Wolf Creek Dam (Lake Cumberland)
Reconnaissance–Level Evaluation of Dissolved Oxygen Improvement Study

Section 1. Introduction. The purpose of this evaluation is to identify, compare and assess the costs of various technologies available to improve dissolved oxygen (DO) levels in hydropower discharges from Wolf Creek Dam (WOL). In 2017, the Southeastern Power Administration (SEPA) and other hydropower stakeholders requested that the Corps consider installation of technologies, such as oxygen diffusers, to prevent hydropower revenues lost through water releases via sluice and orifice gates during seasonal periods of poor water quality.

Wolf Creek Dam is located at Cumberland River mile 460.9 in south central Kentucky with a vicinity map shown in Figure 1. The dam is 258 feet (ft) high and consists of a combination earth fill and concrete structure totaling 5,736 feet long. Wolf Creek powerhouse has six 45-megawatt (MW) turbines, for a total (non-overload) capacity of 270-MW. US Highway 127 currently crosses the crest of the dam but is expected to be relocated in the near future. Lake Cumberland, created by the dam, impounds 6,089,000 acre-feet (ac-ft) at the top of the Flood Control Pool elevation of 760 ft (National Geodetic Vertical Datum of 1929). All project uses except flood control, are drawn from the power pool located between elevations 673 ft and 723 ft. Under normal operations, summer pool elevation of 723 ft and is targeted in mid-May and held until mid-June. The lake is then gradually drawn down to reach the targeted winter pool elevation of 695 ft by January. Figure 2 shows Wolf Creek Dam outflow and pool levels during 2017. In general, the lake's elevation typically follows the upper SEPA band (upper black band) with divergences due to changing hydrologic conditions throughout the year.

The Commonwealth of Kentucky has classified the reach of the Cumberland River from Wolf Creek Dam to the Kentucky-Tennessee state line as cold-water aquatic habitat which has a DO standard of 6.0 mg/l and a temperature standard of 20^{o} Celsius (68^{o} Fahrenheit). Due to Lake Cumberland's seasonal thermal stratification, hydropower releases are generally below the DO standard from mid-July until the lake destratifies in mid to late-November. This period varies from year to year depending on meteorological and hydrologic conditions. Years with large late spring and summer inflow events are generally worse due to flushing of cold water from the Lake Cumberland pool. During months with low DO, turbine releases are blended with orifice/sluice gate releases to attempt to improve tailwater DO levels.

These non-turbine releases have been estimated to result in losses ranging from $600K to $1.4M per year in lost hydropower revenues over the years 2004, 2006, and 2014-2016. These were years in which dam safety projects were not underway. Average annual costs were estimated to be $798K-$867K using applied energy prices from the local market using both the lowest and highest possible hourly price (source –HDC, Parrish).

