American Fisheries Society Symposium 80:000–000, 2012

Oxygen Diffusers to Create and Maintain Summer Fish Habitat

Mark Mobley*
Mobley Engineering, Inc.
Post Office Box 600, Norris, Tennessee 37828, USA

Ed Shallenberger
Colville Confederated Tribes
64 Schoolhouse Loop Road, Nespelem, Washington 99155, USA

Marc W. Beutel
Department of Civil and Environmental Engineering, Washington State University
Post Office Box 642910, Pullman, Washington 99164, USA

Paul Gantzer
Gantzer Water Resources Engineering, LLC
14816 119th Place NE, Kirkland, Washington 98034, USA

Brian Sak
Fisheries and Wildlife Section, Natural Resources and Lands Management Division
San Francisco Public Utilities Commission
8653 Calaveras Road, Sunol, California 94586, USA

Abstract.—Habitat for striped bass *Morone saxatilis*, hybrid striped bass, salmonids, and other coolwater and coldwater fishes can be limiting in stratified reservoirs during summer and early autumn as surface water temperatures increase above tolerable ranges and deeper waters are depleted of dissolved oxygen (DO). Usable habitat can be increased in these reservoirs using oxygen diffusers to increase DO concentrations in the cooler, deeper waters. Several oxygen diffuser systems are currently in operation. Some of the systems were originally designed to increase DO in hydropower reservoir releases, but have also created fish habitat as a result of the diffuser system's efficient oxygen transfer capabilities in the reservoir. Several other systems are operated to improve water quality in the reservoir for water supply, and two systems have specific fish habitat maintenance goals. Improvements in DO for fish have been obtained at Calaveras Reservoir, California by the San Francisco Public Utility Commission, and fish studies at this reservoir are currently underway. In North Twin Lake, Washington, the Colville Confederated Tribes and Washington State University have documented improved trout habitat and reduced sulfide concentrations. Oxygenation of cool, deep water is now a proven technology that can alleviate summertime thermal and oxygen stress on striped bass and hybrid striped bass and can minimize habitat-related mortalities. The technology is being implemented specifically for striped bass with a large installation

* Corresponding author: mark@mobleyengineering.com

in J. Strom Thurmond Reservoir, South Carolina, for the Savannah District of the U. S. Army Corps of Engineers.

Introduction

Deterioration of summertime habitat can be a major cause of striped bass *Morone saxatilis* mortality and was first identified in Cherokee Reservoir, Tennessee (Coutant 2012, this volume). Suitable habitat is typically lost by warming of surface waters above about 25–27°C and depletion of dissolved oxygen (DO) to 2 mg/L or less in cooler, deep waters isolated by thermal stratification. This seasonal habitat restriction for striped bass and hybrid striped bass and its detrimental consequences have been confirmed as a general feature of many freshwater bodies into which these fish have been introduced (Coutant 2012; Rice et al. 2012; Thompson and Rice 2012; Van Horn 2012; all this volume). The temperature and oxygen limitations also affect distribution and abundance of prey for these large, pelagic predators, contributing to varying degrees of tolerance for the marginal physico-chemical conditions among water bodies (Thompson and Rice 2012). Various approaches have been used to maintain fisheries for large striped bass and their hybrids in the face of summer habitat limitations, including protection and expansion of naturally oxygenated thermal refuges such as cool tributary springs (Long et al. 2012, this volume), and summer fishing restrictions. Although artificial cooling is impractical, artificial oxygenation has been more promising, especially since it has additional benefits beyond in-reservoir habitat for striped bass.

In 1992, the Tennessee Valley Authority (TVA) installed oxygen diffusers in Cherokee Reservoir to improve DO conditions in the Holston River, downstream of the dam. Cherokee was the third TVA hydropower project to utilize oxygen diffusers in the reservoir to improve the water quality of hydropower releases, but the first with abundant striped bass in the reservoir. The Cherokee oxygenation system is the largest operated by TVA and is capable of delivering more than 136,000 kg/d of pure oxygen gas to counteract extremely low summertime DO conditions in the reservoir and enhance DO levels in released waters. The diffusers extend over 3 km upstream of the dam and spread oxygen over an even larger area. Operation of the diffusers increased DO levels in the deeper, cooler waters of the reservoir (Figure 1), which included the depth range that contained optimal temperatures for adult striped bass. The improved oxygen content created additional usable fish habitat near the dam during the warm summer months that attracted striped bass. As a result, the area became so heavily used by anglers that the Tennessee Wildlife Resources Agency closed the area to fishing 15 July–15 September due to substantial catch and release mortality of striped bass (http://news.tn.gov/node/7454). Since 1992, TVA has installed oxygen diffusers at other sites and currently operates reservoir oxygen diffuser systems at nine hydropower projects. Reservoir conditions have been enhanced near the diffusers at all of these reservoirs, but none have experienced the extreme striped bass response that occurred at Cherokee.

Since 1999, Mobley Engineering, Inc. has applied state-of-the-art bubble plume modeling techniques pioneered at Eawag, the Swiss Federal Institute of Aquatic Science and Technology (Wuest et al. 1992), Virginia Tech University (McGinnis et al. 2004; Singleton and Little 2006; Singleton et al. 2007), and TVA (Brown et al. 1989) to design and build reservoir oxygen systems nationwide. A small percentage of the systems had specific requirements for creating and maintaining usable fish habitat in reservoirs and lakes. Others were concerned simply with water quality.

