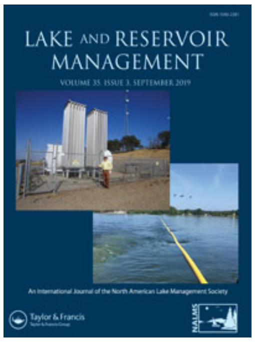

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Hypolimnetic oxygenation 1: win–win solution for massive salmonid mortalities in a reservoir tailwater hatchery on the Mokelumne River, California

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ABSTRACT
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More than 300,000 hatchery fish supplied with deep hypolimnetic water from Camanche Reservoir, California died during two short, late summer events during the 1987–1992 drought. A criminal complaint cited the water agency for negligence. Fisheries agencies blamed the fish kills on low water levels but retaining more water would cut supplies to 1.4 million city residents, downstream farmers, and wild river fish. The reservoir was assumed to be unproductive due to its undeveloped mountain watershed but no measurements had been made. Hydrogen sulfide (H_2S) was suspected as the toxic agent since it acts rapidly. Later examination of sediment redox indicated the potential for H_2S formation which was confirmed by odor. A cure for H_2S in the hatchery and river below the dam was a Hypolimnetic Oxygenation System (HOS). In addition, a management system was devised to guarantee a minimum volume of cool (<16.4 C), oxygenated, hypolimnetic water. The two management strategies (HOS and cool pool) greatly improved conditions. H_2S was eliminated, fish moved into deep water in the reservoir, and no fish kills have occurred in 24 yr. The HOS was superior to permanganate treatments or maintaining high reservoir water levels during droughts. The criminal lawsuit was settled, no one went to jail, and inter-agency cooperation improved. Following HOS operation, Chinook salmon returns rose significantly ($p < 0.05$) from 3550/yr to 7660/yr (2009) and 19,867/yr (2018), with 10,000/yr spawning naturally in the river. Returns during a recent drought increased tenfold. Endangered steelhead trout returns rose from 8/yr to 1,168/yr (2017).

KEYWORDS
Chinook salmon; fish kills; hydrogen sulfide; hypolimnetic oxygen system; steelhead trout

Chinook salmon (*O. tshawytscha*), a main Pacific Coast commercial and sport fish, and steelhead trout (*Oncorhynchus mykiss*) migrate from the Pacific Ocean to breed in California rivers. In 1964, completion of the Camanche Reservoir dam on the Mokelumne River tributary of the Sacramento River blocked fish passage. Nowadays, some returning fish are captured below the dam and their young are raised in a large hatchery. Some fish spawn in the river below the dam, so a cool, well-oxygenated water supply is needed in both locations (Myrick and Cech 2001). Thus, hatcheries are often constructed downstream of large reservoirs to access the cold hypolimnetic water supply (Thornton et al. 1990).

Camanche Reservoir (31 km^2; 7680 acres) is a multipurpose reservoir owned and operated by the East Bay Municipal Utility District (EBMUD). It supplies water for farms, flood control, hydropower, and public recreation (Figs. 1a–1c). The hatchery is located directly below the dam. It was built by EBMUD as mitigation for the loss of spawning gravels (Fig. 1c). The original hatchery featured innovative "naturalistic" fish-rearing channels, but the California Department of Fish and Wildlife (CDFW), which operates the hatchery, was not impressed by these channels and constructed traditional concrete raceways. The initial design and disputes over water releases caused interagency friction,

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Figure 1. Views of the subject system. (a) Camanche Reservoir aerial view. Triangle is site of Speece cone close to the dam. Stars are main index sampling stations. Rectangle is site of fish hatchery below dam. (b) View from lower end of reservoir in autumn at normal elevation; white buoys show location of submerged Speece cone. Oxygen and electricity supply pipes are small black lines on far shore and the evaporator is the white structure at far side of dam. (c) Mokelumne River and Fish Hatchery directly below Camanche Reservoir dam.

especially during droughts. When large fish kills of young steelhead trout and Chinook salmon occurred in the 1987–1992 drought, there was fertile ground for lawsuits.

In the autumns of 1987 and 1989, sudden deaths of about 300,000 young hatchery fish about 8 cm long occurred, up to 20,000/d (Messersmith 1989, Miyamoto 1989). The reservoir dried up in 1988 so supplied no water to people or fish. In May 1990, the local district attorney in San Joaquin County filed a criminal complaint against the Board of Directors and its managers about the fall 1989 kills, stating that the CDFW considered that EBMUD had released water downstream that was harmful to the fish, rather than keeping it in the reservoir. Misdemeanor criminal offenses carry a possible 1-yr county jail sentence. An added complication was that the fisheries agencies proposed that the low reservoir water level (equivalent to 21 m, vs. 27 m as maximum depth) was the main cause of the fish kills. The difference in reservoir level, and thus volume, was important in the lawsuits. The difference between 21 and 27 m is about 114 million m^3 (92,450 acre-feet), which is enough to supply 185,000 homes, or 13% of EBMUD's customers, for a year.

This article reports how the toxic agent for the fish kills was deduced when no limnological data were available, how a win–win solution was found, and what the results were in terms of H_2S, fish kills in the hatchery, adult fish returns to the river below the dam, and fish distribution in the reservoir. The solution used was a hypolimnetic oxygenation system (HOS) where an electric water pump and a submerged device, the Speece cone, mix pure gaseous oxygen with bottom water (Fig. 2). It has been 30 yr since the fish kills occurred, so this and accompanying

