Fall Midwater Trawl Survey End of Season Report: 2022

California Department of Fish and Wildlife

Bay Delta Region (Stockton)

James White, PhD

February 14, 2023

Interagency Ecological Program

Cooperative Ecological Investigations Since 1970

Introduction

The Fall Midwater Trawl (FMWT) survey has been conducted by the California Department of Fish and Wildlife (CDFW) since 1967, making it one of the longest monitoring programs for fishes in existence. The survey was established to examine relative abundance and distribution of juvenile (typically 30-140 mm FL) pelagic fish species in the San Francisco estuary. Age-0 Striped Bass was the initial focus (Stevens 1977) of the survey because it was an important sport fish and there were concerns over the environmental changes in the estuary resulting from the development of the federal and state water projects. Thus a need to develop operating criteria for the water projects was necessary to minimize damage to the Striped Bass population (Stevens 1977).

The sampling range for FMWT was originally designed for the upper San Francisco Estuary from the western Delta downstream through San Pablo Bay. This was the known nursery area for young Striped Bass (Turner and Chadwick 1972) and these stations were believed to best represent the abundance of young-of-year (“age-0”) Striped Bass for the calculated index. FMWT also developed abundance and distribution information for other upper-estuary pelagic fishes, including American Shad (*Alosa sapidissima*), Threadfin Shad (*Dorosoma petenense*), Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), and Splittail (*Pogonichthys macrolepidotus*) (Stevens and Miller 1983; White and Baxter 2022). Low outflow conditions led to the addition of “non-index” stations in 1990 and 1991, and an expansion into the north Delta in 2009 for better coverage of smelt habitat (*see* FMWT Station Map). Currently, FMWT is among the most spatially broad sampling programs in the estuary, currently sampling 122 stations monthly from September through December (Fig. 1). Trawl sampling ranges from western San Pablo Bay to Hood on the Sacramento River, and from Sherman Lake to Stockton on the San Joaquin River. Since 2009, we also conduct meso- and macro-zooplankton sampling at a subset of 32 stations to track the food web dynamics impacting the local fish community. This additional sampling helps inform if reduced or altered prey abundance is a contributing factor in fish population declines (part of the CDFW Diet and Condition Study).

With the FMWT sampling annually for over 50 years, this dataset has provided a solid baseline for understanding relative abundance and distribution trends of fishes in the San Francisco Estuary (White and Baxter 2022). The FMWT is one of many long-running surveys conducted in the San Francisco Estuary (Tempel et al. 2021), and is a monitoring element of the Interagency Ecological Program (IEP; see: Interagency Ecological Program 2023 Annual Work Plan). Over 50 peer reviewed publications have used these data and it is frequently used by water managers to determine water export volumes for the multi-billion dollar agricultural industry in the Central Valley and municipal use for over 25 million residents throughout California. Long-term monitoring studies like the FMWT are important in describing how and why the environment is changing, understanding the regulation and functioning of ecological communities, linking biological patterns to environmental variability, and informing of human influences on ecosystems (McGowan 1990; Cody and Smallwood 1996; Ducklow et al. 2009; Clutton-Brock and Sheldon 2010; Magurran et al. 2010; Nelson et al. 2011; Likens 2012; Lindenmayer et al. 2012; Hofmann et al. 2013; Hughes et al. 2017). For example, FMWT data has helped highlight a dramatic estuary-wide decline in fish populations (Sommer et al. 2007; Baxter et al. 2010; Mac Nally et al. 2010; Thomson et al. 2010) and resilience abilities of fish communities to long term drought cycles in the estuary (Mahardja et al. 2021). The FMWT also collaborates with other IEP efforts, such as the Diet and Condition Study and Suisun Marsh Salinity Control Gate (SMSCG) to inform summer and fall resource management actions.

The objective for this report was to summarize the annual environmental variables and catch patterns that are not reported in other annual memos. The goal of the 2022 field season was to sample all stations safely and efficiently, identifying and counting all fish and macro-invertebrates and measuring the fork lengths (FL) of the first 50 individuals of each fish species for each station. Meso- and macro-zooplankton samples were also collected at 32 stations to help inform food availability for young fish. Various weather and water quality conditions were also recorded at each station (see below). The first survey began September 6, 2022, and the final survey was completed on December 16, 2022.

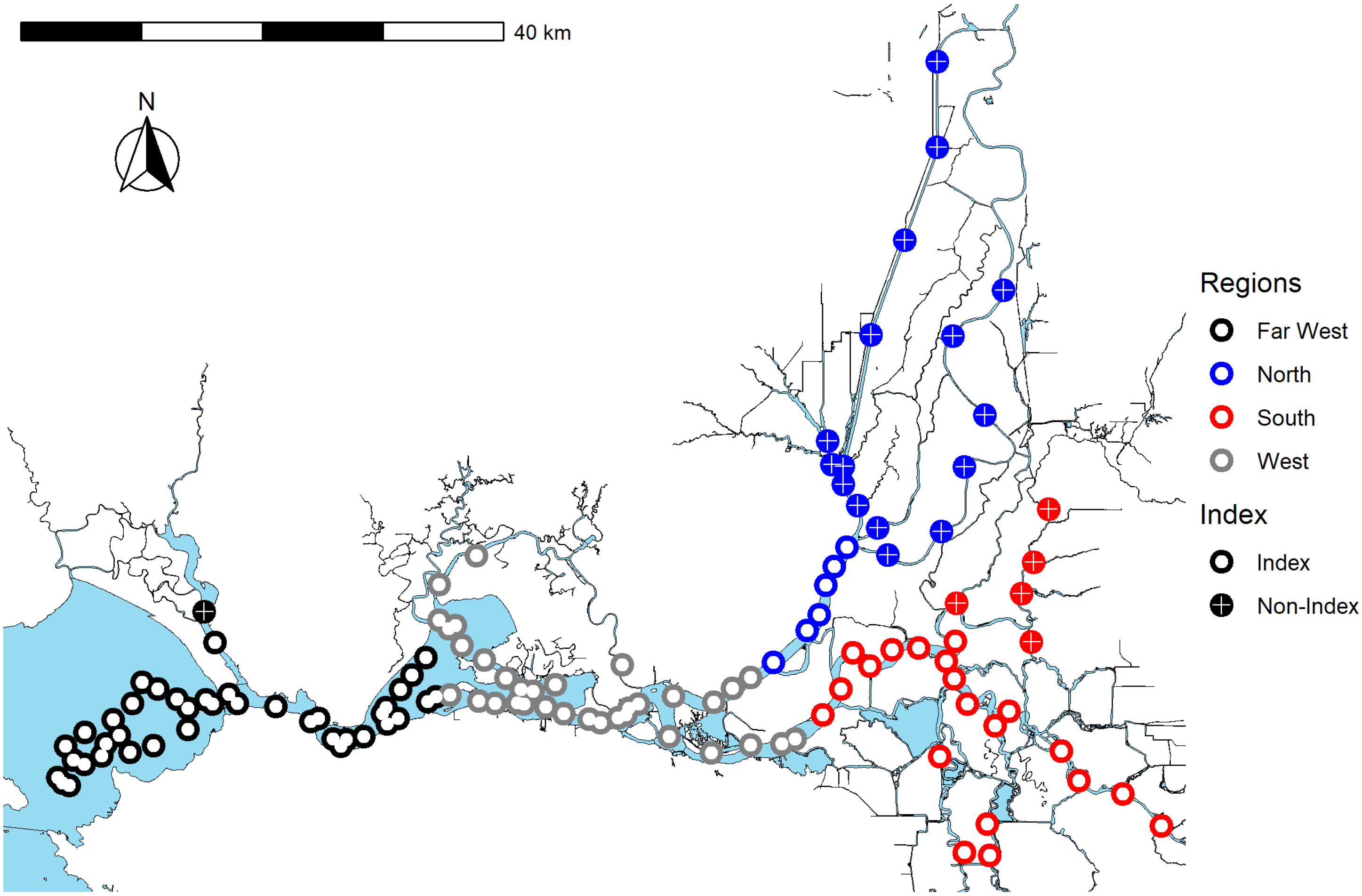


Figure 1. Map of Fall Midwater Trawl station locations, regional groupings, and station index designations.

Methods and Gear

The FMWT trawl net consists of a 12 x 12 ft mouth, 58 ft long, starting with 8 inch mesh near the mouth tapering down multiple mesh sizes to 1/2 inch stretched mesh at the cod end. The net is retrieved obliquely through the water column according to a tow schedule which varies with water depth. Metal planing doors fixed at each corner of the mouth of the net help keep the mouth open during sampling. Further details on sampling methods and gear can be found in the FMWT protocol document. Each oblique tow is 12 minutes long and each of the 122 FMWT stations receives one tow. The survey currently takes 10-12 days to cover the FMWT spatial range each month (September-December).

Figure 2. Crew deploying the trawl net off the back deck of the research vessel.

The typical unit for reporting catch used below is catch per tow or per unit effort (CPUE). For FMWT, we calculate CPUE as total species catch divided by water volume of the trawl (calculated from flowmeter values) in units of cubic hectares (i.e. catch per cubic hectare; see CPUE Calculation Instructions.)

The regional groupings depicted here are modified from the U.S. Fish and Wildlife (USFWS) Enhanced Delta Smelt monitoring (EDSM) survey geographic stratifications (see Fig. 1 in Polansky et al. (2019)). The intent is to provide broad geographical groupings of stations both for ease of reference and species abundance patterns.

2022 Field Season

The 2022 field season was challenging but completed successfully. FMWT staff conducted both the routine monitoring (n = 488 tows) and year 2 of a Special Study sampling concurrently for a subset of regions (n = 253 fish tows; Table 1). The Special Study added a suite of randomly assigned stations in the same day and region of ongoing fixed site sampling as the second year in examining differences in catch. A second boat and crew were needed to conduct the added sampling, so staff prioritized field effort resulting in a delay of some ongoing laboratory sample processing and data entry. Colleagues from the U.S. Bureau of Reclamation (USBR) lent us the R/V Compliance as our secondary vessel which was critical to the success of this expanded effort. The routine survey generally takes 10-12 days to sample all 122 stations each month. The Special Study added 7-10 days of sampling per month. Surveys began in San Pablo and sampled working upstream through to the Delta. For San Pablo Bay sampling days, crews stayed in Vallejo at survey start for a few days which created time savings avoiding long daily commutes. A summary of FMWT Special Study effort and results will be forthcoming in a separate report. This report is a summary of the routine long-term monitoring results.

Table 1. Fall Midwater Trawl Special Study regional station sampling frequency per month in 2022.

Survey	San Pablo Bay & Carquinez Strait	Napa River	Suisun & Honker Bays	Suisun Marsh	Confluence	Cache Slough	Sacramento Deepwater Ship Channel	Total
Sept	0	0	0	0	2	3	5	10
Oct	0	0	23	2	27	3	5	60
Nov	26	3	23	4	27	3	5	91
Dec	27	3	23	4	27	4	4	92
Total	**53**	**6**	**69**	**10**	**83**	**13**	**19**	**253**

Routine sampling of 122 fish tows and 32 zooplankton tows (Clark-Bumpus (CB) and Mysid nets) was completed for all months (Sept.-Dec.) in 2022 (Table 2). Besides routine sampling, additional zooplankton and phytoplankton sampling was conducted at 11 stations biweekly in September and October for the Suisun Marsh Salinity Control Gate (SMSCG) study on behalf of the California Department of Water Resources (DWR; Table 2). Overall, 2022 sampling contributed to the FMWT annual abundance indices, USFWS Delta Smelt Recovery Index, and DWR SMSCG special study with additional phytoplankton samples collected at a subset of stations.

Table 2. Number of Fish, Clark-Bumpus (CB), Mysid, and Phytoplankton samples collected at each station during the 2022 Fall Midwater Trawl Survey season conducted monthly September-December.

Station	Regions	Index	Delta Smelt Recovery Index	Fish net	CB net	Mysid net	Salinity Control Gate	Phytoplankton
305	Far West	Index		4	0	0	0	0
306	Far West	Index		4	0	0	0	0
307	Far West	Index		4	0	0	0	0
308	Far West	Index		4	0	0	0	0
309	Far West	Index		4	0	0	0	0
310	Far West	Index		4	0	0	0	0
311	Far West	Index		4	0	0	0	0
314	Far West	Index		4	0	0	0	0
315	Far West	Index		4	0	0	0	0
321	Far West	Index		4	0	0	0	0
322	Far West	Index		4	0	0	0	0
323	Far West	Index		4	0	0	0	0
325	Far West	Index		4	0	0	0	0
326	Far West	Index		4	0	0	0	0
327	Far West	Index		4	0	0	0	0
328	Far West	Index		4	0	0	0	0
329	Far West	Index		4	0	0	0	0
334	Far West	Index		4	0	0	0	0
335	Far West	Index		4	0	0	0	0
336	Far West	Index		4	0	0	0	0
337	Far West	Index		4	0	0	0	0
338	Far West	Index		4	0	0	0	0

Station	Regions	Index	Delta Smelt Recovery Index	Fish net	CB net	Mysid net	Salinity Control Gate	Phytoplankton
339	Far West	Index		4	0	0	0	0
340	Far West	Index		4	0	0	0	0
341	Far West	Non-Index		4	0	0	0	0
401	Far West	Index		4	0	0	0	0
403	Far West	Index		4	0	0	0	0
404	Far West	Index		4	0	0	0	0
405	Far West	Index		4	4	4	0	0
406	Far West	Index		4	0	0	0	0
407	Far West	Index		4	0	0	0	0
408	Far West	Index		4	0	0	0	0
409	Far West	Index		4	0	0	0	0
410	Far West	Index	Sept-Oct	4	0	0	0	0
411	Far West	Index		4	4	4	0	0
412	Far West	Index	Sept-Oct	4	0	0	0	0
414	Far West	Index	Sept-Oct	4	0	0	0	0
415	Far West	Index		4	0	0	0	0
416	Far West	Index	Sept-Oct	4	4	4	2	0
417	Far West	Index		4	0	0	0	0
418	Far West	Index	Sept-Oct	4	4	4	0	0
413	West	Index		4	0	0	0	0
501	West	Index	Sept-Oct	4	4	4	0	0
502	West	Index		4	0	0	0	0
503	West	Index	Sept-Oct	4	0	0	0	0
504	West	Index		4	4	4	0	0
505	West	Index	Sept-Oct	4	0	0	0	0
507	West	Index	Sept-Oct	4	0	0	0	0
508	West	Index		4	4	4	2	0
509	West	Index	Sept-Oct	4	0	0	0	0
510	West	Index		4	0	0	0	0
511	West	Index	Sept-Oct	4	0	0	0	0
512	West	Index		4	0	0	0	0
513	West	Index	Sept-Oct	4	4	4	2	0
515	West	Index	Sept-Oct	4	0	0	0	0
516	West	Index		4	0	0	0	0
517	West	Index	Sept-Oct	4	0	0	0	0
518	West	Index		4	0	0	0	0
519	West	Index	Sept-Oct	4	4	4	2	0
601	West	Index		4	0	0	0	0
602	West	Index	Sept-Oct	4	4	4	2	0
603	West	Index		4	0	0	0	0
604	West	Index	Sept-Oct	4	0	0	0	0
605	West	Index		4	0	0	2	3
606	West	Index	Sept-Oct	4	4	4	2	3