This paper presents a brief description of the diffuser system, discusses two recent case studies where oxygenation was used for improv-

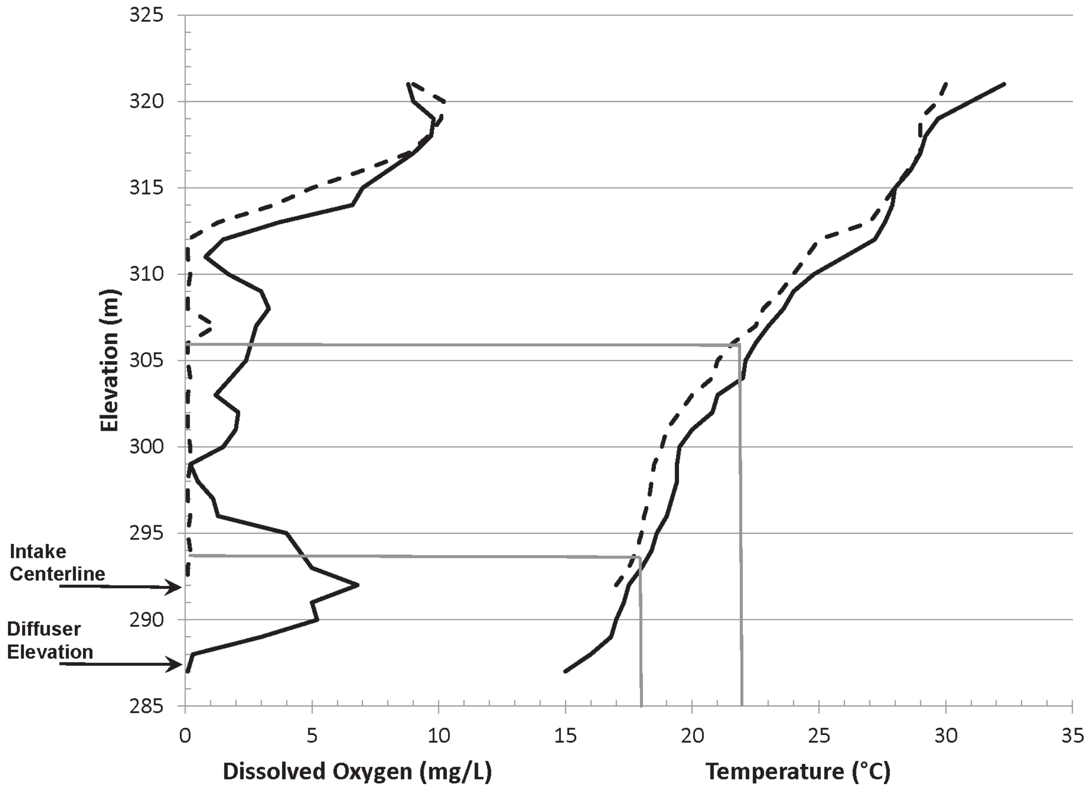

FIGURE 1. Dissolved oxygen and temperature profiles in Cherokee Reservoir, Tennessee, 14 August 1995, upstream (dashed lines) and downstream (solid lines) of oxygen diffusers (Mobley 1997). Elevations of the hydropower water intake and the oxygen diffuser are indicated. Gray lines indicate approximate depth of the estimated optimal temperature range for adult striped bass.

ing coldwater habitat for trout, and describes an ongoing project specifically designed for striped bass. In 2005, the San Francisco Public Utilities Commission installed a diffuser system to expand summer habitat for resident rainbow trout *Oncorhynchus mykiss* in Calaveras Reservoir, California. In Washington state, the Colville Confederated Tribes and Washington State University began conducting the first full year of a pilot study in 2009, operating a test diffuser system installed in 2008 to increase summertime habitat for stressed rainbow trout and brook trout *Salvelinus fontinalis* in North Twin Lake, Washington while using South Twin Lake as a study reference (Beutel et al. 2011). While these projects were specifically focused on enhancing habitat for trout with temperature preferences below 20°C (Biggs 2007), it is clear that similar reservoir oxygen systems can provide comparable habitat enhancements for other coolwater and coldwater species such as striped bass and its hybrids. A recent installation in J. Strom Thurmond Reservoir, South Carolina–Georgia is an example of a project where habitat for striped bass was the primary concern.

Reservoir Diffuser System

The line diffuser system for these applications was based on a design initially developed at TVA (Mobley 1997; Beutel and Horne 1999). This type of diffuser design is currently installed and operated at nine TVA reservoirs and at 11 reservoirs for other utilities from Maine to California. The line diffuser is a simple and economical design that spreads bubbles over a large area and is installed and retrieved for required maintenance from a 6 × 2.5 m "jon" boat without the assistance of divers. The system uses long lines of flexible porous hose (commercial "soaker hose" often used for irrigation, formed from shredded automobile tires) to avoid clogging and other maintenance problems experienced by previous designs that used ceramic diffusers. The diffuser is a two-pipe system that includes a high-density polyethylene supply pipe to distribute the gas along the length of the diffuser and a buoyancy pipe that can support the entire weight of the diffuser system when filled with air (Figure 2). Flow control orifices control the oxygen flow to independent lengths of porous hose to maintain a continuous flow of small gas bubbles along the full length of the diffuser. Concrete anchors are attached to the diffuser piping with stainless steel cable and saddle connections. The line diffuser has proven to be an economical oxygenation diffuser design that transfers oxygen efficiently to deep water, minimizes temperature destratification to preserve the coolwater habitat, and avoids sediment disruption. The three case studies (Calavares Reservoir, Twin Lakes, and J. Strom Thurmond Reservoir) illustrate its deployment and oxygenation performance.

