Lake and Reservoir Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ulrm20

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To cite this article: Alex J. Horne & William K. Faisst (2022) Hypolimnetic oxygenation 6. Improvement in fisheries, hydropower, and drought management with costs of installation and operation in Camanche Reservoir, California, United States, Lake and Reservoir Management, 38:3, 268-285, DOI: 10.1080/10402381.2022.2049404

To link to this article: https://doi.org/10.1080/10402381.2022.2049404

Published online: 24 May 2022.

LAKE AND RESERVOIR MANAGEMENT
2022, VOL. 38, NO. 3, 268–285
https://doi.org/10.1080/10402381.2022.2049404

Hypolimnetic oxygenation 6. Improvement in fisheries, hydropower, and drought management with costs of installation and operation in Camanche Reservoir, California, United States

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ABSTRACT

Horne AJ, Faisst WK. 2022. Hypolimnetic oxygenation 6. Improvement in fisheries, hydropower, and drought management with costs of installation and operation in Camanche Reservoir, California, United States. Lake Reserv Manage. 38:268–285.

A hypolimnetic oxygenation system (HOS) was installed in Camanche Reservoir, California, in 1993 to eliminate hatchery fish kills caused by hydrogen sulfide in dam tailwaters. It operates from about June through October each year. Algae, nutrients, heavy metals, and turbidity also declined. Fall run Chinook salmon (*Oncorhynchus tshawytscha*) increased by 3550/yr or 265%. Threatened steelhead trout (*O. mykiss*), which spend more time in the river than Chinook, benefited more (625%). A 3 yr delay in elevated adult returns indicated that the HOS's main effect was improved in-river water quality for juvenile fish, rather than better adult attraction flows. Using the California State economist's value of $1172 for an adult Chinook to freshwater anglers, the increase due to HOS added $6.5 million/yr to California's recreation. The in-reservoir coldwater fishery improved because dissolved oxygen in the hypolimnion increased from <1 mg/L to ~5 mg/L. Oxygenation allowed summer operation of a 10.7 MW hydropower plant, making HOS carbon neutral. During droughts, improved water quality at lower reservoir levels reduced dependence on alternative supplies and supported full hatchery operation and in-river spawning. Oxygen addition ($0.64/kg) was much cheaper than nitrate addition ($104/kg). Averaged over 20 yr, HOS reduced phosphorus ($19.3/kg vs. alum addition at $16/kg) and ammonia/nitrate ($2/kg). Iron ($0.0005/kg) and manganese were reduced at lower cost than for conventional methods ($9/kg). Copper ($4441/kg) and zinc ($2169/kg) fell below chronic toxicity levels. Capital cost for HOS was $1.87 million in 1993 or $30,390/km^2 ($1248/acre). Operation and management averaged $191,288/yr (1993–2000).

KEYWORDS
Carbon neutrality; Chinook salmon; cost of oxygenation; hydropower; steelhead trout

The water management community uses several methods to reduce toxicants, nutrients, turbidity, and eutrophication and thus to prevent fish kills in reservoirs and their tailwaters. This article describes one cost-efficient solution to prevent harm to fisheries downstream of Camanche Reservoir. Kills had occurred intermittently from the time of reservoir construction in 1963–1964 until 1993, when East Bay Municipal Utility District (EBMUD), Oakland, California, the owner and operator of the reservoir, installed a submerged downflow contact oxygenation device (Speece cone) as a hypolimnetic oxygenation system (HOS) in the reservoir near the dam (Fig. 1a). Effects on fish, oxygen dynamics, nutrients and eutrophication, turbidity, and heavy metals are presented in 5 accompanying papers (Horne 2019a, 2019b, Horne and Jung 2022, Horne et al. 2019a, 2019b).

From an initial 14 possibilities, 2 solutions for the fish kills were proposed in the late 1980s:

- Keeping more water in the reservoir during droughts. This would entail reducing water to downstream farmers, rafters, and river biota, and reducing drinking water to small communities.
- Oxygenating the reservoir's deep water to reduce toxic hydrogen sulfide (H_2S) released from anoxic sediments to the

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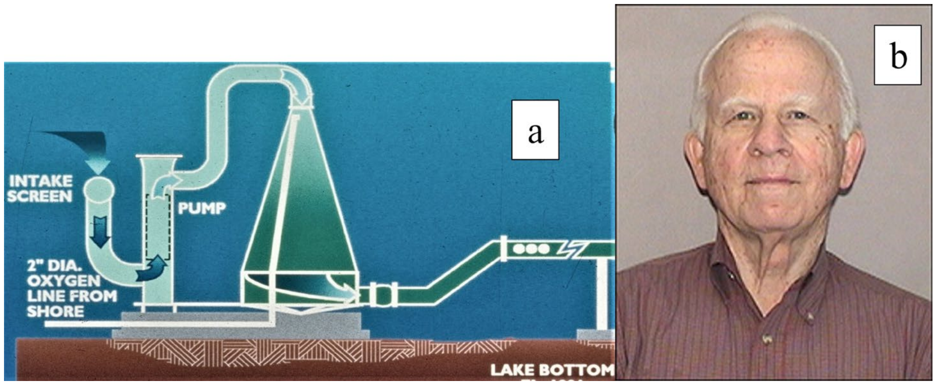

Figure 1. (a) Diagram of the Camanche Reservoir Speece cone (7 m high, 3.7 m wide at the base), showing the 5.1 cm (2 inch) diameter inlet pure oxygen gas hose, the inlet pipe containing the 0.9 m^3/s water pump leading to the top of the cone, and the outlet from the bottom of the cone to the 45 m long diffuser pipe. (b) Professor Richard Speece, inventor of the cone.

water in summer and fall. If successful, this would avoid reducing downstream supplies.

Fortunately, H_2S generation by sediment bacteria is highly sensitive to dissolved oxygen (DO) concentrations and is inhibited at levels <1 mg/L (Dunnette et al. 1985). If H_2S was the cause of the fish kills in the hatchery, then oxygenation was a viable cure for fish kills. In contrast, increasing water storage by keeping the reservoir 3 m deeper (14% increase) was less certain at the time to prevent H_2S generation.

Aeration mixing with compressed air bubbles would provide atmospheric oxygen to deep water, but the concomitant destratification would increase the temperature of summer–fall tailwater releases, violating agreements for cool water attraction flows for migrating salmon. Destratification would also destroy the 2-story in-reservoir summer fishery, which includes trophy bass in the upper warm water and trout and kokanee salmon (*Oncorhynchus nerka*) in the cool water below. To preserve thermal stratification and ensure maximum DO at the H_2S-generating sediment–water interface, EBMUD selected an HOS as the best alternative at the time. The local price of liquid oxygen (LOX) was \$56/ton (0.0000006 cents/mg) in 1993 and had doubled by 2018. At the expected total oxygen depletion rate in the reservoir (0.23 mg DO/L/d), a charge of 10 mg of oxygen/L would last for 43 d for a cost of 0.0000001 cents/L/d, but there are more than 500 billion liters of water in Camanche Reservoir. This article examines the costs of HOS and improvements in fisheries over 20 yr.

Hypolimnetic oxygenation system (HOS)

The HOS is critical to this series of papers, and full details of the form of HOS used in Camanche Reservoir, the Speece cone, are described in detail by Horne (2019) and Horne et al. (2019b). The HOS system (Fig. 1a) was designed by Dr. Faisst with advice from Professor R. Speece (Fig. 1b). The primary purpose of HOS in Camanche Reservoir was suppression of sediment anoxia. This was needed after 1987–1989 when 300,000 young steelhead trout (*O. mykiss*) died in a hatchery located just downstream of the dam. Other fish including Chinook salmon (*O. tshawytscha*) would have been affected in the Mokelumne River below the dam. The hatchery receives bottom hypolimnetic water. Poor water quality, especially with elevated concentrations of hydrogen sulfide (H_2S) in the reservoir outflow, was the most probable cause of fish deaths (Horne 2019a).

