California Regional Water Quality Control Board

San Francisco Bay Region

Lake Merritt Fall 2022 Water Quality and Fish Kill Observations

Final Staff Report

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CALIFORNIA REGIONAL WATER QUALITY CONTROL BOARD

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1 Summary

This report summarizes water quality and biological observations collected by the San Francisco Bay Regional Water Quality Control Board (Water Board) and community partners in response to the mass fish kill in Lake Merritt in August 2022. The mass fish kill was associated with a harmful algal bloom (HAB) and likely caused by the subsequent dissolved oxygen (DO) depletion. The species responsible for the HAB was *Heterosigma akashiwo,* a type of marine species that can cause a red tide. Red tides are often attributed to oxygen depletion in the water that marine life need to survive. In addition, *Heterosigma akashiwo* can cause toxicity in fish leading to fish kills, although the exact mechanism is not well understood (Gómez et al., 2022). There was no evidence of toxins in water samples surrounding the HAB.

2 Background

Lake Merritt is a tidal lagoon that is adjacent to the San Francisco Bay. Lake Merritt's beneficial uses, as outlined in the Water Quality Control Plan for the San Francisco Bay Basin (Basin Plan), are commercial and sport fishing, shellfish harvesting, estuarine habitat, fish spawning, warm freshwater habitat, wildlife habitat, water contact recreation, and noncontact water recreation. Lake Merritt was designated as the first protected wildlife refuge in America, and it is still home to large populations of breeding and migratory birds. Today, Lake Merritt is a popular location for boating, picnicking, jogging, and dog walking. It is listed on the 303(d) list as impaired for organic enrichment/low DO and trash.

In late July 2022, observations of rusty-brown water near Alameda were reported to the Water Board's spill line. Samples collected by California Department of Public Health (CDPH) determined the cause of the discolored water was a harmful algal bloom known as a red tide. CDPH identified the species associated with this bloom as *Heterosigma akashiwo.* By early August, the bloom had migrated into Lake Merritt, and by late August it had expanded throughout most of the San Francisco Bay. Fish deaths around the San Francisco Bay were being reported as early as August 22. However, the most obvious fish deaths in Lake Merritt did not occur until August 28.

Red tides are often attributed to oxygen depletion in the water that marine life needs to survive. In addition, *Heterosigma akashiwo* can be toxic to fish leading to fish kills, although the exact mechanism is not well understood (Gómez et al., 2022). There are four proposed mechanisms by which *Heterosigma akashiwo* causes toxicity to fish (Gomez et al., 2022; Mehdizadeh Allaf, 2023):

1. Production of excess mucus which smothers fish gills (Nakamura et al., 1998)
2. Production of brevetoxin-like neurotoxins (Khan et al., 1997)
3. Production of hemolytic compounds (compounds that breakdown or destroy red blood cells) that impact organ function (Ling and Trick, 2010)
4. Production of excessive reactive oxygen species, which cause gill damage and subsequent asphyxiation (Oda et al., 1997; Twiner and Trick, 2000; Twiner et al., 2001)

The red tide and fish kill received attention from media outlets across the nation. On August 28, 2022, Damon Tighe, an Oakland naturalist, first posted on Twitter he observed over 10,000 dead fish from at least 10 species at Lake Merritt. This observation was reported by both local and national organizations including the Oaklandside, the National Audubon Society, USA Today, Bay Nature, and NBC Bay Area. Jon Rosenfield, a senior scientist with San Francisco Bay Keeper, told KQED "the number of fish dying off in the San Francisco Bay could easily exceed hundreds of thousands, and that…might even be a 'low' estimate." Mark Westlund, communications director of

San Francisco Bay Keeper, told the San Francisco Chronicle a Bay Keeper staff scientist estimated “as many as 10,000 dead fish” were observed at Lake Merritt the day after the fish kill.

The algae bloom and fish kill were not isolated to Lake Merritt; the red tide and extensive fish kills were observed throughout the San Francisco Bay. Headlines such as “Toxic Red Tide Kills ‘Uncountable’ Numbers of Fish in the Bay Area” and “Thousands of dead fish in San Francisco Bay Area blamed on toxic red tide” ran in the New York Times and Los Angeles Times. The California Department of Fish and Wildlife (CDFW) aggregated data from multiple sources and found at least 864 sturgeon died in the San Francisco Bay during the HAB event; CDFW concluded toxicity must have contributed to these deaths because DO in the Bay was still high enough to support aquatic life (Ortega et al., 2023). However, the focus of this report is HAB conditions and impacts to Lake Merritt, where we believe low DO was likely the main cause of the fish kill since levels dropped well below levels that kill fish and invertebrates.

3 Data Collection

In response to the bloom and fish kill, the Water Board conducted water quality monitoring and aquatic wildlife observations at Lake Merritt. Water samples were sent to laboratories for freshwater and marine toxin analysis. Recent fish mortalities were collected for necropsy. Sample sites are shown in Figure 1. This report summarizes field observations and laboratory results; complete data sets and laboratory reports are included as attachments.

