman@water.ca.gov

Rosemary Hartman, PhD (she/her)
Environmental Program Manager
Department of Water Resources
916-882-2926

Ecological Impacts of Drought on the Sacramento-San Joaquin Delta

with special attention to the extreme drought of 2020-2022

February 1, 2023

Prepared By the Interagency Ecological Program Drought Synthesis Team

Interagency
Ecological Program
COOPERATIVE ECOLOGICAL
INVESTIGATIONS SINCE 1970

Drought Synthesis team members:

- Rosemary Hartman[1]
- Arthur Barros[2]
- Christina Burdi[2]
- David Bosworth[1]
- Ted Flynn[1]
- Jereme Gaeta[2]
- Elizabeth Keller[3]
- Peter Nelson[1]
- Amanda Maguire[1]
- Sarah Perry[1]
- Nicholas Rasmussen[1]
- Jenna Rinde[2]
- Evan Sawyer[3]
- Tyler Salman[1]
- Elizabeth Stumpner[1]
- Laura Twardochleb[1,6]
- Elizabeth Wells[1]

With technical assistance from:

- Keith Bouma-Gregson[5]
- Samuel Bashevkin[4,6]

1. California Department of Water Resources
2. California Department of Fish and Wildlife
3. NOAA Fisheries, West Coast Region
4. Delta Science Program, Delta Stewardship Council
5. U.S. Geological Survey, California Water Sciences Center
6. California State Water Resources Control Board

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Disclaimer

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Executive Summary

In this report we integrated long-term data from the Interagency Ecological Program (IEP)'s long-term monitoring, as well as other data sources, where available, to assess the impacts of droughts on the upper San Francisco Estuary (Suisun Bay, Suisun Marsh, and the Delta). We describe certain key changes that occur during droughts:

1. Net Delta inflows and outflows decrease, but tidal flows and maximum velocities are similar when compared to wet years.
2. Lower flows result in higher water clarity, higher salinity, higher nutrients, higher residence time, and lower connectivity for migratory fishes.
3. The combination of higher residence time, higher temperatures, and higher nutrients results in higher chlorophyll and zooplankton in the South Delta. This includes increased frequency of harmful algal blooms.
4. Increased salinity, reduced import of phytoplankton and zooplankton from upstream, combined with increased benthic grazing rates result in decreased chlorophyll and zooplankton in Suisun Bay.
5. Increased temperature, increased salinity, and decreased connectivity result in decreased pelagic fish populations.

The current drought (2020-2022) shares many similar features to previous droughts, but there are a few key differences, some of which may be linked to drought management actions as noted below:

1. Water temperatures are hotter than previous droughts, particularly in 2020.
2. Recent upgrades to wastewater treatment plants resulted in less increase in nutrients than previous droughts.
3. Despite lower-than-expected nutrients, *Microcystis* observations were similar to other dry years.
4. Salinity in the Confluence was slightly higher than previous droughts in 2021, due to the extremely dry conditions. Regional salinities were modified by the SWB's modification of western Delta salinity standards and the installation of the Emergency Drought Barrier reduced the water cost of maintaining those modified standards.
5. The long-term increases in water clarity in the Delta means that the current drought has higher water clarity than previous droughts.
6. Long-term trends in pelagic fish abundances, combined with the current drought, means that many species' abundance indices were the lowest on record. Surprisingly, Longfin Smelt experienced higher than expected population growth in 2020 and 2021.

Contents

Introduction

The record-breaking drought of 2020-2022 highlighted the need for increased understanding of the impact of droughts on the Delta ecosystem and how management actions undertaken during droughts impact ecosystem processes. Therefore, the Interagency Ecological Program (IEP) Drought Synthesis Team began an analysis to investigate changes to major ecosystem parameters that occur during droughts. The team analyzed flow, water quality, nutrients, phytoplankton, zooplankton, aquatic vegetation, clams, jellyfish, and finfish to see which parameters increased and which decreased during droughts. The team also compared these parameters as measured during the 2020-2022 drought versus previous data categorized by water year type to see whether this drought stands out against the historical record, and to see whether management actions taken during 2021 and 2022 impacted ecosystem responses to the drought.

This report focuses on comparing the water years of 2020-2022 to previous data. A series of companion papers is being prepared for publication in a peer-reviewed journal (planned submission to San Francisco Estuary and Watershed Sciences). These papers will look at the long-term data set from 1975-2021 to identify patterns in historical droughts and the effect of drought in general on the ecosystem.

Drought team and collaboration

The IEP Drought Synthesis Team was originally formed in 2014 to assess the impact of the major drought of 2012-2016. This team was reformed in spring of 2021 with several of the original members as well as many new members to assess the drought of 2020-2021 and future drought impacts. The team contains members from the California Department of Water Resources (DWR), The Delta Science Program (DSP), California Department of Fish and Wildlife (CDFW), National Oceanic and Atmospheric Administration Fisheries (NOAA Fisheries), and the United States Geological Survey (USGS) who are all committed to synthesis and monitoring of ecosystem drought impacts. The team works closely with the US Bureau of Reclamation-led effort to develop a Drought Toolkit and the joint DWR/Reclamation team developing the annual Drought Contingency Plan.

Predicted Impacts of Drought

The conceptual model of droughts developed by the IEP Drought Synthesis team postulates that all ecosystem changes are triggered by changes in flow that alter the residence time of water in the system and the connectivity between different parts of the system (Figure 1). Increased air temperature during droughts also drives changes to water temperature with impacts up and down the food web. Decreased flow will lead to increased salinity. Increased residence time will lead to increased water clarity, increased grazing and turnover rates, and increased nutrients with increased opportunities for phytoplankton and zooplankton growth. Actual biomass of phytoplankton and zooplankton will vary by region of the estuary (Figure 2) and whether changes to salinity, changes to grazing rates, or changes to nutrients are the limiting factor in predicting outcomes. Impacts on fishes are driven by shifts in the location of optimal water quality habitat and changes to connectivity between habitat patches.

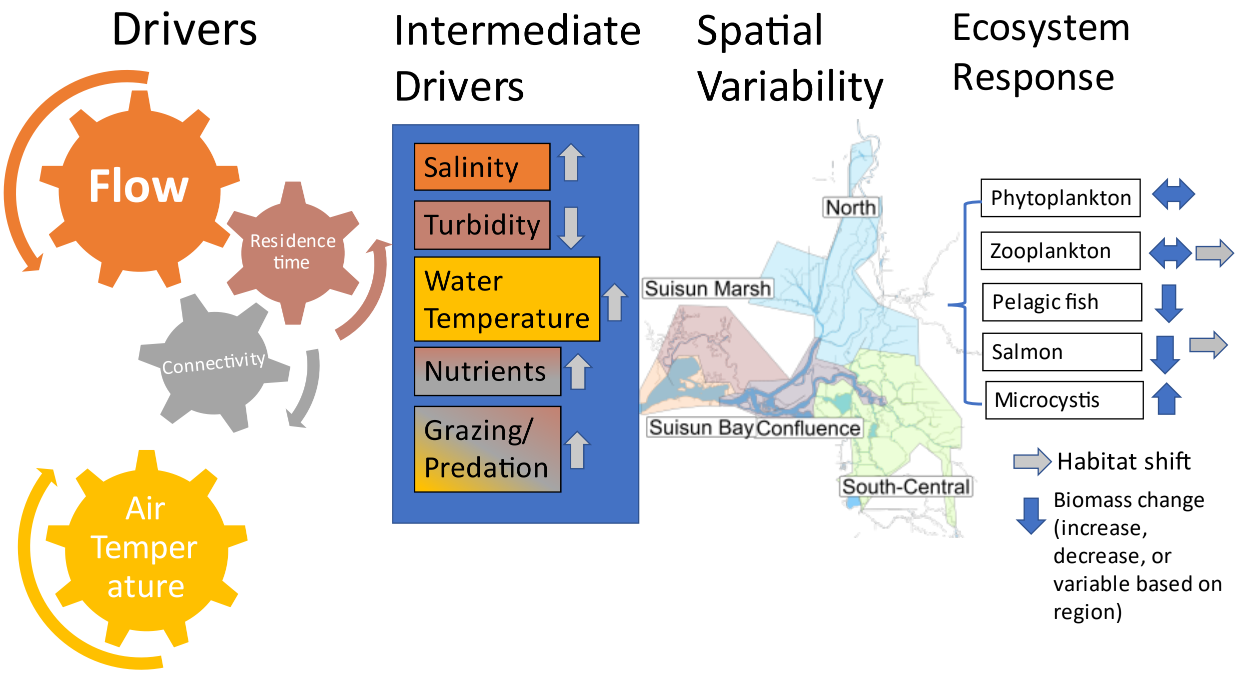

Figure 1. Conceptual model of drought impacts on the Delta ecosystem. Decreased flow causes increased residence time, decreased connectivity, increased salinity, water temperature, nutrients, and grazing rates, and decreased turbidity. These changes influence the ecosystem differently in different regions of the Delta.

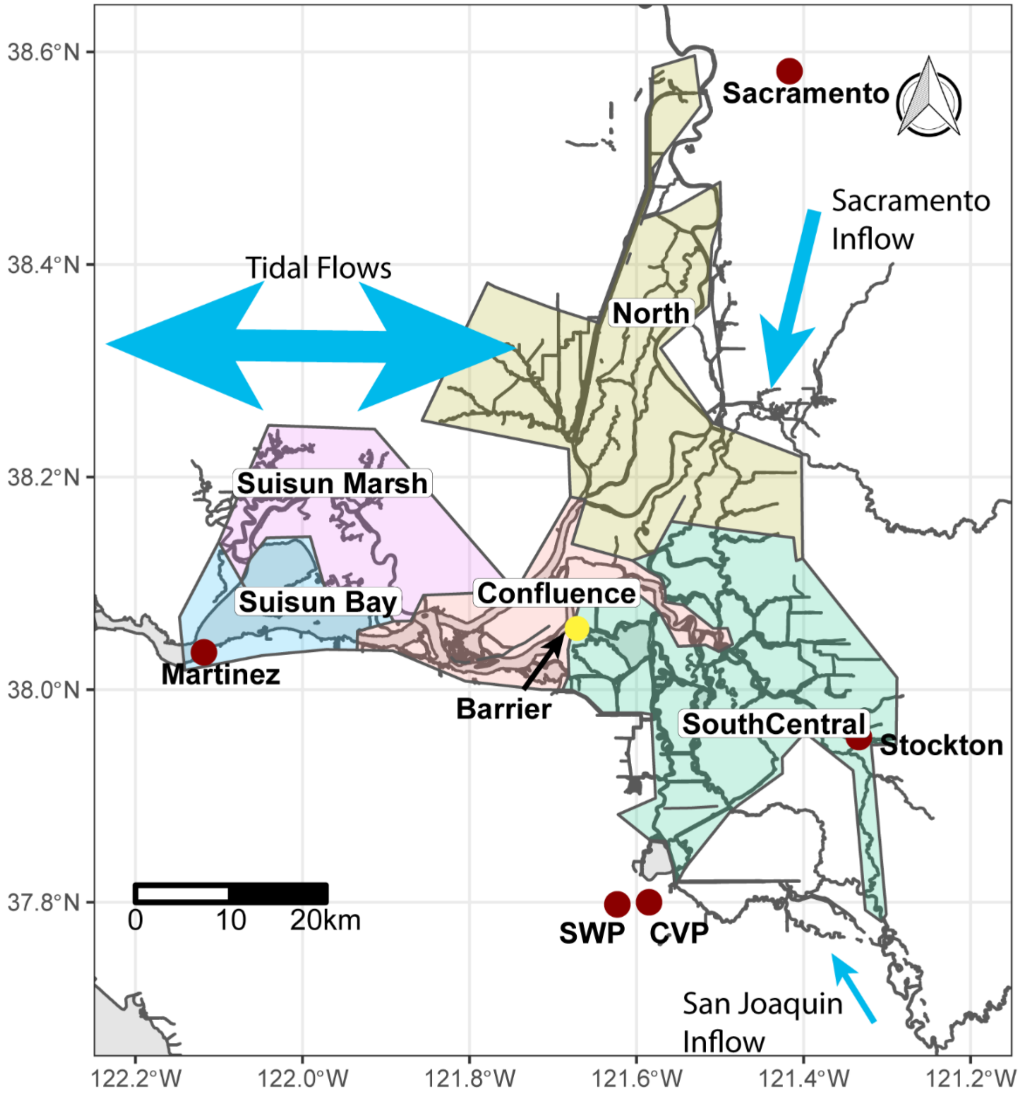

Figure 2. Map of the estuary with major cities, points of interest (Emergency Drought Barrier (Barrier), State Water Project pumps (SWP), and Central Valley Project Pumps (CVP), and regions used for analysis. Blue arrows indicate major flow parameters (not to scale).

Regulatory Background

California's Mediterranean climate is characterized by hot, dry summers, and cool, wet winters. The central and southern regions of the state receive little to no rainfall for six to nine months out of the year. There is also high inter-annual variability, with average rainfall varying from a low of 23.8 cm in 1924 to a high of 105.8 cm in 2017 (CDWR 2022a), usually depending on just a few massive storms each year (Dettinger 2011). This high variability leads to frequent floods and multi-year droughts that result in massive year-to-year changes in both the aquatic community and the ability of managers to provide water for consumptive use.

Due to California’s high inter-annual variation in precipitation and well-developed water storage and conveyance infrastructure, a single dry year does not necessarily constitute a drought. Droughts may be classified based on meteorology (a period of low precipitation), hydrology (period of low in-stream flows), or sociological (a shortage of water supply for human use). While there is no single agreed-upon definition for “drought”, droughts in California generally occur when there are multiple years of low precipitation and a resulting water supply shortage (DWR 2020). The CDFW Incidental Take Permit (ITP) for the State Water Project (SWP) requires drought contingency planning when there are consecutive Dry or Critically Dry years (CDFW 2020).

Throughout this report, we will be comparing the 2020-2022 drought to previous data as classified by the Sacramento Valley Water Year Index (Figure 3). The Sacramento Valley Water Year Index is defined by Water Rights Decision 1641 (D-1641) and is calculated from an estimate of unimpaired runoff in the Sacramento watershed. The index is calculated by DWR’s Flood Management and Hydrology Branch and reconstructed historical indices are made available on the CDEC website[1].