The Speece cone in Camanche Reservoir is 7 m high and 3.7 m wide at the base, set on the reservoir bed near the dam (Fig. 1a). An underwater electric pump pulls the deepest and normally lowest water quality water to the top of the cone. Pure gaseous oxygen evaporated from the LOX tank on shore is piped to near the top of the cone. The 2 counterflowing streams of water (down) and oxygen gas (up) mix until all bubbles are dissolved. The cool, dense, oxygenated, and bubble-free water flows out of the bottom of the cone and is dispersed back into bottom water to approximately saturation levels via ports in a diffuser pipe (Fig. 1a). Because the water discharged from the cone has not changed in density, it forms a 9 m high plume that flows along the reservoir bed, oxidizing the sediment–water interface (Horne et al. 2019a).

Improvement in fall-run Chinook returns

In California's Central Valley rivers, Chinook salmon are differentiated into 4 seasonal runs (fall, late fall, winter, and spring), indicating when the adults migrate back from the ocean into freshwater to spawn. Historically, the spring run may have been the largest, but it is functionally extinct, and the fall run is now the largest. This article considers only the fall run of Chinook salmon in the Mokelumne River, which is part of the much larger California Central Valley River system. The HOS is operated mostly between June and October, but effects last through at least November so will benefit the different life stages accordingly.

Chinook salmon in California spend about three-quarters of their lives at sea. For the Mokelumne River and other tributaries to the Sacramento River, fall-run adults migrate from the ocean to their natal spawning areas between mid October and early December (Miyamto and Hartwell 2001). Early arrivals in August may spawn in early September (Table 1) and would most benefit from HOS. Most adult Chinook return at age 3–4 yr. They return to their birthplace in river gravels or the hatchery by tracking their unique chemical signature, and detecting this odor could be adversely affected by water quality. Effects of temperature, flow, and dissolved oxygen (DO) on migration returns have been the most studied water quality parameters (Lehman et al. 2017), but these will be little affected by HOS once well downriver from the dam. In addition, sediment and heavy metals affect salmon at all stages but pre-HOS concentrations were relatively low and the measured reductions due to HOS were too small to account for the large differences in returning adults following HOS (Horne 2020, Horne and Jung 2022). Iron, which fell dramatically, may be an exception, but no reports of the effect of high dissolved or particulate oxidized iron on salmonid migrations were found.

Having reached the dam, some adult Chinooks are captured, killed, or spawned artificially, and the eggs are incubated in troughs fed with the hypolimnetic water from Camanche Reservoir. In the river, uncaptured wild females dig a slot in the gravel, the redd, into which each deposits about 5000 eggs. The male nearby fertilizes them as they settle, and the female covers the eggs with gravel. Pacific salmon die within weeks of spawning. The eggs need a good supply of oxygen, which requires porous gravel through which water can pass readily, so should benefit from HOS. Both hatchery and river eggs are sensitive to pollution, including heavy metals like copper, smothering by fine sediments, metal hydroxide slimes, and overgrowth by biofilms, which are stimulated by nutrients. All these potential downriver deleterious effects were reduced by the decreases in algae and homogenization of the bottom water layers due to the operation of

Table 1 Schematic of effects of HOS on life stages of Chinook salmon and steelhead.

Life stage/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chinook												
Spawning adults									[large fish icon]	[large fish icon]	[large fish icon]	[large fish icon]
Eggs in gravel	ooo	ooo	ooo						**ooo**	**ooo**	**ooo**	ooo
Parr emerging	x	x	x	x	x	**x**					**x**	x
Parr in upper river	X	X	X	X	X	**X**	**X**	**X**	**X**	**X**	**X**	X
Smolts	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]
Steelhead												
Spawning adults	[large fish icon]	[large fish icon]									[large fish icon]	[large fish icon]
Eggs in gravel	ooo	ooo	ooo	ooo	ooo						**ooo**	ooo
Parr emerging		x	x	x	x	**x**	**x**					
Parr in upper river	X	X	X	X	X	**X**	**X**	**X**	**X**	**X**	**X**	X
Smolts	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]	[small fish icon]

Symbol indicates presence in river in that month. Boldface type indicates HOS was affecting water quality (Jun–Nov). Fish are shown as large fish icons (returned adults) and small fish icons (parr or smolt in hatchery or river). Lower case x indicates small parr emerging from near-dam gravels, and upper case X indicates larger parr living throughout the upper river (~0–10 km from the dam).

the Speece cone in the upstream reservoir (Horne 2020). More than half of the Chinook eggs, those laid between September and December, will potentially benefit from this aspect of HOS (Table 1).

After 40–60 d, the eggs hatch and the emerging juvenile fish (parr) are reared in hatchery runways, which are fed with hypolimnetic water. Wild parr receive identical water from the dam tailwaters. The timing of parr emergence from the gravel only slightly overlaps with any improvement in water quality due to HOS. In contrast, about half of the rest of the Chinook parr life stage in the Mokelumne River occurs when HOS is having maximum effect (Table 1). The parr remain in the upper river, but after a few months they become smolts (older juveniles that migrate to sea) and drift to the lower 20 km reach of the Mokelumne River. Peak juvenile passage to the lower river occurs in January and February (Bilski et al. 2013). Hatchery releases are based on optimum size, and most releases take place between April and May. About half of the smolt stage is also influenced by HOS. Most hatchery smolt, but not necessarily wild ones, will be gone from the upper river by fall. However, in October 1989, the massive kills of juvenile steelhead trout that occurred in the hatchery showed potential problems for any river fish. This large fish kill was documented and attributed to H_2S, which was eliminated by HOS (Horne 2019a).

Juvenile chinook in the hatchery raceways are fed artificially with pellets, while wild fish feed on benthic insects like stoneflies and mayflies, which, each night, drift from upstream in large numbers (Hynes 1979, Horne and Goldman 1994). However, Camanche and Pardee dams block such drift. Wild Lower Mokelumne River salmon juveniles feed mostly on large zooplankton like *Daphnia*, which come from the reservoir during high flows (Merz 2001). During low flows, chironomid (midge) larvae and young sucker fish are their main food supply. *Daphnia* requires a moderate supply of oxygen but was not clearly shown to change in numbers in the upper waters of the reservoir after HOS (Horne et al. 2019b). The deeper water was not sampled. However, following HOS in 1993, *Daphnia* would be able to move into the hypolimnion, where it would have been prohibited from July to October prior to HOS (Horne et al. 2019b). Thus, the food supply to the river juveniles probably increased after HOS.

The most dramatic result of HOS was the large increase in the fall-run Chinook. The number of fish most immediately related to HOS, which began in 1993, was the 1996–1997 cohort, when fish born in 1993 returned to the hatchery or the river to spawn. This cohort averaged 9100/yr for 1996–1997 (Table 2, Fig. 2) The 1996–2005 returns were similar, with 9699 fish/yr, and the 2014 returns were a bit higher at 12,117/yr. The increase due to HOS was determined by subtracting the long-term baseline number of 3550/yr (1940–1992) from 9100/yr (1996–1997), giving an increase of 5550/yr (Table 2). Because the other time periods after HOS show similar numbers (6050/yr, 1996–2005), the increase in Chinook returns was robust and unlikely to be due to natural fluctuations (Horne 2019a). The hatchery used 7000 fish/yr for spawning in 1996–1997, of which 4231/yr were attributable to HOS.

California's State Economist reported that the value to a recreational salmon angler of an adult California Chinook salmon caught in freshwater is $1172/fish (Ransom 2001, CDFW 2010). For comparison, the 58,000 striped bass (*Morone saxatilis*) caught in California generated about $494/fish. The annual increased number of Chinook returns described herein due to HOS was 5550; therefore, at $1172/fish, the total dollar improvement was just over $6.5 million/yr. To put this

Table 2. Effects of HOS on returning adult Chinook salmon before and after HOS, which began in July 1993, compared with the long-term average of record prior to HOS.

Time periods	Returning Chinook, #/yr	Increase after HOS, #/yr	Droughts
1940–1992 before HOS	3550		3
1996–1997 returns 3–4 yr after HOS	9100	5550	1987–1992
1996–2005 returns after HOS but before other upgrades	9600	6050	3

(i) 1996–1997: the first returning adults that would have been eggs in late 1993 through spring 1994 and (ii) a longer term average 1977–2005 before major upgrades were made.

