Fall Midwater Trawl Survey End of Season Report: 2021

California Department of Fish and Wildlife

Bay Delta Region (Stockton)

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February 8, 2022

Introduction

The Fall Midwater Trawl (FMWT) survey has been conducted by the California Department of Fish and Wildlife (CDFW) since 1967. The survey was established to examine relative abundance and distribution of juvenile (typically 6-14 cm FL) pelagic fish species in the San Francisco estuary, focusing initially on age-0 Striped Bass (Stevens 1977). Striped Bass was the initial focus of the survey because it was considered an important sport fish and there were concerns over the environmental changes in the estuary resulting from the development of federal and state water projects and thus a need to develop operating criteria for the water projects that would minimize damage to the bass populations (Stevens 1977). The sampling range for FMWT was spread throughout the Delta downstream to San Pablo Bay because this was the known nursery area for young Striped Bass (Turner and Chadwick 1972). Later, FMWT developed abundance and distribution information for other upper-estuary pelagic fishes, including American Shad (*Alosa sapidissima*), Threadfin Shad (*Dorasoma petenense*), Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), and Splittail (*Pogonichthys macrolepidotus*). FMWT is among the oldest and 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 better understand the food web dynamics of the local fish community. This additional sampling helps inform if reduced or altered prey abundance is a contributing factor in fish population declines.

With the FMWT sampling annually for over 50 years, this dataset has provided a solid baseline of understanding of relative abundance and distribution trends of fish in the San Francisco Estuary. The FMWT is a monitoring element of the Interagency Ecological Program (IEP; see: Interagency Ecological Program 2021 Annual Work Plan). FMWT is one of many long-running surveys conducted in the San Francisco Estuary, each targeting different species, life stages, and time of year (Tempel et al. 2021). 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 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; 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 2021 field season was to sample all stations safely and efficiently, counting all fish and invertebrates and measuring the fork lengths of the first 50 individuals of a single fish species for each station. Various weather and water quality conditions were also recorded at each station. The first survey began September 1, 2021 and the final survey was completed on December 16, 2021.

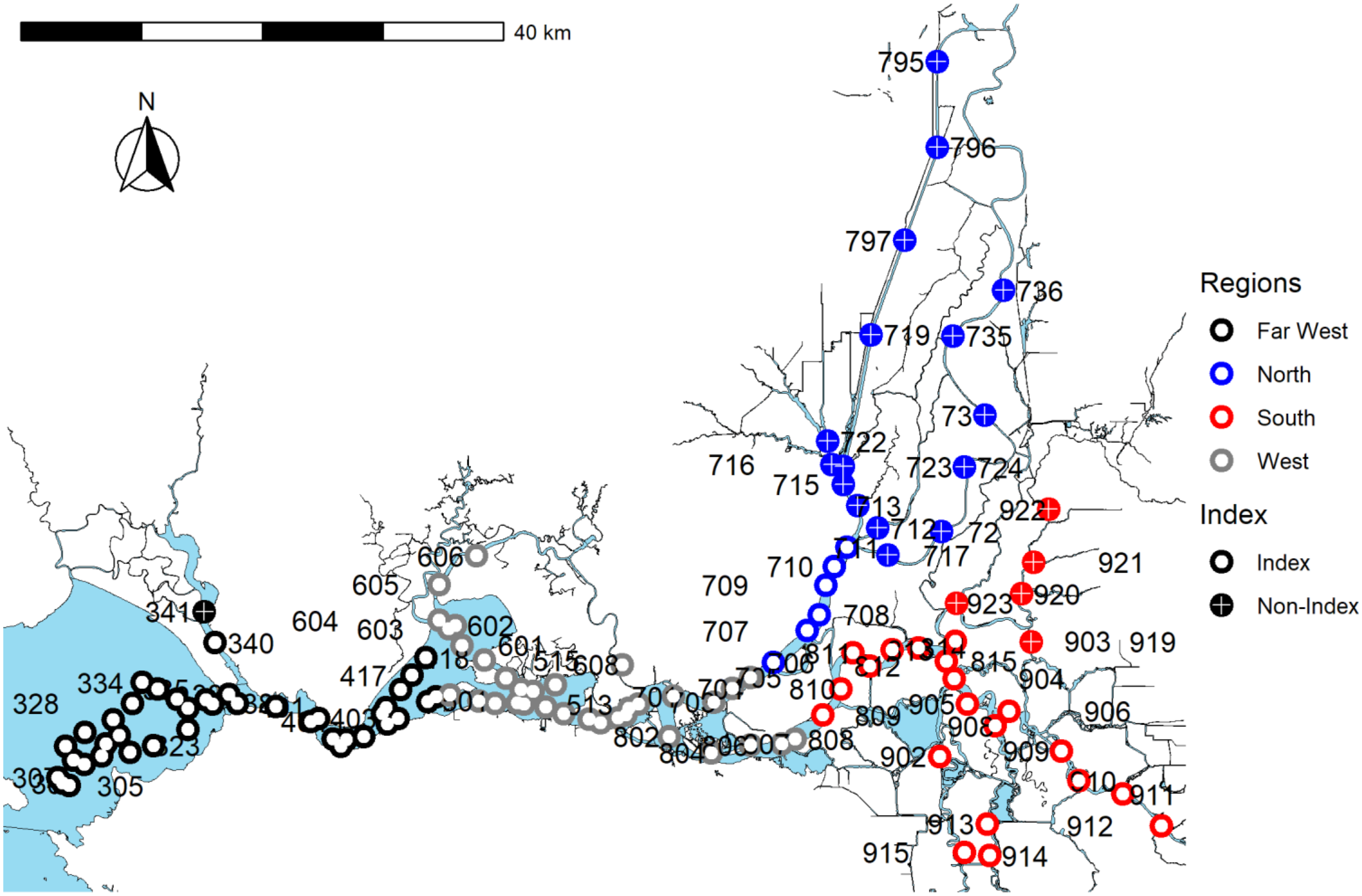

Figure 1. Map of FMWT station locations, regional groupings, and station index designations.

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.

The typical unit for reporting catch used below is catch per unit effort (CPUE). For FMWT, we calculate CPUE as total species catch divided by water volume of the trawl (as 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.

The crew typically includes an Environmental Scientist (ES), a Fish and Wildlife Scientific Aid (Sci Aid), and a Mate. The Mate is responsible for driving and maintaining the boat, while the ES and Sci Aid operate the winches, deploy the net, and conduct all sample collection. The survey currently takes 10-12 days to sample all 122 stations every month.

2021 Field Season

Despite many challenges this year from the Coronavirus Disease 2019 (COVID-19) global pandemic, sampling was nearly complete at 122 fish tows and 32 zooplankton tows (Clark-Bumpus and Mysid nets) for October through December sampling in 2021 (Table 1). Station 903 was missed in September because of heavy boat traffic but was the only skipped station for the year. Station 721 in Cache Slough has been abandoned as of this year as it had been increasingly difficult to sample the past few years due to increasing amounts of an invasive aquatic plant, Brazilian waterweed (*Egeria densa*), fouling sampling gear (Fig. 2). Thus the decision was made this year to sample instead further downstream (approx. 2 km) where there is greater depth and less vegetation. This new station is labeled 722 and is at the same location as Summer Townet (STN) 722 and Spring Kodiak Trawl (SKT) 716. 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 study on behalf of the California Department of Water Resources (Table 1). Overall, 2021 sampling contributed to the FMWT annual abundance indices, USFWS Delta Smelt Recovery Index, and DWR Suisun Marsh Salinity Control Gate the DWR Suisun Marsh Salinity Control Gate (SMSCG) special study with addition of phytoplankton samples collected at a subset of stations.

The 2021 field season was filled with unique challenges due to COVID restrictions. Potential COVID exposures caused last minute schedule changes to prevent exposure to other staff. In addition, delays were caused by diesel fuel shortages or faulty pumps at local marinas. This required shortened or extra-long days to make detours to other marinas.

Figure 2. Approximately 200 pounds of invasive aquatic vegetation fouling FMWT net at station 721 in Cache Slough (image taken in Oct. 2018 and used for illustrative purposes). This station was replaced with Station 722 in Cache Slough further downstream.

Table 1: Number of Fish, Clark-Bumpus (CB), Mysid, and Phytoplankton samples collected at each station during the 2021 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
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

Station	Regions	Index	Delta Smelt Recovery Index	Fish net	CB net	Mysid net	Salinity Control Gate	Phytoplankton
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	1	1	2	3
606	West	Index	Sept-Oct	4	4	4	2	3
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	3	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				487	129	129	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 Sacramento and Mokelumne Rivers saw unusually high secchi values of over 300 centimeters. Water was relatively clear (200-300 cm Secchi depth) throughout the southern and eastern stations (stations in the 900s) for for all months excluding November. Previous studies have documented a negative correlation between fish catch and high Secchi values (MacNally 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 2021 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 the Sacramento River showed the most turbidity while the rest of the estuary was relatively clear. However, this pattern varied among months with the Sacramento River stations being most turbid in December (after a recent rainstorm) and the DWSC stations being more turbid in October and December.