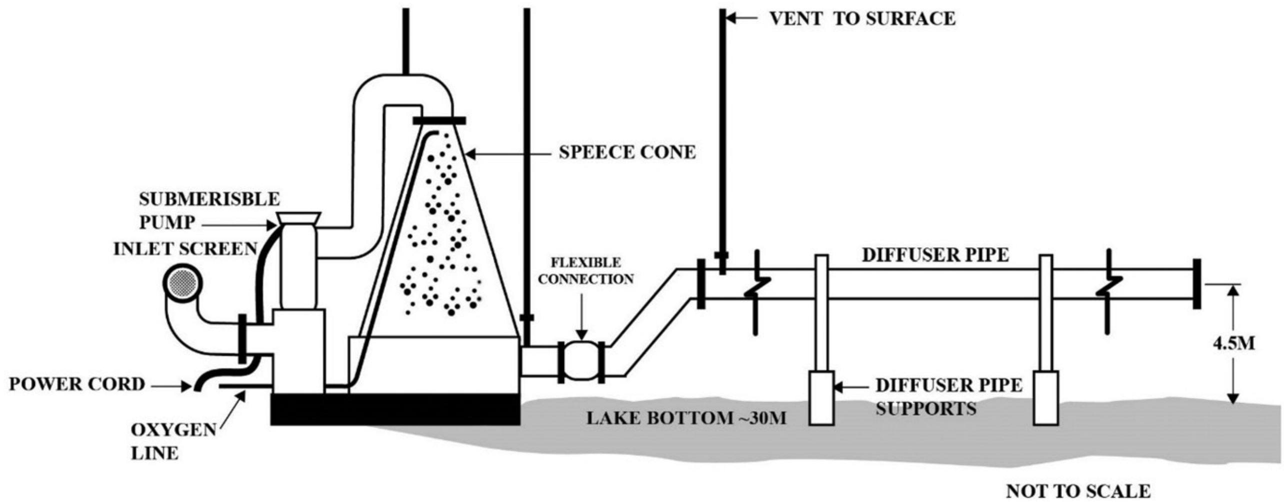

Figure 2. Diagram of the Speece cone installed at the bottom of Camanche Reservoir near the dam. Poor-quality, low-DO water is pumped from 5 m above the sediments into the top of the cone, where it mixes with rising pure oxygen bubbles, dissolves them, and then is released as a highly oxygenated blanket over the sediments (from Brown and Caldwell 1995).

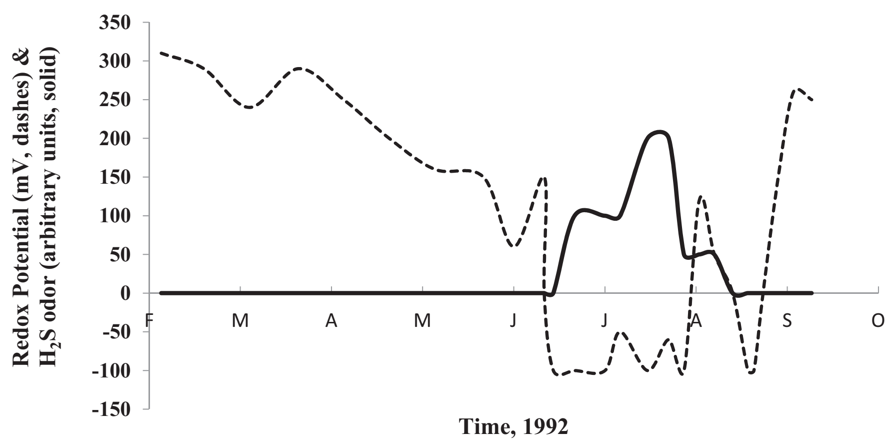

Figure 3. Relationship of redox potential in bottom hypolimnion water (dashes) and sulfide odor (solid line) in water samples collected at the same depth and station. Sulfide odor is shown in arbitrary units as absent (0), mild (100), and strong (200).

articles report full details and long-term results for oxygen dynamics, nutrients and eutrophication, turbidity, heavy metals, and the economics of operation.

Methods

The source of H_2S was estimated indirectly via the oxidation–reduction potential (ORP) of sediments and water. ORP was measured using a Hydrolab probe at 2 m intervals down to 0.5 m above the sediments at 5 stations spread over the reservoir (Fig. 1a). As a reality check, H_2S was measured directly by sniffing the deepest water sample. Human noses vary in sensitivity, with a minimum detection ranging from 1 to 130 ppb (AIHA 1989). The results were compared with the water ORP at the same site and depth. The methods proved quite comparable (Fig. 3), with an inverse relationship between ORP and H_2S smell. Chemical analysis (Fe, Cu, Al, turbidity, NH_4) applied standard methods at EBMUD's state-certified laboratory. Calibrated probes were also used to measure temperature, pH, and dissolved oxygen (DO).

The time needed for H_2S oxidation in the reservoir was measured using deep hypolimnetic water in the autumn when H_2S concentrations were expected to be highest. To prevent outgassing, samples were transported in vacuum flasks to the laboratory and then gently aerated in 1 L glass flasks. H_2S flux from the water was measured directly at 3-h intervals. A simplified gas purging method (Sugawara 1939) modified for monitoring water over mud flats in San Francisco Bay was used to quantify H_2S (Beutel et al. 2016; Horne et al. 1978).

Fisheries agencies were concerned that oxygen or aeration devices on the reservoir bed might adversely affect fish in the reservoir, even though fish were not able to use the anoxic deep water during stratified periods. The distribution of fish was measured using the acoustic reflection from gas-bladder-containing fish by Biosystems Analysis, Inc., Santa Cruz, CA, using a Lowrance model X-16 hydro-acoustic graphic employing a 20-degree cone angle, using a model THA-1192 transducer mounted on a Boston Whaler. Transect surveys were made before and after HOS operation in deep water over the thalweg to avoid habitat preference bias. The numbers of adult fish returning to the hatchery and river below the dam are both a recreational and legal concern since downstream dam releases depend on reaching a minimum number of returning Chinook salmon. Returns have been counted systematically in various ways since 1940, most recently using an automatic counter and underwater photography at fish ladders (Miyamoto and Hartwell 1998). Return estimates were complicated by dry periods, the natural cycles of anadromous fish, and changes in measurement methods. The minimum hypolimnion volume needed to supply the fish hatchery and river without a premature overturn was determined by using a multiple repetitive synoptic survey (MRSS; Horne et al. 1979). Temperature–DO profiles at 16 sites and 8 depths were taken every third day in September and October 1993.

The addition of permanganate on 13 October 1989 was an emergency response, not a planned experiment. Had it been instantly available, permanganate would have been used as soon as the fish deaths increased. Also, permanganate additions have drawbacks due to the slime produced by the manganous oxide formed. With no other alternative rapid response available, permanganate additions were considered in the weeks after the first H_2S odor was noted in the hatchery field log on 3 September 1989, followed by the change in the incoming redox potential of water to a negative value at the dam index site (13 Sep 1989), and later in the raw water to the hatchery (20 Sep 1989). The amount of permanganate to be added required jar tests (initial dose of 0.5 mg/L) and installation of the feed system, all of which took more time, so that the first day of addition was 13 October 1989, well into the period of die-off.

Hypolimnetic oxygenation system (HOS)

The HOS is the key to the success of this project, and full details of one form of HOS, the Speece cone, are described in detail by Horne et al. (2019) and Horne and Beutel (2019). The first reservoir Speece cone was installed in Newman Lake, Washington, in 1991, 2 yr before the one in Camanche Reservoir, and it had a primary purpose to reduce eutrophication (Moore and Christensen 2009). For Camanche Reservoir, HOS was selected because in 1988 it seemed the most likely method to guarantee suppression of H_2S toxicity. Oxygen needs (~8 tons/d) were based on measured hypolimnetic DO decline and estimated sediment oxygen demand.

