RECLAMATION

Managing Water in the West

Top-Down Water Storage Mixing Systems Scoping Report

Research and Development Office
Science and Technology Program
Final Report No. ST-2016-6415-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Acronyms and Abbreviations

ac-ft	acre-feet
AMSL	above mean sea level
BOD	biological oxygen demand
cfs	cubic feet per second
COD	chemical oxygen demand
DDP	down draft pumps
DO	dissolved oxygen
ECAO	Reclamation’s Eastern Colorado Area Office
ft	feet
hp	horse power, 1 hp =746 Watts
kW	kilo Watt
mg/L	milligrams per liter
ppm	parts per million
TVA	Tennessee Valley Authority
WEARS	WEARS Australia ResMix™ manufacturer

Executive Summary

A review of top-down mixers are presented in this report. The review includes a survey of current literature regarding top-down mixer systems, and includes a review of relevant commercial systems from selected operational settings.

Top-down mixers are used to move oxygenated water from surface layers to depths to improve water quality of releases. As an example, increasing release of dissolved oxygen (DO) concentrations at a mid- or lower-level dam outlet could be a typical application for a top-down mixer. Furthermore, top-down mixers can transport algae out of the photosynthetic zone in a localized intake area thereby reducing algal production. Such reductions in algal production can help address taste and odor problems of intake water.

Finally, the literature review identifies the advantages and limitations of this technology with an objective to guide evaluation of top-down mixer systems to address water quality related issues in Reclamation facilities, and in particular, its applicability to Grand Lake clarity.

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1. Introduction

Top-down mixing systems were developed primarily to mix oxygen-rich surface waters with deeper oxygen-poor waters to increase dissolved oxygen (DO) concentrations of water releases. Quintero and Garton (1973), Dortch and Wilhelms, (1978), Holland (1983), Mobley et al. (1995), among others, provide descriptions of developments and applications of the top-down mixing systems in a range of reservoir settings to address water quality related issues. Wagner (2015) provides a synthesis of oxygenation and circulation techniques along with an evaluation of these techniques for use in reservoir water quality management.

The report is structured as follows. First, a review from literature broadly describing the top-down mixing technology along with its application and findings is presented. This also includes a brief reference to contemporary commercial systems from selected operational settings. Finally, a summary of the advantages and limitations of this technology is presented for consideration to address water quality related issues. This literature review was performed at the request of Reclamation’s Eastern Colorado Area Office (ECAO) to take an objective look at the technology itself, and at the same time, identify whether or not it may address site specific issues associated with Grand Lake (located in Grand County, Colorado) clarity (based largely on Secchi depth measurements).

2. Literature Review

Quintero and Garton (1973) describe top-down mixing systems or downward surface pumps as a destratification technique. Garton and Jarrell (1976) demonstrated water quality enhancement through the use of top-down mixing system. The top-down mixers or downward surface pumps or down draft pumps (DDP) are also commonly referred to as Garton pumps. These pump terminologies are used interchangeably in this report.

Dortch and Wilhelms (1978) describe the effectiveness of localized mixing (Figure 1) for enhancing the quality of low-level low-flow releases from a stratified impoundment using a Garton pump at Corps of Engineers Okatibbee Lake, Mississippi. Lake Okatibbee is shallow with a maximum depth of about 33 feet (ft). The surface area is approximately 3,800 acre at elevation of about 343 ft above mean sea level (AMSL; normal summer pool) and the corresponding storage capacity is about 42,157 acre-feet (ac-ft).