Calaveras Reservoir

Calaveras Reservoir is part of a water supply system owned and operated by the San Francisco Public Utility Commission (SFPUC), San Francisco, California. The reservoir is located above and between Sunol and Milpitas, California and has a surface area of 581 ha, a

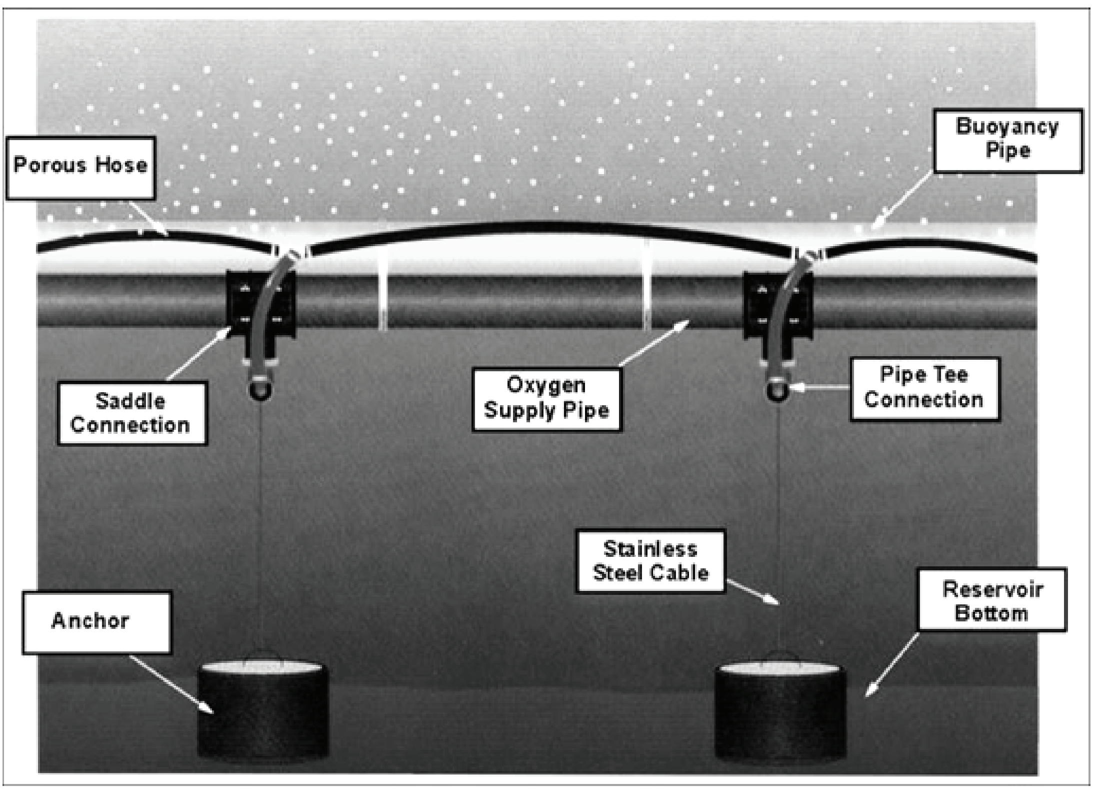

FIGURE 2. Schematic of diffuser system components.

maximum depth of 43 m, and a volume of 120 million m^3 at full pool elevation of 230 m. In 2004, the SFPUC undertook an improvement program to replace Calaveras Dam. In the interim, the California Division of Safety of Dams mandated an operational reservoir level of 215 m, reducing the water depth to less than 27 m, the surface area to 348 ha, and the storage capacity to 42 million m^3. The reduced size of the reservoir resulted in reduced fish habitat and algal blooms that caused taste and odor problems. The fish habitat issue was especially important to the SFPUC (2005), state and federal fisheries agencies, and environmental advocates because the reservoir contained a unique, self-sustaining population of rainbow trout.

In 2004, the SFPUC undertook several studies that determined that a hypolimnetic oxygenation system (HOS) was a viable means to maintain reservoir water quality and fish habitat. Dissolved oxygen objectives for the HOS were defined as a minimum of 2 mg/L in the hypolimnion and 5 mg/L in the volume of water between 18°C and 22°C for favorable trout habitat (also the preferred temperature range for large striped bass; Coutant 2012). After an extensive evaluation of alternatives, the reservoir oxygen diffuser system was recommended as the best approach to achieve the project objectives at Calaveras Reservoir (Weiss and Associates 2004).

A site study evaluated potential diffuser layouts utilizing state-of-the-art bubble plume modeling to predict oxygen placement over a range of reservoir conditions, diffuser layouts, and oxygen flow rates (Mobley 2004). To enhance key fish habitat, it was particularly important to place oxygen at the correct elevation in the reservoir water column to oxygenate waters that corresponded with optimal temperatures for fish. A diffuser layout that consisted of two diffuser lines, each 305 m long, was recommended. One diffuser was placed in the deepest part of the reservoir near the dam. The second diffuser was extended almost 1.6 km upstream of the dam to place oxygen higher in the water column and spread oxygen into an upstream cove, named Arroyo Hondo, to maintain prime fish habitat. The recommended oxygen system delivery capacity was 3,600 kg/d of oxygen to match the maximum measured oxygen demands in the reservoir. Reservoir oxygen demand is calculated from measured DO and temperature profiles in the reservoir during the onset of oxygen depletion and stratification. The reduction in DO over time during development of summer stratification multiplied by the affected reservoir volume estimates reservoir oxygen demand. In the Calaveras Reservoir design additional oxygen delivery capacity was specified to provide the capability to increase DO levels after a shutdown or failure.