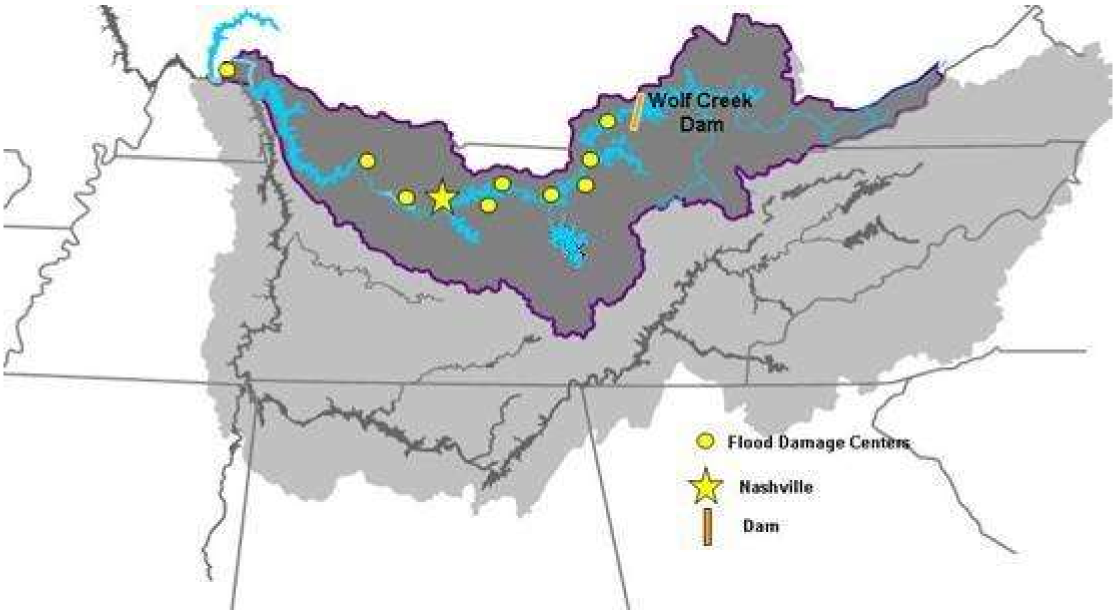


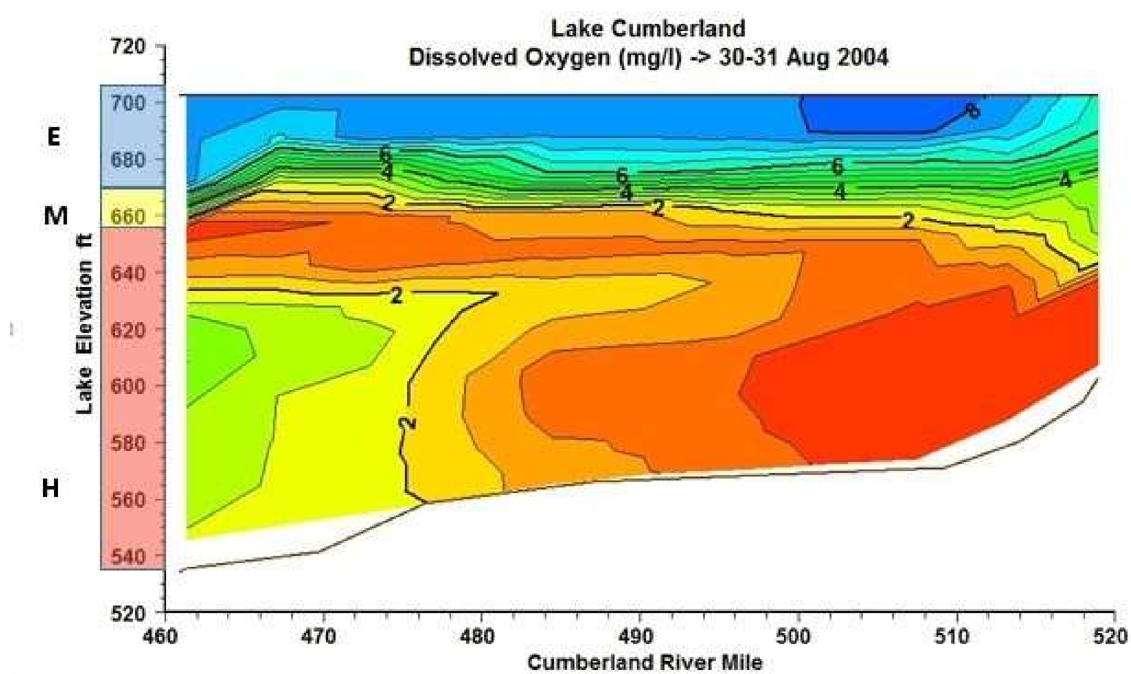
Figure 1 – Location of Wolf Creek Dam within the Cumberland River Basin

Figure 2
Wolf Creek Dam Outflow (top/blue) and Lake Cumberland Elevation (bottom/red)

Stratified lakes form three distinct vertical zones until the waters cool in the fall and lakes destratify. The epilimnion is the upper zone where waters are warmer and generally oxygenated by algae and wind and wave action. The metalimnion or thermocline is the zone of rapid temperature and DO change with depth due to lack of mixing and decaying algal organic loads. The hypoliminion is the bottom zone and once the lake stratifies is essentially cutoff from surface aeration. This zone has colder water that declines in DO levels over time until fall turnover and destratification.

Lake Cumberland exhibits thermal-stratification patterns typical of lakes in the southeast. Figure 3 shows DO and profiles for the lake from August, 2004. As Lake Cumberland thermally-stratifies, water quality within the turbine withdrawal zone determines release DO and temperature levels. The bottom of the 20' diameter turbine penstocks is at elevation 610 ft. A turbine withdrawal zone study by the Corps in 1983 indicated little water is withdrawn below elevation 590' (per. conversation, Jackson K. Brown, former Corps Hydraulic Engineer, Application of CEQUAL-W2 to Lake Cumberland, 1996). With a thermocline depth of about 50' in fall months, the turbine withdrawal zone would pull water within the 50-140 foot depth zone range. Examining conditions in the Figure 3, the epilimnion (E) is roughly elevation 670' to 705', metalimnion (M) 655' to 670' and withdrawal zone hypolimnion (H) 590' to 655' and a relatively-dead zone of hypolimnion below 590'. There is variability in stratification zones during the year and from year-to-year.

Figure 3



In the early 2000's, the Corps made operational changes (sluicing under certain conditions) and modifications to the dam, retrofitting two sluice gates with orifice gates. The sluice gate were modified to provide a flow of approximately 250 cubic feet per second (cfs) that is aerated by its turbulent release. In conjunction with staff from the Tennessee Valley Authority (TVA), additional alternations were made to hydropower turbines (Units 1, 3, and 5) to increase turbine venting capabilities by installing hub baffles and enlarging air lines to improve DO levels in turbine releases. This allowed modest improvements above baseline DO levels in turbine releases of up to 1.5 mg/l, however, this alone could not meet the State water quality standard of 6.0 mg/l.

Cumberland River Reservoir-System Effects. The Corps constructed and operates ten dams and reservoirs within the Cumberland River Basin (see Figure 5). Barkley, Cheatham, Old Hickory, and Cordell Hull Dams are located on the mainstem of the Cumberland River with navigation locks that cumulatively provide 452 miles of navigation from the mouth of the Cumberland River up to Celina, Tennessee. Wolf Creek Dam spans the Cumberland, but does not permit navigation. Wolf Creek Dam provides a significant water storage capacity. The Cumberland River tributary dams are Martins Fork Dam, on Martins Fork; Laurel Dam, on Laurel River; Dale Hollow Dam on the Obey River; Center Hill Dam on the Caney Fork River; and, J. Percy Priest Dam on the Stones River.