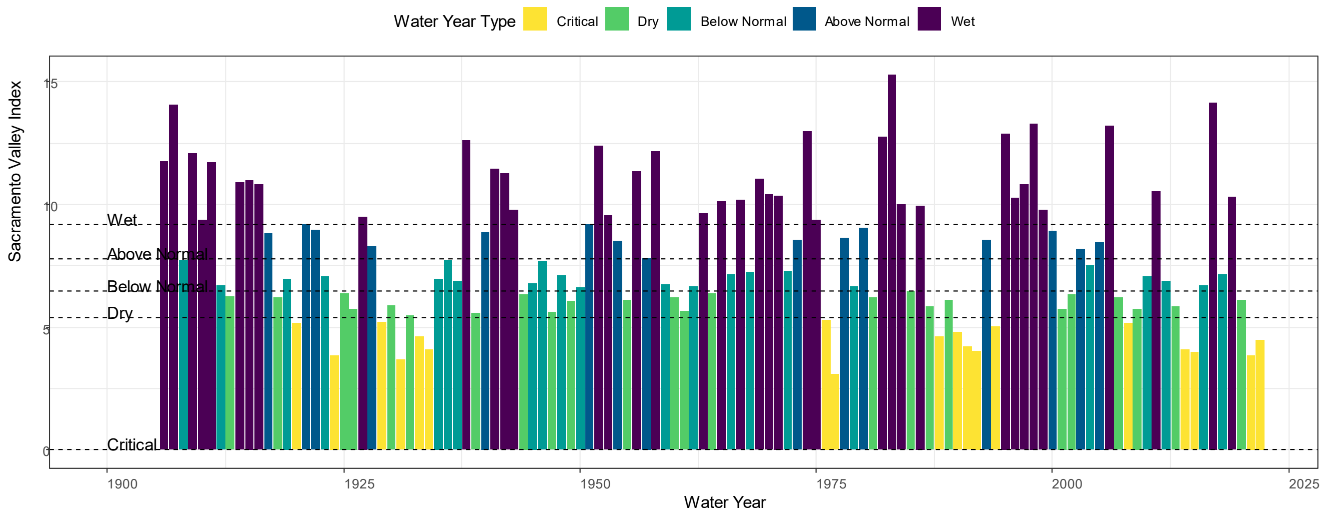

Figure 3. Plot of water year indexes for the Sacramento Valley from 1905 to 2021. Data is from the California Department of Water Resources[1].

The 2020-2022 Drought

The current drought (2020-2022, ongoing), has resulted in record low stream flows, record low reservoir levels, extremely dry soils, low groundwater reserves, and problems providing enough water for wildlife and human uses. Water Year 2021 was the driest on record since 1977 (Figure 3). Rainfall was well below average, but the snowpack in March 2021 indicated that sufficient reservoir inflow was likely available to meet requirements. Conditions significantly changed at the end of April 2021 when it became clear that expected reservoir inflow from snowmelt failed to materialize. The May 90% exceedance forecast for the water year Sacramento Valley Four River Index identified a reduction of expected runoff of 685 TAF from the forecast generated only a month earlier in April. Governor Newsom made an emergency proclamation on May 10, 2021 on drought conditions for the Bay-Delta and other

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[1] https://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST

watersheds. The May 2021 proclamation suspended Water Code section 13247 requiring State compliance with water quality control plans and, thus, implied that there may not be an adequate supply to meet water right permit obligations for instream flows and water quality under D-1641.

The 2020 Record of Decision on the Long-Term Operations of the Central Valley Project (CVP) and SWP and the 2020 ITP for the SWP required development of a “Drought Toolkit”, containing voluntary actions which may help address the impact of drought and dry year conditions. The ITP also contains the requirement for a Drought Contingency Plan, containing specific actions to be undertaken in a drought year. These plans were developed by the DWR and Reclamation, in coordination with the US Fish and Wildlife Service (USFWS), NOAA Fisheries, the CDFW, the State Water Resources Control Board (Water Board), and SWP and CVP Contractors. By February of each year following a Critical year, DWR must report on the measures employed and assess their effectiveness. The 2022 Drought Contingency Plan includes a commitment to ecosystem monitoring to assess the impact of drought and drought actions. This report comprises the report on the effectiveness of ecosystem monitoring in the Delta and the ecosystem response to the drought and drought actions within the Delta.

This report is a follow-up to the preliminary Drought Synthesis report submitted in February of 2022 (IEP Drought MAST 2022). In this report we provide data with more robust quality control procedures, better methods for summarizing, and a more streamlined discussion.

Several related reports are also in development:

- A draft report on the impact of the 2022 TUCP and Emergency Drought Barrier on harmful algal blooms and aquatic weeds in the Delta[2]. Submitted Dec. 15th 2022, with a final report to be completed in April 2023.
- A report on all drought toolkit actions, to be submitted Feb 1st, 2023.
- A report on the effectiveness of the Emergency Drought Barrier, draft to be completed by March 2023.
- A series of papers on impacts of drought in the Delta over the long-term record.
    - Barros, A., R. Hartman, S. Bashevkin, and C. Burdi. in prep. Years of drought and salt; decreasing flows determine the distribution of zooplankton resources in the estuary. Draft manuscript,
    - Bosworth, D. H., S. M. Bashevkin, K. Bouma-Gregson, R. Hartman, and E. B. Stumpner. In prep. The anatomy of a drought in the upper San Francisco estuary: water quality and lower-trophic responses to multi-year droughts over a long-term record (1975-2021). Draft manuscript,
    - Nelson, P. A., R. Hartman, E. Keller, and E. B. Sawyer. in prep. Fishes Faulter When Flows Fail: Historical effects of drought on fish populations in the Sacramento-San Joaquin Delta. Draft manuscript,
    - Bouma-Gregson, K., D. Bosworth, T. M. Flynn, A. Maguire, J. Rinde, and R. Hartman. In prep. Delta Blue(green)s: The Impact of Drought and Drought Management Actions on *Microcystis* in the Sacramento- San Joaquin Delta. Draft manuscript,
    - Hartman, R., and IEP Drought MAST. In prep. Dry me a river: Ecological effects of drought in the upper San Francisco Estuary. Draft manuscript,
    - Hartman, R., L. Twardochleb, C. Burdi, and E. Wells. In prep. Amazing graze: Shifts in distribution of Maeotias and Potamocorbula during droughts. Draft manuscript,

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[2] Available: https://www.waterboards.ca.gov/drought/tucp/docs/2021/20211215_cond8-report.pdf

2021 TUCP

Reclamation and DWR jointly submitted the TUCP to request the Water Board consider modifying requirements of Reclamation's and DWR's water right permits to enable changes in operations of CVP and SWP (collectively Projects) that will allow for delivery of water with conservation for later instream uses and water quality requirements. On June 1, 2021, the Water Board issued an order conditionally approving modified conditions requiring compliance with Delta water quality objectives in response to drought conditions (SWRCB 2021). The TUCP modification to some D-1641 requirements was intended to limit Delta salinity intrusion while preserving some storage in upstream reservoirs including Shasta and Oroville.

The Petitioners requested the following temporary changes to requirements that were imposed pursuant to D-1641 for the period June 1 through August 15:

- For June 1 – June 30, reduce the required minimum 14-day running average Delta outflow from 4,000 cfs to 3,000 cfs.
- For July 1 – July 31, reduce the required minimum monthly average Delta outflow from 4,000 cfs to 3,000 cfs, with a seven-day running average of no less than 2,000 cfs;
- For June 1 through July 31, limit the combined maximum export rate to no greater than 1,500 cfs when Delta outflow is below 4,000 cfs, and allow the 1,500 cfs limit to be exceeded when the Petitioners are meeting Delta outflow requirements pursuant to D-1641 or for moving transfer water; and
- From June 1 through August 15, move the compliance point for the Western Delta agricultural salinity requirement from Emmaton on the Sacramento River to Threemile Slough on the Sacramento River.

2022 TUCP

Due to continued dry conditions, Reclamation and DWR jointly submitted another TUCP to request the Water Board consider modifying requirements of Reclamation's and DWR's water right. On April 4, 2022, the Water Board issued an order conditionally approving modified conditions requiring compliance with Delta water quality objectives in response to drought conditions (SWRCB 2021). The TUCP modification to some D-1641 requirements was intended to limit Delta salinity intrusion while preserving some storage in upstream reservoirs including Shasta and Oroville.

Reclamation and DWR requested the following temporary changes to requirements that were imposed pursuant to D-1641 for the period of April 1 to June 30:

- From April 1 – April 30, reduce the minimum Delta outflow requirement as measured by the NDOI from a minimum of 7,100 cfs on a 3-day running average to 4,000 cfs on a 14-day running average. For May 1 – June 30, a minimum NDOI of 4,000 cfs on a 14-day running average is requested if the May 1 forecast of the Sacramento River Index is greater than 8.1 million acre-feet (MAF) at the 90% exceedance level. If the index is less than 8.1 MAF, D-1641 already includes an offramp allowing for the lower outflow level.
- Move the Western Delta agricultural salinity compliance point on the Sacramento River at Emmaton 2.5-3 miles upstream to Threemile Slough.
- Limit the maximum export rate to 1,500 cfs when the unmodified D-1641 requirements are not being met.

- Reduce the minimum monthly average flow requirement on the San Joaquin River at Airport Way Bridge, Vernalis from 710 – 1140 cfs (April 1 – 14 and May 16 – June 30) and 3,110 – 3,540 cfs (April 15 – May 15) to a minimum monthly average of 710 cfs from April 1 – June 30.

Emergency Drought Barrier

Along with the TUCP, DWR requested emergency authorization for installation of the 2021–2022 West False River Emergency Drought Salinity Barrier (Barrier) in May of 2021. The Emergency Drought Barrier is a temporary physical rock fill barrier which reduces the intrusion of high-salinity water into the Central and South Delta, and such barriers have proven effective in the past (DWR 2019).

During drought conditions, reservoir water storage may not be sufficient to prevent the movement of high-salinity water upstream from San Francisco Bay while also preserving storage for later in the year when it is needed for species protection. Intrusion of salty water into the Central and South Delta would significantly impair the quality of local and exported water, impacting the ability for agriculture and millions of California residents to use the water and the maintenance of habitat quality for aquatic species. On June 22, 2021, DWR installed an emergency drought salinity barrier (Barrier) in West False River to reduce the intrusion of high-salinity water into the Central and South Delta. The barrier is a temporary, physical rock barrier that can be removed or notched when water quality conditions improve. On January 18, 2022, DWR cut a notch in the top of the barrier to allow fish passage. On April 1, 2022, the notch was re-filled to again prevent high-salinity water from intruding into the Central and South Delta. DWR removed the barrier during October and November of 2022, with hydrologic breaching achieved on November 1, 2022 and full removal by the end of November.

Methods

Metrics reported

This report includes data on several of the most important components of estuarine water quality, phytoplankton, zooplankton, and fishes in the estuary (Table 1). It is not an exhaustive list of all the metrics monitored by IEP, and instead focuses on parameters that are of management relevance, have a strong response to flow/drought, or influence fish populations of concern. Some metrics were excluded due to lack of data and some were excluded due to a lack of direct connection to management decisions.

Table 1. Metrics included in this analysis with sources of data, summary methods, and definitions for each data set.

Metric	Dataset used	Summary method	Definition
Net Delta Outflow Index (Outflow)	Dayflow (DWR 2002)	Daily average	Daily average flow (in CFS) as calculated by DWR's Dayflow model. Data from 2022 uses CDEC station DTO, which is provisional.
CVP+SWP Exports	Dayflow (DWR 2002)	Daily average	Daily average flow (in CFS) as calculated by DWR's Dayflow model. Data from 2022 uses CDEC stations TRP and HRO, which are provisional.

Sacramento River flow	Dayflow (DWR 2002)	Daily average	Daily average flow (in CFS) as calculated from USGS Flow station # 11447650
San Joaquin River flow	Dayflow (DWR 2002)	Daily average	Daily average flow (in CFS) as calculated from USGS flow station 11303500
Temperature	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Seasonal average	Water temperature as measured 1-meter below the surface at discrete stations sampled by IEP's long-term monitoring programs.
Water Velocity	USGS National water Information System	Daily average and maximum	Daily absolute maximum current speed and tidally filtered net velocity at USGS flow stations Cache Slough at Ryer Island, San Joaquin River at Jersey Point, Middle River, and Old River at Bacon Island
Secchi Depth	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Annual Average	Secchi depth in cm at discrete stations sampled by IEP's long-term monitoring programs.
Salinity	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Annual Average	Salinity (practical salinity units), converted from measured specific conductance at discrete stations sampled by IEP's long-term monitoring programs.
Nutrients	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Annual Average	Dissolved nitrate + nitrate, dissolved ammonium, and dissolved orthophosphate concentrations in the water as measured by EMP and USGS discrete monitoring programs.
Chlorophyll	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Regional Average	Chlorophyll-a concentration as measured by EMP, NCRO, and USGS discrete monitoring programs.
Microcystis	Discrete Water Quality Integrated dataset (Bashevkin et al. 2022c)	Annual average, summer only	Visual *Microcystis* index (scale of 1-5, 1 = Absent, 5 = Very high) as measured by IEP's long-term monitoring surveys.
Zooplankton	Zooplankton integrated dataset (Bashevkin et al. 2022b)	Regional Average, Spring-Fall only	Total biomass of zooplankton taxa most important to pelagic fishes from EMP, Summer Townet, Fall Midwater Trawl, and the 20mm survey
Delta Smelt	CDFW's Fall Midwater Trawl indices	Annual Index	Annual population index as calculated by the FMWT survey.

Longfin Smelt	CDFW's Fall Midwater Trawl indices	Annual Index	Annual population index as calculated by the FMWT survey.
Striped Bass	CDFW's Fall Midwater Trawl indices	Annual Index	Annual population index as calculated by the FMWT survey.
American Shad	CDFW's Fall Midwater Trawl indices	Annual Index	Annual population index as calculated by the FMWT survey.