Station	Regions	Index	Delta Smelt Recovery Index	Fish net	CB net	Mysid net	Salinity Control Gate	Phytoplankton
608	West	Index	Sept-Oct	4	4	4	0	0
701	West	Index	Sept-Oct	4	0	0	0	0
703	West	Index	Sept-Oct	4	0	0	0	0
704	West	Index		4	4	4	2	3
705	West	Index	Sept-Oct	4	0	0	0	0
802	West	Index	Sept-Oct	4	4	4	2	3
804	West	Index	Sept-Oct	4	4	4	0	0
806	West	Index	Sept-Oct	4	0	0	0	0
807	West	Index		4	0	0	0	0
808	West	Index	Sept-Oct	4	0	0	0	0
706	North	Index		4	4	4	2	3
707	North	Index	Sept-Oct	4	4	4	2	0
708	North	Index		4	0	0	0	0
709	North	Index	Sept-Oct	4	0	0	0	0
710	North	Index		4	0	0	0	0
711	North	Index		4	4	4	0	0
712	North	Non-Index		4	0	0	0	0
713	North	Non-Index		4	0	0	0	0
715	North	Non-Index		4	0	0	0	0
716	North	Non-Index		4	4	4	0	0
717	North	Non-Index		4	0	0	0	0
719	North	Non-Index		4	4	4	0	0
72	North	Non-Index		4	0	0	0	0
722	North	Non-Index		4	4	4	0	0
723	North	Non-Index		4	4	4	0	0
724	North	Non-Index		4	0	0	0	0
73	North	Non-Index		4	0	0	0	0
735	North	Non-Index		4	0	0	0	0
736	North	Non-Index		4	0	0	0	0
795	North	Non-Index		4	4	4	0	0
796	North	Non-Index		4	4	4	0	0
797	North	Non-Index		4	4	4	0	0
809	South	Index		4	4	4	0	0
810	South	Index	Sept-Oct	4	0	0	0	0
811	South	Index		4	0	0	0	0
812	South	Index	Sept-Oct	4	4	4	0	0
813	South	Index		4	0	0	0	0
814	South	Index	Sept-Oct	4	0	0	0	0
815	South	Index		4	4	4	0	0
902	South	Index		4	0	0	0	0
903	South	Index	Sept-Oct	4	0	0	0	0
904	South	Index	Sept-Oct	4	0	0	0	0

Station	Regions	Index	Delta Smelt Recovery Index	Fish net	CB net	Mysid net	Salinity Control Gate	Phytoplankton
905	South	Index		4	0	0	0	0
906	South	Index	Sept-Oct	4	4	4	0	0
908	South	Index	Sept-Oct	4	0	0	0	0
909	South	Index		4	0	0	0	0
910	South	Index		4	4	4	0	0
911	South	Index		4	0	0	0	0
912	South	Index		4	4	4	0	0
913	South	Index		4	0	0	0	0
914	South	Index		4	0	0	0	0
915	South	Index		4	0	0	0	0
919	South	Non-Index		4	4	4	0	0
920	South	Non-Index		4	0	0	0	0
921	South	Non-Index		4	0	0	0	0
922	South	Non-Index		4	0	0	0	0
923	South	Non-Index		4	0	0	0	0
Total				488	128	128	22	15

Abiotic variables

Water clarity

Secchi disk depth (cm) varied considerably across the estuary (Fig. 3). Generally, water was least clear throughout Carquinez Strait (stations in the 400s), Suisun Bay (Stations in the 500-600 range), and the upper portion of the Sacramento River Deep Water Shipping Channel (stations 795-797; DWSC). In October, stations in the upper Sacramento River saw unusually high secchi values of over 500 centimeters. Water was relatively clear (200-300 cm Secchi depth) throughout the southern and eastern stations (stations in the 900s) for most months with some improvement in December. Previous studies have documented a negative correlation between fish catch and high Secchi values (Mac Nally et al. 2010), which varies between species. For example, larval Longfin Smelt are more likely to be caught in the secchi depth range of 0-80 cm (Grimaldo et al. 2017) and adult Longfin Smelt catch is greatest at depths less than 50 cm (Lewis et al. 2019). Latour (2016) found CPUE decreased 75% once Secchi depth reach 35, 50, 53, and 112 cm for Delta Smelt, Longfin Smelt, Age-0 Striped Bass, and Threadfin Shad, respectively. Therefore, in the heatmap of Secchi values below (Fig. 3), stations with dark purple boxes (<100 cm Secchi depth) represent stations with the highest likelihood of fish occurrence, which quickly decreases as the color scale transitions to blues, greens, and yellow.

Turbidity (NTU) is a similar but more precise metric of measuring water clarity compared to Secchi depth. Higher turbidity values indicate more opaque water. The heatmap and boxplot of turbidity values during the 2022 FMWT survey (Figs. 4 & 5) show a similar pattern as the Secchi values. The northern part of the DWSC, northern Suisun Bay/Montezuma Slough, and a station in Honker Bay in October showed the most turbidity while the rest of the estuary was relatively clear. However, this pattern varied among months with the San Pablo Bay and Suisun Bay stations being most turbid in November.

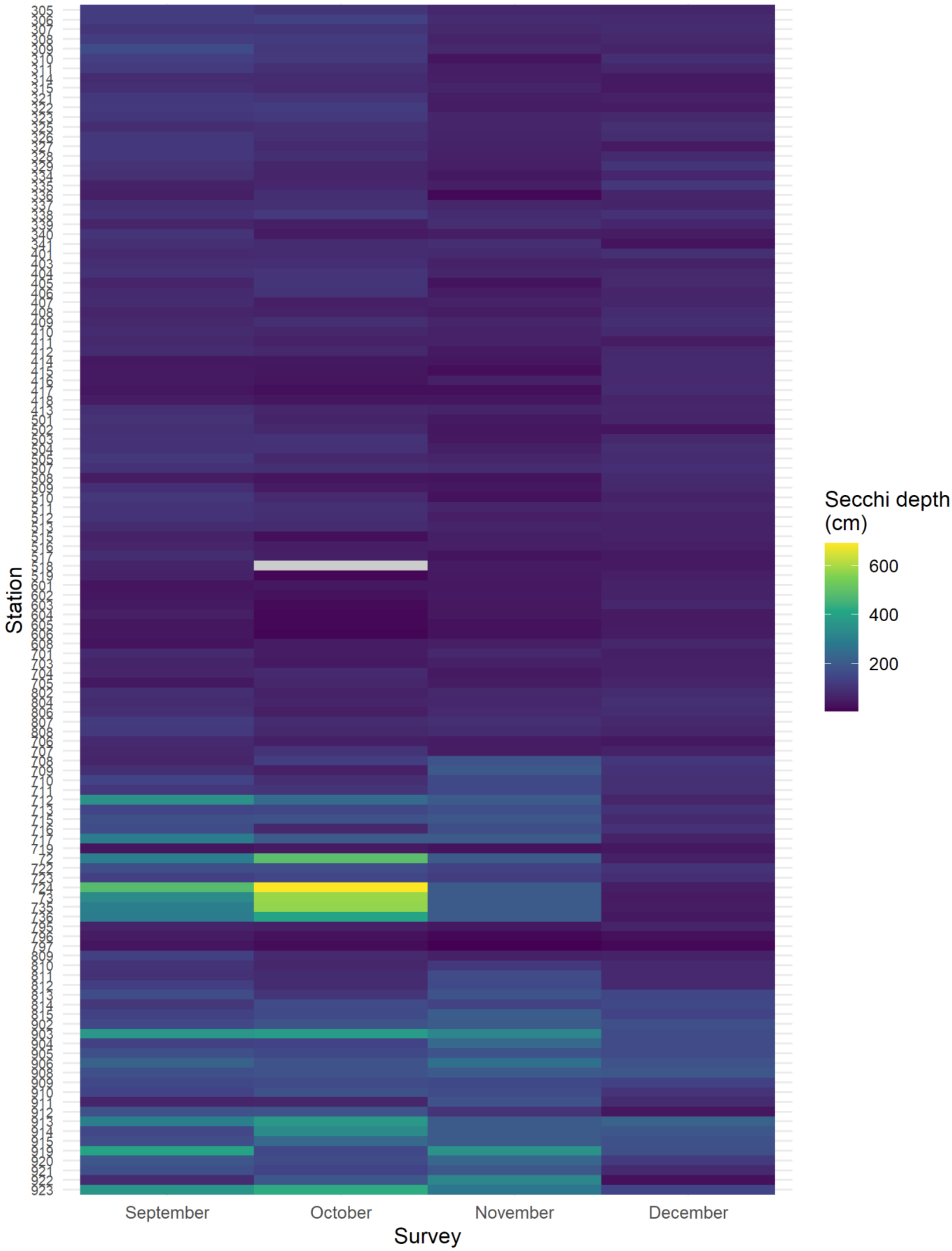


Figure 3. Heatmap of monthly Secchi disk values (cm) recorded during the 2022 FMWT season. White values indicate missing data. Dark purple values represent the most suitable conditions for many fish species with preference for turbidity.

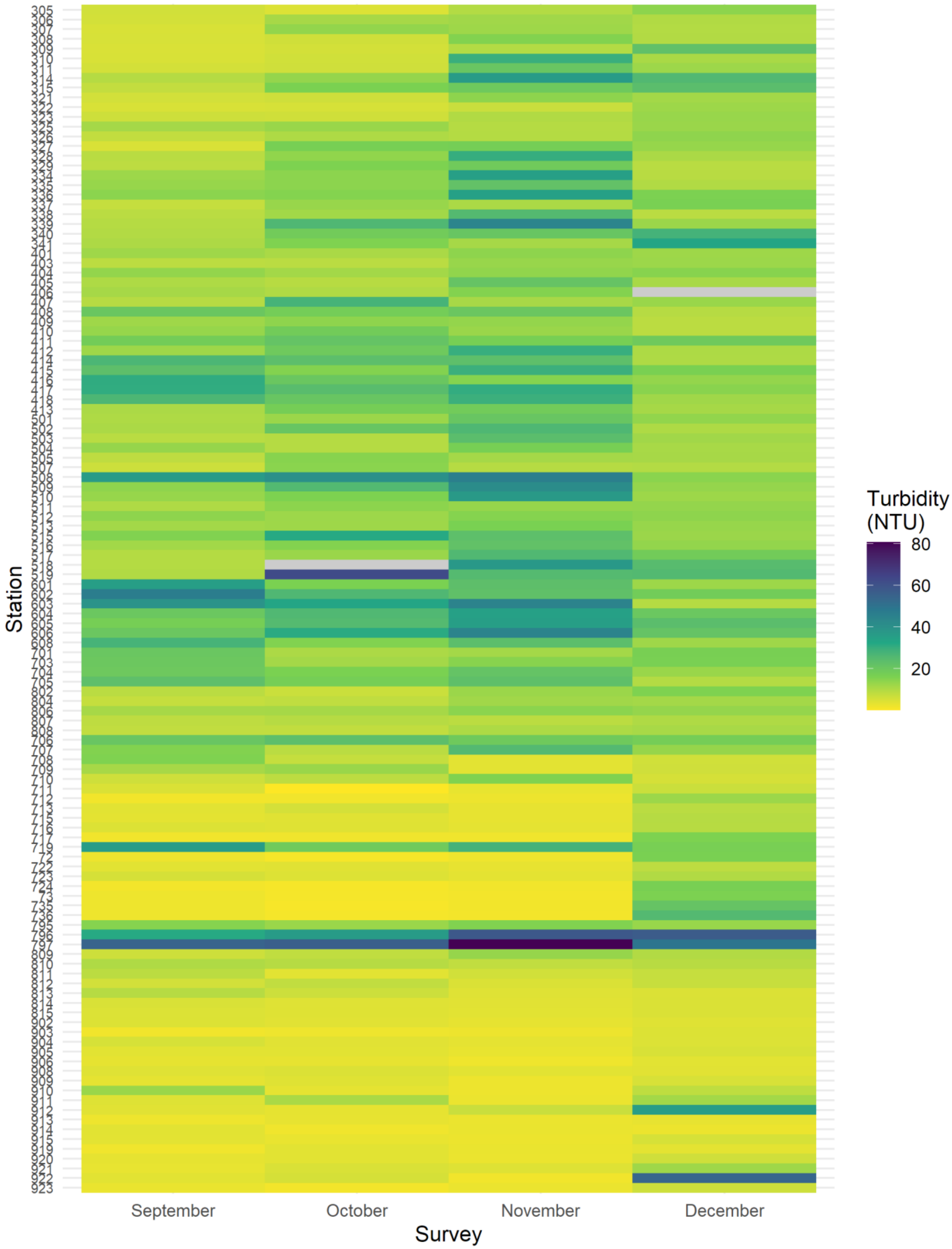


Figure 4. Heatmap of surface water turbidity (NTU) recorded during the 2022 FMWT season. White values indicate missing data. The northern part of the DWSC, northern Suisun Bay, and San Pablo Bay were the most turbid regions which varied among months.

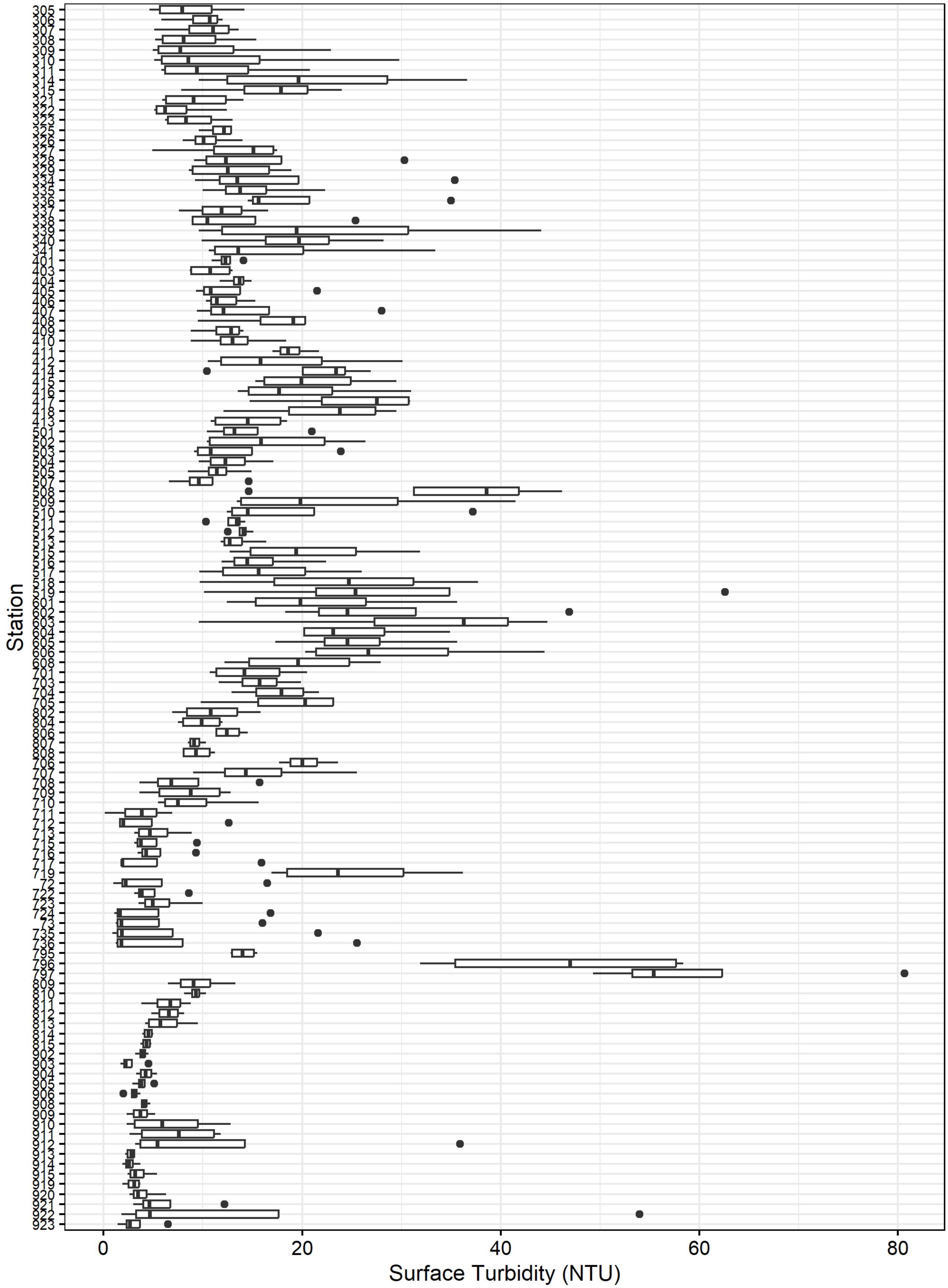


Figure 5. Distribution of monthly surface turbidity (NTU) recorded during the 2022 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

Temperature

Many estuary species have habitat preferences that include a range of suitable water temperatures (Baker et al. 1995; Swanson et al. 2000; Moyle et al. 2004; Bennett 2005). Past research has linked long term seasonal Delta Smelt occurrence with changes in abiotic habitat metrics such as temperature (Feyrer et al. 2007; Nobriga et al. 2008; Feyrer et al. 2011). Other research has shown adult Longfin Smelt prefer temperatures under 17.8°C (Hobbs and Moyle 2015), larval Longfin Smelt are most abundant in the 8-12°C range (Grimaldo et al. 2017) and adults are most abundant in water 12-16°C (Lewis et al. 2019). Also, Longfin Smelt tend to spawn when temperatures are between 7-14.5°C (Moyle 2002) and Delta Smelt are likely to stop spawning once temperatures are greater than 20°C (Swanson et al. 2000).