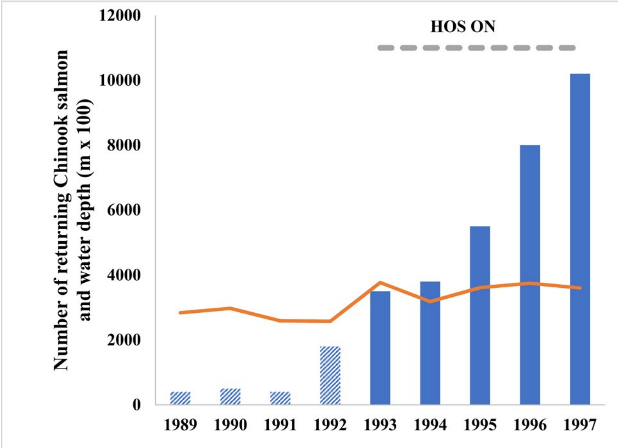

Figure 2. Annual returns for adult Chinook salmon between 1989 and 1997 before (hatched bars) and after (clear bars) HOS operating in summer–fall (dashed line). Increases can be attributed to improved water quality conditions in the river below the dam once pollutants had been reduced by HOS. It takes 3–4 yr before a fish hatched either in the hatchery or river in 1993 migrates to sea, matures, and returns, i.e., 1996–1997. During the 1987–1992 drought water depth (line) averaged 27.4 m, compared with 35.8 m post-drought (1993–1997), but both depths permit stable thermal stratification.

improvement due to HOS in perspective, the total California salmon fishery was valued at $183 million in 2015. The increase in fish due to HOS in Camanche Reservoir accounts for only 3.6% of the statewide Chinook value (CDFW 2018).

The initial HOS-derived improvements in Chinook returns encouraged further management changes. Minor fishery improvements began in 1990 but had no apparent effect prior to HOS (500–1800 fish/yr, 1990–1992, Fig. 2), probably because of continued poor water quality. Perhaps the most important later upgrade, after HOS, was the addition of more than 50,000 m^3 of gravel in the river, which, based on earlier plans and experiments, probably resulted in half of the redds being constructed in the new, enhanced habitats (EBMUD 1999, Merz and Setka 2004). In 2004, improvements were made in the hatchery operation. Barges were introduced to transport some smolts around the unsuitable conditions of the delta for release in San Francisco Bay. The combination of HOS and the CFWD hatchery managers' actions, including improvements funded by EBMUD, have further increased the average returning fall-run Chinook numbers to about 18,000/yr (2017–2019), 5 times pre-HOS numbers. EBMUD completed a $12.5 million hatchery renovation in October 2020 to add space to promote fish health and survival rates. Assuming all the additional fish were valued at the State Economist's angler value, the increase would be almost $17 million. In this case, the 2018 improvements contribute 9.2% of the state's fish value, in line with recent estimates that the Mokelumne River Chinook population is now about 8.3% of the Sacramento River stock.

A key factor in evaluating fish returns is in-river spawning, because anglers and ecologists place more value on natural "wild"-born fish (Parrish 2017). Since HOS, there have been years when as many wild fish spawned in the river as at any time since 1940, when recordkeeping began. Prior to HOS, an average of 2467 Chinook spawned in the river (1966–1993—the period between the hatchery construction and the first year of HOS). Between 1994 and 2019 there were over 1.7 times more in-river spawning fish, and in the most recent decade there were 6182 naturally spawning fish or 2.5 times more than pre-HOS numbers. The addition of more spawning gravels was a major factor in the more recent increases, but prior to gravel supplements and after HOS (1994–2005), there was still an average of 8775 fish spawning naturally in the river (Fig. 3). Most recently, in 2018, the in-river spawning population was 10,194 salmon out of the total of 17,474 total returning fish. Also of concern is percentage of wild in-river spawned fish and hatchery-raised fish. The wild-born adult population is "diluted" by hatchery fish, which gives a percentage loss in genetic diversity. Since the start of HOS, in-river spawning has ranged from 10 to 58%, with an average of 37% over the last decade, although there is still concern in some years (Johnson et al. 2012).

Improvements in threatened steelhead trout fishery

Steelhead trout are rainbow trout (*O. mykiss*) that go to sea like salmon, rather than remaining in freshwater for all their lives. In 1993 prior to HOS, adult steelhead were rare in the Mokelumne River despite the release of hundreds of thousands of young hatchery-raised fish to the river each year. The California Central Valley stocks are classified as threatened. This is not unusual since nearly half of the 400 naturally spawning stocks of salmon and trout in the Western states are extinct, and half of the remaining stocks are at high risk of extinction (Nehlsen et al. 1991).

Unlike Pacific salmon that die within 3 weeks of spawning, adult steelhead linger longer in rivers because many do not die after spawning. They can return to the sea and may spawn again in later years. This behavior is like that of the Atlantic salmon (*Salmo salar*). Steelhead migrate into the Mokelumne River later than Chinook (Nov–Feb) and return to the ocean during the winter and early spring months, usually following heavy rainfall. Also different from the Chinook is that juvenile steelhead may spend 2 to 3 yr in freshwater after hatching. Thus, steelhead are more exposed to any summer–fall pollution in the tailwaters of Camanche Reservoir than juvenile Chinook and benefit most from any reduction in toxicants. The reported hatchery fish deaths in 1989 were all young of the year steelhead. Of the 425,000 fish present, 35% died in only 3 weeks (Horne 2019a). Their deaths were attributed to H_2S poisoning.

In percentage terms, the improvement to the steelhead fishery was greater than that for the Chinook. In the 3 to 4 yr after HOS when the adults spawning in 1993 would return to spawn, the numbers rose from 8/yr to 50/yr, a 625% improvement, while Chinook, though present in much larger numbers, rose by only 256%. This difference may be due to the longer time both adult and juvenile steelhead spend in the river exposed to pollution from the anoxic hypolimnion prior to HOS. Steelhead have continued to increase substantially, with adult returns averaging 625/yr (2017–2018).

Improvements in the Camanche Reservoir fishery

The coldwater fishery of Camanche Reservoir itself was also improved since oxygenated coldwater habitat is now present in much of the hypolimnion (Horne et al. 2019a). Both fish and their benthic invertebrate prey would benefit. The HOS had a dramatic effect on the larger coldwater species such as rainbow trout and kokanee salmon (Fig. 4). Camanche Reservoir is best known for bass fishing and is also a favorite of trout anglers. Each year, 27,000 kg of trout (0.5–3.6 kg/individual) are stocked between October and June. Fish distribution was determined by echolocation (Horne 2019a), which targets larger individuals and was confined to deeper water away from the shorelines. In June 1992 (before HOS) most fish (69.1%) were present in the epilimnion (0–7 m, DO 5–10 mg/L, temperature 22.5 C), and 23.6% in the thermocline or metalimnion (7–12 m, DO 2.7–5 mg/L, temperature 16.3–22.3 C) for a total of 92.7% (Table 3). No fish were found in the lower hypolimnion

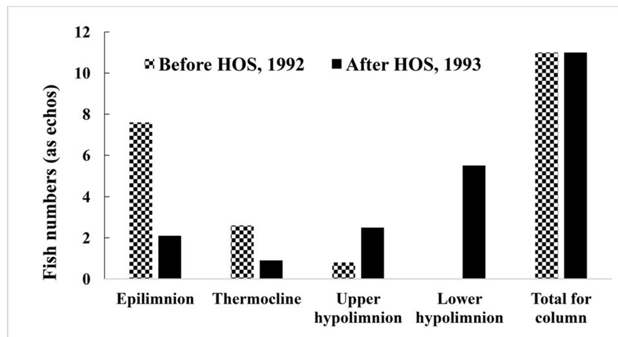

Figure 3. Improvement in depth fish distribution due to HOS. Data show distribution of fish, as shown by echolocation, in 4 layers of the reservoir. Prior to HOS, fish were confined to the oxygenated upper water. No fish were recorded in the lower hypolimnion prior to HOS.