Figure 1 – Map of Lake Merritt and sample sites mid-lake (ML) and along the shoreline (S)

3.1 Continuous Water Quality Data

The day after the mass fish kill event, the Water Board deployed a continuous monitoring device (YSI EXO sonde) about a meter below the water surface at the City of Oakland boat dock. The sonde was deployed from August 29, 2022, through October 5, 2022. The sonde recorded DO, pH, temperature, and specific conductivity every 15 minutes (Figures 2, 4 – 6). From September 10 – September 16, a private company (Lake Tech) deployed sondes to monitor water quality conditions in the middle of the lake at two depths (Figure 3). The complete data set recorded by the Water Board's sonde is available in Attachment J.

3.1.1 Dissolved Oxygen

Dissolve oxygen (DO) levels were likely a main contributor of fish mortality, indicated by DO levels near 0 mg/L during and following the fish kill in Lake Merritt. The Basin Plan designates 5 mg/L of DO as the water quality objective for saline, marine, and warm fresh waters. DO levels below 2 mg/L are considered hypoxic and unable to support aquatic life. Data from the continuous monitoring device at the boat dock showed DO near 0 mg/L on August 29. These readings were corroborated by instantaneous water quality measurements around the lake, as discussed in Section 3.2. On September 3, DO increased to approximately 4 mg/L, but then dropped again early morning on September 4 (Figure 2). From September 5 – 9, DO increased to life supporting levels (>2 mg/L), but was elevated during the day with peaks up to 20.3 mg/L (301% saturation), suggesting that an algal bloom was still active. From September 10 – September 21, the DO stabilized with smaller daily fluctuations and within levels that support aquatic life. From September 22 – October 5 (sonde retrieval), DO regularly dropped below 5 mg/L in the mornings, although it was still above hypoxic conditions. Data collected from the middle of Lake Merritt by Lake Tech showed conditions at the surface and bottom of the lake were similar (Figure 3) and were comparable to data collected at the boat dock by the Water Board.

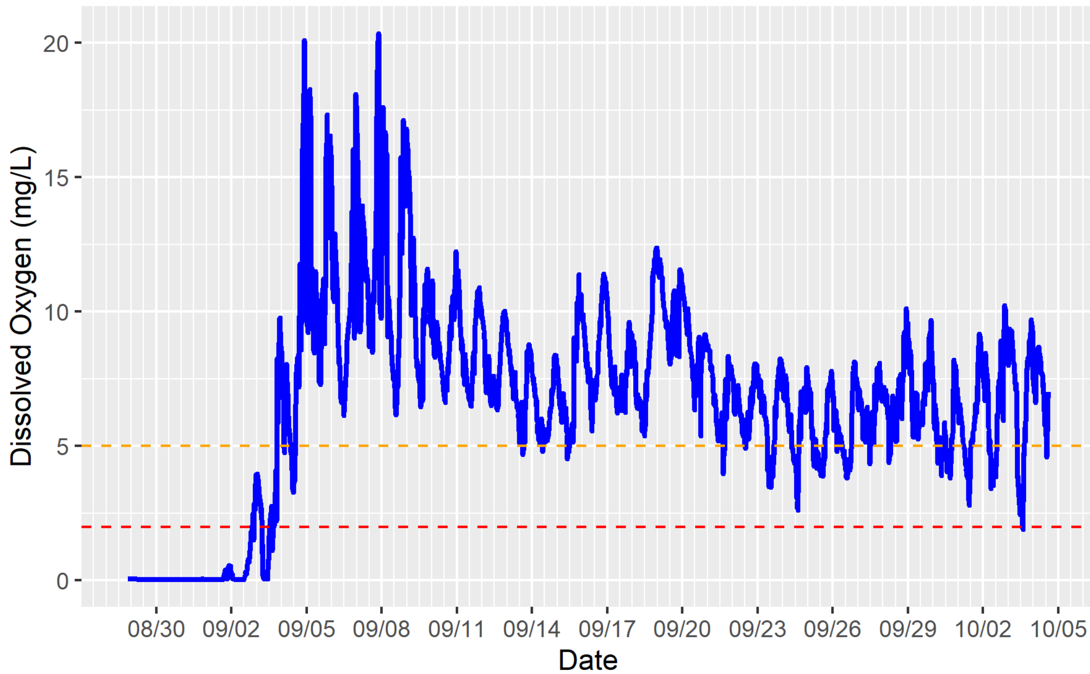

Figure 2 – Continuous dissolved oxygen at the boat dock starting on August 29, one day following the mass fish kill. The orange dashed line represents the Water Board's dissolved oxygen water quality objective for warm, marine, or saline water bodies (5 mg/L). The red dashed line represents hypoxic conditions that cannot support aquatic life (2 mg/L).