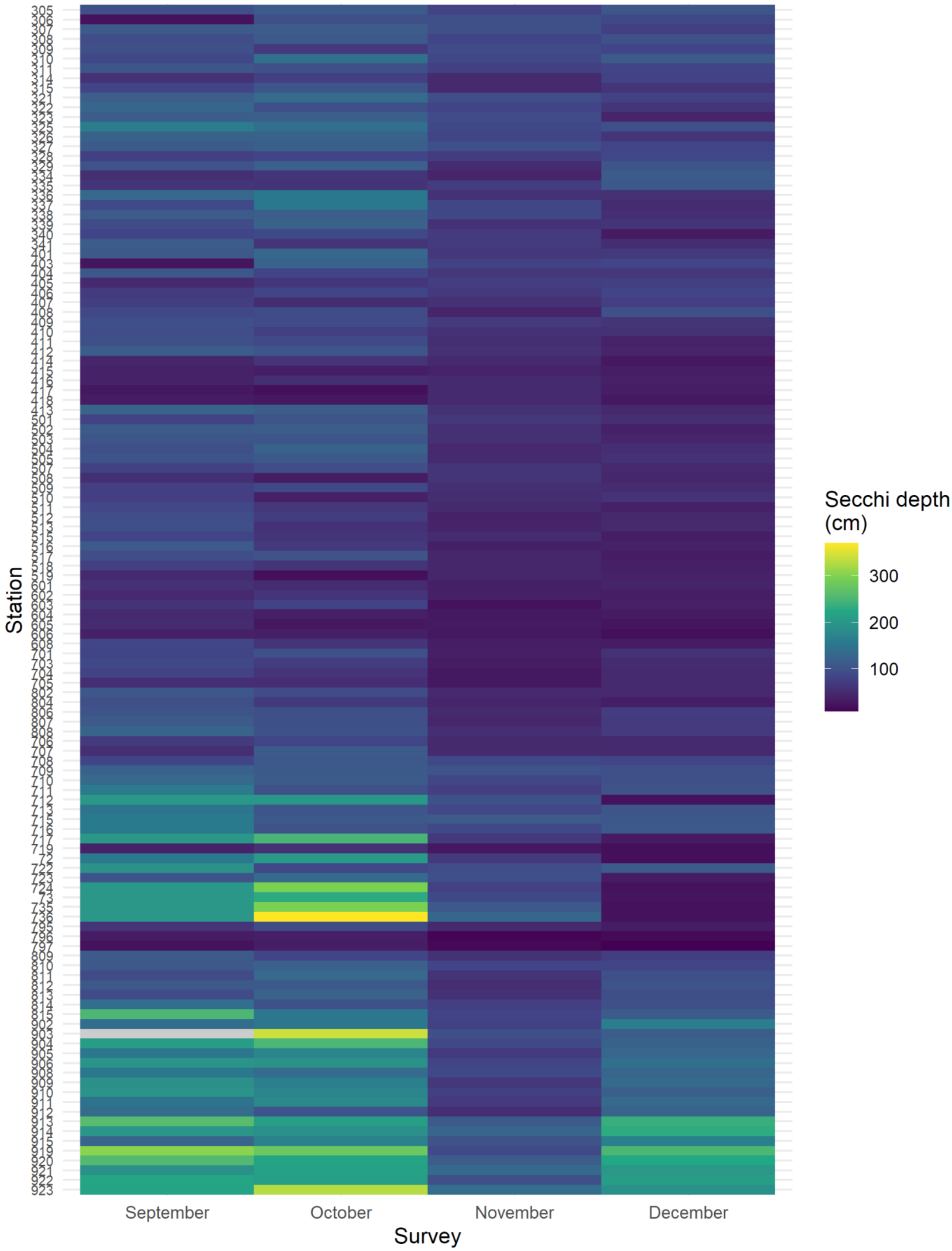

Figure 3. Heatmap of monthly Secchi disk values (cm) recorded during the 2021 FMWT season. Dark purple values represent the most suitable conditions for many fish species with preference for turbidity.

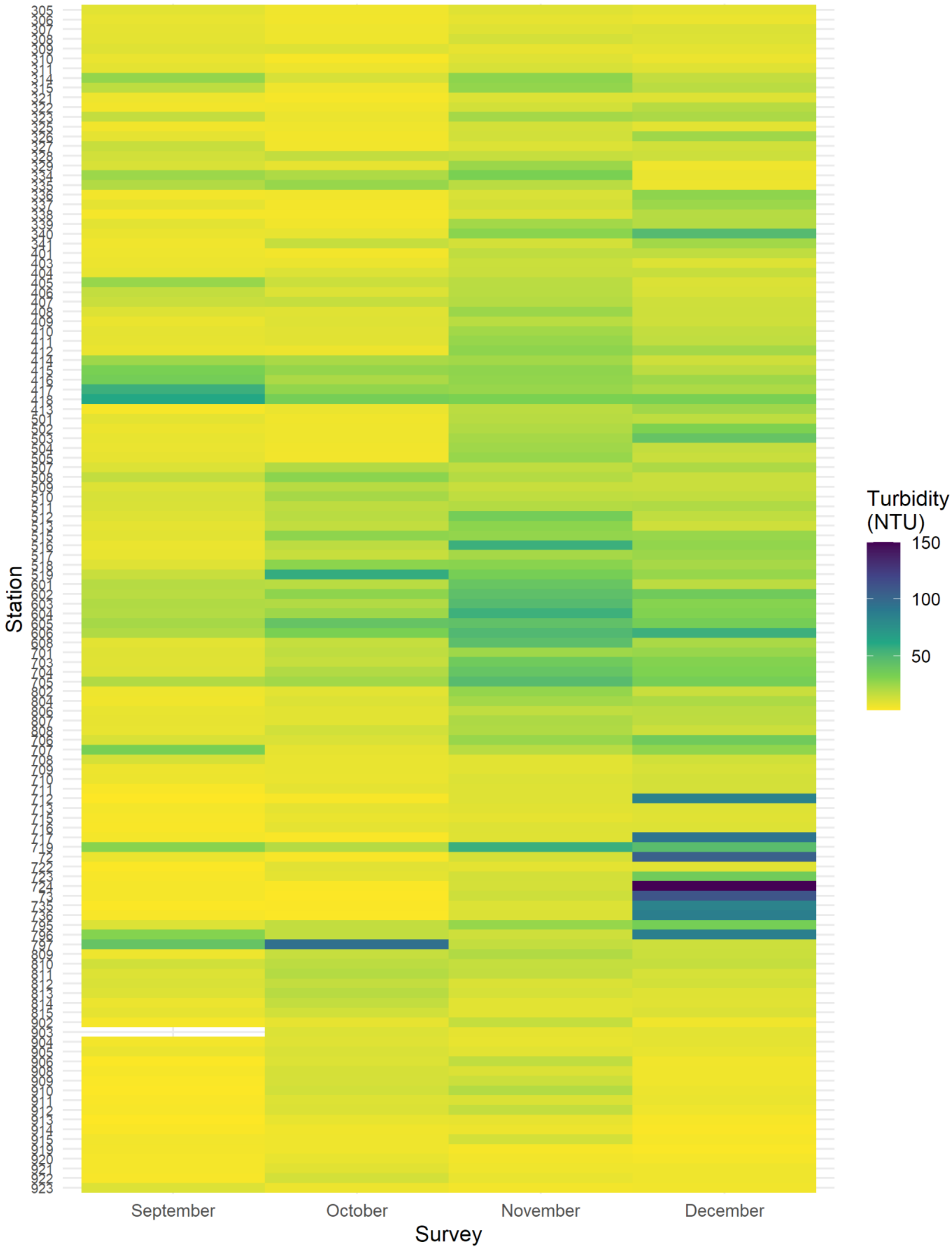

Figure 4. Heatmap of surface water turbidity (NTU) recorded during the 2021 FMWT season. White values indicate missing data. The northern part of the DWSC, western and northern Suisun Bay, and Sacramento River were the most turbid regions which varied among months.

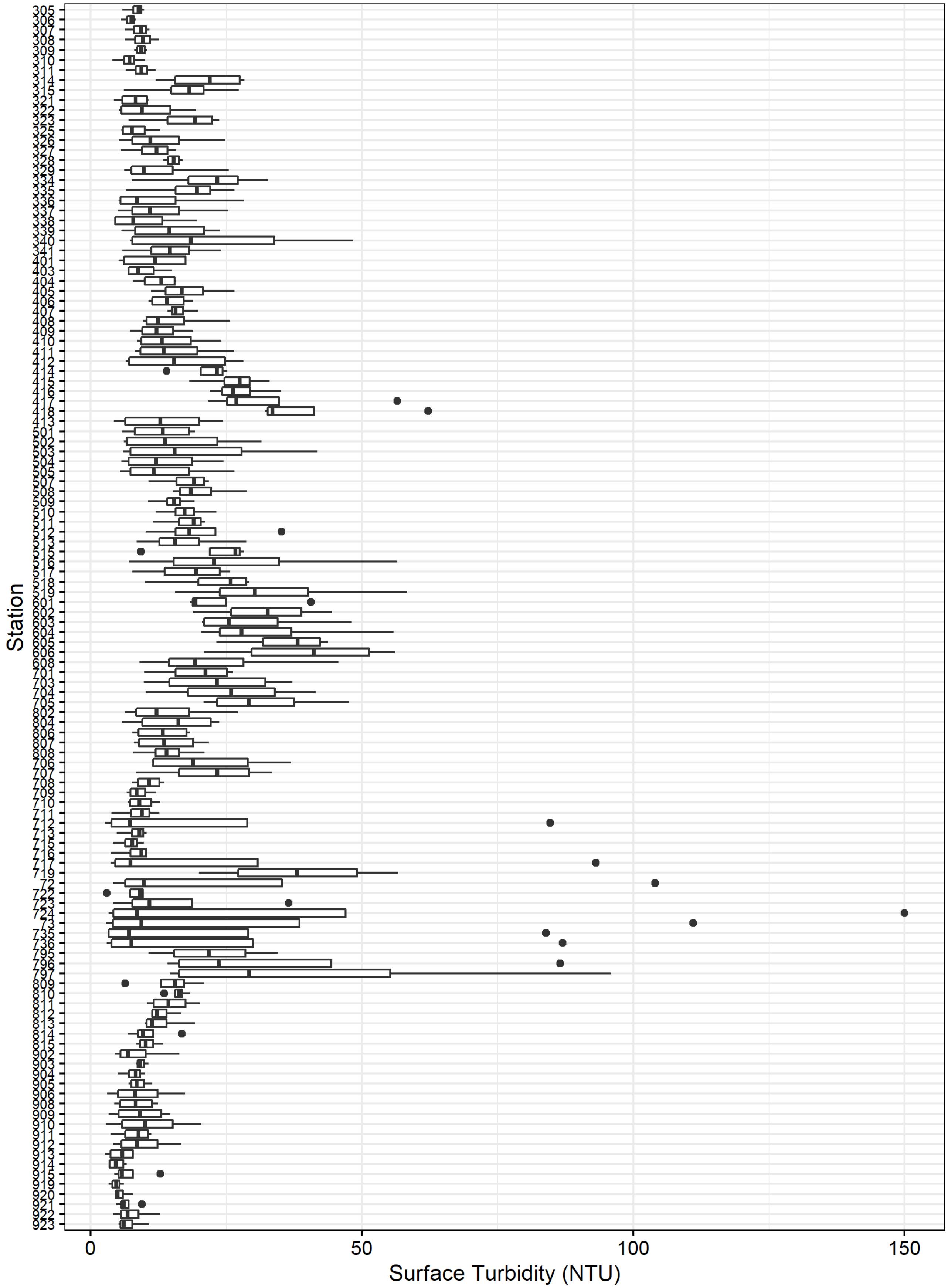

Figure 5. Distribution of monthly surface turbidity (NTU) recorded during the 2021 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

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, possibly at the upper range of thermal tolerance for many fish species throughout September and October. By November, temperatures had cooled into the 15-20°C range. By December, the water cooled to preferential levels estuary wide. The areas of greatest monthly temperature variability was at stations to the east of the confluence between the San Joaquin and Sacramento Rivers (Fig. 7).

Temperatures were usually warmer at surface waters compared to bottom water samples (Fig. 8). The most extreme differences were observed at a couple of stations at the confluence of the San Joaquin and Sacramento Rivers and a station in the lower region of the DWSC. However, these temperature differences do not necessarily indicate stratification at these stations since these differences may not be consistent or prolonged across tides.