Metrics not included:

- Submerged aquatic vegetation – While drought has been hypothesized as a driver of aquatic vegetation abundance and distribution (Kimmerer et al. 2019), recent data analysis on submerged aquatic vegetation in the Delta has not been able to find a trend between distribution and drought conditions (Hartman et al. 2022). However, data are limited and analysis of additional data may be better able to determine a trend.
- Benthic invertebrates – There is some evidence for shift in the distribution and abundance of the invasive clams *Potamocorbula amurensis* and *Corbicula fluminea* during droughts, but mostly in the year following a Dry year, making it difficult to analyze data on distributional shifts for the most recent drought.
- Salmonid indices or survival – Salmonid survival data as derived from acoustic telemetry studies is difficult to compare across years. The true effect of drought on the salmon population will only become apparent when adult salmon return three years later.
- Multivariate analyses of zooplankton or fish communities – While many complicated changes in community composition and range shifts occur during droughts, they are difficult to translate to actionable information on which to base management decisions, so are not presented here.

Data analysis and plotting

All of the plots presented in the following section were synthesized from IEP's long-term monitoring programs. Data from 1975-2019 were collated from publicly available data sources or from requests to the principal investigators. Some metrics did not have data going back to 1975, in which case the entire period of record was used. To account for differences in sampling effort over time, we calculated the average value for each parameter in each region in Figure 2 by season. For the purposes of this analysis, seasons were defined as: Winter (December-February), Spring (March-May), Summer (June-August), Fall (September-November). Because the "Fall" period straddles two water years, we adjusted the water year to run from December 1-November 30th instead of October 1 – September 30th. This reflects the fact that the aquatic environment in the fall are often more dependent on conditions the previous summer than they are on any rainfall occurring early in the new water year.

Some parameters, such as fish abundance indices, are already summarized across the entire area for each year, so were not processed further. Other parameters, such as flow, were summarized on a daily time step instead of a seasonal time step to better capture variation.

We categorized all the historical data according to the water year types associated with the Sacramento Valley Water Year Hydrologic Classification Indices released by the California Department of Water Resources California Cooperative Snow Surveys (CDWR 2022a). The historical data was compared to data from 2020, 2021, and 2022 (when available, not all data from 2022 have been collected and quality assured at the time of this report). We then graphed all the historical data by water year type using box plots and compared these to data from 2020-2022 to visually demonstrate the differences in each parameter experienced during drier years and the differences experienced during the most recent drought.

These analyses are a qualitative approach for putting conditions of 2020-2022 in context. For a more detailed analysis of the impact of drought, please see the additional drought manuscripts described in the introduction (Barros et al. in prep, Bosworth et al. In prep, Bouma-Gregson et al. In prep, Hartman and IEP Drought MAST In prep, Hartman et al. In prep, Nelson et al. in prep).

Metric-specific analyses

Flow

Data from 1975-2021 on Delta Outflow, SWP Exports, CVP Exports, Sacramento River flow at Freeport, and San Joaquin River flow at Vernalis were obtained from DWR's Dayflow model available on the CNRA Open Data Portal (DWR 2002). Dayflow for 2022 were not available, so CDEC daily average flow data were obtained for stations DTO (Delta Outflow), VNS (San Joaquin River at Vernalis), FTP (Sacramento River at Freeport), HRO (Harvey O. Banks pumping plant) and TRP (Tracy Pumping Plant). Data were categorized by water year type and a generalized additive model was plotted through the data for each water year. Data from 2021 and 2022 were plotted on top of the data from previous years to show how the most recent drought compares to previous years.

Delta Outflow, Sacramento flow, and San Joaquin flow all have clear trends with water year type, with higher flows throughout the year in wetter water year types. Peak flows occurred in March or April, with lowest flows in August and September. For combined SWP and CVP Exports, most water year types had similar rates of pumping, with highest export rates in August through October and lowest export rates in May. However, Critically Dry years tend to have much lower summer export rates, with highest Exports in January and February, very low June and July Exports, and only a small increase in Exports in the Fall.

In 2020, most flow metrics were similar to other Dry years. The peak of Sacramento River flow occurred slightly earlier than in other Dry years, but in the range of historical values. In 2021, all flow metrics were lower than previous Critically Dry years for much of the year. Low Sacramento River flow, Delta Outflow, and Delta Exports were partially controlled by drought activities consistent with the summer TUCO, but the TUCO was necessitated by the extremely low reservoir storage, high heat, high evapotranspiration, and other contributors to the drought. Releases from New Melones Dam in summer of 2021 did provide higher-than-average flow for a Critically Dry year on the San Joaquin in July and August. In water year 2022, a major storm in October provided an early peak in flows, with other spikes in Outflow and Sacramento River flow in December and January, with smaller peaks in April. Exports also had peaks in October and January but were lower than the historical average for Critically Dry years for April -September.

Low Outflow in drier years drives many of the resulting ecosystem impacts of drought. Lower flows reduce transport of suspended sediment, lowering turbidity (Livsey et al. 2021). Lower flows also reduce dilution of nutrients and increase water residence time – allowing growth of phytoplankton in certain regions (Glibert et al. 2014, Hammock et al. 2019). Lower Outflow allows salinity to intrude further into the delta – changing the distribution of fish and invertebrates (Ghalambor et al. 2021). Lower flows also reduce migration cues for upstream migration and slow outmigration of salmonids (Connor et al. 2019, Hassrick et al. 2022). All of these impacts are analyzed in more detail below, but the basis of impacts to the ecosystem is, fundamentally, reduced flow.

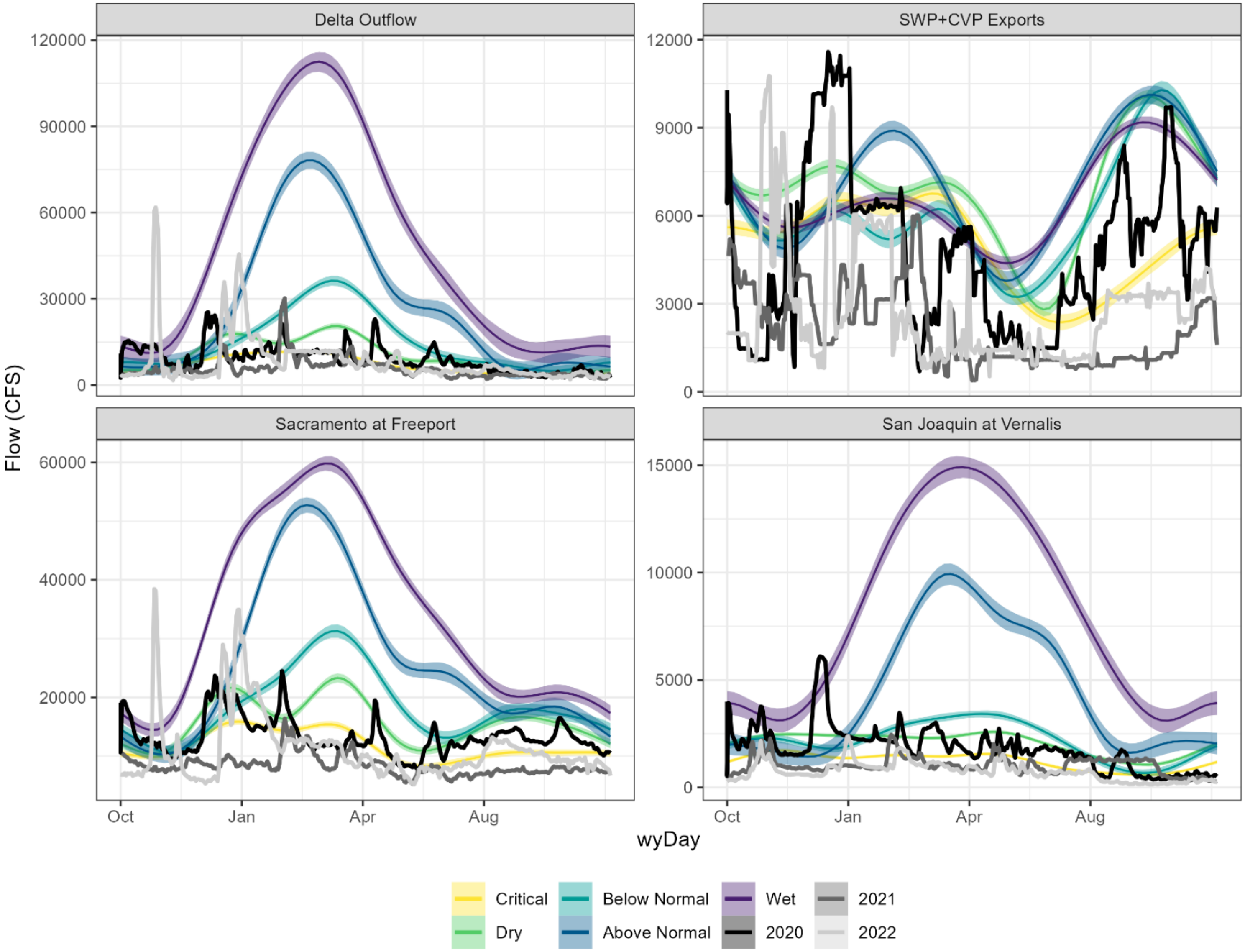

Figure 4. Mean daily flow parameters by water year type from 1975-2019, with daily flow parameters for 2020, 2021, and 2022.

Velocity

Water velocity data collected from 2007-2022 at five stations in the Delta were obtained from the USGS National Water Information System (USGS 2022) using the dataRetrieval R package (De Cicco et al. 2022). The five water velocity stations operated by the USGS and used in this study are: Cache Slough at Ryer Island, Cache Slough above Ryer Island Ferry near Rio Vista, San Joaquin River at Jersey Point, Middle River at Middle River, and Old River at Bacon Island. The Cache Slough at Ryer Island station was discontinued in April 2019 and was replaced by the Ryer Island near Ryer Island Ferry station. Data for these two stations located on Cache Slough were combined to represent Cache Slough above its confluence with the Sacramento River.

The instantaneous water velocity data, collected at 15-minute intervals, was processed through a low-pass filter to remove tidal-period variation and calculate net velocity (Godin 1972). The difference of the instantaneous velocity and net velocity resulted in the tidal velocity. Net velocity was grouped into weekly mean values whereas tidal velocity was grouped into weekly maximum absolute values. When greater than 5% of the instantaneous data were missing in a 24-hour period, data were removed and imputed using the imputeTS R package (Moritz and Bartz-Beielstein 2017).

At Cache Slough and Jersey Point, net velocity was positive most of the time with very little difference in net velocities during Critical, Dry and Below Normal years. Only during wet years did higher net velocities occur. Net velocities at Cache Slough were slightly higher than other Dry and Critically Dry years in 2020 and 2021, but similar to other critically dry years in 2022. At Jersey Point net velocities in recent years were similar to other dry years. For maximum tidal velocity, there was very little difference by water year type at Cache Slough, though 2020-2022 had slightly lower maximum velocities (less than 0.1 m/sec) than previous Dry and Critically Dry years. There was a slight trend toward increasing maximum velocities with water year type at Jersey Point, with highest maximum velocities in wet years. Maximum velocities at Jersey Point in 2020 and 2021 were similar to other Dry years, but 2022 had slightly lower maximum velocities.

At Old and Middle River, net velocity was negative for most of the time, and velocities were more negative in wetter year types. Wetter water year types had slightly higher maximum velocities (less than 0.05 m/sec). 2020 -2021 were similar to other Dry years, but 2022 had slightly lower maximum velocities than normal.

Taken together, these results show that velocities vary significantly across the Delta, with the North Delta (as exemplified by Cache Slough) and San Joaquin corridor (as exemplified by Jersey Point) being dominated by net-positive flow and the central Delta (Old and Middle River) being dominated by net-negative flow that is more negative during wetter years, most likely due to increased exports. The lack of change in maximum velocities at the Cache station indicates velocities are primarily driven by tides, rather than outflow, except during extreme outflow events experienced in wet years. In contrast, there was more of a trend toward increased velocities in wetter year types at Old and Middle River. The different patterns in maximum velocities in 2021 and 2022 at Old River, Middle River, and Jersey Point when compared to previous years may be due to installation of the Emergency Drought Barrier at West False River.

Operations of the Delta Cross Channel operations can affect flow and velocities in the Cache Slough area. The Delta Cross Channel was open more than normal for a Dry year in 2020 (data not shown), but closed more than normal for a Critical year in 2021 and 2022, which might have influenced the velocities at the Cache Slough station, but more research is needed to determine the precise relationship between gate operation and regional velocities.

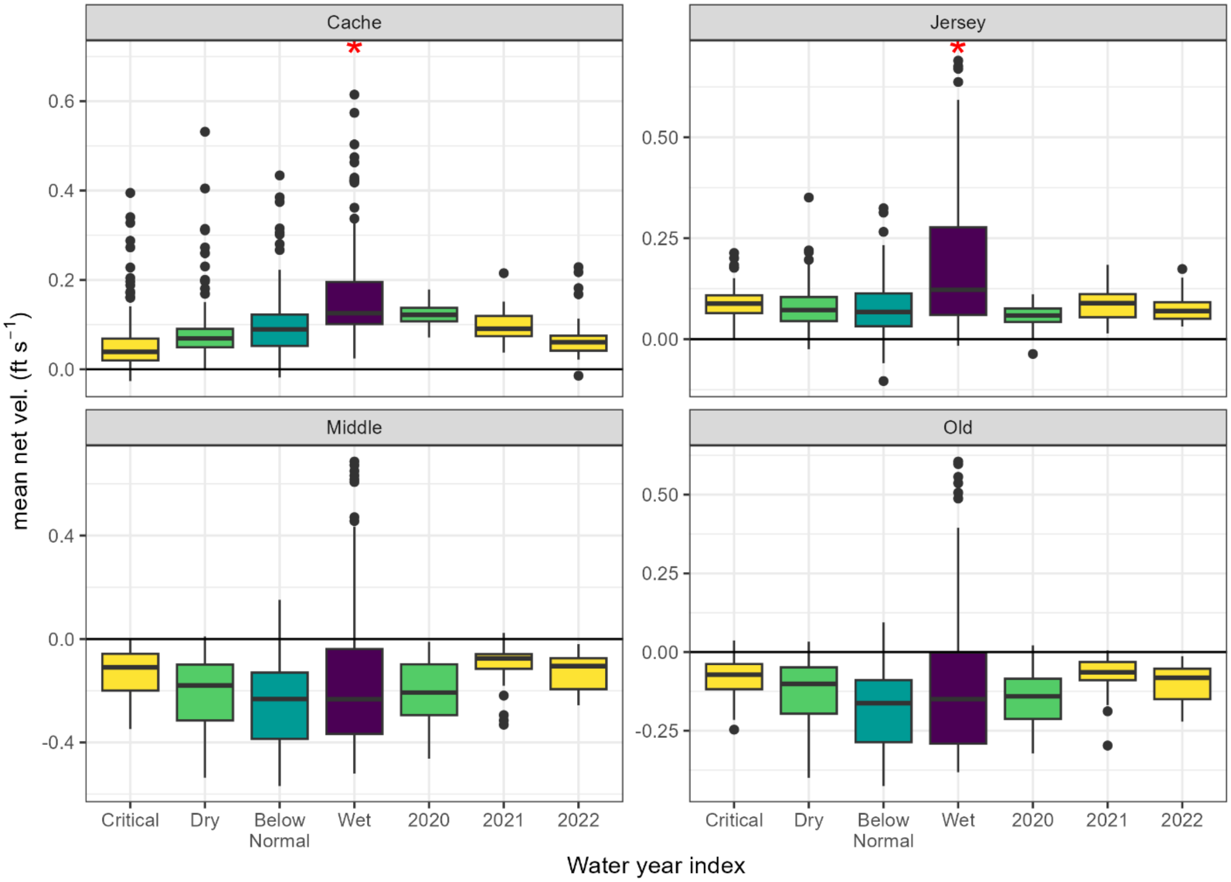

Figure 5. Mean net velocity at four stations within the Delta. * approximately 10% of values at Cache and Jersey in wet years were significantly above 0.7 ft/sec, truncated here to allow clear visualization of the remaining data.