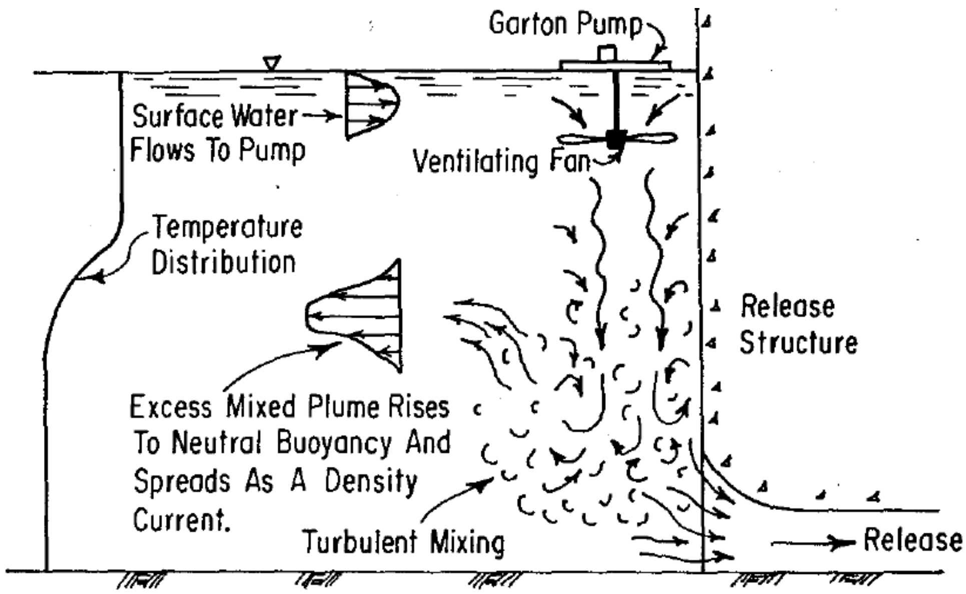

Figure 1. Localized mixing (after Dortsch and Wilhelms, 1978).

It was found that the dissolved oxygen of the release water was increased by causing epilimnetic water being forced toward the lake bottom where it was mixed with hypolimnetic water and then released through the fixed low-level flood control outlet. The quality of this water mixture was an improvement over the quality of the water released without the pump operating in terms of increased dissolved oxygen concentration and increased water temperature. It was also estimated that the epilimnetic water comprised about 50 percent of the total release in this case. These results demonstrate that the use of a Garton pump to induce localized mixing upstream of a fixed low-level flood control outlet was effective in improving the quality of low-flow releases from a stratified reservoir by increasing release dissolved oxygen (DO) concentrations. The installed Garton pump, consisted of a 6 ft diameter ventilating fan suspended about 3.3 ft below the water surface by a 6.6 ft square raft. The fan was driven by a 1.12-kW (kilo Watt) electric motor at a design speed of 17 rpm. The pumping rate at this speed was approximately 60 cubic feet per second (cfs).

Holland (1983) developed a procedure based on laboratory tests to develop an initial design for a localized mixing system. According to Holland (1983), localized mixing is often a viable method of enhancing the water quality of releases from low-level hypolimnetic outlets, and points out that two conditions are necessary for successful localized mixing. These two conditions are: (1) the epilimnetic jet as measured from the thermocline down into the hypolimnion must penetrate to the outlet or well within the withdrawal zone; and (2) the epilimnetic jet must provide sufficient volume of epilimnetic water to effectively dilute the hypolimnetic release component to enhance the total quality of the releases.

Mobley et al. (1995) describes the development, installation, and performance testing of a large surface water pump system (9 total; Figure 2) at Tennessee Valley Authority's (TVA's) Douglas Dam for large flow releases (16,000 cfs total plant flow rate) through this hydropower facility. The reservoir capacity at elevation 1,002 ft above mean sea level (AMSL; top of gates) is nearly 1.47 million acre-ft and is about 150 ft deep near the dam at summer pool levels. The water releases from this dam show extended periods of low DO content during the summer months due to thermal stratification, biological oxygen demand (BOD), and chemical oxygen demand (COD) in the reservoir. Periods of less than 0.5 mg/L of DO have historically averaged more than 30 days per year.