Besides preferences, there are physiological thermal limitations that have been documented for some species. For instance, Jeffries et al. (2016) found Longfin Smelt show a cellular stress response once water temperature is greater or equal to 20°C and Bennett (2005) showed Delta Smelt experience mortality at temperatures above 25°C.

The heatmap of surface water temperature (Fig. 6) shows temperatures throughout most of the estuary remained very high (22-25°C), possibly at the upper range of thermal tolerance for many fish species throughout September and October. By November, temperatures had cooled into the 11-16°C range. By December, the water cooled estuary-wide. The areas with the greatest temperature variability were at stations in the eastern Delta near Stockton (i.e. 911 and 912; Fig. 7).

Temperatures were usually warmer at surface waters compared to bottom water samples (Fig. 8). The most extreme differences were observed at single stations in Honker Bay and San Pablo Bay. However, these temperature differences do not necessarily indicate stratification at these stations since these differences may not be consistent or prolonged across tides.

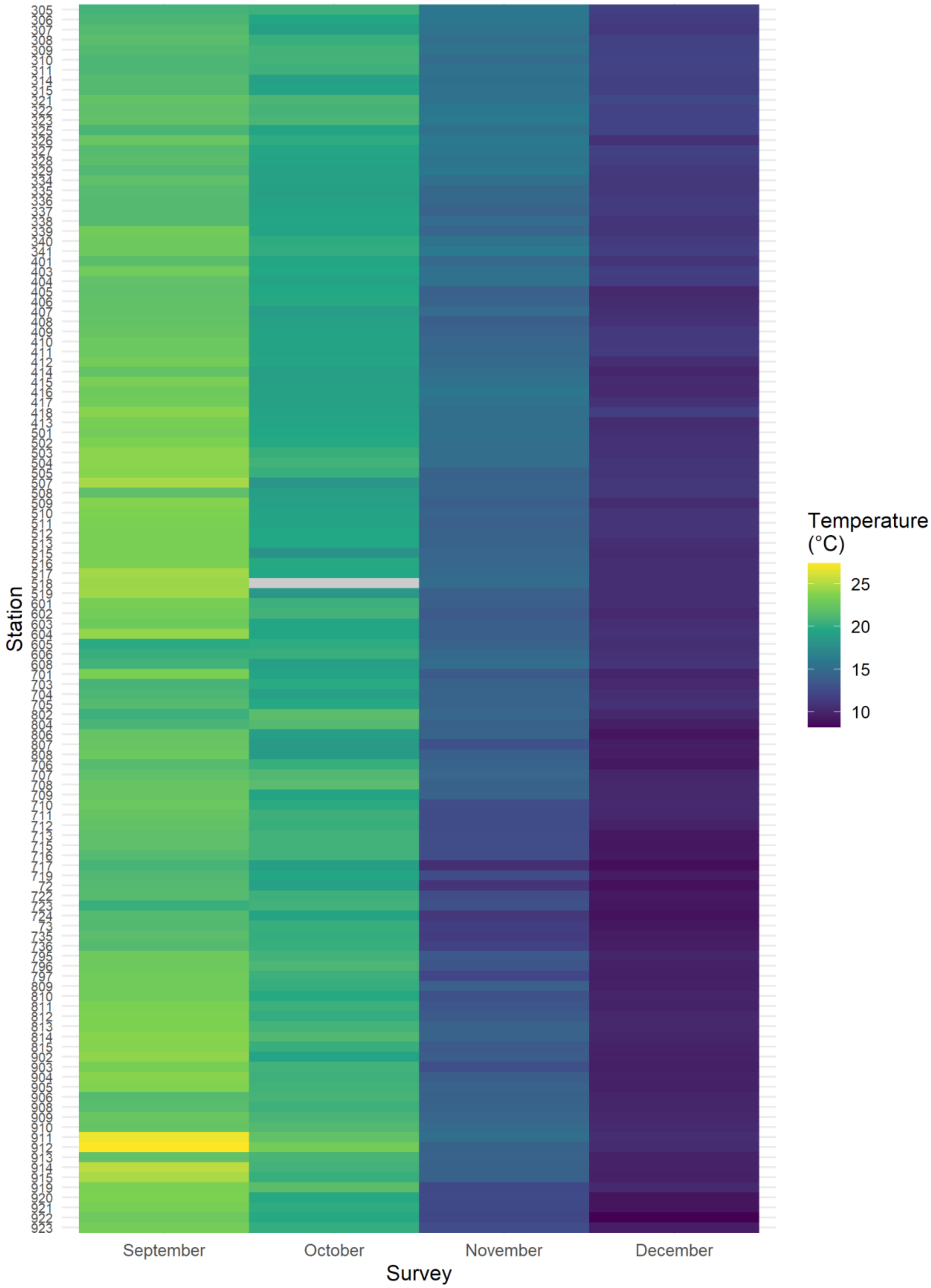


Figure 6. Heatmap of monthly surface water temperature (°C) recorded during the 2022 FMWT season. White values indicate missing data. Temperature values at 20 °C or greater induce cellular stress in Longfin Smelt and values above 25 °C induce Delta Smelt mortality; therefore, stations in the purple and blue ranges are most suitable. Stations in the green to yellow range are potentially unsuitable for many species.

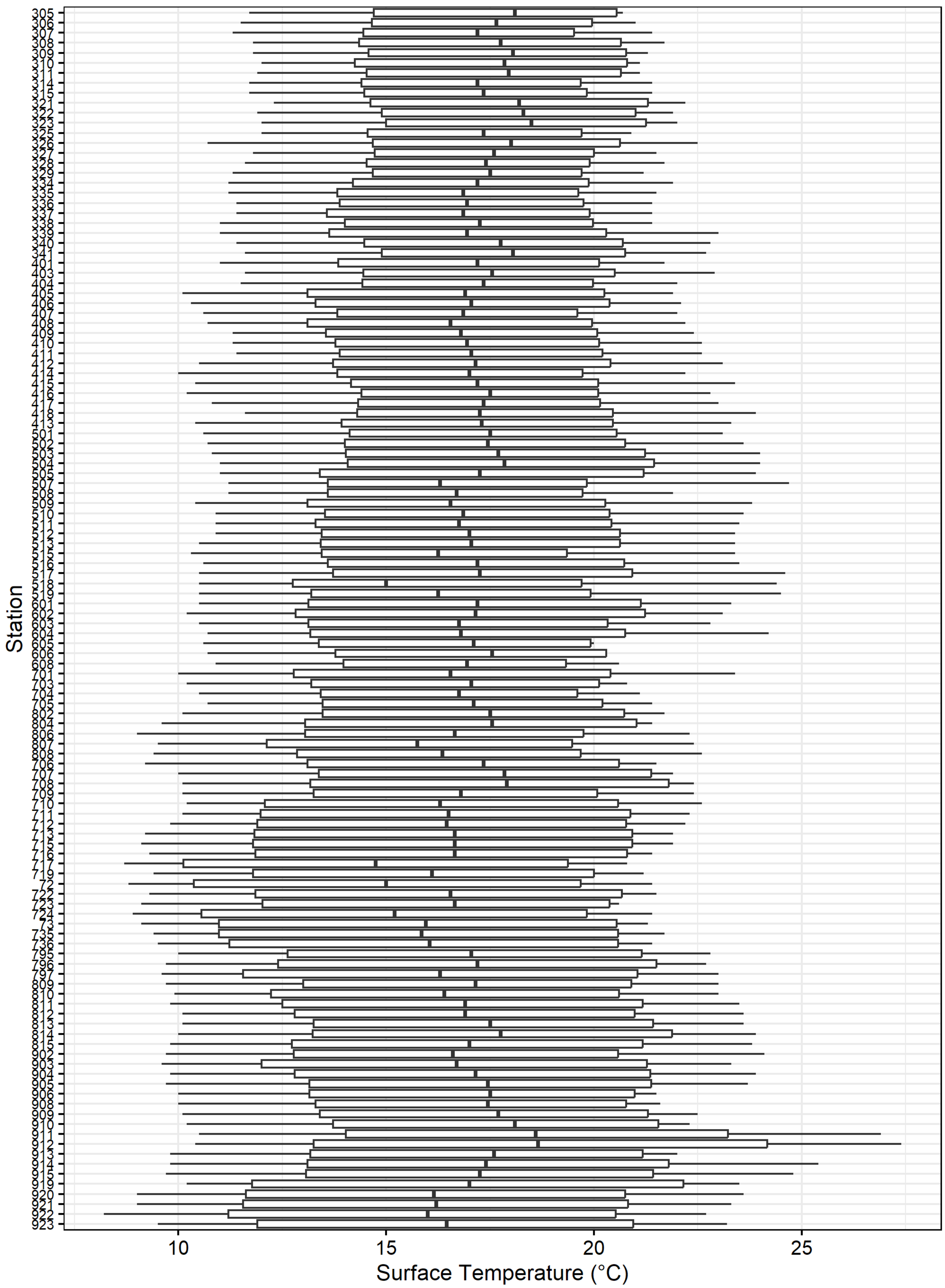


Figure 7. Distribution of monthly surface water temperature (°C) recorded during the 2022 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

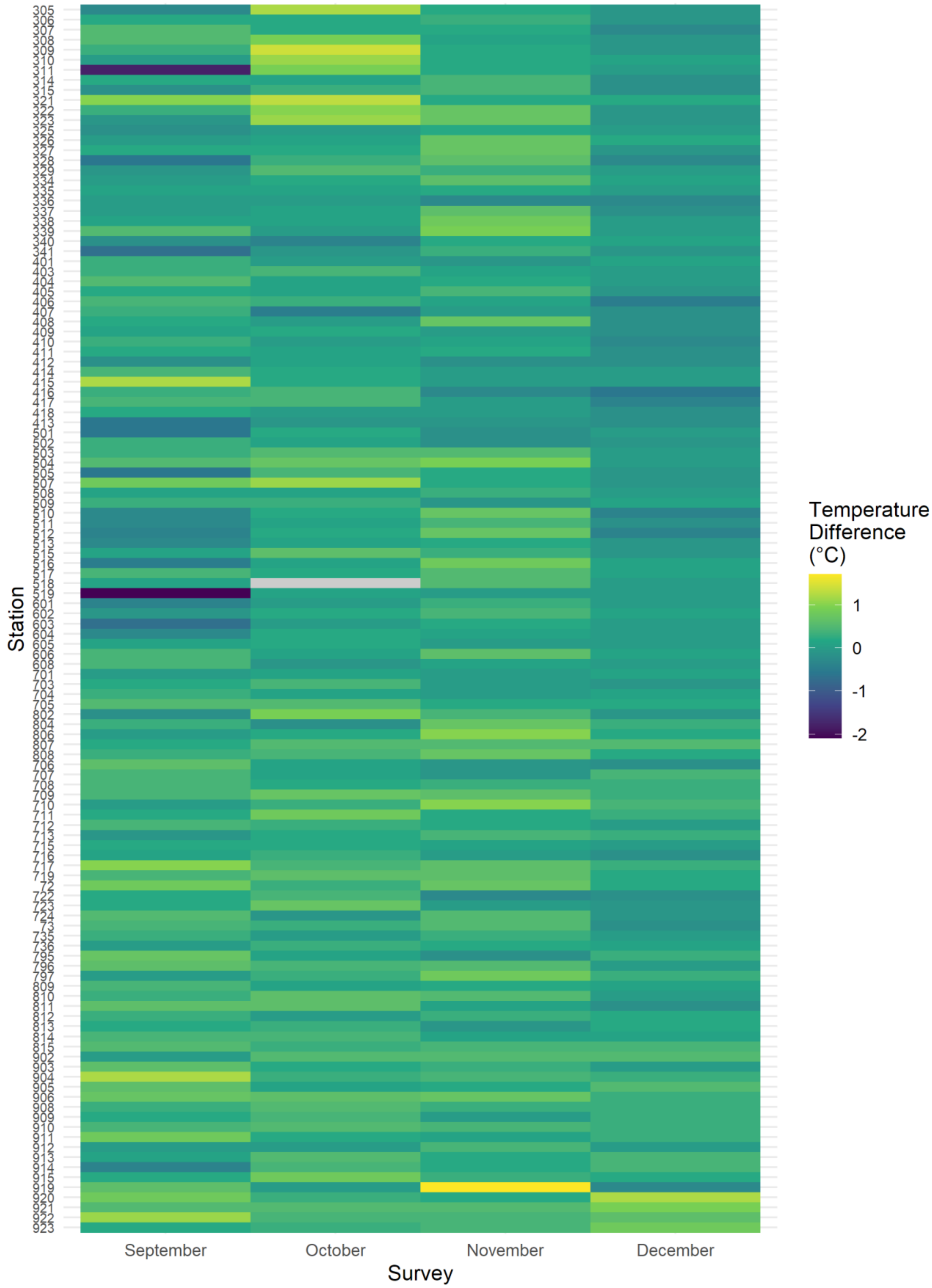


Figure 8. Heatmap of temperature (°C) differences between surface and bottom water recorded during the 2022 FMWT season. White values indicate missing data. Negative (blue to purple) values are warmer bottom temperature compared to the surface. Positive (green to yellow) values indicate greater temperatures at the surface.

