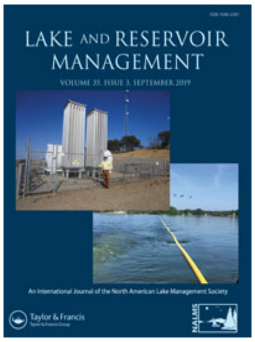

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Hypolimnetic oxygenation 2: oxygen dynamics in a large reservoir with submerged down-flow contact oxygenation (Speece cone)

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ABSTRACT
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Low dissolved oxygen (DO) in the sediments of Camanche Reservoir, California (513 million m^3, 31 km^2), produced toxic hydrogen sulfide (H_2S). Direct hypolimnetic oxygenation suppressed H_2S without provoking early destratification and cold-water fish problems downstream. A cool, bubble-free plume directed horizontally over the sediments was chosen over a rising bubble plume. A submerged, down-flow contact oxygenator (Speece cone) pumped anoxic water from 5 m above the sediments to the top of a 7 m high cone to dissolve a counterflow of rising pure oxygen bubbles. The bubble-free, highly oxygenated discharge (80 mg/L) was diluted to fish-safe levels (8 mg/L) and directed up-reservoir via jets in a 45 m long manifold. Placing the cone on the bottom near the dam increased hydraulic pressure and doubled oxygen solubility. Poor-quality hypolimnion water (DO $<$2 mg/L, redox 18–100 mV, H_2S odors) was converted to good-quality water (DO 3–7 mg/L, redox $>$300 mV, no H_2S odors). Comparing preoxygenation hypolimnion DO decline (0.1 mg/L/d) with oxygenation temporarily switched off (0.23 mg/L/d) gave a full-scale estimate of induced hypolimnion oxygen demand. In 1994, the oxygenated plume moved 4.5 km upstream at 0.1 cm/s via natural water motion. No long pipes were needed. About 18% of the bottom hypolimnion was directly oxidized in the cone and 1.8 times the total volume was indirectly oxidized via entrainment in the plume. After 10 yr, oxygen additions were reduced by $>$50% with no deleterious effects.

KEYWORDS
Deep water currents; hypolimnion oxygenation; sediment oxygen demand; Speece cone

The pressing problem at Camanche Reservoir was to prevent further fish kills downstream of the dam (Horne 2019a). Kills had occurred despite vigorous oxygenation of the hatchery inflow and reservoir tailwater flowing to the Mokelumne River. Hydrogen sulfide (H_2S), which is not fully removed by short-term aeration, was the likely direct cause of fish problems. In turn, lack of dissolved oxygen (DO) in the hypolimnion, especially above the reservoir sediments, favored production of H_2S. Since oxygen depletion was the cause, one engineering solution was to add more oxygen, using either air or pure oxygen itself. Aeration is a commonly used lake and reservoir water quality management tool (Muller et al. 2002, Cooke et al. 2005), and McComas (2003) mentions aeration in England as far back as 1882. However, aeration destratifies the water column, warming the deeper water. Aeration by mixing was excluded for Camanche Reservoir since it would result in the loss of the important cold-water fisheries in the reservoir and especially in the downstream Chinook salmon and steelhead trout hatchery.

Hypolimnetic oxygenation systems (HOS) were uncommon in 1987, though improving reservoir tailwater quality with pure oxygen bubbles behind dams was used by the Tennessee Valley Authority

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ulrm.

as early as 1978 (Speece 1994, Mobley and Brock 1995, Gemza 1997, Beutel and Horne 1999). The pioneering work of Professor Barry Moore installing a Speece cone for in-lake water quality improvement at Newman Lake, Washington, was still 5 yr in the future (Moore and Christensen 2009). However, there still are uncertainties about how much oxygen is needed and how to place the Speece cone so it will move oxygen through the lake or reservoir, especially upstream. Past projects often underestimated the additional sediment oxygen demand induced by suppling more air or pure oxygen to anoxic water. Reasons for mediocre performance are discussed elsewhere (Little and McGinnis 2001), and design is now assisted by a recent review of both oxygenation and circulation (Wagner 2015). The current concern about mercury methylation in anoxic sediments of many lakes (California Dept. Water Resources 2007) gives oxygenation new urgency since, unlike H_2S, once created, methylmercury cannot be directly oxidized away.

Lack of monitoring is common in lake management, but here the legal disputes at Camanche Reservoir over the fish kills and the upcoming long-term relicensing of the hydropower plant by the Federal Energy Regulatory Commission (FERC) promoted unusually detailed data collection. This article presents detailed spatial and temporal dynamics of a then-novel kind of pure oxygen addition. It covers the 2 yr before and after installation in 1993 and snapshots of the situation in 2004 and 2014. Effects on fish, nutrients and eutrophication, turbidity, heavy metals, and economics are presented in accompanying papers (Horne and Beutel 2019, Horne and Faisst 2019, Horne and Jung 2019, Horne 2019a, 2019b).

Reservoir description

First placed into operation in 1964, Camanche Reservoir is a medium-sized storage system in northern California (513×10^6 m^3, 427,000 acre-feet, TAF) in the lowest foothills of the Sierra Nevada Mountains about 50 km northeast of Stockton. It is owned and operated by the East Bay Municipal Utility District (EBMUD), based in Oakland, CA. Details (Table 1) are discussed in more detail by Horne (2019a). To maximize storage, the dam stretches 5 km across the Mokelumne River valley, so it is relatively shallow for its volume. The main inflow is from Pardee Reservoir immediately upstream. Camanche Reservoir supplies water for a Chinook salmon and steelhead trout hatchery and downstream river fishery, irrigation, and hydropower; other uses include flood control and in-reservoir fishing for trout and bass. The main outflow is from near the bottom of the dam. The location near the Central Valley of California has mild winter temperatures that result in hypolimnion temperatures starting >10 C in spring.

Though no measurements were made before the fish kills of 1987–1989, it is now assumed that the reservoir was eutrophic with hypolimnion anoxia and H_2S production. H_2S odors were noted in tailwaters in the 1980s but did not generate a limnological investigation. Fish kills during the 1986–1992 drought were traced to hydrogen sulfide (H_2S; Horne 2019a). This article focuses on the dynamics of hypolimnetic oxygenation.