The Calaveras Reservoir oxygenation system was installed in late summer of 2005 at a cost of about US$1.2 million. The diffusers at Calaveras Reservoir are supplied with oxygen from an onsite bulk oxygen storage facility. The facility includes a 41,000-L liquid oxygen tank, two vaporizers, and associated equipment to supply pressurized gaseous oxygen to the diffusers. Oxygen is stored in the tank at approximately –150°C and vaporized as needed to supply the system. Pressure caused by the vaporization is sufficient to provide the oxygen flow to the diffusers in the reservoir. When operating in the reservoir, the oxygen diffusers produce a long, straight curtain of very small bubbles that are spread out enough to create only a weak upwelling plume. Most of the bubbles dissolve before they reach the surface as oxygen is transferred to the surrounding water. Those that reach the surface create a faint bubble pattern that is visible when the water is calm. Oxygen transfer efficiency is 85% to 90% with the 20–27-m depths targeted at Calaveras Reservoir.

The Calaveras Reservoir oxygenation system was placed in operation on 6 September 2005. Initially, the system was operated at higher than normal oxygen flow rates to overcome the existing hypoxic conditions in the reservoir. The reservoir DO levels responded quickly to the oxygen input, reaching objectives within 3 weeks of start-up (Figure 3). Dissolved oxygen levels were increased well into Arroyo Hondo,

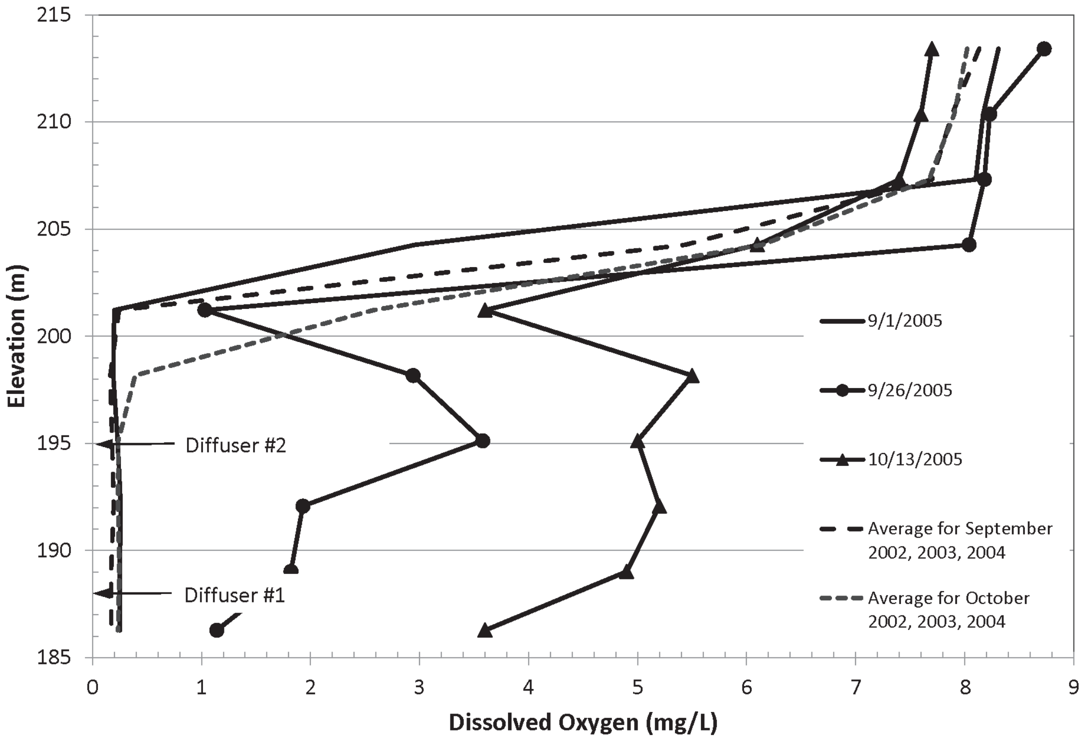

FIGURE 3. Depth distribution of dissolved oxygen (DO) 5 d before start-up of the Calaveras Reservoir oxygenation system on 6 September 2005 (1/9), 3 weeks after start-up (26/9) and about 5 weeks after start-up (13/10). Average DO depth distributions from September and October 2002, 2003, and 2004 are plotted for comparison.

even though high sediment oxygen demand reduced the levels near the bottom. Similar DO levels have been maintained every year since the system was installed, providing suitable coldwater trout habitat. Costs for operation and maintenance have been about $50,000, annually.

The Calaveras Reservoir oxygenation system has successfully met SFPUC objectives for increased DO levels in the hypolimnion. The system has been so successful that SFPUC installed a similar hypolimnetic oxygen system in the larger San Antonio Reservoir in 2009 to achieve similar goals for water quality and fish habitat enhancement.

