Statewide Mercury Control Program for Reservoirs

CALIFORNIA Water Boards

The State Water Resources Control Board and nine Regional Water Quality Control Boards are in the process of developing a statewide mercury control program for reservoirs.

Overview

Fish containing potentially harmful amounts of mercury are found in numerous reservoirs across the state. Mercury is a heavy metal that is poisonous in very small amounts. Infants, young children, and women of childbearing age are most at risk. It is known to cause brain damage as well as kidney and lung problems in humans and wildlife. To begin to address this widespread mercury contamination, the Water Boards are developing a multi-part program that will focus first on mercury in California's reservoirs. There are currently 74 reservoirs identified as impaired and that number is expected to increase substantially as more data are collected.

Content and purpose of this September 2013 fact sheet

This fact sheet provides an overview of the scientific topics that will be addressed in detail in the upcoming technical staff report.

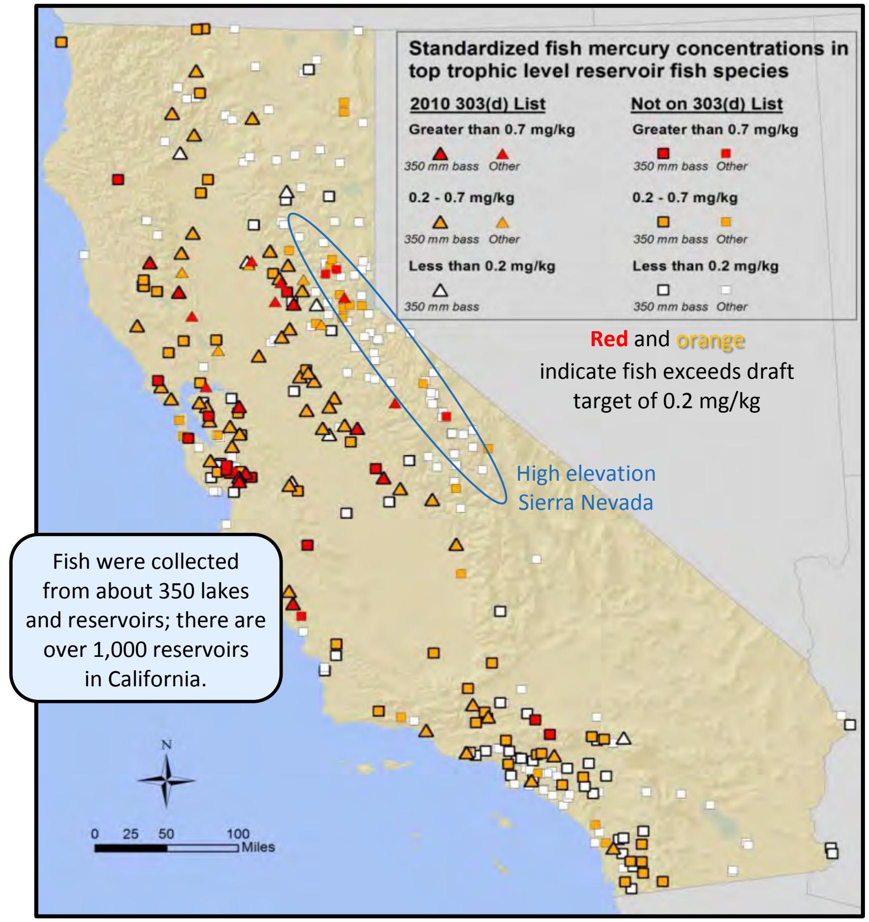
The program's **July 2012 fact sheet** provides introductory information, including:

- ✓ How are humans exposed to mercury?
- ✓ What is "methylmercury"?
- ✓ What is "bioaccumulation"?
- ✓ Map and list of mercury-impaired reservoirs