Temperature and Water Clarity

Leveraging the 50+ year FMWT dataset, I created a series of regional maps showing Longfin Smelt habitat suitability from combined Secchi and temperature values for 2022 (Fig. 9). This map displays the average monthly temperature and secchi values in the regions FMWT samples and plots these values on a combined color scale. The breaks in this scale were first determined by plotting a cumulative frequency distribution of Longfin Smelt catch over the entire history of the survey compared to temperature and Secchi separately (Fig. 10). Then taking the corresponding temperature and Secchi values for each of the catch quantiles. These maps show the estuary was largely unsuitable for Longfin Smelt (and likely other species) in September and October. By November, San Pablo Bay, Carquinez Strait, Suisun Bay, Montezuma Slough, the DWSC and the confluence of the San Joaquin and Sacramento Rivers were in the moderate range of suitability. Napa River was on the high end of suitability during this time. By December, most regions of the estuary were suitable with the exceptions of Cache Slough, the San Joaquin River, and the eastern Delta (Fig. 9).

Habitat suitability was also readily apparent at the start of the season as weeks of low flows and high water temperatures from late July through early September led to a massive harmful algal bloom (HAB) of *Heterosigma akashiwo*, an invasive species of marine algae. This bloom spread from southern and central San Francisco Bays into San Pablo Bay, making it the largest in recorded history and killing tens of thousands of fish (Ocean Protection Council 2022).

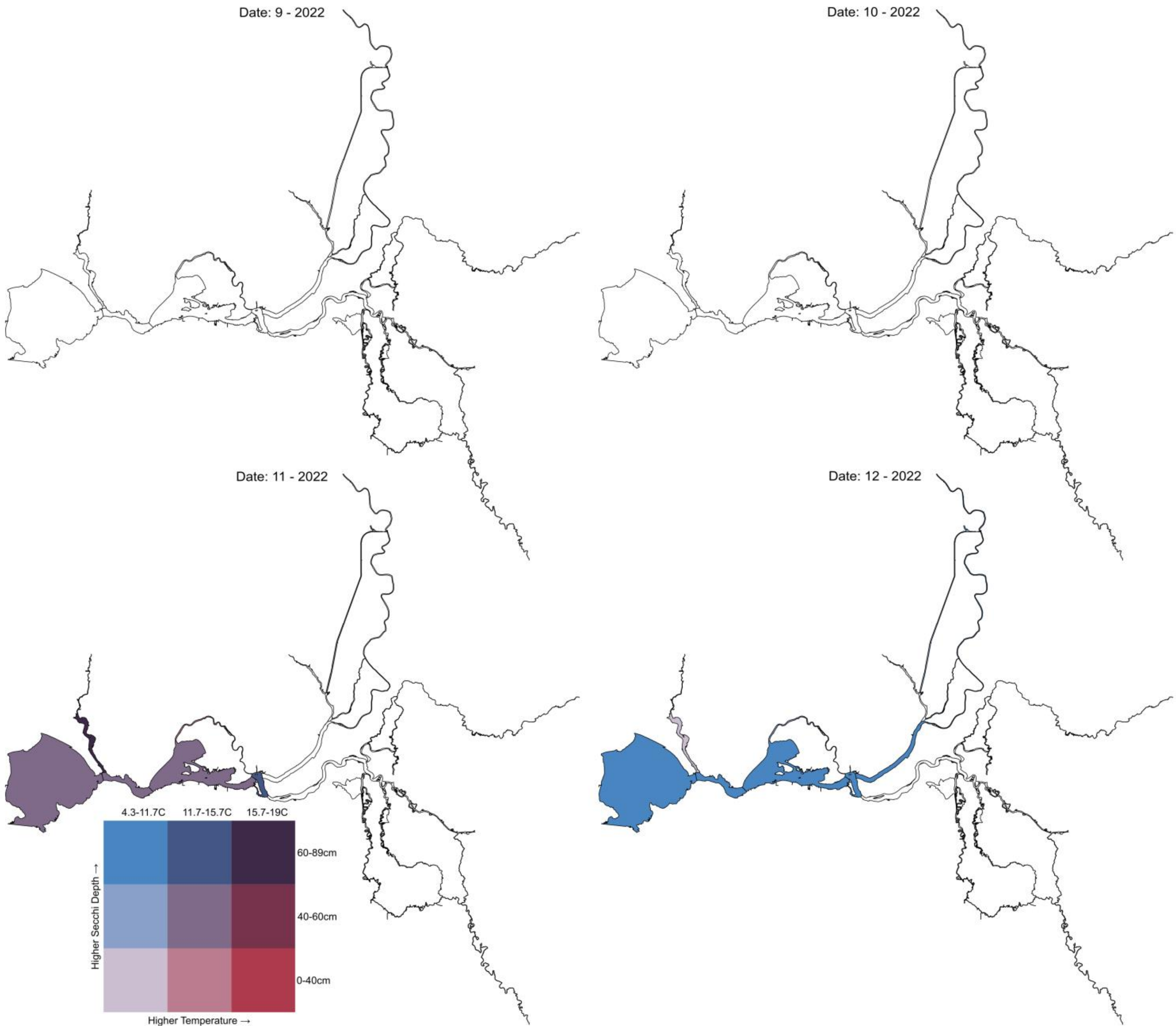
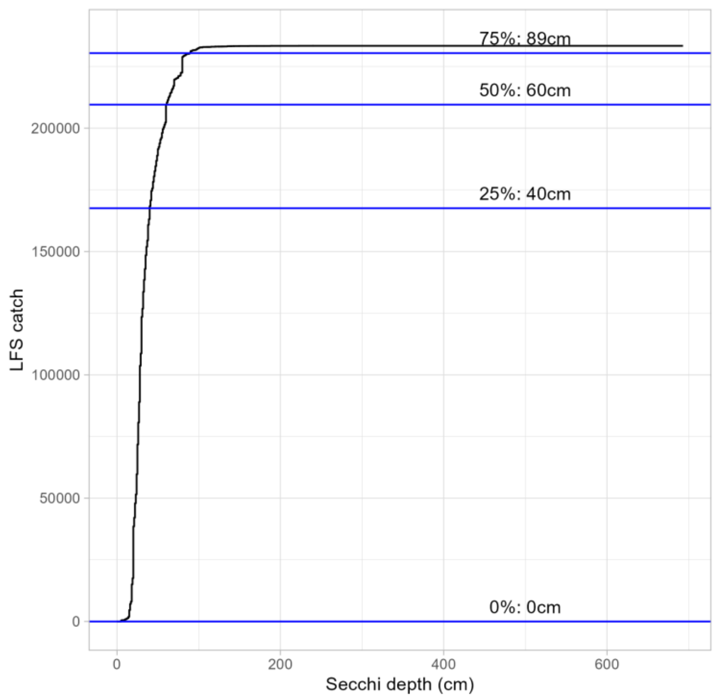


Figure 9. Map showing Longfin Smelt habitat suitability across each month of FMWT sampling in 2022 according to historical catch. White regions indicate values were out of suitable range. The habitat suitability was limited throughout the estuary until November, when regions downstream of the confluence reached a moderate range of suitability. By December, most of the estuary was suitable except for the eastern Delta.



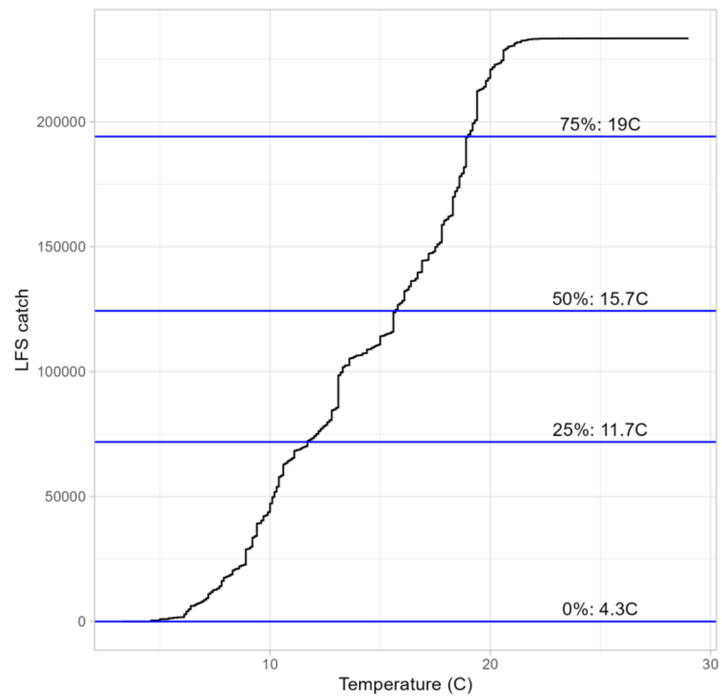


Figure 10. Cumulative frequency distributions of FMWT Longfin Smelt catch from 1967-2022 with abiotic variables. Left: Associated Secchi depth (cm) with catch and quartile values. Right: Associated surface water temperature (C) with catch and quartile values.

Salinity

In the San Francisco upper estuary, the low-salinity zone (LSZ, salinity 0.5-6 ppt) is recognized as an important nursery habitat for young fishes, partially due to the relatively high abundances of their zooplanktonic prey (Kimmerer 2002 a; Kimmerer 2002 b; Bennett 2005) and correlation with water clarity (Kimmerer et al. 1998; Schoellhamer 2000). A few species in the estuary have been documented to modify migration behavior to stay in this preferred salinity zone under different hydrodynamic conditions (Bennett et al. 2002; Kimmerer 2002 a; Kimmerer 2002 b). Temporal variability in freshwater outflow regulates the position of the LSZ (Jassby et al. 1995; Hobbs et al. 2006) which can occur as far west as the Carquinez Strait under high outflow or as far east as the lower Sacramento River and Delta under low outflow conditions (Hobbs et al. 2006). The heatmap and boxplot of salinity values observed during the 2022 FMWT showed this LSZ largely remained inland, in Montezuma Slough, at the confluence of the Sacramento and San Joaquin rivers, and the eastern Delta (Figs. 11 & 12). Carquinez Strait and western Suisun Bay had moderate salinity levels which remained consistent all four months. This corresponds well with the low outflow observed during this period of a “Critical” water year as classified by the Department of Water Resources.

Most stations did not have extreme differences in salinity between the surface and bottom sections of the water column (Fig. 13). However, there was some slight stratification at a few stations in mid San Pablo Bay in October and Carquinez Strait and Suisun Bay November and December. These comparisons do not account for the water depth or tidal condition at the time of sampling.

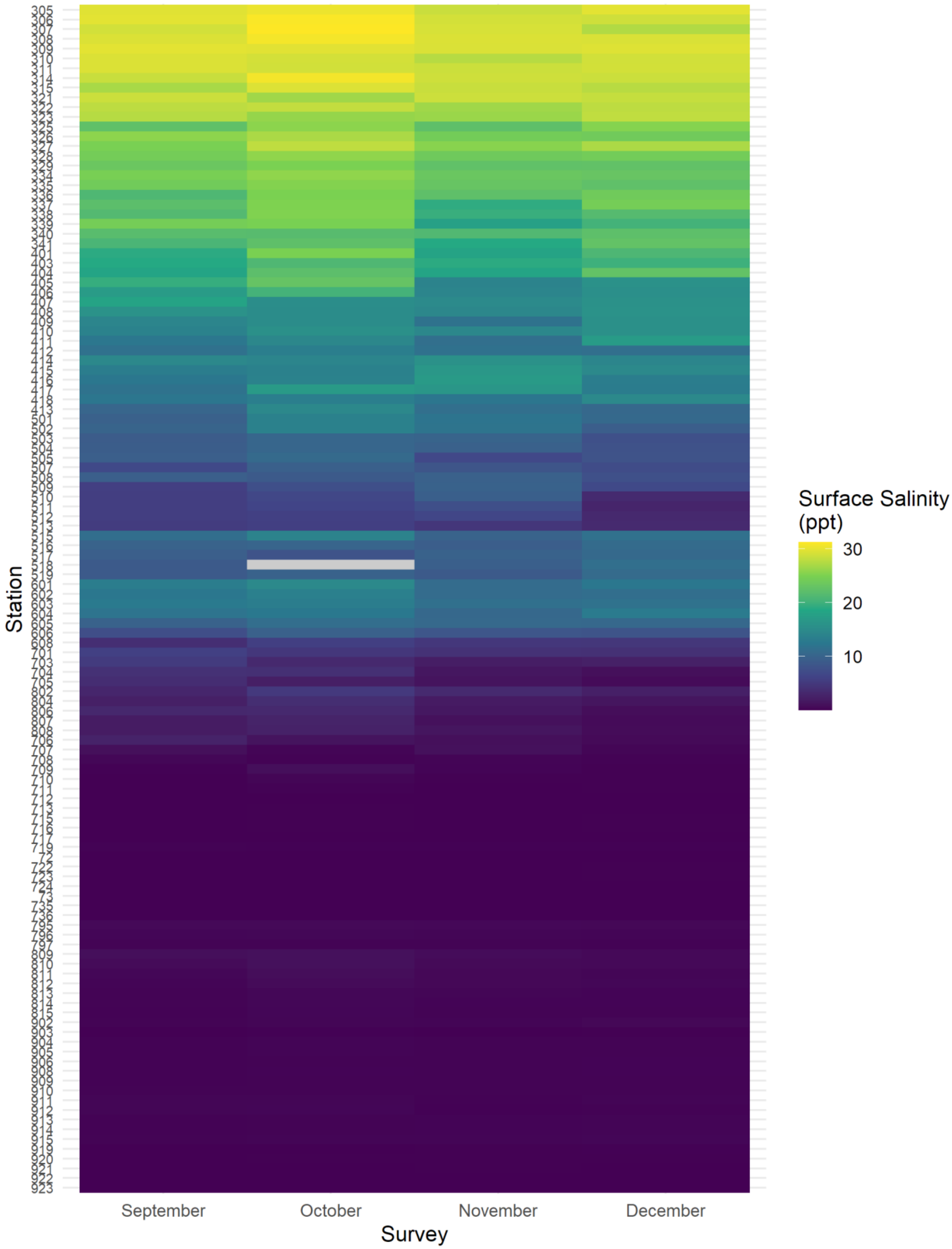


Figure 11. Heatmap of monthly surface water salinity (ppt) recorded during the 2022 FMWT season. White values indicate missing data. The low salinity zone (0.5-6 ppt, dark purple stations) stayed inland upstream of the confluence of the San Joaquin and Sacramento Rivers.

