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MERCURY IN FISH IN CALIFORNIA LAKES AND RESERVOIRS: 2015-2023

PREPARED FOR THE
SURFACE WATER AMBIENT MONITORING PROGRAM

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Executive Summary

This document presents a draft final report for a survey to track status and trends in concentrations of contaminants in sport fish in the many California lakes and reservoirs (collectively referred to as “lakes” in this document) where bass species are present.

This work was performed as part of the California State Water Resources Control Board's (State Water Board) Surface Water Ambient Monitoring Program (SWAMP) Statewide Bioaccumulation Monitoring Program (Program). The mission of SWAMP is to provide resource managers, decision makers, and the public with timely, high-quality information to evaluate the condition of all waters throughout California.

In consultation with staff from California’s nine Regional Water Quality Control Boards (Regional Boards), a list of 187 priority bass lakes to be monitored was established. The plan called for sampling these lakes throughout the state over a 10-year period. The sampling was done in five rounds or “panels”, with approximately 38 lakes in each panel and the rounds occurring every other year (Figure 2).

Two primary management questions were articulated to guide the design of this long-term monitoring effort:

- **Management Question 1 (MQ1): Current Status**: What are the recent average concentrations of contaminants of concern in each priority bass lake or reservoir?
- **Management Question 2 (MQ2): Statewide Trend**: What is the trend in statewide average bass mercury concentrations in fish in priority bass lakes and reservoirs?

In addition, two secondary management questions were identified to guide interpretation of the results of the monitoring.

- What fractions of the lakes show decreases, increases, or no change in mercury concentration in fish?
- What factors appear to be driving changes in mercury concentrations in fish?

Answer to MQ1: Current Status

Of the 158 lakes where bass were successfully sampled, 113 (72%) had a mean concentration greater than or equal to 0.2 ppm - the statewide water quality objective for sport fish. Sixty of the 158 lakes (38%) had a mean concentration greater than or equal to 0.44 ppm - the advisory tissue level (ATL) established by the California Office of Environmental Health Hazard Assessment (OEHHA) above which no consumption is generally advised for the sensitive population of fish consumers (children ages 1-17 and women ages 18-49) (orange dots in Figure 3). The median concentration for the 158 lakes was 0.35 ppm, and the mean concentration was 0.46 ppm.

The degree of beneficial use impairment varied regionally, with greater impairment in regions in northern California. Water Board Regions 1, 2, 3, and 5 (North Coast, San Francisco Bay, Central Coast, and Central Valley Regions, respectively) all had mean concentrations of 0.2 ppm or greater in 80% or more of the sampled lakes. Most of the lakes in Regions 6 and 8 (Lahontan and Santa Ana Regions, respectively) also exceeded 0.2 ppm, but the numbers of lakes sampled in these regions were low. Regions 4 and 9 (Los Angeles and San Diego Regions, respectively) had better sample sizes (24 and 18 lakes, respectively), and less impairment: less than half of the lakes in these regions were above 0.2 ppm. Region 7 (Colorado River Region) stood out by having no lakes exceeding 0.20 ppm, but only five lakes were sampled.

In addition to exceeding thresholds of concern for risks to human health, the bass mercury concentrations observed in this study are also high enough to indicate significant risks to piscivorous birds and to the fish themselves. The median concentration in the 158 lakes (0.35 ppm) would correspond to concentrations in grebe blood that are well-within the medium risk range for potential impaired reproduction in birds. Mercury concentrations in prey fish samples also frequently (approximately 50% of samples) exceeded the statewide mercury objective of 0.05 ppm established to protect piscivorous birds. Twenty-three percent of the 158 lakes exceeded a fish risk threshold of 0.58 ppm, a range where effects on biochemical function, gene expression, behavior, reproduction, and histology are possible.

Answer to MQ2: Statewide Trend

Statewide average concentrations from five rounds of sampling in this survey are suggestive of a statewide increase in mercury in bass lakes after 2015. The statewide mean for 2015 was 0.30 ppm. This mean was higher than the statewide water quality objective for predator fish (0.2 ppm), but well below the 0.44 ppm OEHHA ATL for no consumption by the sensitive population. The means for Panels 2-5 were all above 0.45 ppm, in other words at least 50% higher than the mean for 2015 and all above the 0.44 ppm OEHHA ATL. The highest mean was 0.52 ppm in 2023.

Data from individual lakes where prior data were available for comparison also suggested a shift toward increasing concentrations of mercury in bass. In 2015, 15 of the 20 lakes where interannual comparisons were possible generally did not exhibit a significant difference from prior results, five lakes had significantly lower concentrations, and no lakes had an increase. In 2017, 2019, and 2021, the results generally indicated a lack of trend, with most lakes showing no significant change, and an even balance of small numbers of lakes with increases and decreases. A more pronounced deviation from the general pattern was observed in 2023, however, with the highest count (10 of 20 lakes) in the increase category.

Interannual variation in hydrological conditions and a phenomenon known as the reservoir effect is a possible driver of the shift toward higher bass mercury concentrations after 2015. Many studies have shown that newly inundated reservoirs exhibit post-impoundment increases in mercury in aquatic food webs of from three-fold up to 30-fold within the first few years of impoundment, and it often takes one to three decades for concentrations to fall to background levels. The mechanism for these increases is thought to be enhanced microbial methylation of mercury resulting from inundation of terrestrial plant matter and the anaerobic conditions that are created in the flooded areas. This same process can occur in existing reservoirs that undergo major water level fluctuations.

The period during which this survey was conducted coincided with particularly intense interannual hydrologic fluctuations. The first year of sampling in 2015 was the fourth year of a five-year drought. The five-year drought ended in 2017, followed by a dry year in 2018, another wet year in 2019, dry conditions from 2020-2022, followed by a wet year in 2023. Water levels of California reservoirs fluctuated widely in response to the hydrologic fluctuations. For example, in July 2015, in the middle of the fish collection season, California's major reservoirs were generally far below their storage capacity and their historical average storage levels. In contrast, in July 2017 most of the major reservoirs were above their historical average levels and at or near their full capacity.

Information regarding the importance of the reservoir effect in western North America and the observations of hydrological variation in California during the study period support the hypothesis that water level fluctuations could have driven and sustained the statewide increase in bass mercury observed beginning in 2017. The five-year drought could have allowed the establishment of vegetation on exposed lakebeds and oxidation of reduced forms of sulfur to sulfate, which then fueled net methylmercury production and food web accumulation when the lakebeds were inundated again in 2017. Based on studies elsewhere, the effect of the increase in 2017 would have been expected to persist for several years. The increase of 2017 was then likely further added to by continued fluctuations in 2018-2023, including a dry year in 2018 followed by a wet year in 2019, and then three dry years in 2020-2022 followed by a wet year in 2023.

The extreme variation in hydrological conditions observed in California in the past decade may be an indication of conditions that can be expected in the decades to come. Climate change may have contributed to the variation observed and is expected to result in more extreme variation in the future. Increased net methylmercury production and higher concentrations of mercury in fish in California reservoirs seem to be a probable consequence of this variation.

Introduction

This document presents a draft final report for a survey to track status and trends in concentrations of contaminants in sport fish in the many California lakes and reservoirs (collectively referred to as "lakes" in this document) where bass species are present. This work was performed as part of the California State Water Resources Control Board's (State Water Board) Surface Water Ambient Monitoring Program (SWAMP) Statewide Bioaccumulation Monitoring Program (Program). The mission of SWAMP is to provide resource managers, decision makers, and the public with timely, high-quality information to evaluate the condition of all waters throughout California. The mission of the Program is to provide statewide bioaccumulation monitoring data and information that can be used to:

1. Assess and contribute to the protection and restoration of fishing and aquatic life beneficial uses that are impacted by the bioaccumulation of pollutants in California's waterbodies, and

2. Assess the human health risks associated with the consumption of contaminated fish and shellfish in California's freshwater and coastal ecosystems, and use that information to support the development of advisories that would inform consumers of significant health risks associated with the consumption of particular species.

The Program sport fish surveys have accomplished a great deal to document the status of bioaccumulation impacts on beneficial uses in California (Davis et al. 2010, 2012, 2013, 2018, 2019a, b, 2022). Mercury has been shown to be a particular concern across all water body types (Figure 1).

In 2015 the Program took a significant step by initiating a survey to provide status and trend monitoring of bioaccumulation across the three major water body categories that support the fishing beneficial use: lakes and reservoirs, rivers and streams, and the coast. For water bodies where bioaccumulation has been determined to be a concern, a 10-year cycle for providing updated information on status was determined to be a practical minimum revisit frequency. The information generated from these updates will be useful to the State and Regional Water Boards in impairment assessments and 303(d) List updates. The monitoring began with a plan for repeated, systematic sampling of lakes with black bass (largemouth, smallmouth, and spotted bass), starting in 2015.

Lakes with black bass account for a large number and proportion of the water bodies that are not being monitored by other programs and need to be sampled at a 10-year frequency. In consultation with staff from California's nine Regional Water Quality

Control Boards (Regional Boards), a list of 187 priority bass lakes to be monitored was established. The plan called for sampling these lakes throughout the state over a 10-year period. The sampling was done in five rounds or "panels", with approximately 38 lakes in each panel and the rounds occurring every other year (Figure 2).

This survey will address the critical need of managers and the public for updated, high-quality information on the status of contaminant bioaccumulation in these important water bodies. The plan is designed in a way that will also allow tracking of long-term statewide and regional trends in mercury contamination of lake food webs as they respond to factors such as increasing global atmospheric emissions and climate change. Understanding these background trends is critically important in evaluating the effectiveness of mercury control plans (Total Maximum Daily Loads [TMDLs]).