Figure 4 - Cumberland River System of Reservoirs

The ten projects are managed as one system with the goal of managing the flow of water through the entire Cumberland River basin, although Martins Fork and Laurel have little effect on the mainstem Cumberland River. This system-approach allows the Cumberland River flow to be held or released at different projects depending on hydrologic conditions within the river basin. During floods, water is stored and then time-released to minimize damage downstream. During typical and dry years, water releases are coordinated to ensure that enough water flows to meet downstream needs.

Only three dams sustain the desired Cumberland River flows through Barkley Dam during drought. Wolf Creek, Dale Hollow, and Center Hill Dams supply 65%, 15%, and 16%, respectively, of the total flow in the Cumberland River system during dry conditions. The ability of a project to contribute flow to the system is linked to the summer pool storage volume maintained at a Wolf Creek, Dale Hollow and Center Hill projects.

Impoundment of the Cumberland River by Wolf Creek Dam created a deep lake and altered the river downstream of the dam by significantly lowering the water temperatures and changing the daily flows. The consequences of impoundment were the conversion of a diverse cool water stream, along with most of the fish and aquatic life it supported including a number of now endangered species of freshwater mussels, into a cold water reservoir with a cold tailwater. The effects of the cold water releases from Wolf Creek and Dale Hollow drive water temperatures through Cordell Hull Lake and, after adding releases from Center Hill, into the upper reaches of Old Hickory Lake (above Lebanon, TN).

The following description is “paraphrased” from a report by the Tennessee Wildlife Resources Agency (TWRA) on the mussel community of the Cumberland River (Orangefooted Pimpleback and Catspaw Survey, TWRA Project 7367, Don Hubbs, 2012). Historically the Cumberland River contained a diverse mussel fauna with approximately 80 species reported from the drainage (Wilson and Clark, 1914); however habitat alteration from impoundment and maintenance dredging of the navigation channel has substantially reduced the species richness and abundance. Mussel habitat is highly fragmented in the main channel in Tennessee. The upper reach of Old Hickory Lake between Lebanon and Carthage (49 river miles) contains much of the physical habitat favorable to mussel colonization and still holds approximately 33 species including 13 Tennessee Greatest Conservation Need and five federally endangered.

Mussel recruitment in this reach has long been suppressed by cold water resulting from hypolimnetic releases from upstream reservoirs (Wolf Creek, Dale Hollow, and Center Hill). However, warmer temperatures observed during the period of lower lake levels at Lake Cumberland (Wolf Creek) (2007-2012) (conditions actually continued until lake returned to normal operation in 2014) caused some species to become gravid and some Lampsiline species performing active spawning displays. Surveys were performed in the Rome Ferry mussel sanctuary (TWRA, 2012).

These TWRA findings led to inter-agency discussions between the Corps, US Fish and Wildlife Service, and others that a more-natural river temperature may lead to sustainable native mussels in the Cumberland below Cordell Hull Dam. Reaching a river temperature of 20-22^{o}C (68-72^{o}F) in summer months appeared to trigger the reproductive cycle of some native mussels in the mainstem Cumberland River around Carthage. During the drawdown of Lake Cumberland for repairs at Wolf Creek Dam, native mussels appeared gravid and displayed in response to warmer conditions.   It is recognized that some mussel species (short-term brooders) may have more recovery potential than others (long-term brooders) due to the limited ability to restore more natural temperatures. It is also recognized that other factors such as fish hosts and altered sediment loads may limit mussel productivity. However, given the large percentage of flow coming from Wolf Creek Dam, increases in hydropower discharge temperature could be a critical improvement for the downstream river reach.

Section 2. Alternatives considered to improve DO levels. Several alternatives have been implemented by owners of reservoirs that produce hydropower. In this report, the Corps has attempted to screen through those technologies to focus and prioritize those that appear to show promise based on Wolf Creek Dam site conditions and improvement limitations of each technology. In follow-up evaluation, full review may identify other alternatives available but those discussed in this report have been used by others. Figure 4 is an illustration (from SEPA) of two technologies that are installed in or on a lake near the dam.