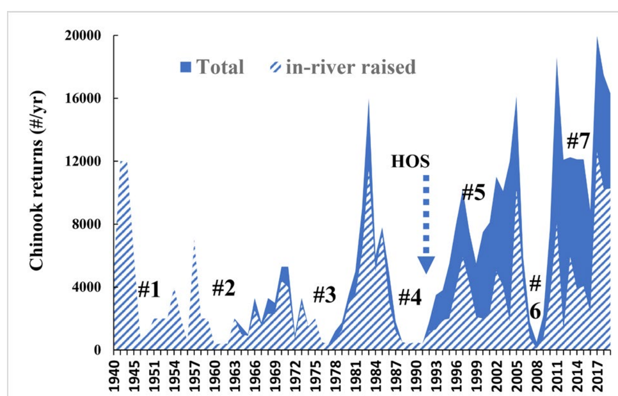

Figure 4. Long-term (1940–2019) returns of adult Chinook salmon. Total fish returns (solid) and hatchery spawned fish (hatched area). Arrow shows HOS start in 1993. Low returns occurred in droughts (1–4) prior to HOS but were higher in droughts after HOS. Best return was drought 7, where HOS was supplemented with upstream reservoir releases. Low drought returns for drought 6 (2007–2009) were due to "poor ocean conditions," but 3–4 yr after, in 2012–2015, returns were high.

Table 3. Depth distribution of larger fish, as sonar echoes, in 4 layers of water before (Jun 1992) and after (Sep 1993) HOS, which commenced in late July 1993.

	Before HOS		After HOS	
Fish echolocation	1992	%	1993	%
Epilimnion (0–7 m)	7.6	69.1	2.1	19.1
Thermocline (8–12 m)	2.6	23.6	0.9	8.2
Upper hypolimnion (13–18 m)	0.8	7.3	2.5	22.7
Lower hypolimnion (19–31 m)	0	0	5.5	50
Total	11	100	11	100

(19–31 m, DO 1.4–2.2 mg/L, temperature 14.2–15.2 C) and only 7.3% were in the upper hypolimnion (13–18 m, DO 2.2–2.6 C, temperature 15.2–16.2 C). This distribution corresponds to the generally accepted "temperature–oxygen squeeze (Beutel et al. 2001, Welch et al. 2011) and the salmonid guidelines where DO of 5–7 mg/L is preferred and <2 mg/L is always avoided.

After HOS, in September 1993, larger fish moved into deep water, including the bottom layer. HOS began in July 1993 and thus measurements could not be made in June as in 1992, but the same total number of echoes (Table 3) indicates similarity in the size of the large fish stocks for both years. Warmwater Florida-strain large-mouthed bass (*Micropterus salmoides*) probably accounted for the fish remaining in the warmer, upper waters showing 19.1% (epilimnion) and 8.2% (thermocline) of the echoes after HOS (Table 3). Temperatures in these 2 layers were identical to those in the previous year, while DO was lower but still in a mostly favorable range for the epilimnion (1.5 to 7.3 mg/L) but marginal (2.3–4 mg/L) in the thermocline.

The dramatic change was in the deep hypolimnion (18–31 m), previously fishless, which contained half of all the large individuals in the reservoir after HOS (Table 3). This was expected from other HOS operations (Preece et al. 2019), and in Camanche Reservoir the differences in fish at each depth layer were statistically significant ($P = 0.01$, 2-tailed test, equal variance, $n = 60$). The DO increase due to HOS was responsible for the occupation of the deepest water by large fish. Smaller trout and kokanee may have used the new dark oxygenated bottom zone as a refuge from predation by larger adults. The temperature profile following the initial HOS use in 1993 was almost identical to that of the previous year, while the oxygen profile showed large changes (Fig. 5 in Horne et al. 2019a). In summer–fall 1992, before HOS, DO in the 21 to 27 m layer was zero. In 1993 after only a few weeks of HOS, the DO at 27 m had risen to 6.3 mg/L at 27 m and 4.8 mg/L at 21 m. This bottom layer has the approximate dimensions of the oxygenated plume from the Speece cone (Horne et al. 2019a). HOS has been used in almost all years since, and in 2014 the DO in the entire hypolimnion ranged from 4.8 to 6 mg/L (see Horne et al. 2019b).

Recreational fishing has improved in Camanche Reservoir, but the dollar benefits are not easily estimated. Stocking practices, including the introduction of kokanee salmon, occurred between 1990 and 2000, which is during the HOS initiation period.

Restoration of hydropower generation

Because salmon in the Mokelumne River downstream of Camanche Reservoir need at least 7 mg/L DO, low DO in the tailwaters of Camanche Reservoir had prevented the use of EBMUD's 10.7 MW hydropower plant between August and November. Prior to HOS in 1993, the DO need was satisfied by bypassing the turbines and diverting the penstock flow to a fixed cone known as a Howell–Bunger valve. The valve dissipates the energy in the discharge in a huge semicircular shower of water without causing erosion and incidentally aerates the water. It also volatilized some H_2S, but removal of enough H_2S to prevent fish kills requires at least 6 h (Horne 2019a), so the few seconds of exposure in the Howell–Bunger valve shower was not the ideal solution. After aeration, H_2S would re-form as the equilibrium between H_2S and the HS^- ion reestablished. In addition, the Howell–Bunger valve would not affect ammonia, heavy metals, and turbidity. Prior to HOS, river water quality was poor even with the vigorous aeration.

The Federal Energy Regulatory Commission (FERC) is responsible for renewing licenses for hydropower. EBMUD was due for renewal in the early 1990s, soon after the fish kills. Consequently, EBMUD was considering abandoning hydropower generation due to the summer restrictions despite the concomitant increase of greenhouse gas emissions and loss of revenue. However, once the effectiveness of HOS had been demonstrated, the FERC relicensing application was granted. EBMUD now generates enough electrical hydropower to fully offset the electrical cost of running the water pump in the Speece cone. The in-reservoir operation of the cone is thus carbon neutral.

Drought management—operational flexibility

Water in the 17 semi-arid states of the United States is always a scarce resource and more so during droughts. In contrast, oxygen supplies are not affected by droughts. The amount of oxygen needed to oxygenate the hypolimnion of even larger reservoirs is a small fraction of the cost of other water management actions, including purchase of additional water during droughts (see "Capital, operation, and management costs"). An alternative to HOS suggested by the fisheries agencies was a higher water level in the reservoir during droughts. Higher water levels are sometimes better for water quality, since the hypolimnetic volume is greater, holds more oxygen, and might delay or eliminate whatever was causing fish kills downstream. However, additional water held in the reservoir would then not be available for downriver purposes.

The higher minimum water level suggested for Camanche River was 24.2 m vs. 21.2 m—a volume of 57 million m^3 (~46,000 acre-feet, af), 11% of the full reservoir and 16% of its typical summer volume. The delay in onset of deepwater anoxia due to a 3 m increase in water level in Camanche Reservoir given the hypolimnetic water DO decline of ~0.1 mg/L/day was calculated as only a few days. Fish kills would still have occurred, and the additional water would have provided no reduction in H_2S production, nutrients, algae, ammonia, heavy metals, and turbidity. With HOS, Camanche Reservoir can now operate at a lower level in droughts and still provide good quality hypolimnetic releases. Nonetheless, levels cannot be allowed to decrease too much since destratification will occur. This was a contributing factor for the 1987 fish kills, and a minimum volume for cool water in the hypolimnion was adopted as an operational rule along with HOS in 1993 (Horne 2019a). Therefore, HOS with a minimum hypolimnion pool was more cost-efficient than the higher water level alone alternative.

Using HOS during droughts, even with lower water depths, enabled hypolimnion releases with adequate water quality for downstream fish. EBMUD had no need to purchase additional water supplies. Especially in droughts, emergency supplies are costly and were avoided with use of HOS while still avoiding any fish kills.