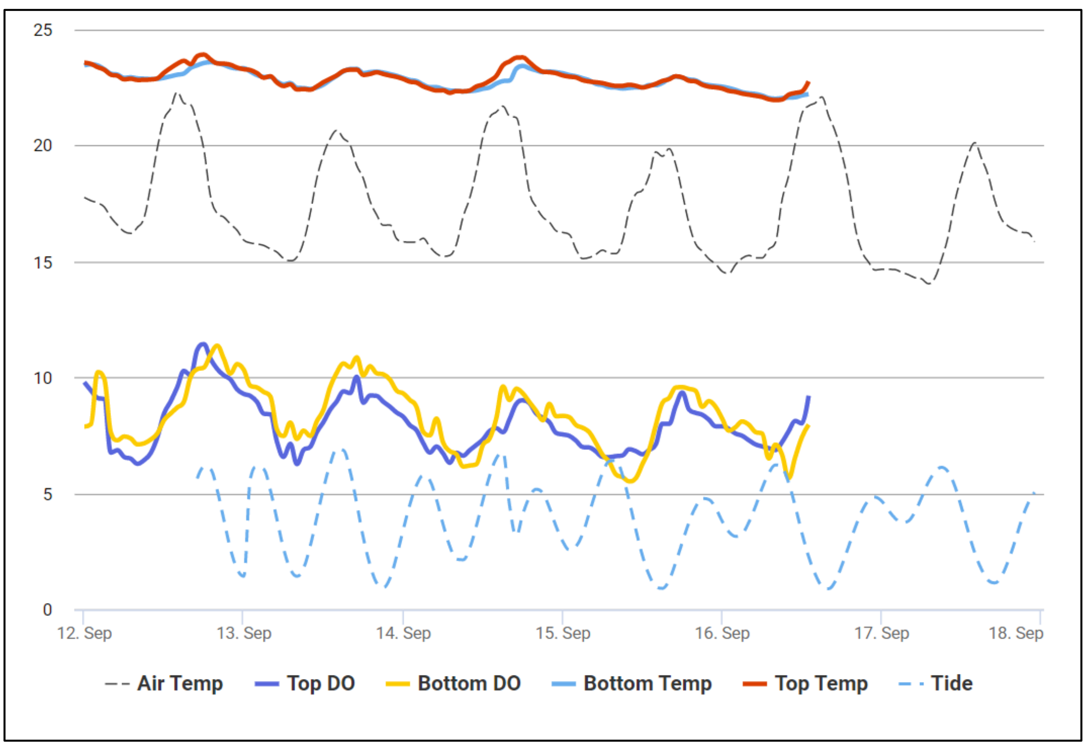

Figure 3 – Continuous water quality data collected by Lake Tech from the middle of the lake starting on September 12, 2022.

3.1.2 pH

The pH conditions following the fish kill were characteristic of waterbodies experiencing algal blooms. The Basin Plan states that pH shall not be depressed below 6.5 nor raised above 8.5. During the hypoxic event, pH was within normal ranges; however, from September 5 – 9, the pH was >8.5 for 21.4% of the readings (Figure 4). Like DO, pH stabilized on September 10.

3.1.3 Temperature

An increase in water temperatures following the fish kill was observed, which can be explained by an increase in ambient air temperatures. From August 29 – September 3, during the low DO event, water temperature fluctuated between 22 and 24°C. From September 4 – 9, the water temperature increased ranging from 23 and 26°C; this increase is explained by above average air temperatures in early September, with air temperatures peaking at 38°C (100°F) on September 5. Beginning September 10, water temperatures decreased as air temperatures cooled (Figure 5). Air temperatures during the HAB were obtained from the National Centers for Environmental Information's Record of Climatological Observations (Menne et al., 2012), which are available in Attachment K.

3.1.4 Specific Conductivity

Specific conductivity was relatively stable during the low DO period, and this low mixing period may have contributed to the drop in DO. Lake Merritt is a tidally influenced water body; specific conductivity can be high and fluctuate from tides, rain, runoff, and tidal gate operations. During the low DO period (August 29 – September 1), the specific conductivity had small daily fluctuations (136.5 µS/cm average daily magnitude) compared to September 2 – October 2 (368.77 µS/cm average daily magnitude; Figure 6).