Selection of oxygenation approach

The selection of oxygenation had to be made rapidly with whatever data were available. After the two large fish kills in 1987 and 1989, the outcry from environmental groups and the press led to a criminal lawsuit against EBMUD for negligent fish kills (300,000 hatchery trout and salmon). Implementing proposed solutions from the federal and state fisheries agencies and environmental groups would have been costly for EBMUD, reduced the supply to downstream fish, and threatened the drinking water supply for EBMUD's 1.3 million customers. Full details are given in Horne (2019a). In summary, the judge asked for both a cause and solution for the fish kills in only 3 weeks. This left little time for conventional procedures. Horne's opinion was that the most likely cause was H_2S because it was the mostly likely agent for rapid and massive fish kills. The solution was HOS using submerged downflow contact oxygenation (SDCO, hereafter a Speece cone) because H_2S is very sensitive to oxygen, especially if prolonged for more than 6 h

Table 1. Morphometric parameters for Camanche Reservoir, California at full pool

Parameters	Metric units	English units
Maximum volume, V—full (typical summer)	514 million m^3 (353)	417,000 acre-feet (287,000)
Length, L	9.5 km	6 miles
Width at dam, b	4.8 km	3 miles
Reservoir area, A_r—full (typical summer)	31 km^2 (25.7)	12 square miles (9.9)
Catchment area A_c	1,500 km^2	577 square miles
Ratio A_c:A_r	48	48
Predicted trophic state based on A_c:A_r	Mesotrophic	Mesotrophic
Maximum depth, z_{max} full (typical)	41 m (34.6)	135 ft (120)
Mean depth, $\check{z}$ full (typical)	17 m (36.4)	56 ft (45)
Mean inflow	911 million m^3	741,000 acre-feet
Hydraulic residence time, HRT	∼1.8 yr	∼1.8 yr
Elevation, full amsl	73 m	220 ft
Height of dam	52 m	171 ft
Year constructed	1964	1964

(Williams and Commins 1988, Horne 1989). Both opinions were controversial, in part because a Speece cone was innovative and untested (USFWS 1991) and because other causes and solutions were championed by the fisheries agencies and environmental groups. Competing methods included a higher summer reservoir level, increased flows from EBMUD's upstream Pardee Reservoir, injection of permanganate into the outflow, creation of a groundwater well supply, and different reservoir operation schedules.

Before HOS could be proposed to the judge, the cost and thus the amount of oxygen needed was required. Only a few days were left after the choice of HOS was made; DO–temperature profiles were available only for 1988, when the reservoir was operating at low, drought levels before it dried out completely. The following assumptions were made:

- The seasonal thermocline would begin around 6 m from the surface.
- A layer 10 m thick below the upper thermocline would provide a buffer for early destratification due to the Speece cone's horizontal plume in the bottom water.
- Using the 1960s hypsographic curve, the remaining reservoir volume (16 m from the surface to the bottom at normal summer operating elevation) was 36 billion m^3 (107 TAF). This was the volume to be oxygenated.
- Hypolimnetic oxygen depletion rate was 0.1 mg/L/d.
- This suggests an oxygen demand of 6.6 tons/d. Though little was known about the additional sediment demand caused by oxygenation, a factor of 2 was assumed to yield a total need of 13.2 tons/d.

Fisheries agencies contended that HOS with the Speece cone's plume of oxygenated water at the bottom of the reservoir would destabilize the thermocline a few weeks earlier than normal. At this time, it would already be weakening, and the volume of the entire reservoir would be at its annual low. Even a few days of earlier overturn and warmer bottom water releases could result in lawsuits since a cool hypolimnion outflow temperature was mandated until 1 November each year. The purpose of the cool water was to keep fall-run Chinook and steelhead attraction flows in the Mokelumne River below the dam.

Once the decision to use HOS, specifically a Speece cone, was accepted, a second oxygen need calculation was performed in 1991–1992. The task was modified from oxygenating the entire reservoir bottom water to only the daily bottom water mass to be released to the river and salmonid hatchery. Based on the measured decay rate, any H_2S formed up-reservoir well away from the dam would be oxidized as it reached the dam. About 6 h was needed (Horne 2019a), and for a margin of safety 24 h was used in the design. The oxygenated block of bottom water (DO >8 mg/L) would provide the required volume for 24 h of downstream discharge (8.5 m^3/s, 300 cfs). By 1992, there were 3 yr of DO declines in the bottom water measured from spring high to zero in summer. Despite the changing depth in the reservoir over these years due to the drought, the DO decline rates, measured at the bottom of the water column from the spring high

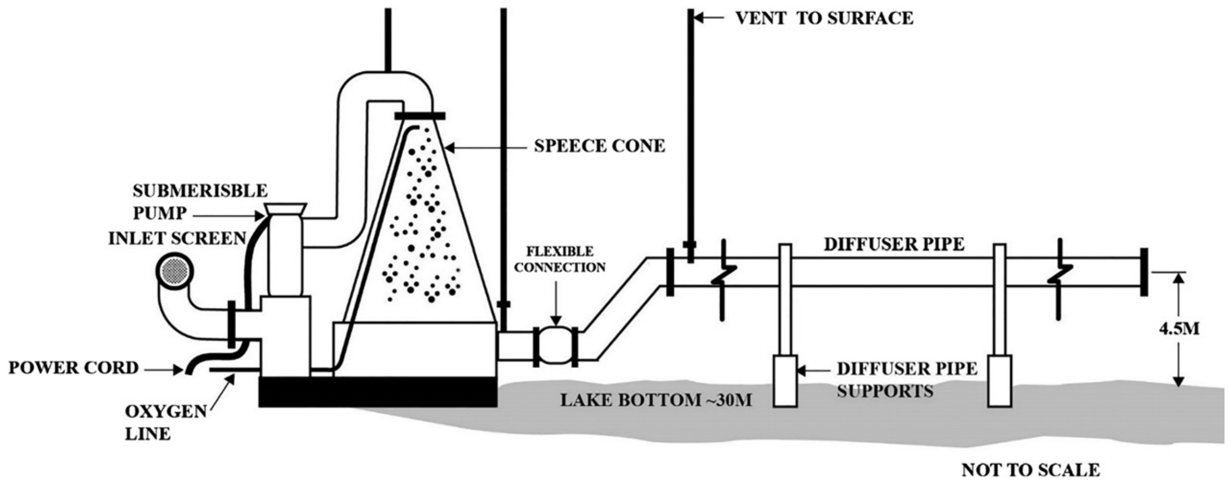

Figure 1. Sketch of the Speece cone and ancillary devices installed at Camanche Reservoir (from Brown and Caldwell 1995).

to zero, were similar (0.0042 to 0.0049 mg DO/L/d).

In 1989, the areal hypolimnion oxygen deficit (AHOD) was calculated at 676 mg oxygen/m^2/d using the Water Quality for Reservoir Systems (WQRRS) model (CH2M-Hill Consultants 1991) using an average hypolimnion area of 4 km^2 and a hypolimnion depth of 18.5 m. Dr. Speece was hired as a consultant, did the appropriate calculations, ran a bench-scale cone test, and produced a specification for the size of the cone and its ancillaries (Speece 1992). His necessary oxygen input estimate was 8 tons/day. The main remaining concern was that the oxygenated plume would short-circuit and the cone would take in already oxygenated water. Placement of the cone on the center line of the dam face with its manifold jets facing up-reservoir was chosen to limit short-circuiting.

The two estimated oxygen demands for the bottom hypolimnion layer alone of 6.6 tons/d (Horne, without safety factor) and 8 tons/d (Speece 1992) were sufficiently similar for the cone to be fabricated with an 8 tons/d maximum size. Because the cost of this Speece cone was estimated at more than $1 million (1992 dollars), a second cone was to be installed if needed following the results from the first one. The second cone was not needed.