North Twin Lake

North and South Twin Lakes are natural lakes on the Colville Confederated Tribes (CCT) Reservation northwest of Spokane, Washington. The lakes are in the hills above Inchelium, Washington are very similar in volume, shape, and depth and are connected by a short channel. North Twin Lake has a surface area of 371 ha, a maximum depth of 15 m, and a volume of 36 million m^3. The lakes have historically been stocked with rainbow trout (coastal) and brook trout by the CCT Fish and Wildlife Department. The Twin Lakes support a strong tribal trout fishery and are a tourist attraction. More recently, CCT has emphasized stocking and reestablishment of Columbia basin redband trout *O. m. gairdneri*, a rainbow trout subspecies native to Northwest lakes and streams east of the Cascade Mountain Range (Clegg 2010) in the Twin Lakes.

The water quality and fisheries in the lakes have been monitored and studied by researchers at Washington State University (WSU) and

CCT (Christensen and Moore 2008, 2009, 2010). Both lakes experience low DO levels in the bottom waters that typically become anoxic below about 7 m depth in the late summer when surface temperatures reach 22°C. The lack of cool, oxygenated water has limited trout habitat in the lakes. Trout have exhibited signs of stress and reduced growth rates during the summer, and total annual mortality has exceeded 90% (Clegg 2010).

Seeking a way to improve summertime fish habitat, WSU and CCT collaborated on a proposal to the Columbia River Water Management Program to design, install, and operate an on-site pilot oxygenation system that would deliver oxygen to the bottom waters of one lake (North Twin), with the other (South Twin) serving as a reference location. The dual nature of North and South Twin lakes provides an ideal setting to scientifically evaluate the effect of lake oxygenation on trout habitat.

In the summer of 2008, an oxygen diffuser system was installed in North Twin Lake to enhance DO levels. The total installation cost, using a temporary oxygen supply facility, was about $400,000. Initial funding for the project was provided by the Columbia River Water Management Program. The system included a 745-m line diffuser that distributes oxygen near the bottom of the lake; oxygen is supplied from a 23,000-L temporary liquid oxygen facility onshore.

The oxygen delivery capacity for the North Twin Lake oxygenation system was based on lake dissolved-oxygen profiles measured about monthly in the center of the lake from 2004 through 2007. The delivery capacity included factors to account for diffuser-induced oxygen demand, recovery from a shutdown, diffuser oxygen transfer efficiency, plus an additional safety factor. The diffuser-induced oxygen demand is the increased demand exerted by the reservoir sediments when water is stirred over them. This factor can range from 2 to 4 depending on site-specific conditions. The total capacity requirement was calculated to be 4,300 kg/d, a conservative engineering estimate for the design capacity. About 1,500 kg/d was estimated to be required from May to November, starting with aerobic conditions.

Monitoring during the study was conducted by WSU and CCT and included extensive monitoring of temperature, dissolved oxygen, and fish distribution. Prior to initial testing of the system in the fall of 2008, the hypolimnion exhibited severe oxygen depletion with DO levels less than 0.5 mg/L. Within 24 h of starting oxygenation DO levels were observed to increase to 1–2 mg/L near the diffuser.

In 2009, operation of the oxygenation system was initiated as soon as DO levels began to decline in late spring. Over the course of the summer of 2009, an oxygen flow rate of 540 to 800 kg/d was sufficient to maintain high DO levels in North Twin Lake, while the hypolimnion of South Twin Lake became severely hypoxic or anoxic (Figure 4). In June, DO levels were 5–10 mg/L in the bottom waters of North Twin Lake, while bottom waters were less than 1 mg/L in South Twin Lake. Overall oxygen transfer efficiency for the 2009 oxygenation season was estimated to be 83%. Installation of the diffuser system and site preparation was about $400,000. Operating costs have run about $80,000 per year, including liquid oxygen tank rental and remote delivery surcharges. The tribe is pursuing installation of an onsite oxygen generation system to reduce operating costs.

Recent fishery studies suggest enhanced deepwater habitat for trout in North Twin Lake (Clegg 2010; Lanouette 2011; Shallenberger 2011). In 2010, horizontal gill nets were set overnight on a monthly basis in the pelagic zones of both North and South Twin lakes at depths of 2–5 m, 5–8 m, and 9–12 m, as well as along shore and bottom. The fish captured in the nets (Table 1) demonstrate that trout did not use the hypoxic hypolimnion of South Twin Lake during periods of stratification, while the oxygenated hypolimnion of North Twin Lake was regularly used. These studies were corroborated by monthly hydroacoustic surveys.

As with Calaveras Reservoir, the results were so positive that an additional deepwater