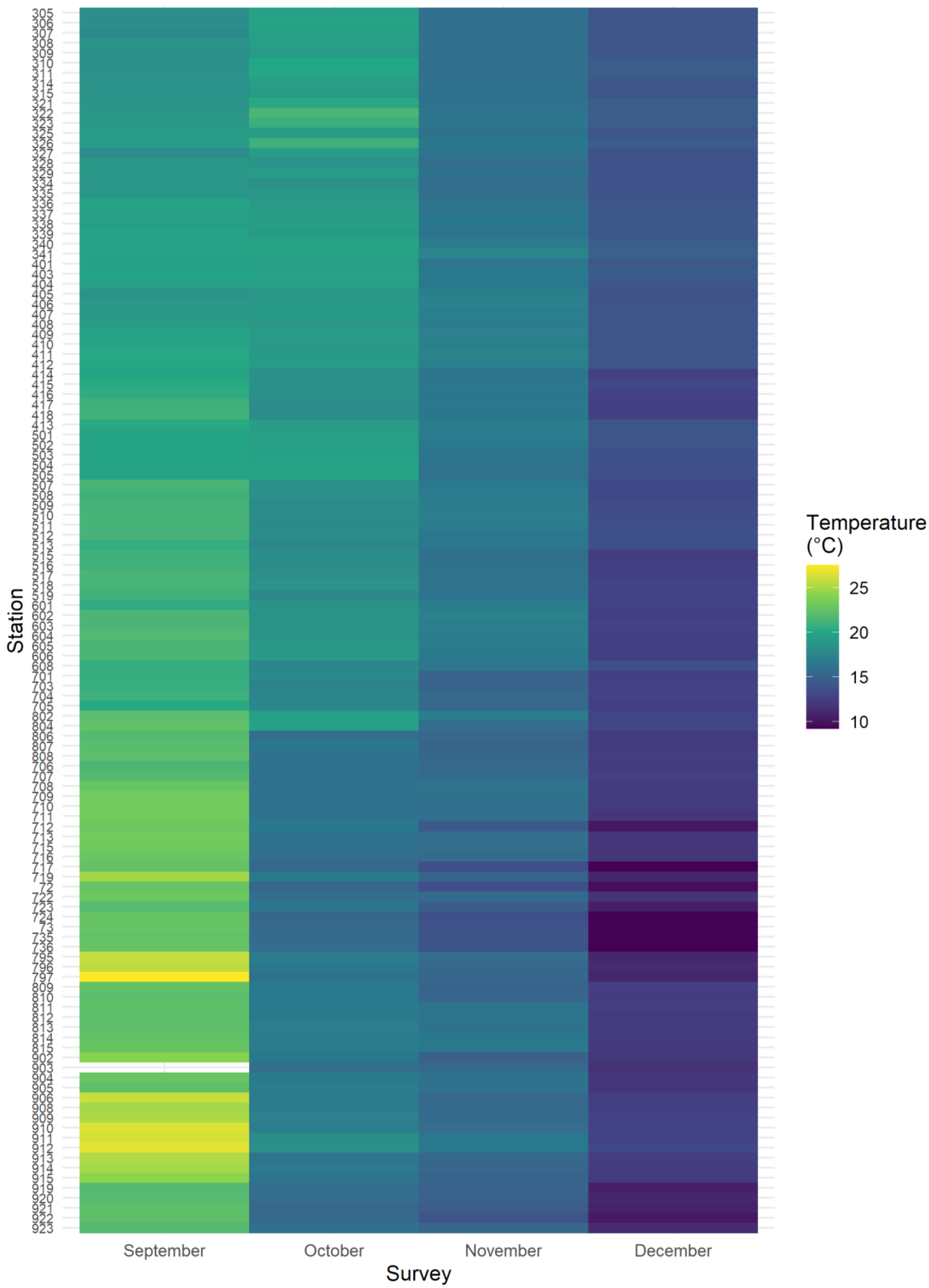

Figure 6. Heatmap of monthly surface water temperature (°C) recorded during the 2021 FMWT season. White values indicate missing data. Temperature values at 20 °C or greater induce cellular stress in Longfin Smelt and values above 25 °C induce Delta Smelt mortality, therefore stations in the purple and blue ranges are most suitable. Stations in the green to yellow range are potentially unsuitable for many species.

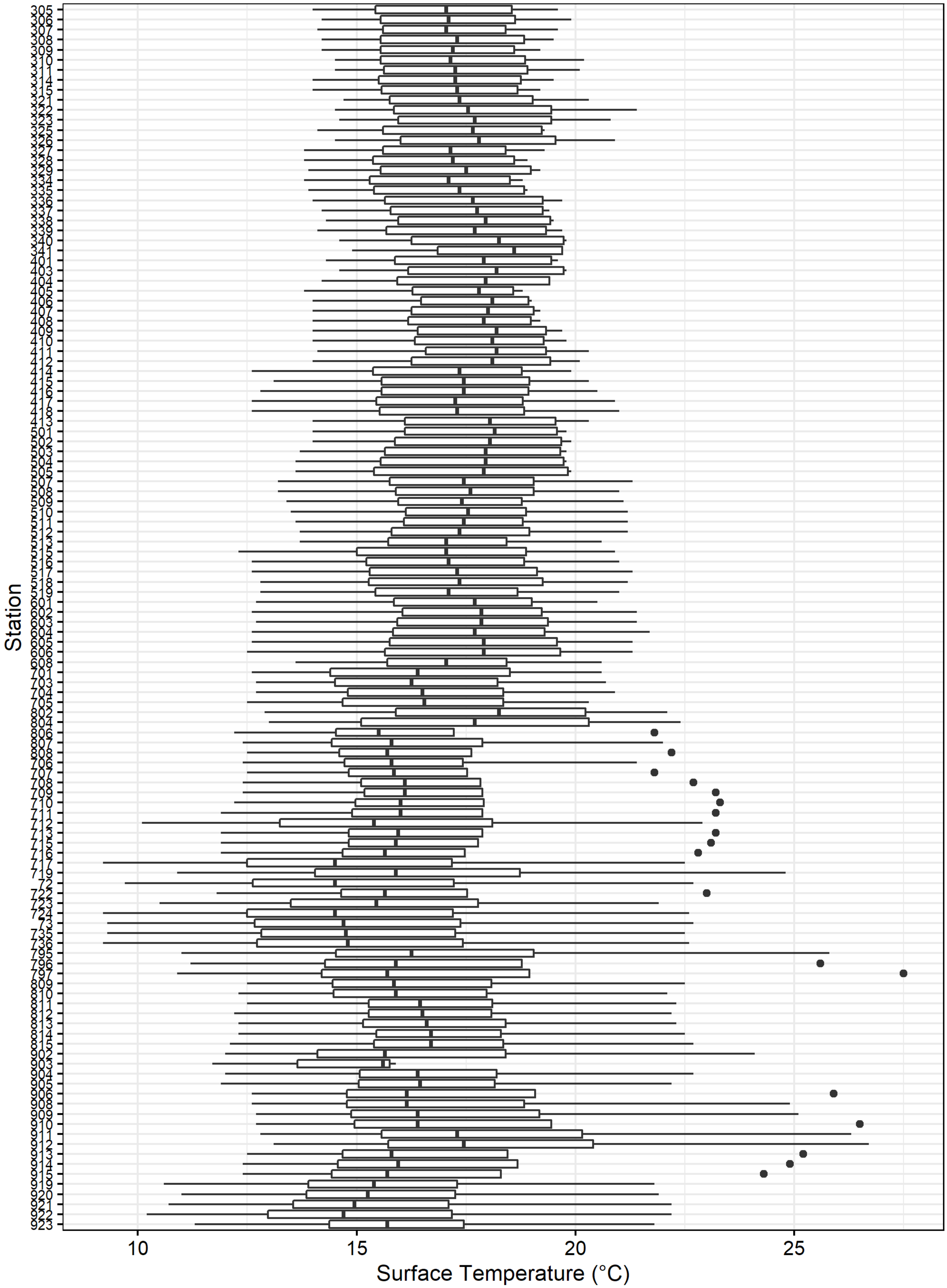

Figure 7. Distribution of monthly surface water temperature (°C) recorded during the 2021 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

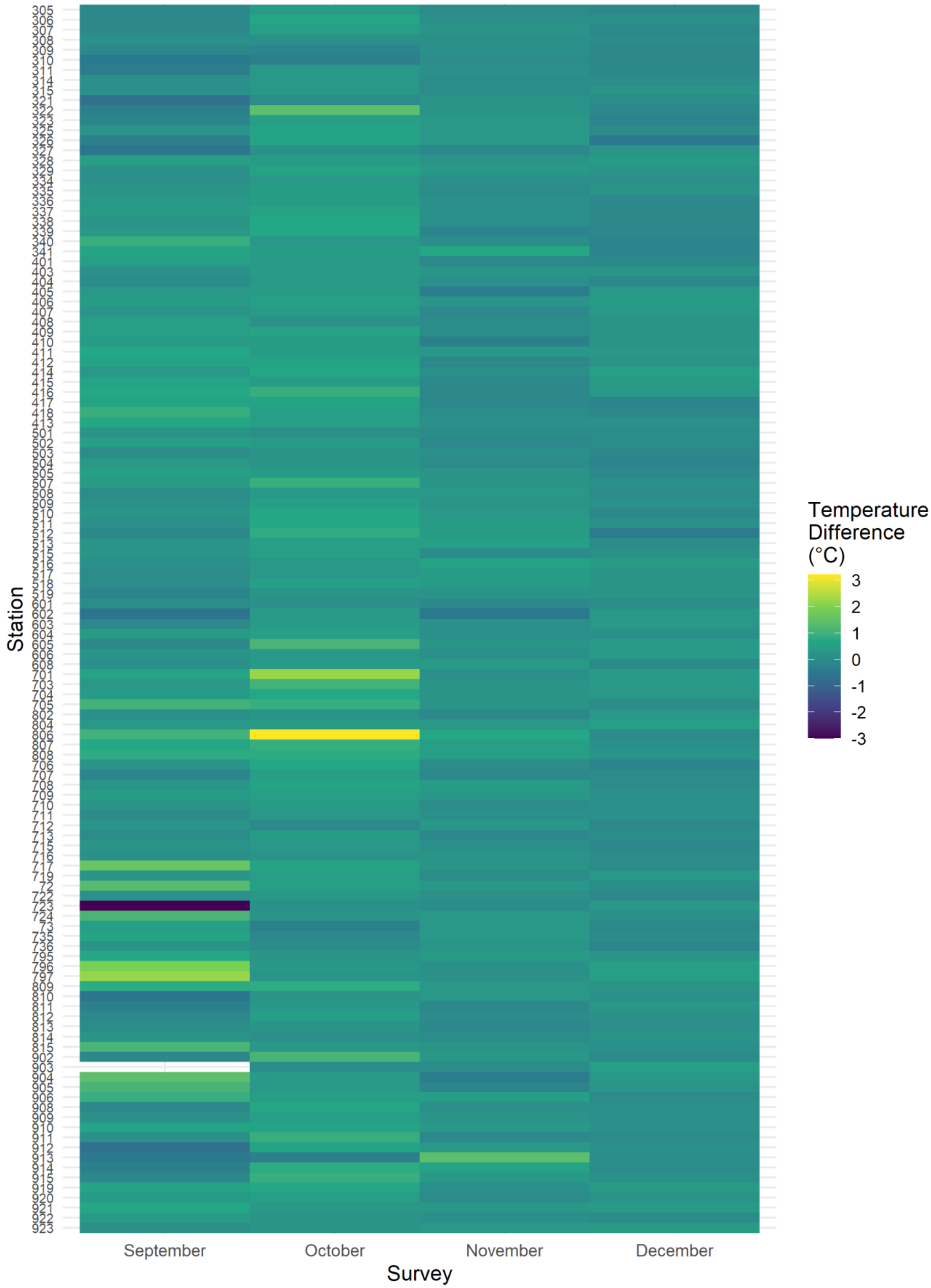

Figure 8. Heatmap of temperature (°C) differences between surface and bottom water recorded during the 2021 FMWT season. White values indicate missing data. Negative (blue to purple) values are warmer bottom temperature compared to the surface. Positive (green to yellow) values indicate greater temperatures 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 2021 (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. By October, Suisun Bay was on the high range of suitability. From November through December, most regions of the estuary were suitable (Fig. 9).