A direct oxygenation system using 100% oxygen instead of air (20% oxygen) will be 5 times smaller. Indirect oxygenation as provided by an aeration-mixing lift pump for destratification will, however, require more gas. The TVA-Mobley system (Gantzner et al. 2009) is a good example of a pure oxygen bubble plume HOS, which adds oxygen to the bulk hypolimnion but indirectly oxygenates the surface sediments (Mobley et al. 2003). Deployment of a submerged downflow contact oxygenation, a Speece cone, is an option when a buoyant, rising plum is not desirable. It was invented by Professor Robert Speece (Department of Civil Engineering, Vanderbilt University, Nashville, TN). The key to the design is that the water plume contains only dissolved oxygen with no bubbles, so it is denser than a bubble plume where the bubbles reduce bulk density. Both kinds of oxygenation entrain surrounding water. The Speece cone's horizontal plume entrains cool water and stays on the bottom and oxygenates the sediment directly. The rising bubble plume entrains warmer water and thus has an equilibrium density at an intermediate depth and so affects the sediments less directly. Thus, the Speece cone provides a layer of oxygenated water over the mud while the bubble plume oxygenates most of the hypolimnion. Since bacterial production of H_2S is suppressed with even traces of oxygen (0.14 µg/L: Marschall et al. 1993), the Speece cone provides the most effective way to place oxygen over the sediments, which then can suppress releases of H_2S, methylmercury, iron, and manganese (Beutel et al. 2008). A Speece cone can work in deep or shallow water so was ideal for Camanche Reservoir, where the entire hypolimnion plus metalimnion thickness at the dam was only 19 m in normal years (e.g., 1993) but was reduced to about 7 m during multiyear droughts (e.g., 1987–1989).

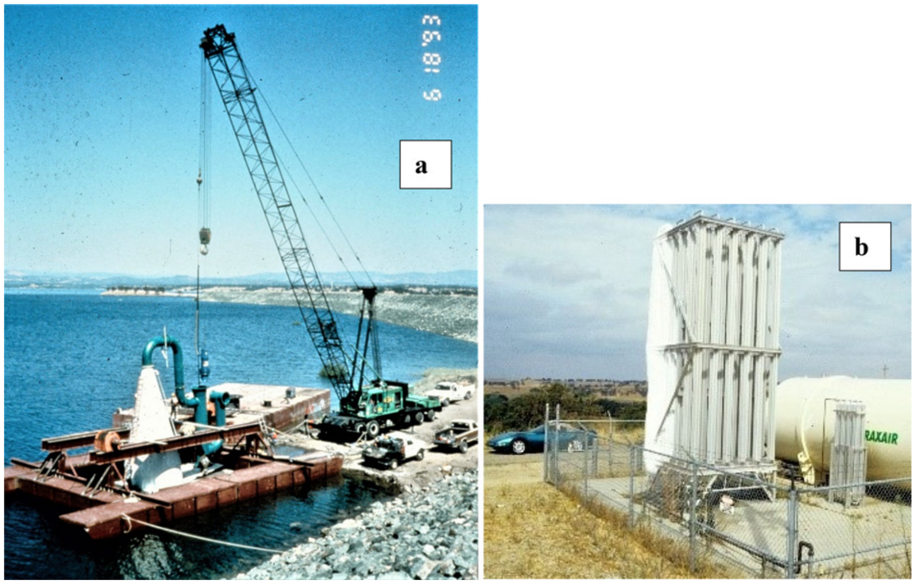

Figure 2. (a) Photograph of Speece cone assembly using a raft near the dam in June 1993. The white cone and green ancillary piping are shown, including T-shaped intake. The water pump is being lowered into the vertical piping. Several workers show scale. (b) Shoreline facilities; ~10 m high evaporator and 50 m^3 liquid oxygen tank; automobile shows scale.

The SDCO system's electric pump passes hypolimnion water from any predetermined depth to the top of a large cone (Fig. 1). The water flows downward at about 3 m/s, faster than the rising bubbles of pure oxygen (Singleton and Little 2006). Water slows to <0.1 m/s as the cone widens but this is designed so that oxygen dissolves almost completely within the enclosed space (McGinnis and Little 1998, Ashley 2002, Ashley et al. 2008). The oxygenated water exits the base of the cone and into the reservoir via jets in a manifold at whatever depth and direction are required. For Camanche Reservoir, the cone was submerged at the deepest point near the dam (23 to 27 m depending on reservoir level), where the hydrostatic pressure was more than twice that at the surface so dissolved proportionally more oxygen than a cone located on shore. This greatly increased efficiency and further reduced overall size.

The first Speece cone was set up in a relatively small, natural lake, Newman Lake in Washington state ($z_{max} = 9$ m, V = 28 million m^3, A = 4.5 km^2). Its Speece cone is now operated in conjunction with alum addition (Moore and Christensen 2009, Moore et al. 2012) and watershed cleanup. Another no-bubble system uses a shoreline-located, highly pressurized container to achieve even higher initial DO concentrations (>300 mg/L: Blue-in-Green, Inc., Fayetteville, AK; http://www.Blueingreen.com). The Camanche Speece cone was constructed to the design of Professor Speece by Ford Construction, a local firm. It is 7 m high, 3.7 m wide at the base, fixed to a concrete slab, and able to transfer more than 8 tons of oxygen/d to the water (Figs. 1 and 2a). It was installed in spring 1993 by Pan Marine Construction, San Francisco, CA, within a year of initial design. The Camanche Speece cone was an early design of the type now manufactured by ECO_2 Oxygen Technologies of Philadelphia, PA (http://www.eco2tech.com).

The rest of the system consisted of a 127 kW, 0.9 m^3/s (170 hp, 35 cfs) Flygt submersible water pump, a 50 m^3 (13,000 gals) onshore liquid oxygenation tank and its large evaporator (Fig. 2b), and a 400 m underwater oxygen pipeline and electrical conduit. A 45 m long diffuser manifold was installed on legs 4.5 m above the reservoir bed to release oxygenated water horizontally up-reservoir via 90 orifices, each of 5 cm diameter (Fig. 1). Originally the manifold was to be only 2 m off the sediments but it was elevated further to give a safety factor for sediment disturbance. The jets dilute the initial high oxygen concentrations to a level safe for fish. When Camanche Reservoir is at its lower operating water elevation, the water depth near the dam is 23 m. At this