Drought management—fish

Operating the Mokelumne River fish hatchery at full capacity during droughts was previously considered impossible. For the first 4 of the 7 droughts since 1940 when recordkeeping began, few adult Chinook returned to their spawning areas (Figs. 3 and 5, Table 4). The situation was the same before and after construction of the Camanche Dam in 1964. The severity of each drought, as indicated by the average Palmer Drought Severity Index (PDSI; Palmer 1965), explained 51–53% of the variances with the Chinook returns expressed as a percentage of the long-term mean (Table 4), both before and after HOS ($P = 0.18$, $n = 9$). Chinook returns are based on the most conservative estimate of the long-term pre-HOS mean (1940–1987, Horne 2019a).

In late summer–fall during droughts 1–4, the reservoir was shallow and unstratified, so the water was too warm for young in the hatchery or river or for returning adults. The hatchery was closed during these droughts, with consequent reductions in adult returns 3–4 yr later (Fig. 3). Prior to HOS, returns during droughts 1–4 averaged 28% of the long-term mean, and returns after 3–4 yr (i.e., mature adults that would have been born during the droughts) were 90% of the mean (Table 4). After HOS, returns during droughts 5–7 averaged 195% of the long-term mean (all years), or 292% if the aberrant drought 6 was omitted. Greatly reduced returns occurred in drought 6 for all fish in the Central Valley River basin and were attributed to poor ocean conditions (Lindley et al. 2009), not reservoir operations.

Chinook post-drought returns before HOS showed a good natural ability to rebound after stress (90% of mean, Table 4, Fig. 5). Nonetheless,

Table 4. Sacramento River Basin drought intensities and returns of adult Chinook salmon during droughts as a percentage of the long-term mean.

Returning adult Chinook salmon as a percent of long-term average (1940–1987)					
Number	Droughts	PDSI Index	Returns in droughts	Returns 3–4 yrs after	Notes
1	1948–1951	−1.04	34	85	
2	1959–1962	−2.28	22	35	
3	1976–1977	−3.23	12	120	Severe, short drought
4	1986–1992	−2.43	42	120	Long drought
5	2001–2002	−1.49	220	310	HOS + short drought
6	2007–2009	−3.61	42[1]	343	HOS + volume augmentation
7	2012–2016	−3.06	324	395	Long drought, HOS + volume augmentation
	No HOS	−2.25	28	90	Low returns in droughts
	With HOS	−2.75	195	292	High returns during and after more severe drought average
	With HOS	−2.75	292	395	Excludes "poor ocean" 2007–2009

Returns 3 yr after a drought would be adults whose eggs hatched during the drought. PDSI = Palmer Drought Severity Index.
[1]All California Central Valley returns in 2007–2009 were low due to "poor ocean conditions," not reservoir operations.

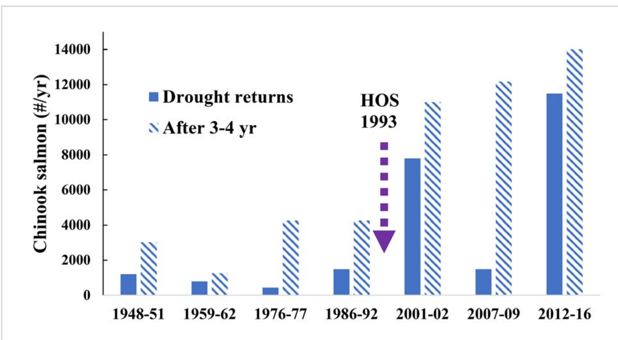

Figure 5. Effect of HOS on adult Chinook returns in droughts (solid bar) and 3 yr later (hatched bar). Drought returns and the 3 yr post-drought returns were low prior to HOS, but most droughts after HOS showed higher returns during and after droughts. The 2007–2009 returns were due to poor ocean conditions that affected all of California's Sacramento River hatcheries.

similar average 3 yr post-drought returns after HOS were much larger ranging from 292 to 395%. Although HOS was a driver in this increased post-drought success, an important management change was made between droughts 5 and 7 (both after HOS). The reservoir volume can be increased with hypolimnion discharges from the smaller but deeper Pardee Dam 15 km upstream. At one time it was thought that the cool, oxygenated Pardee Dam releases would pass along the bottom of Camanche Reservoir to its outlet and thus benefit the hatchery. Unfortunately, the water becomes heated and loses oxygen while flowing between the 2 reservoirs in summer at this low elevation of 73 m. Once in Camanche Reservoir, Pardee releases find an equilibrium density depth just below the thermocline, not at the bottom near the outlet, so added inflow was rejected as a solution after the fish kills of 1987–1989 (Horne 2019a). However, once HOS had been shown to be a reliable method to maintain an oxygenated bottom water layer, EBMUD staff thought of an innovative solution using upstream releases, even if warmer. The volume of added water was adjusted to maintain an overall minimum hypolimnion volume (31 million m^3) and cool temperature (<16.4 C). These numbers were established after the drought-related hatchery fish kills of 1987 and 1989 (Horne 2019a). The original bottom water remained cool enough to be discharged to the benefit of the hatchery and wild fish during drought 7, while the added upper hypolimnion water prevented early turnover. Drought 7 was the first time the hatchery could work at full capacity during a drought. This was so successful that juvenile fish from other hatcheries were transplanted to the Mokelumne River hatchery. A similar manipulation might have been possible in drought 5 had the idea been thought about then.

Heavy metals reduction

HOS resulted in lower amounts of some chronic pollutants in the deeper hypolimnetic zone affected by oxygenation. In particular, the water flowing out to the river and hatchery after HOS contained 12% less copper, 33% less zinc, 73% less manganese, and 96% less iron on a unit volume basis (μg/L; Horne and Jung 2022). These reductions were partially due to precipitation of Fe and Mn caused by the oxygen itself and partially due to homogenization of the deepwater layers by the Speece cone plume (Cu, Zn, turbidity). Prior to HOS, the deepwater levels of Cu and Zn were already low (Cu average 3.3 μg/L, Zn average 17.7 μg/L). However, even these low copper concentrations can be toxic to salmonids (aquatic life criterion 3 μg/L), depending mostly on the amounts of chelating agents, carbonates, and the acidity. The runoff to Camanche Reservoir from the Sierra Nevada Mountains is "soft," containing few calcium ions or chelating ligands that can bind heavy metals.

Soluble iron and manganese in many kinds of water supplies is a nuisance; it causes undesirable taste, stains porcelain in sinks and laundry, and causes a precipitate in tanks. The Mokelumne River below Camanche Dam is used as a drinking-water supply but only well downstream, after any soluble iron would have been precipitated naturally to the riverbed. However, iron precipitate in rivers is usually as the hydroxide which is a slime and can blanket the gravels and prevent the flow of water and oxygen needed by fish eggs, fry, and aquatic invertebrate prey items, such as midge and mayfly larvae. Soluble iron in Camanche Reservoir tailwater was reduced from 7800 to 200 μg/L by HOS (Horne and Jung 2022). Early spawned eggs of both Chinook and steelhead would be affected by any occlusion of oxygen-containing water through the gravels due to iron precipitation (Table 1). HOS implementation greatly decreased soluble iron in released waters (97%) and hence potential slime formation, substantially decreasing the risk for emerging fry. Emergence of parr for late-spawned steelhead might also be adversely affected. The reduction in iron-based slimes in the river below the dam could account for part of the surveyed large increase in in-river or wild salmonid spawning that began after HOS (Merz and Setka 2004, Bilski et al. 2013).

Capital, operation, and management costs

The HOS system (Fig. 1a) was installed in summer 1993 on a rapid design-build schedule and assembled by a local contractor in Lodi, California. Design engineering, fabrication, and installation of the HOS system cost $1.5 million, of which the custom-made, fusion-bonded, epoxy-coated steel Speece cone accounted for $500,000 (Table 5). Other options for adding oxygen to the sediments included aeration mixing, pure oxygen bubble plumes, and nitrate additions, but they were not implemented for Camanche Reservoir (Horne 2019a).

The main operation and management (O&M) costs for HOS were electricity for the submerged water pump (127 kW, 0.9 m^3/s; 170 hp, 32 cfs) and LOX. The annual mean O&M cost for the first 8 yr was $191,288, with average operation time 95 d/yr (Table 6, Fig. 6). Of this total, $75,000 was for LOX, a similar cost for electricity, and the remainder was staff time. Since 2000, costs have fallen as the daily oxygen supply was reduced because algae biomass, the main biochemical oxygen demand (BOD) source, fell 79% (Horne et al. 2019b). Total O&M costs have varied little between 2000 and 2018.