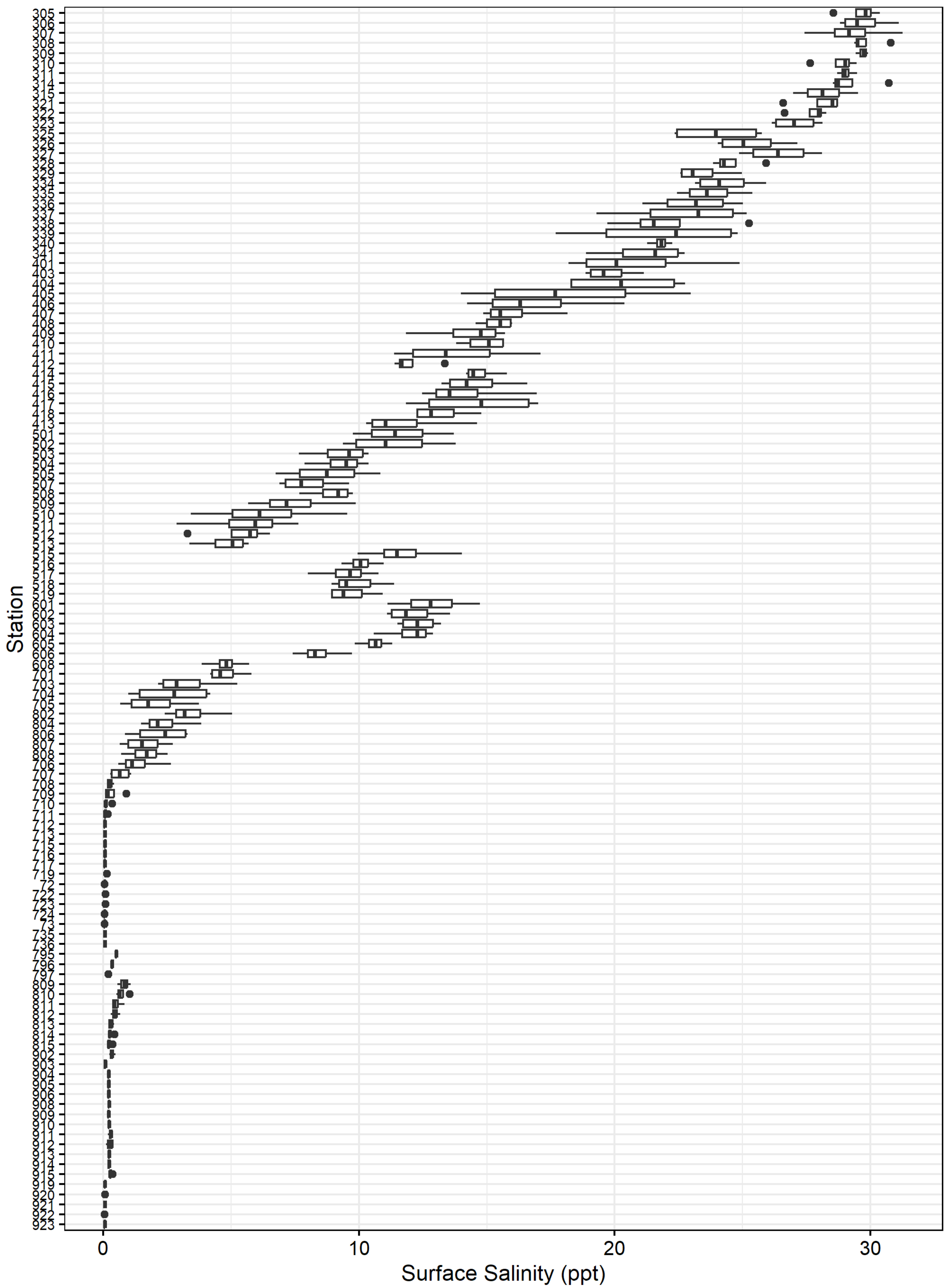


Figure 12. Distribution of monthly surface salinity (ppt) recorded during the 2022 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

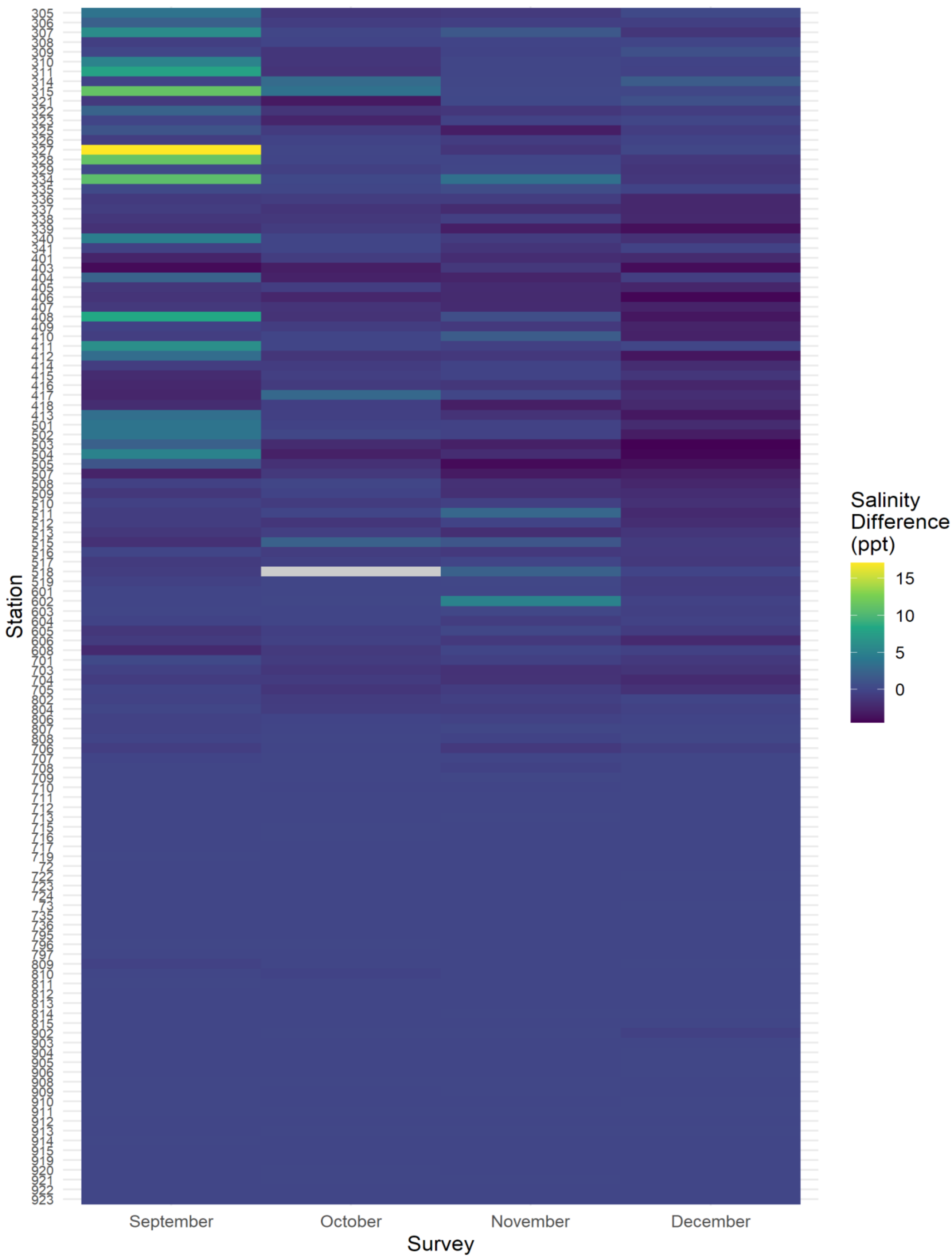


Figure 13. Heatmap of salinity (ppt) differences between surface and bottom water recorded during the 2022 FMWT season. White values indicate missing data. Negative (blue to purple) values are higher salinity on the bottom compared to the surface. Positive (green to yellow) values indicate higher salinity at the surface.

Microcystis

The colonial cyanobacteria *Microcystis aeruginosa* was first discovered in the San Francisco Bay estuary in the early 2000s (Lehman et al. 2005). *Microcystis* in high abundance has toxic effects on the local food web, accumulating in dominant zooplankton species (Ger et al. 2010) and bioaccumulating up the trophic levels to predatory fish (Lehman et al. 2010). *Microcystis* becomes seasonally abundant during periods of low water flow and high water temperature (Lehman et al. 2008). FMWT assigns a qualitative rank of 1-5 based on visual inspection for flakes (Fig. 14; Morris and Civiello (2013)). During the 2022 FMWT survey, *Microcystis* was found to be in low abundance at stations throughout Suisun Bay and the southern and eastern Delta in September and October (Fig. 15). By November, only a handful of stations in the southern Delta still had low *Microcystis* levels. In December, the estuary was cool enough that *Microcystis* was not detected anywhere.

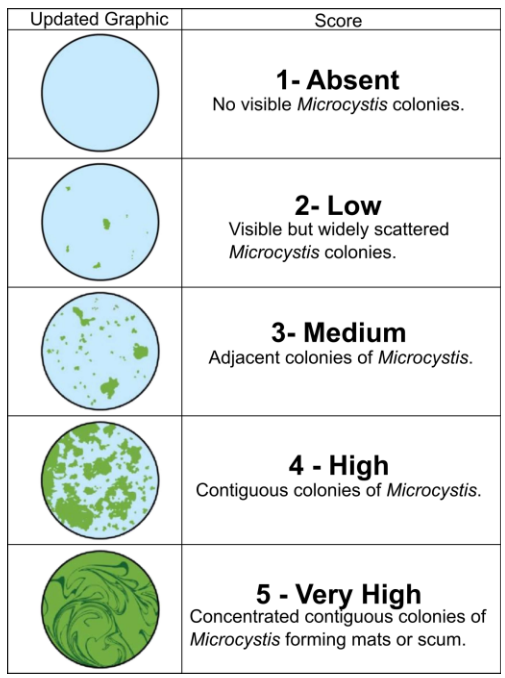


Figure 14. Qualitative rankings used to assess *Microcystis aeruginosa* blooms on the water surface.

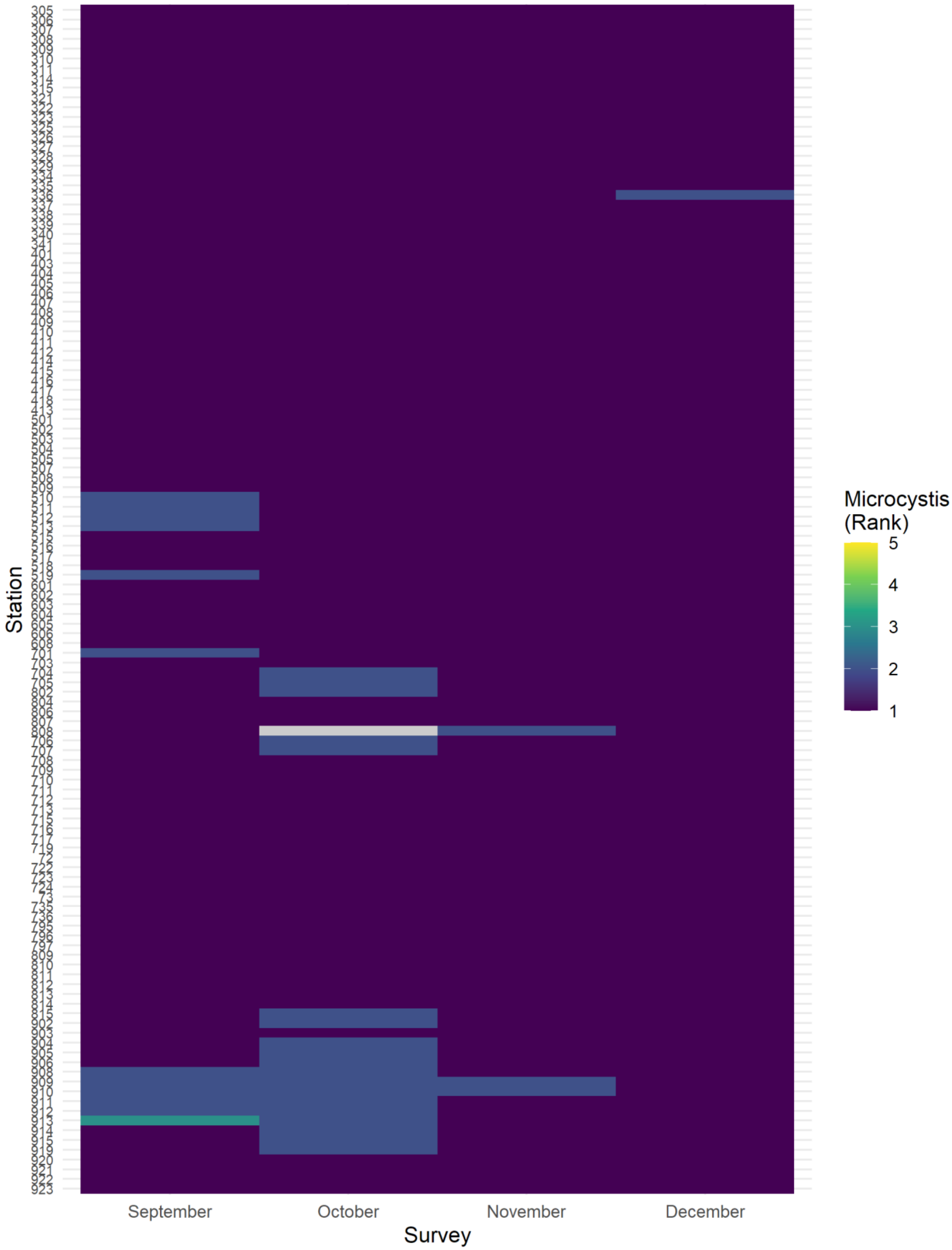


Figure 15. Heatmap of *Microcystis spp.* rankings recorded during the 2022 FMWT season. White values indicate missing data. Scale is a qualitative assessment of *Microcystis* density.

Fish & Invertebrate Catch

Fish

The FMWT survey records all species of fish and macro-invertebrates (i.e. shrimp, crabs, and jellies) caught in the trawl net having recorded over 100 different species to date. Since the onset of the Pelagic Organism Decline (Sommer et al. 2007) in the early 2000s, catch has been concentrated in a few regions of the estuary by a few abundant species. During 2022, Northern Anchovy (*Engraulis mordax*) in San Pablo Bay made the majority of our catch (Fig. 16, Table 2). An unusually large catch of Plainfin Midshipman (*Porichthys notatus*) at a handful of stations in San Pablo Bay in October made this species our second highest catch for the season. Threadfin Shad was the third most abundant species, mostly caught in the DWSC (Stations 795 & 796), which have only been sampled since 2009 (Fig. 17). With more years of sampling, this region will likely overtake San Pablo Bay to become the most abundant region. Other relatively abundant species include American Shad (Table 3). Other species were caught but comprised less than 1% of the total catch for the year. Lumping the fish species by those used for index calculations, again one can see Threadfin Shad catch in September, October, and December in the DWSC comprised most of index species catch (Fig. 16).

The relative abundance and spatial distribution of the species caught is likely related to their life histories. For example, Northern Anchovy are marine opportunists that can occur in brackish waters (Moyle 2002), so with 2022 being critically dry with low outflow, the salinity field was distributed well into San Pablo Bay. Likewise, Threadfin Shad are freshwater opportunists (Moyle 2002) and were more abundant in freshwater regions such as the DWSC.