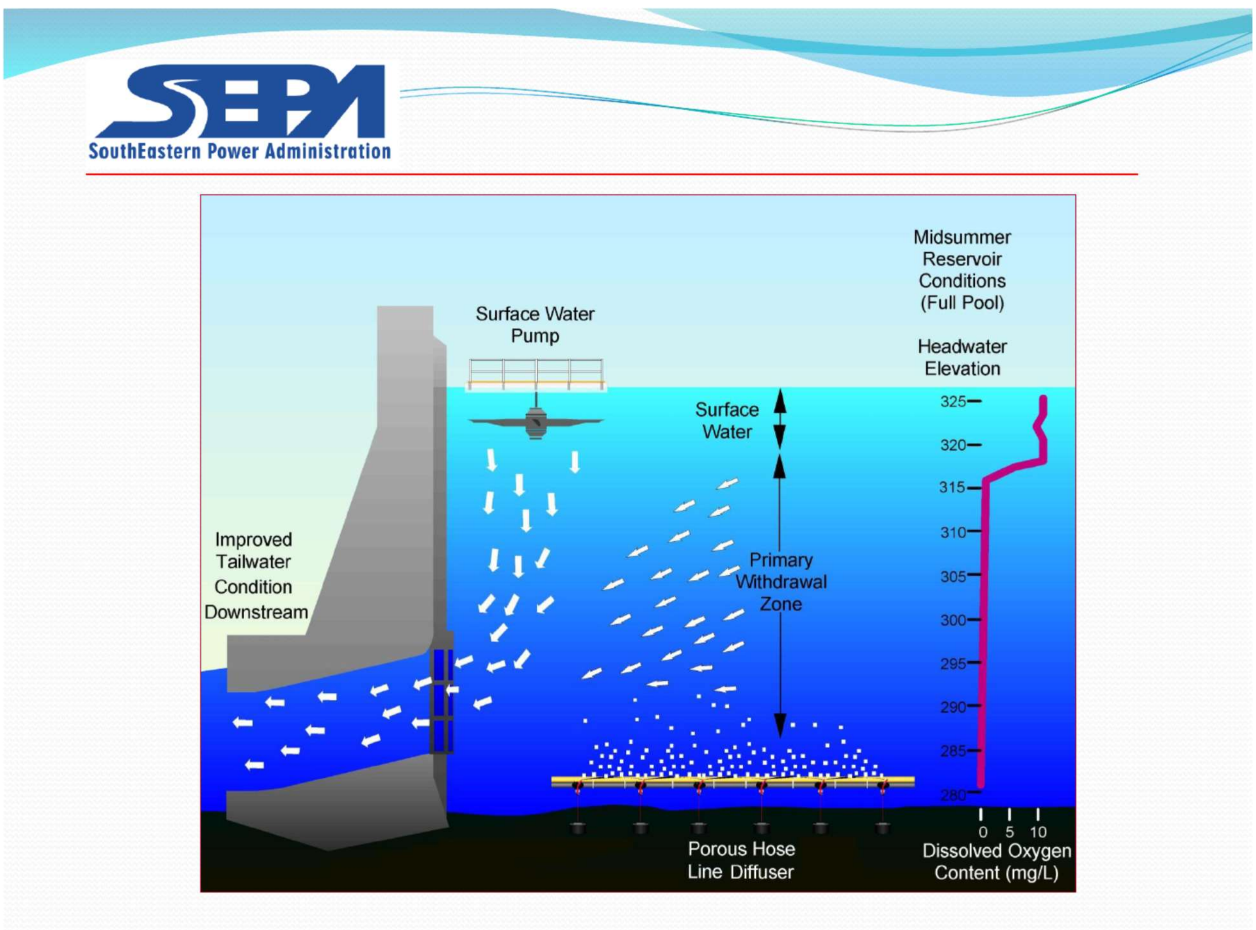


Figure 5 SEPA Dissolved Oxygen Improvements Presentation.

Section 2.1. Alternative 1 - No Action: Existing turbines (with hub baffles) and blending turbine and orifice and sluice gate discharges. This alternative would be continuation of the existing operations which involve a combination of hub baffles, sluice and orifice gate releases. To provide minimum oxygenated water flow below Wolf Creek Dam orifices gates were installed over two of the six sluice gates in 2007. With both orifice gates in place and the lake at normal pool levels, a discharge of approximately 540 cubic feet per second (cfs) is achieved. The remaining four unmodified sluice gates are available to release water which can be oxygenated due to turbulence, these are often used to meet the state DO requirement of 6.0 mg/l in the late summer and fall. Each sluice gate could discharge approximately 1600 cfs per sluice gate for a total of 6400 cfs.

Water released through orifice/sluice gates is cold, with DO levels as high as 10 mg/l, and mixes with water released through hydropower turbines having lower DO levels. This raises DO levels in the tailwater below Wolf Creek Dam once the two flows are mixed. This procedure has been used to reduce water quality impacts associated with DO since 2004 (EIS 2007).

Hub baffles were installed in the early 2000's to allow some air uptake while generating hydropower. Air intake lines were modified as well to increase air uptake (air drawn into the turbines). This improved DO levels in turbine releases to a limited degree, with a maximum improvement of 1.5 mg/l above baseline. To date, only WOL Units 1, 3 and 5 have hub baffles installed and this alone raises DO levels about 0.5-1.5 mg/l depending on the number of units in operation.

The effects of No Action, or continued operations, are the continued loss of hydropower revenues as a result of water being released from the lake without passing through the turbines. Seasonal releases by orifice and sluice gates typically are used from early August until mid-November when the DO recovers. Average annual costs were estimated to be $798K-$867K using applied energy prices from the local market using both the lowest and highest possible hourly price (source –HDC, Parrish). Temperatures in the Wolf Creek tailwater would follow current patterns, which generally range between 11° C and 16° C from early August to mid-November under normal pool operations.