A recent survey of circulation, aeration, and oxygenation systems showed a wide range of costs (Wagner 2015, Table 7). One variable is that the cost can be for the entire reservoir or for the targeted area, in this case the oxygenated plume on the reservoir bed. The capital cost/target area

Table 5. Capital costs for the Camanche Reservoir Speece cone.

Fabrication/purchase with engineering	($1000) 1993	($1000) 2017
Design cone, pump, diffuser	85	141
Fabricate and deliver 127 kW (170 hp) submersible pump	240	398
Fabricate, deliver, install cone	185	307
Fabricate, deliver, install diffuser and stilts	51	85
Anchors	25	42
LOX tanks, evaporators, purchase and install	284	471
Installation of cone, base, electrics, fencing	149	247
Barge, crane, trailer, divers	99	164
Mobilization to site, bottom and land surveys	162	269
Base fabrication and installation	30	50
Electrical work, switchgear	27	45
ROV underwater survey rentals	6	10
Equipment testing, site cleanup	54	90
Oxygen monitoring system in reservoir	119	198
Total construction and installation costs	1516	2517
Other costs		
EBMUD staff time including permitting	115	191
Monitoring limnology 1988–1994	237	393
Total cost including monitoring	1868	3101
Capital cost straight line 20 yr amortized	93.4/yr	N/A

N/A = not applicable.

of Camanche's HOS ($3083/target ha or $1248/acre, 2017 dollars, Table 7) was only 16% of the midrange price per acre for similar cones ($19,249/target ha or $7793/acre, Wagner 2015). On a volume basis, Camanche cone costs for capital or O&M were also low, about 10–20% of the midrange of Wagner (2015). The differences in cost/target area or volume between the Camanche and the Wagner (2015) report can be reconciled using modern estimates for Speece cone costs. Based on a 2018 predesign study for a new Speece cone in a smaller reservoir in EBMUD's system today, the Camanche Reservoir could cost an order of magnitude more (~$18 million; 2018 dollars, Table 7). This yields a cost of ~$7714/target acre, about equal with the $7793 of Wagner's (2015) range.

For Camanche Reservoir, the costs were low because

- Long-term algal reduction and hypolimnetic BOD declines occurred, so less oxygen needs to be added. Such declines have been found in other waters (Preece et al. 2019) but were not factored into the design in 1993. Initially, 2 cones were planned based on expected oxygen demand, but it was decided to install only one cone and monitor the results. The second Speece cone was not needed.
- Low nutrient inflows (most years). Water inflows for Camanche Reservoir are normally low in biologically available nutrients, unlike many of the reservoir surveyed by Wagner (2015). Also, internal cycling was causing the reservoir's eutrophic state in summer and not a combination of internal and external nutrient inflows. The origin of Camanche's nutrient-rich sediments is not clear (Horne 2019a, Horne et al. 2019a). Nutrients that nourished the extensive cyanobacterial blooms prior to 1993 may have accumulated from occasional fluxes from upstream overlogging events (EBMUD 1996) or the substantial aerosol and dust

Table 6. Details of operating and maintenance costs of the Camanche Reservoir HOS.

Year	Days of operation	Electric ($/yr)	LOX ($/yr)	Total ($/yr)
Supplies				
1993	67	20,100	36,180	52,280
1994	132	39,600	71,280	110,880
1995	13	3900	7020	10,920
1996	75	22,500	40,500	63,000
1997	126	37,800	68,040	105,840
1998	108	32.400	58,320	90,720
1999	136	40,800	73,440	114,240
2000	104	31,200	56,160	87,360
Means	95	28,538	51,300	71,280
Repairs				2500
Total supplies				Mean = 73,780
Personnel				
1993–2013	2 staff 0.3 time			117,500
Total O&M				191,288

Electric power in 1993–1997 cost was estimated for 0.08/kW-hr ($400/d) and liquid oxygen (LOX) at $540/d. In the first few years, LOX was used at 8 t/d but was reduced to <4 t/d after 1995. N/A = no data.

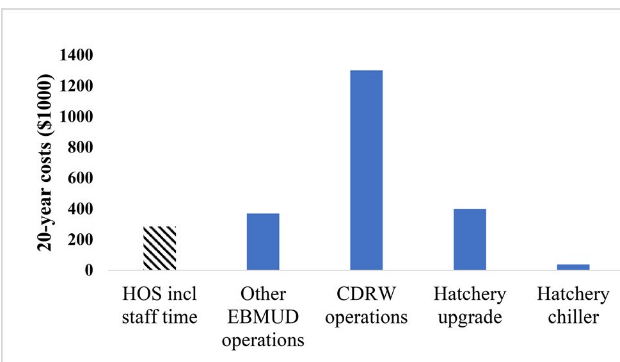

Figure 6. Operation and management costs for the Camanche Reservoir HOS relative to other costs for the reservoir and fish hatchery. Costs inflation-adjusted; 2 recent upgrades also amortized over 20 yr to be comparable with HOS.

Table 7. Cost comparison with other Speece cones and pure oxygen addition systems (Mobley-type bubble plumes) and Blue-in-Green Inc.-type superoxygen side stream (from Wagner 2015).

	Capital cost/area		O&M/area		Capital cost/volume		O&M/volume	
Source/site	$/ha	$/acre	$/ha	$/acre	$/Tm³	$/af	$/Tm³	$/af
Wagner; all Speece cones	19,257	7793	195	79	174	214	4	5
Camanche cone 1993	**3083**	**1248**	**62**	**25**	**3.6**	**4.4**	**0.37**	**0.46**
Camanche cone 2018	19,062	7714	62	25	36.4	44.8	0.37	0.46
Wagner; O_2-bubble plumes	4428	1792	741	300	44.7	55	8.9	11
Wagner; super O_2	10,139	4103	1441	583	320	393	43	53

$/Tm³ = dollars/1000 m³. Bolded text = current study

drift from the Central Valley farmlands (Aciego et al. 2017).
- The locations of the Speece cone and evaporator were conveniently close on land owned by the agency with support infrastructure (road access and electrical systems) already in place. LOX is less expensive near large cities due to lower transport costs, and Camanche Reservoir is only 80 km from the Sacramento Metro Area (population 2.2 million).

The Camanche Reservoir HOS has been corrosion free for 28 yr with only 3 electrical repairs (Table 6). A lightning bolt shut down the HOS for 11 d in 1993, and the oxygenated area shrank but H_2S suppression was maintained. Above-ground facilities including the electric lines and controls for Speece cones are often on higher ground near the top of the dam, so in future installations a lightning conductor would be a good idea. In 1998, the electrical cable leaked, requiring hard-hat divers at $20,000/d (including barge transport and support staff). Another electric line short a few years later required water pump replacement by 2 SCUBA divers. This took one day, costing $50,000—again mostly diver time and barge rental. Repairs were amortized to $2500/yr. Experience elsewhere indicates water pump replacement every 7 yr, if run year-round (TMC 2018). The pumps are normally run to failure. Most temperate zone reservoirs need only a 6 month/yr HOS operation, so replacement can be anticipated every 14 yr.

The capital cost for construction and installation of the Speece cone HOS and associated monitoring in 1992–1993 was about $1.9 million (~$3.1 million in today's dollars, Table 5). EBMUD serves 1.4 million customers and has an annual budget of $1 billion, 85% of which is for the overall water supply. The HOS costs were thus small compared with the other costs associated with the operation of the Mokelumne River and the Camanche Reservoir collection, treatment, and supply facilities (Fig. 3). The O&M for HOS is also small relative to other facilities costs involved in the management of the reservoir, the Mokelumne River, and its fishery.