The July 2012 fact sheet is available on the Water Board's Statewide Mercury Program webpage at:

http://www.waterboards.ca.gov/water_issues/programs/mercury/

The Mercury Problem: Elevated methylmercury in fish



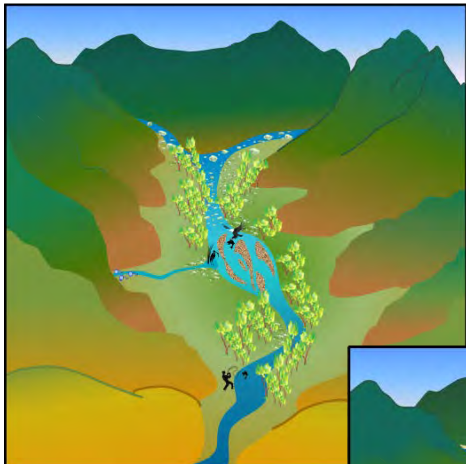
Average methylmercury concentrations in 350 mm (standardized length) black bass or other high trophic level fish

High elevation Sierra Nevada reservoirs tend to have the lowest fish methylmercury concentrations, likely because they are dominated by trout, which is lower in the food chain than black bass.

Statewide Mercury Control Program for Reservoirs

Conceptual Model

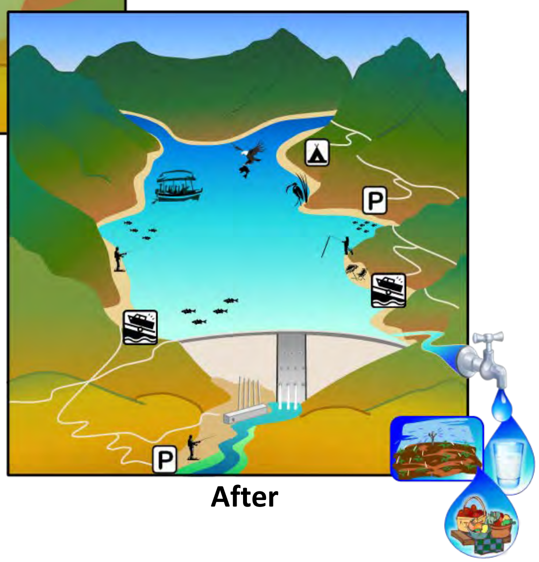
The Conceptual Model provides the theoretical basis that guides the linkage analysis and source assessment. Water Board staff conducted an extensive literature review to understand mercury cycling in reservoirs and identify factors that affect fish methylmercury levels.



Before

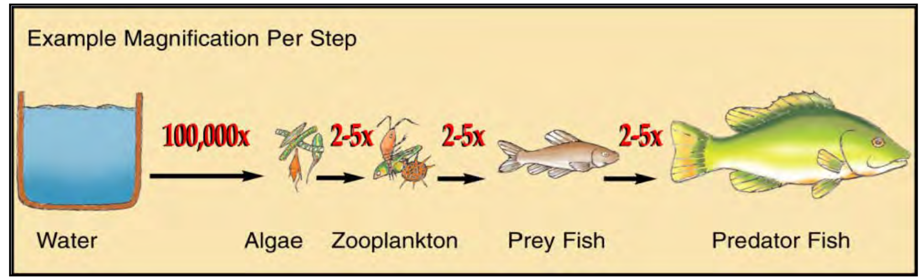
Dams create reservoirs and also slow water velocity, change water chemistry, and create conditions that increase the sources and bioavailability of mercury and organic matter to the aquatic environment.

Reservoirs have been shown to increase methylmercury in fish throughout the world.