A Speece cone is a downflow submerged contact oxygenation device and consists of a large metal cone (here 7 m high, 3.7 m wide at the base) set on the bottom in the deepest part of the reservoir by the dam (Fig. 2). A 0.9 m^3/s submersible electric water pump sucks cool, low-oxygen water from near the bed and raises it to the top of the cone, from where it is pushed down. Pure gaseous oxygen evaporated from a shoreline liquid oxygen tank is piped to the cone and the bubbles rise. The two counterflowing streams mix, and flows are designed to keep bubbles within the cone until they dissolve. The now highly oxygenated water flows out of the bottom of the cone and is dispersed back into bottom water at approximately saturation levels via ports in a diffuser. The diffuser plume of cool, dense, and well-oxygenated water leaves the diffuser manifold at 4.5 m above the bottom and entrains more than 10 times its volume from the surrounding water. The entrainment causes the plume to expand vertically to 9 m above the sediment surface and horizontally to the width of the reservoir at that depth (Horne and Beutel 2019). The plume moves slowly up-reservoir at about 0.1 cm/s (Horne and Beutel 2019), propelled by natural bottom water currents, so long runs of pipe are not essential.

Results

Fish kills

The two major fish kills occurred in 1987 and 1989 during a prolonged drought. The better-documented 1989 deaths were all subyearling steelhead trout in the hatchery because the young fall Chinook were all released by 1 September. The hatchery was closed in 1988 because the reservoir was almost empty. Thirteen possible causes of hatchery fish kills were ranked (Table 1). Each agency favored different causes, but I (Horne) considered H_2S to be the most likely toxicant because it can act so quickly (Bonn and Follis 1967). For legal reasons, other information was kept from me at the time, but after the case was settled, it was revealed that in October 1989 hatchery employees complained that H_2S odors were making them ill, even though OSHA measurements showed that the "gas was within acceptable limits" (Messersmith 1989). Also, the hatchery water supply was aerated twice before it reached the fish so H_2S was not considered a threat (Horne 1989; Miyamoto 1989). At the time, the CDFW thought that low water releases were the cause of the kills (Messersmith 1989). In response EBMUD increased discharges, which had the unfortunate effect of increasing the mass loading of H_2S to the hatchery and river.

Reservoir level and water releases were discounted as immediate causes of the fish kills (Table 1), but something about water volume was involved since the recent kills occurred only during droughts. The CDFW strongly requested more cold-water releases from Pardee Reservoir, a smaller but deeper oligotrophic drinking water supply upstream of Camanche Reservoir also

Table 1. Review of possible causes for observed fish kills in the hatchery downstream of Camanche Reservoir.

Possible cause	Comment	Final ranking
Hydrogen sulfide (1987 and 1989)	No data but likely present in deeper hypolimnion[a]	*High*: H_2S is a rapidly acting fish toxin. Deep water outlet sends H_2S to hatchery in <5 min. Overturn occurred after the fish kills in 1989.
Early holomixis (1987 only)	Hatchery supply rose $\sim$2 C prior to fish kills	*High*: Depletion of hypolimnion induced holomixis, stirring H_2S from sediments to water.
Turbidity	Sediment accumulation on fish egg trays	*Moderate:* Mean 9.7 NTU, range 8–17, rose prior to fish kills but then fell (Fig. 5).
Ammonia + pH	Hypolimnion ammonia high, $\bar{x}$ = 702 max: 1700 µg/L.	*Low*: Hatchery ammonia low (mean 110 µg/L, range 110–140) and pH moderate (mean 7.1, range 6–5–8).
Heavy metals	Abandoned copper mine had caused kills in upstream river, low water hardness, high metal concentration in sediments	*Low*: Soluble metal levels in reservoir very low (dissolved Cu <2 µg/L at time of kills) so toxicity small even at low hardness (Horne and Jung, 2019). Dissolved Fe (mean 244 µg/L, range 260–590) not unusual.
Brown slimes in hatchery	Diatom chains and organic detritus	*Low*: Unlikely to produce mass sudden death.
Blue-green algae	Reservoir was eutrophic	*Low*: Algae probably like other years.
Low water level	Level fell from 32 to 21 m in droughts	*Low*: Reservoir well stratified at 21 m (as long as hypolimnion intact).
Fluctuations in dam releases	Water-hammer effect induced sediments stirring in reservoir	*Low:* No effect seen on fish kills in other years with similar flow regimes.
Low upstream reservoir releases	Cool, oxygenated water from upstream reservoir was thought to reach the hatchery	*Low:* Inflowing cold water does not reach the hatchery even at maximum upstream releases.
Temperature in hatchery	Mean 15.5 C, range 14.9–16.3 C.	*Low*: Temperature normal for October and increase not enough to cause mass deaths of fish of this size.
Low dissolved oxygen	Reservoir hypolimnion likely to have zero DO	*Low*: Hypolimnion anoxic for previous 30 yr, efficient prehatchery aeration system.[b]
Methane	Is released from anoxic sediments at about the same redox as H_2S	*Low:* Rates are low at $\sim$13 C reservoir sediment temperature. Methane is not very soluble and bubbles would rapidly be vented to the surface and/or oxidized to CO_2 in epilimnion (Horne 2009b).

[a]No sulfide data available at the time, but later it was found that H_2S odors were detected around the river and hatchery for years prior to the 1987–1989 fish kills (Messersmith 1989). In the 1980s hypolimnion pressure head of 30 m was used to drive an aeration fountain 20 m high, which then splashed back into a very large redwood tank built on a concrete base. DO in the water exiting the tank to the hatchery was at saturation. Estimated residence time from hypolimnion to hatchery was <5 min. Further mechanical aeration occurred at the head of each fish channel using propellers.
[b]DO in hatchery was raised from <0.5 mg/L to $\sim$8 mg/L by aeration (Fig. 5).

owned and operated by EBMUD. The idea was that cold, naturally well-oxygenated water would pass unchanged from Pardee Reservoir along the short length of the Mokelumne River through Camanche Reservoir to the base of Camanche dam and thus to the hatchery. Later, tests showed that upstream dam releases heat up as they flow between the two reservoirs under the hot summer Central Valley sun, even at the highest releases from Pardee Reservoir (Rachel 2007). The heating is greater in dry years (Simods 2007) when the water level in Camanche Reservoir drops and its area shrinks considerably, giving a longer distance between the reservoirs. The inflowing plume of warm, less dense water spreads horizontally and mixes at an intermediate depth in Camanche Reservoir, where it is unavailable to the bottom water outlet.