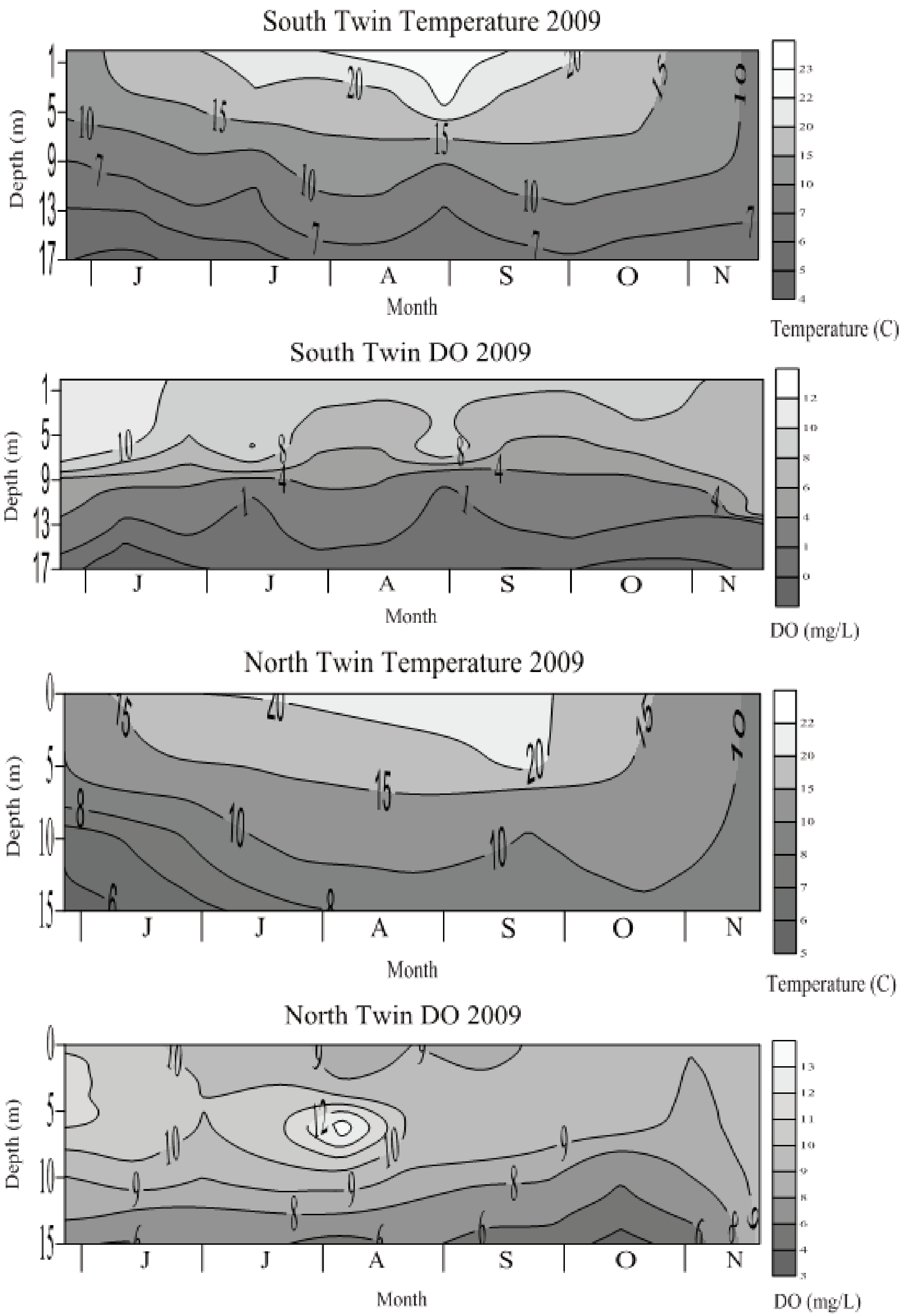

Figure 4. Depth distributions of temperature (°C) and dissolved oxygen (mg/L) in North and South Twin Lakes from late May through late November 2009. North Twin Lake is oxygenated by a diffuser at a depth of 14 m. Figures compliments of Dr. Barry Moore, Washington State University.

TABLE 1. Fish captured in 2010 in gill-net surveys in North and South Twin Lakes, Washington by lake, sampling stratum, and sampling date.

Stratum	6 Apr	19 Apr	6 May	9 Jun	14 Jul	11 Aug	10 Sep	21 Oct	Total
North Twin Lake									
Inshore	37			7				60	104
2–5 m		4	18	6	0	0	4	8	40
5–8 m		2	11	13	5	31	10	4	76
9–12 m		0	3	1	1	5	1	0	11
Benthic		0	0	0	0	0	1		1
South Twin Lake									
Stratum	6 Apr	19 Apr	6 May	9 Jun	14 Jul	11 Aug	10 Sep	21 Oct	Total
Inshore	39			4				14	57
2–5 m		1	5	1	0	0	0	4	11
5–8 m		2	6	9	3	4	0	0	24
9–12 m		0	0	1	0	0	0	0	1
Benthic		0	0	0	0	0	0	0	0

diffuser system with a capacity around 4,300 kg/d was installed in South Twin Lake in 2010 to improve trout habitat in that lake.

J. Strom Thurmond Reservoir

Work was recently completed by a team, including the senior author, to design, install, and test a striped bass habitat enhancement system for the U.S. Army Corps of Engineers' J. Strom Thurmond Reservoir near Augusta, Georgia, on the Savannah River. Oxygenation of the lower reservoir is intended to mitigate for loss of cool, oxygenated water in the tailrace of the upstream Richard B. Russell Dam (a popular striped bass fishery) when that dam operates as a pumped-storage hydropower facility (thus eliminating the persistent coolwater summer discharges typical of previous single-pass hydropower generation). The reservoir oxygen diffuser system was installed in the summer of 2010 and spring of 2011 and is capable of delivering up to 182,000 kg/d of oxygen. It is designed to maintain a large volume (1.6 km long) of striped bass habitat in the reservoir approximately 8 km upstream of the J. Strom Thurmond Dam. The specific design goals are 5 mg/L DO for 1.6 km (no less than 4.5 mg/L) and 4 mg/L DO for 6.4 km (no less than 3.5 mg/L) in the lower 13 km and in the 18–24°C temperature zone of the reservoir. A further goal is 3 mg/L DO at the entrance to the turbines to enhance the downstream water quality of the hydropower releases from J. Strom Thurmond Dam.