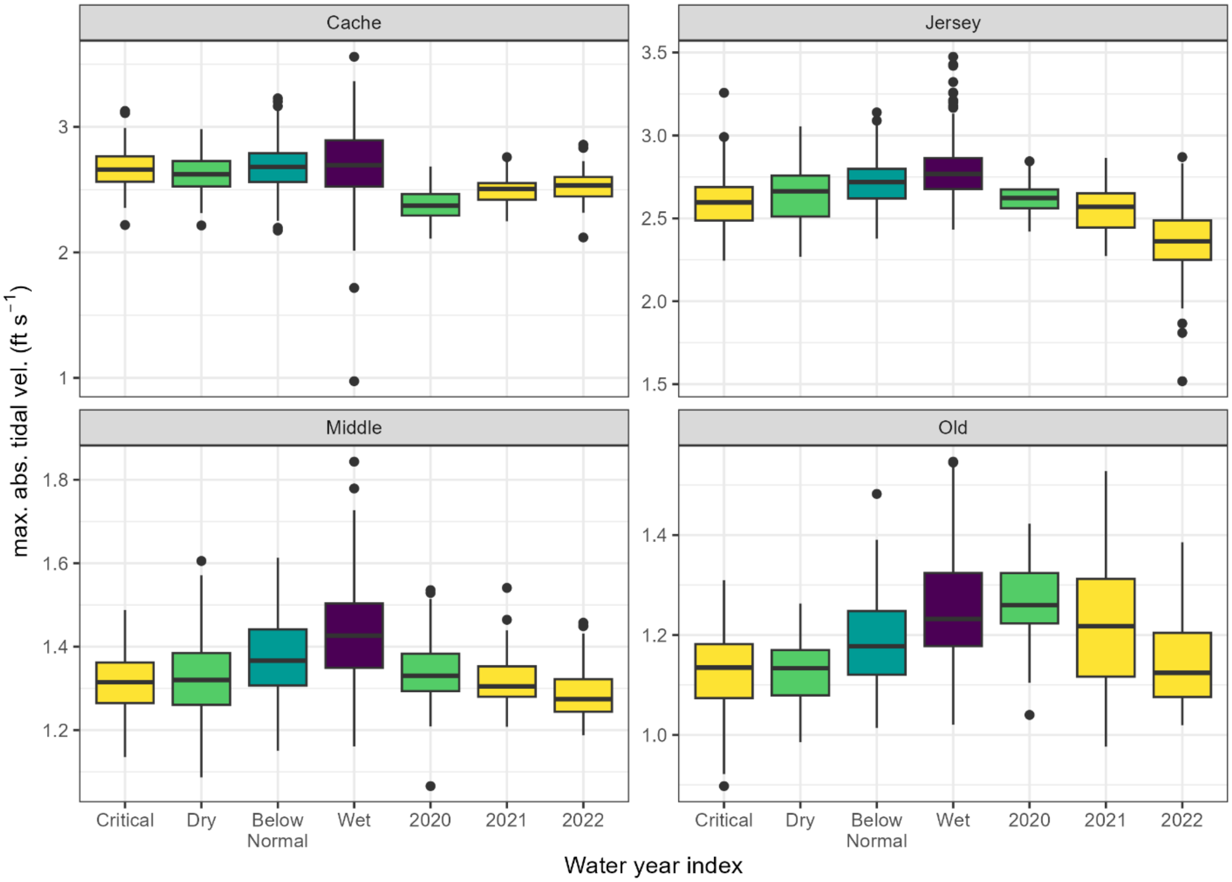

Figure 6. Maximum absolute tidal velocity by station and water year type, 2007-2022, at four stations within the Delta.

Secchi Depth, Salinity, and Temperature

Secchi depth, as a proxy for water clarity, salinity, and water temperature came from ten different Interagency Ecological Program surveys, as described in Bosworth et al. (In prep):

- DWR's Environmental Monitoring Program and Stockton Dissolved Oxygen Monitoring Program
- CDFW's Fall Midwater Trawl, Summer Townet Survey, Spring Kodiak Trawl, 20mm Survey
- UC Davis's Suisun Marsh Survey
- USGS's San Francisco Bay Survey
- USFWS's Delta Juvenile Fish Monitoring Program
- DWR's North Central Region office

To account for different levels of sampling effort over space and time, we divided the Delta and Suisun Marsh into subregions as defined by the Enhanced Delta Smelt Monitoring Program. The data sets were merged and filtered so that only subregions with samples from the entire time frame were included (see Bosworth et al, in prep, for details). We then calculated the regional mean value for each season and year for analysis.

Secchi Depth

There is a clear trend toward higher Secchi depth during drier years (Figure 7). Because much of the turbidity in the Delta is derived from suspended sediment transported by high flow events, dry years have lower suspended sediment concentrations and thus higher Secchi depth (Bosworth et al, in prep). This trend comes on top of an ongoing trend of increasing Secchi depth over time (Schoellhamer 2011). As a result, the most recent drought is clearer than previous Dry and Critically Dry years.

Increased water clarity during droughts may partially drive the increase in harmful algal blooms, since *Microcystis* requires high light, and increased Secchi depth has been correlated with incidence of *Microcystis* (Visser et al. 2016). Reduced turbidity during droughts may also partially explain the reduced population abundance of several pelagic fish species during droughts, since many pelagic species are more susceptible to predation in low turbidity (Gregory and Levings 1998, Ferrari et al. 2014).

Temperature

Droughts are warmer than wetter years in every season except for winter, when temperatures had less of a clear relationship with flow (Figure 8). 2020 was warmer than previous Dry years, though 2021 was similar to previous Critically Dry years. This trend has been seen in previous publications that correlated higher inflows with lower temperatures (Nobriga et al. 2021, Bashevkin and Mahardja 2022), though it is important to note that it is not clear whether higher inflows cause the decreased temperature, or whether atmospheric conditions that result in higher flows also result in lower air temperatures.

Higher temperatures during droughts may be another driving factor between increases in *Microcystis* and changes in chlorophyll during droughts, since high temperatures are one of the most important factors in predicting *Microcystis* blooms. High temperatures may also contribute to reduced fish populations, since higher temperatures may increase predation (Nobriga et al. 2021), increase the consequences of food limitation (Beauchamp 2009, McCullough et al. 2009), decrease dissolved oxygen (Pörtner 2010), and increase disease susceptibility (Richter and Kolmes 2005).

Salinity

Reduced freshwater outflow during drier years results in higher salinity, though this trend is much more pronounced in the western regions of the Delta than in the North and South-Central (Figure 9). The impact of reduced outflow on salinity has been well-described, and options to manage salinity in future droughts have been the subject of multiple papers (Knowles 2002, Reis et al. 2019, Durand et al. 2020, Ghalambor et al. 2021) and a recent workshop (https://deltacouncil.ca.gov/pdf/science-program/2022-03-07-salinity-management-workshops-info-sheet-march-2022.pdf).

The Emergency Drought Salinity Barrier installed in West False River in 2021 reduced salinity in the South/Central Delta. Salinity in the Confluence was allowed to increase under the modified western Delta salinity standards approved by the SWB (CDWR 2022b). The barrier provided the best water savings when operated in combination with the 2021 TUCO, which shifted the salinity compliance point on the Sacramento River further East (SWRCB 2021) allowing the increased salinity in the Confluence region (Figure 9), but preserves the water cost of preventing salinity intrusion regardless. As a result, while salinity in the South Delta was still relatively high in 2021, it was lower than other Critically Dry years, while salinity in the Confluence was higher than other Critically Dry years where the SWB did not approve a TUCP modifying western Delta salinity standards. The effectiveness of the barrier at restricting salinity intrusion was seen both on the regional scale (Figure 9), and at the local scale (CDWR 2022b). However, it is important to recognize that the difference between 2021 and other Critically Dry years was much lower than between Critically Dry years and Wet years.

Increasing salinity in Suisun Marsh, Suisun Bay, and the Confluence during drier years directly impacts the phytoplankton, zooplankton, and fish communities that can survive in these regions. Zooplankton communities shift from being dominated by freshwater calanoid copepods, such as P. forbesi to taxa that thrive in higher salinities, such as *Acartiella sinensis*, *Acartia* sp., and *Limnoithona tetraspina* (Kayfetz and Kimmerer 2017, Bashevkin et al. 2022a). Higher salinity can also exacerbate the impact of other stressors, including food limitation (Hammock et al. 2015). Higher salinities also allow the invasive clam, *Potamocorbula amurensis*, which has greatly reduced phytoplankton and zooplankton populations in the estuary, to move upstream (Crauder et al. 2016, Hartman et al. In prep). At the top of the food web, the Low Salinity Zone (0.6-6 PSU), considered a critical salinity zone for Delta Smelt, shifts from the extended shallows and marshes of Suisun in Wet years to the channelized, armored areas of the Sacramento and San Joaquin rivers, limiting foraging opportunities and refugia from predation (Sommer and Mejia 2013).

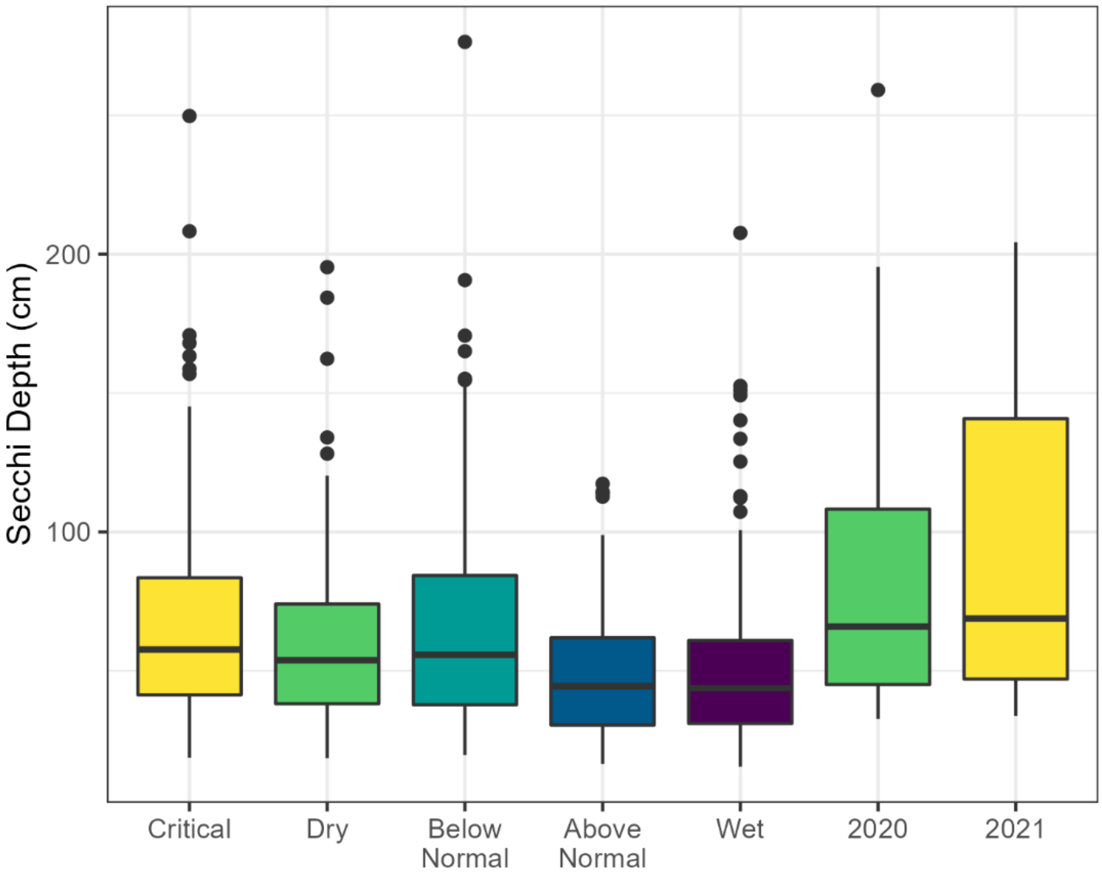

Figure 7. Mean Secchi Depth (cm)for historical years (1975-2019) and the most recent data (2020, 2021).