A detailed description of the goals, design, and methods for sample collection and chemical analysis is provided in the document "Sampling and Analysis Plan for Long-term Monitoring of Bass Lakes and Reservoirs in California" (Bioaccumulation Oversight Group 2015) and the update to this document published in 2021 (SWAMP 2021a). Data reports were prepared to document the methods and results for each panel (Davis et al. 2019a, b, 2022, 2025).

Management Questions

Two primary management questions were articulated to guide the design of this long-term monitoring effort. In addition, two secondary management questions were identified to guide interpretation of the results of the monitoring.

Primary Management Question 1 (MQ1): Current Status

What are the recent average concentrations of contaminants of concern in each priority bass lake or reservoir?

Answering this question will address the critical need of managers and the public for timely, high-quality information on the status of contaminant bioaccumulation in priority water bodies. This information will be useful to the Water Boards in impairment assessments and 303(d) list updates. A list of priority bass lakes to include in this monitoring was developed with input from the Regional Boards.

Mercury is the contaminant of greatest concern in most bass lakes and was the primary focus of this monitoring. However, PCBs and organochlorine pesticides also reach levels of concern in a small subset of these lakes and were monitored in those situations.

The data needed to answer this question are average concentrations of contaminants of concern in the species with a tendency to accumulate high concentrations. For mercury, top predators such as black bass tend to accumulate relatively high concentrations. Furthermore, black bass have been established as an excellent quantitative mercury bioaccumulation indicator for California because they are amenable to length-standardization.

Primary Management Question 2 (MQ2): Statewide Trend

What is the trend in statewide average bass mercury concentrations in fish in priority bass lakes and reservoirs?

A statewide control program for mercury is being developed by the State Water Board. Mercury TMDLs have also been developed for other water bodies, including the Delta, San Francisco Bay, and some lakes and reservoirs. For all of the mercury control plans in the state, it is critically important to know whether food web mercury concentrations are trending up or down on a regional or statewide scale. A statewide increasing trend could obscure the beneficial effects of management actions to reduce mercury bioaccumulation. In the absence of awareness of such a trend, false conclusions could be drawn that actions are not having the desired effect. On the other hand, the existence of a general declining trend could give the impression that actions are more effective than they actually are.

It is plausible to hypothesize that food web mercury could be increasing across the state, either due to increasing atmospheric mercury emissions in Asia (Chen et al. 2012, Drevnick et al. 2015) or due to global warming (Schneider et al. 2009). Several studies have reported evidence of regional increases in food web mercury in north-central North America (e.g., Monson 2009, Monson et al. 2011, Gandhi et al. 2014), although more recent data from Minnesota suggest a return to a long-term pattern of decline (Bruce Monson, personal communication). Hypothesized causes of these regional trends include global atmospheric emissions, climate change, invasive species, and changes in food web structure.

The data needed to answer this question are measurements of statewide average concentrations that are repeated over time. The large number and wide distribution of bass lakes that have been identified as priorities for sampling provide a population of water bodies that can be sampled to assess statewide and regional trends in food web mercury over time. Repeated rounds of sampling of randomly selected subsets of these lakes have yielded a time series of representative, average statewide concentrations. These statewide averages are based on concentrations in black bass, which have been demonstrated to be indicator species that are representative of conditions in the water body where they are collected and that yield data that are comparable across water bodies and over time.

Secondary Management Questions to Guide Data Interpretation

What fractions of the lakes show decreases, increases, or no change in mercury concentration in fish?

Monitoring of mercury in groups of lakes in other regions of North America have shown that temporal trends in fish mercury levels commonly vary among lakes, with some lakes showing decreases, some showing increases, and some showing no change. Examination of fish mercury levels from the small number of California lakes that have been sampled twice (first in 2007-2008 and again in 2012 or 2013) suggest that this outcome can be expected in California as well.

What factors appear to be driving changes in mercury concentrations in fish?

Environmental managers will want to know what causal factors of processes are contributing to variability in temporal trends among lakes. The monitoring data obtained in this program will be used to develop hypotheses regarding factors and processes causing observed trends. The development of hypotheses may stimulate focused investigations by scientists in academic, state, federal and Tribal sectors.

A detailed description of the methods for sample collection and chemical analysis is provided in the Sampling and Analysis Plan documents (Bioaccumulation Oversight Group 2015, SWAMP 2021b).

Answers to Management Questions

Answer to Management Question 1 (MQ1): Current Status

Black Bass

Information for each lake sampled during the eight-year survey is summarized in Tables 1-9, organized by Water Board Region. To summarize status, the table shows the lake-wide mean concentrations measured in black bass. Where available, the table presents values based on length-adjusted means. In some lakes, bass were not available, and this is indicated in the table. In other cases, bass were not caught in sufficient numbers, or did not yield a significant regression - in these cases simple averages of fish between 305 mm and 395 mm are presented. The table also summarizes information on interannual variation - this is discussed below in the section "Answer to Management Question 2 (MQ2): Statewide Trend."

The monitoring design, based on collecting black bass across size ranges to support linear regression of mercury versus length to allow calculation of length-adjusted means, was successfully implemented across the state. Length-adjusted mean concentrations for black bass were successfully generated for 139 of the 167 lakes that were sampled, providing a robust dataset for evaluating spatial and temporal variation (Tables 1-9, Figures 3 and 4). Black bass were successfully collected at 158 of the 167 lakes sampled. At 19 of the lakes with bass, the numbers collected were insufficient to support regression, or the regressions were not statistically significant - for these lakes, simple means of fish between 305 mm and 395 mm were calculated. Eighteen of the 187 lakes originally identified for sampling in this survey were not sampled due either to access issues (caused by low lake levels during dry years, wildfires, or permission on private lakes) or to lakes being deprioritized by the Regional Boards.

Most of the lakes sampled exceeded one or more thresholds established to protect human health. Of the 158 lakes where bass were sampled, 113 (72%) had a mean concentration greater than or equal to 0.2 ppm - the statewide water quality objective for sport fish (Palumbo and Iverson 2017). Sixty of the 158 lakes (38%) had a mean concentration greater than or equal to 0.44 ppm - the advisory tissue level (ATL) established by the California Office of Environmental Health Hazard Assessment (OEHHA) (Klasing and Brodberg 2017) above which no consumption is generally advised for the sensitive population of fish consumers (children ages 1-17 and women ages 18-49) (orange dots in Figure 3). The median concentration for the 158 lakes was 0.35 ppm, and the mean concentration was 0.46 ppm. Seven of the 158 lakes (4%) had a mean concentration greater than or equal to 1.31 ppm - the OEHHA ATL above which no consumption is generally advised for the general population of fish consumers (including women over 49 and men) (orange dots in Figure 4):

- 2.71 ppm: Almaden Reservoir
- 1.81 ppm: Soulejoule Lake
- 1.70 ppm: Little Rock Reservoir
- 1.52 ppm: Davis Creek Reservoir
- 1.43 ppm: Uvas Reservoir
- 1.35 ppm: Hernandez Reservoir
- 1.34 ppm: Rollins Reservoir

The distribution of length-adjusted mean concentrations obtained in the bass lake survey was very similar to the distribution obtained by the Program overall from 2007-2023. As mentioned previously, the bass lake survey obtained length-adjusted means for 139 lakes. Overall, the Program obtained length-adjusted means for 209 lakes (Figure 5). For this larger dataset, 67% were over the 0.2 ppm statewide water quality objective for sport fish, the median concentration was 0.32 ppm, and the mean was 0.43 ppm.

The degree of beneficial use impairment varied regionally, with greater impairment in regions in northern California (Tables 1-9). Regions 1, 2, 3, and 5 (North Coast, San Francisco Bay, Central Coast, and Central Valley Regions, respectively) all had mean concentrations of 0.2 ppm or greater in 80% or more of the sampled lakes. Most of the lakes in Regions 6 and 8 (Lahontan and Santa Ana Regions, respectively) also exceeded 0.2 ppm, but the numbers of lakes sampled in these regions were low. Regions 4 and 9 (Los Angeles and San Diego Regions, respectively) had better sample sizes (24 and 18 lakes, respectively), and less impairment: less than half of the lakes in these regions were above 0.22 ppm. Region 7 (Colorado River Region) stood out by having no lakes exceeding 0.20 ppm, but only five lakes were sampled.

An ATL of 0.07 ppm, below which the sensitive population can safely consume 3 servings per week, can be used to identify lakes at the low end of the overall distribution of mean concentrations. Lakes with mean concentrations below 0.07 ppm were all in southern California, with three in Region 4, one in Region 7, and five in Region 9 (dark purple dots in Figure 3).

In addition to exceeding thresholds of concern for risks to human health, the bass mercury concentrations observed in this study are also high enough to indicate significant risks to piscivorous birds and to the fish themselves. Ackerman et al. (2015), as part of a SWAMP study, established quantitative relationships between mercury concentrations in black bass, prey fish, and grebes. Based on these relationships, they estimated that a concentration of 0.2 ppm in sport fish corresponds to a total mercury concentration of 1.0 ug/g wet weight in grebe blood. This concentration in avian blood corresponds to the beginning of the “medium risk” benchmark for potential impaired reproduction in birds. The median concentration in the 158 lakes (0.35 ppm) was well above 0.2 ppm and would correspond to concentrations in grebe blood that are well-within the medium risk range. Since 0.35 ppm is just the median concentration for bass, many lakes in California have mercury levels in bass that would translate to high or extra high risk to grebes or other piscivorous birds.

The concentrations observed in many of the lakes sampled are also in a range associated with potential risks to fish (Figure 6). A low effect range for fish, where effects on biochemical function and gene expression are possible, is from 0.36 - 0.58 ppm in muscle. Approximately the upper half of the distribution for the 158 lakes therefore has high enough mean bass mercury concentrations to elicit these effects. An intermediate effect range is from 0.58 - 2.1 ppm, where effects on behavior, reproduction, and histology are also possible. Twenty-three percent of the 158 lakes exceeded 0.58 ppm.