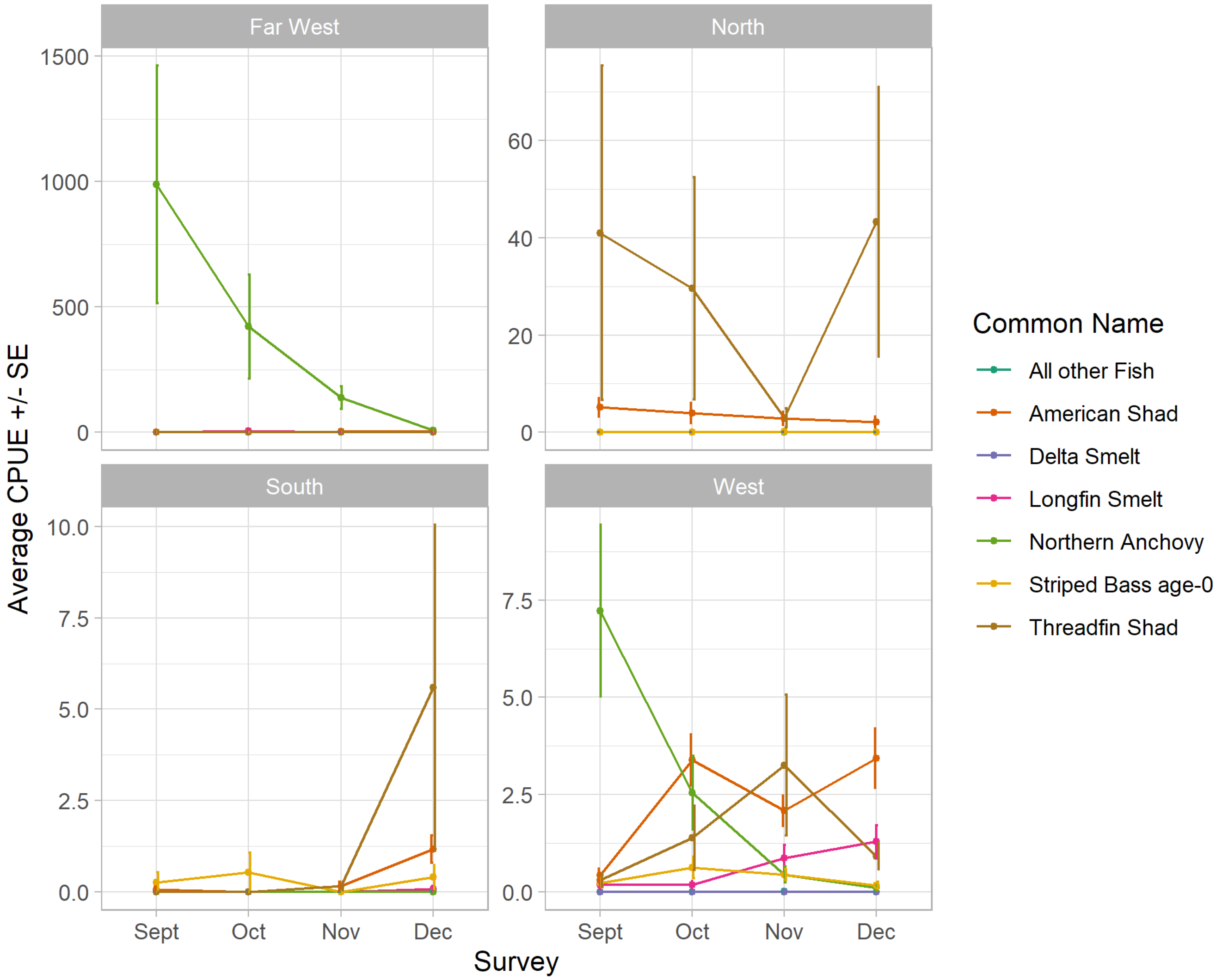


Figure 16. Regional fish catch for the 2022 FMWT survey organized by species used for index calculations. Lines represent monthly average catch per unit effort (CPUE) values and error bars represent +/- standard error. Number of stations per region varies; Far West (n=41), North (n=22), South (n=25), West (n=34).

Table 3. Total monthly fish catch during the 2022 FWMT season.

Species	September	October	November	December	Total	Total percent
Northern Anchovy	24,287	10,707	3,205	176	38,375	89.8
Plainfin Midshipman	15	1,716	15	0	1,746	4.1
Threadfin Shad	501	369	100	581	1,551	3.6
American Shad	111	153	148	170	582	1.4
Longfin Smelt	5	99	29	54	187	0.4
Striped Bass age-0	13	26	11	10	60	0.1
Chinook Salmon	0	1	0	29	30	0.1
Jacksmelt	11	13	5	1	30	0.1
Striped Bass age-1	4	9	13	1	27	0.1
Wakasagi	15	1	7	2	25	0.1
Topsmelt	6	6	5	4	21	0.0
White Catfish	3	2	1	10	16	0.0
Pacific Herring	10	2	1	2	15	0.0
Shiner Perch	1	2	4	2	9	0.0
Goby (unid)	6	0	0	0	6	0.0
Striped Bass age-2	0	3	2	1	6	0.0
Mississippi Silverside	0	1	0	4	5	0.0
Yellowfin Goby	3	0	1	1	5	0.0
Redear Sunfish	1	0	1	2	4	0.0
Bluegill	1	0	1	1	3	0.0
California Halibut	0	1	2	0	3	0.0
Hitch	0	2	0	1	3	0.0
Starry Flounder	1	1	1	0	3	0.0
Bat Ray	1	1	0	0	2	0.0
Chameleon Goby	0	2	0	0	2	0.0
Speckled Sanddab	0	0	2	0	2	0.0
Black Crappie	0	0	0	1	1	0.0
Channel Catfish	0	0	0	1	1	0.0
Rainwater Killifish	1	0	0	0	1	0.0
Sacramento Pikeminnow	0	0	0	1	1	0.0
Sacramento Sucker	0	0	0	1	1	0.0
Spotted Bass	0	1	0	0	1	0.0
Striped Bass age-3+	0	0	1	0	1	0.0

Invertebrates

Similarly, the invertebrate catch was dominated by catch of the Siberian prawn (*Exopalaemon modestus*) followed by *Crangon* shrimp which were mostly caught in the DWSC and together comprised 82% of total catch (Table 3, Fig. 18). However, a high catch of *Crangon* and *Palaemon* shrimp in October at a single station in San Pablo Bay was notable. Otherwise, *Maeotias* jellies were the third most abundant species caught. Other species comprised less than 6% of the total catch.

Again, life histories of the invertebrates caught likely explain their spatial distribution within the estuary. The Siberian prawn historically has been found estuary-wide, but tends to be found in lower salinity habitat than other shrimps (Brown and Hieb 2014). *Crangon* shrimp generally are associated with brackish water but can tolerate freshwater (Hatfield 1985). *Maeotias* jellies are considered a brackish species but can tolerate a wide range of temperature and salinity conditions. Increased *Maeotias* abundance, later bloom termination, and increased duration of medusae bloom are associated with conditions of low to moderate salinity (<1-10 ppt) and higher temperatures (≥19°C; Schroeter (2008)) which may explain their high abundance in the DWSC in September and October.

Table 4. Total monthly invertebrate catch during the 2022 FWMT season.

Species	September	October	November	December	Total	Total percent
Exopalaemon modestus	3,513	4,174	762	148	8,597	57.7
Crangon spp.	312	3,164	181	52	3,709	24.9
Maeotias spp.	674	426	74	3	1,177	7.9
Palaemon spp.	90	405	239	21	755	5.1
Pleurobrachia spp.	0	0	2	525	527	3.5
Polyorchis spp.	0	1	0	69	70	0.5
Aurelia labiata	14	23	3	2	42	0.3
Shrimp (unid)	17	0	1	0	18	0.1
Jellyfish	0	0	2	0	2	0.0

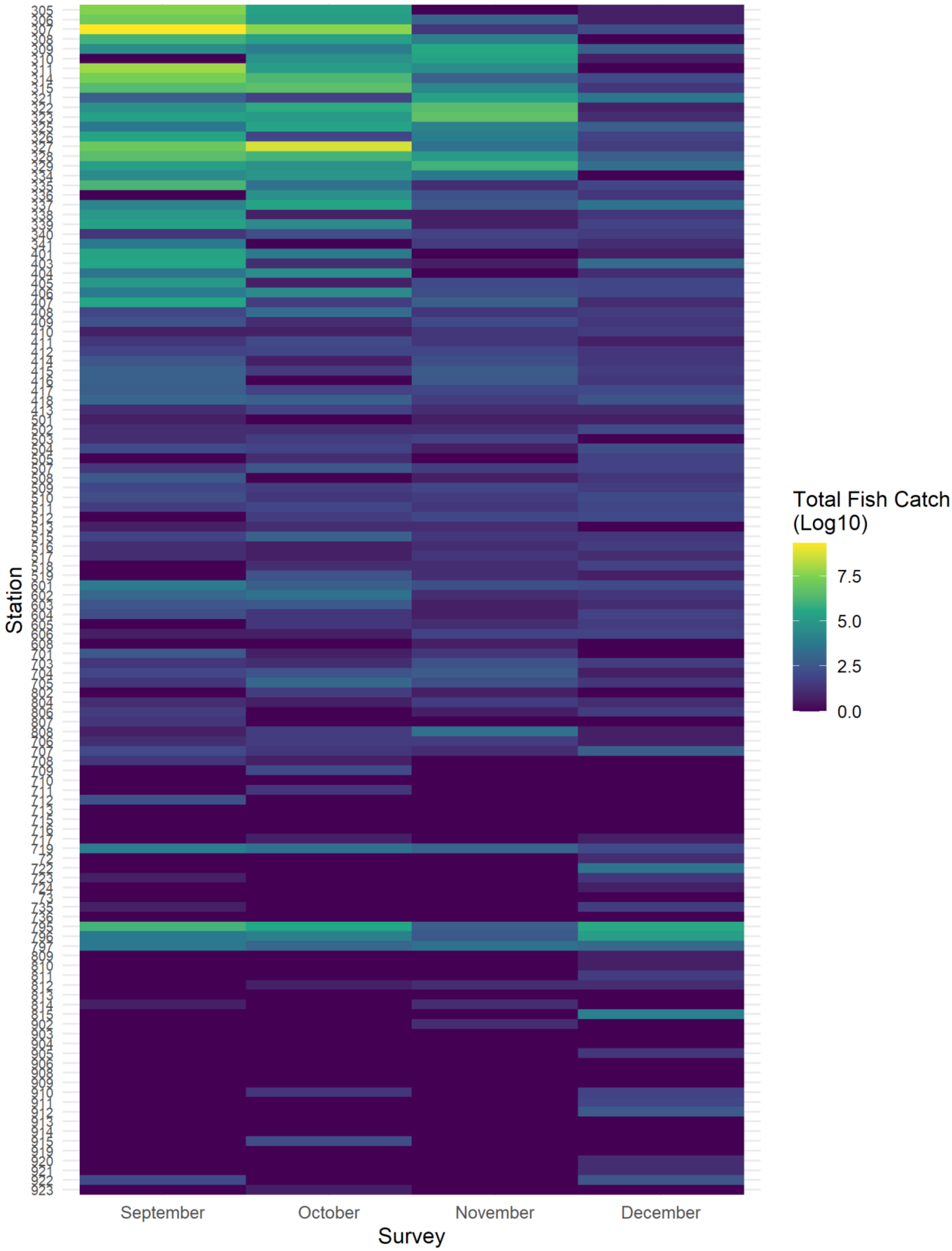


Figure 17. Heatmap of $\log_{10}(x+1)$ total fish catch by station recorded during the 2022 FMWT season. White values indicate missing data. San Pablo Bay and the northern part of the DWSC had the highest fish catch.

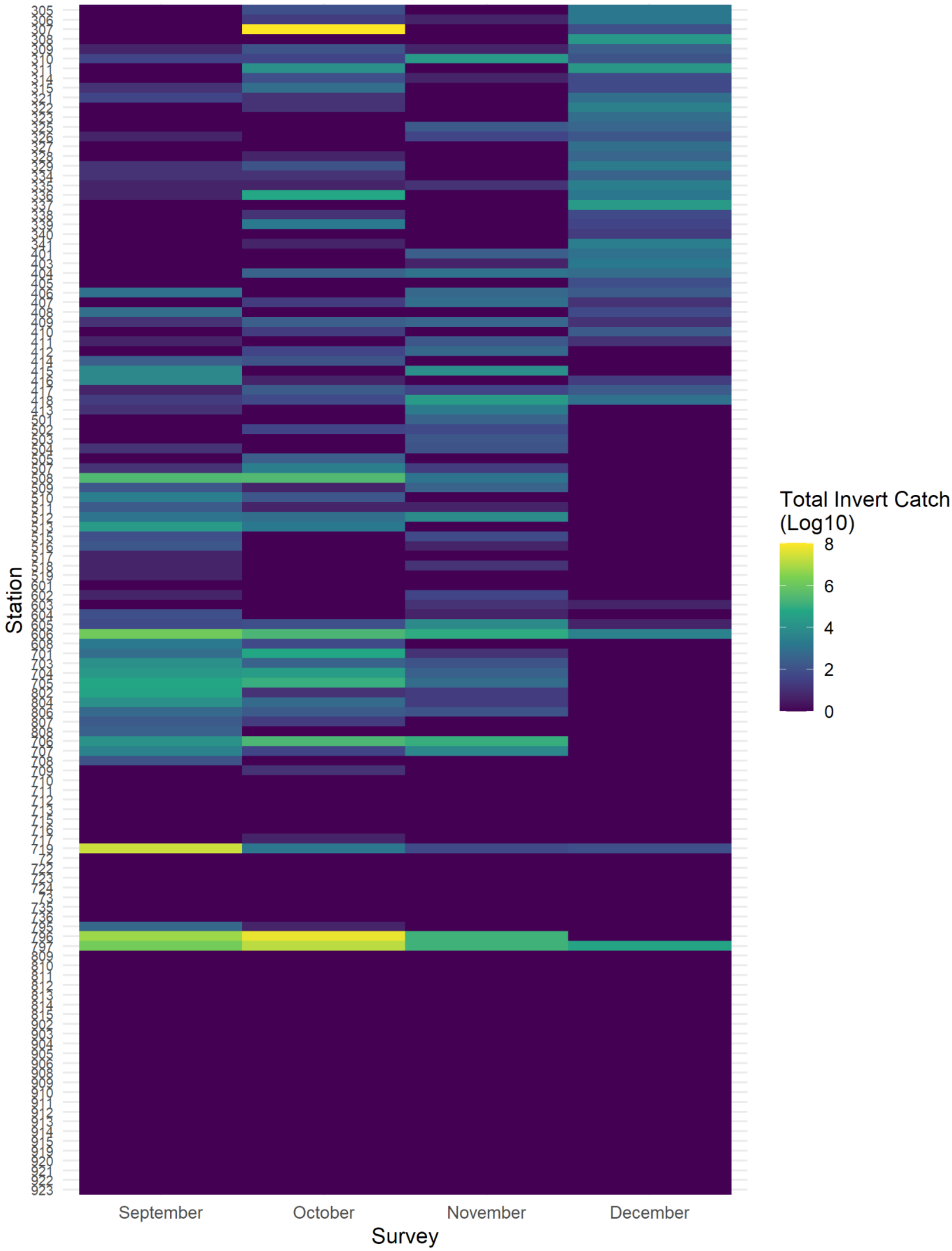


Figure 18. Heatmap of $log_{10}(x+1)$ total invertebrate catch by station recorded during the 2022 FMWT season. White values indicate missing data. The northern part of the DWSC and a single station in San Pablo Bay had the highest invertebrate catch.

Outflow relationships

The FMWT catch patterns observed in the estuary are in part driven by the relationship between their life history and seasonal environmental factors. Specifically, the relationship between the timing of the larval stage and the outflow of water through the estuary has historically been used as a tool to examine relationships in relative fish abundance and distribution (Bay-Delta Region et al. 2010). Outflow is closely associated with environmental variables such as salinity (of particular interest is X_2, which is the distance from the Golden Gate Bridge in river kilometers to the location of salinity at 2 ppt one meter above the bottom) (Jassby et al. 1995), water clarity, and planktonic food availability (Alpine and Cloern 1992; Kimmerer 2002 a; Bay-Delta Region et al. 2010; Feyrer et al. 2011; Cloern et al. 2017). Therefore, outflow has a strong effect on habitat suitability and survival for larval fish (Baxter 1999; Dege and Brown 2004).