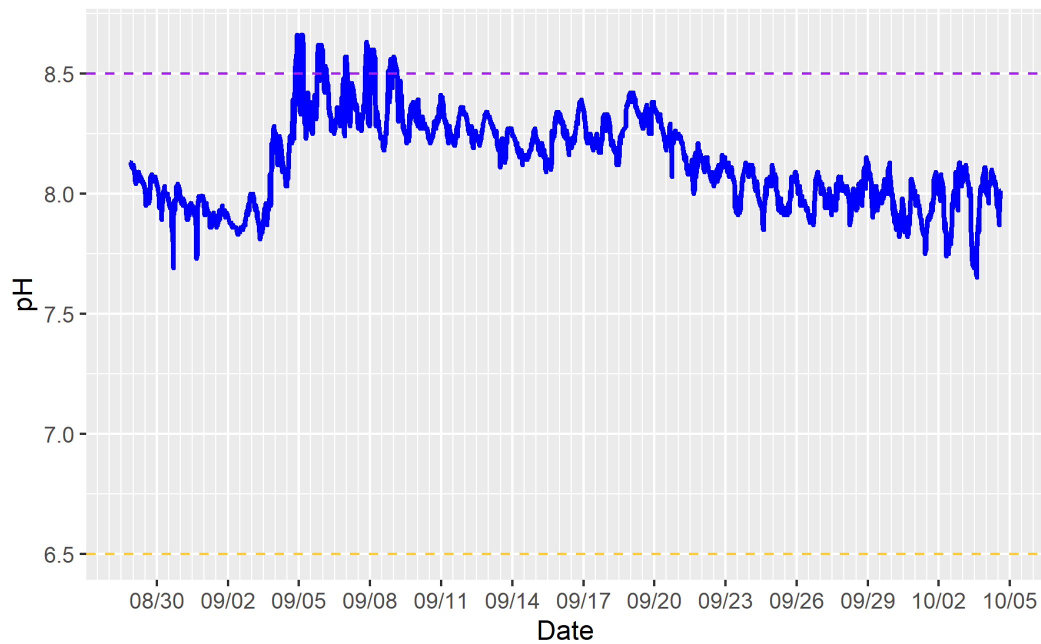

Figure 4 – Continuous pH at the boat dock starting on August 29, one day following the mass fish kill. The yellow dashed line represents the lower pH level under the Water Board's water quality objective. The purple dashed line represents the upper pH limit.

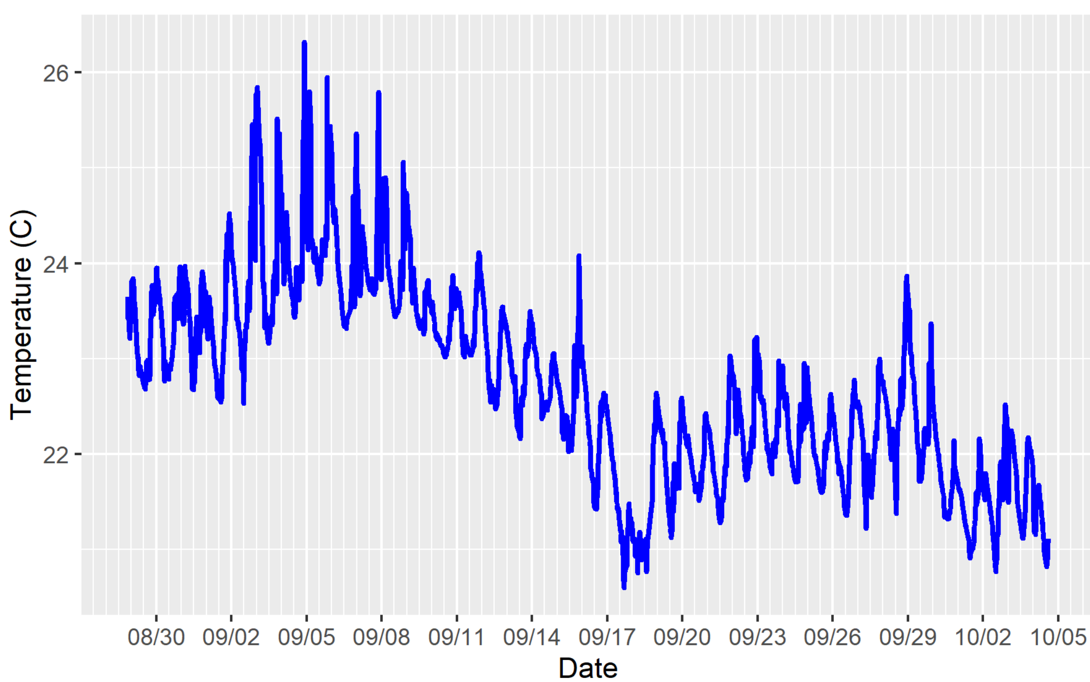

Figure 5 – Continuous temperature (°C) data at the boat dock starting on August 29, one day after the mass fish kill.