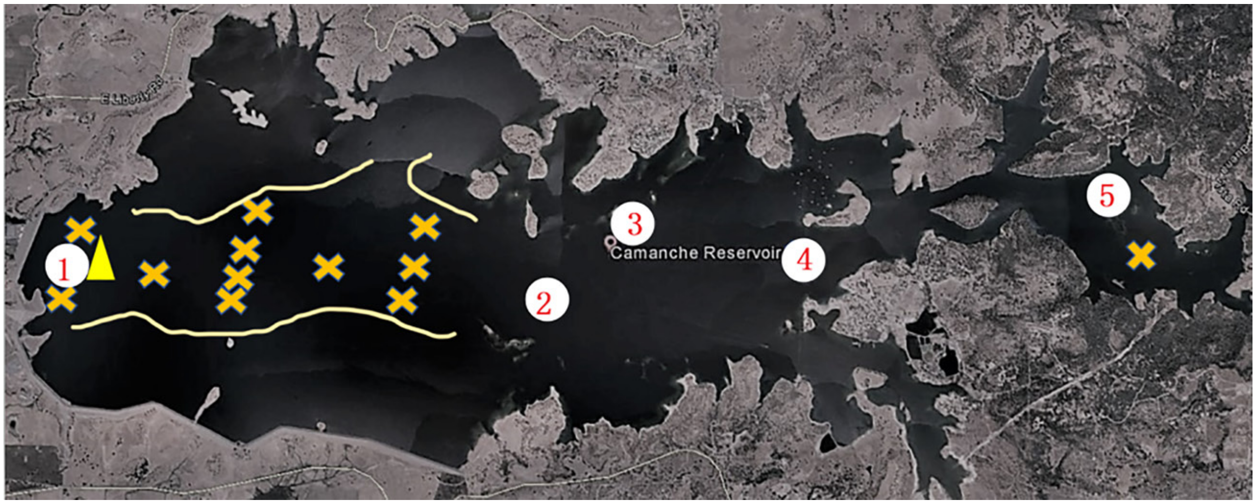

Figure 3. Map of station locations. Multiple repetitive synoptic sampling stations (X), longitudinal stations (numbers 1–5, dam index station is number 1) and Speece cone (Δ) in Camanche Reservoir. Line indicates approximate boundary of thalweg, representing deeper water (>18 m).

depth, the cone releases water with a DO of 80 mg/L (Speece, 1992). Fish breathing dissolved gas at high pressure at one depth can be harmed if they rapidly reach a shallower depth, where the lower pressure cause the gas to come of out solution in bubbles in the blood and causes the fish swim bladders to expand, with lethal consequences (Abernethy et al. 2001). The best examples are the nitrogen gas "bends" that killed fish below dams prior to modern redesign (Weitkamp and Katz 1980). Oxygen supersaturation can also produce similar fish deaths, so the diffuser was designed to entrain enough surrounding water for a minimum dilution of 10:1 to meet the ambient target of 8 mg/L (Speece 1992). This is below the saturation level at bottom water temperatures (13–15 C), so even if the fish swim rapidly to the surface their swim bladders will not be affected.

Installation took a few weeks using a barge and hard-hat divers (Fig. 2a), but the pump can be changed by SCUBA divers. Capital costs were $1.9 million ($3.1 million in 2017 dollars); operation and maintenance (O&M) averaged $285,000/yr over the last 20 yr. Full economic details are given elsewhere (Horne and Faisst 2019).

Calculating the extent of the initial oxygen plume

It was vital that the Speece cone plume did not cause premature destratification or stir up sediments. Early destratification would eliminate the cold-water supply to the hatchery and river, while sediments are detrimental to early salmon egg stages. Temporal and spatial plume dynamics were calculated with standard hydrodynamic equations and conventional sediment-shear coefficients calibrated to the reservoir contours (Dr. Carl Chen, Systech 1992). The results indicated that the plume would spread to only a maximum of 9 m high and have energy to push the plume for only 300 m from the manifold. It would be confined to the lower hypolimnion, it would not cause destratification, and plume shear-stress on the sediments would not increase turbidity. These predictions were correct, and further details on sediments, turbidity, and HOS are given elsewhere (Horne 2019b). The submerged 127 kW pump is cooled by hypolimnion water, but the calculated heat gain over the entire stratified period was negligible (0.01 to 0.03 C increase). For comparison, the hypolimnion temperature would naturally rise about 0.03 C/day (Jun–Oct), mostly due to solar radiation. The movement of the plume up-reservoir away from the manifold was not modeled but measured directly after the cone installation using multiple probes, as is shown in later sections.

Methods

District staff collected occasional DO–temperature profiles near the dam beginning in June 1987 and monthly measurements in 1988 as the reservoir dried up completely in June. Some water still flowed from the upstream dam releases down the old channel, but the reservoir bed was dry. Measurements continued for 4 more years before (1989–1992) and 11 yr after (1993–2004) HOS operation, which was started in July 1993. For the first part of this article, measurements were made at the dam index station (number 1 on map, Fig. 3), and "bottom" indicates approximately 0.5 m above the sediments. The dam index station is 70 m down-reservoir from the Speece cone, for which the manifold jets point up-reservoir. For detailed spatial coverage reported here, rapid spatially variable multiple repetitive synoptic surveys (MRSS) were used (Horne et al. 1979). Three boats were used simultaneously to speed the measurement of depth profiles at 14 to 17 stations in a modified rectangular grid up to 9 km from the HOS manifold (Figs. 1 and 3).

All MRSS stations were above the deep hypolimnion, roughly the old river valley thalweg with depths >24 m (except in droughts). Vertical profiles recording depth, temperature, DO, pH, conductivity, and redox potential were made using cross-calibrated Hydrolab probes. Profiles were run at all MRSS stations at intervals of 1, 3, 5, and 8 m from the bottom and, above this, at 5 m intervals from the surface. The MRSS stations included 3 transects across the reservoir's width (oxygenation site and 1.5 and 3 km upstream: Fig. 3). Stations at the center of each transect were used to take measurements at 1 m intervals from top to bottom. Secchi disc depths were measured at all stations. Weather, waves, and the color of the water were recorded from visual observations. Four sites (numbers 2–5, Fig. 3) extended spatial coverage upstream to 11 km. The plethora of stations provided a detailed map of the oxygenated plume. The temporally variable measurements were biweekly depth profiles collected near the dam and a continuously recording temperature–DO probe located 2 m from the bottom near the Speece cone. Water from this depth is expected to be similar to that in the outflow.

Results

Dissolved oxygen

Initial results for the initial HOS operation (Fig. 4) reflect the startup of the HOS in partial operation on 23 July 1993 and in full operation on the 28 July. The DO in the bottom layer 0.5 m from the sediments increased from 3.7 to 5.6 mg/L. At the top of the 5 m thick bottom layer DO rose less, from 5.5 to 6.0 mg/L (Fig. 4). The intake to the cone and the discharge from the elevated manifold were both 4 to 5 m from the sediments, so the layer with the elevated DO is where the plume from the Speece cone would be expected. The uppermost hypolimnion (8–19 m from the surface) showed a decrease of about 1 mg/L, which was probably unrelated to the HOS operation because the remainder of the hypolimnion above 5 m from the bottom (20–32 m from the surface) showed no change (Fig. 4). The epilimnion DO remained unchanged.