Prey Fish

Mercury concentrations in prey fish were also monitored and frequently exceeded the statewide water quality objective of 0.05 ppm for mercury in prey fish that was established to protect piscivorous birds (Palumbo and Iverson 2017). The prey fish dataset for 2023 has not yet been reported. However, the datasets for 2015, 2017, 2019, and 2021 have been published (Davis et al. 2019a,b; 2022; 2025).

Concentrations of mercury in the composite prey fish samples frequently exceeded the statewide objective: 30% of the 2015 samples, 59% in 2017, 45% in 2019, and 46% in 2021. The higher percentages above 0.05 ppm in 2017 and beyond match the general pattern of higher concentrations observed in those years in black bass.

Lakewide average concentrations of mercury in prey fish exceeded 0.05 ppm in similar frequencies: 24% in 2015, 56% in 2017, 45% in 2019, and 42% in 2021.

Answer to Management Question 2 (MQ2): Statewide Trend

Statewide Average Concentrations

The time series of statewide means from the five panels (Figure 7) is suggestive of a statewide increase in mercury in bass lakes after 2015. The statewide mean for Panel 1 in 2015 was 0.30 ppm. This mean was higher than the statewide water quality objective for predator fish (0.2 ppm), but well below the OEHHA ATL for no consumption by the sensitive population (0.44 ppm). The means for Panels 2-5 were all above 0.45 ppm, in other words at least 50% higher than the mean for 2015 and all above the 0.44 ppm OEHHA ATL. The highest mean was 0.52 ppm in 2023.

A non-parametric analysis of variance using the Kruskal-Wallis (KW) test resulted in a p value of 0.083, slightly higher than the conventional alpha of 0.05. Running the KW test with outliers excluded resulted in a p value of 0.035, below the conventional alpha of 0.05. The KW test with outliers removed indicated that the mean ranks were not statistically equal but multiple comparisons using Dunn's test did not show enough evidence for a statistical difference between any pair of groups.

The consistency of the series of higher means after 2015 adds to the evidence suggesting an increase.

Trends in Individual Lakes

Data from individual lakes also suggested a shift toward increasing concentrations of mercury in bass (Table 10). Many of the lakes sampled in the 2015-2023 survey were also included in previous rounds of Program sampling. In many cases (about 20 lakes per panel), length-adjusted means from the panel could be compared to length-adjusted means from prior sampling. The most recent prior results were used for these comparisons. Most of the prior data were generated during the Program's first statewide lakes survey in 2007-2008, but some were more recent.

In 2015, 20 lakes where interannual comparisons were possible generally showed a lack of change, with a slight skew toward decreases. Fifteen of the 20 lakes did not exhibit a significant difference from prior results, five lakes had significantly lower concentrations, and no lakes had an increase. In 2017, 2019, and 2021, the results generally indicated a lack of trend, with most lakes showing no significant change, and an even balance of small numbers of lakes with increases and decreases. A more pronounced deviation from the general pattern was observed in 2023, however, with the highest count (10 of 20 lakes) in the increase category.

Possible Drivers of Interannual Trends

The data from the bass lake survey suggest a statewide shift toward higher concentrations after 2015. Interannual variation in hydrological conditions is a possible driver of this pattern.

A phenomenon known as the "reservoir effect" is a strong candidate for explaining the shift in statewide mean bass mercury concentrations. Many studies have shown that newly inundated reservoirs exhibit rapid post-impoundment increases in mercury in aquatic food webs (Hecky et al. 1991, Bodaly and Fudge 1999, Bodaly et al. 2007, Willacker et al. 2016, Eagles-Smith et al. 2018). The increases can be from three-fold up to 30-fold and occur within the first few years of impoundment (Eagles-Smith et al. 2018), and it often takes one to three decades for concentrations to fall to background levels (Willacker et al. 2016). The magnitude of the increases has been linked to the amount of area flooded relative to the surface area of the reservoir (Bodaly et al. 2007). Willacker et al. (2016) did an extensive review of data for western North America and found that fish mercury concentrations peaked in three-year-old reservoirs then rapidly declined.

The mechanism for these increases in food web mercury concentrations is thought to be enhanced microbial methylation of inorganic mercury resulting from inundation of terrestrial organic matter and the anaerobic conditions that are created in the flooded soils (Willacker et al. 2016). This same process can occur in existing reservoirs that undergo major water level fluctuations. Of particular importance are water level fluctuations that lead to multi-year periods of sediment drying and exposure to the atmosphere, which allows re-oxidation of the sediment/soil and colonization by vegetation - this vegetation decays when the area is again inundated and creates the anaerobic conditions that favor the presence and activity of the sulfate-reducing bacteria that produce methylmercury. In addition, sediment sulfate concentrations and subsequent methylmercury production are positively correlated with the duration of sediment exposure (Eckley et al., 2015), and are particularly high in sediment that has been exposed for a year or more (Selch et al., 2007).

The period during which this survey was conducted coincided with particularly intense interannual hydrologic fluctuations (Figure 8). The first year of sampling in 2015 was the fourth year of a five-year drought, and 40% of the state was classified as being in an exceptional drought for the entire year. The five-year drought ended in 2017, greatly reducing the area and severity of the area impacted by drought. This was followed by a dry year and a return of drought conditions in 2018, and then another wet year that had even less area under drought than 2017. Dry conditions prevailed again from 2020 to 2022, followed by a wet year and sharp reduction in drought area in 2023.

Water levels of California reservoirs fluctuated widely in response to the hydrologic fluctuations (Figures 9-11). In July 2015, in the middle of the fish collection season, California's major reservoirs were generally far below their storage capacity and their historical average storage levels (Figure 9). In contrast, in July 2017 most of the major reservoirs were above their historical average levels and at or near their full capacity (Figure 10). Storage level fluctuations continued from 2018-2023 (Figures 10 and 11).

Information regarding the importance of the reservoir effect in western North America and the observations of hydrological variation in California during the study period support the hypothesis that water level fluctuations could have driven and sustained the statewide increase in bass mercury observed beginning in 2017. The five-year drought could have allowed the establishment of vegetation on exposed lakebeds and oxidation of reduced forms of sulfur to sulfate, which then fueled net methylmercury production and food web accumulation when the lakebeds were inundated again in 2017. Based on studies elsewhere, the effect of the increase in 2017 would have been expected to persist for several years. The increase of 2017 was then likely further added to by continued fluctuations in 2018-2023, including a dry year in 2018 followed by a wet year in 2019, and then three dry years in 2020-2022 followed by a wet year in 2023.

The extreme variation in hydrological conditions observed in California in the past decade may be an indication of conditions that can be expected in the decades to come. Climate change may have contributed to the variation observed and is expected to result in more extreme variation in the future. Increased net methylmercury production and higher concentrations of mercury in fish seem to be a probable consequence of this variation.