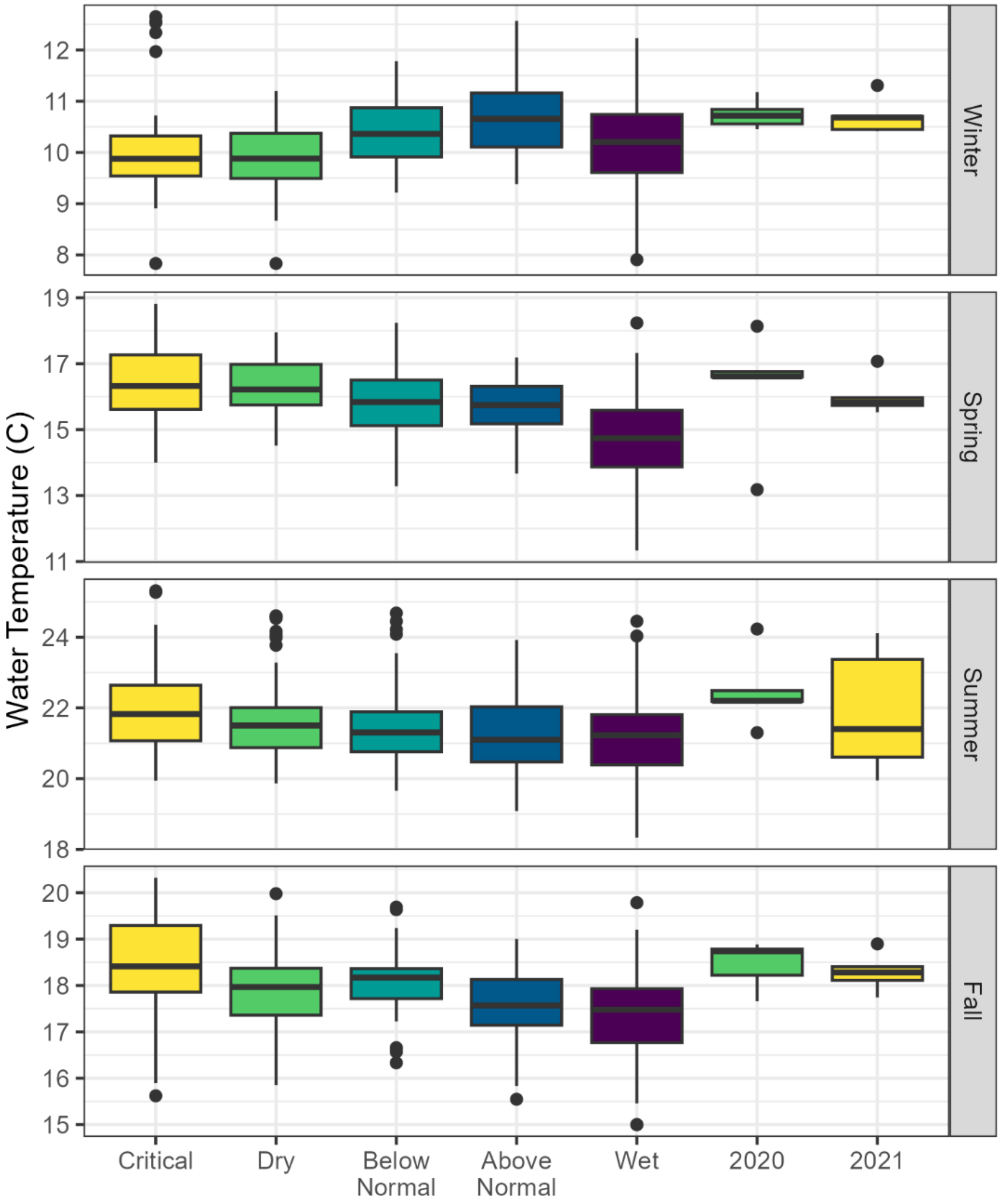

Figure 8. Mean water temperature (°C) by season for historical years (1975-2019) and the most recent data (2020, 2021).

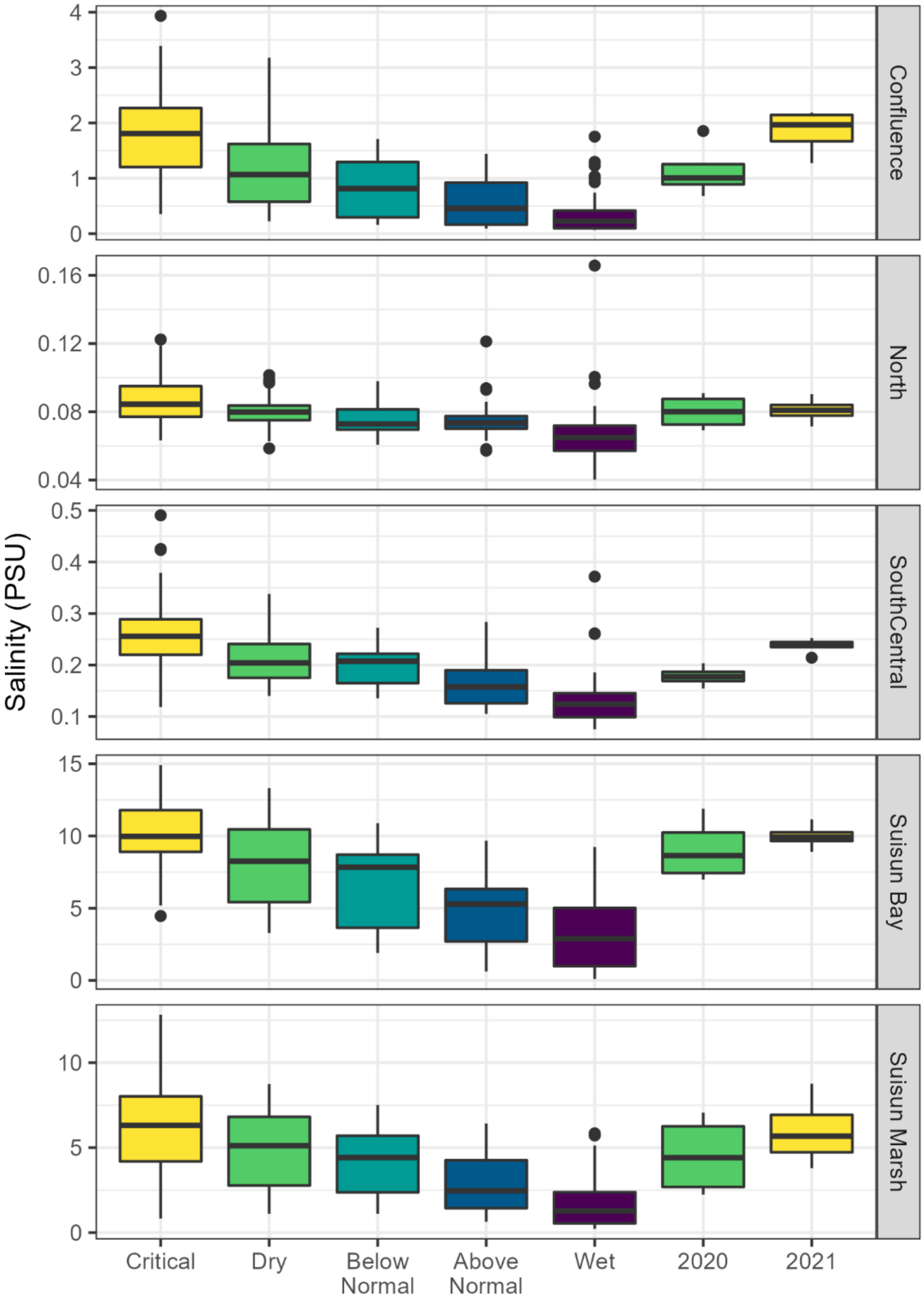

Figure 9. Mean salinity (PSU) by region and water year type for historical years (1975-2019) and the most recent drought (2020, 2021).

Chlorophyll

Chlorophyll data came from several different sources, as described in the Bosworth et al. (In prep). These sources were, in brief:

- DWR's Environmental Monitoring Program, which collects data monthly at stations throughout Suisun Marsh, Suisun Bay, and the Delta. Data has been collected from 1975-present, though stations numbers and locations have changed over time.
- USGS's San Francisco Bay Survey, which collects data monthly at stations throughout the San Francisco Bay, Suisun Bay, and the central Delta.
- DWR's North Central Region office, which has collected chlorophyll for the south and central Delta from 2000-2021.

These three data sets were merged and filtered so that only subregions with samples from the entire time frame were included. We then calculated the regional mean value for each year for analysis.

Chlorophyll-a concentrations changed with drought, but these changes were different in different regions (Figure 10). There was an overall increase in chlorophyll during wetter year types in Suisun Bay, but a decrease during wetter years in the South-Central Region. The current drought of 2020-2021 has had somewhat lower chlorophyll than past years in the South-Central and North Regions, but higher than expected in Suisun Bay in 2021.

Phytoplankton can produce spatially discrete and temporally short blooms during many different situations, making it difficult for discrete, monthly monitoring surveys to extract trends. Some of the largest phytoplankton blooms (greater than 40 ug/L, indicated by outliers in Figure 10) occurred during Critically Dry and Dry years, however these did not occur at a predictable frequency.

Kimmerer (2002a) pointed out the lack of correlation between spring and summer chlorophyll and X2, though did find a positive relationship between total chlorophyll loading and freshwater inflow. However, Jassby (2008) found a negative relationship between Delta chlorophyll and Delta inflow from 1995-2006 (Jassby 2008), and Glibert et al. (2014), cited the low flow and altered nutrient loads caused by the 2014 drought for the phytoplankton blooms seen in that year.

The lower chlorophyll in the South-Central Delta during the most recent drought may be due to unique conditions during the past few years, but it may be obscured by linear trends in chlorophyll over time. There is also an overall trend towards decreased chlorophyll over time (Cloern 2019), making it difficult to compare 2020 and 2021 to previous similar water years. The 2020-2022 drought is also one of the hottest droughts on record (see temperature section), and Secchi depth is highest on record (see Secchi depth section). Under these conditions, one would expect higher chlorophyll, not lower chlorophyll as we have seen the past two years.

The cause for recent lower chlorophyll in the South Delta may be based in increases to harmful cyanobacterial blooms. The chlorophyll samples presented here were discrete grab samples taken from 1-meter depth. They are therefore inefficient at picking up surface-oriented phytoplankton blooms, such as the *Microcystis* bloom in the central Delta in 2021 (see *Microcystis* section). The lower levels of chlorophyll in these grab samples may be partially caused by competition with surface-oriented cyanobacteria (Huisman et al. 2004, Wilhelm et al. 2020). In contrast, chlorophyll values in Suisun are somewhat higher in 2021 than previous Critical years, and this region typically has very low *Microcystis*. It is also important to note that this data is for chlorophyll concentrations, not primary production. High rates of grazing from benthic filter-feeders or zooplankton could mask high production by reducing standing stock of phytoplankton before it can be measured.

In Suisun Bay, chlorophyll has been very low since the introduction of the invasive benthic overbite clam – *Potamocorbula amurensis*. Clam biomass and grazing rates increase during drier years (Crauder et al. 2016, Hartman et al. In prep), and import of chlorophyll from upstream decreases (Kimmerer 2002a), leading to the pattern of lower chorophyll in Suisun during dry years (see also Bosworth et al. In prep).

The lack of a consistent pattern between chlorophyll and water year type makes it difficult to predict when blooms of beneficial phytoplankton – such as diatoms and green algae – will occur. It also indicates that the decrease in pelagic fish populations seen during droughts is unlikely to come from a bottom-up decrease in primary productivity.

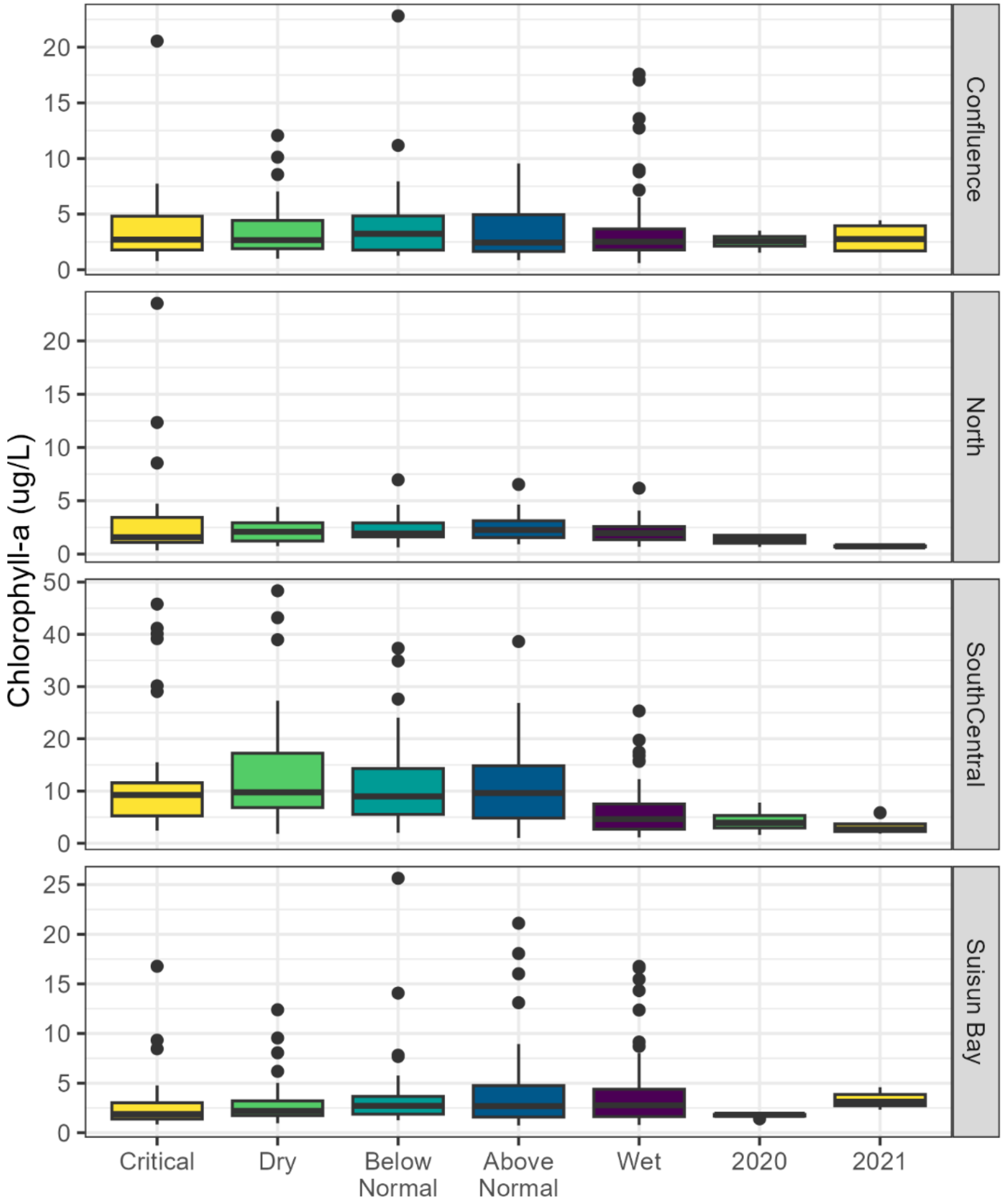

Figure 10. Chlorophyll-a concentration (µg/L) by water year type and region for 1975-2021

Nutrients

Data on dissolved orthophosphate and dissolved nitrate + nitrite data came from several different sources, as described in Bosworth et al. (In prep). These sources were, in brief:

- DWR's Environmental Monitoring Program, which collects data monthly at stations throughout Suisun Marsh, Suisun Bay, and the Delta. Data has been collected from 1975-present, though station numbers and locations have changed over time.
- USGS's San Francisco Bay Survey, which collects data monthly at stations throughout the San Francisco Bay, Suisun Bay, and the central Delta.
- USGS's California Water Science Center, which has collected data throughout the Delta from 1979-2021, though station numbers and locations have changed over time.