About 6 million Chinook salmon and half a million steelhead trout are raised in the hatchery each year, but the best dataset was for September and October 1989, when, partially because of the 1987 fall fish kills, all the Chinook had been removed from the hatchery and planted in the river or estuary. Approximately 413,000 subyearling steelhead were still present in the hatchery on 1 October 1989. In addition, because the 1987 deaths which were provisionally attributed to H_2S, an emergency permanganate addition system designed to oxidize H_2S became available in mid-October 1989.

The fish deaths in 1989 were rapid. On 25 September only 71 dead fish were found out of a total of 413,000 subyearling fish at that time. Most subsequent deaths occurred in only 18 d in October (Fig. 4), when the rate rose from 310/d (30 Sept) to 1344/d (1 Oct), peaked at 20,050/d (10 Oct), and decreased to 80/d (22 Oct). The total dead were almost 35% of the hatchery stock at the time. The usual problems in fish hatcheries, including low DO or ammonia, were not at problem levels and did not change much over the short fish death episode (Fig, 5). DO entering the hatchery was low for most of the summer after August, since the hypolimnion in the reservoir was measured as anoxic (<0.1 mg/L) below 10 m on 20 September 1989. However, this anoxia had probably been going on for years and in 1989 the hatchery aeration system described earlier raised the incoming DO of <0.5 mg/L to

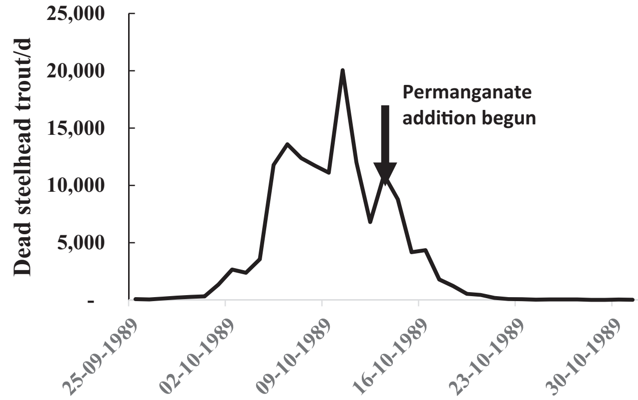

Figure 4. Time course of the autumn 1989 steelhead trout fish kills. Most deaths occurred in 18 d starting 1 October. Fearing a repeat of the 1987 deaths, all the young Chinook salmon had been planted by 25 Sep 1989. Permanganate addition to oxidize H_2S was begun on 13 Oct. Based on Miyamoto (1989).

8.6–9.2 mg/L before it reached the fish rearing channels (Fig. 5). Only turbidity changed much over the short fish kill episode and rose from 12 to 17 NTU prior to the main deaths (Fig. 5). Background turbidity in July was <2 NTU. These levels of turbidity are unlikely to cause a rapid die-off in well-oxygenated water (Horne 2019).

The start of the emergency permanganate addition began on 13 October 1989. Two effects happened almost immediately. First, fish kills rapidly declined (Fig. 4), although they were trending down after 10 October 1989. Second, any H_2S previously present in the water would have been oxidized by permanganate before it reached the rearing channels and could explain the observed sharp decline in fish deaths.

Disease is another common cause of hatchery death. The California Fish and Game (CFG) pathology report dated 11 October 1989 notes several external protozoan parasites, but not at levels that would account for the mortality rates experienced. The pathology report also states that the gills appear to be "burned, hyperplasic, and brown-tinged," which are characteristics of H_2S stress and the sulfurous acid effect found in severe H_2S poisoning. Within 1 h of the addition of permanganate, the "behavior of the fish improved markedly, demonstrated by an improved reaction response with few fish hugging the sides of the channels … steelhead also resumed feeding with hours." Based on the behavior of the fish, the condition of the gills, and the H_2S odor at the

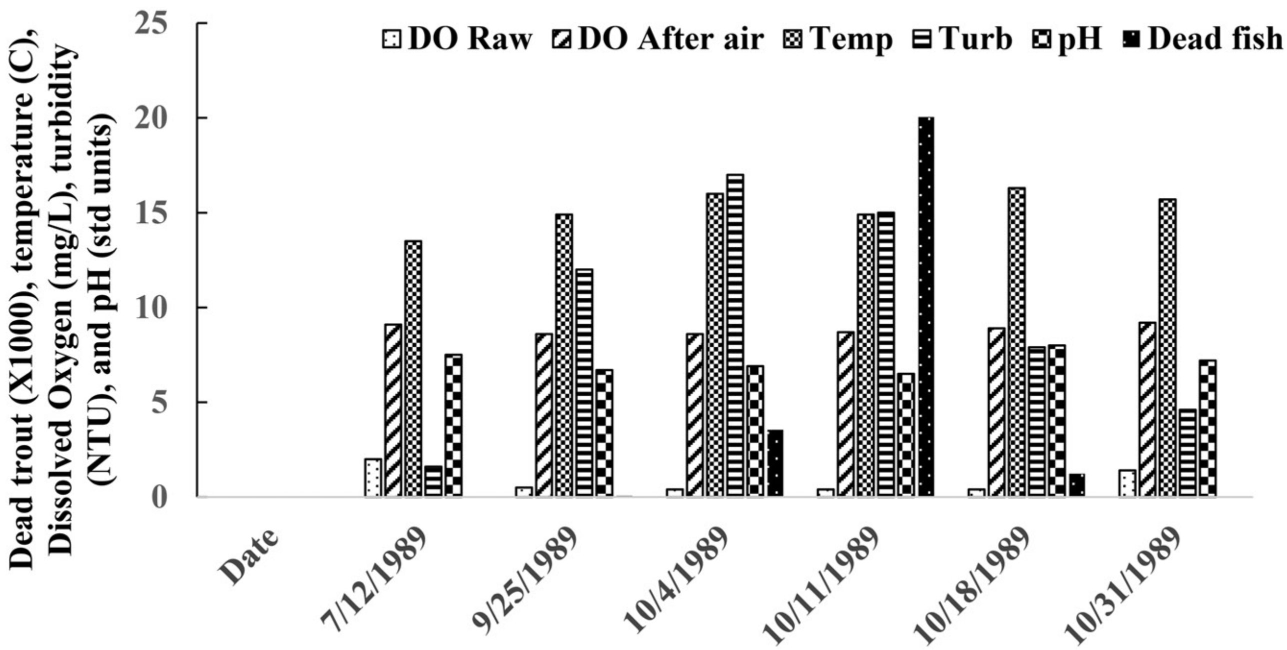

Figure 5. Time course of selected variables during the autumn 1989 steelhead trout deaths. Daily die-offs (solid bar) peaked on 10 Oct, while most other variables did not change much. DO supplied from reservoir hypolimnion (dotted line) was always low in DO but always high in DO at the head of hatchery after aeration (diagonally cross-hatched line). Temperature (pattern) and pH (circles) remained similar and suitable for salmonids. Turbidity (horizontal hatching) did increase before the start of the deaths. H_2S was not measured but odors were detected during the fish kills. Based on Miyamoto (1989).

hatchery, the preliminary cause of the fish mortality was "most likely toxic level of H_2S," according to EBMUD's fish biologist (Miyamoto 1989).