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Figures

Figure 1. Mercury concentrations in California fish, 2007-2017

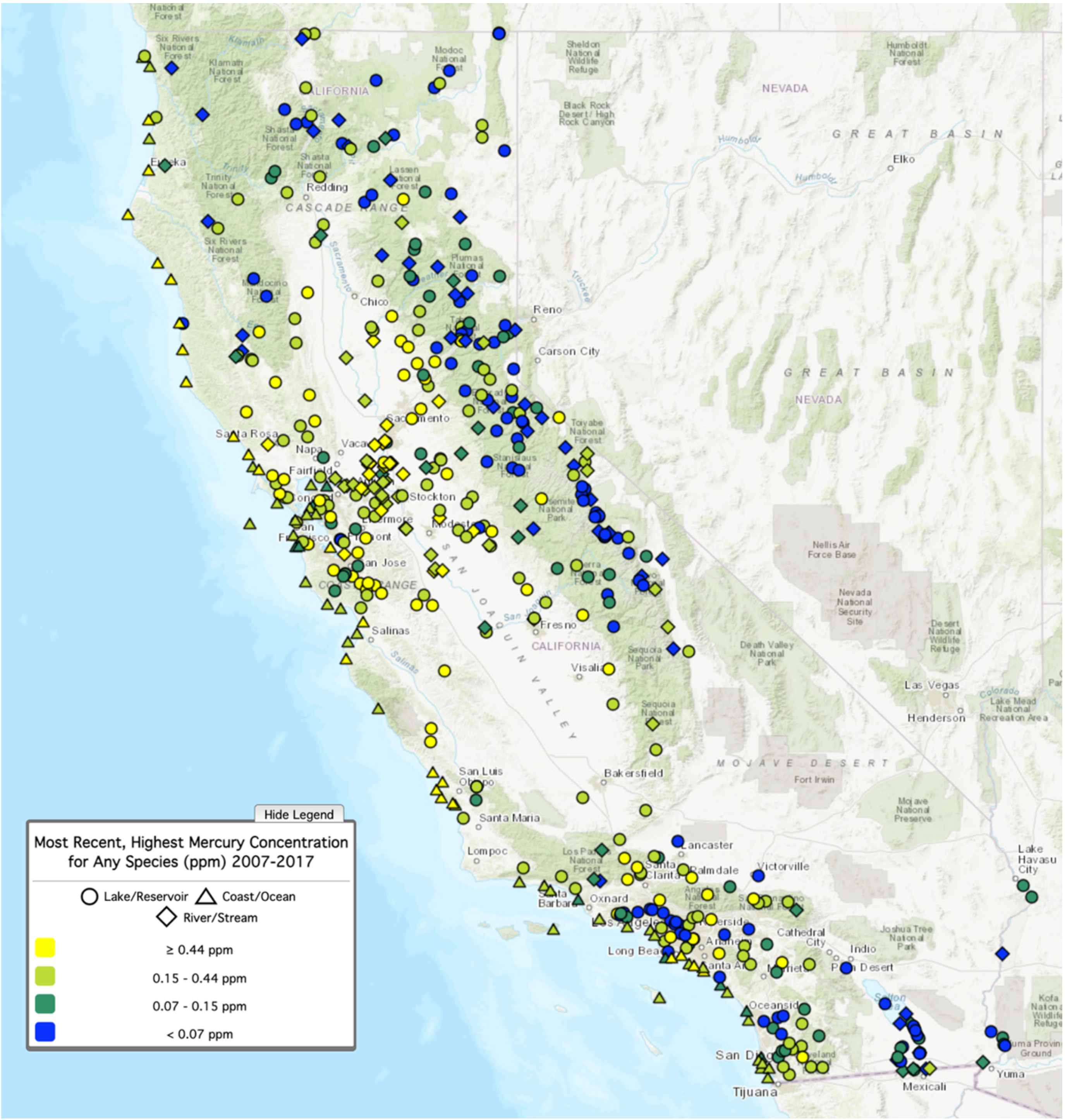


Figure 2. Priority bass lakes included in the 2015-2023 survey

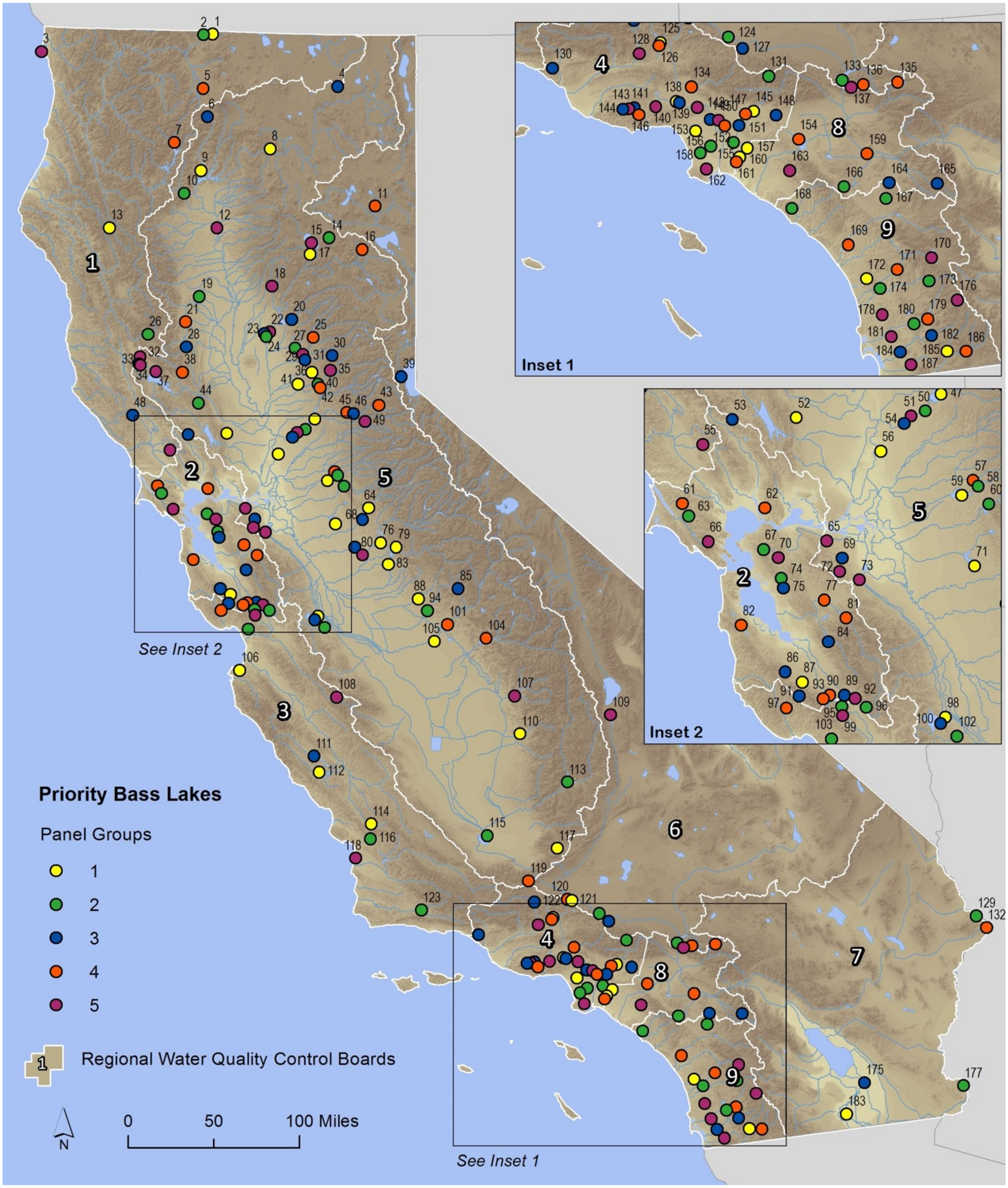


Figure 3. Average length-adjusted mercury concentrations in black bass, 2015-2023, compared to ATLs for the sensitive population

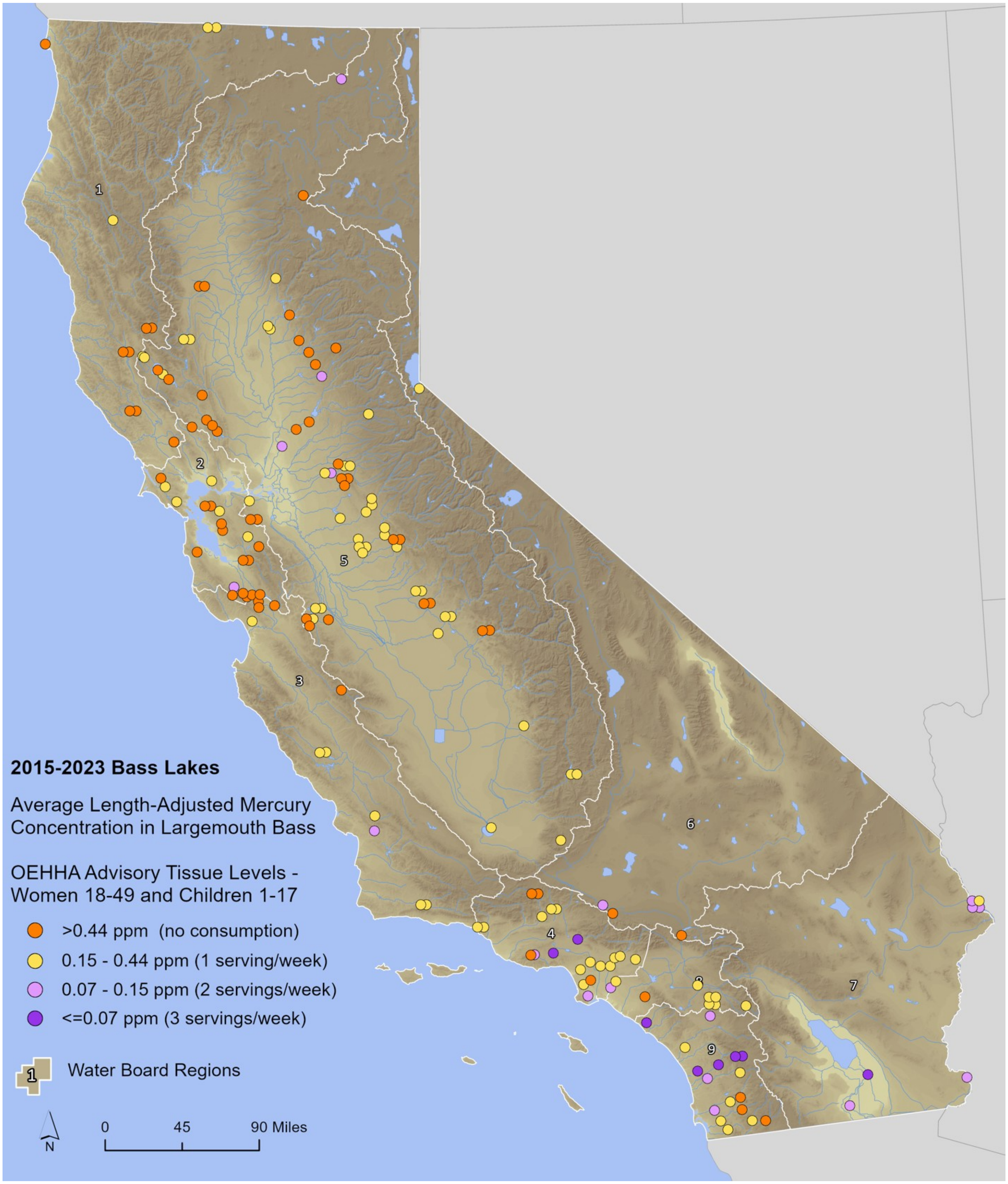


Figure 4. Average length-adjusted mercury concentrations in black bass, 2015-2023, compared to ATLs for the general population