These three data sets were merged and filtered so that only subregions with samples from the entire time frame were included. Values below the reporting limit were replaced by random draws from a uniform distribution between 0.0001 and the reporting limit. We then calculated the regional mean value for each season and year for analysis.

Boxplots showing the mean value for each region and season are shown below (Figure 11, Figure 12). We found that nutrient concentrations decrease with increasing flow, with average levels of both dissolved orthophosphate and dissolved nitrate and nitrite decreasing during wetter years and increasing during drier years. This trend is more dramatic for phosphorus than for nitrate. The drought of 2020-2021 drought had levels of phosphorus and nitrogen that were similar, if slightly lower than other Dry and Critically Dry years.

Increased nutrient concentrations during droughts is to be expected because a large percentage of nutrient inputs in the system come from municipal waste water treatment plants, particularly the Sacramento and Stockton WWTPs (Cloern 2019, Cloern et al. 2020). Inputs from WWTPs tend to be similar across all seasons, increasing only with population increases, so are diluted at higher flows (Saleh and Domagalski 2021). Orthophosphate, total Keijeldahl nitrogen, and ammonium concentrations have decreased over the period of record, with the largest decreases being from 1970-1995, whereas nitrate concentrations and loadings have been roughly stable, with only a slight decrease over time (Saleh and Domagalski 2021). However, total loading of nutrients may differ from concentration trends. During high-flow periods increased runoff from agricultural areas will add shorter-term pulses to the steady supply of nutrients produced at WWTPs.

The slightly lower levels of nitrate + nitrate seen in 2021 when compared to previous Critically Dry years may have been due, in part, to the upgrade of the Sacramento regional wastewater treatment plant, which reduced nitrogen output by 65%, and reducing ammonium input by 99% (Senn et al. 2020).

Changes to nutrient concentration and loading will directly impact the frequency and severity of algal blooms (see *Microcystis*, below), particularly in conjunction with the clearer water seen during droughts (see Secchi Depth, above), higher temperatures (see Temperature, above), and lower outflow (see Flow, above).

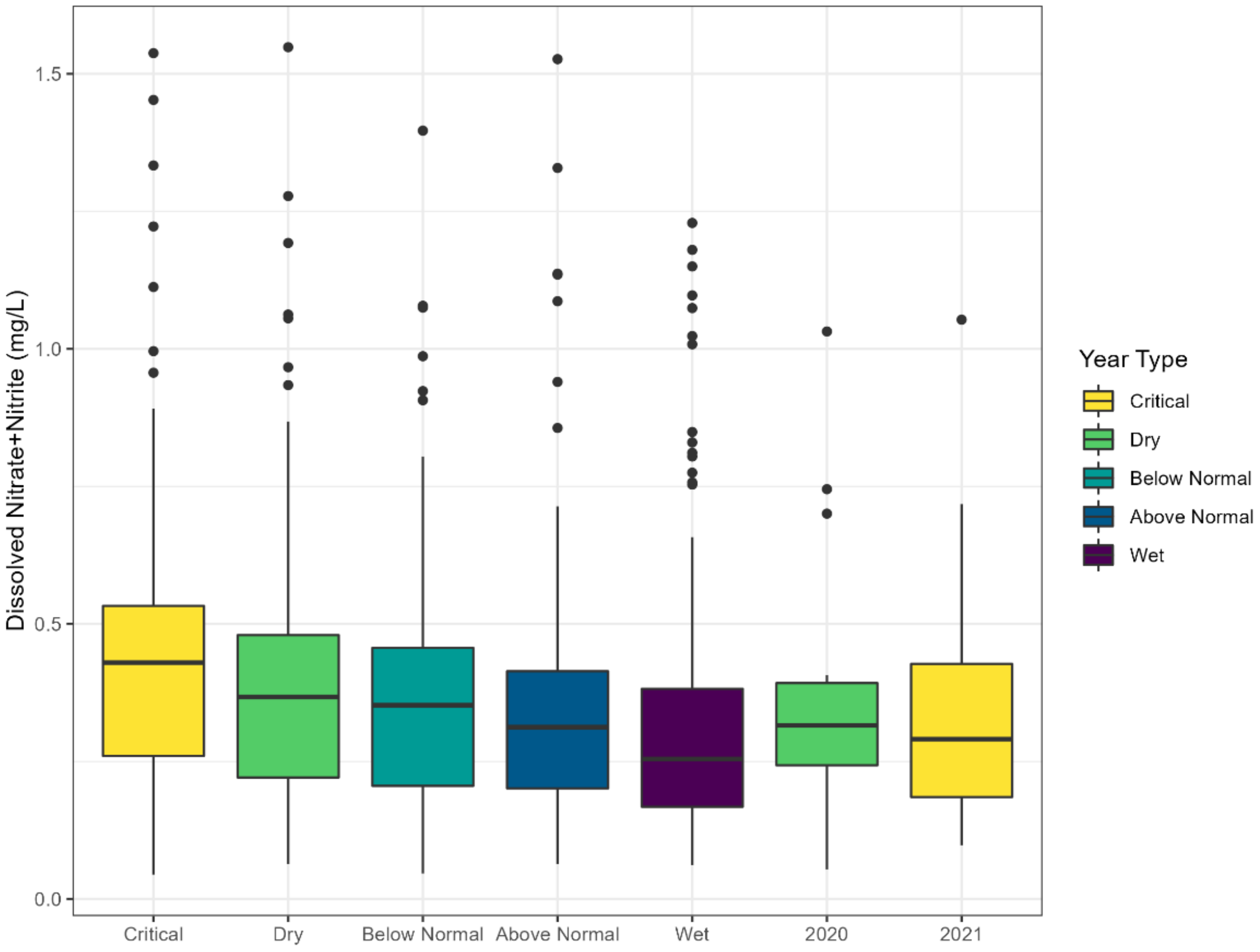

Figure 11. Nitrate+Nitrite concentration (mg/L) by water year type from 1975-2021

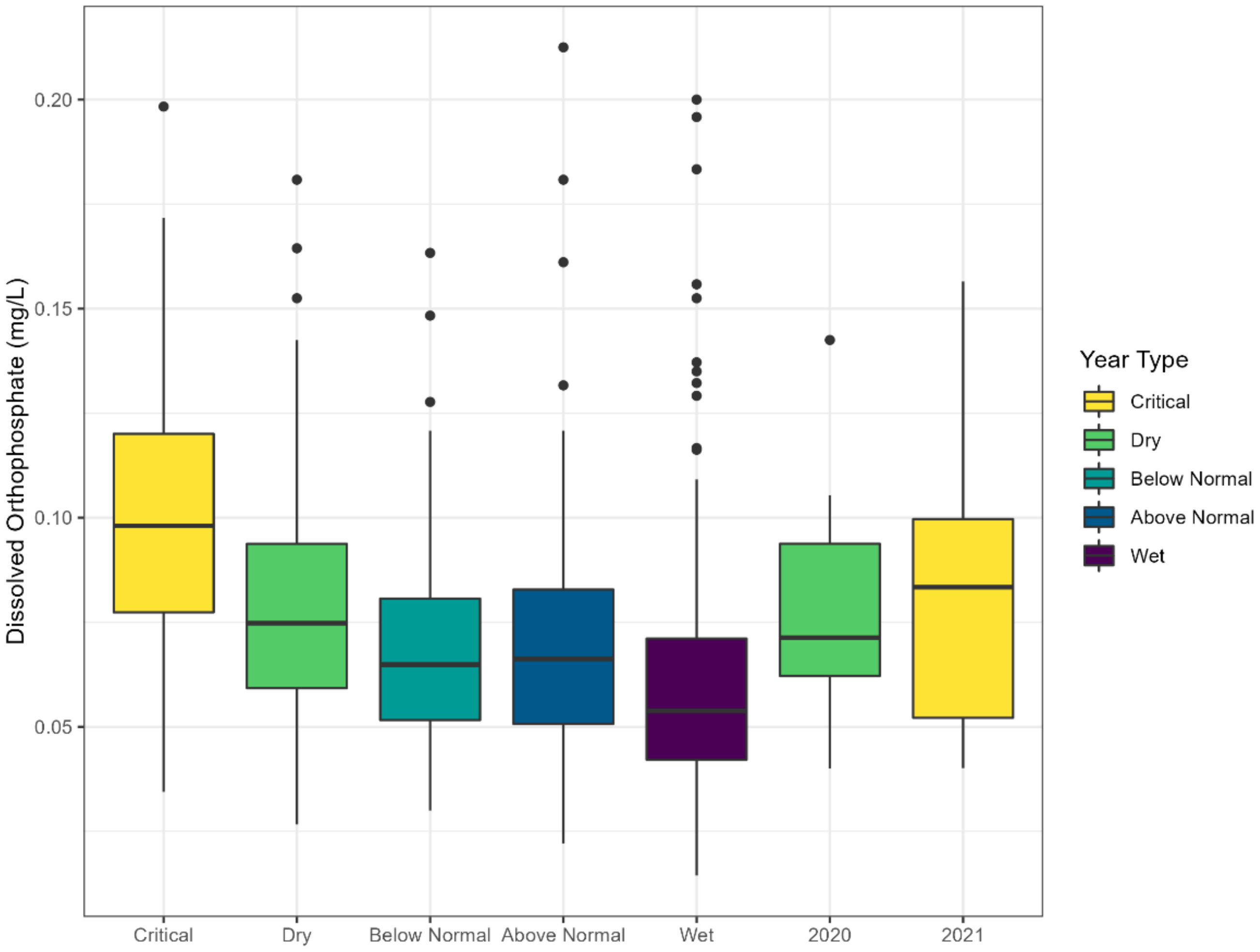

Figure 12. Orthophosphate concentration (mg/L) by water year type from 1975-2021

Zooplankton

Zooplankton data came from several IEP programs integrated into a single dataset by Bashevkin et al. (2022b). To provide an estimate of zooplankton most commonly found in pelagic fish diets, we subset the data to include *Acartia* sp., *Acartiella sinensis*, *Bosmina longirostris, Daphnia* sp., *Diaphanosoma* sp. (adults), *Eurytemora affinis* (adults and copepodids), *Limnoithona tetraspina* (adults), *Neomysis mercedis*, *Pseudodiaptomus forbesi* (adults and copepodids), *Tortanus* sp.(adults), *Hyperacanthomysis longirostris*, and *Neomysis kadiakensis*. We calculated biomass based on average biomass per organism for copepods and cladocera and based on length-weight regressions for mysid shrimp.

Total Zooplankton biomass does not show overall patterns in regard to drought, instead impacts of droughts are highly regional, driven by different factors in different regions (Figure 13). The South-Central region has higher BPUE in drier years, Suisun Bay has higher BPUE in wetter years, and there is no trend in the Confluence or Suisun Marsh.

The higher biomass in the South-Central region is most likely driven by the observed increases in chlorophyll in this region (see Chlorophyll, above), increased residence time, and potentially decreases in pelagic fish abundance. Since many zooplankton taxa feed primarily on phytoplankton, chlorophyll is often used as a proxy for zooplankton food supply, and there is frequently a correlation between zooplankton biomass and chlorophyll (Orsi and Mecum 1986). However, this is not a straightforward relationship, and many taxa show a varying relationship between chlorophyll and growth rates depending on type of phytoplankton and other environmental conditions (Kimmerer et al. 2014, Owens et al. 2019, Gearty et al. 2021, Jungbluth et al. 2021). Increased temperatures and increased residence time also contribute to increased zooplankton biomass, since higher flows increase transport of zooplankton out of freshwater and higher temperatures increase growth rates (Gearty et al. 2021).

Given the extremely dry conditions in 2020 and 2021, we would have expected zooplankton BPUE to be relatively low in Suisun Bay, however average biomass in Suisun Bay was similar to previous Wet years. This was particularly surprising because Kimmerer et al. (2019) found a reduction in transport of the calanoid copepod, *Pseudodiaptomus forbesi* to downstream regions during the 2015 Barrier installation. Subsidy of zooplankton from freshwater to the Low Salinity Zone is considered key for provisioning food for Delta Smelt and other Pelagic fish species, so we had predicted the 2021 Barrier installation would have decreased zooplankton in Suisun Bay. Further analysis of long-term zooplankton data has shown that various zooplankton taxa respond to drought conditions differently (Barros et al. in prep), which may be causing unexpectedly high abundances seen in Suisun Bay in 2020 and 2021.