Here, I have updated abundance-outflow relationship plots used in previous CDFW reports with up-to-date data and grouped years based on the introduction of the invasive clam, *Potamocorbula amurensis* (Alpine and Cloern 1992; Kimmerer et al. 1994), and the start of the Pelagic Organism Decline (Sommer et al. 2007). Daily total outflow was averaged by month then by selective periods (months when specific fish species are known to be in their spawning and nursery stages). Descriptive metadata and raw data are available from the Dayflow website (California Natural Resources Agency 2002). FMWT abundance indices (calculated from catch at the 100 index stations) were used for outflow relationship comparisons for age-0 Striped Bass, American Shad, and Longfin Smelt. Both outflow and index values were $\log_{10}$ transformed. While much of California received unusually high precipitation in late December and early January 2023 due to a series of atmospheric rivers, this came after completion of FMWT and is not reflected in the data here.

In 2022, California was in a continuing multi-year drought, marked by record low precipitation and corresponding low outflow. As such, the corresponding catch of age-0 Striped Bass was very low as well. This linear positive relationship between outflow and Striped Bass catch during their spawning and nursery periods has been a consistent and statistically significant trend since the Pelagic Organism Decline (POD) began around 2002 (Fig. 19). Interestingly, this pattern was also significant for the time period before introduction of the over-bite clam, *Potamocorbula amurensis*, but not during the years after clam introduction and before the POD. This pattern suggests outflow is one of many important factors in influencing Striped Bass abundance. Kimmerer et al. (2009) found that Striped Bass survival, abundance, and habitat all increased as X_2 location moved downstream, suggesting the location of X_2 is the mechanism driving the relationship between outflow and abundance.

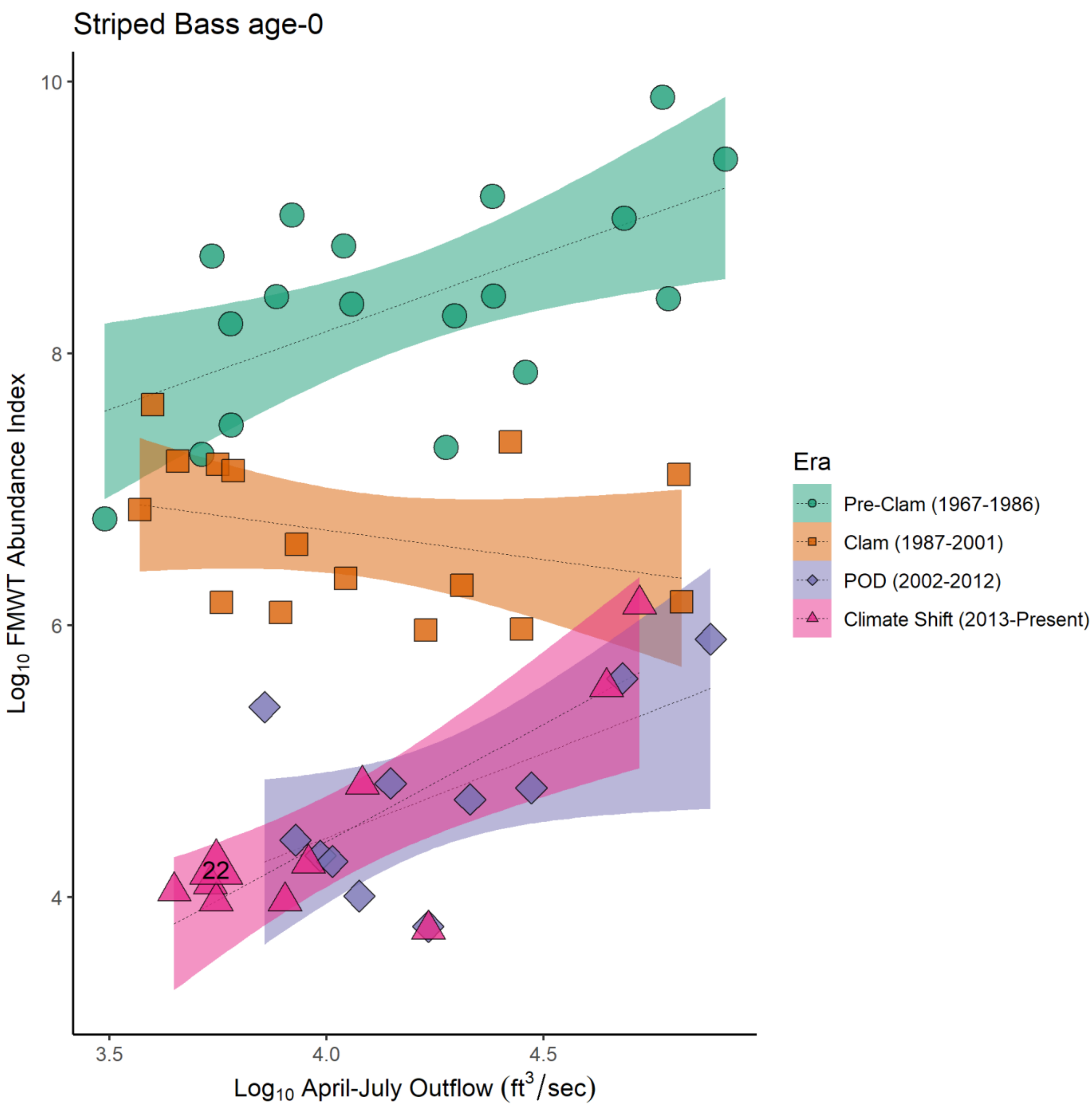


Figure 19. Relationship between $\log_{10}$ transformed age-0 Striped Bass FMWT abundance index and the $\log_{10}$ transformed monthly average of daily April-July Delta outflow (ft^3/sec) for the year 2022 (labeled pink triangle) compared to the years 1967-1987 (Pre-Clam; green circle), 1988-2001 (Clam; orange square), 2002-2012 (Pelagic Organism Decline; purple diamond), and years 2002-2021 (Climate Shift; pink triangle).

Similarly, American Shad showed the same linear positive relationship between outflow and abundance, but with 2022 showing a pattern of low outflow and higher than expected relative abundance compared to other Climate Shift years (Fig. 20). American Shad also shows the same pattern of this relationship not being significant during the post-clam years. Like Striped Bass, American Shad have been previously shown to have similar outflow to abundance relationships driven by X_2 influencing available habitat (Kimmerer et al. 2009).

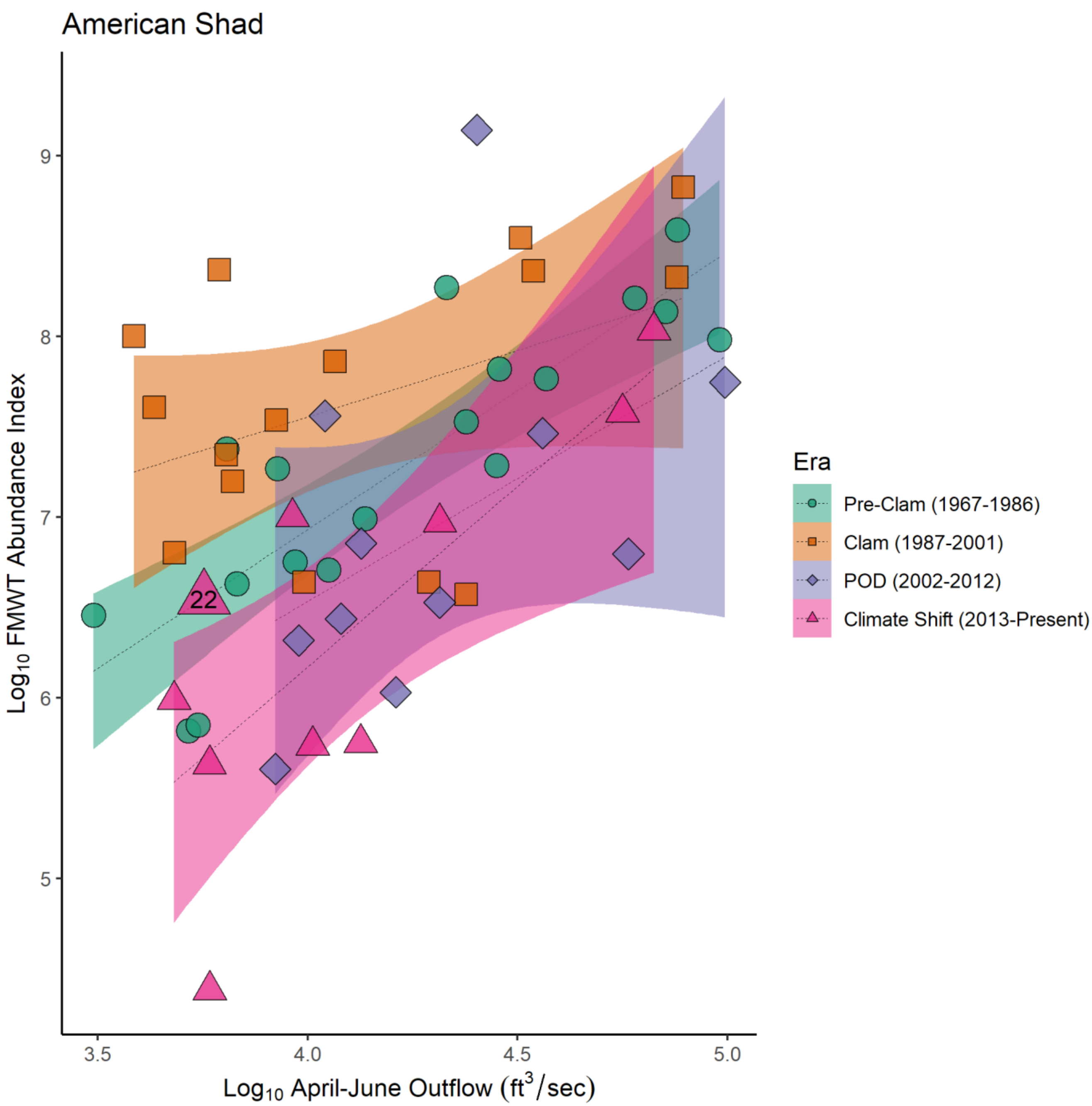
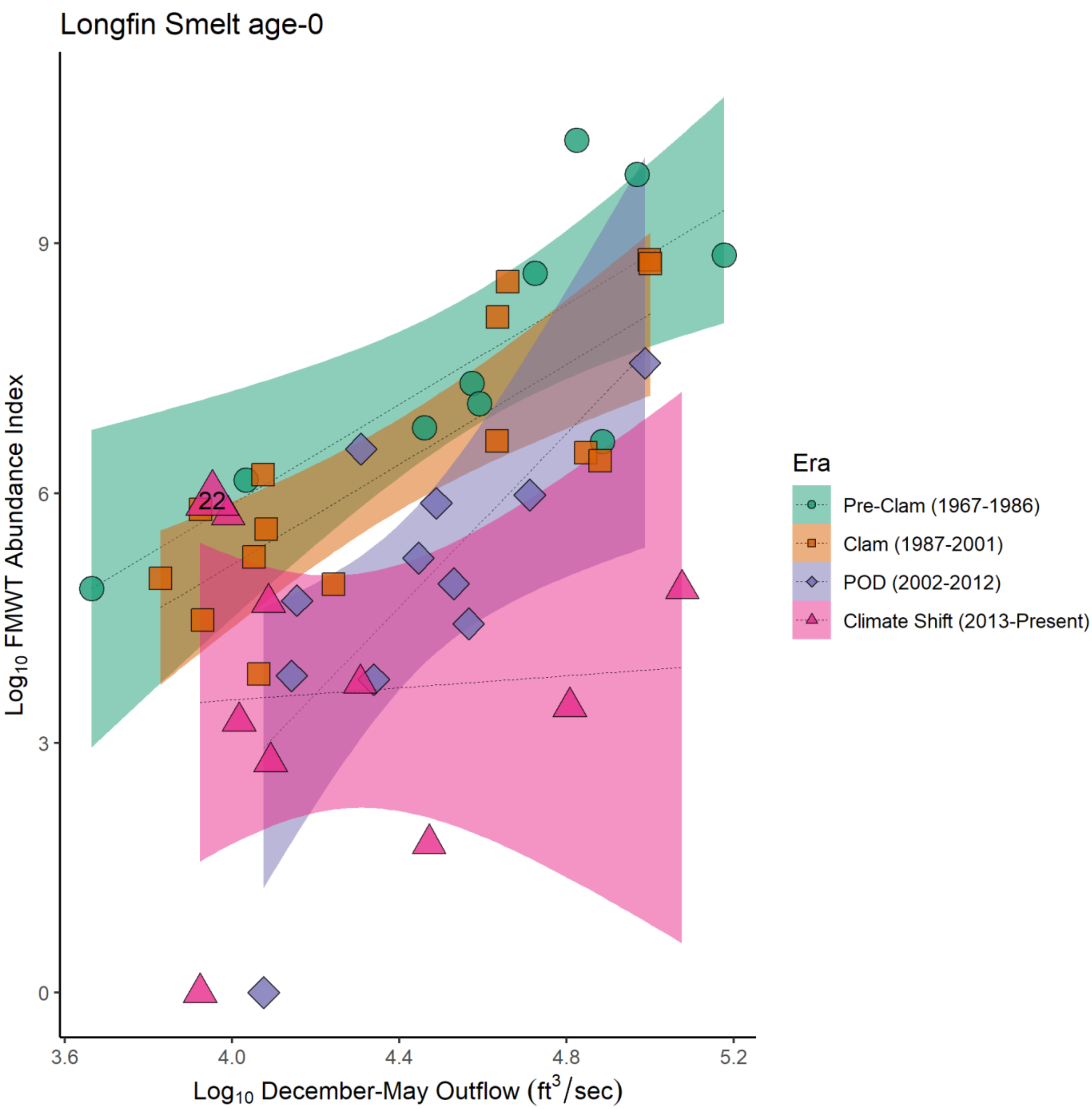


Figure 20. Relationship between $\log_{10}$ transformed American Shad FMWT abundance index and the $\log_{10}$ transformed monthly average of daily April-August Delta outflow (ft^3/sec) for the year 2022 (labeled pink triangle) compared to the years 1967-1987 (Pre-Clam; green circle), 1988-2001 (Clam; orange square), 2002-2012 (Pelagic Organism Decline; purple diamond), and years 2002-2021 (Climate Shift; pink triangle).

Longfin Smelt relative abundance has shown a consistent positive linear relationship with outflow across the POD and Pre-Clam eras. The 2022 abundance was high when compared the 2022 Water Year low outflow, putting it on par with Pre-Clam years (Fig. 21). However, the most recent available outflow dataset is from the 2022 Water Year, which ran from October 1st, 2021 through September 30th, 2022, so the 2022 Longfin Smelt relative abundance and outflow relationship is not represented well here. According to Kimmerer et al. (2009), the mechanism driving the earlier observed relationship between Longfin Smelt abundance and outflow is because ideal larval and early juvenile habitat is largely determined by salinity and Secchi depth, which are both functions of outflow (Bay-Delta Region et al. 2010).