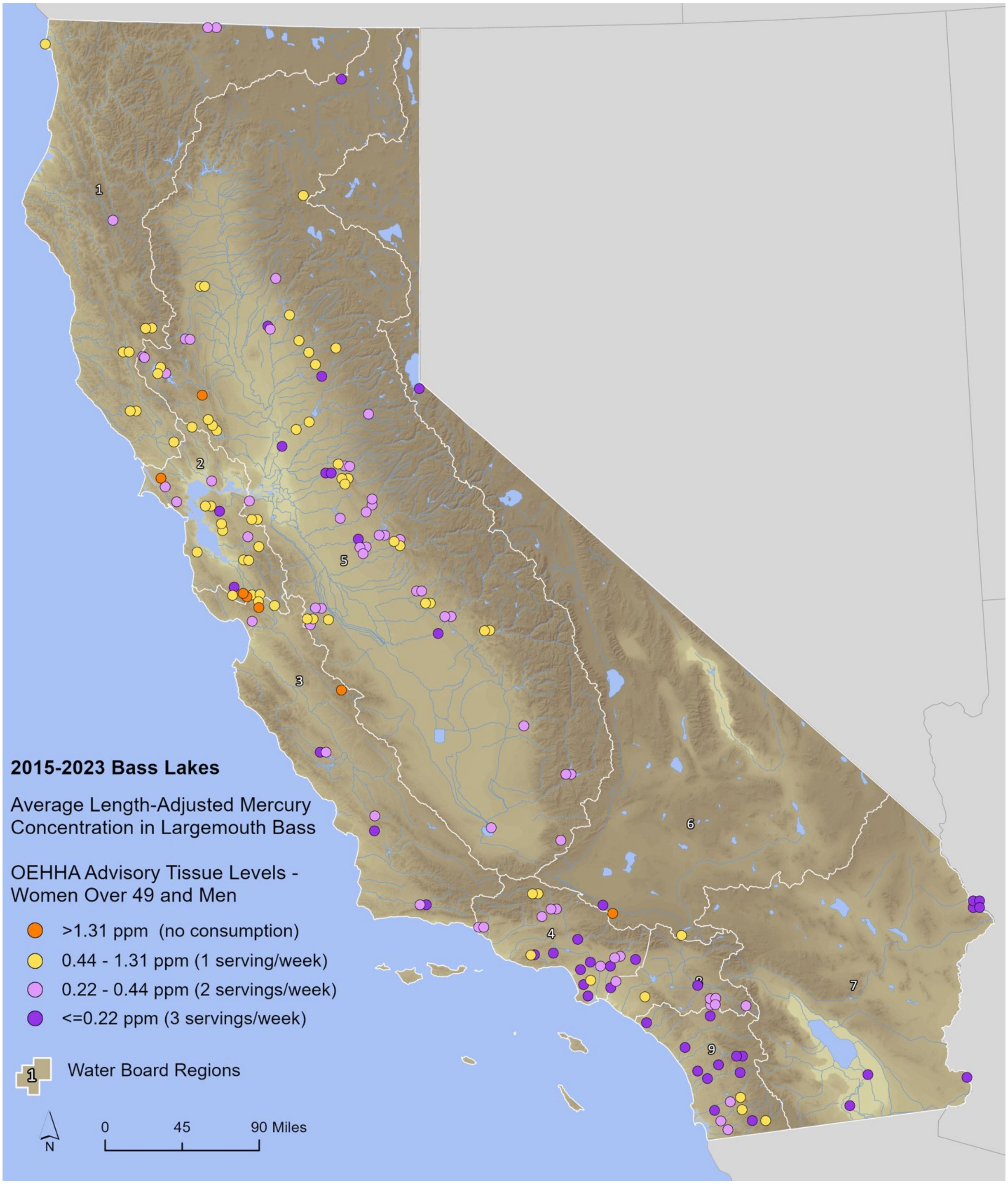


Figure 5. Overall distribution of length-adjusted mean mercury in black bass in California lakes generated by the Program

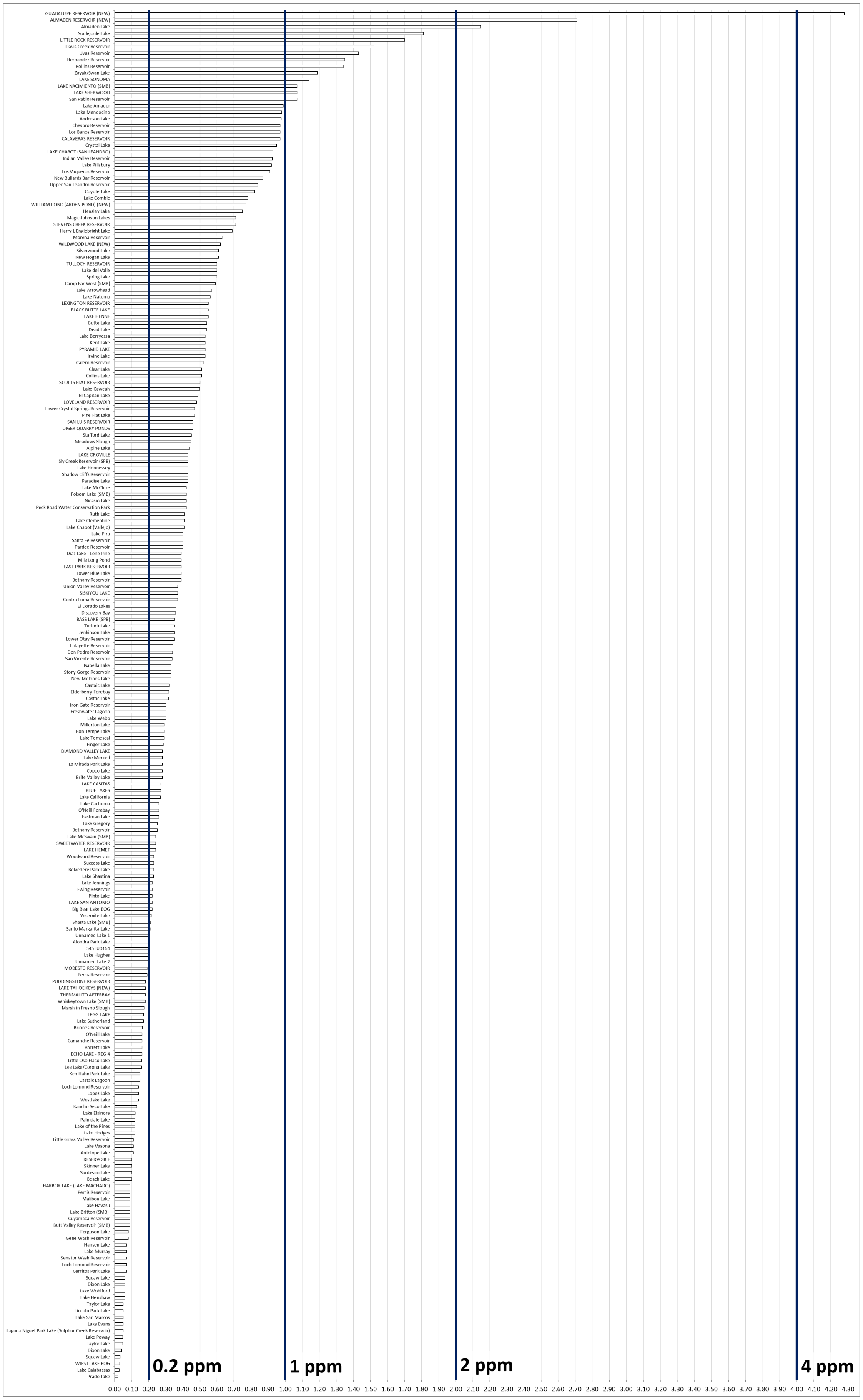


Figure 6. Four ranges of whole-body mercury concentrations in fish and their potential adverse effects on fish health

From Seymour et al. (2023). These whole-body concentrations translate to cutoffs of 360 ng/g, 580 ng/g, and 2100 ng/g for muscle based on Peterson et al. (2005).

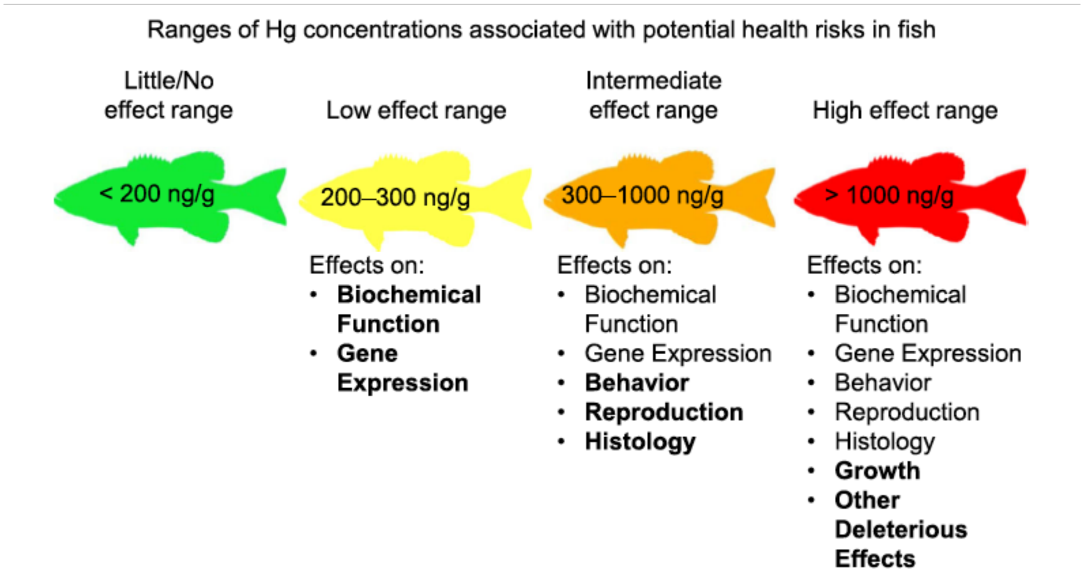


Figure 7. Statewide mean mercury concentrations in black bass, 2015-2023

Based on length-adjusted mean mercury concentrations (ppm wet weight) for lakes from the randomized panel for each year (excluding lakes added to the panels in response to Regional Board requests). Error bars show ± 2 times the standard error of the mean. Red dashed line indicates the 0.2 ppm California statewide water quality objective for predator fish. C: critically dry year; W: wet year.