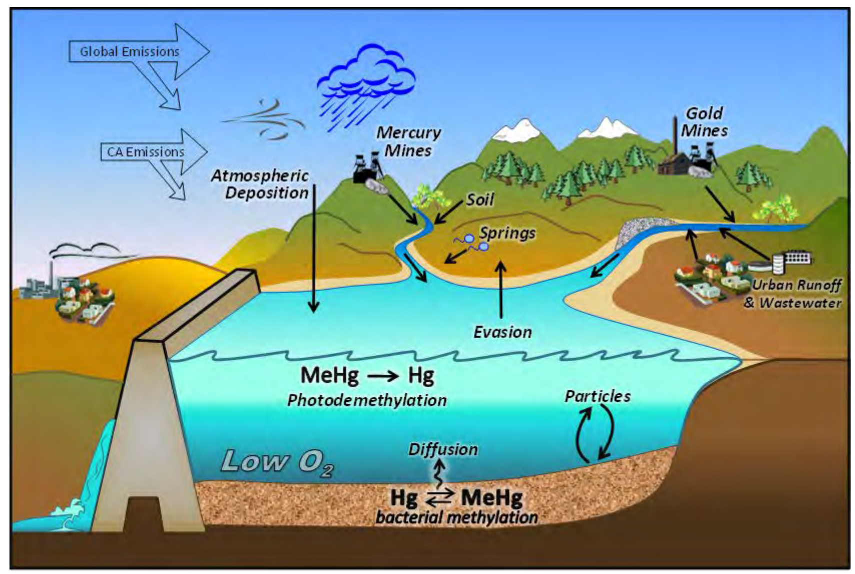
After

Reservoirs increase the water surface area and hence collect more mercury from atmospheric deposition. Similarly, reservoirs increase the area of inundated sediment that can become anoxic, which can stimulate methylation by naturally-occurring sulfate-reducing bacteria. However, they also create more habitat for sport fish for recreation, ensure a stable supply of drinking and irrigation water, and provide flood protection.



Bioaccumulation of methylmercury in fish

The single largest increase in methylmercury concentration occurs between water and algae. Subsequent trophic level transfers from algae up the food chain to predator fish have much lower increases. It is this process of biomagnification of methylmercury through the food web that results in the greatest risk from mercury, which is to human and wildlife consumers of contaminated fish.



Mercury cycling in reservoirs

This figure shows thermal stratification (lighter blue color for warm top water, and darker blue for cold deep water). There's very little mixing between top and bottom water with the result that oxygen is depleted in bottom waters, which enhances methylmercury production.

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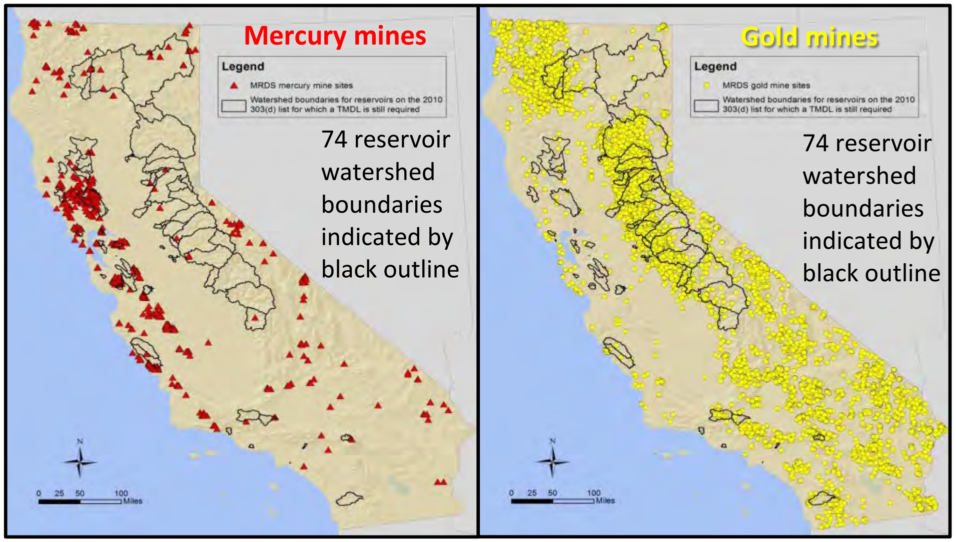
Mercury sources



Historic mercury and gold mines sites in California (above)

Historic mercury and gold mining activities were widespread across California. Even so, 30% of the 74 mercury-impaired reservoirs have no record of upstream mercury and gold mines.