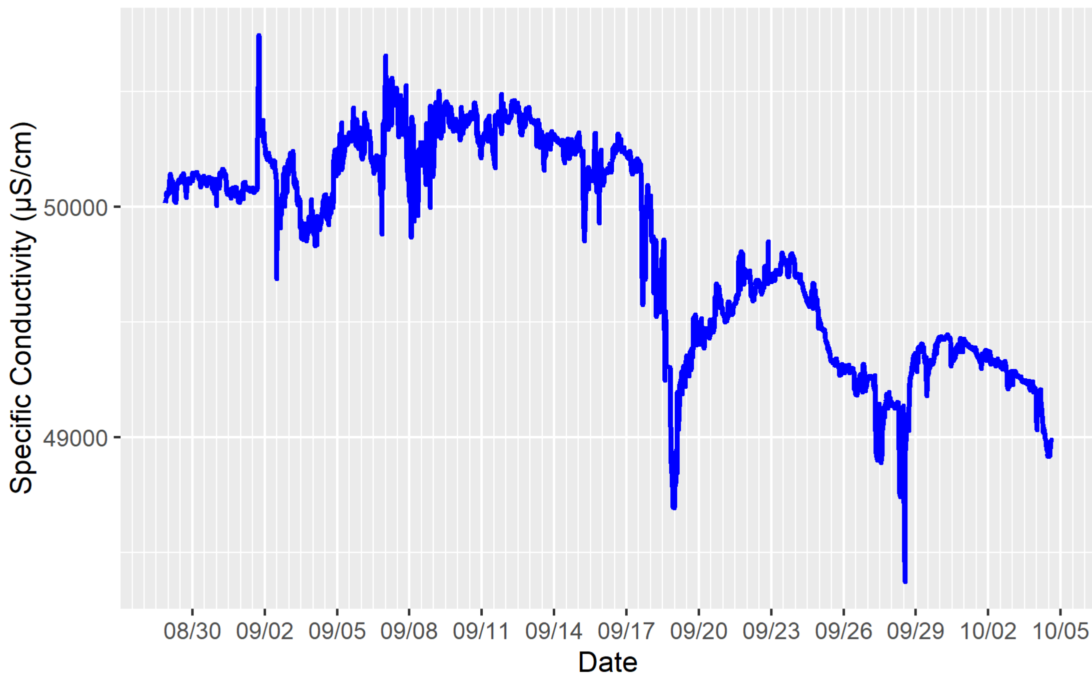

Figure 6 – Continuous specific conductivity (µS/cm) data at the boat dock starting on August 29, one day following the mass fish kill.

3.2 Instantaneous Water Quality Data

Instantaneous water quality measurements from around Lake Merritt were similar to continuous monitoring data collected at the boat dock. On August 29, Water Board staff and Janai Southworth, a local plankton scientist, collected water quality measurements at six sites around Lake Merritt. Ms. Southworth continued to gather daily measurements at these sites as well as five mid-lake measurements through September 7 (Figure 1). Data from all the sites were comparable to results from the deployed sonde; DO readings were at or near 0 mg/L from August 29 – September 2, steadily increased to above 4 mg/L by September 4, and then increased to approximately 12 mg/L by September 7 (Figure 7). During the low DO period, the Lakeshore and 19th St. dock had the highest DO levels (average 1.28 mg/L) compared to other shoreline and mid-lake sites (average 0.28 mg/L), which may explain the larger presence of fish in this section of the lake. This section of the lake is close to an aeration fountain, although it was not functioning during the fish kill. Freshwater inputs from creeks and urban runoff, differences in tidal mixing, and changes in water depth may impact DO concentrations throughout the lake. More research is needed to understand the oxygen dynamics in Lake Merritt; in 2023, the City of Oakland began studying DO conditions as part of an oxygenation pilot program to address the organic enrichment/low DO impairment.