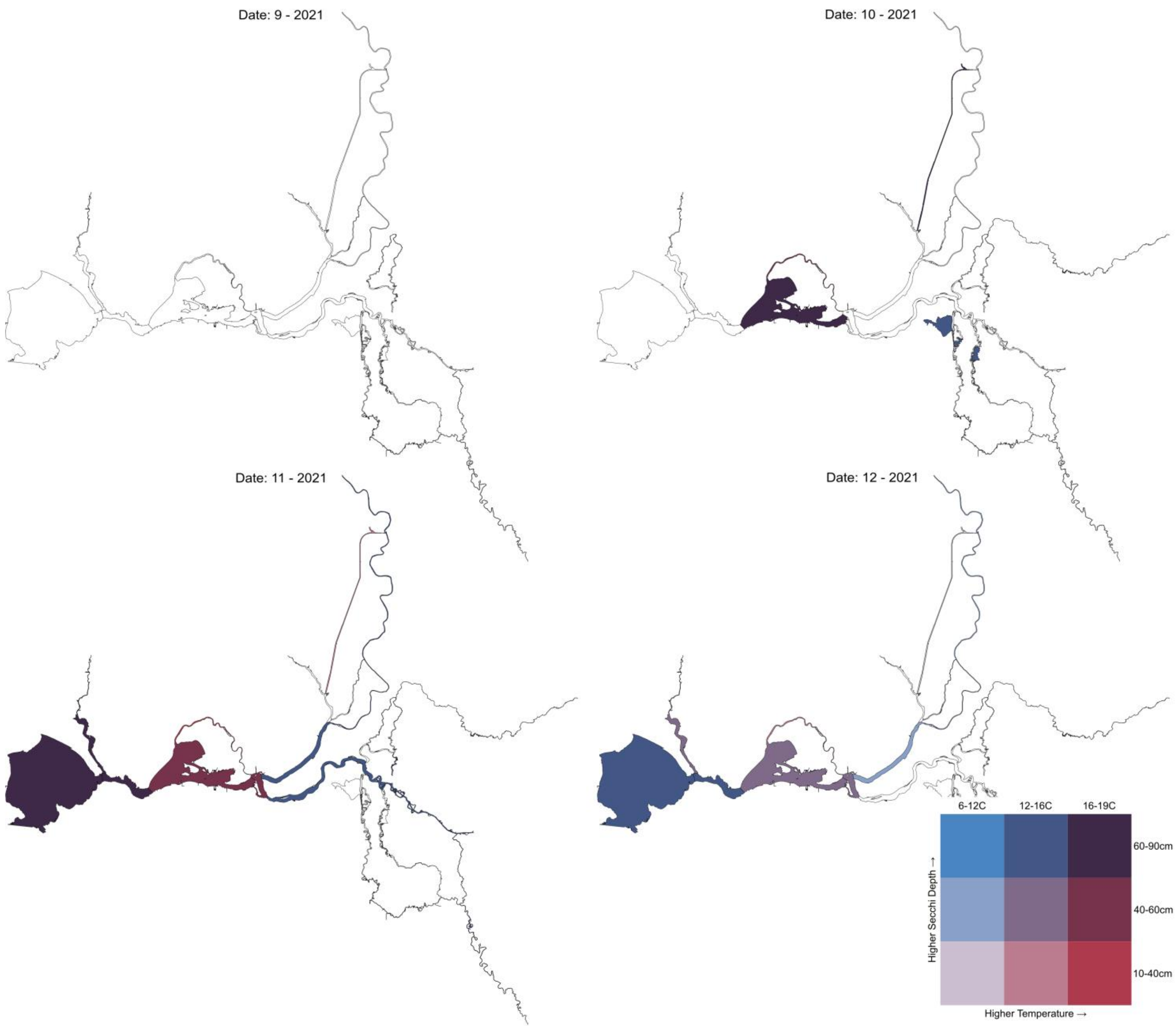

Figure 9. Map showing Longfin Smelt habitat suitability across each month of FMWT sampling in 2021 according to historical catch. White regions indicate values were out of suitable range. The habitat suitability was limited throughout the estuary until October, when Suisun Bay reached the high end of suitability. By November through December, most of the estary was suitable.

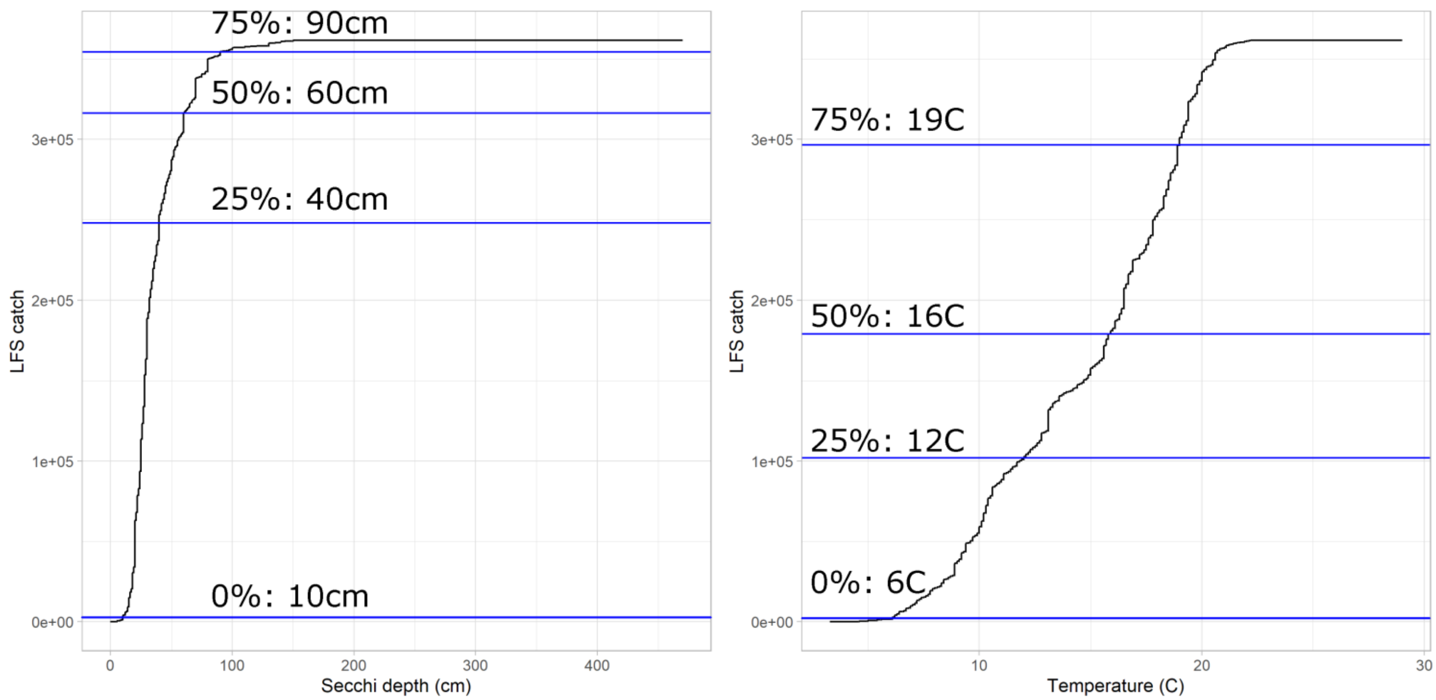

Figure 10. Cumulative frequency distributions of FMWT Longfin Smelt catch from 1967-2021 with abiotic variables. Left: Associated Secchi depth (cm) with catch and quartile values. Right: Associated surface water temperature (C) with catch and quartile values.

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 2021 FMWT showed this LSZ largely remained inland, in Montezuma Slough, at the confluence of the Sacramento and San Joaquin rivers, and eastward except for November when the LSZ was observed east of Grizzly Bay (Figs. 11 & 12). Carquinez Strait and western Suisun Bay had moderate salinity levels which increased towards the end of the year. 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 couple of stations in mid San Pablo Bay during October and another at a nearby San Pablo station in December. These comparisons do not account for the water depth or tidal condition at the time of sampling.

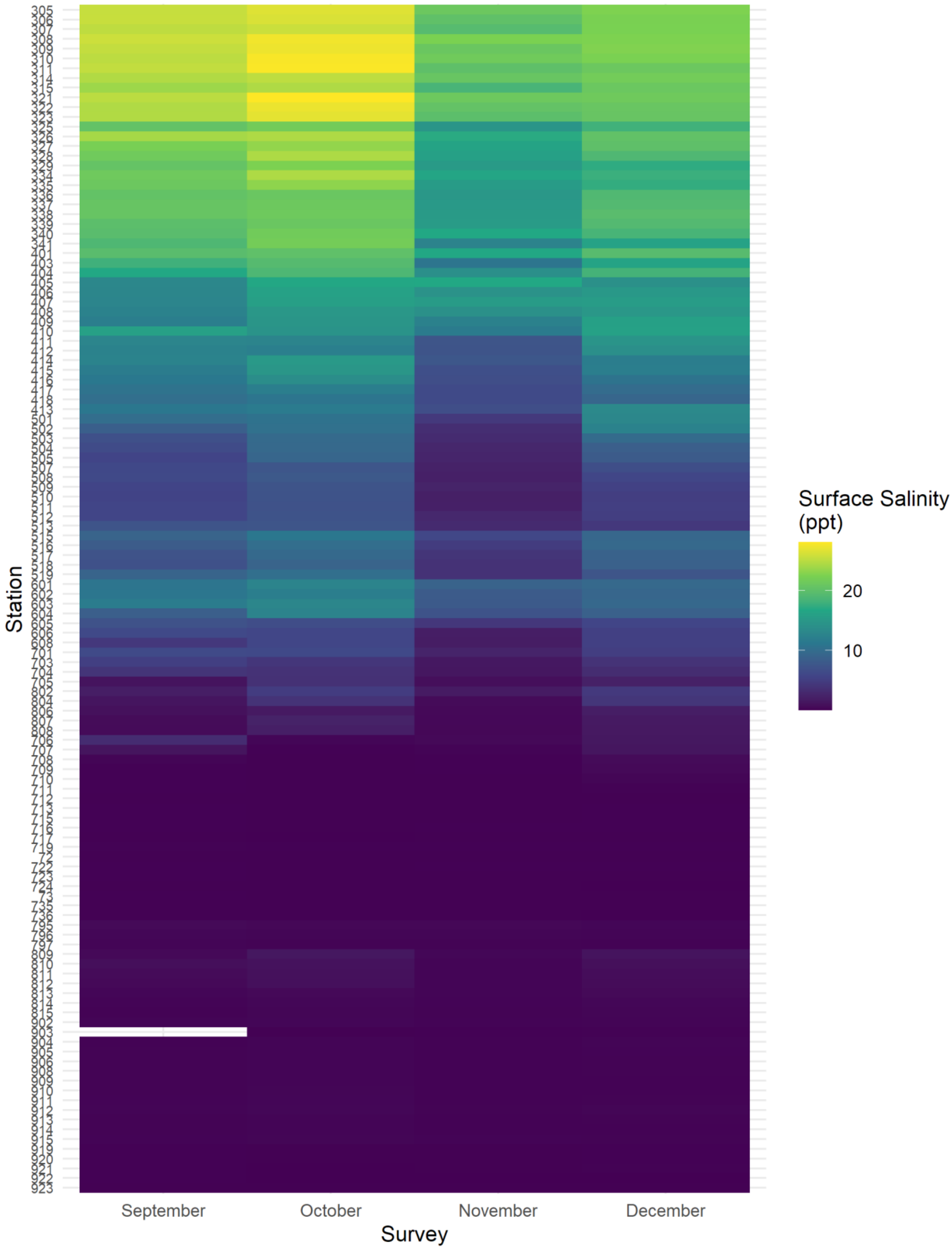

Figure 11. Heatmap of monthly surface water salinity (ppt) recorded during the 2021 FMWT season. White values indicate missing data. The low salinity zone (0.5-6 ppt, dark purple stations) stayed inland upstream of the confluence of the San Joaquin and Sacramento Rivers.