Section 2.2. Alternative 2 - Installation of Auto-Venting Turbines (AVT). In the Corps' Hydropower Master Plan dated 2014, AVTs are scheduled for Units at Wolf Creek Dam for 2024. The installation of AVTs could be moved up in priority and installed sooner. Installation of AVTs would be expected to provide 1.5 to 3.0 mg/l improvement in DO levels of water exiting the turbines based on results seen at TVA and Corps plants. More detailed analyses to determine the uptake potential for Wolf Creek Dam, and additional computational fluid dynamics modelling is required to refine this estimate.

Recently, the Corps installed an AVT at Center Hill Dam but initial results have been hampered by lower lake levels. At Norris Dam, TVA has seen an improvement of 3.0 mg/l in DO from an AVT. The Corps has installed AVTs at J. Strom Thurmond Dam on the Savannah River. Shown below are two photos (Figure 5) of turbine releases at Thurmond Dam with (bottom photo) and without AVTs being utilized (SEPA, Hobbs). The entrainment of air is obvious in the photos. Dissolved oxygen improvement at J. Strom Thurmond ranges from 2-3 mg/l depending on the number of units in operation. Initial capital costs are high for AVTs but the plan would be to install AVTs as turbines are being replaced. The three Center Hill AVTs had a capital and design cost of $9.8M in 2014. Adjusted to 2017 dollars and doubling the number of the same-sized turbines being replaced is estimated at $20 M with a design life of 35 years.

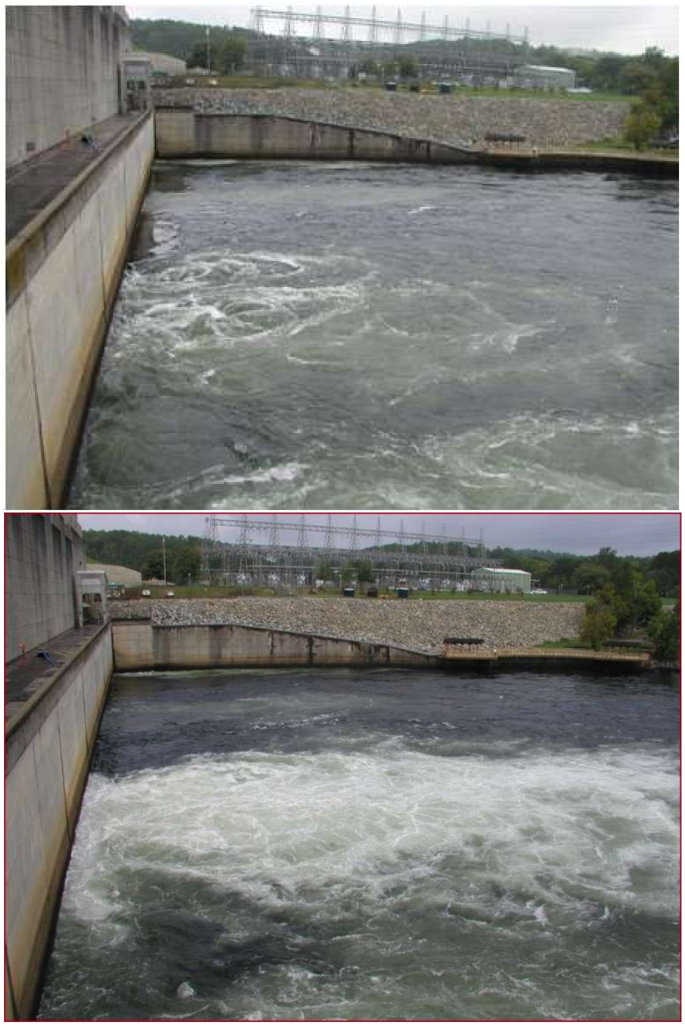


Figure 6 Photograph of J. Strom Thurmond Dam Turbine Discharge
With and Without AVT Operation (courtesy SEPA)

Section 2.3. Alternative 3 – Installation of Surface Water Pumps (mixers). TVA utilizes surface water pumps at Cherokee and Douglas Dams in east Tennessee. Cherokee and Douglas Dams are two tributary storage projects similar in operation to WOL, except their tailwaters are designated as warmwater aquatic habitats. Refer to Table 1 for a comparison of the three lake's characteristics. The surface water pump systems consist of multiple pumps with circulating impellers located on a floating structure on the face of the dam vertically above the penstocks (intakes to the hydropower turbines). The pumps are effective in mixing to the bottom of the lake as TVA adjusts the impeller speed to not disturb bottom sediments. Several photographs taken during a site visit by the Corps with TVA to Cherokee Dam are shown in Exhibit 1. Also included is a 2014 photograph showing an impeller from Douglas Dam. The pumps are used to move epilimnetic (surface) water that is warmer and higher in DO down into the withdrawal zone for the hydropower turbines. Pumps have been operational at Douglas and Cherokee Lakes since 1994 (Mobley, 1994). The pumps have been documented to increase DO in turbine discharge between 1.5-2.0 mg/l (Higgins, 1999). Electrical costs to operate the mixers were adsorbed by the Dam's powerplant but were estimated at $5,000 per month at local 1994 commercial rates (or $10.50 per hour). For comparison, the costs to achieve the same uptake using an oxygen diffuser system (described in Alternative 3) were estimated at $188 per hour (Mobley, 1994).