Hydrogen sulfide, ORP, and dissolved oxygen

Low ORP measured in the water above the sediments a few years after the fish kills but before HOS installation indicated the presence of H_2S in summer (Figs. 3 and 6). The ORP profile prior to HOS showed low values in the deeper hypolimnion (<50 mV), relative to >325 mV in the oxygenated epilimnion or upper hypolimnion (Fig. 6). A redox of +50 mV is above the value that thermodynamically favors H_2S generation (−100 mV), but the potential in the mud can be expected to be lower than in the water above. Declines in ORP began at 22 m, showing a stable 4 m thick bottom layer overlying the sediments prior to HOS operation. Such poorly mixed layers are common in reservoirs (Horne et al. 2003).

After HOS operation, ORP rose from <50 mV to almost 400 mV in deep water (Fig. 6), while the naturally oxygenated epilimnion remained at about 345 mV. The preoxygenation ORP depth profile also shows a typical reservoir or lake metalimnetic minimum of about 290 mV spread over 8–12 m around the thermocline (Fig. 6). The metalimnetic DO minimum disappeared following HOS. The metalimnetic zone is attractive to fish since the thermocline density inflection traps algae that become food for zooplankton. Thus, a

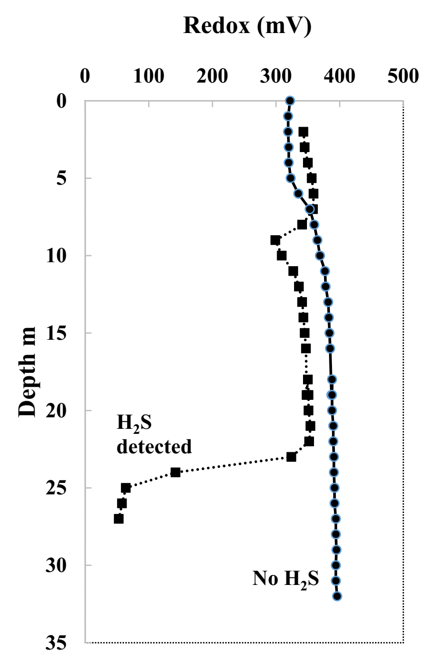

Figure 6. Redox depth profile for a typical summer before (squares on dashed line) and after (dots on solid line) use of a hypolimnetic oxygenation system (HOS).

healthy metalimnion is a plus for fish relative to the pre-HOS state.

Hydrogen sulfide kinetics

Even at low concentrations, oxygen represses H_2S production, so aeration or oxygenation should reduce it. However, aeration alone was unsuccessful in H_2S removal at the hatchery since fish kills occurred with a fully saturated DO of ~8 mg/L (Fig. 5). Probable reasons were that (1) aeration removes only some dissolved H_2S gas and not the sulfide ion (HS^-) and (2) the time required to vent or convert H_2S or HS^- to sulfate was less than the aeration time. The pH of hatchery supply water was 7.1 (Fig. 5) so would contain about equal amounts of H_2S and HS^-. Immediately after aeration (which vents some H_2S gas), dissolved H_2S gas would increase as chemical equilibrium was restored. Slow oxidation can be overcome using a more powerful oxidizing agent, such as shock chlorine treatment, but even then, 20 min of contact time is recommended (McFarland and Provin 2014). For the hatchery, where <5 min separated aeration and fish, a much longer aeration would have been needed. Oxidation of H_2S to sulfate is an 8-electron transfer and takes time. Experiments showed that it took 6–12 h of aeration to remove all detectable H_2S (<5 ppb) in the hypolimnetic water sample (Williams and Commins 1988). Thus, HOS was designed to provide a block of H_2S-free water in front of the dam that would last for at least 1 d (safety factor of two- to fourfold) at discharge volumes up to 17 m^3/s (600 cfs).

Metalimnion temperature–oxygen squeeze

A problem for cold-water fish in eutrophic waters is low DO in the cool hypolimnion, which forces the fish into a narrow band around the thermocline, the "oxygen–temperature squeeze" zone (Beutel et al. 2001; Welch et al. 2011). Echo-location surveys before HOS, made in mid July 1992, showed most fish concentrated around the thermocline, which stretched from 5 to 7 m from the surface (Fig.7a). In this band, DO ranged from 0 to 8 mg/L and temperature ranged from 20 to 24 C. The remainder of the hypolimnion was anoxic or nearly so but cool (12.4–17.5 C).

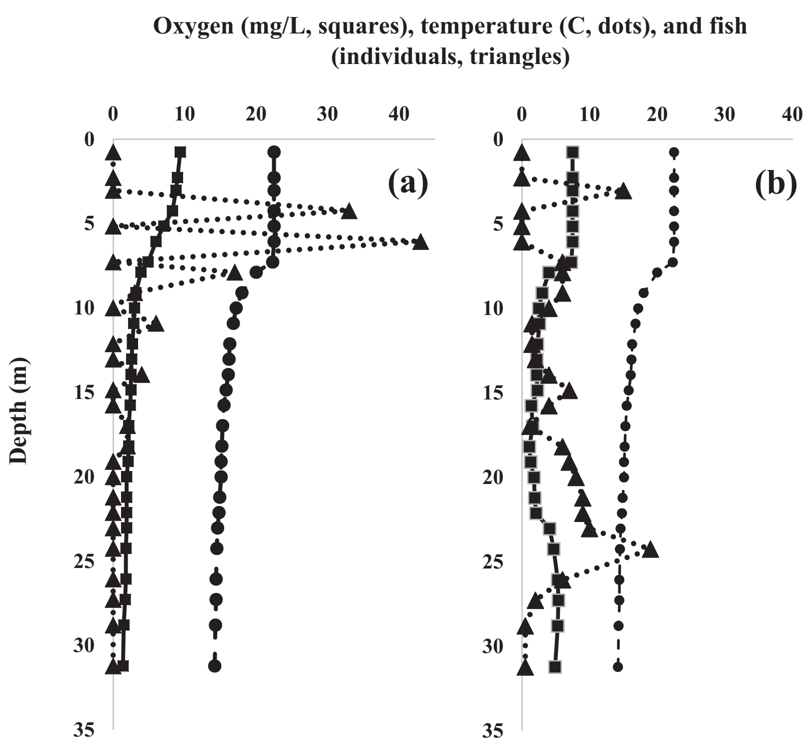

Figure 7. Distribution of fish (arbitrary units [triangles on dotted line]) in Camanche Reservoir with depth (a, 1992) before and (b, 1993) after HOS operation. Fish formerly squeezed around the thermocline moved throughout the entire water column after HOS operation. Also shown are DO (mg/L [squares on solid line]) and temperature (C [dots on dashed line]). Fish numbers are counts from the echo-sound reflection.