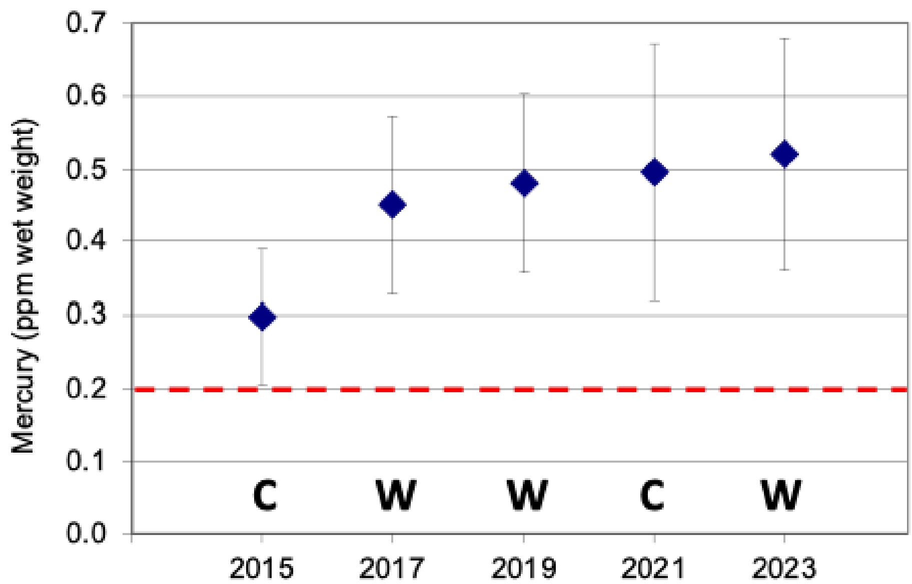


Figure 8. Drought area in California, 2000-2024

C: critically dry year; W: wet year. Source: Phoenix7777, CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0, via Wikimedia Commons