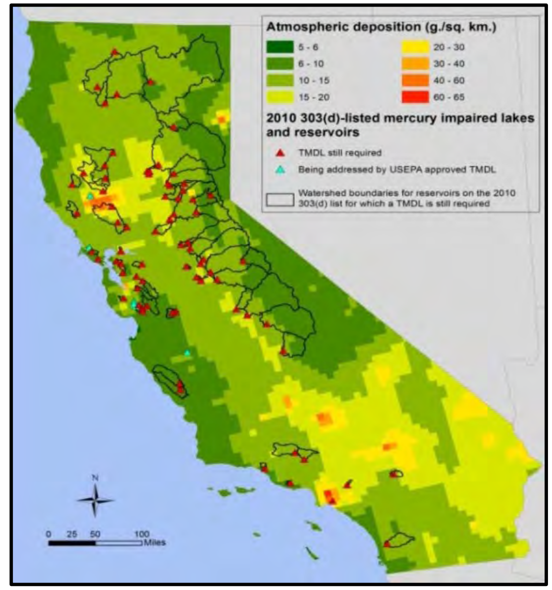
Other sources of mercury

Mercury from sources other than mines and atmospheric deposition to California reservoirs is minor or uncontrollable.

Industrial and municipal wastewater discharges to rivers upstream of reservoirs, and the few discharges directly to reservoirs, are already highly treated and regulated. Consequently, there are only a couple of mercury-impaired reservoirs for which discharges from industrial or municipal wastewater facilities might contribute a substantial amount of mercury.

Most urbanized areas in California are downstream of reservoirs. Therefore, most reservoirs receive very little runoff from urbanized areas.

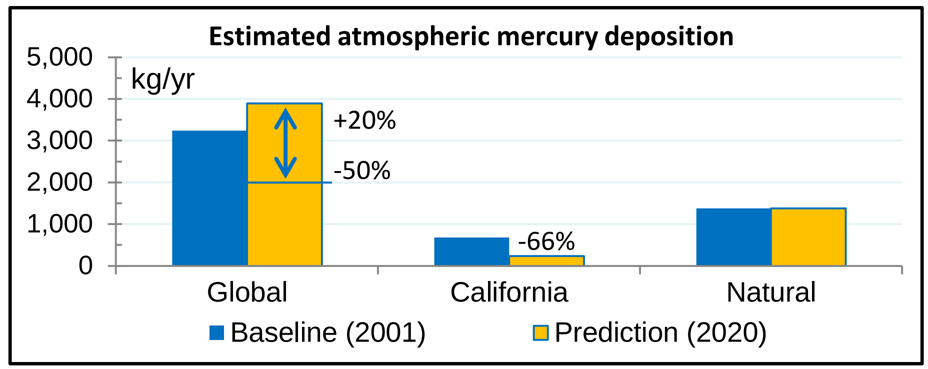
Naturally-occurring mercury in California soil and sediment is particularly elevated in some regions and is a constant source to reservoirs.



Mercury from atmospheric deposition to California

The map to the left was developed from the U.S. Environmental Protection Agency's REMSAD model output for 2001.

Importantly, deposition is not equal across California; some reservoirs receive more mercury per unit area than others, as highlighted by the red and orange areas of this map.



Projections in atmospheric mercury deposition (above)

The 2001 deposition estimates are from U.S. EPA's REMSAD model, and the prediction for 2020 is based on a literature review. If status quo continues, the global anthropogenic rate is estimated to increase 20% by 2020, but could decrease by 50% if robust emissions controls are implemented.

In California, several industries have reduced emissions for various reasons since 2001, and further substantial reductions are expected long before 2020 due to stringent national and state emissions regulations.