Extensive water quality modeling (Ruane et al. 2012, this volume) was done in support of a diffuser design that could place oxygen as needed to maintain striped bass habitat in the 18–24°C temperature zone of the reservoir as it broadens and deepens over the course of the summertime stratification. The final diffuser system design included nine diffusers at four elevations and more than 10 km of underwater supply piping. The system was fully operational in June of 2011 and was operated during the summer of 2011 to verify performance of contractual requirements, demonstrate flexibility, and maintain design goals. More than 400 water quality profiles were obtained to document distribution of the oxygen along the length and width of the lower 13 km of the reservoir; design goals were met or exceeded for the entire summer (Figure 5). Further monitoring of the habitat and response of the striped bass is ongoing.

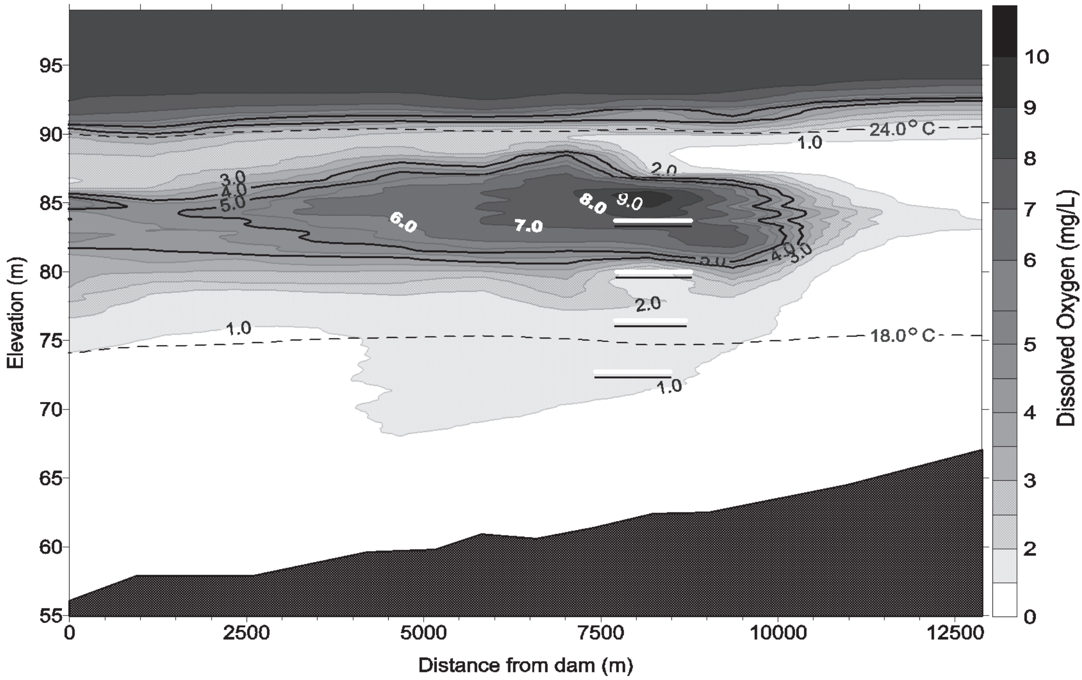

FIGURE 5. Example depth distribution of dissolved oxygen concentrations throughout the lower 13 km of J. Strom Thurmond Reservoir based on water quality profiles from 2011. Dashed lines indicate the 18°C and 24°C depth contours. Black-and-white bars indicate the four oxygen diffusers and their elevations.

Discussion

The DO and fish-habitat enhancements achieved in Calaveras Reservoir and North Twin Lake demonstrate the capability of a reservoir oxygen diffuser system to create and maintain coldwater fish habitat in diverse settings. At each of these sites, the gaseous oxygen bubble plumes placed oxygen in specific depths or temperature ranges in the lake or reservoir based on the habitat requirements of the desired fish species. Oxygen was added at rates that were determined by analyses of oxygen demand of the deep water during summer stratification. These calculations could have been improved with currently available reservoir water quality models (Ruane et al. 2012).

The examples we have described clearly demonstrate that reservoir oxygen diffuser systems can enhance habitat for coldwater and coolwater species, including striped bass and their hybrids. Striped bass habitat can be enhanced in habitat-limited reservoirs by placing oxygen in the optimal temperature regions of the reservoir (18–24°C) that may normally lack sufficient oxygen content during the summer months. Installation of a diffuser system upstream of Cherokee Dam in 1992 for tailwater oxygenation serendipitously demonstrated the attractiveness of artificially oxygenated water to striped bass in the summer. The two trout-related case studies presented here confirm that the diffuser system, which often includes thousands of feet of diffuser, can be located to distribute oxygen into specific areas and thermal strata of a reservoir as needed to optimize coolwater or coldwater fish habitat. Preliminary results from the initial year of operation of the system installed in J. Strom Thurmond Reservoir specifically to enhance striped bass habitat suggest that similar success can be achieved on a much larger scale.

As further experience is gained by deploying the system in water bodies of varying sizes and water-quality conditions, it should be technically feasible to artificially remove the temperature-DO habitat limitations for striped bass and their hybrids, which have been demonstrated in many inland waters across the country. Whether the technical feasibility is matched by economic desirability will depend on public attitudes toward striped bass and their hybrids in inland waters and the values of striped bass and hybrid fisheries (McMullin 2012; Miranda and Rayborn 2012; Whitehead 2012; all this volume). In most cases, oxygenation is likely to be too expensive to implement solely for striped bass habitat enhancement. The economic desirability increases when it is also the best option for meeting tailrace water quality standards (as in TVA reservoirs), as environmental mitigation for development projects (as at J. Strom Thurmond Reservoir), or as part of water treatment improvements at a water supply reservoir (Calaveras Reservoir). A multipurpose design that optimizes in-reservoir and downstream benefits would seem most fruitful and cost-effective. Where corollary benefits are not present, the scale of oxygenation might be scaled down to provide smaller volumes of enhanced DO in lake hypolimnia. This approach could provide DO-temperature refuges for striped bass during critical periods of summer, so long as angling for concentrated fish is controlled.