#

Figure 21. Relationship between $\log_{10}$ transformed Longfin Smelt FMWT abundance index and the $\log_{10}$ transformed monthly average of daily December-May Delta outflow (ft^3/sec) for the year 2022 (labeled pink triangle) compared to the years 1967-1987 (Pre-Clam; green circle), 1988-2001 (Clam; orange square), 2002-2012 (Pelagic Organism Decline; purple diamond), and years 2002-2021 (Climate Shift; pink triangle).

Acknowledgments

This work was conducted under the auspices of the Interagency Ecological Program. Funding for the Fall Midwater Trawl study was supported by contracts with the Department of Water Resources and the US Bureau of Reclamation. We thank all personnel involved in this project in 2022: Andrew Amaral, Denisse Anaya, Spencer Breining-Aday, Darian Dungey, Ken Flowers, Mike Grady, Dave Hull, Margaret Johnson, Kevin Juranek, Spencer Lewis, Trevin Li, Zach Liddle, Allegra Rocha, Paul Macias, Tim Malinich, Steven Slater, Phil Smith, Ramiro Soto, and Nene Ugbah. Their hard work and dedication to accurate and timely data collection has provided continued success for this long-running survey.

References

Alpine A, Cloern J. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography. 37(5):946–955. doi:czkmzw. https://onlinelibrary.wiley.com/doi/abs/10.4319/lo.1992.37.5.0946.

Baker P, Ligon F, Speed T. 1995. Estimating the influence of temperature on the survival of Chinook salmon smolts (*Oncorhynchus tshawytscha*) migrating through the Sacramento–San Joaquin River Delta of California. Canadian Journal of Fisheries and Aquatic Sciences. 52(4):855–863. doi:c9p7fb.

Baxter R. 1999. Report on the 1980-1995 fish, shrimp, and crab sampling in the San Francisco Estuary, California. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Report No.: 63. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt091412/sldmwa/baxter_dfg_1999.pdf.

Baxter R, Breuer R, Brown L, Conrad L, Feyrer F, Fong S, Gehrts K, Grimaldo L, Herbold B, Hrodey P, et al. 2010. Interagency ecological program 2010 pelagic organism decline work plan and synthesis of results. California Department of Water Resources. http://www.science.calwater.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf.

Bay-Delta Region, Fisheries Branch, Water Branch. 2010. Effects of Delta Inflow and Outflow on Several Native, Recreational, and Commercial Species. Sacramento, CA: California Department of Fish and Game Prepared for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources Before the State Water Resources Control Board Report No.: DFG Exhibit 1.

Bennett W. 2005. Critical assessment of the delta smelt population in the San-Francisco Estuary, California. San Francisco Estuary and Watershed Science. 3(2):1–71. doi:10.15447/sfews.2005v3iss2art1. https://doi.org/10.15447/sfews.2005v3iss2art1.

Bennett W, Kimmerer W, Burau J. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. Limnology and Oceanography. 47(5):1496–1507. doi:fwt4hg.

Brown T, Hieb K. 2014. Status of the Siberian Prawn, *Exopalaemon modestus*, in the San Francisco Estuary. San Francisco Estuary and Watershed Science. 12(1). doi:gmbmr6. https://escholarship.org/uc/item/36t046cq.

California Natural Resources Agency. 2002. Dayflow. https://data.cnra.ca.gov/dataset/dayflow.

Cloern J, Jassby A, Schraga T, Nejad E, Martin C. 2017. Ecosystem variability along the estuarine salinity gradient: Examples from long-term study of San Francisco Bay. Limnol Oceanogr. 62(S1). doi:gcn9t5. https://onlinelibrary.wiley.com/doi/10.1002/lno.10537.

Clutton-Brock T, Sheldon B. 2010. Individuals and populations: the role of long-term, individual-based studies of animals in ecology and evolutionary biology. Trends in ecology & evolution. 25(10):562–573. doi:cbdd3b.

Cody M, Smallwood J. 1996. Long-term studies of vertebrate communities. Academic Press.

Dege M, Brown L. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. In: Feyrer F, Brown L, Orsi J, editors. American Fisheries Society Symposium. Vol. 2004. Bethesda, Maryland: American Fisheries Society. p. 49–65. http://pubs.er.usgs.gov/publication/70026240.

Ducklow H, Doney S, Steinberg D. 2009. Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. Annual Review of Marine Science. 1:279–302. doi:d2dmm5.

Feyrer F, Newman K, Nobriga M, Sommer T. 2011. Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. Estuaries and Coasts. 34(1):120–128. doi:dxn6zd.

Feyrer F, Nobriga M, Sommer T. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Can J Fish Aquat Sci. 64(4):723–734. doi:10.1139/f07-048. [accessed 2020 Apr 27]. https://doi.org/10.1139/f07-048.

Ger K, Teh S, Baxa D, Lesmeister S, Goldman C. 2010. The effects of dietary *Microcystis aeruginosa* and microcystin on the copepods of the upper San Francisco Estuary. Freshwater Biology. 55(7):1548–1559. doi:dpd87n. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2427.2009.02367.x.

Grimaldo L, Feyrer F, Burns J, Maniscalco D. 2017. Sampling uncharted waters: Examining rearing habitat of larval longfin smelt (*Spirinchus thaleichthys*) in the upper San Francisco Estuary. Estuaries and Coasts. 40(6):1771–1784. doi:gb29xn.

Hatfield S. 1985. Seasonal and interannual variation in distribution and population abundance of the shrimp *Crangon franciscorum* in San Francisco Bay. In: Cloern J, Nichols F, editors. Temporal Dynamics of an Estuary: San Francisco Bay. Dordrecht: Springer Netherlands. (Developments in Hydrobiology). p. 199–210. https://doi.org/10.1007/978-94-009-5528-8_12.

Hobbs J, Bennett W, Burton J. 2006. Assessing nursery habitat quality for native smelts (Osmeridae) in the low-salinity zone of the San Francisco estuary. Journal of Fish Biology. 69(3):907–922. doi:https://doi.org/10.1111/j.1095-8649.2006.01176.x. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1095-8649.2006.01176.x.

Hobbs J, Moyle P. 2015. Last Days of the Longfin? https://www.newsdeeply.com/water/community/2015/09/08/last-days-of-the-longfin.

Hofmann G, Blanchette C, Rivest E, Kapsenberg L. 2013. Taking the pulse of marine ecosystems: The importance of coupling long-term physical and biological observations in the context of global change biology. Oceanography. 26(3):140–148. doi:f4899f.

Hughes B, Beas-Luna R, Barner A, Brewitt K, Brumbaugh D, Cerny-Chipman E, Close S, Coblentz K, de Nesnera K, Drobnitch S, et al. 2017. Long-Term Studies Contribute Disproportionately to Ecology and Policy. BioScience. 67(3):271–281. doi:f9x4pb. https://doi.org/10.1093/biosci/biw185.

Jassby A, Kimmerer W, Monismith S, Armor C, Cloern J, Powell T, Schubel J, Vendlinski T. 1995. Isohaline Position as a Habitat Indicator for Estuarine Populations. Ecological Applications. 5(1):272–289. doi:10.2307/1942069. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.2307/1942069.

Jeffries K, Connon R, Davis B, Komoroske L, Britton M, Sommer T, Todgham A, Fangue N. 2016. Effects of high temperatures on threatened estuarine fishes during periods of extreme drought. Journal of Experimental Biology. 219(11):1705–1716. doi:f8p7p5. https://jeb.biologists.org/content/219/11/1705.

Kimmerer W. 2002 a. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? Marine Ecology Progress Series. 243:39–55. doi:10.3354/meps243039. https://www.jstor.org/stable/24866158.

Kimmerer W. 2002 b. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. Estuaries. 25(6):1275–1290. doi:10.1007/bf02692224. https://doi.org/10.1007/BF02692224.

Kimmerer W, Burau J, Bennett W. 1998. Tidally oriented vertical migration and position maintenance of zooplankton in a temperate estuary. Limnology and Oceanography. 43(7):1697–1709. doi:b8h3h7. https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.4319/lo.1998.43.7.1697.

Kimmerer W, Gartside E, Orsi J. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Mar Ecol Prog Ser. 113:81–93. doi:ckr5wf. http://www.int-res.com/articles/meps/113/m113p081.pdf.

Kimmerer W, Gross E, MacWilliams M. 2009. Is the Response of Estuarine Nekton to Freshwater Flow in the San Francisco Estuary Explained by Variation in Habitat Volume? Estuaries and Coasts. 32(2):375. doi:c2jwnj. https://doi.org/10.1007/s12237-008-9124-x.

Latour R. 2016. Statistical modeling of delta smelt (*Hypomesus transpacificus*) survey data in the San Francisco-San Joaquin Delta, with reference to temporal and spatial autocorrelation. Hayes, VA: Latour Environmental Consulting Report No.: DWR-1258.

Lehman P, Boyer G, Hall C, Waller S, Gehrts K. 2005. Distribution and toxicity of a new colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California. Hydrobiologia. 541(1):87–99. doi:fwjcbc. https://doi.org/10.1007/s10750-004-4670-0.

Lehman P, Boyer G, Satchwell M, Waller S. 2008. The influence of environmental conditions on the seasonal variation of *Microcystis* cell density and microcystins concentration in San Francisco Estuary. Hydrobiologia. 600(1):187–204. doi:c9wrbw. https://doi.org/10.1007/s10750-007-9231-x.

Lehman P, Teh S, Boyer G, Nobriga M, Bass E, Hogle C. 2010. Initial impacts of *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary. Hydrobiologia. 637(1):229–248. doi:fqsh98. https://doi.org/10.1007/s10750-009-9999-y.

Lewis L, Barros A, Willmes M, Denney C, Parker C, Bisson M, Hobbs J, Finger A, Auringer G, Benjamin A. 2019. Interdisciplinary Studies on Longfin Smelt in the San Francisco Estuary.

Likens G. 2012. Long-term studies in ecology. Springer.

Lindenmayer D, Likens G, Andersen A, Bowman D, Bull C, Burns E, Dickman C, Hoffmann A, Keith D, Liddell M. 2012. Value of long-term ecological studies. Austral Ecology. 37(7):745–757. doi:f2zphv.

Mac Nally R, Thomson J, Kimmerer W, Feyrer F, Newman K, Sih A, Bennett W, Brown L, Fleishman E, Culberson S, et al. 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). Ecological Applications. 20(5):1417–1430. doi:dgm43f. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/09-1724.1.

Magurran A, Baillie S, Buckland S, Dick J, Elston D, Scott E, Smith R, Somerfield P, Watt A. 2010. Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends in ecology & evolution. 25(10):574–582. doi:dqxgb5.

Mahardja B, Tobias V, Khanna S, Mitchell L, Lehman P, Sommer T, Brown L, Culberson S, Conrad J. 2021. Resistance and resilience of pelagic and littoral fishes to drought in the San Francisco Estuary. Ecological Applications. 31(2):e02243. doi:10.1002/eap.2243.

McGowan J. 1990. Climate and change in oceanic ecosystems: the value of time-series data. Trends in ecology & evolution. 5(9):293–299. doi:fgv9wf.

Morris T, Civiello M. 2013. *Microcystis aeruginosa* status and trends during the Fall Midwater Trawl Survey and a comparison to trends in the Summer Townet Survey. IEP Newsletter. 2:33–39.

Moyle P. 2002. Inland fishes of California: revised and expanded. Univ of California Press.

Moyle P, Baxter R, Sommer T, Foin T, Matern S. 2004. Biology and Population Dynamics of Sacramento Splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: A Review. San Francisco Estuary and Watershed Science. 2(2):1–47. doi:10.15447/sfews.2004v2iss2art3. https://escholarship.org/uc/item/61r48686.

Nelson M, Vucetich J, Peterson R, Vucetich L. 2011. The Isle Royale Wolf–Moose Project (1958-present) and the wonder of long-term ecological research. Endeavour. 35(1):31. doi:cbrwv2.

Nobriga M, Sommer T, Feyrer F, Fleming K. 2008. Long-term trends in summertime habitat suitability for delta smelt, *Hypomesus transpacificus*. San Francisco Estuary and Watershed Science. 6(1):13. doi:ggvxdg.

Ocean Protection Council. 2022. Harmful Algal Bloom in San Francisco Bay Results in Aquatic Mortality, Fish Kills. https://www.opc.ca.gov/2022/09/harmful-algal-bloom/.

Polansky L, Mitchell L, Newman K. 2019. Using Multistage Design-Based Methods to Construct Abundance Indices and Uncertainty Measures for Delta Smelt. Transactions of the American Fisheries Society. 148(4):710–724. doi:gf6d7j.

Schoellhamer D. 2000. Influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay. In: McAnally W, Mehta A, editors. Proceedings in Marine Science. Vol. 3. Elsevier. (Coastal and Estuarine Fine Sediment Processes). p. 343–357. https://www.sciencedirect.com/science/article/pii/S1568269200801308.

Schroeter R. 2008. Biology and Long-Term Trends of Alien Hydromedusae and Striped Bass in a Brackish Tidal Marsh in the San Francisco Estuary. University of California, Davis. https://escholarship.org/uc/item/5gh43754.

Sommer T, Armor C, Baxter R, Breuer R, Brown L, Chotkowski M, Culberson S, Feyrer F, Gingras M, Herbold B, et al. 2007. The Collapse of Pelagic Fishes in the Upper San Francisco Estuary: El Colapso de los Peces Pelagicos en La Cabecera Del Estuario San Francisco. Fisheries. 32(6):270–277. doi:d2qrf5. https://doi.org/10.1577/1548-8446(2007)32[270:TCOPFI]2.0.CO;2.

Stevens D. 1977. Striped Bass (*Monrone saxatilis*) monitoring techniques in the Sacramento-San Joaquin Estuary. In: Van Winkle W, editor. Proceedings of the conference on assessing the effects of power-plant-induced mortality on fish populations. New York, New York: Pergamon Press. p. 91–109.

Stevens D, Miller L. 1983. Effects of River Flow on Abundance of Young Chinook Salmon, American Shad, Longfin Smelt, and Delta Smelt in the Sacramento-San Joaquin River System. North American Journal of Fisheries Management. 3(4):425–437. doi:10.1577/1548-8659(1983)3<425:EORFOA>2.0.CO;2.

Swanson C, Reid T, Young P, Cech Jr J. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. Oecologia. 123(3):384–390. doi:ch6dcg.

Tempel T, Malinich T, Burns J, Barros A, Burdi C, Hobbs J. 2021. The value of long-term monitoring of the San Francisco Estuary for Delta Smelt and Longfin Smelt. California Fish and Wildlife Journal.(CESA

Special Issue):148–171. doi:gk55qp.
https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=193400&inline.

Thomson J, Kimmerer W, Brown L, Newman K, Mac Nally R, Bennett W, Feyrer F, Fleishman E. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. Ecological Applications. 20(5):1431–1448. doi:10.1890/09-0998.1.
https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/09-0998.1.

Turner J, Chadwick H. 1972. Distribution and abundance of young-of-the-year striped bass, Morone saxatilis, in relation to river flow in the Sacramento-San Joaquin estuary. Transactions of the American Fisheries Society. 101(3):442–452.

White JR, Baxter RD. 2022. Incorporating expanded sampling into an alternative abundance index for the Fall Midwater Trawl survey. California Fish and Wildlife Journal. 108(4):1–16. doi:10.51492/cfwj.108.21.