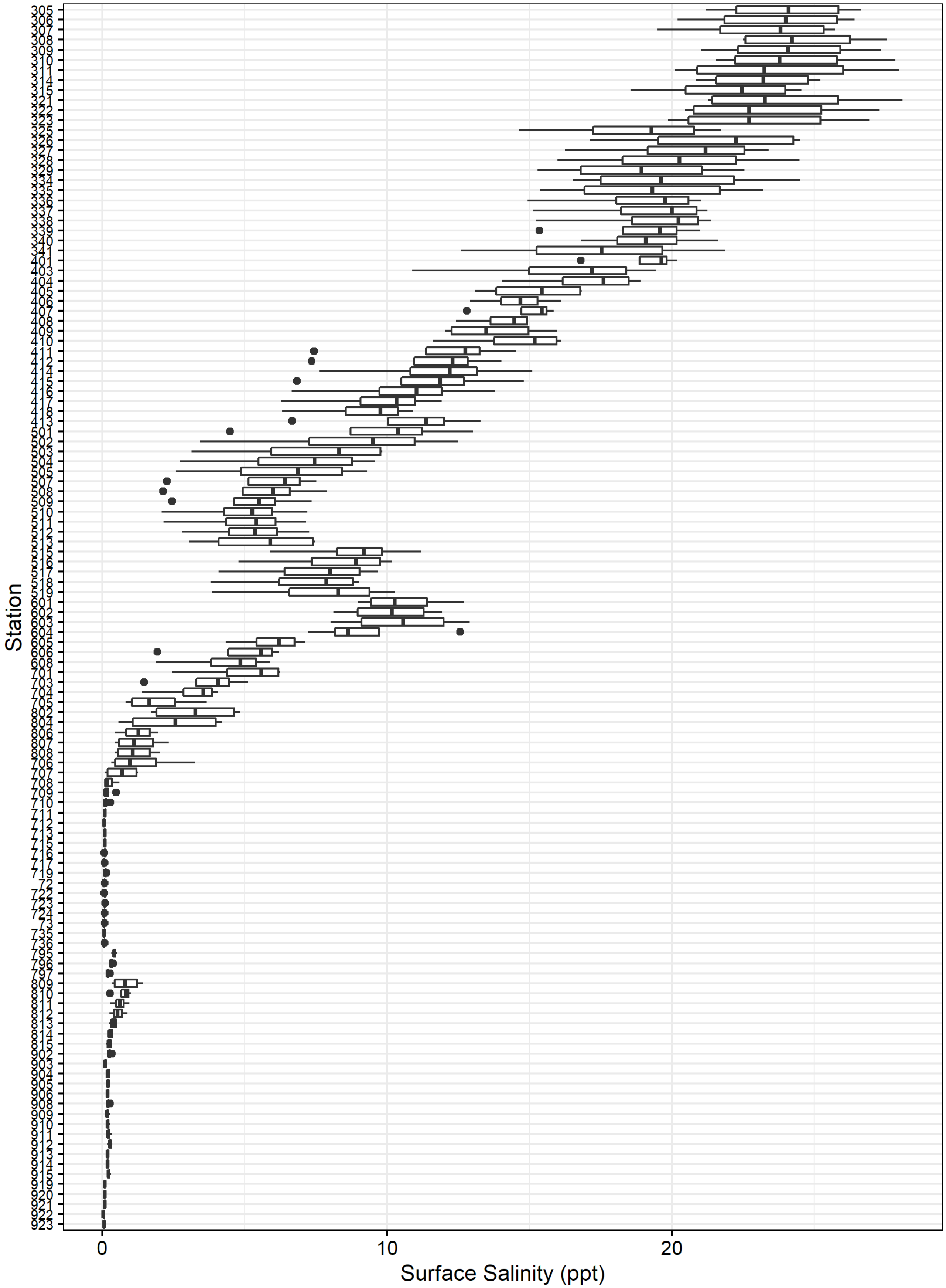

Figure 12. Distribution of monthly surface salinity (ppt) recorded during the 2021 FMWT season. Boxplots show the median as a vertical line, 1st and 3rd quartile by a box, range by a horizontal line, and outliers by points.

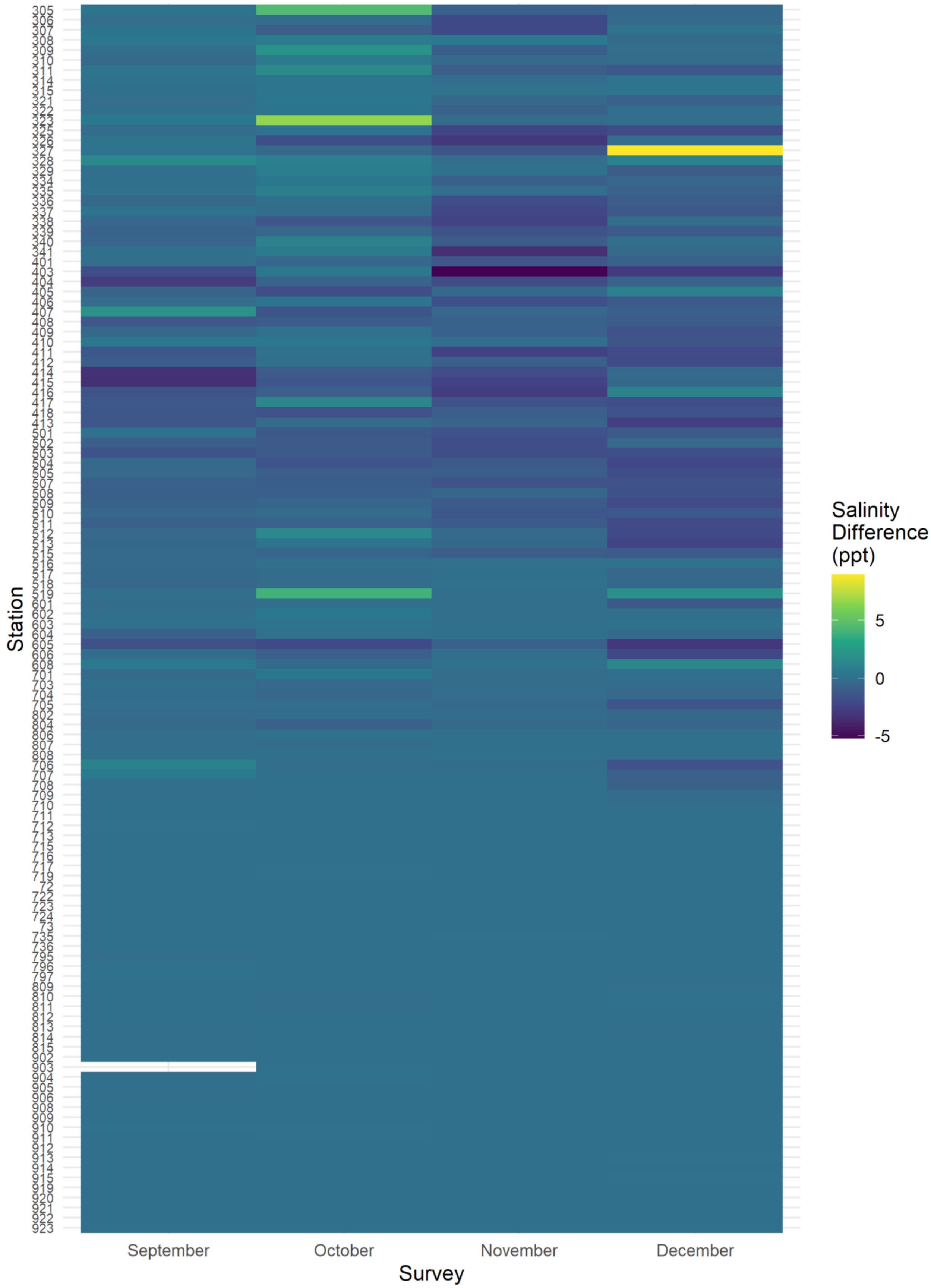

Figure 13. Heatmap of salinity (ppt) differences between surface and bottom water recorded during the 2021 FMWT season. White values indicate missing data. Negative (blue to purple) values are higher salinity on the bottom compared to the surface. Positive (green to yellow) values indicate higher salinity 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 in 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 2021 FMWT survey, *Microcystis* was found to be in moderate abundance at stations throughout Suisun Bay, lower Sacramento and San Joaquin Rivers, and the southern and eastern Delta in September (Fig. 15). By October, only a handful of stations in the southern Delta still had low *Microcystis* levels. In December, the estuary was cool enough where *Microcystis* was not detected anywhere.

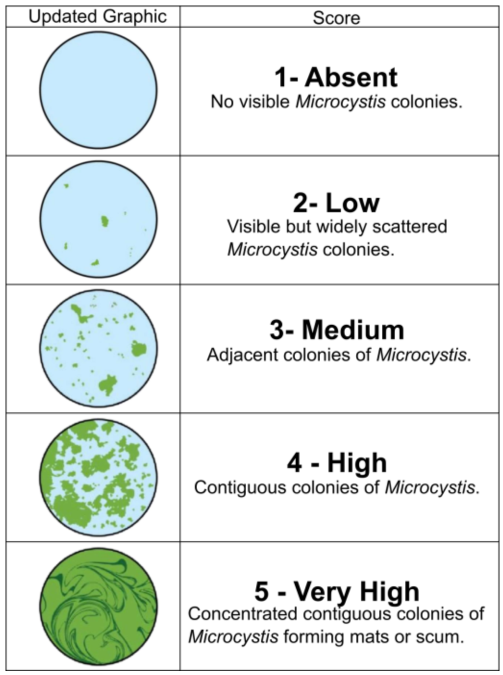

Figure 14. Qualitative rankings used to assess *Microcystis aeruginosa* blooms on the water surface.