References

Beutel, M. W., and A. J. Horne. 1999. A review of the effects of hypolimnetic oxygenation on lake and reservoir water quality. Lake and Reservoir Management 15:285–297.

Beutel, M. W., B. C. Moore, P. Gantzer, and E. Shallenberger. 2011. Ease the squeeze in Twin Lakes: the Colville Confederated Tribes work to enhance a trout fishery and improve water quality in reservation lakes. Lakeline 30(4):31–37.

Biggs, M. J. 2007. Seasonal habitat use and movement by Columbia River redband trout in Twin Lakes, WA. Master's thesis. Washington State University, Pullman.

Brown, R. T., J. A. Gordon, and C. E. Bohac. 1989. Measurement of upwelling flow from air diffuser. Journal of Environmental Engineering 115:1269–1275.

Christensen, D. R., and B. C. Moore. 2008. Diet composition and overlap in a mixed warm- and coldwater fish community. Journal of Freshwater Ecology 23:195–204.

Christensen, D. R., and B. C. Moore. 2009. Using stable isotopes and a multiple mixing model to evaluate fish dietary niches in a mesotrophic lake. Lake and Reservoir Management 25:167–175.

Christensen, D. R., and B. C. Moore. 2010. Largemouth bass consumption demand on hatchery rainbow trout in two Washington lakes. Lake and Reservoir Management 26:200–211.

Clegg, E. 2010. Movement and distribution of trout following hypolimnetic oxygenation in Twin Lakes, Washington. Master's thesis. Washington State University, Pullman.

Coutant, C. C. 2012. When is habitat limiting for striped bass? Three decades of testing the temperature-oxygen squeeze hypothesis. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Lanouette, B.P. 2011. Changes in salmonid vertical distribution following hypolimnetic oxygenation in North Twin Lake, Washington. Master's thesis. Washington State University, Pullman.

Long, E. A., C. L. Messing, K. J. Herrington, R. R. Wheeler, and I. I. Wirgin. 2012. Restoration of gulf striped bass: lessons and management implications. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

McGinnis, D. F., A. Lorke, A. Wuest, A. Stöckli, and J. C. Little. 2004. Interaction between a bubble plume and the near field in a stratified lake. Water Resources Research 40, W10206, doi:10.1029/2004WR003038.

McMullin, S. L. 2012. Managing user conflicts in reservoirs. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Miranda, L. E., and S. W. Rayborn. 2012. Interactions between striped bass and other game fish in reservoirs. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Mobley, M. H. 1997. TVA Reservoir Aeration Diffuser System (TVA Technical Paper 97-3), ASCE WaterPower '97 Conference Proceeding Papers, August 5-8, Atlanta, GA. American Society of Civil Engineers, Reston, Virginia.

Mobley, M. H. 2004. Oxygen diffuser system for water quality and fish habitat enhancement at Calaveras Reservoir. Site study report prepared for the San Francisco Public Utility Commission, San Francisco.

Rice, J. A., D. J. Coughlan, W. J. Foris, J. A. Sykes, J. S. Thompson, D. H. Barwick, and C. T Waters. 2012. The role of metalimnetic oxygen minimum zones in striped bass summer kills and forage fish entrainment: consequences and management implications. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Ruane, R., G. Hauser, and A. Sawyer. 2012. Reservoir modeling for temperature and dissolved oxygen for striped bass habitat. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

SFPUC (San Francisco Public Utility Commission). 2005. Population size estimates for adult rainbow trout (*Oncorhynchus mykiss*) in San Antonio and Calaveras reservoirs. SFPUC, Water Quality Bureau, Technical Memorandum No. 2-04-006, Sunol, California.

Shallenberger, E. 2011. Twin Lakes enhancement annual report for 2010. Colville Confederated Tribes Fish and Wildlife Department, CCT/RF-2011-1, Nespelem, Washington.

Singleton, V. L., P. Gantzer, and J. C. Little. 2007. Linear bubble plume model for hypolimnetic oxygenation: full-scale validation and sensitivity analysis. Water Resources Research 43, W02405, doi:10.1029/2005WR004836.

Singleton, V. L., and J. C. Little. 2006. Designing hypolimnetic aeration and oxygenation systems—a review. Environmental Science & Technology 40:7512–7520.

Thompson, J., and J. Rice. 2012. How reservoir striped bass respond to unsuitable habitat conditions: habitat selection rules, energetic consequences, and the importance of prey availability. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Van Horn, S. 2012. History of striped bass and striped bass hybrids. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Weiss and Associates. 2004. Feasibility study for Calaveras Reservoir hypolimnetic oxygenation system. Prepared for City and County of San Francisco Public Utilities Commission, San Francisco.

Whitehead, J. 2012. Economics of recreational fisheries for inland striped bass and hybrid striped bass. Pages xxx–xxx *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and striped bass hybrids. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Wuest, A., N. Brooks, and D. Imboden. 1992. Bubble plume modeling for lake restoration. Water Resources Research 28:3235–3250.