Table 1. Lake/Dam Characteristics

	Wolf Creek	Cherokee	Douglas
Drainage Area (sq.miles)	5,789	3,429	4,541
Average Flow (cfs)	9,160	4,591	6,957
Normal Pool Flux (ft)	28	28	44
Max Pool Flux (ft)	50	55	44?
Depth at Dam (ft)	200	175	140
Flood Storage Pool (ac-ft)	2,094,000	749,000	1,082,,000
Total Storage non-FC	2,142,000		
Turbines (Units/MW)	6/270 MW	4/148 MW	4/111 MW
Turbine Flow (cfs)	24,000	16,000	16,000
Summer Pool (ac-ft)	2,142,000	1,400,000	
Depth to Penstock	113'	110'	
Elev. of Penstock	610'		885'
Unit MW	45 MW each		

To develop a preliminary surface pump system for Wolf Creek Dam, the Corps pro-rated costs from TVA's Douglas Dam capital costs and capacity for the turbine flows at WOL. The Douglas Dam installation cost was estimated at $2.5 million in 1994 for nine pumps. Adjusting to turbine capacity at WOL, 14 pumps would be required at a cost of $3.8 million dollars (1994 dollars). Adjusting to 2017 dollars, the capital costs would be approximately $5 million dollars using an inflation factor (Source https://www.bls.gov/data/inflation_calculator.htm). Using TVA's estimated monthly electrical 1994 cost for Douglas Dam (see previous paragraph) and adjusting to 2017, 14 surface pumps would cost about $13,000 per month (2017). Assuming five months of operation (July-November), electrical costs would be about $65,000 each year plus any maintenance items for the pumps.

At Cherokee Dam, each mixer was estimated to increase DO by 0.25 mg/l when generating. When generating one unit, three mixers are turned on (approximate 0.75 mg/l increase), when generating two units, four mixers are operational (approximately 1.0 mg/l). The mixers are operational in the summer, when the reservoir is at full pool and fans are shut off in the winter, when the lake has dropped because the mixers can stir up sediment. However, the mixers have variable speed drives and can be adjusted to achieve a target depth to minimize stirring up sediment from the lake bottom.

Some maintenance issues with the mixers were noted, including a tendency for stainless steel aerator blades to separate from the motor unit and fall into the forebay. The blades are estimated to cost $60,000-$70,000 and a common life span for the blades is 10 years. TVA recently switched to fiberglass composite blades and the lighter blades lessen strain on the lock rings which hold impellers in place. Other than the engine clutch, the top bearing is the part in the engine most likely to fail, although the engines in place have lasted 12 years. TVA installed an oil-containment system around the engine shaft to help prevent oil from being released to the lake and a food-grade oil is used. The units have screens to keep debris out of the mixers. Standard maintenance of the units includes changing gear oil and grease every year, and the units are inspected monthly.

In a paper by Higgins and Brock in 1999, TVA provided an overview of reservoir release improvement equipment within the Tennessee River system, and discussed operational priority/order for dams that had multiple technologies. For Cherokee and Douglas Dams, the prioritized use order was first turbine venting, then surface pumps, topped off by hypolimnetic oxygen diffusers. This order was driven by O&M costs. Based on discussion during the Corps site visit with TVA at Cherokee, this priority is still being utilized. However, it is recognized that each site (dam) may have site-specific limitations to consider when determining prioritization.

At Wolf Creek Dam, two key local considerations related to the operation of surface mixers would be compliance with the cold water temperature water quality standard of 20^{o} C and potential influences on intake water temperatures to the Wolf Creek National Fish Hatchery. The hatchery requires cold water for the production of trout. One positive effect of surface mixers would be downstream Cumberland River system warming and benefits to native mussels below Cordell Dam approximately 150 miles downstream. This is discussed in more detail in Section 3 but in essence a more natural seasonal pattern (warmer water) would benefit reproduction of native mussels. A second benefit would be to prolong storage of cold water within Lake Cumberland by increasing withdrawal from the epilimnion. This could eliminate periodic die-offs of cool-water fish such as walleye and striped bass (rockfish) in the lake during early fall months. With surface mixer operation, the withdrawal zone would be increased to include the upper 25 feet of the epilimnion layer. Without mixers, the withdrawal zone utilizes little of epilimnetic water as described in the No Action Alternative. A balance would be sought where some marginal improvement to temperatures below Wolf Creek Dam would still meet the coldwater aquatic habitat standards while providing some regional benefit to critical downstream reaches of the Cumberland River. It may also have some locailized benefits to the lake and tailwater.

Section 2.4. Alternative 4 - Hypolimnetic Oxygen Diffuser System (TVA Design). Hypolimnetic oxygen diffusers have been implemented at many lakes within the TVA system and have been utilized by the Corps' South Atlantic Division on Savannah River projects. This design has been shown to be effective at raising DO levels in the hypolimnion layer. The Corps visited Cherokee Dam in 2017 to discuss this system with TVA staff. Several photographs from Cherokee Dam are included in Exhibit 1. The Cherokee Dam system consists of two liquid oxygen storage tanks located near the dam with a series of evaporators to convert the liquid oxygen to gaseous state, and a set of control values feeding multiple individual diffuser lines. Each diffuser segment consists of two separate lines. One line is weighted to suspend the oxygen feeder line near the lake bottom. Oxygen is released as fine bubbles by the porous hose second line located just above the weighted-line. These fine bubbles rise and most dissolve in the water. If the system malfunctions, larger bubbles are observed reaching the lake surface, an indication of inefficient oxygen transfer. If the system is working properly, only very fines bubbles are seen reaching the surface. A network of feeder lines extend across the lake bottom, some located in the immediate forebay of the dam for final dosing and others running up channel to provide an initial dose of DO in times of heavy demand. A key operational aspect of this design is the ability to float the diffuser lines to surface for maintenance by adding air to the weighted-line.