Comparing the year before HOS to the first year of HOS operation shows some longer term effects. Comparisons were made after 5 weeks of HOS operation in 1993 and a similar time of year in 1992 prior to HOS use. The temperature–depth profiles were very similar in 1992 and 1993 (Fig. 5a). In 1993, shakedown testing of the cone released some oxygen, so the hypolimnion DO prior to full HOS operation in mid July 1993 was not as low as in previous years. The average bottom water DO concentration in July 1989–1992

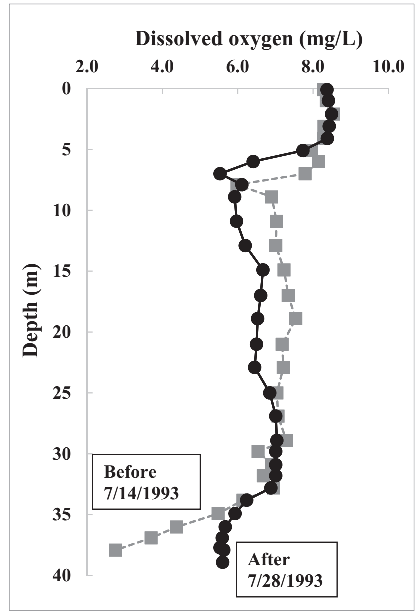

Figure 4. Initial effect of the HOS on deeper water layer. HOS started in partial operation on 23 July 1993 and was in full operation by the 28 July. Squares and gray dotted line correspond to 14 July 1993 before oxygenation; circles and full line represent 28 July 1993 after oxygenation.

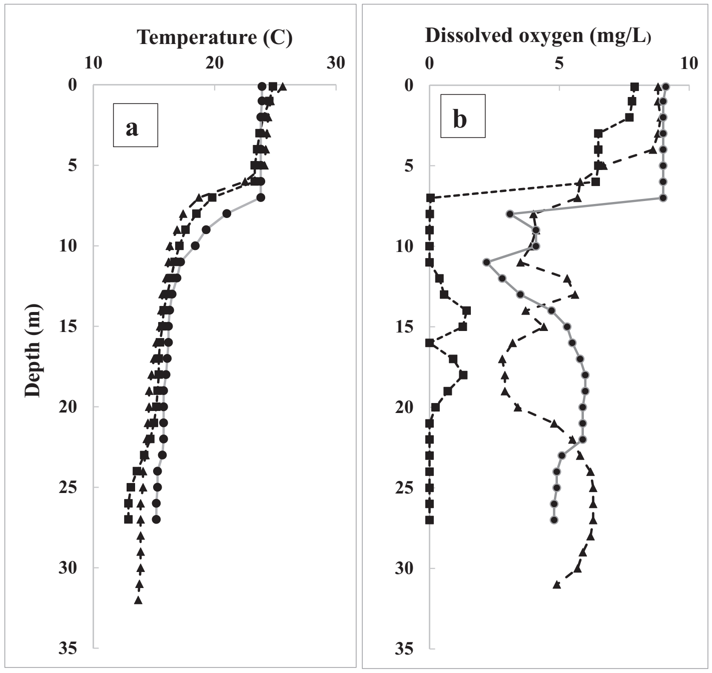

Figure 5. (a) Temperature and (b) dissolved oxygen depth profiles at similar times of year before HOS showing anoxia throughout the hypolimnion before HOS (26 Aug 1992, squares, short dashed line), initial results after about 5 weeks of HOS (3 Sep 1993, triangles, long dashed line) and a profile 21 yr later (17 Sep 2014, circles, gray full line) using about one-third of the oxygen initially added. HOS had little effect on the thermocline, which begins at 6 to 7 m.

was 2.2 mg/L, relative to 3.7 mg/L at the same time and depth in 1993 when HOS was started. In 1992, the year before HOS operation, the hypolimnion showed large zones of zero DO (7–11 m and 20–27 m from surface) with 1.5 mg/L in the submetalimnion at 15–20 m from the surface (Fig. 5b). After 5 weeks of HOS operation in 1993, DO in the entire hypolimnion remained much higher than at the same time in 1992 (Fig. 5b). The bottom 10 m of water showed the greatest DO, increasing from 0 to 5–6 mg/L (deepest water 4.8 mg/L). Above the plume in the upper hypolimnion, DO after HOS varied from 2.2 to 5.6 mg/L, higher than before HOS operation (0–1 mg/L up to 2–3 mg/L). Metalimnion DO rose from zero before HOS operation to 4 mg/L afterward.

Short-term changes in bottom water near the dam were important since the design was to provide only 24 h of oxygenated water supply near the dam at normal outflow rates to the river and fish hatchery downstream. DO measured every 2 or 3 d between 5 July and 12 August 1993 indicated favorable conditions (Fig. 6, Table 2). HOS full operation began on 23 July 1993. The increase in bottom water DO was very rapid. Within 2 d of starting the HOS in July 1993, DO near the Speece cone climbed from 3.5 to 5.8 mg/L (Table 2, Fig. 6). The DO remained at about this level (5.8–6.2 mg/L) for the next 2 weeks. Also of interest was the effect of a cessation of the HOS as would occur with a breakdown. In 1994 the HOS was deliberately switched off after about 7 weeks of operation. Bottom water DO near the dam began to decline at once, dropping from 5.9 to 4.9 mg/L in 1 d (Table 2, Fig. 6b). However, the rate of decline slowed to only 0.3 mg/L/d the next day and took 7 d to decline a further 1 mg/L. The rate of DO decline over 12 d (2–14 Sep) was 0.23 mg DO/L/d.

An oxygen demand more than twice that present prior to HOS lasted for at least 10 d. Others have demonstrated an increased oxygen demand when sediments are oxygenated (relative to non-oxygenated controls) or have the water flow above them slightly increased (Beutel et al. 2006, 2007). Here the increased oxygen demand when HOS was switched off is termed the induced hypolimnion oxygen demand (IHOD). It was 2.3 times the initial non-oxygenated HOD and provides an empirical basis for estimating oxygen needed above HOD for at least Camanche Reservoir. The IHOD will likely vary with the trophic state of the lake and may reach as high as

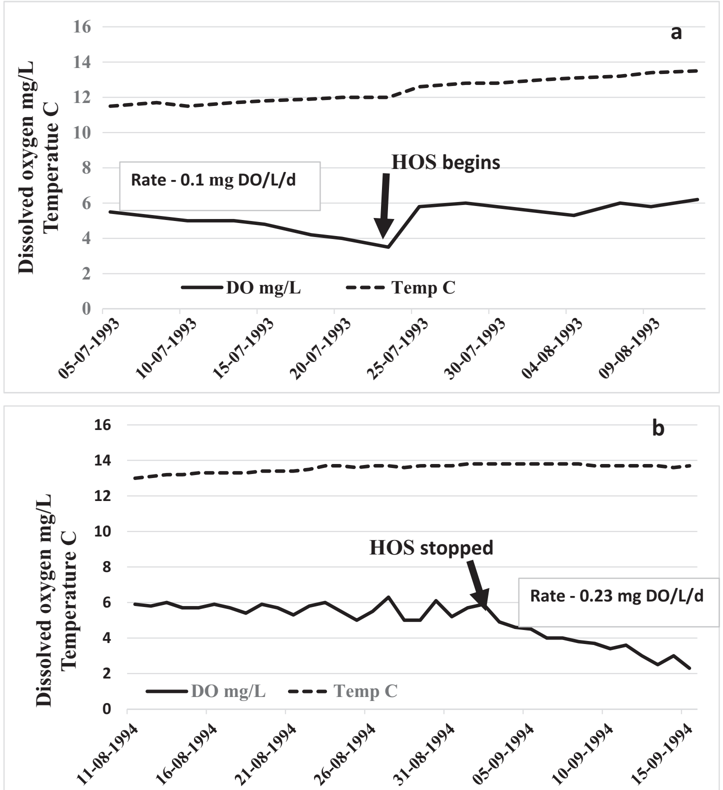

Figure 6. Dissolved oxygen (DO) and temperature at the bottom near the Speece cone during off/on tests in 1993–1994. (a) In 1993 DO rose rapidly and remained constant after HOS was switched on in July 1993. Temperature rose slightly. (b) In 1994 when HOS was switched off DO fell rapidly while temperature rise ceased.