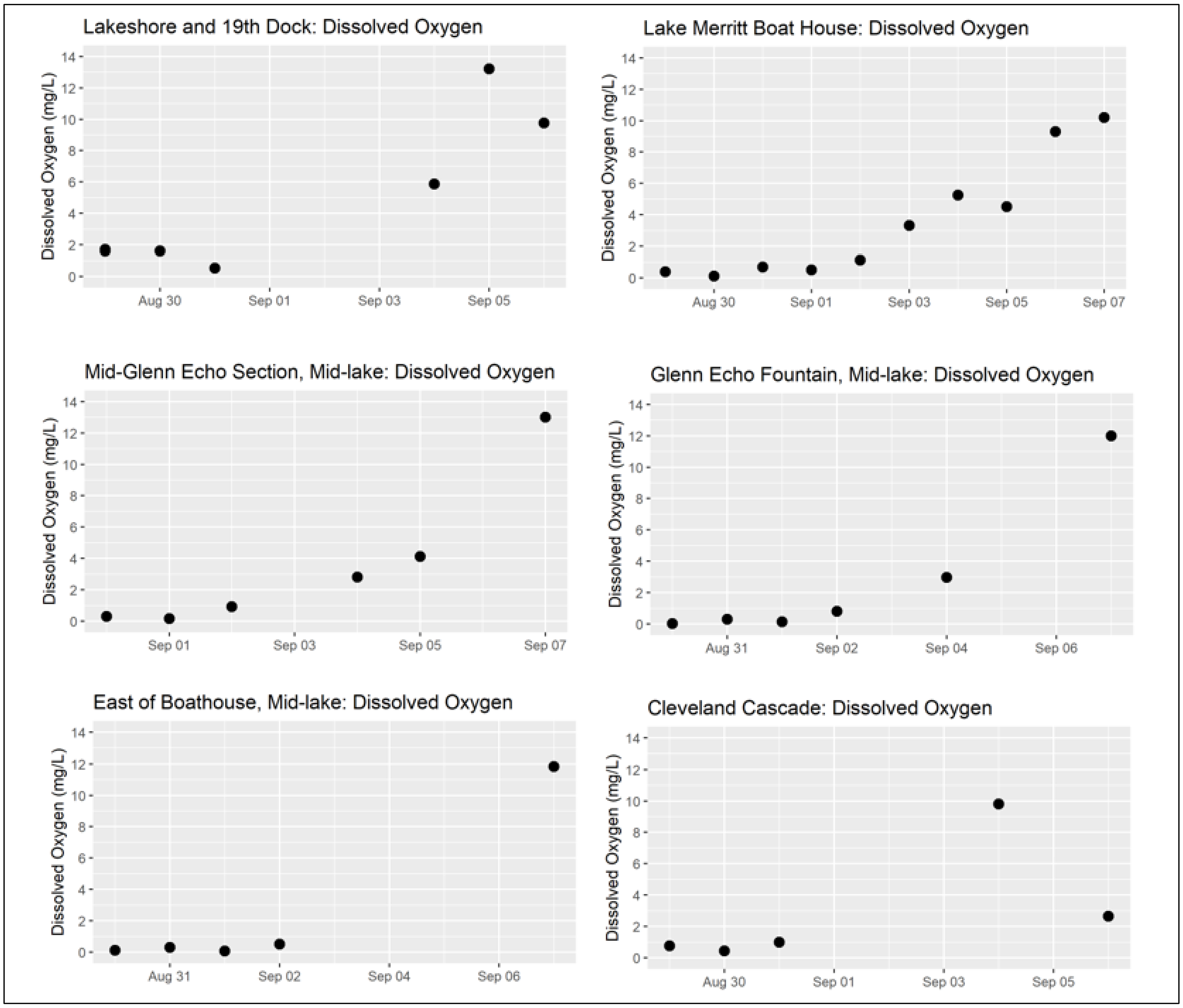

Figure 7 – Instantaneous dissolved oxygen data at select shoreline and middle lake sites.

3.3 Aquatic Wildlife Observations

The first sign of an impending mass kill was observed on August 24 when the Rotary Nature Center Friends and other community members reported dead mussels on the sides of docks. On August 28, the large fish kill was first visible along the Lake Merritt shoreline and the channel connecting to the Oakland Estuary.

Damon Tighe, an Oakland naturalist, posted on Twitter an estimated 10,000 fish had died, including over 522 adult striped bass, although this number is likely an underestimate. Sightings of dead fish in Lake Merritt were reported by the public through iNaturalist, the SFEI Harmful Algal Bloom Fish Mortality Documentation Portal, California's Harmful Algal Bloom Portal, and the CDFW Wildlife Health Lab. Despite the abundant reporting, it is difficult to estimate how many fish died because multiple accounts of the same sightings may have been submitted within and across portals. The "SF Bay Harmful Algae Bloom 2022" report on iNaturalist included observations of dead Bay Ray, California Halibut, European Green Crab, Mediterranean Mussel, Northern Anchovy, Striped Bass, and Yellowfin Goby.

On August 29, Water Board staff surveyed approximately 1000 m of shoreline (approximately 20% of the total shoreline) to document the fish kill. Water Board staff surveyed 100 – 250 m long transects at six shoreline sites (Figure 1). Complete field observations are included in Attachment A. During this survey, there were fewer visible dead fish compared to images taken on August 28. This may be because the dead fish were dispersed throughout the lake by tidal movement or sank to the bottom. Staff noted that fish carcasses were not uniformly distributed throughout the lake. For example, there were no fish carcasses at the pergola or the southside of Lakeshore Ave. In contrast, there was a high abundance of small pelagic fish carcasses on the shallow banks near the amphitheater. The difference in carcass distribution could be because fish were not in high abundance in this area prior to death or because the carcasses were dispersed or no longer visible.

The largest number of visible dead fish were located on the bottom of the lake in the northwest Glen Echo section; observed species included large striped bass, bat rays, yellowfin gobies, jacksmelt and northern anchovies. This section of the lake had the highest dissolved oxygen (between 1.05 and 1.7 mg/L) of the measured sites following the fish kill, suggesting they were attracted to higher (although still lethal) levels of DO. On August 29, there were still large schools of smelt and anchovies swimming and surface breathing (an adaptive behavior to survive during hypoxic events) at the Glen Echo section as well as near the boat docks (Figure 8). By September 1, it appeared that most of these fish had died; only a few small groups of pelagic fish were observed surface breathing on September 1. Larger fish began to bloat and rise back to the surface by August 31; large fish were concentrated in the Glen Echo section, although intermittent patches were observed throughout the lake (Figures 9 and 10).

It is difficult to quantify the number of fish that died during the fish kill due to limited visibility, natural conditions shifting carcasses, and inconsistent abundances throughout the lake. Likewise, some benthic species like leopard shark, halibut, and long-jawed mudsuckers were present prior to the fish kill but were less visible when they died. During the August 29 survey, Water Board staff counted 23 bat rays and 66 striped bass. The number of small pelagic fish and gobies on the shoreline were estimated in 0.5 m^2 quadrants and extrapolated to the total surveyed shoreline for each site. This yielded an estimated 94,000-117,000 dead small fish.