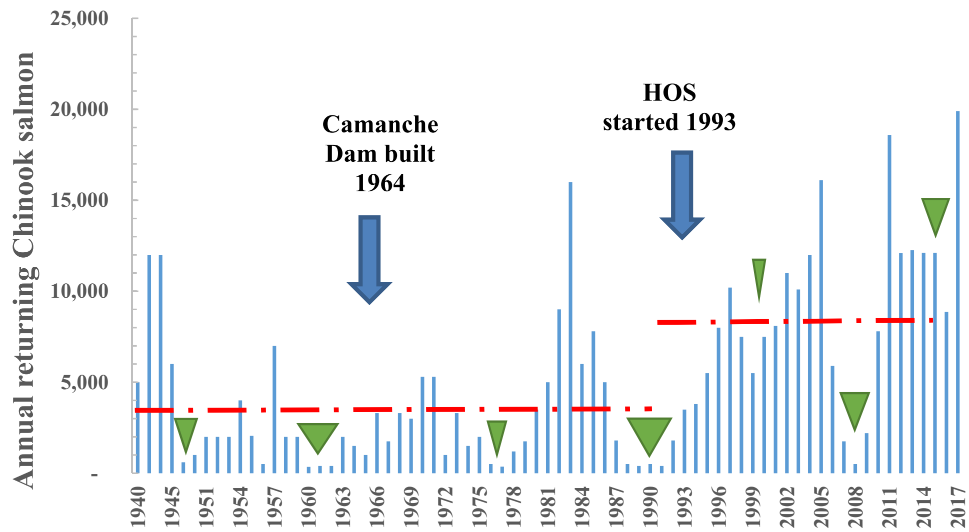

Figure 8. Seventy-three years of fall-run Chinook salmon returns (1944–2017) showing immediate increases due to HOS operation in 1993 and later improvements made possible by oxygenation. Also shown are droughts (triangles of varying width) and averages before and after HOS (dash-dot lines). Source: EBMUD and California Department of Fish & Wildlife continuous monitoring at the hatchery and fish counting facility at the downstream Woodbridge Irrigation District's Dam.

The rainbow trout stocked in Camanche Reservoir can briefly tolerate water temperatures up to 25 C, though growth declines above 19 C (Myrick and Cech 2001). These fish presumably survived the summer months by moving up and down in the suboptimal conditions of the metalimnion. In contrast, 2 mo of HOS operation a year later in September 1993 substantially increased DO in the metalimnion and hypolimnion (Fig. 7b). Cold-water fish followed. Most were probably stocked rainbow trout. They concentrated in the 18–24 m deep layer around the oxygenated plume where DO averaged about 10 mg/L. Despite the homogenization of the deepest water layers by the Speece cone plume, the water temperature at this depth remained cool, peaking at 14–15 C. Large warm-water fish, probably largemouth bass, were present in the epilimnion at 3 m. Importantly for reservoir management, fish were now present at all depths, though in varying abundance (Fig. 7b).

Increases in steelhead and Chinook salmon

The annual average number of fall-run Chinook salmon returning after dam construction, but before HOS operation, was 2585/yr (1963–1992; Fig. 8). After HOS, returning adults increased about threefold (7660 fish/yr, 1993–2011; Table 2). The 1963–1992 data are influenced by the 1987–1992 drought and are lower than the long-term returns before HOS operation (3272 fish/yr). A more conservative estimate removes the 1987–1992 drought counts and compares 1940–1987 counts (3548/yr) with post-HOS values (7660 fish/yr); this is a 2.3-fold increase. Due to low returns in droughts, the standard deviations for data groupings for the last 71 years are high (Table 2). Nonetheless, the Chinook salmon increase after HOS was statistically significant ($p < 0.001$, 2-tailed analysis, $n = 71$, assuming unequal variances). Using peak returns, 16% more fish returned in 2011 (after HOS) than in 1983, the highest count before HOS operation (Fig. 8). Returns of endangered adult steelhead trout, zero between 1976 and 1992, increased to 50/yr by 3 yr after HOS, averaged 278 (2005–2009), and totaled 1168 in 2018.

Table 2. Chinook salmon returns in the Mokelumne River for various periods of time.

Time period	Total annual number returning Chinook	Standard deviation
1940–1987	3548	3,492 (98%)
1940–1992	3272	3,421 (105%)
1940–2011	4516	4,275 (95%)
1963–1992	2585	4,702 (182%)
1993–2011	7660	4,679 (61%)
2012–2015	12,145	63 (0.5%)

Substantial natural spawning in the river below the dam has resumed. Prior to HOS operation (1963–1992) an average of 1883/yr wild adult

Chinook returned to the river in the fall run each year, compared with 3366/yr wild fish after HOS (1993–2011). More recently, for 2011–2015, which were drought years, an annual average of more than 12,000 Chinook salmon returned. Of these, about 3000 spawned in the Mokelumne River; the remaining 9000 were spawned in the hatchery. In 2018, a record number of 19,867 Chinook had returned, of which more than 10,000 spawned in the river.

Of the 7 droughts lasting more than 1 yr since 1940, 4 occurred before HOS installation and 3 afterward. Prior to HOS (1940–1992), drought returns were 786 fish/yr, while after HOS (1993–2015) drought returns were more than 10 times higher at 7963/yr (Table 3). Some of the improvements in Chinook returns during the last 2012–2015 drought are not directly due to HOS operation and can be attributed to better water management in the two reservoirs and the hatchery. Nonetheless most of these improvements would not have been possible without the HOS. If the last drought data are removed, the improvement due to HOS operation for the previous droughts is still more than 6 times the pre-HOS returns.