Table 2. Short-term variations in dissolved oxygen and temperature (Temp) for the bottom water (0.5 m above sediments) near the Speece cone for the first few days before and after the HOS was started on 23 July 1993. Also shown is the effect of turning the HOS off in mid-season (2 Sep 1994)

1993	DO, mg/L	Temp, C	1994	DO, mg/L	Temp, C
5 Jul	5.5	11.5	23 Aug	6.0	13.7
8 Jul	5.2	11.7	24 Aug	5.5	13.7
10 Jul	5.0	11.5	25 Aug	5.0	13.6
13 Jul	5.0	11.7	26 Aug	5.5	13.7
15 Jul	4.8	11.8	27 Aug	6.3	13.7
18 Jul	4.2	11.9	28 Aug	5.0	13.6
20 Jul	4.0	12.0	29 Aug	5.0	13.7
23 Jul a.m.	HOS partial start		30 Aug	6.1	13.7
23 Jul	3.5	12.0	31 Aug	5.2	13.7
25 Jul	5.8	12.6	1 Sep	5.7	13.8
28 Jul	HOS full operation		2 Sep	5.9	13.8
28 Jul	6.0	12.8	2 Sep	HOS shut down	
30 Jul	5.8	12.8	3 Sep	4.9	13.8
2 Aug	5.5	13.0	4 Sep	4.6	13.8
4 Aug	5.3	13.1	5 Sep	4.5	13.8
7 Aug	6.0	13.2	6 Sep	4.0	13.8
9 Aug	5.8	13.4	7 Sep	4.0	13.8
12 Aug	6.2	13.5	8 Sep	3.8	13.8
			9 Sep	3.7	13.7
			14 Sep	3.0	13.6

4 × HOD in warm, eutrophic reservoirs (Beutel et al. 2006, 2007).

Changing the supply of oxygen to the Speece cone is a simple matter of turning the supply valve on shore. In the first 2 yr, 6 to 8 tons/d of oxygen were added, with oxygenation beginning when DO fell close to 5 mg/L and keeping the oxygen supply at 6–8 tons/d and running until overturn. Over the next two decades and continuing to the present, operators tested various combinations of daily oxygen supply rates and number of days used based on the measured bottom DO at the dam index station. The oxygen supply was gradually reduced. In 2014, only 2 tons/d was added. The results (Fig. 5b) were remarkably like the early years of HOS operation despite lower oxygen input. For example, DO in the deepest water in 2014 was identical to that in 1993 at 4.8 mg/L and the bottom 10 m of hypolimnion fed directly by the oxygen plume remained at 5 to 6 mg/L. The difference between the profiles 21 yr apart included slightly higher metalimnion DO and slightly lower mid-hypolimnion DO concentrations. In part this difference may be due to the shallower water in 2014, a drought year, with maximum autumnal water depth of 27 m, versus 31.7 m in 1993.

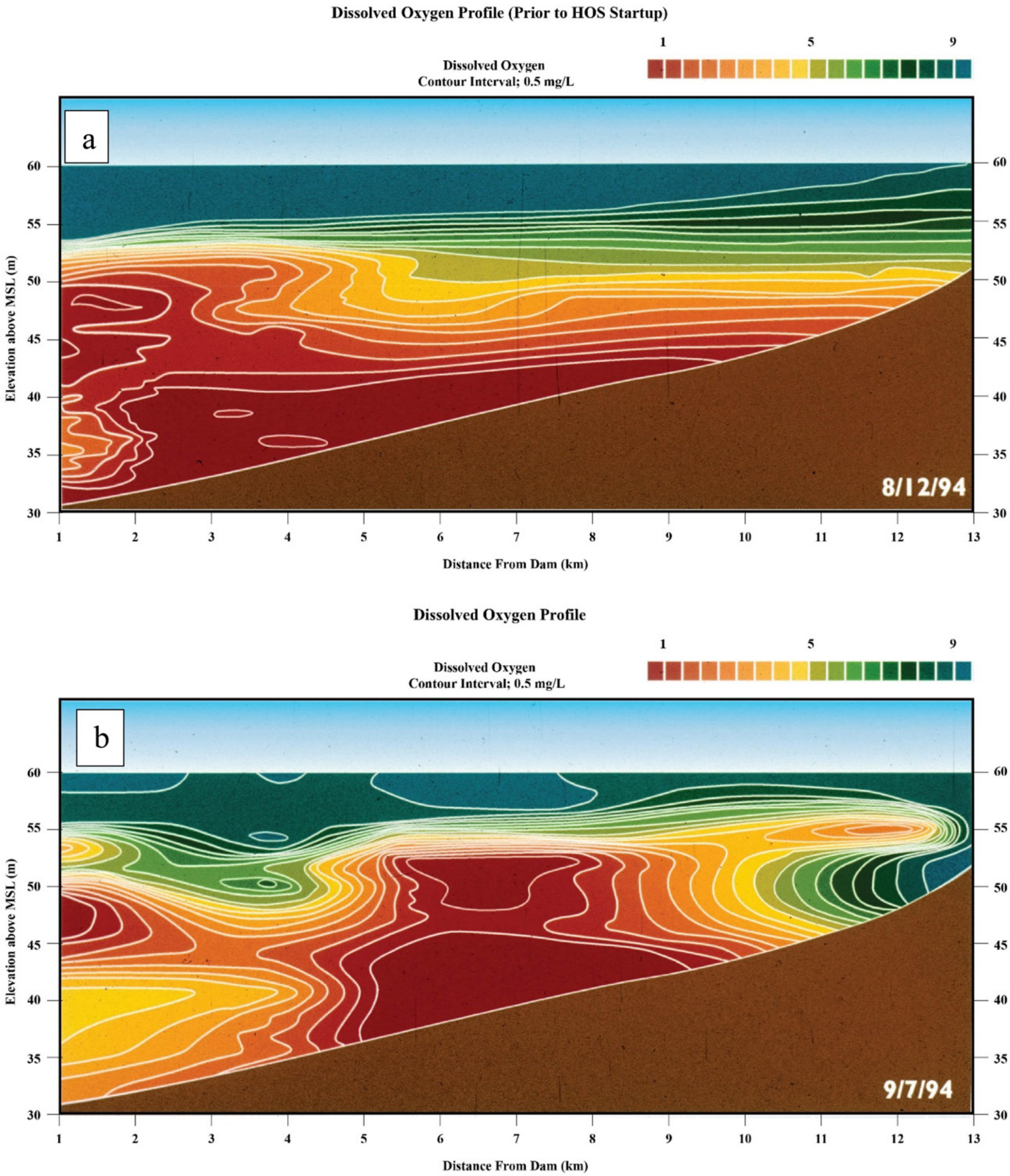

Figure 7. Spatial extent of oxygenation plume during HOS on/off testing in 1994. Most water volume is contained in the first 5 km of the reservoir. (a) Oxygenation shut down for 24 d; most hypolimnion deep water is red (anoxic), and small area of DO ~1 mg/L near bottom near dam and Speece cone is the remnant of earlier HOS operation. (b) After 29 d of oxygenation. The oxygenated plume (orange yellow >5 mg/L) extended 4.5 km upstream.