TVA determined the area of water that turbines pull from is large so they inject oxygen into a large footprint within the forebay. Liquid oxygen is held in two tanks (20,000 gallons and 21,000 gallons) on shore and supply the network of diffuser lines. At times of high use the tanks needed to be refilled with 9,800 gallons of liquid oxygen per day (two trucks/4,900 gallons each with daily cost of $6,400 per day). For Cherokee Dam, TVA estimated an annual cost of $300K-$370K per year for liquid oxygen.

The Corps' Savannah District has installed the TVA-type system at Richard B. Russell Dam and J. Strom Thurmond Dam on the Savannah River. At Russell, they replaced an earlier ceramic diffuser head system that experienced more maintenance (clogging) problems and required divers for maintenance. The new TVA design is dependable and oxygen costs at Richard B. Russell Dam are estimated at $500K per year. Routine O&M Costs are also estimated around $50K per year. A similar system at J. Strom Thurmond lake cost about $9 million in 2010, $3 million above ground and $6 million underwater. It is intended to both improve tailwater DO and also provide in-lake DO to maintain a Striped bass fishery so its capacity is greater than needed for just improving releases (Keith Crowe, USACE-SAS). Temperatures would not be expected to deviate substantially from current conditions since the systems don't effect thermal stratification and water would still be drawn from the hypolimnion.

The advantage of this system is its operational flexibility to meet seasonal increases in oxygen demand. It also provides a localized zone of the reservoir with improved DO levels for fisheries and can reduce hypolimnetic metal levels by maintaining some DO on the bottom sediments.

Disadvantages are O&M costs of the system, including costs of liquid oxygen and system maintenance. At Cherokee Dam, during peak demand periods, multiple trucks deliver liquid oxygen each day using a dedicated, locked delivery access to independently provide oxygen.

Various costs information was estimated to develop an annualized costs for the hypolimnetic oxygen system (summarized later in Table 2). In order to develop an estimated cost of installing a hypolimnetic oxygen system for Wolf Creek Dam, costs from the Cherokee Dam system were prorated to Wolf Creek Dam flows. Cherokee Dam has an 80 ton per day system that was installed for $0.6 million (M) in (1997 dollars). Based on flows at Wolf Creek Dam, a 120 ton per day system would have a capital costs of $2.5M (2017). Oxygen supply costs from Cherokee (16,000 cfs turbine flow- $0.37M per year) were increased by 33% for Wolf Creek turbine flow (24,000 cfs – 0.56M). Other operational costs were estimated including routine O&M ($0.05M/yr) and electrical power costs based on a rate of $188 per hour (1997-Mobley, Douglas Dam), adjusting for five months of operation at Wolf Creek Dam to $1.24M each year. Design life of the system was estimated at 20 years to develop an annualized cost of $2.043.

Section 2.5 Alternative 5 - Inverted Cone (Speece Cone) – Another variation of hypolimnetic oxygenation is by pumping pure oxygen into an inverted cone located on the lake's bottom, then distributing this high oxygen water across the forebay. This system is called an Inverted Cone or Speece Cone. In the mid-1990's, Dr. Richard Speece developed a proposed system for J. Percy Priest Reservoir near Nashville. The intent was to improve oxygen in the hypolimnion of the lake for both hydropower generation during the summer and to improve hypolimnetic water quality and aquatic habitat. While it was not justifiable at J. Percy Priest due to the project's limited hydropower production in summer months, this type of system has been recently installed for the Savannah River Harbor Project in Savannah, Georgia. It is intended to mitigate negative effects of deepening the harbor. It was not considered in detail in this reconnaissance due to the proven operation of the previously discussed alternative.

Section 3. Future (Post-Reconnaissance) Evaluations. Prior to deciding on which type of technology is best for WOL, additional design would be required to inform a final selection and the Corps would be required to document compliance with the National Environmental Policy Act (NEPA). Compliance with NEPA allows public and agency review of proposed plans and an evaluation of alternatives considered and related effects on local resources and water uses. This decision is anticipated to require an Environmental Assessment (EA) which would lead either to a signing of a Finding of No Significant Impact (FONSI) or a decision that an Environmental Impact Statement (EIS) is required.

Factors to be evaluated in more detail for Alternative 2 (Surface Mixers) include impacts on tailwater fisheries. A key point would be what degree of warming of the tailwater would be acceptable without detrimental impacts on popular cold-water fisheries. During the recent Wolf Creek Dam repairs, the tailwater warmed drastically due the lake being held at a lower pool level (of 681') which reduced normal hydropower generation. Studies by Kentucky Department of Fish and Wildlife Resources (KDFWR) during the period of lower lake levels showed reduced growth of trout and reductions in the length of Cumberland River suitable for cold-water fisheries with loss of trout over the lower half of the KY tailwater (Burkesville to KY-TN line). With operation of surface mixers, an acceptable maximum turbine discharge temperature could be sought to see if detrimental effects occur or if increased release of more water from the epilimnion (surface water) could possible stimulate more productivity in the tailwater (from increased river temperatures and algae). This could stimulate a more productive aquatic community.