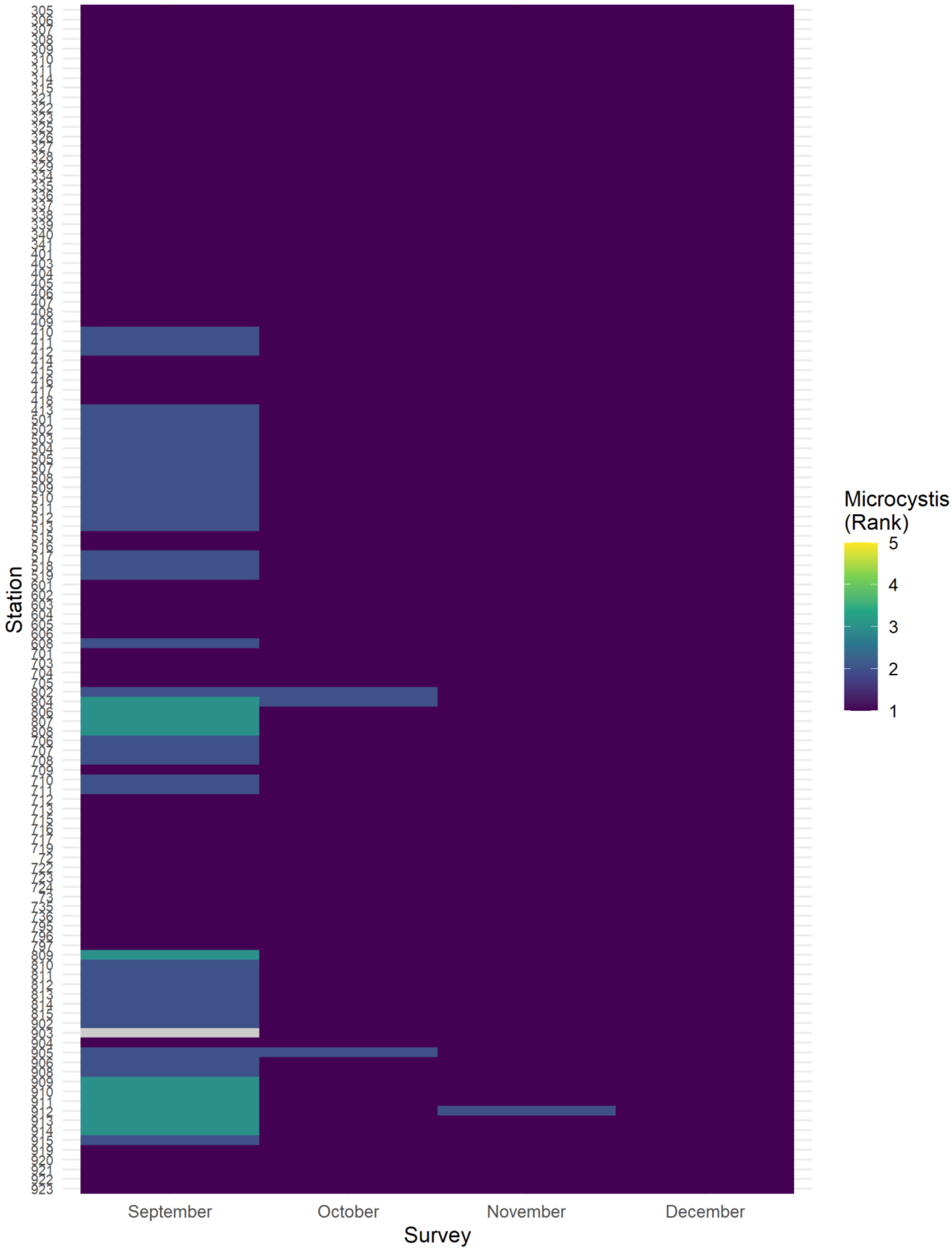

Figure 15. Heatmap of *Microcystis spp.* rankings recorded during the 2021 FMWT season. White values indicate missing data. Scale is a qualitative assessment of *Microcystis* density.

Fish & Invertebrate Catch

Fish

The FMWT survey records all species of fish and invertebrates 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 2021, Northern Anchovy (*Engraulis mordax*) in San Pablo Bay made the majority of our catch (Fig. 16, Table 2). Threadfin Shad was the second must abundant species, mostly caught in the DWSC (Stations 795 & 796), which have only been sampled since 2009. 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, Longfin Smelt, and Topsmelt (*Atherinops affinis*; Table 2). 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 November and December in the DWSC comprised most of index species catch (Fig. 16). Here, the contributions of Northern Anchovy are suppressed because it is averaged in with other non-index species with low or zero catch.

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 2021 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 the freshwater regions such as the DWSC.

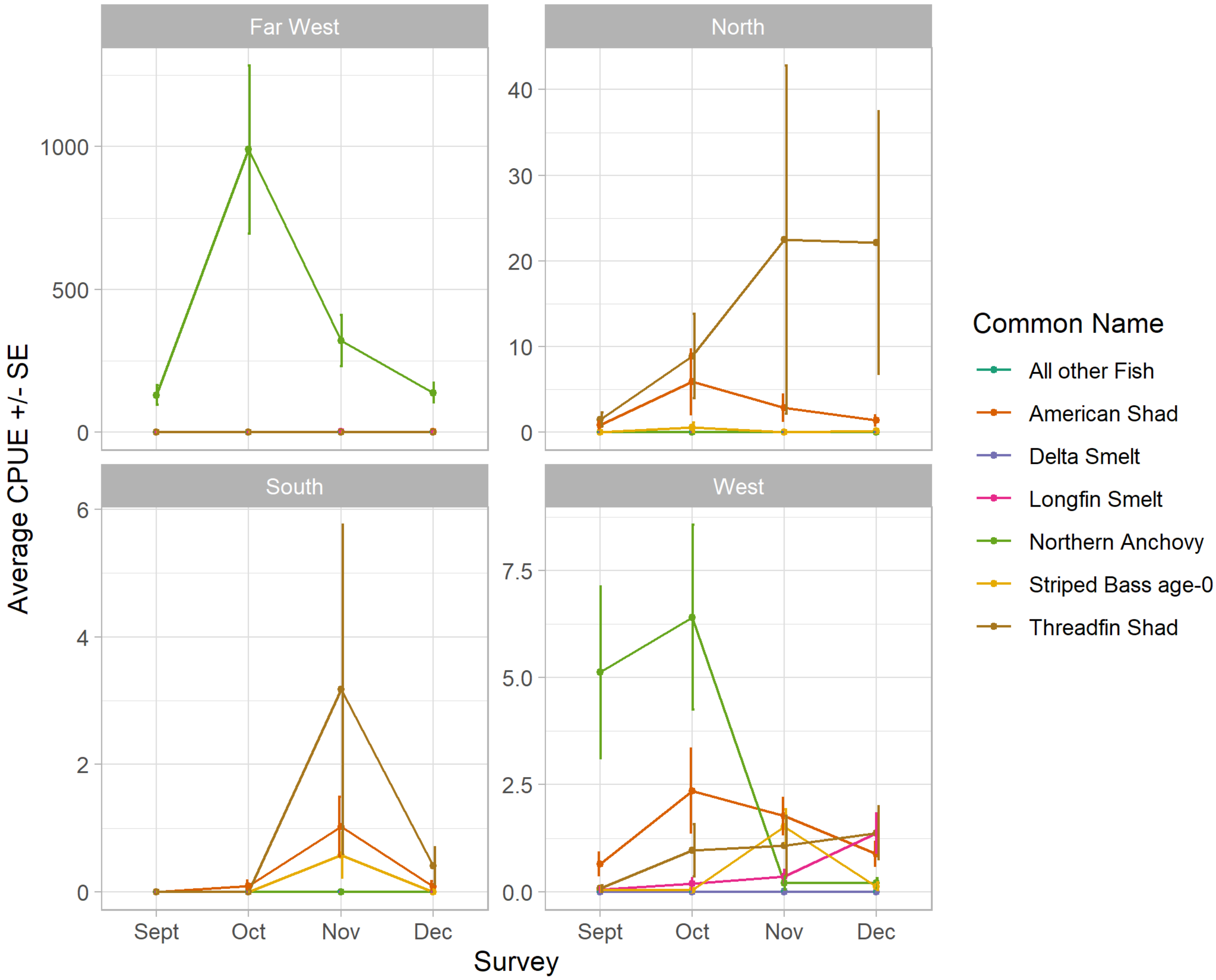

Figure 16. Regional fish catch for the 2021 FMWT survey organized by species used for index calculations. Lines represent monthly average catch per unit effort (CPUE) values and error bars represent +/- standard error. Number of stations per region varies; Far West (n=41), North (n=22), South (n=25), West (n=34).

Table 2: Total monthly fish catch during the 2021 FWMT season.

Species	September	October	November	December	Total	Total percent
Northern Anchovy	2,894	22,543	7,294	3,119	35,850	95.7
Threadfin Shad	17	124	315	347	803	2.1
American Shad	25	129	113	81	348	0.9
Longfin Smelt	1	6	61	56	124	0.3
Topsmelt	45	47	4	18	114	0.3
Striped Bass age-0	1	8	36	6	51	0.1
Striped Bass age-1	5	0	10	5	20	0.1
Shiner Perch	3	1	10	4	18	0.0
White Catfish	7	5	4	1	17	0.0
Wakasagi	0	6	4	6	16	0.0
Yellowfin Goby	2	0	11	3	16	0.0
Mississippi Silverside	0	4	7	2	13	0.0
Pacific Herring	4	3	1	3	11	0.0
Striped Bass age-2	1	1	2	1	5	0.0
Hitch	0	0	1	3	4	0.0
Pacific Lamprey	0	0	0	4	4	0.0
Splittail	0	1	1	2	4	0.0
California Halibut	0	2	0	1	3	0.0
Chinook Salmon	0	0	1	2	3	0.0
Striped Bass age-3+	0	0	2	1	3	0.0
Bluegill	0	0	2	0	2	0.0
Goby (unid)	1	1	0	0	2	0.0
Jacksmelt	0	0	2	0	2	0.0
Plainfin Midshipman	2	0	0	0	2	0.0
Rainwater Killifish	0	1	1	0	2	0.0
River Lamprey	0	0	1	1	2	0.0
Largemouth Bass	0	1	0	0	1	0.0
Pacific Tomcod	0	0	0	1	1	0.0
Prickly Sculpin	0	0	1	0	1	0.0
Redear Sunfish	0	0	1	0	1	0.0
Starry Flounder	0	0	1	0	1	0.0
White Croaker	0	0	0	1	1	0.0

Invertebrates

Similarly, the invertebrate catch was dominated by catch of the Siberian prawn (*Exopalaemon modestus*) followed by *Maeotias* jellies which were mostly caught in the DWSC and together comprised 92% of total catch (Table 3, Fig. 17). Otherwise, *Crangon* shrimp were the third most abundant species caught. Other species comprised less than 2% 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 3: Total monthly invertebrate catch during the 2021 FWMT season.