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Linkage analysis

Water Board staff conducted a statistical analysis to identify the most important factors that control methylation and bioaccumulation. Overall, the analysis assessed the influence of almost 40 factors on predatory fish methylmercury concentrations "[MeHg]" in California reservoirs (Table 1). More than 90 reservoirs had a variety of data that were used in different components of the analysis. The environmental factors were initially screened using correlation coefficients similar to Table 1, and important factors were included in the multivariable model development. All data were Box-Cox power transformed to aid in the parametric statistical analyses.

Model equation:

LN [Fish methylmercury] = 0.56 x [aqueous total mercury]
+ 0.34 x ratio [aqueous methylmercury] / [chlorophyll-a]
+ 0.39 x (average water level fluctuation) - 0.91

R^2 = 0.83, Adjusted R^2 = 0.81, Predicted R^2 = 0.72,
n = 26 reservoirs, $P < 0.001$

These three factors together explained the greatest amount of variability in fish methylmercury levels in California reservoirs. This model equation is supported by scientific literature and the Conceptual Model in the following ways:

- **[aqueous total mercury]** in reservoir water likely reflects the overall magnitude of mercury sources to the reservoir, and higher aqueous total mercury likely results in higher aqueous methylmercury
- The **ratio [aqueous methylmercury] / [chlorophyll-a]** represents the magnitude of methylmercury entering the food chain
- The magnitude of **water level fluctuation** may act upon multiple pathways of mercury cycling (methylation and bioaccumulation)

All individual coefficients were statistically significant at P<0.05, and the variables showed minimal multicollinearity (VIF<2). The model was cross-validated using PRESS to prevent over-fitting the model. Predictor variables were z-score standardized to give them equal weights.

Table 1: Correlation coefficients for 350 mm standardized predatory fish [MeHg] versus reservoir and watershed factors

Environmental Factors*	Lambda Trans-formation	Pearson's r	Spearman's Rho
		Correlation Coefficient	
[aq MeHg] Geomean / [Chl-a] Geomean	0	0.67	0.70
Reservoir Sediment [THg] Geomean	0	0.50	0.47
Watershed Soil [THg] Geomean	0	0.40	0.44
Reservoir Longitude	5	0.39	0.40
Reservoir [Chl-a] Geomean	-0.22	0.34	0.27
Average Water Level Fluctuation	0	0.33	0.35
Watershed Percent Vegetation	3	0.32	0.29
[aq MeHg] Geomean	-0.5	-0.31	-0.38
[aq THg] Geomean	0	0.30	0.25
Watershed Percent Open Water	0	-0.27	-0.30
Reservoir Dam Height	0.5	0.25	0.34
Reservoir Elevation	0.21	-0.22	-0.27
Watershed Percent Forests	2	0.22	0.12
CA Hg Atm Dep Rate to the Watershed	0	0.19	0.17
Watershed Productive Mines per Mile	-3.77	-0.17	-0.05
Number of Mines in Watershed (PAMP)	-0.5	-0.15	-0.17
Year Dam Built	5	0.15	0.19
Watershed Mines per Mile	-2	-0.14	-0.01
Number of Dams Upstream of Reservoir	-0.22	-0.13	-0.06
Reservoir Maximum Capacity	0	0.10	0.17
Watershed Area/Reservoir Surface Area	-0.11	-0.09	-0.19
CA Hg Atm Dep Rate to the Reservoir Surface	0	0.08	0.12
Reservoir Latitude	5	0.08	0.04
Watershed Surface Area	0	-0.05	0.13
All Hg Atm Dep Rate to the Watershed	-1	-0.03	-0.02
All Hg Wet Atm Dep Rate to the Reservoir Surface	0	-0.03	0.03
Number of Productive Mines in Watershed	-0.13	-0.03	-0.002
Watershed Percent Wetlands	-5	0.02	0.002
All Hg Atm Dep Rate to the Reservoir Surface	-1	0.02	-0.05
All Hg Wet Atm Dep Rate to the Watershed	0	0.01	-0.04
Watershed Percent Agriculture	-5	0.01	0.08
Reservoir Surface Area	0	0.01	0.05
Number of Mines in Watershed (MRDS)	0	-0.002	-0.03

* Highlighted environmental factors indicate statstically signficant correlations with fish tissue mercury concentrations for the parametric, non-parametric, or both analyses (using their respective two-sided tests of signficance, P < 0.05).