The spatial extent of the oxygen-rich plume is shown in two examples: low DO following a prolonged shut-down of the HOS (Fig. 7a) followed by an extended oxygenation period (Fig. 7b).

Without HOS operation for 29 d, DO in the hypolimnion was <2 mg/L with a 10 m thick bottom layer <1 mg/L. A small area >3 mg/L near the Speece cone was the relic of the HOS

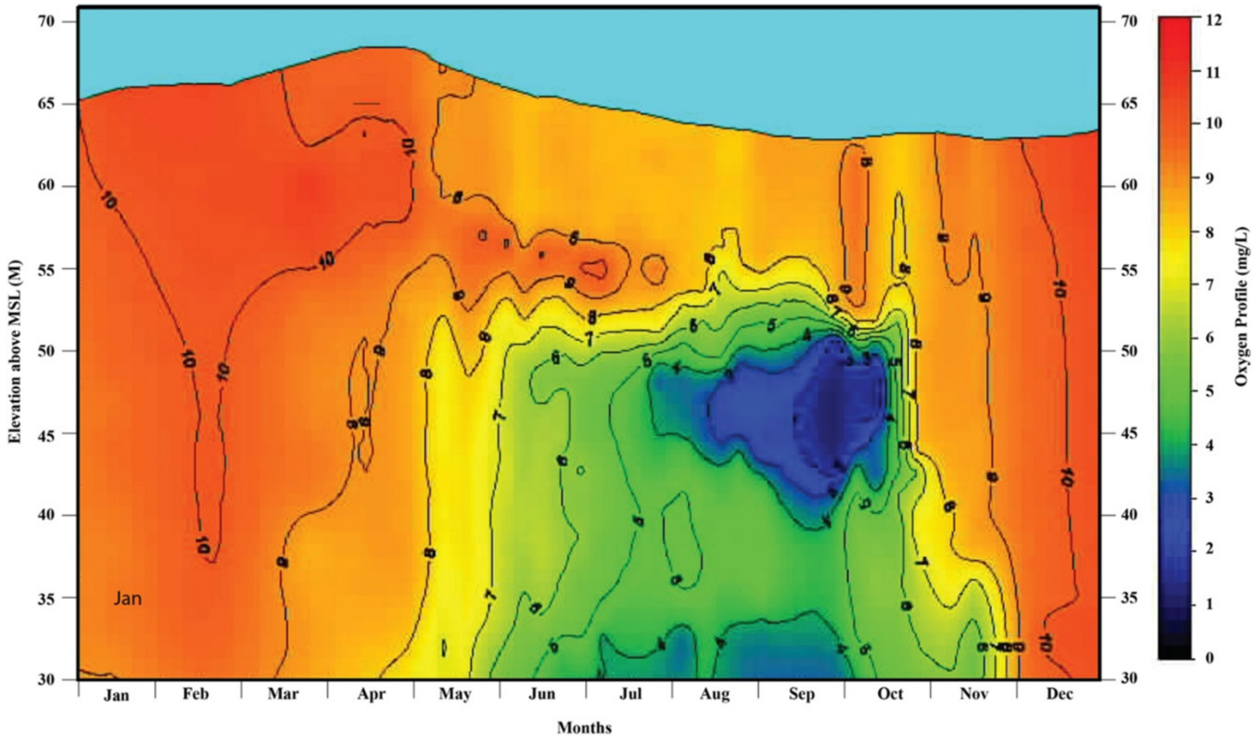

Figure 8. Moving surface, whole-year depth–time isopleths of dissolved oxygen in 2004, 11 yr after HOS installation with less oxygen used. Note: Colors here are reversed relative to Figure 7; here blue = low DO and red high DO. The bottom water DO was maintained at >2 mg/L and the mid-upper hypolimnion is almost anoxic in the fall since fish can pass through or around this potential barrier (Horne et al. 2019a).

operation 29 d earlier. Twenty-four days after resumption of oxygenation, the up-reservoir extent of the oxygenated HOS plume is clearly shown as the yellow–pale green area (DO >5–7 mg/L). The 5 m thick tip of the plume (>2 mg DO/L) had moved 2.5 km up-reservoir from 2 km from the dam (relic plume tip from previous oxygenation) to 4.5 km up-reservoir in only 24 d—a rate of 0.12 cm/s. The HOS plume became depleted as it moved up-reservoir over the anoxic sediments, but bottom water DO was >2 mg/L for all the 4.5 km from the dam and cone. The integrity of the plume was such that a 7 m thick layer of hypolimnion above the plume was little affected and protected against early turnover as expected (Speece 1994). In 1994, even intermittent HOS operation moved the oxygenated plume 4.5 km up-reservoir.

Hypolimnetic oxygenation is now routine at Camanche Reservoir. After 11 yr, oxygen additions were reduced as much as two-thirds. DO over the sediments remained about 3–4 mg/L but DO in the metalimnion, more distant from the bottom oxygen plume, dropped to <2 mg/L (Sep–Oct, Fig. 8). A zone of low DO (~3 mg/L) in the upper hypolimnion remained but no problems occurred with H_2S generation or hatchery fish survival. Horne (2019a) showed that fish were able to move from shallow to deep water once HOS was operating, even if there was a zone of low DO in the upper hypolimnion.

The hypolimnion volume per 180 d season passing through the Speece cone was 16×10^6 m^3 (12.5 TAF). The measured plume thickness was ~9 m, giving a volume of anoxic water to be treated of about 86×10^6 m^3. Thus, only 18% of the water was oxygenated directly inside the cone. Using the 10-fold entrainment for the manifold jets (Speece 1992) and ignoring any short-circuiting, 1.8 times the volume of the deep-water layer was indirectly affected by oxygen.