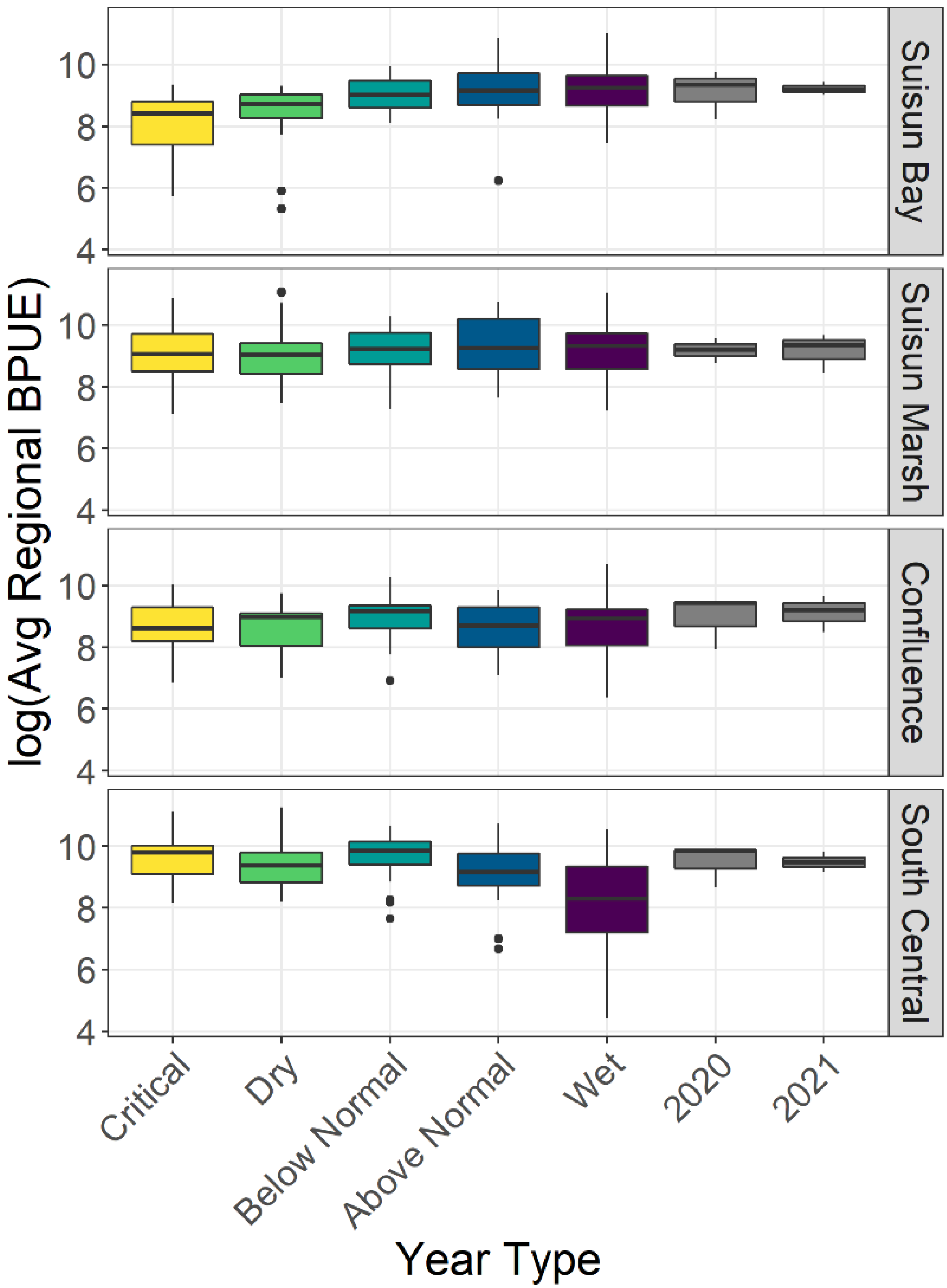

Figure 13. Zooplankton biomass per unit effort by region and water year type for 1975-2019, 2020, and 2021.

Microcystis

Microcystis data were obtained from visual observations collected by CDFW's Summer Townet Survey (2007-2022), CDFW's Fall Midwater Trawl Survey (2007-2022), DWR's Environmental Monitoring Program (2015-2022), and DWR's North Central Region Office (2017-2022). Visual observations are recorded on a scale of 1-5, with 1 being "absent" and 5 being "very high"(Flynn et al. 2022). We subset the data to only include stations in the legal Delta, and only the months of June-December. Data are plotted by calendar year, not water year. Because this is a qualitative rather than a quantitative scale, instead of box plots these data were displayed as stacked bar plots displaying the relative frequency of observations in each category.

We found that frequency of *Microcystis* observations (presence versus absence) increases with drier water year types (Figure 14). This pattern is well established in the literature, with low outflows and drought years consistently having higher frequency of occurrence, biomass, and toxicity of *Microcystis* blooms (Lehman et al. 2013, Hartman et al. 2022, Lehman et al. 2022). The severity of *Microcystis* observations (low, medium, high, and very high) did not follow as consistent of a pattern, with more "high" and "very high" observations in below normal years than Dry years. Some of this variability may be due to differences between surveys. The qualitative nature of the visual index makes it difficult to standardize, leading some researchers to collapse the 5-point scale into a 3-point scale or 2-point scale (presence/absence) (Hartman et al. 2022). More quantitative evaluations of *Microcystis* have also found large differences between similar water year types, with differences in *Microcystis* severity being linked to water temperature and landward extent of salinity intrusion (Lehman et al. 2018).

Some of this pattern is likely also due to the relatively short time span over which the data have been averaged. While we have data on temperature, turbidity, zooplankton, and fishes since the 1960s and 1970s, *Microcystis* data have only been collected consistently since 2007. From 2007 to 2019 (which were summarized for the first four bars in Figure 14), there were three Critically Dry years, three Dry years, four below normal years, three Wet years, and no Above Normal years. Increased replication at the water year type level may better elucidate the relationship between water year type and *Microcystis*.

The recent drought experienced some of the highest frequency of *Microcystis* occurrences seen to date, with particularly high levels in 2020 and 2021. The summer and fall of 2020 had some of the highest water temperatures seen in the Delta (Figure 8), so the high incidence of *Microcystis* is not surprising, despite it being a "Dry" rather than a Critically Dry year. Water temperature is well known to be one of the most important factors in predicting a *Microcystis* bloom (Lehman et al. 2018, Lehman et al. 2022). In 2021, conditions were much drier, with lower inflow, outflow, and exports. All of these flow parameters increase residence time in the South Delta (Hammock et al. 2019, Hartman et al. 2022), creating conditions appropriate for *Microcystis* blooms (Hartman et al. 2022). However, frequency of *Microcystis* occurrence was similar between 2020, 2021 and 2022. This is likely because the change in flow between a Wet year and a Dry year is so large in comparison to the difference in flow between 2020, 2021, and 2022 that the small differences seen in recent years was not enough to significantly change *Microcystis*. No two drought years and no two drought management actions result in the same frequency or severity of *Microcystis* blooms, and we currently do not have analysis tools capable of predicting the outcome of drought management actions with regards to *Microcystis*.

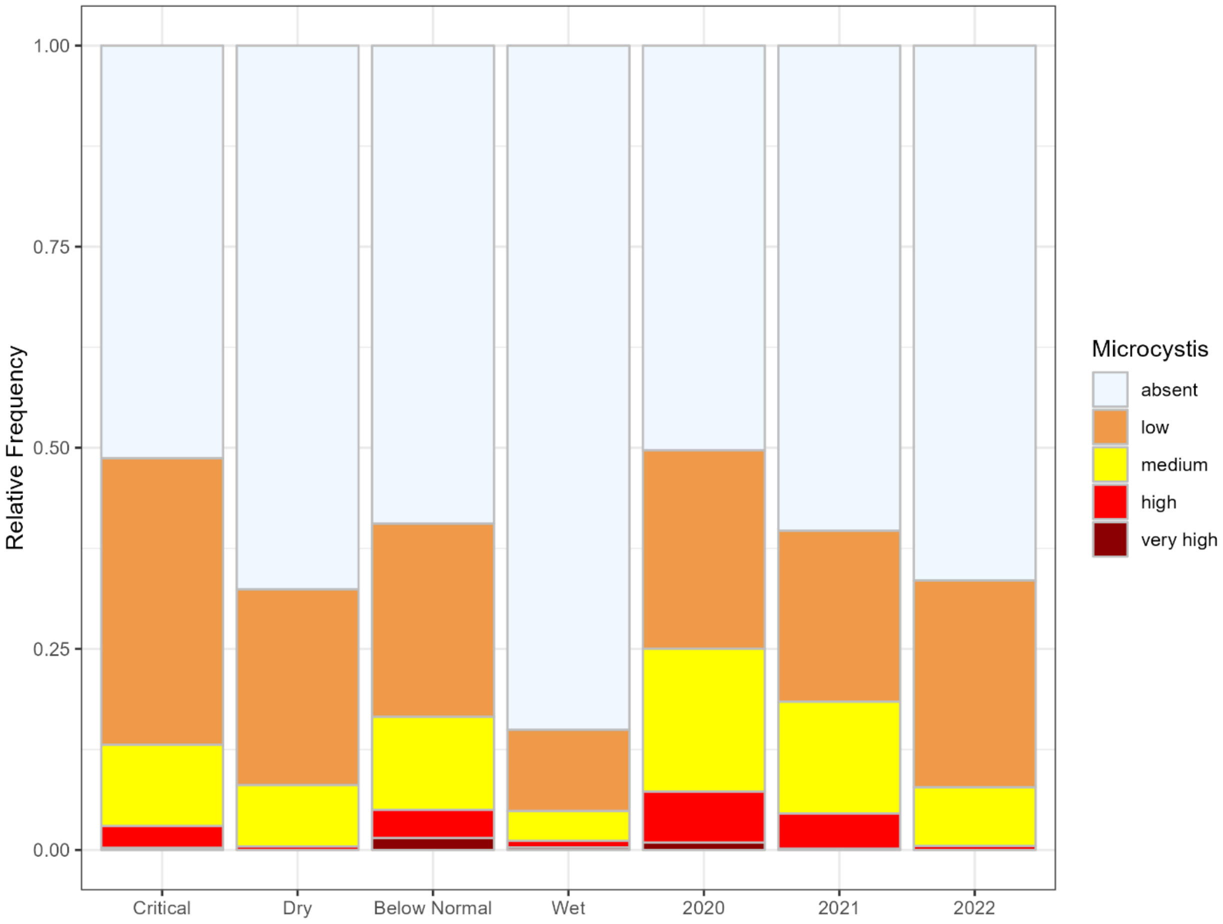

Figure 14. Relative frequency of *Microcystis* observations by water year type for the legal Delta in the months of June-December, 2007-2019 (previous years), 2020, 2021, and 2022.

Pelagic fishes

To evaluate the response of pelagic fishes to drought, we used the CDFW Fall Midwater Trawl (FMWT) index. The FMWT is a survey conducted since 1967 that specifically targets young-of-the-year striped bass, but the use of this data has expanded to include population indices for many pelagic fishes in the estuary. We filtered these data to 1975-2021 (missing 1979) and plotted the data by water year type.

Most pelagic fishes have higher abundance indices in Wet and Above Normal water year types, and all species have had lower indices of abundance in recent years than previous years (Figure 15). However, declines in fish abundance over time obscure some of these trends. From 1975-2000, when pelagic fishes were starting to decline, but before the 'POD' of 2001-2010, there were four Above Normal years and only one Below Normal year. After 2000, there have been five below normal years and only two Above Normal years (2003 and 2005). Because recent years have lower fish abundances, Below Normal years have lower fish abundance than would be otherwise expected. Additional discussion of differences in FMWT abundances is available in Nelson et al. (in prep).

Striped Bass have their highest abundances during Wet years, though Critically Dry years in the 1970s experienced very high abundances. Between the ongoing decline over time and the recent drought, 2020 - 2022 experienced some of the lowest FMWT indices on record. This aligns with the analysis of Mahardja et al. (2021), who found that Striped Bass had low resistance to droughts, and Kimmerer (2002b) who found increased survival with increased freshwater flow. Feyrer et al. (2007), documented a steep decline in striped bass over time, and also found Striped Bass had lower abundances when salinity was higher and when Secchi depth was higher, both of which increase during droughts.

Delta Smelt experienced their highest abundances during Above Normal years followed by Wet years. Previous research has not found a strong relationship between Delta Smelt abundance and freshwater flow (Kimmerer 2002b), but habitat for Delta Smelt is believed to be optimized when X2 is located in Suisun Bay in the fall (conditions of higher outflow) (FLOAT MAST 2021). Mahardja et al. (2021) found Delta Smelt to generally have lower resistance to drought, but this trend was only significant for the 2012-2016 drought. The Delta Smelt index was zero in 2020-2022. Delta smelt abundances are positively associated with lower temperatures and lower Secchi depths (Sommer and Mejia 2013). While it is not clear the degree to which the ongoing drought is impacting Delta Smelt abundance, increases in Secchi depth and temperature, as well as shift in X2 may be worsening conditions for Delta Smelt during the most recent droughts.

Longfin smelt have one of the strongest flow-abundance relationships of any estuarine fish in the Delta, as is clear from their highest abundances in Wet and Above Normal water year types and lowest abundances in Dry and critical years. This has been documented in numerous other publications (Nobriga and Rosenfield 2016, Kimmerer and Gross 2022), though the mechanism remains unknown. While 2020 had one of the lowest Longfin Smelt indices on record, 2021 and 2022 had higher than expected indices, the highest since 2011. While the indices for 2020 and 2021 are in the range of previous critically dry years in the 1970s-1990s, they are much higher than expected given recent declines in the population overall, and surpassed the indices from the wet years of 2017 and 2019.

American Shad also had higher indices of abundance in Wet and Above Normal years than drier year types, though not as large a difference as for Longfin Smelt. This corroborates FMWT end of season reports (White 2022), correlating abundance with freshwater flows, and we note that monitoring in

Suisun Bay recorded record high American Shad abundance in 2017 (O'Rear et al. 2021). This is also corroborated by Mahardja et al. (2021) that found American Shad had low resistance to droughts, but 'bounced back' following several previous droughts. The American Shad index for 2020 was similar to other critically dry years, however abundance dropped in 2021 and 2022.

Threadfin Shad did not show as clear a decline during drier water years, with similar median abundance in Critical, Dry, Above Normal, and Wet years. This may be due, in part, to their relatively high temperature tolerance (Monirian et al. 2010) and their evolutionary history in the Southeastern US, where flow regimes are less variable (Moyle and Mount 2007). Despite a lack of consistent drought effects, the past three years saw lower Threadfish Shad abundance than previous Dry and Critical years.