Another consideration for surface mixers would be avoiding impacts to the Wolf Creek National Fish Hatchery which currently draws water from a multi-level intake in the lake. One possible solution would be extending the lowest intake horizontally to pull water from upstream of the zone of influence of the surface pumps. One benefit to the Hatchery may be availability of cold water later in the year in the lake with the release of a higher percentage of epilimnetic (surface) water with pumps operating.

Increasing temperature of turbine releases at WOL could serve some restorative function for native aquatic life in parts of the mainstem Cumberland River System, including positive effects on federally-listed, native mussel species. This is discussed in more detail in Section 3 of this document.

Increased water temperatures in the mainstem Cumberland could also affect cooling water for the TVA Gallatin Fossil Plant at CRM 244 which uses river water as once-through cooling water. TVA's Gallatin Fossil Plant lacks cooling towers and is dependent on cooler river water for its operations. If intake water temperatures reach certain trigger levels, coal-fired power production has to be reduced in order to meet NPDES permit limits for water temperature.

Programmatic Biological Assessment (PBA) on Non-Navigation Operation and Maintenance (O&M) (for endangered mussels below Cordell Hull Dam). The Corps is preparing a PBA to evaluate O&M activities unrelated to navigation. While most Corps dams were built prior to the Endangered Species Act (ESA), any changes to operation, including hydropower upgrades, are subject to ESA review. In addition, ESA Section 7(a)(1) instructs Federal agencies to be pro-active in minimizing effects of its projects on species protected under the ESA. A key consideration in the above PBA is depressed water temperatures prohibiting natural reproduction of native mussels in the mainstem Cumberland. While other factors also play a role, including changes in fish communities, mussel food (algae) availability, and sediment alterations, temperature has been attributed to a declining and aging mussel community. Any alternatives proposing to change water temperatures would require careful balancing of effects on other considerations such as coldwater reaches (Cumberland tailwater from Wolf Creek Dam to the Kentucky-Tennessee state line) and Caney Fork River Center Hill Dam tailwater.

Section 4. Conclusions and Future Follow-up. This reconnaissance-level evaluation examined technologies that are under consideration for improving DO levels in hydropower releases at Wolf Creek Dam. While it is not all inclusive, proven technologies that are being utilized in similar reservoirs were considered. Advantages and disadvantages of each system were briefly discussed and need to be flushed out in additional detail. Based on the comparison, a combination of No Action (Hub Baffles) or Auto Venting Turbines plus installation of Surface Pumps appears to offer the greatest average annual benefit. Average annual benefit is defined as the recovered cost to hydropower due to sluicing minus the average annual cost of the applied technology. While this technology appears best from a capital cost/generation benefit perspective, environmental and system impacts must be considered in further depth as designs are developed. A multi-discipline team should be assembled to conduct additional design and evaluation before implementing the tentatively-recommended alternative. NEPA compliance would follow, including considering views of agencies, water users, and the general public, before implementation of a technology at Wolf Creek Dam. Table 2 summarizes cost and future anticipated level of National Environmental Policy Act (NEPA) evaluation required for each technology. This paper has tried to emphasize the importance of the system of Corps reservoirs on many users of the Cumberland River Basin. This evaluation was initiated by the interest of Hydropower Stakeholders who share water use in the basin. Future efforts under the Section 212 Hydropower Rehabilitation Program would require approval of a ballot or sub-agreement detailing the scope of work, budget and preliminary schedule to complete NEPA analyses, documentation and coordination and project design. Team Cumberland members have suggested the potential to use remaining uncommitted funds in the Legacy MOA to support design and installation of dissolved oxygen remediation measures at Wolf Creek Dam. The Corps and external stakeholders should also discuss a long-term strategy for funding any additional Operations and Maintenance (O&M) costs above current levels given the challenges of increasing the appropriated O&M budget.

Table 2
Cost and Review Summary

Technology (Design Life years)	Estimated Capital Cost ($Million)	Estimated Average Annual O&M Cost	Estimated Total Annual Cost	NEPA Required EA/EIS
No Action	$ 0	$minimal	$0.87M	none
Auto-Venting Turbine (35)	$20M	$minimal	$0.909M	EA
Surface Pumps (20)	$5M	$.09M	$0.425M	EA/EIS
Oxygen Diffusers (20)	$2.5M (120 tons/day)	$.37M	$2.043M	EA
Average Annual Cost to Hydro Due to Sluicing for D.O.				$.8M-.87M

List of References

1. HDC-Parrish
2. CEQUAL-W2 Report, 1996
3. Mobley paper
4. Higgins and Brock Paper
5. Orangefooted Pimpleback and Catspaw Survey, Tennessee and Cumberland Rivers, Tennessee; For Kentucky Waterways TWRA Project 7367; Don Hubbs, Mollusk Recovery Coordinator Study Period May 2011-November 2012.

List of Figures