Minimum cool-water pool

In the absence of any direct evidence, the 1987 fish kill was assumed to be due to mixing H_2S from the sediments into overlying water once the hypolimnion volume was drained out early in the season to meet legally mandated downstream requirements. In 1987, the hypolimnion volume was zero by the end of August (Table 4). In contrast, the predrought hypolimnion volume at the same time in 1986 (no fish kills) was more than 100 million m^3. When the hypolimnion was used up, the entire water column including surficial sediment mixed. Above some minimum volume

Table 3. Chinook salmon returns in the Mokelumne River during drought years before and after operation of a hypolimnetic oxygenation system (HOS).

Year	Chinook salmon in droughts before HOS (1940–1992)	Year	Chinook salmon in droughts after HOS (1993–2015)
1948	600	2000	7500
1949	1000	2001	8100
1959	2000	2002	11,000
1960	350	2007	1750
1961	400	2008	500
1962	400	2009	2200
1976	500	2012	12,091
1977	360	2013	12,252
1987	1800	2014	12,117
1988	500	2015	12,118
1989	400		Average = 7963
1990	500		
1991	400		
1992	1800		
	Average = 786		

Table 4. Comparison of hypolimnion volume decline in Camanche Reservoir between 2 yr representing drought (1987) and nondrought (1986) conditions.

Month/year	Outflow or net loss (million m^3)	Hypolimnion volume (million m^3)
Jun 1986	165	
Jul 1986	47	118
Aug 1986	10	108
Sep 1986	27	81
Oct 1986	39	42
Total	288	
Jun 1987	27	81
Jul 1987	26	49
Aug 1987	27	15
Sep 1987	26	0
Oct 1987	20	0
Total	126	

of cool hypolimnion such mixing would not occur.

Extensive monitoring showed that overturn occurred once the surface temperature of the reservoir fell to 20 C and the temperature in the deepest area near the dam was >16.4 C. The volume of remnant stable hypolimnetic water that was <16.4 C was 31 million m^3 (25,000 acre-ft). A reservoir operating rule was instituted so discharge from the reservoir would stop at a cool pool of 31 million m^3. There have been no unwanted early turnovers in Camanche Reservoir over the last 24 yr, which included several droughts. The operating rule has also increased flexibility for other EBMUD operations.

Discussion

Role of H_2S

Streams receiving water from the deep hypolimnion fail to support trout fisheries for various reasons (Marshall et al. 2006). Low DO is the most common cause, especially if accidental toxin spills are discounted (Catchings 2006; Helfrich 2000; USEPA 1988), but at Camanche Reservoir, water was mechanically aerated twice before the hatchery and once before reaching the river. Typical oxygen concentrations in the fish rearing channels during fish kills were high (>8 mg/L or ~100% saturation at 15 C in October 1989).

It was initially difficult for all parties to accept H_2S as the main toxic agent in the fish kills. It merits only a brief mention in the limnological literature, usually in terms of the overall sulfur cycle. The outgassing of CO_2 in Nyos Lake, Cameroon (Kling et al. 1987), resulted in the deaths of about 1700 people, ascribed to CO_2 asphyxiation. H_2S was ignored as a cause of mortality despite the postmortem observation of burned lungs in some victims, the odor of H_2S in the area of the deaths, and the anoxia of tropical Nyos Lake below 10 m.

In aquatic ecosystems, sulfur-reducing bacteria produce H_2S as a dissolved gas by reducing sulfate when oxygen and nitrate have been depleted (Dunette et al. 1985; Horne and Goldman 1994). Anoxic water (near zero DO) in the hypolimnion is characteristic of many eutrophic lakes, but the high-quality water supply from the Sierra Nevada Mountains was assumed to yield an oligo- to mesotrophic state for Camanche Reservoir. After the fish kills, it was obvious that the reservoir was eutrophic with anoxic sediments.

Vigorous mechanical aeration did not remove enough H_2S from the hatchery supply. Other methods of removal were tried for the hatchery after the fish kills but were infeasible for the river. Permanganate additions successfully removed H_2S but were expensive, and the resulting brown precipitate in the rearing channels and slime would smother eggs in the hatchery egg trays. The federal fisheries agency considered permanganate to have "many drawbacks and is unreliable" (USFWS 1991). The best solution was thus to prevent generation of H_2S in the first place by oxidizing the sediments in the reservoir. The Speece cone HOS fulfilled that need. However, during the lawsuit deposition in 1991, prior to construction of HOS, the CFG attorney stated that the Speece cone was "highly experimental," was a "technological fix," and "the technology is unproven and should not be relied on as the sole means to improve water" (CSWRB 1991). These statements drove the state and federal fisheries agencies to demand more water releases downstream, to require minimum reservoir pool elevations, and to express strong concerns about heavy metal toxicity. It was therefore with some bravery that the EBMUD staff and Board of Directors pressed ahead with the Speece cone. Fortunately, within a few years the water quality improvements due to the Speece cone allowed CDFW and EBMUD to cooperate willingly without legal threats on other previously contentious fish needs, such as reductions in heavy metals and turbidity, as well as better water releases. These combined for a "win–win" solution that is rare in contentious water battles that can last generations, like the Truckee River, Nevada, water releases, where conflict has been ongoing since 1904 (Federal Register 2008).

It was suggested that other causes, such as methane, high temperatures, or low DO, could have been contributing causes to the fish deaths. Frequent monitoring of water quality in the reservoir and hatchery began in summer 1989 and did not include methane. The generation of methane in the sediments and bottom waters could have occurred since it requires a redox potential similar to that for H_2S formation. However, the bottom temperature in Camanche Reservoir was 13 C in 1989, which is unfavorable for methane production (Horne 2009b). Large methane emissions are best known from warm, shallow, tropical reservoirs, such those in Brazil (Fearnside 2002), although some interpretations based on these results are disputed in terms of mass releases (Hydro-Quebec 2000). In the longer term, methane production would be suppressed by HOS along with H_2S, so its role remains unlikely but possible. Other variables, such as disease, temperature, DO, heavy metals, ammonia, pH, and turbidity, are demonstrated in this study to be unlikely to cause the mortality associated with Camanche Reservoir in 1987–1989, but cannot be discounted elsewhere or at other times.

Importance of maintaining a cool hypolimnion pool

After the fish kills in Camanche Reservoir, two alternatives emerged as a solution: H_2S suppression with an HOS or holding more water in the reservoir. Like other semi-arid areas, California has water wars (Brown 2017; Horne 2009a), and more water is sometimes given as the answer to all environmental problems (Reisner 1986). Although H_2S was the common thread in both fish kills, early overturn was involved in 1987. The cause of the premature overturn was hotly debated. Fisheries agencies and environmental groups claimed that low water during the drought caused the early overturn and thus the fish kills. They thus requested a guaranteed high minimum water depth as part of the settlement. The reservoir operators (EBMUD) were understandably reluctant to break downstream water delivery contracts by storing more water.