Species	September	October	November	December	Total	Total percent
Exopalaemon modestus	2,514	2,798	2,711	462	8,485	49.2
Maeotias spp.	4,819	1,721	866	4	7,410	42.9
Crangon spp.	105	14	668	220	1,007	5.8
Palaemon spp.	13	0	240	86	339	2.0
Aurelia labiata	0	4	1	3	8	0.0
Polyorchis spp.	0	0	3	0	3	0.0
Pleurobrachia spp.	0	0	0	2	2	0.0
Shrimp (unid)	2	0	0	0	2	0.0

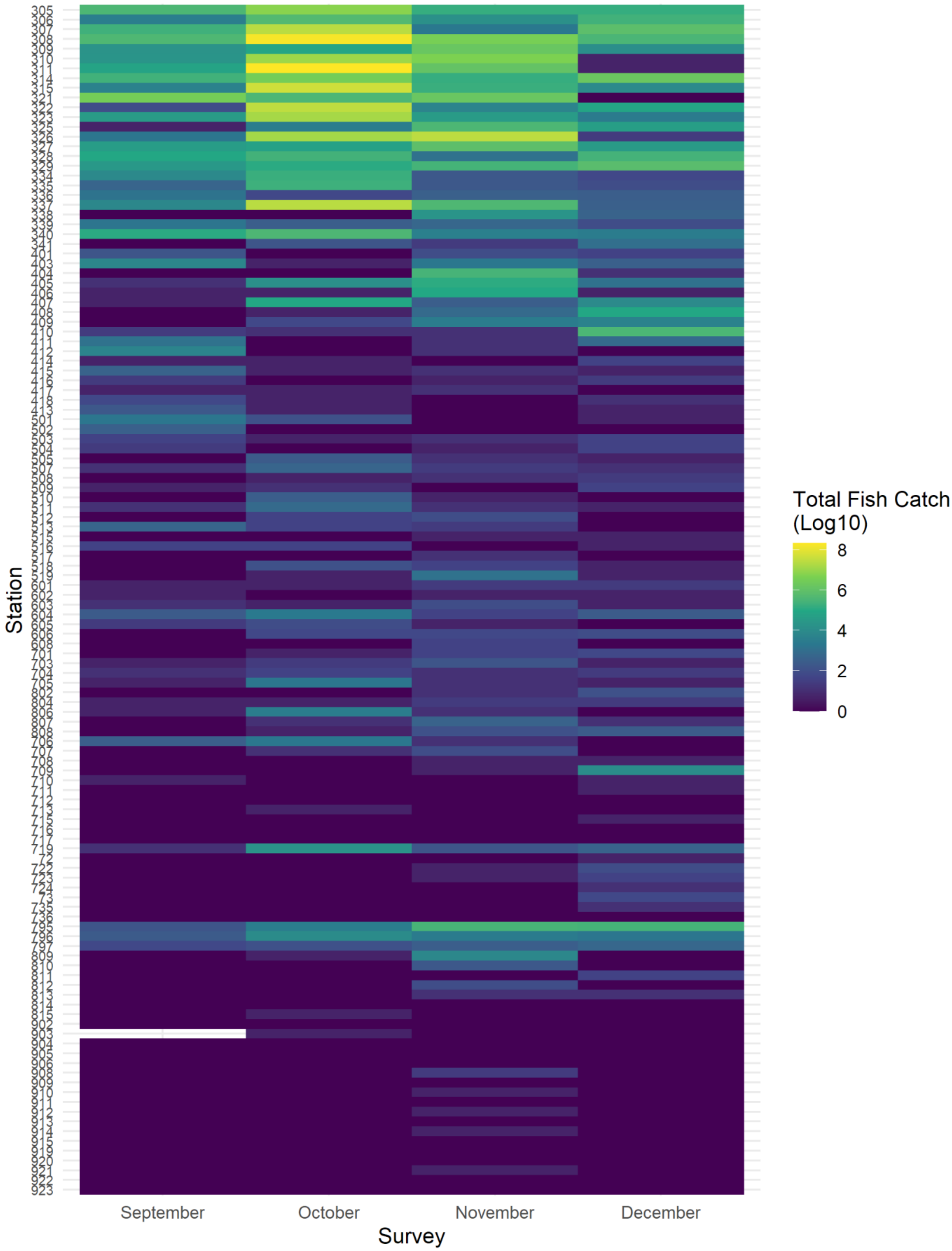

Figure 17. Heatmap of $Log_{10}(x+1)$ total fish catch by station recorded during the 2021 FMWT season. White values indicate missing data. San Pablo Bay and the northern part of the DWSC had the highest fish catch.

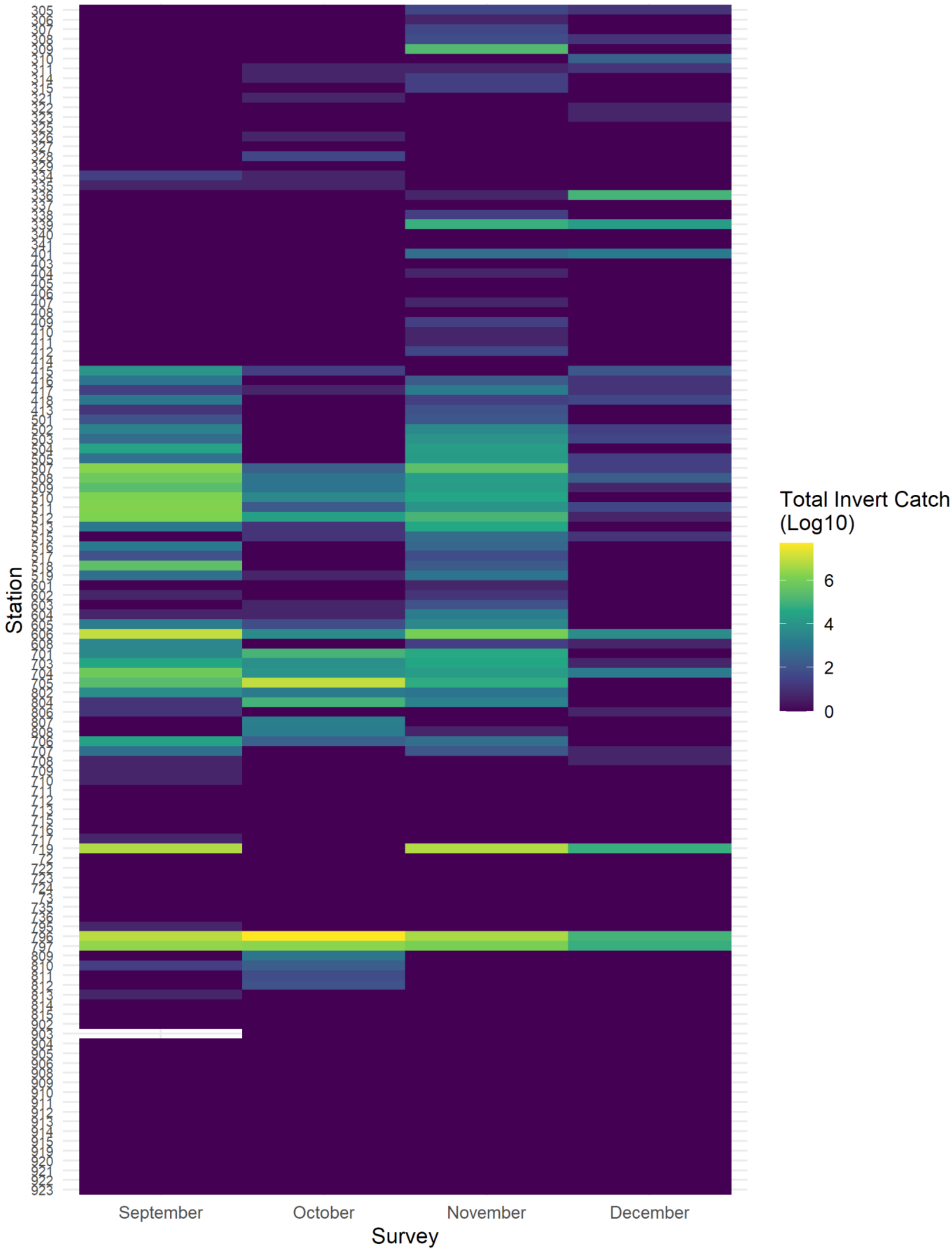

Figure 18. Heatmap of $Log_{10}(x+1)$ total invertebrate catch by station recorded during the 2021 FMWT season. White values indicate missing data. The northern part of the DWSC had the highest invertebrate catch.

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, *Corbula 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.

In 2021, 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 (April-July) 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, *Corbula 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. More recently, Kimmerer et al. (2009) found that Striped Bass survival, abundance, and habitat all increased as X_2 location moved downstream, suggesting the location of the X_2 is the mechanism driving the relationship between outflow and abundance.

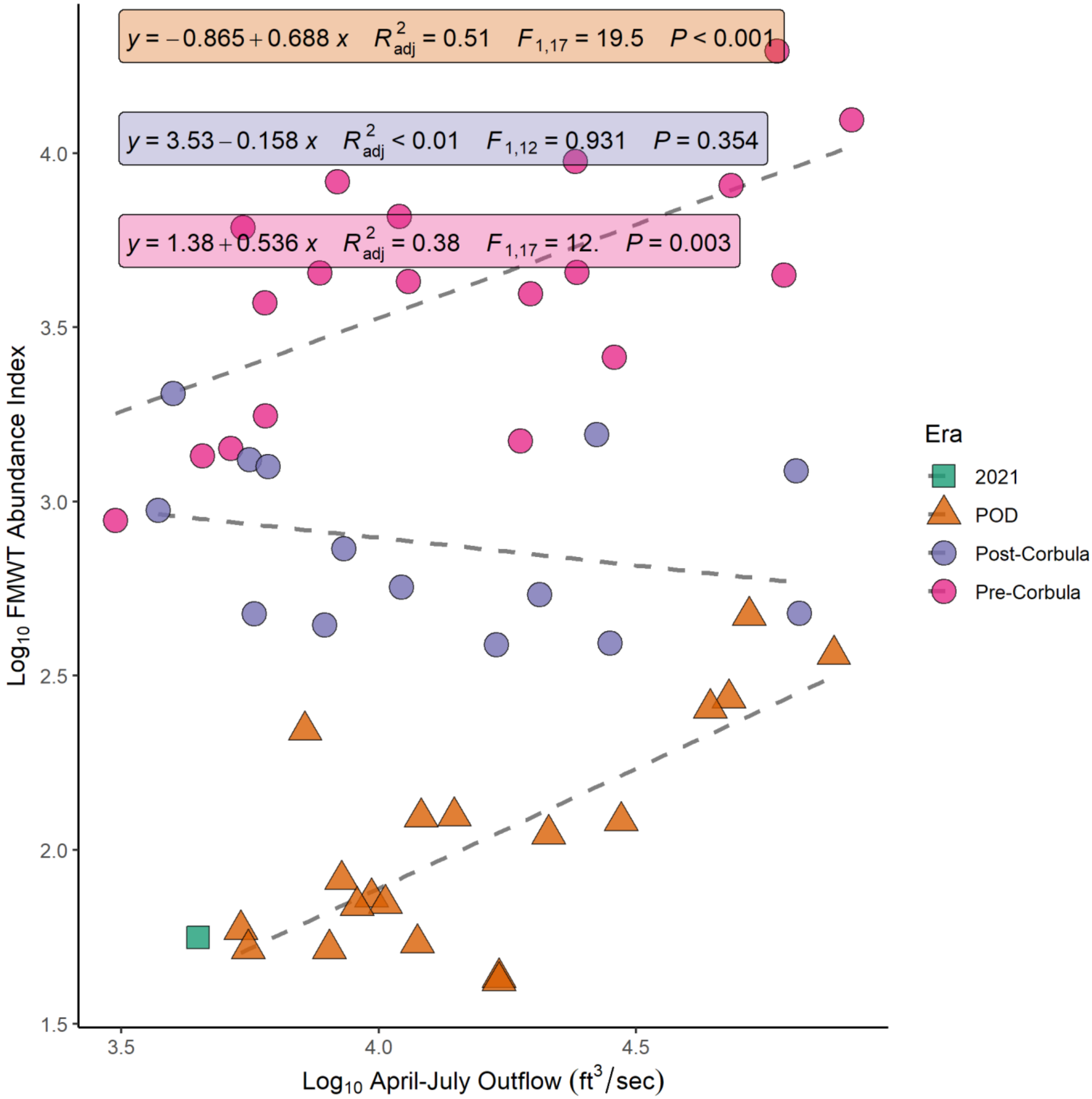

Figure 19. Relationship between Log_{10} transformed age-0 Striped Bass FMWT abundance index and the Log_{10} transformed monthly average of daily April-July Delta outflow (ft^3/sec) for the year 2021 (green square) compared to the years 1967-1987 (pre-Corbula clam; pink circle), 1988-2001 (post-Corbula clam; purple circle), and years 2002-2020 (pelagic organism decline; orange triangle).