Multiple large surface water pumps about 15 ft in diameter were designed to move large flow rates of 530 cfs of highly oxygenated surface water down to a level where it is withdrawn through the hydropower intakes to improve the water quality of hydropower releases. Under average conditions, the system demonstrated a capability to increase the dissolved oxygen content of the hydropower discharge to 2.0 mg/L. Installation and operating costs of the pumps were also presented by Mobley et al., (1995) along with a discussion of experience with equipment, floatation, and mooring design.

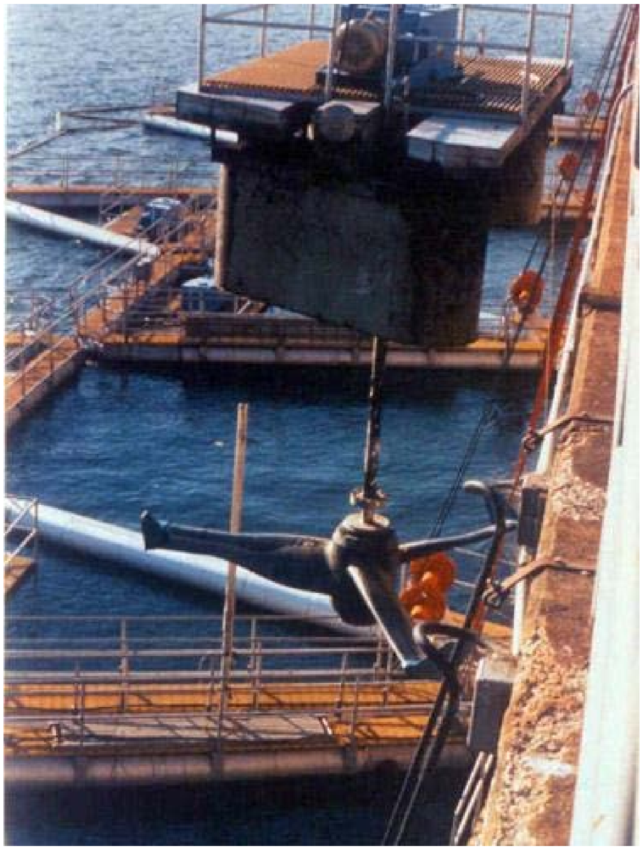

Figure 2. Large surface water pump being installed (credit to Mobley Engineering, Inc.)

Wagner (2015) provides a comprehensive review of oxygenation and circulation techniques in the context of reservoir water quality management. Wagner (2015) summarizes that available equipment and approaches can be divided into four forms of oxygenation and three forms of circulation systems. This publication presents findings from seventy case studies itemizing lessons learned from the cases along with available literature. Out of the seventy case studies, nine case studies used the top-down mixer (DDP) as the circulation system. The nine case studies are labeled by Wagner (2015) as OC-63 through OC-70 and, OC-09, where the DDP is a component of the multi-element oxygenation system for the studied reservoir. A summary of the salient points from these nine case studies are presented here following Wagner (2015).

Each case study summary includes, a brief background of the reservoir system, the water quality concerns and issues in the specific reservoir, a description of the top-down mixer (i.e. DDP) system used along with its application, followed by a general presentation of results, and finally a listing of key findings.

Case Study OC-63

Background

- Australian drinking water supply reservoir first filled in the late 1960s and used for offline storage.
- Approximately 64 acres in size with an average depth of 29 feet (approximate volume, 1,850 ac-ft), and a maximum depth of 53 feet.
- Reservoir has one major input consisting of water pumped from an adjacent river and three minor tributaries.
- Watershed consists of a mix of natural (60%), developed (25%) and agricultural (15%) uses.
- Sedimentary geology overlain by soils of limited permeability.

Water Quality Concerns/Issues

- Reservoir thermally stratified and anoxia occurred below 17 feet.
- Cyanobacteria and associated taste and odor, toxicity, and filter clogging concerns.
- Treatment issues include reduced substances such as iron, manganese and hydrogen sulfide.