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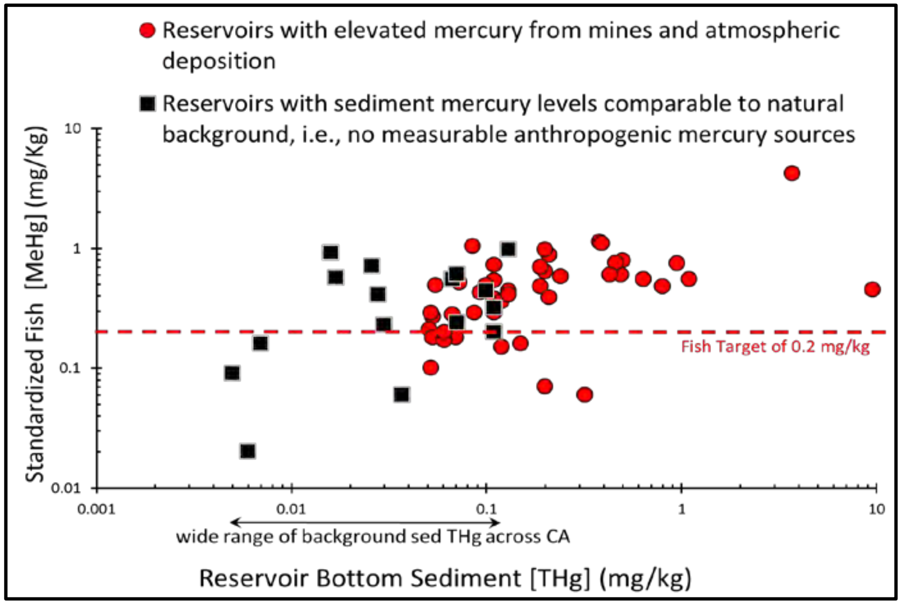
More than source reduction alone is needed



The above plot shows that source control (reductions) alone may not solve the fish methylmercury problem in many California reservoirs.

There is a significant positive correlation between reservoir bottom sediment total mercury concentration [THg] and methylmercury concentration [MeHg] in predatory fish, see previous page (Linkage and Table 1).

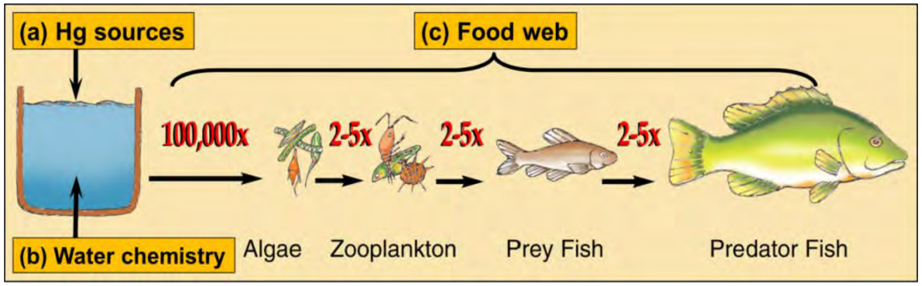
The 11 black squares above the red dotted line indicate reservoirs with elevated fish methylmercury levels despite very low mercury levels in reservoir sediment. In these reservoirs, source control is unlikely to substantially reduce fish methylmercury levels.