The upfront costs of a capital project of several million dollars would not normally be a problem for agencies that supply drinking water. Their reservoir sizes would be proportional to the number of customers. For example, a small water and wastewater treatment agency in Charlottesville, Virginia (110,000 customers, <10% that of EBMUD), is now in the middle of a $150 million capital improvement program, much of which is to protect against taste and odor, and filter clogging, due to elevated concentrations of cyanobacteria in its reservoirs (Rivanna Water and Sewer Authority 2019). However, the upfront capital cost or bond issue for a Speece cone for a large private waterbody with only a few cabins around it would be cost-prohibitive. If the lake is deep enough for oxygen microbubbles to dissolve (>20 m), Mobley-type long diffuser lines or central deep aeration disks may be a better and cheaper option. For the vexing problem of small and shallow lakes with sediment anoxia, mini cones located on the shore are feasible (DiNatale Water Consultants 2016). Small Speece cones (ECO_2 2020) or high-pressure side-stream oxygenation tanks (Blue-in-Green 2020) are now available, though primarily used in wastewater treatment. For a lake or reservoir with public access, public funds may be available.

Groundwater could have been a new cool, high-quality water source for the Mokelumne River fish hatchery, but it was expensive, and at this hot, low elevation location the water proved too warm. Refrigeration would have required adding more recurring expenses, ruling out a new groundwater source as cost inefficient. As a partial solution, in 2013, EBMUD spent $175,000 to install a 150 ton water auxiliary hatchery chiller for the existing tailwater outlets to the fish hatchery.

HOS costs relative to other methods

Excessive H_2S is a widespread problem in sites other than lakes and reservoirs. Anoxia creates H_2S in wastewater pipes, out-of-balance wastewater treatment plants (USEPA 1991), and oxidation ponds on cloudy days (Ku et al. 2015). Algal decay on the bottom of Camanche Reservoir was the cause of the H_2S—as it is in many lakes

(Reese et al. 2008). In retrospect, this was not surprising since H_2S gas from rotting seaweeds on beaches can quickly blacken white lead paint on nearby buildings (Horne and Nonamura 1976). Oxidants used for H_2S removal include potassium permanganate, which was used as an emergency treatment at the Mokelumne River fish hatchery in the early 1990s once H_2S had been established as the main cause of fish kills (Horne 2019a). Permanganate successfully eliminated H_2S, but the resultant MnO_2 slime was not welcome in the egg trays. Treating the entire tailwaters for Camanche Reservoir with permanganate, as occurs with HOS, would be economically infeasible (>$1 million/yr) and MnO_2 would still slime both the hatchery egg trays and river gravel. Direct aeration of the tailwaters using the Howell–Bunger valve was only partially successful in the past.

For biologically important nutrients, HOS in the summer–fall reduced TP, soluble reactive phosphate, ammonia, nitrate, and iron in the reservoir in the following late winter (Feb–Mar) before the spring algae bloom (Horne et al. 2019b). The likely mechanism was reduction in nutrient carryover from the winter of the previous year. The reservoir was fully mixed, so the surface values represent concentrations in the entire reservoir. Nutrient concentrations in late winter are often used to predict maximum blooms in the summer algal growth season and thus trophic state (Carlson 1977). In Camanche Reservoir, there was a whole-reservoir, late-winter reduction of 19 µg/L (TP) and 175 µg/L (total inorganic nitrogen, TIN), equivalent to 10 tonnes of P and 91 tonnes of N (Table 8). The reduction found for the first year has been maintained, since hypolimnion nutrients never increased again. The cost of TP removal was $19.3/kg ($8.8/lb), which is 2.4 times the cost of many alum treatments (Table 8). However, over 20 yr, the cost of the 2 methods is closer since alum treatments need to be repeated about every 10 yr in temperate climates. The cost of whole-reservoir bioavailable TIN removal was $2.03/kg ($0.95/lb), which is comparable to the cost of treatment wetlands ($1.6 kg/ha, Table 9). Areal costs for both N and P were the same at $61.4/ha ($24.8/acre, Table 8).

Table 8. Whole-reservoir costs for removal of the main nutrients that cause eutrophication calculated from decreases in concentration in Camanche Reservoir due to HOS and comparison with 2 other methods to achieve the same reduction.

Whole reservoir	TP	TIN
Reduction (µg/L)	19	175
Reduction (tonnes)	10	91
HOS, $/kg	19.3	2.03
HOS, $/lb	8.75	0.95
HOS, $/ha	61.4	61.4
HOS, $/acre	24.8	24.8
Alum, $/life cycle	110,250	N/A
Wetlands, $/life cycle	Incl. in TIN	104,791

Many cleanup methods report costs for the target area only, which is usually much smaller volume than the whole waterbody. An example is alum, typically applied over a selected area of lakebed previously sampled to determine the most effective sites. In the HOS-targeted area in Camanche Reservoir, in the oxygenated plume, which covered most of the deep water, HOS substantially reduced the concentrations of soluble and total phosphorus, iron, and manganese. Then this reduced these contaminants in the reservoir's tailwater flowing to the fish hatchery and Mokelumne River. HOS costs for in-plume TP removal (as PO_4) were higher than alum for the entire reservoir ($22.1/kg HOS vs. $16/kg alum, Table 9). The life-cycle cost of an alum treatment for the target plume area was $110,250/yr (10 yr P-suppression period), which is about two-thirds of the 10 yr targeted HOS cost ($304,000/yr for 20 yr, so $152,000/yr for 10 yr). However, alum treatments may not have the same fisheries benefit and will not remove other pollutants that occurred with HOS (other than alum continuously binding phosphate in the sediments even during anoxia).

Oxidizing power can be added to reservoirs in other ways than as air or pure oxygen, usually as nitrate (Ripl 1976, Horne and Roth 1979, Matthews et al. 2013, Beutel et al. 2016). To give the same effect as HOS in Camanche Reservoir, nitrate addition costs for the plume only were high ($15/kg O_2 in NO_3 vs. $0.64/kg LOX added, Table 9). Camanche Reservoir is large compared with other sites where nitrate additions have been used. The largest site so far used for nitrate oxidation of sediments and bottom water is Lake Onondaga, New York, which is only 40% of the

Table 9. Targeted in-plume (smaller volume) costs to remove TP, turbidity, and heavy metals or add oxygen in the hypolimnion outlet region using HOS in Camanche Reservoir.

Target zone only	TP	TIN	Cu	Zn	Fe	Oxygen
Reduction (µg/L)	173	692	0.8	8.6	7600	6000
Reduction (tonnes)	13	52	0.1	0.7	575,441	(454)
HOS, $/kg	22.1	5.5	4771	2169	0.0005	(0.64)
Alum, $/kg	2.4	N/A	N/A	N/A	N/A	N/A
NO_3 addn., $/kg	N/A	(−ve)	N/A	N/A	N/A	(15)
Wetlands, $/kg	N/A	1.6	97	N/A	N/A	N/A

Wetlands have a greater capital cost (about ×4.8), but the life cycle of a treatment wetland (50 yr) is longer than alum (10 yr) so life-cycle costs of the 2 techniques are similar. Wetlands filtration costs based on Southern California data (OCWD 2019), NO_3-additions (Beutel et al. 2016), nutrients, metals, and turbidity (Horne 2009a, Kadlec and Wallace 2009, Wagner 2015). N/A = not an applicable method, no data. Because oxygen was added, not removed, it is shown in parentheses. Similarly, the addition of nitrate increases TIN so is shown as a negative (−ve) addition.

volume of Camanche Reservoir. Also, at Lake Onondaga, most of the nitrate was provided fortuitously as "waste" in the discharge of a newly upgraded $1 billion secondarily treated wastewater plant that originally discharged ammonia (OCDWEP 2017). For capital costs, nitrate addition with a barge and pipes for Camanche Reservoir would cost about $7 million/yr, vs. less than the measured $93,400/yr for HOS over the last 20 yr. Early in the process of Lake Onondaga cleanup, a Speece cone was proposed as an alternative to calcium nitrate addition (Horne and Pastorak 2003) and could still be used if needed.