Similarly, American Shad showed the same linear positive relationship between outflow and abundance, with 2021 showing a pattern of low outflow and low relative abundance as other POD years (Fig. 20). American Shad also shows the same pattern of this relationship not being significant during the post-*Corbula* 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).

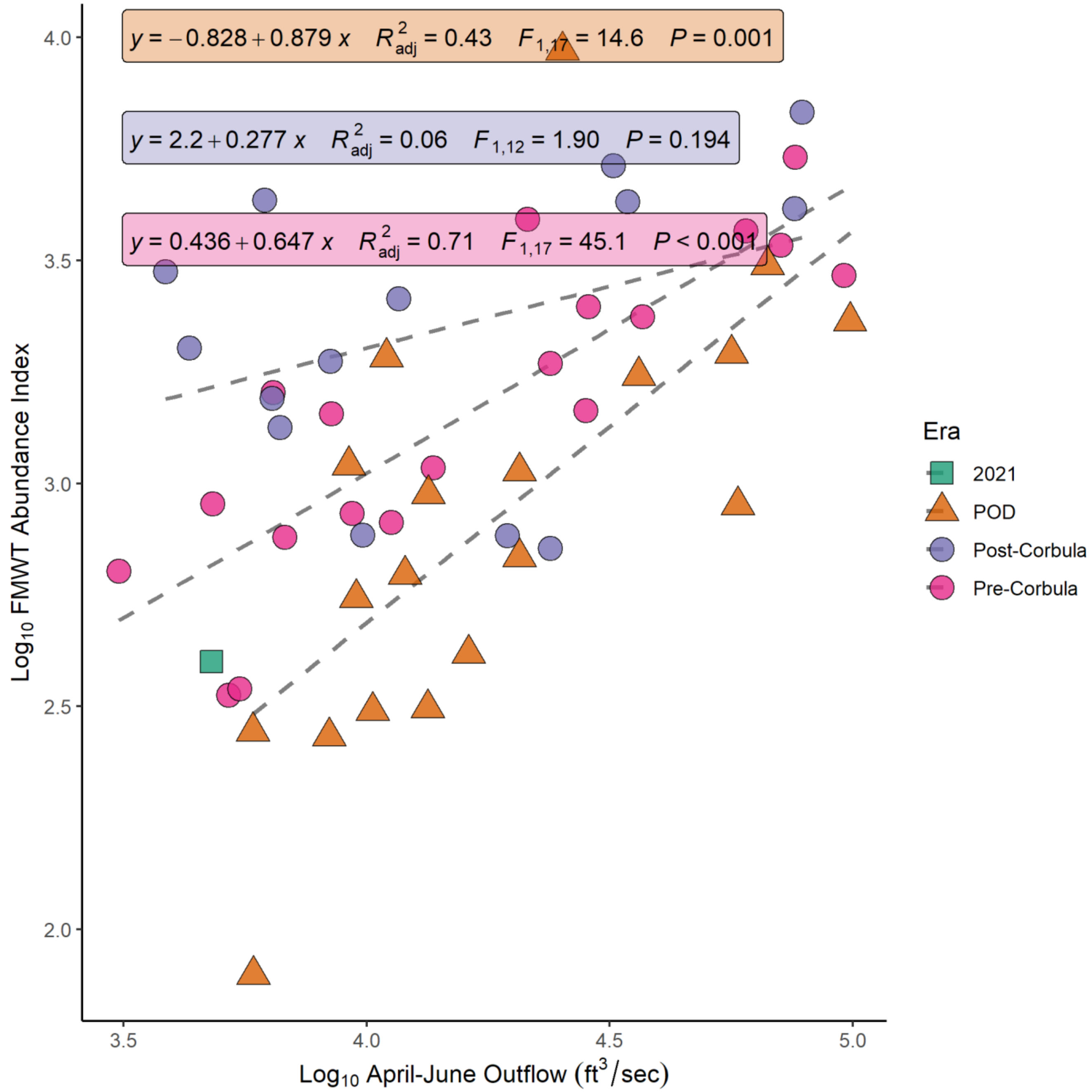

Figure 20. Relationship between Log_{10} transformed American Shad FMWT abundance index and the Log_{10} transformed monthly average of daily April-August Delta outflow (ft^3/sec) for the year 2021 (green square) compared to the years 1967-1987 (pre-Corbula clam; pink circle), 1988-2001 (post-Corbula clam; purple circle), and years 2002-2020 (pelagic organism decline; orange triangle).

Longfin Smelt relative abundance has shown a consistent positive linear relationship with outflow across all time periods. Northern California saw high precipitation in October and December, with 16 inches of total precipitation recorded in San Francisco over those months, making the 2022 Water Year total to date 135% of the average for those months (CNRFC 2022 Feb 8). This helped create the ideal water temperature and clarity that was widespread by November as shown earlier (Fig. 9). The 2021 abundance was high when compared the 2021 Water Year low outflow, putting it on par with pre-*Corbula* years (Fig. 21). However, the most recent available outflow dataset is from the 2021 Water Year, which ran from October 1st, 2020 through September 30th, 2021. So the high precipitation recorded in October and December 2021 is not represented in this figure because the 2022 Water Year data is not yet available. According to Kimmerer et al. (2009), the mechanism driving the 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).

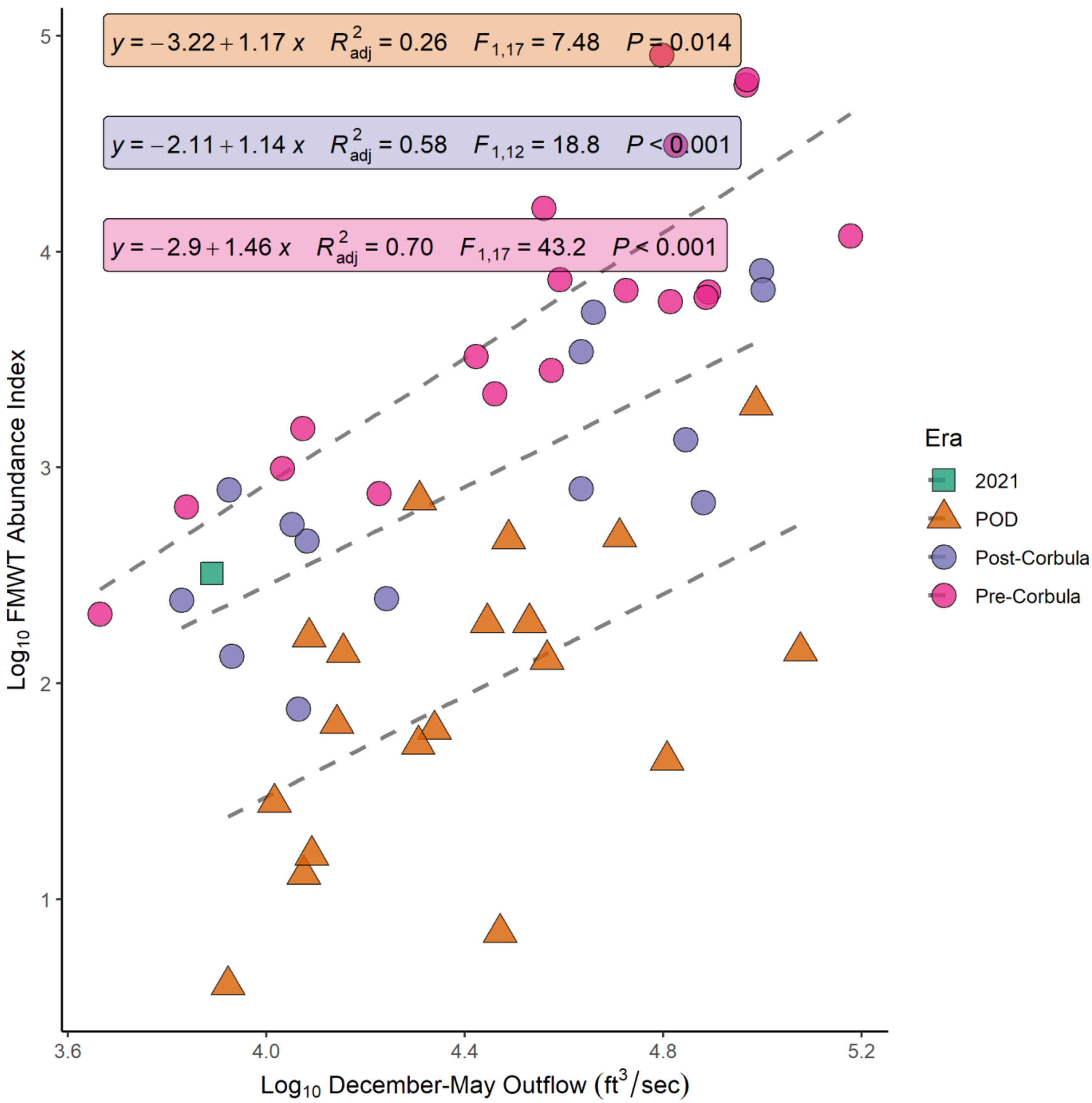

Figure 21. Relationship between Log_{10} transformed Longfin Smelt FMWT abundance index and the Log_{10} transformed monthly average of daily December-May Delta outflow (ft^3/sec) for the year 2021 (green square) compared to the years 1967-1987 (pre-Corbula clam; pink circle), 1988-2001 (post-Corbula clam; purple circle), and years 2002-2020 (pelagic organism decline; orange triangle).

Acknowledgments

We thank all personnel involved in this project. Their hard work and dedication to accurate and timely data collection has provided continued success for this long running survey.

Denisse Anaya; Cole Anderson; Spencer Breining-Aday; Evan Broberg; Christina Burdi; Ken Flowers; Mike Grady; Spencer Lewis; Paul Macias; Tim Malinich; Steve Slater; and Nene Ugbah.

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