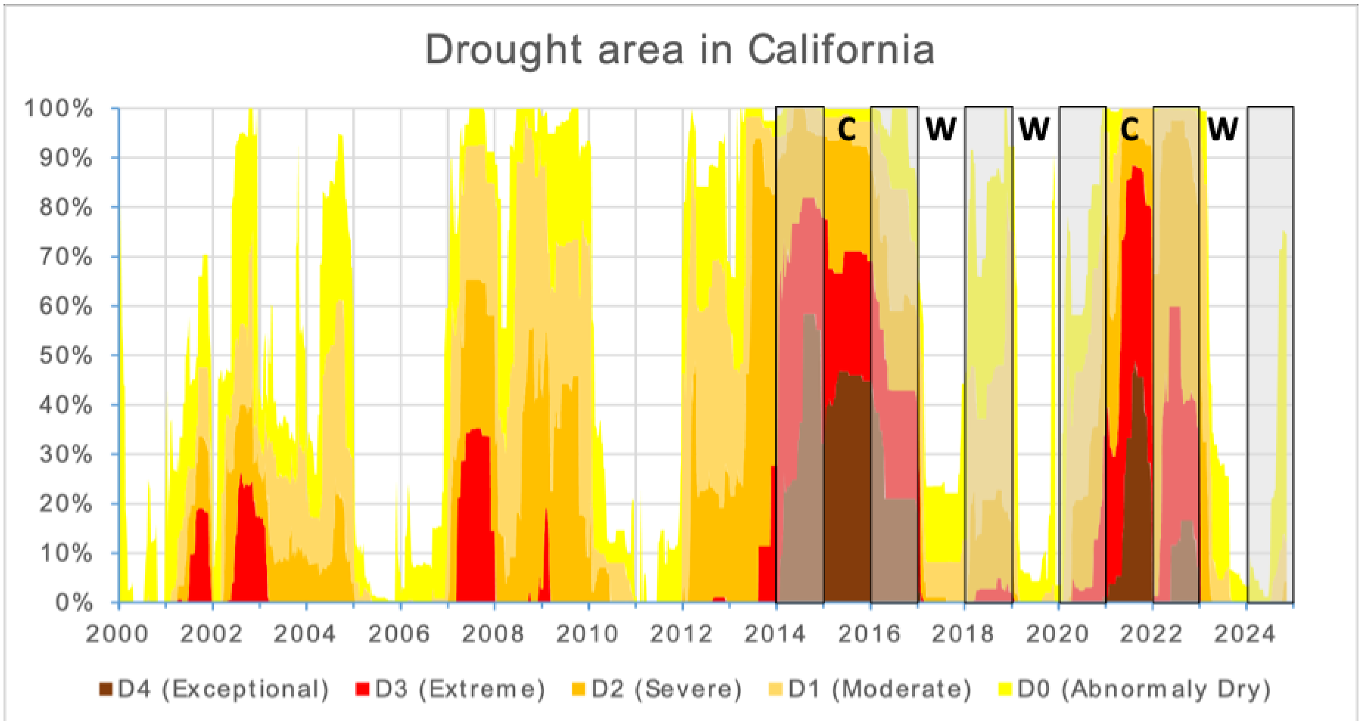


Figure 9. Storage levels for major reservoirs in California, 1 July 2015

Data from https://cdec.water.ca.gov/resapp/RescondMain

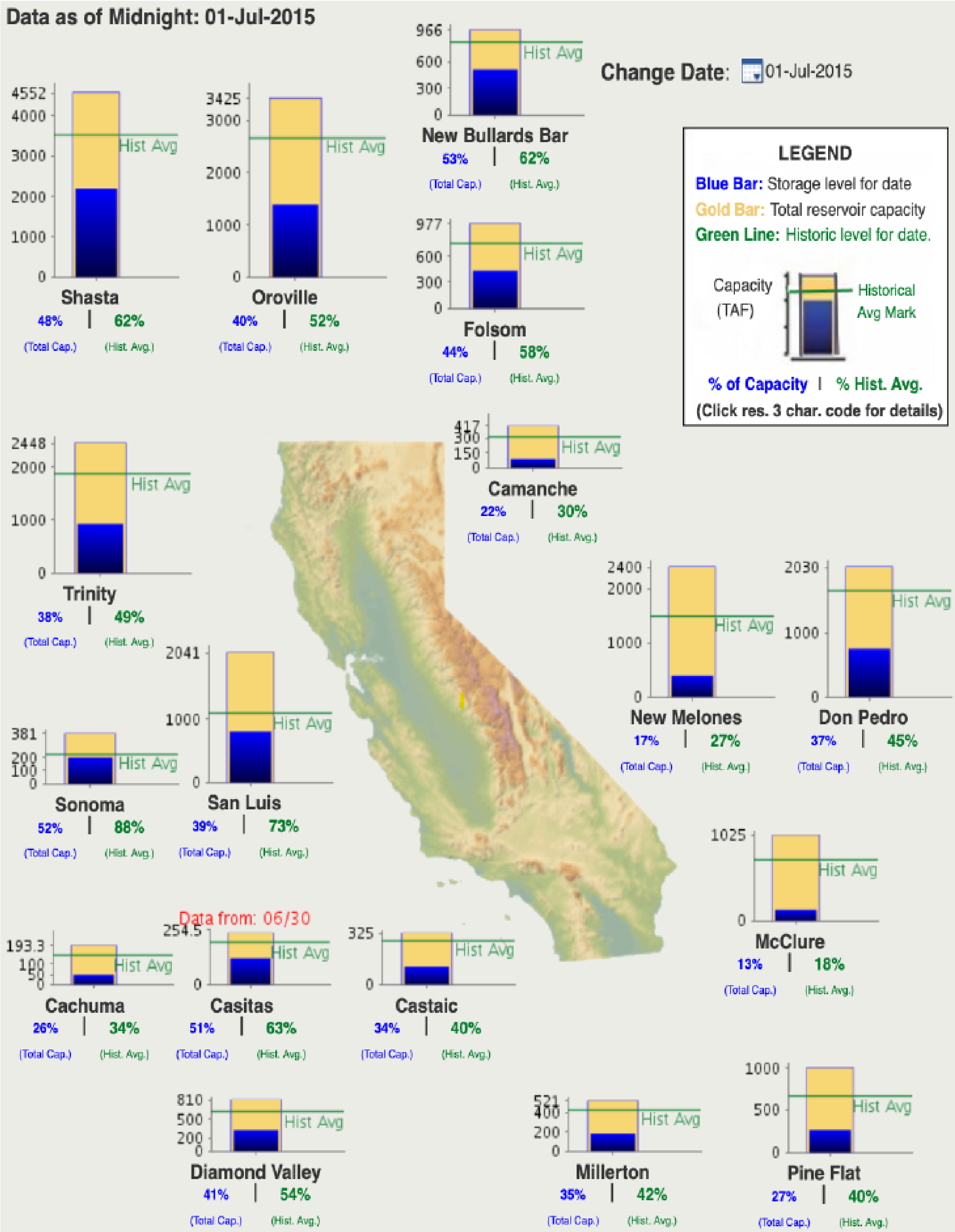


Figure 10. Water storage of major reservoirs in California: 2015, 2017, and 2019

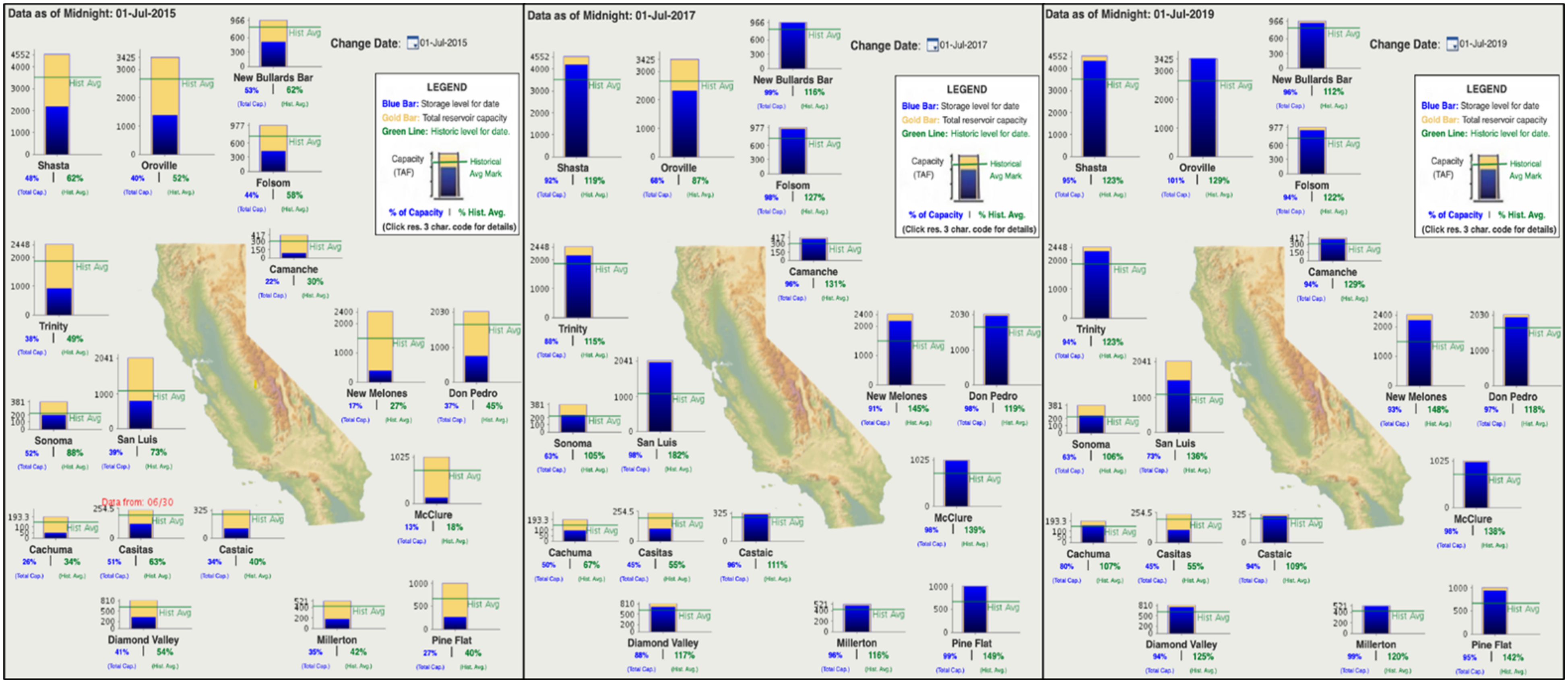
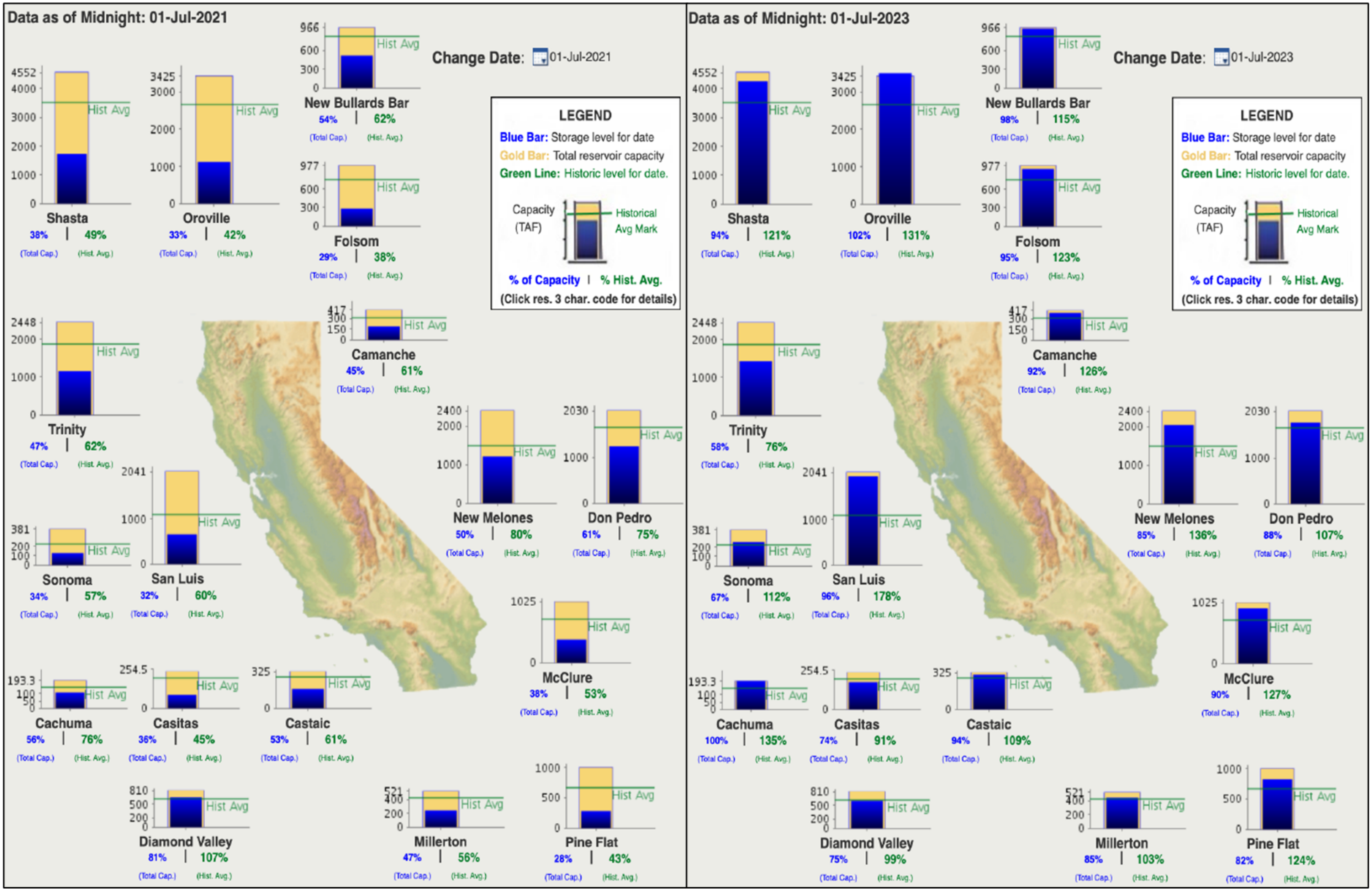


Figure 11. Water storage of major reservoirs in California: 2021 and 2023



Tables

Table 1. Summary of bass results for Region 1

See text for further explanation. Abbreviations: Region 1 - North Coast Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	1	Copco Lake	not sig					0.33	
1	1	Ruth Lake	dec					0.40	
2	1	Iron Gate Reservoir		not sig				0.30	
2	1	Pillsbury, Lake		not sig				0.92	
3	1	Reservoir F			not sig			0.10	
3	1	Sonoma, Lake			inc			1.13	
4	1	Shastina, Lake				#		#	
4	1	Trinity Lake				#		#	
5	1	Dead Lake					not sig	0.54	
5	1	Mendocino, Lake					inc	0.98	
5	1	Spring Lake					inc	0.60	

Table 2. Summary of bass results for Region 2

See text for further explanation. Abbreviations: Region 2 - San Francisco Bay Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	2	Vasona Reservoir	not sig					0.14	
2	2	Coyote Lake		not sig				0.82	
2	2	Nicasio Lake		not sig				0.42	
2	2	San Pablo Reservoir		not sig				1.07	
2	2	Upper San Leandro Reservoir		NA				0.84	
3	2	Calaveras Reservoir			NA			0.97	
3	2	Chabot, Lake (San Leandro)			NA			0.93	
3	2	Henne, Lake			not sig			0.55	
3	2	Lexington Reservoir			NA			0.55	
3	2	Ogier Quarry Ponds			not sig			0.46	
3	2	Stevens Creek Reservoir			NA			NLA	0.66
4	2	Almaden Reservoir			not sig			2.71	
4	2	Calero Reservoir				dec		0.52	
4	2	Chabot, Lake (Vallejo)				not sig		0.41	
4	2	Del Valle Reservoir				not sig		0.60	
4	2	Lower Crystal Springs Reservoir				not sig		0.47	
4	2	Shadow Cliffs Reservoir				not sig		0.43	

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
4	2	Soulejoule Lake				inc		1.81	
5	2	Anderson Lake					deleted	#	
5	2	Bon Tempe Lake					not sig	0.29	
5	2	Lafayette Reservoir				dec		0.17	

Table 3. Summary of bass results for Region 3

See text for further explanation. Abbreviations: Region 3 - Central Coast Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	3	Nacimiento, Lake	not sig					1.07	
1	3	Roberts Lake (Laguna Del Rey)	deleted					#	
1	3	Santa Margarita Lake	#	NA				NLA	0.31
2	3	Cachuma, Lake		not sig				0.25	
2	3	Chesbro Reservoir		NA				0.97	
2	3	Lopez Lake		not sig				0.14	
2	3	Pinto Lake		NA				0.22	
3	3	San Antonio, Lake			not sig			0.22	
4	3	Loch Lomond Reservoir				NA		NLA	0.14
5	3	Hernandez Reservoir					inc	1.35	
5	3	Oso Flaco Lake					#	NBC	
5	3	Uvas Reservoir					inc	1.43	