Discussion

Initial estimates of the cost of the Speece cone and its operation as well as the complete elimination of fish kills proved quite accurate. Unanticipated was that an average of 95 d/yr of HOS in the reservoir would increase the returns of adult Chinook salmon and steelhead trout to their spawning grounds below the dam. Also unexpected was that these increases would be so rapid (3 yr after HOS began), large (265% Chinook, 625% steelhead), and valuable (~$6.5 million/yr) relative to the cost of HOS (~$0.3million/yr). Finally, it was unanticipated that full hatchery operation would be possible during droughts. The improvements found for in-reservoir fish habitat, summer hydropower generation, and more flexible water management during droughts were more predictable.

Improved success of Chinook returns during droughts proved of great economic importance during drought 6 (2007–2009) when poor ocean conditions depleted the ocean stock for all the Central Valley River basin (Lindley et al. 2009). Between 2004 and 2009, coastal upwelling of deep, cool, nutrient-rich water was reduced by shifting winds resulting in less plankton. Upwelling water was replaced by warmer water from the Southern California Bight where zooplankton have a lower lipid content (Hooff and Peterson 2006). Even coastal stocks of coho salmon were reduced, so the Mokelumne hatchery was not unique in its low adult returns during drought 6. The United States Congress appropriated $170 million to ameliorate the economic losses on the West Coast. Despite the minimal adult returns in 2007–2009 due to ocean conditions, the post-drought returns from Camanche with HOS and hypolimnion volume augmentation were much higher than before HOS.

The explanation proposed for the overall long-term improvement in Chinook and steelhead returns during normal and dry periods in this and the 5 other papers in this series on HOS in Camanche Reservoir is that the increases were due to the combined beneficial effects of several water quality variables (Horne 2019a, 2019b, Horne et al. 2019a, 2019b, Horne and Jung 2022). Water quality improvements included decreases in H_2S but also substantial declines in ammonia, with lesser declines in heavy metals and turbidity. These were combined with increases in DO in the tailwater releases that fed the river and hatchery. The improvements were not confined to assisting adult migration in the autumn because that would have occurred as soon as HOS was started in 1993 or the following year. It took 2–3 yr, the time for fish from eggs to mature to spawning adults, before returns rose steeply (Fig. 2).

The timing of increased adult returns strongly suggests that it was the cleaner environment for the eggs, parr, and smolt stages in the river and hatchery that drove the observed success. These river life stages often overlapped with the operation of HOS, especially for young steelhead, in which adult returns increased 2.4 times more than Chinook, which is about the same difference in average time spent in the river for the 2 species (~24 months for steelhead vs. 10 months for Chinook).

The salmon increases were solely due to HOS. Since that time, Chinook returns have more than doubled again, reaching over 20,000 in 2017. The second wave of improvements still relies on the better tailwater quality due to HOS, but it included changes in the fish hatchery operation, added spawning gravels, installing a hatchery water cooler, improved timing of reservoir water releases, trucking some young fish around the nonnative predators of the Sacramento–San Joaquin Delta, and ocean fishing restrictions that included total prohibitions for commercial operations in dry years.

The improvement in steelhead trout survival in the hatchery and returns of adults due to HOS is especially important because steelhead is a threatened species with declining populations in many California coastal rivers. The increase from zero fish in the Mokelumne River in the 1980s to 50/yr soon after HOS to the current returns of 1600/yr is gratifying. Prior to HOS, up to 450,000 yearling steelhead were released annually to the river but no adults at all returned in some years. These hatchery juveniles must have died or been eaten in the river, so the steelhead increases support the main effect of HOS as being an in-river improvement.

A benefit of HOS was the increase in wild fish spawning in the approximately 20 km of river below Camanche Dam, which is considered the prime rearing habitat. Further downstream, agriculture and the degraded Sacramento–San Joaquin Delta are currently less suitable for small fish. Within 4 yr of starting the HOS there were twice as many wild and hatchery raised Mokelumne River Chinook salmon in the Pacific Ocean than before HOS.

The resumed hydropower generation due to HOS covered the costs of electric power for the Speece cone pump. Thus, the project was considered carbon neutral. Larger quantities of oxygen produced with more energy are used for striped bass enhancement in 2 large hydropower reservoirs operated by the Tennessee Valley Authority (TVA; Mobley et al. 2012). The Speece cone in Camanche Reservoir was originally designed to add up to 9 tonnes/d of LOX, while the TVA system has used up to 200 tonnes/d. Although hydropower has environmental drawbacks (St. Louis et al. 2000), it is classified as green power with a low carbon footprint—at least for deeper and nontropical reservoirs.

More flexibility for water management in droughts was a valuable improvement for EBMUD in part because of increased recreational water use, such as rafting on the Mokelumne River downstream of Camanche Dam, and increased numbers of drinking-water customers. The reduction in the 2 chronically toxic tailwater heavy metals, copper and zinc, was a minor benefit. However, the history of copper toxicity from Penn Mine upstream of Camanche Reservoir caused EBMUD to spend $12 million on a mine cleanup in 1997. This expenditure would have been negated if the legacy copper and zinc in the reservoir sediments continued to reach critical levels, even if only occasionally.

The simple benefit/cost ratio for the HOS was favorable at 21.7 ($6.5 million/yr benefit vs. $0.3 million/yr cost as 20 yr straight line amortization) and benefited all aquatic species in the Mokelumne River. The primary beneficiaries were the salmonid fish that live and spawn below the dam, as well as those that live in Camanche Reservoir itself. The HOS technology is becoming more popular as its benefits are appreciated more widely. ECO_2 (2020) lists 31 Speece cone installations in North America, and Mobley Engineering (2020) lists 25 pure oxygen bubble plume diffusers. The suite of 7 benefits described in this article is not unique to Camanche Reservoir or the Mokelumne River, though details will vary with location. For waterbodies with an anoxic bottom water layer in the United States and elsewhere, this study suggests that HOS should be on the short list of technologies considered in their restoration.

Conclusions

- The improvement in the Mokelumne River salmonid fishery has been dramatic and was directly due to HOS. Effects occurred within 3 yr, as evidenced by an approximate doubling in fall-run Chinook salmon returns for an increase of 5550/yr, which is worth $6.5 million in recreational angling benefits. The HOS enabled further improvements in the river and hatchery such that the Chinook returns in 2018 increased to 20,000/yr or 5 times the pre-HOS numbers.
- Increased returns for the threatened steelhead trout paralleled the Chinook, with returns increasing from near zero to 50/yr soon after HOS to an average of 625/yr (2017–2018).
- Wild fish spawning in the river below the dam after HOS was over 1.7 times more than that of pre-HOS years. This improvement is likely due to the overall better tailwater quality attributable to HOS (lower H_2S, ammonia, Fe, Mn, Cu, Zn, and turbidity).
- The hatchery can now operate at full capacity in droughts. Prior to HOS the hatchery either was shut down in droughts or ran at a much-reduced level. During the last drought (2011–2014), the Mokelumne hatchery produced at normal rates and even took in fish from other Sacramento River hatcheries that were unable to continue.
- Fisheries improvement occurred in the reservoir since HOS provides sufficient oxygen for large fish to live in the hypolimnion. Prior to HOS no fish were found in the deeper waters.
- Hydropower production can now occur in summer–fall since there is no need for the Howell–Bunger valve to aerate the tailwaters (and lose the hydraulic head needed for hydropower).
- EBMUD can operate Camanche Reservoir at lower levels in droughts and still release high-quality water. This increased flexibility eliminates the purchase of expensive additional drinking water during dry periods.
- The $1.3 million capital cost of HOS in 1993 was acceptable to all parties, considering the large numbers of steelhead trout killed by H_2S in the hatchery and the general poor summer–fall water quality of Camanche Reservoir's tailwaters prior to HOS.
- The O&M costs (electric power, liquid oxygen, staff time, $191,288/yr) were small relative to EBMUD's drinking-water supply budget (~$700 million/yr).

Acknowledgments

This article is dedicated to the inventor of the Speece cone, Dr. Richard Speece, professor emeritus at the Civil & Environmental Engineering Department, Vanderbilt University, Tennessee. At a scientific meeting in Gatlinburg in the Smokey Mountains in 1974, Dr. Speece told then assistant professor Alex Horne that oxygen additions to lakes and reservoirs were good value for the money; he was correct!

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