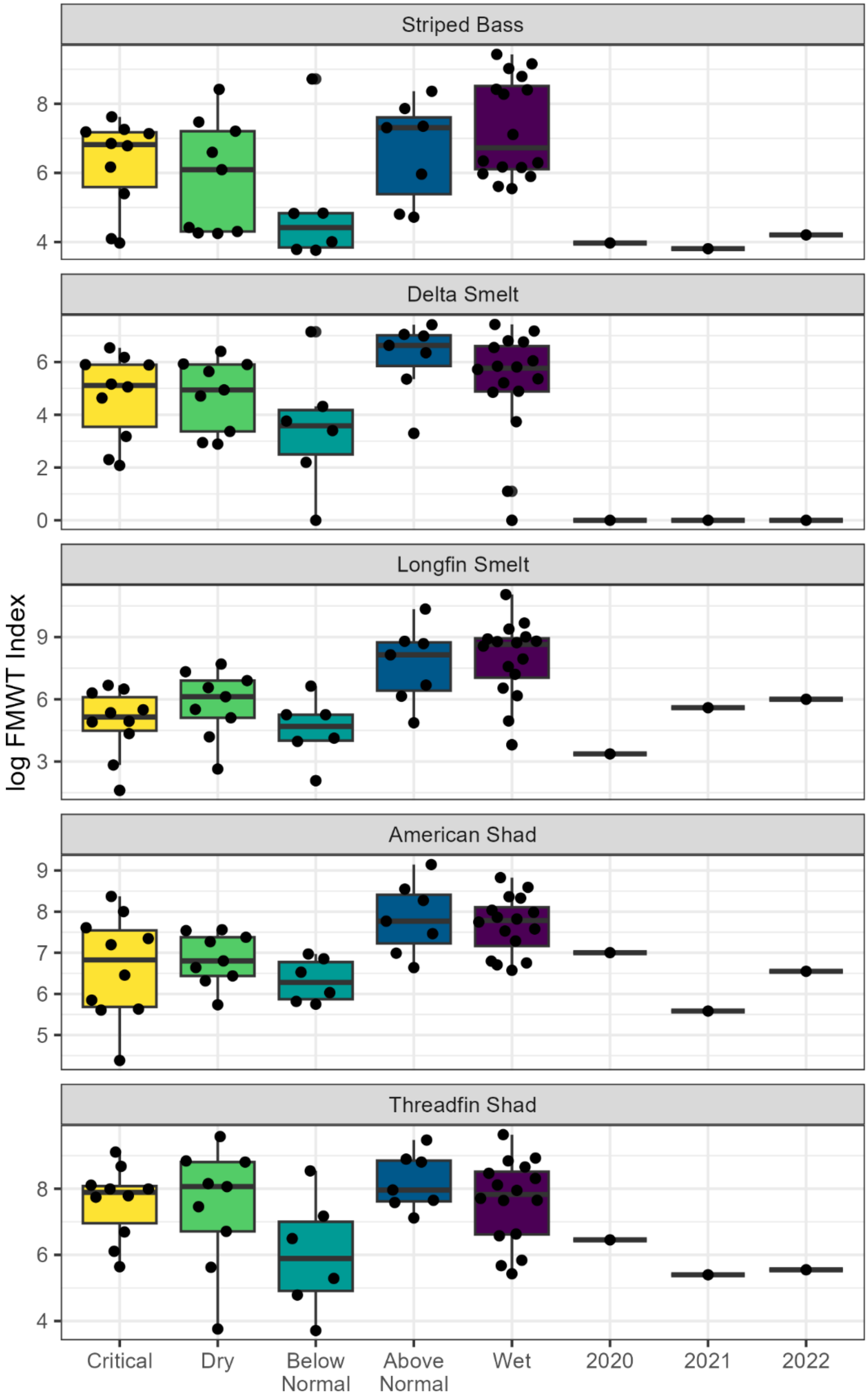

Figure 15. Log-transformed Fall Midwater Trawl indices of abundance for pelagic fish in the estuary for 1975-2019 (previous years), 2020, 2021, and 2022.

Summary and synthesis

Droughts in the Delta are characterized by lower flows, higher salinity, higher temperature, higher water clarity, and higher nutrient concentrations (Figure 16). This leads to local increases in chlorophyll, *Microcystis*, and zooplankton, particularly in the South-Central Delta. However, higher temperatures and lower flow also leads to increased benthic grazing rates, which, combined with increased salinity, leads to lower phytoplankton and zooplankton in Suisun (Figure 16). Most fish decrease in abundance during droughts, however Longfin Smelt and Striped Bass are particularly hard hit, whereas Threadfin Shad and Delta Smelt do not decline as much during droughts (Figure 16).

During the 2020-2022 drought, temperatures were even higher than previous droughts, showing the influence of climate change on the Delta (Figure 17). Water was clearer than previous droughts, but salinity was similar to previous droughts. Nutrient concentrations were somewhat lower than previous droughts, likely due to improvements in wastewater treatment plants. The decreased nutrients may be responsible for the somewhat lower than normal chlorophyll in the South Delta, though zooplankton was somewhat higher than normal in the South Delta (Figure 17). In contrast, chlorophyll was higher than normal in Suisun Bay, whereas zooplankton was lower than normal. Most pelagic fish had extremely low population indices, however, Longfin Smelt had increases in population in 2021 and 2022, contrary to expectations (Figure 17).

Overall, we see that the Delta is characterized by hot, clear, slow-moving water during droughts, and the 2020-2022 drought is clearer and hotter than normal. As climate change continues, the frequency and severity of droughts is expected to increase along with an increase in temperatures. Management actions during the recent drought caused local impacts on salinity and velocity (from actions consistent with the TUCO and Emergency Drought Barrier (California Department of Water Resources (CDWR) 2022b)), and nutrients (from wastewater treatment plant upgrades). On the broader scale, inter-annual changes in precipitation and water availability drive most of the ecosystem changes, with water management sometimes acting to mitigate for reduced precipitation by increasing summer baseflows (Mathias Kondolf and Batalla 2005), while sometimes exacerbating reduced precipitation by reducing freshwater flow even further (Grantham et al. 2013, Van Loon et al. 2022).

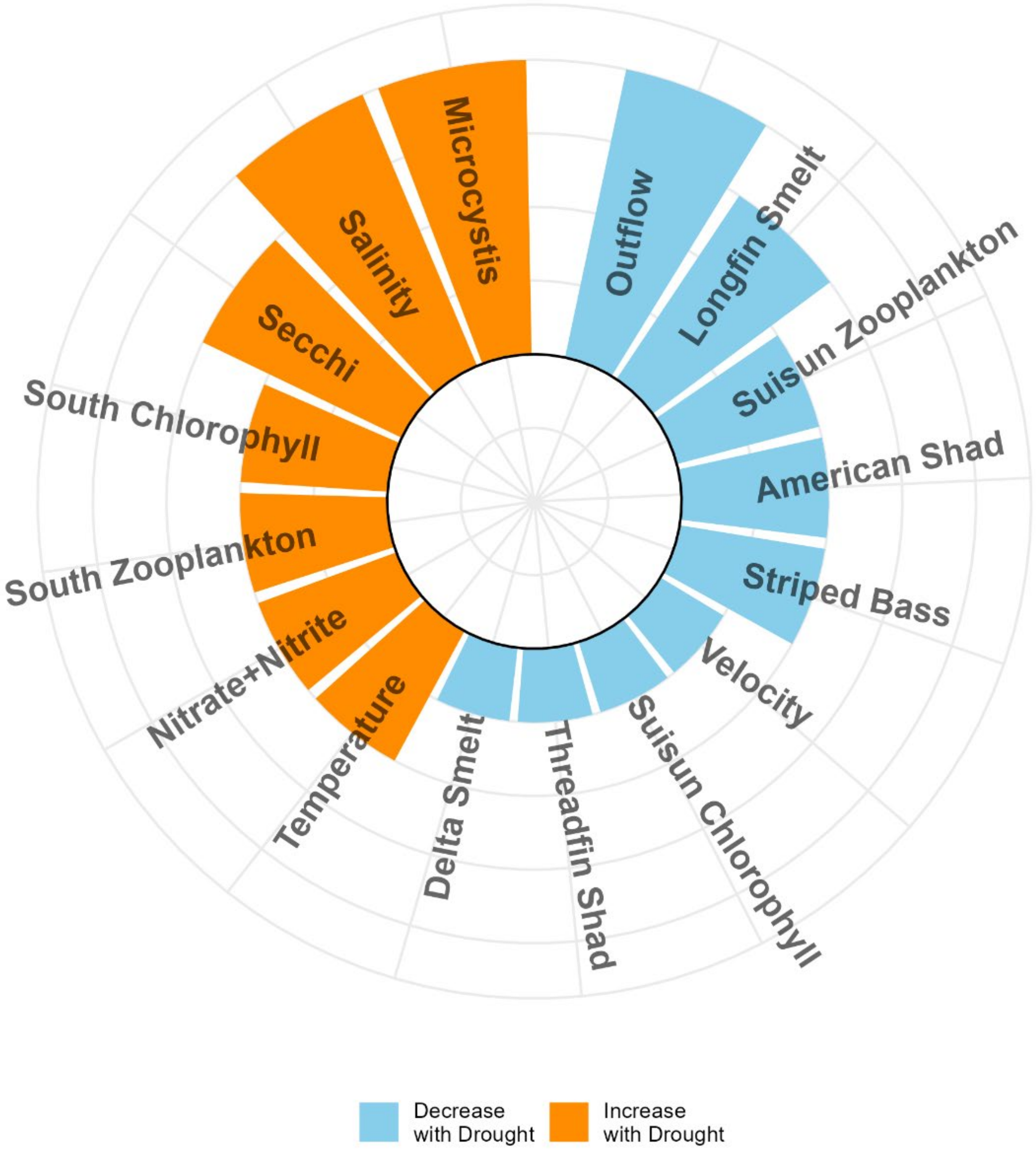

Figure 16. Changes in major ecosystem components during droughts. Larger bars indicate a larger impact of droughts on a qualitative scale of 1-5. Blue bars indicate decreases during droughts, orange bars indicate increases during droughts.

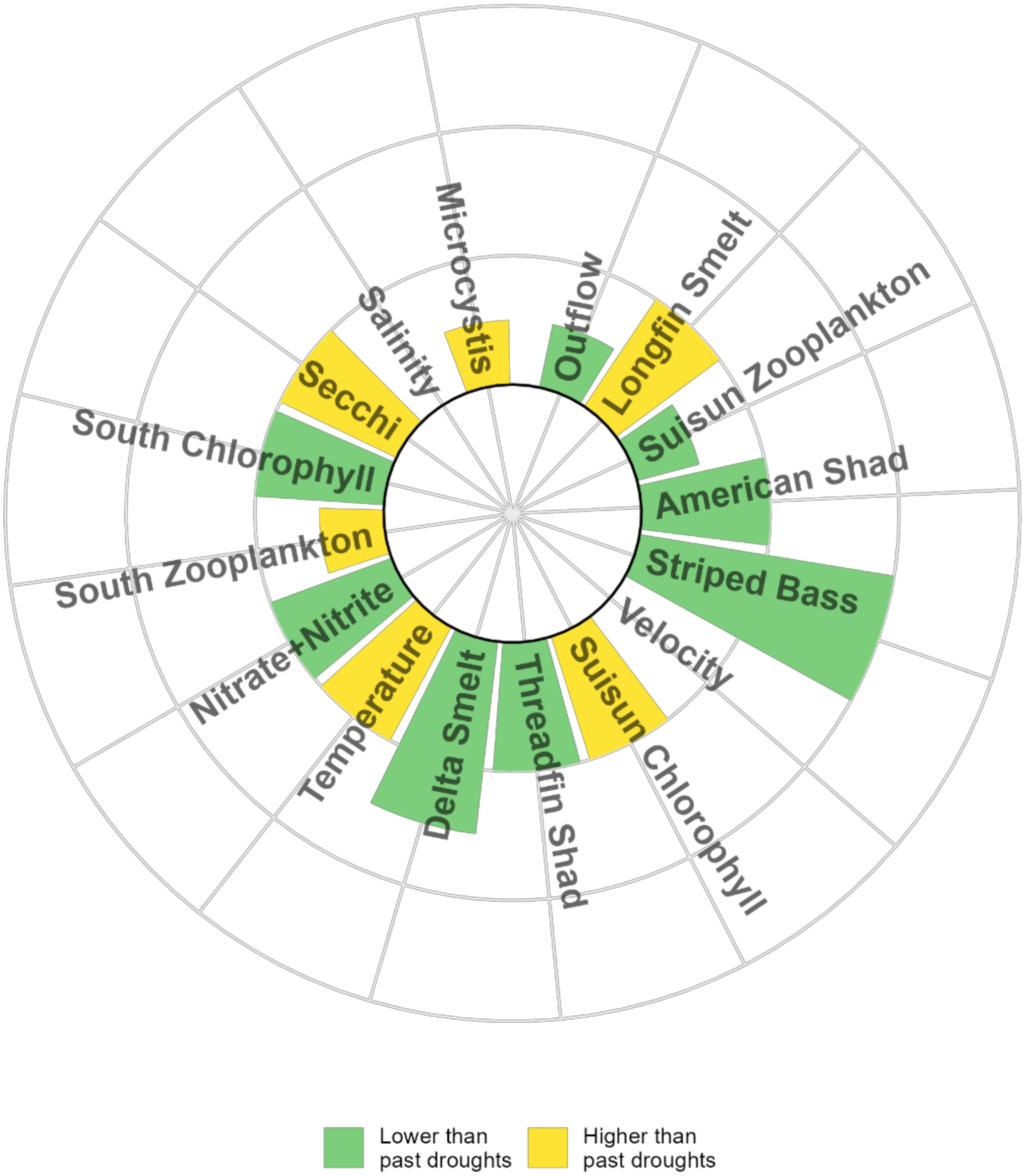

Figure 17. Changes in ecosystem components during the 2020-2022 drought in comparison to previous droughts. Green indicates parameters that were lower than previous droughts, yellow indicates parameters higher than previous droughts. Salinity and velocity were similar to previous droughts.

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