Table 4. Summary of bass results for Region 4

See text for further explanation. Abbreviations: Region 4 - Los Angeles Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	4	Balboa, Lake	#					NBC	
1	4	Castaic Lake	not sig					0.36	
1	4	Cerritos Park Lake	not sig					0.10	
1	4	Elizabeth Lake	#	#	#	#		#	
1	4	Ken Hahn Park Lake	NA					0.15	
1	4	La Mirada Park Lake	#					0.29	
1	4	Santa Fe Reservoir	dec					0.41	
2	4	Alondra Park Lake		not sig				0.20	
2	4	Crystal Lake		#		#		#	
2	4	Magic Johnson Lakes		NPS				0.71	
2	4	Wilderness Park Lake		#				NBC	
3	4	Casitas, Lake			not sig			0.27	
3	4	Echo Park Lake			not sig			0.16	
3	4	Legg Lake			not sig			0.17	
3	4	Lindero, Lake			#			#	
3	4	Puddingstone Reservoir			dec			0.18	
3	4	Pyramid Lake			not sig			0.53	

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
3	4	Sepulveda Lake			#			NBC	
3	4	Sherwood, Lake			inc			1.07	
4	4	Belvedere Park Lake				NA		0.23	
4	4	Castaic Lagoon			not sig			0.15	
4	4	El Dorado Park Lakes			NA			NLA	0.09
4	4	Hansen Dam Lake				dec		0.07	
4	4	Hughes, Lake			#			#	
4	4	Malibou Lake			NA			NLA	0.08
4	4	Peck Road Water Conservation Park				not sig		0.42	
5	4	Calabasas Lake					NA	0.03	
5	4	Harbor Lake (Machado Lake)			NA			0.09	
5	4	Lincoln Park Lake					NA	NLA	0.03
5	4	Piru, Lake					not sig	0.40	
5	4	Toluca Lake					deleted	#	
5	4	Westlake Lake					not sig	0.14	

Table 5. Summary of bass results for Region 5

See text for further explanation. Abbreviations: Region 5 - Central Valley Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	5	545TU0164-BOG Other Lake 164	#					0.21	
1	5	Beach Lake	NPS					0.12	
1	5	Berryessa, Lake	not sig					0.60	
1	5	Brite Valley Lake	not sig					0.30	
1	5	Britton, Lake	NA					NLA	0.11
1	5	Butt Valley Reservoir	NA					NLA	0.12
1	5	Camanche Reservoir	NA					NLA	0.19
1	5	Camp Far West Reservoir	not sig					0.61	
1	5	Don Pedro Reservoir	not sig					0.40	
1	5	Eastman Lake	dec					0.29	
1	5	Folsom Lake	not sig					0.50	
1	5	McClure, Lake	not sig					0.49	
1	5	McSwain, Lake	dec					0.25	
1	5	New Melones Lake	NA					0.39	
1	5	O'Neill Forebay	not sig					0.27	
1	5	Shasta Lake	dec					0.19	
1	5	Success Lake	NA					0.27	

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
1	5	Woodward Reservoir	not sig					0.25	
1	5	Zayak/Swan Lake	not sig					1.16	
2	5	Black Butte Lake		dec				0.55	
2	5	Collins Lake		NA				0.51	
2	5	Davis Creek Reservoir		NPS				1.52	
2	5	Hensley Lake		not sig				0.79	
2	5	Isabella Lake		NA				NLA	0.31
2	5	Lake of the Pines		NA				NLA	0.08
2	5	Los Banos Reservoir		inc				0.97	
2	5	Mile Long Pond		NPS				0.39	
2	5	Mountain Meadows Reservoir		#		#		#	
2	5	Natomas, Lake		not sig				0.56	
2	5	New Hogan Lake		not sig				0.54	
2	5	Pardee Reservoir		NPS				0.40	
2	5	Webb, Lake		not sig				0.30	
2	5	Whiskeytown Lake		not sig				0.18	
3	5	Bass Lake			inc			0.35	
3	5	Blue Lakes			not sig			0.27	
3	5	East Park Reservoir			not sig			0.39	
3	5	Marsh Creek Reservoir			#	#		#	
3	5	Modesto Reservoir			not sig			0.20	
3	5	Oroville, Lake			not sig			0.45	

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
3	5	San Luis Reservoir			not sig			0.46	
3	5	Scotts Flat Reservoir			NPS			0.50	
3	5	Siskiyou Lake			NA			NLA	0.34
3	5	Slab Creek Reservoir			#			NBC	
3	5	Thermalito Afterbay			not sig			0.18	
3	5	Tulloch Reservoir			not sig			0.43	
3	5	Wildwood, Lake			NPS			0.62	
3	5	William Pond (Arden Pond)			NPS			0.77	
4	5	Amador, Lake				not sig		0.99	
4	5	Antelope Lake				#		#	
4	5	Castac Lake				#		#	
4	5	Combie, Lake				NA		NLA	0.98
4	5	Finnon Reservoir				NA		NLA	0.27
4	5	Indian Valley Reservoir				#		#	
4	5	Millerton Lake				not sig		0.29	
4	5	New Bullards Bar Reservoir				inc		0.87	
4	5	Pine Flat Lake				not sig		0.47	
4	5	Stony Gorge Reservoir				#		#	
4	5	Union Valley Reservoir				#		NBC	
5	5	Almanor, Lake					not sig	0.10	
5	5	Bethany Reservoir					NA	NLA	0.23
5	5	California, Lake					NA	NLA	0.25

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
5	5	Clear Lake					inc	0.46	
5	5	Contra Loma Reservoir					inc	0.37	
5	5	Englebright Lake					NA	0.69	
5	5	Jenkinson Lake					NA	0.35	
5	5	Kaweah, Lake					#	NBC	
5	5	Los Vaqueros Reservoir					inc	0.91	
5	5	Lower Blue Lake (Lake County)					not sig	0.39	
5	5	Paradise Lake					inc	0.43	
5	5	Robinson Pond					deleted	#	
5	5	Rollins Reservoir					NA	1.34	
5	5	San Juan Pond					#	#	
5	5	Turlock Lake					not sig	0.35	

Table 6. Summary of bass results for Region 6

See text for further explanation. Abbreviations: Region 6 - Lahontan Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
2	6	Palmdale Lake		not sig				0.12	
2	6	Silverwood Lake		NA				0.61	
3	6	Little Rock Reservoir			NA			1.70	
3	6	Tahoe, Lake (Tahoe Keys)			NPS			0.18	
4	6	Arrowhead, Lake				inc		0.57	
4	6	Pete's Valley Reservoir				deleted		#	
5	6	Gregory, Lake					#	NBC	
5	6	Haiwee Reservoir					NA	NLA	0.44

Table 7. Summary of bass results for Region 7

See text for further explanation. Abbreviations: Region 7 - Colorado River Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available; NLA - not length-adjusted.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	7	Havasu, Lake	not sig					0.13	
1	7	Sunbeam Lake	NA					NLA	0.09
2	7	Ferguson Lake		not sig				0.08	
3	7	Wiest Lake			not sig			0.03	
4	7	Gene Wash Reservoir				NA		NLA	0.08

Table 8. Summary of bass results for Region 8

See text for further explanation. Abbreviations: Region 8 - Santa Ana Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average; length-adjusted comparison not available.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
2	8	Elsinore, Lake		#				NBC	
3	8	Hemet, Lake			not sig			0.24	
4	8	Big Bear Lake				not sig		0.22	
4	8	Perris Reservoir				not sig		0.19	
4	8	Prado Lake				NA		NBC	
5	8	Irvine Lake					not sig	0.53	

Table 9. Summary of bass results for Region 9

See text for further explanation. Abbreviations: Region 9 - San Diego Regional Water Quality Control Board; Latest BB (l-a) - latest black bass mean, length-adjusted; Latest BB (not l-a) - latest black bass mean, simple mean; NPS - not previously sampled; not sig - not significant; inc - increase; dec - decrease; # - lake not sampled; NBC - no bass caught, or not enough to calculate an average.

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (l-a)	Latest BB (not l-a)
1	9	Barrett	NPS					0.17	
1	9	San Marcos, Lake	NPS					0.06	
2	9	Hodges, Lake		not sig				0.12	
2	9	Jennings, Lake		not sig				0.22	
2	9	Laguna Niguel Park Lake		NPS				0.05	
2	9	Lake Skinner		NPS				0.10	
2	9	Sutherland, Lake		dec				0.17	
3	9	Diamond Valley Reservoir			not sig			0.36	
3	9	Loveland Reservoir			not sig			0.48	
3	9	Sweetwater Reservoir			not sig			0.24	
4	9	El Capitan				not sig		0.49	
4	9	Morena Reservoir				not sig		0.63	
4	9	O'Neill Lake				NPS		0.16	
4	9	Wohlford, Lake				not sig		0.06	
5	9	Cuyamaca, Lake					inc	0.22	
5	9	Lake Henshaw					dec	0.06	
5	9	Lower Otay Reservoir					inc	0.35	
5	9	Miramar Reservoir					#	NBC	

Panel	Region	Station Name	2015	2017	2019	2021	2023	Latest BB (I-a)	Latest BB (not I-a)
5	9	Murray Reservoir					not sig	0.07	

Table 10. Interannual variation in length-adjusted mean bass mercury at individual lakes

Changes assessed by comparing length-adjusted means for bass in the survey year with the most recent length-adjusted bass means from prior sampling. Statistical significance was determined based on non-overlapping 95% confidence intervals of the mean concentrations.

	2015	2017	2019	2021	2023
Decrease	5	2	1	3	1
Not significant	15	17	22	13	9
Increase	0	1	3	3	10