Although DO levels were near 0 mg/L at both the surface and bottom of the lake for at least five days, areas such as creek and storm drain outlets may have maintained DO high enough to support fish and invertebrates. Community scientists and Water Board staff noted high tolerant invertebrates like snails and crabs throughout the fish kill. On September 17, community volunteers captured adult yellowfin goby, long-jawed mudsuckers, and rainwater killifish by the City of Oakland boat docks. These individuals may have survived the low DO period rather than entering the lake through the tidal gates after the fish kill.

Recolonization of Lake Merritt will vary depending on species. Fast growing planktonic species like barnacles were quick to recolonize from inflowing Bay water once DO conditions improved. In the first two weeks of the fish kill, Water Board staff noted an absence of invertebrate growth on sonde equipment, but by mid-September sondes were covered in encrusting invertebrates. Community scientists also observed live barnacle plankton from plankton tow nets by mid-September. In contrast, most of the large and long-lived species like leopard shark, striped bass, and bat rays died in the fish kill. Although young individuals may have reentered the lake since the DO conditions improved, it will be many years before the important ecological role that these large predators play will be filled.

Figure 8 – Pelagic fish surface breathing near Lake Merritt boat docks (August 29, 2022).

Figure 9 – Dead adult striped bass and schools of live anchovy or jacksmelt near the boat docks

Figure 10 – Dead fish near Jackson St. and Lakeside Dr. (August 30, 2022).

4 Lab Analyses

4.1 Freshwater Algal Toxins

Prior to the red tide and fish kill, low levels of the freshwater cyanotoxins microcystin, anatoxin-a, cylindrospermopsin, and saxitoxin were detected in samples collected by the Water Board. In late April 2022, a dead turtle, blue heron, and striped bass at Lake Merritt were reported to the Water Board. In response to the wildlife deaths, and given the recreational uses, Lake Merritt was added to the Water Board's Freshwater Harmful Algal Bloom (FHAB) holiday assessment sampling plan; holiday assessment monitoring is part of a Statewide sampling effort to test for freshwater algal toxins before major recreational holidays. The Water Board collected water samples at shoreline sites at Lake Merritt on May 11, June 20, and August 22 (Table 1). Additional samples were collected at the amphitheater and boat dock on August 29 following the fish kill (Figure 11). Samples were sent to Bend Genetics (Sacramento, CA) where the quantification of total cyanobacterial toxins was determined by enzyme linked immunosorbent assay (ELISA). Complete laboratory reports are available in Attachments B – H.

Samples collected on May 11, 2022, had detectable levels of the freshwater toxins cylindrospermopsin and saxitoxin. The Water Board recommended the City of Oakland post "caution" advisory signs around the lake because of the presence of saxitoxin (a neurotoxin) and the April reports of a dead heron, a turtle and striped bass. Low levels of the freshwater cyanotoxins microcystin, anatoxin-a, cylindrospermopsin, and saxitoxin were consistently detected in samples (Table 1). Two anatoxin-a samples collected on August 22 (6 days before the fish kill event) and August 29 (1 day after the fish kill event) exceeded the California Cyanobacteria and Harmful Algal Bloom Network (CCHAB) caution advisory level. Anatoxin-a from cyanobacteria may have contributed to reported deaths of domestic animals, livestock, and waterfowl (U.S. EPA, 2015); limited information on anatoxin-a's impacts to fish is available, but fish are generally thought to be more tolerant of cyanotoxins than mammals (ILS, 2000). All other anatoxin-a, cylindrospermopsin, and microcystin samples were below the CCHAB advisory levels. There are not advisory levels for saxitoxin, but it was present at low levels in all samples. In sum, we did not see any temporal trends or toxin levels to suggest these toxins caused fish mortality.

4.2 Marine Algal Toxins

On August 29, the Water Board sent water samples from the boat dock, Cleveland Cascade, and the amphitheater to a marine toxin and algae identification lab (Greenwater Lab) to test for brevetoxins because some research suggests brevetoxins may be produced by *Heterosigma akashiwo*. The lab did not observe *Heterosigma* sp. in the samples, but they noted this species is very unstable in samples and likely decayed while in transit. Brevetoxins were not detected in the samples so we conclude this toxin was not the cause of the fish kill. However, all samples included diverse algal species, including some potentially toxigenic cyanobacteria in the Cleveland Cascade sample, so it is possible that algae produced toxins outside of those we measured.

Table 1 – Freshwater and marine algal toxin results for water samples collected in Lake Merritt. Anatoxin-a, cylindrospermopsin, and microcystin were evaluated against the California Cyanobacteria and Harmful Algal Bloom Network (CCHAB) advisory levels for human o or dog safety. Samples exceeding the CCHAB cautionary advisory trigger level are shown in yellow. Toxin concentrations below the laboratory reporting levels are considered non-detect (ND). Saxitoxin, a neurotoxin, was present in all samples, but there are currently no CCHAB or U.S. EPA advisory levels. Brevetoxins, a marine algal toxin, was only analyzed for samples collected after the fish kill.