System Description and Application

- DDP circulation system installed with an objective to minimize water quality problems and issues, and maintain uniform water quality conditions.
- DDP consists of a flexible vertical tube with a diameter of 13.2 ft and desired length with an electric powered impeller that forces surface water to the bottom of the reservoir.

- DDP unit capacity, about 35,600 gallons per minute or about 157 ac-ft per day.
- Target reservoir volume of water (~1,850 ac-ft) is moved about once every about 12 days, or at a rate of 8.5% per day.
- Operates 24 hours per day all year to ensure homogenized conditions.

Results

- DDP operated for 9 years with moderately successful results.
- Minimum oxygen of 4 mg/L maintained and relatively uniform conditions reported at most depths.
- Deflector plate was added to the bottom of the draft tube to direct flow laterally and avoid resuspension of sediment at high pumping volumes.
- Mixing has limited blooms of cyanobacteria to <2000 cells/mL and provided enough oxygen to deep water to lower the concentrations of reduced substances
- The system did not eliminate the need for better treatment.
- Water quality issues remained requiring construction of a new water treatment facility.

Findings

- DDP mixing system lowered the levels of cyanobacteria, iron, manganese and hydrogen sulfide while providing water of a relatively uniform quality for further treatment.
- Need to plan for excess capacity was stressed, especially for shallow systems and where the reservoir is not bowl shaped, as mixing efficiency decreases and results will not be as uniform for that case.

<u>Case Study OC-64</u>

Background

- Australian reservoir first filled in 1983.

- Approximately 550 acres in size with an average depth of 25 feet (approximate volume, 13,000 ac-ft), and a maximum depth of about 112 feet.

- Watershed (15,000 acre) drained by one major tributary.

- Water supply intake is located downstream of the reservoir dam.

- Land use is dominated by natural uses with mixed vegetation.

- Igneous geology is overlain by limited permeability silty loam type soils.

Water Quality Concerns/Issues

- Reservoir thermally stratifies at about 20 feet in depth and anoxia occurs in deeper water.

- Low dissolved oxygen in deeper waters during periods of stratification lead to release of iron, manganese and phosphorus from the sediment.

- Drinking water concerns - cyanobacteria blooms are common with associated taste and odor as well as possible toxicity.

System Description and Application

- DDP circulation system installed near the dam and discharge with the intent of mixing reservoir prior to discharge and subsequent downstream intake for water supply.

- DDP consists of a flexible draft tube of adjustable length with a diameter of about 16.5 ft on a flotation structure with an electric powered impeller that forces surface water down the tube.

- DDP unit capacity, about 58,000 gallons per minute or about 256 ac-ft per day.

- Target reservoir volume of water (~13,000 ac-ft) is moved about once every 50 days, or at a rate of 2% per day.

- Single unit not intended to mix the entire reservoir. Rather, a target zone area of nearly 50 acres (about 10% of the reservoir area) with an average depth of 80 ft would be mixed prior to discharge; this could be done in just over 15 days, at a rate of 6.4% per day.

- System operates 24 hours per day all year long.

Results

- DDP has been in operation for 11 years with partial success, and continues to operate.

- Unit does not pump enough water to effectively mix the reservoir or even in the estimated smaller target zone.

- Even with one operating unit, temperature much more uniform over depth, some improvement in deep water dissolved oxygen, and downstream iron and manganese levels, the frequency and severity of cyanobacteria blooms has declined, but a major cyanobacteria bloom was publicized in 2011.

- More units recommended and would presumably allow effective mixing. However, given the elongated and dendritic shape of the reservoir, water quality problems arising in unmixed areas cannot be completely solved by mixing in a smaller target zone near the discharge area.

- Flashy nature of runoff in the watershed leads to flooding and flushing in the reservoir beyond what the DDP system can address.

Findings

- DDP system is an aid to water quality management but of inadequate capacity here (early application of DDP system) to improve discharge water quality to the desired extent.

- Problems relating to watershed inputs (flashy nature of runoff and watershed flooding) and water movement through the reservoir (elongated and dendritic shape) call for additional DDP units to be effective, but some problems (e.g., reservoir flushing) may not be readily amenable to solution by circulation.