Temperature

The 10 m buffer between the thermocline and the predicted bottom water oxygen plume proved successful in terms of not altering the thermocline. Profiles from the year before HOS, the first

Table 3. Oxidation–reduction potential (ORP in mV) depth profiles at sites near and far from the Speece cone in 1994 (see Fig. 3). Values in bold = hydrogen sulfide odor smelled by field crew in bottom water samples

Depth above bottom	Site 1 (HOS site)	Site 2 (3.7 km)	Site 3 (5.3 km)	Site 4 (7.3 km)	Site 5 (11 km)
12 Aug 1994 following 24 d of no oxygen					17 Aug
4 m	394	389	414	380	501
3 m	393	386	311	380	501
2 m	371	341	264	346	499
1 m	315	339	**250**	**268**	492
14 Sep 1994 after 33 d of oxygenation					
4 m	394	421	**79**	50	358
3 m	395	422	**71**	**32**	355
2 m	396	421	**61**	**24**	352
1 m	396	420	**54**	**18**	350
5 Oct 1994 after 54 d of oxygenation					
4 m	329	279	355	397	405
3 m	334	300	357	390	388
2 m	336	304	358	385	384
1 m	337	296	353	374	383

year of HOS, and 21 yr later are very similar (Fig. 5a). Nonetheless, the temperature distribution within the thermocline was affected by HOS. There was a slight warming of the bottom water coincident with the start of HOS (Fig. 6a). It was caused by homogenization of deep water by the plume. The warming ceased when HOS was turned off (Fig. 6b). Extrapolation showed that 16.8 C would be reached at overturn rather than 14.8 C with no HOS. The fishery agency required temperatures below 16 C on 1 November. Briefly stopping HOS in summer moderated the warming effect without depressing the DO to levels of concern for fish or H_2S generation.

The HOS at Camanche Reservoir did not erode the thermocline or advance overturn (Fig. 5a). Comparisons of the years with the most similar depths at approximately 1 November show that a year with HOS (2001) had a stronger thermocline near turnover than 1989, 4 yr prior to HOS. The reservoir was 4.5 m deeper in 2001, but this did not affect the temperatures in most of the hypolimnion which were similar in both years. In contrast, the effect of HOS on elevating hypolimnion DO in 2001 was very clear (Fig. 5b).

Redox potential

Well-oxygenated water has a high redox potential, ~500 mV, and we chose <300 mV as a level of concern. During on/off testing in 1994, HOS in the reservoir was stopped in July for 29 d until 12 August. At this time, the redox in the bottom 4 m of the hypolimnion up to 3.7 km from the Speece cone was still quite high (315–394 mV), lowest just over the sediments (Table 3). Only up-reservoir (5.3–7.3 km) and in the deepest water was redox <300 mV because the HOS plume did not reach that far in 1994. These bottom water samples had an H_2S odor, indicating zero DO in the sediments. At the most distant site 11 km from the dam the reservoir was almost riverine (affected by daily release from oligotrophic Pardee Reservoir upstream) and redox was high (492–501 mV), as was DO (9 mg/L).

After 33 d of HOS operation, again in 1994, redox potential in the deep hypolimnion within 4 km of the Speece cone increased to 392–421 mV (Table 3). However, at 5 and 7 km upstream, redox potential had fallen precipitously (18–79 mV), despite oxygenation, and H_2S was detected in most deep-water samples. The most distant riverine station at 11 km maintained a high redox (~359 mV). After 54 d of oxygenation, acceptable redox was finally achieved at all depths and locations. Previously low redox sites 5–7 km from the HOS site rose from 18–79 mV to 353–397 mV and H_2S was no longer detected.

Discussion

The HOS plume in the hypolimnion of Camanche Reservoir moved oxygen up-reservoir more quickly and further than was anticipated (0.12 cm/s; 4.5 km). The hydrodynamic calculations predicted that pumping energy would be exhausted 300 m from the manifold, so a natural mechanism must have moved the bottom water oxygenated plume up-reservoir. The mechanism driving this motion is debatable, but all possibilities depend on propagation of wind energy at the lake surface down to the sediments. Possible scenarios are the Ekman spiral of surface currents down to deeper water (Gross 1977, Stacy et al. 1986, Horne and Goldman 1994), propagation of internal waves (seiches) on the thermocline to the sediments (Lemmin and Imboden 1987), and turbulent diffusion. For reservoir management, the rapid horizontal movement of the oxygenated plume indicates that expensive long runs of pipe may not be needed if the reservoir has no long side arms. A recent design for dentate Soulajule Reservoir, Marin County, California, for suppression of methylmercury and one in Beaver Creek Reservoir, Virginia, both propose a Speece cone with a pipe extension to the most remote arm.

Why did the half-sized system work so well? In Newman Lake, Washington, a Speece cone was set up with only 50% of design capacity due to cost issues and was not successful until more oxygen was added (Moore et al. 2015). However, the initial situation at Newman Lake was complicated by a large increase in lake elevation in a wet year and thus a larger hypolimnion volume to be oxygenated. For Camanche Reservoir the most likely reason that half of the original estimate proved adequate was that HOS reduced internal nutrient loading sufficiently to starve most phytoplankton. Algae, as chlorophyll or algae counts, declined by about 80% in the first 2 yr of HOS operation (Horne and Beutel 2019). The sediment demand and its effect on the IHOD would then fall considerably. In Camanche Reservoir, as in many other inland waters, internal loading dominates the annual nutrient budget (Orihel et al. 2017). The main sediment BOD source in Camanche Reservoir appears to have been autochthonous—the spring and summer algae blooms—as has been shown for a large range of other waters using stable isotope ratios for C and N (USGS 2006), though this may not apply to unproductive lakes with high inputs of allochthonous terrestrial organic particles (Thomas and Meybeck 1996). In addition, the summer inflow to Camanche Reservoir from the oligotrophic Pardee Reservoir upstream was normally low in nutrients (Horne and Beutel 2019), so internal loading was proportionally even more important in its eutrophic state in the 1980s. If the oxygenation reduces algae substantially, as at Camanche Reservoir, the future oxygen demand will be lower. At Camanche Reservoir, the oxygen supplied was reduced by 75% (from 8 to 2 tons/d), which is like the percentage decline in chlorophyll during the growth season (14.6 to 2.8 μg/L; Horne and Beutel 2019) over 11 yr of operation.

The HOS on/off tests in 1994 at Camanche Reservoir show that once oxygenation is stopped for an extended time period, at least several weeks of renewed operation are needed to restore healthy redox potential (>300 mV) in the bottom waters 5 km upstream. Our recommendation is that reservoir managers should oxygenate continuously over the summer–fall periods and normally start before the DO drops below 5 mg/L (USEPA criterion for inland waters) and before redox drops to <300 mV, with both measures being made near the bottom in deep water. However, it is possible to reduce DO in bottom water to lower levels (~2 mg/L) before the sediments themselves become anoxic. Assuming a bottom water DO decline of 0.1 mg/L, this approach leaves 20 d (2 mg DO/L ÷ 0.1 mg DO/L/d) room for error or breakdowns. That may not be enough if divers are needed to resurrect a fallen cone but would be adequate to change the water pump motor or leaking hoses (Horne 2019a).

Conclusions

The following conclusions are offered:

- The submerged down-flow contact oxygenation (SDCO) or Speece cone increased dissolved oxygen and redox potential in the bottom water to levels that suppressed H_2S generation in the sediments.
- When compared with the previous year, the Speece cone elevated the 20 m thick hypolimnion DO levels by 3–5 mg/L.
- No early destratification occurred and the mixing action of the oxygenated plume was confined to the lower 10–12 m of the hypolimnion.
- Submerging the Speece cone in deep water increased efficiency since more hydrostatic

pressured increased DO dissolved per unit volume of water pumped.

- The natural wind-driven circulation of the surface water indirectly powered slower circulation of the bottom water. Similar movement can be expected in other waters, with smaller ones having the lowest speeds.

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