After extensive monitoring, the critical variables that emerged were the volume and temperature of the hypolimnion (minimum cool pool) rather than the total volume stored. This distinction in crucial because the volume of sun-warmed epilimnetic water increases much more than the volume of cool hypolimnetic water as the reservoir elevation increases. In this case, the dispute about water level or hypolimnion volume/temperature was environmentally moot since holding more water in Camanche Reservoir means that less water flows for the naturally spawning salmonid fish in the river below the reservoir. The new minimum cool pool operating rule solved the early overturn problem since HOS gives high water quality despite the smaller hypolimnion. This was a vital difference for EBMUD since under drought conditions less water can be kept in Camanche Reservoir, but a high-quality outflow can be guaranteed. A benefit to the hatchery was the ability to produce fish during droughts when in the past it was often closed due to lack of a good water supply.

Unanticipated benefits for HOS

The HOS installation in Camanche Reservoir was the result of a lawsuit about hatchery fish kills. Thus, the pressing need was to protect future young fish in the hatchery during the early autumn when the 1987 and 1989 hatchery kills occurred. Also anticipated was a similar protection for all kinds of young fish in the river and the reservoir itself. Most of the fish in the hatchery in the autumn were subyearling steelhead trout, although a few Chinook salmon might sometimes be present. However, the effect of HOS operation was not confined to steelhead. Unexpectedly large increases were found for the returning adults of both species, which occurred so rapidly that they can be ascribed to the direct and indirect effects of added oxygen.

In turn, the effect of HOS operation on adult fish returns can be mostly explained by a general increase in water quality in the river (Horne 2019; Horne and Jung 2019). After HOS, the Mokelumne River exhibited a new and improved chemistry that was more attractive to returning adult fall run Chinook and steelhead. In retrospect, this is not surprising since the 1970–1980s water supply in late summer from the anoxic hypolimnion of Camanche Reservoir would have been high in H_2S, ammonia, phosphorus, iron, and manganese, as well as having potentially problematic amounts of turbidity, Cu, and Zn. Also likely was improved health in the young fish in the river and hatchery since they would always experience desirable water quality prior to release (hatchery) or outmigration (river-spawned). Improvements in the reservoir fishery itself have not yet been documented other than the expansion of cold-water fish to deeper water (Fig. 7).

Further increases in adult Chinook and steelhead several years after HOS installation can be attributed to other improvements in the hatchery, river gravel enhancement, and better downstream releases using truck transport for the young fish. Nonetheless, most later improvements, especially the use of the river for wild fish breeding, would not be possible or would be less effective without the HOS.

More than 100 million young Chinook salmon and 20 million young steelhead trout have been raised in the hatchery and released to the Sacramento–San Joaquin Delta since HOS installation. A major concern, common to all hatchery-supported fish stocks, is that hatchery fish dilute and may degrade wild fish stocks. Wild fish (those spawned in the river gravels) are prized by anglers and fish ecologists and have a higher economic value (Horne and Faisst 2019). Thanks to the HOS and the cool pool, wild fish spawning in the river below the dam now contribute a substantial portion (10–50%, more in recent years) of both Chinook and steelhead returns.

Legal consequences of HOS success

Normally, when responsibility for a fish kill or other pollution can be assigned, fines, remedial action, and mitigation may be required. In California, these decisions and actions are assessed by an administrative judge in civil court. However, the California Fish and Game Code makes it a criminal offense to negligently kill fish (Baldridge et al. 1990). A criminal misdemeanor charge filed in the Camanche case made EBMUD take notice. Thus, action to solve the problem was needed urgently, despite the lack of limnological data and the logistical problems with measuring water quality in the dry reservoir in 1988. Thanks to the success of the HOS and new cool pool hypolimnion operating rule, charges of negligence against the staff or board of directors of EBMUD were dropped.

Conclusions

The following conclusions are drawn based on consideration of all available data and deductive reasoning:

- Sudden large autumnal fish kills of young Chinook salmon and steelhead trout in the hatchery and damage to Mokelumne River fish occurred during the 1987–1992 drought. These kills were unanticipated and were a possible criminal offense.
- No water quality data were collected from the reservoir for more than 22 yr prior to the fish kills. It would have been easier to solve the problem if data had been available.
- The most likely direct cause of fish deaths was hydrogen sulfide (H_2S) since the deaths were rapid, H_2S odor was smelled, and tissue pathology and fish behavior in the hatchery channels were characteristic of H_2S poisoning. Twelve other possibilities including lower reservoir water elevation were excluded. However, in the 1987 kills, early release of the entire hypolimnion hastened the delivery of H_2S to the hatchery. In the 1989 kills, lower water elevations, a main demand of the fisheries agencies, was estimated to provide limited protection from hypolimnion anoxia and increase the risk of exposure to H_2S.
- Fish kills of any kind due to poor water quality ceased after installation of the pure oxygen HOS using a Speece cone in late July 1993. The HOS suppressed H_2S production and/or oxidized any that was produced before it left the reservoir.
- In 1987, but not 1989, the discharge of the entire hypolimnion by the end of August and consequent early overturn contributed to the transfer of H_2S from sediments to the hatchery. Institution of a minimum cool water hypolimnion pool has prevented further early destratification.
- More than 120 million hatchery salmonid fish were raised since HOS installation. It is inferred that after HOS installation the improved water quality in the Mokelumne River was more attractive for returning adult fish and rearing of wild, river-spawned fry. Chinook salmon numbers more than doubled, and endangered

steelhead trout increased from zero to hundreds per year. Wild Chinook and steelhead in the river increased substantially.

- Criminal prosecution was not pressed. The fish kills were not due to negligence but due to the coincidence of mandated hypolimnion releases, a long drought, unsuspected and unmeasured eutrophication, and the presence of H_2S. The responsible regulatory agency (California State Water Resources Control Board) was satisfied with the response of the drinking water agency (EBMUD) in terms of HOS performance, the hypolimnion minimum volume operating rule, and continued water quality monitoring.

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This article is dedicated to the late Dr. Noel Williams of the consulting firm CH2M-Hill and the original bass player for the Mo' Waters band well known to NALMS members. Jointly with Dr. Marcie Commins, Noel elucidated the H_2S oxidation kinetics in the hypolimnetic water of Camanche Reservoir that was so crucial to understanding the fish kills and designing the HOS solution. Noel fell to cancer at a relatively early age.

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