The legacy of past industrial emissions and widely-dispersed mine waste is apparent from elevated sediment mercury levels (e.g., 36 red circles above the red dotted line). Even with stringent emissions controls and clean-up of historic mine sites, fish will likely have elevated [MeHg] for a very long time because so much historic mercury is already dispersed throughout the watersheds. This illustrates the limited benefits from mercury source reduction, and the importance of controlling the processes of methylation and bioaccumulation in these and other reservoirs.

More than source reduction alone is needed *[continued]*

Conversely, the 9 red circles at and below the red dotted line are reservoirs with low fish methylmercury levels despite elevated sediment mercury levels; studying these reservoirs might provide insights for potential control options (b) and (c) in figure below.

Potential mercury control options



Potential mercury control options for reservoirs include:

a) Reduce mercury sources to reservoirs to reduce methylmercury production

b) Conduct studies and pilot tests on how reservoir water chemistry might be adjusted to reduce methylmercury production, for example:
   - Reduce anoxia with artificial circulation or oxygenation, or adjust redox potential by adding nitrate
   - If low pH, increase pH by adding lime or reducing air emissions (NO_x, SO_x, etc.) that produce acid rain

c) Conduct studies and pilot tests on how the food web might be managed to decrease methylmercury bioaccumulation, for example:
   - Add nutrients to nutrient-limited (oligotrophic) reservoirs to increase productivity at base of the food web
   - Manipulate food web, e.g., intensive fishing to increase growth rate of remaining fish
   - Restore native anadromous fisheries, which bioaccumulate less methylmercury
   - Change stocking to increase numbers of less predatory (lower trophic level) fish, which bioaccumulate less methylmercury.

Statewide Mercury Control Program for Reservoirs

Region	County(ies)	Water Body	Owner
North Coast Region			
1	Lake	Lake Pillsbury	Pacific Gas and Electric Co.
1	Mendocino	Lake Mendocino	US. Army Corps of Engineers
1	Siskiyou	Lake Shastina	Montague Water Conservation District
1	Sonoma	Lake Sonoma	US. Army Corps of Engineers
1	Trinity	Trinity Lake	U.S. Bureau of Reclamation
San Francisco Bay Region			
2	Alameda	Del Valle Reservoir	California Department of Water Resources
2	Alameda	Lake Chabot (Alameda Co)	East Bay Municipal Utility District
2	Alameda	Shadow Cliffs Reservoir	East Bay Municipal Utility District
2	Alameda, Santa Clara	Calaveras Reservoir	City & County of San Francisco
2	Contra Costa	San Pablo Reservoir	East Bay Municipal Utility District
2	Contra Costa	Lafayette Reservoir	Marin Municipal Water District
2	Marin	Bon Tempe Reservoir	Marin Municipal Water District
2	Marin	Nicasio Reservoir	Marin Municipal Water District
2	Santa Clara	Anderson Reservoir	Santa Clara Valley Water District
2	Santa Clara	Stevens Creek Reservoir	Santa Clara Valley Water District
2	Solano	Lake Herman	City of Benicia
Central Coast Region			
3	Monterey, San Luis Obispo	San Antonio Reservoir	Monterey County Water Resources Agency
3	San Luis Obispo	Nacimiento Reservoir	Monterey County Water Resources Agency
3	Santa Clara	Chesbro Reservoir	Santa Clara Valley Water District
3	Santa Clara	Uvas Reservoir	Santa Clara Valley Water District
Los Angeles Region			
4	Los Angeles	Castaic Lake	California Department of Water Resources
4	Los Angeles	Pyramid Lake	California Department of Water Resources
4	Los Angeles	El Dorado Lakes	El Dorado Irrigation District
4	Los Angeles	Puddingstone Reservoir	Los Angeles County Department of Public Works
4	Ventura	Casitas, Lake	U.S. Bureau of Reclamation
4	Ventura	Lake Sherwood	Westlake Lake Management Association
Central Valley Region			
5	Amador, Calaveras	Pardee Reservoir	East Bay Municipal Utility District
5	Amador, Calaveras, San Joaquin	Camanche Reservoir	East Bay Municipal Utility District
5	Butte	Thermalito Afterbay	California Department of Water Resources
5	Butte	Oroville, Lake	Howell Mountain Mutual Water Company
5	Butte	Mile Long Pond	State Land
5	Butte	Robinsons Riffle Pond	State Land