Date	Location	Anatoxin-a (µg/L)	Cylindrosperm-opsin (µg/L)	Microcystin (µg/L)	Saxitoxin (µg/L)	Brevetoxins (ng/mL)
11-May	Cleveland Cascade	ND	0.1	ND	0.11	-
11-May	Band stand	ND	0.07	ND	0.11	-
20-Jun	Cleveland Cascade	ND	0.11	0.07	0.04	-
20-Jun	Band stand	ND	0.11	0.24	0.06	-
22-Aug	Cleveland Cascade	ND	0.13	0.41	0.09	-
22-Aug	Boat dock	0.16	0.11	0.4	0.09	-
29-Aug	Cleveland Cascade	0.25	0.11	0.24	0.09	ND
29-Aug	Boat dock	ND	0.11	0.2	0.09	ND
29-Aug	Amphitheater	ND	0.11	0.2	0.1	ND

Figure 11 – Water Board staff collecting toxin samples near the Lake Merritt amphitheater

4.3 Fish Necropsy

The mass fish and invertebrate kill was most likely caused by hypoxic conditions due to the red tide. However, there was still interest in determining if toxins or another mechanism from the red tide contributed to mortality. On September 1, 2022, Water Board staff collected recent mortalities (juvenile jacksmelt, *Atherinopsis californiensis*) from the Glen Echo section of the lake (Figure 12). At the time of sampling, juvenile jacksmelt were the only species appropriate for laboratory analysis; larger fish species were too decomposed for necropsy.

Nine recent mortalities were sent to the CDFW Fish Health Laboratory for necropsy. Of the nine fish, five underwent full post-mortem examination and sampling for diagnostic testing; three fish were in relatively good condition, but two appeared to be “older” moralities. The remaining four fish were too small for post-mortem examination and were preserved in formalin.

The Fish Health Lab was unable to definitively determine the cause of death. However, results from the examination support the low DO theory. The body condition of the fish suggests they were in reasonably good health prior to death. Algae was not observed on gill tissue or external surfaces, but that is not sufficient to rule out HAB-related toxicity through an algal toxin or another toxic mechanism. The gills were pale, but no excess mucus or abnormalities were observed. The lab noted gill pallor is a normal postmortem change but can also be caused by compromised respiratory function, and given the algae bloom and hypoxic conditions, this is the most likely scenario.

The full fish health report is included in Attachment I.

Figure 12 – Water Board staff collecting recent mortalities for necropsy.

5 Conclusions

The mass fish kill in Lake Merritt was likely caused by DO depletion associated with a red tide HAB of *Heterosigma akashiwo*. DO levels measured during and following the fish kill were at or near 0 mg/L, which is considered hypoxic and unable to support aquatic life. Low wind, low mixing, and warm temperatures created favorable conditions for an algae bloom and subsequent DO crash. The extent to which some type of direct toxicity of *Heterosigma akashiwo* on the fish kill cannot be evaluated because the specific toxin or toxic pathway produced by this species has not been identified (Gomez et al., 2022; Mehdizadeh Allaf, 2023). However, water quality measurements, necropsy results, and an existing DO impairment suggest low DO caused by the red tide was primarily responsible for the fish kill. We can conclude that brevetoxins, microcystin, anatoxin-a, cylindrospermopsin, and saxitoxin were not found at levels associated with fish toxicity in samples collected one day after the fish kill event.

5.1 Future Work

Beginning in 2023, the Water Board in partnership with the Rotary Nature Center Friends will begin monthly monitoring of HAB conditions in Lake Merritt. Samples will be collected and analyzed for microscopic identification and the ELISA toxin suite during the bloom season (May-October). The Rotary Nature Center Friends is an all-volunteer 501c3 independent charitable nonprofit organization. This monitoring will provide opportunities for HAB outreach and education to the community as well as continued evaluation of the risk for HABs in Lake Merritt. Information gathered by this monitoring is critical to understand HAB conditions in Lake Merritt and inform the public, fulfilling the monitoring and outreach mandates in AB 834. In addition, this data will complement the City of Oakland's pilot project to monitor and improve oxygen conditions in Lake Merritt, which is a Water Board total maximum daily load (TMDL) priority.

The Water Board continues to collaborate with researchers, dischargers, and other agencies through the Nutrient Management Strategy; this collaboration studies impacts of nutrients on San Francisco Bay and evaluates potential management actions to control nutrient inputs to avoid or respond to adverse impacts. The Nutrient Management Strategy is funding the San Francisco Estuary Institute to study the conditions that triggered this HAB in order to reduce the probability of future blooms.

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Attachment A: Field observations

Attachment B: Lab Report for May 11, 2022 cyanobacterial testing

Attachment C: Lab Report for June 22, 2022 cyanobacterial testing

Attachment D: Lab Report for August 22, 2022 cyanobacterial testing

Attachment E: Lab Report for August 29, 2022 cyanobacterial testing

Attachment F: Lab Report for Brevetoxins testing

Attachment G: Lab Report for Qualitative Algae ID

Attachment H: Algae Species List for August 29, 2022 sampling

Attachment I: Fish Health Report

Attachment J: Sonde Data

Attachment K: Record of Climatological Observations