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Region	County(ies)	Water Body	Owner
Continued from previous page			
5	Calaveras	New Hogan Lake	US. Army Corps of Engineers
5	Calaveras, Tuolumne	Tulloch Reservoir	South San Joaquin and Oakdale Irrigation Districts
5	Calaveras, Tuolumne	New Melones Reservoir	U.S. Bureau of Reclamation
5	Colusa	East Park Reservoir	U.S. Bureau of Reclamation
5	Contra Costa	Marsh Creek Reservoir	Contra Costa County Flood Control & Water Conservation District
5	El Dorado	Slab Creek Reservoir	Sacramento Municipal Utility District
5	El Dorado, Placer	Oxbow Reservoir	Placer County Water Agency
5	El Dorado, Placer, Sacramento	Folsom Lake	U.S. Bureau of Reclamation
5	Fresno	Pine Flat Reservoir	US. Army Corps of Engineers
5	Fresno, Madera	Millerton Lake	U.S. Bureau of Reclamation
5	Glenn	Stony Gorge Reservoir	U.S. Bureau of Reclamation
5	Glenn, Tehama	Black Butte Reservoir	US. Army Corps of Engineers
5	Lake	Indian Valley Reservoir	Yolo County Flood Control & Water Conservation District
5	Madera	Hensley Lake	US. Army Corps of Engineers
5	Mariposa	McClure Reservoir	Merced Irrigation District
5	Merced	ONeill Forebay	U.S. Bureau of Reclamation
5	Merced	San Luis Reservoir	U.S. Bureau of Reclamation
5	Napa, Yolo	Berryessa, Lake	U.S. Bureau of Reclamation
5	Nevada	Wildwood, Lake	Lake Wildwood Association
5	Nevada	Scotts Flat Reservoir	Nevada Irrigation District
5	Nevada, Placer	Combie, Lake	Nevada Irrigation District
5	Nevada, Placer	Rollins Reservoir	Nevada Irrigation District
5	Nevada, Placer, Yuba	Camp Far West Reservoir	South Sutter Water District
5	Nevada, Yuba	Englebright Lake	US. Army Corps of Engineers
5	Placer	Hell Hole Reservoir	Placer County Water Agency
5	Plumas	Almanor Lake	Pacific Gas and Electric Co.
5	Sacramento	Beach Lake	Sacramento Regional County Sanitation District
5	Sacramento	Natoma, Lake	U.S. Bureau of Reclamation
5	Shasta	Britton Lake	Pacific Gas and Electric Co.
5	Shasta	Shasta Lake	U.S. Bureau of Reclamation
5	Shasta	Whiskeytown Lake	U.S. Bureau of Reclamation
5	Stanislaus	Modesto Reservoir	Modesto Irrigation District
5	Stanislaus	Woodward Reservoir	South San Joaquin Irrigation District
5	Stanislaus	Turlock Lake	Turlock Irrigation District
5	Tulare	Kaweah Lake	US. Army Corps of Engineers
5	Tuolumne	Hetch Hetchy Reservoir	City & County of San Francisco
5	Tuolumne	Don Pedro Lake	Turlock & Modesto Irrigation District
5	Yolo	Davis Creek Reservoir	Homestake Mining Co.
5	Yolo	Solano, Lake	U.S. Bureau of Reclamation
5	Yuba	New Bullards Bar Reservoir	Yuba County Water Agency
Santa Ana Region			
	San Bernardino	Big Bear Lake	Big Bear Municipal Water District
San Diego Region			
9	San Diego	Lake Hodges	City of San Diego