Case Study OC-65

Background

- Australian water supply reservoir first filled in 1941.
- Approximately 750 acres in size with an average depth of 25 feet (approximate volume, 19,000 ac-ft), and a maximum depth of 76 feet.
- Watershed (40,000 acres) drained by one major tributary and one minor tributary.
- Land use is dominated by livestock grazing with vegetation consisting mainly of shrubs and grasslands.
- Igneous geology is overlain by limited permeability silty loam type soils.

Water Quality Concerns/Issues

- Reservoir thermally stratified at about 15 feet and anoxia occurred below this depth.
- Cyanobacteria blooms are the major concern for this reservoir including elevated concentrations of iron and manganese from low dissolved and deep water oxygen.
- Drinking water concerns include taste and odor as well as possible presence of algal toxins.

System Description and Application

- DDP circulation system installed with the goal of increasing dissolved oxygen to greater than 4 ppm and controlling algae through mixing.
- DDP system consists of a pair of DDP circulation units moored side by side near the center of the reservoir. Each unit has a floating electrically operated axial flow surface impeller and flexible draft tube running from the surface to near the bottom of the reservoir in the deep area.

- Each DDP unit capacity, about 80,000 gallons per minute or about 350 ac-ft per day. With two units running all the time, up to about 700 ac-ft can be moved per day.

- Outside of summer time lower pumping rates of often around 58,000 gallons per minute are used (~256 ac-ft/day) for each unit.

- Target zone is about 75 acres (about 10% of the reservoir area) along the side arm of the reservoir where the raw water intake is located, and encompasses about 4,000 ac-ft of water. The two DDP units would be expected to move this volume once every about 8 days, a rate of nearly 12.8% per day (assuming the low end of normal pumping rate, i.e. about 2 x 256 = 512 ac-ft/day). At peak operation, the rate of movement would be 17.5% per day.

Results

- The DDP system has been in service for 11 years and have generally been considered successful.

- Limited anoxia has been reported, and minimum oxygen levels are usually >2 mg/L. Cyanobacteria abundance has been reduced but algae still abundant at times. Concerns about, taste, odor and possible toxicity have been minimized.

- Variability in weather patterns is likely to have an impact on DDP circulation system results. For example, periods of hot, sunny weather may overwhelm system capacity to maintain mixed conditions.

- Water quality problems from other parts of the reservoir could impact the target zone during periods of higher flow or greater withdrawal; algae and manganese flowing from other parts of the reservoir would not likely be eliminated before the intake was reached.

Findings

- Greatest benefit expected in summer, when stratification might otherwise occur. For example, temperature differences from top to bottom were rarely >3°C in summer of 2001, but exceeded that level much of summer of 2002.

- Oxygen in 2001 exceeded 2 mg/L almost all of the time even in the deepest water, while in 2002 anoxia was observed in the bottom 10 feet of water much of the time. The DDP system was adequate to maintain oxygen through summer of 2001 in even the deepest water.

- The value of circulation to warm water fish habitat was also noted. Conditions in the reservoir within the target zone of the DDP system were improved enough to facilitate more fish stocking and more satisfying fishing was reported as well.

Case Study OC-66

Background

- Australian water supply reservoir was constructed in 1912 with volume increased in 1951, and currently being enlarged again.

- For the period of analysis, the reservoir is about 110 acres in size with an average depth of 29 feet, and a maximum depth of 80 feet.

- Watershed (120,000 acre) is drained by one major tributary.

- Vegetation is mixed but is mostly shrubs and grassland.

- Dominant geologic setting is igneous rocks with a highly variable soil distribution.

Water Quality Concerns/Issues

- Reservoir thermally stratified at about 15 feet and experienced anoxia below this depth.

- Cyanobacteria blooms and elevated levels of iron and manganese from low dissolved and deep water oxygen.

- Drinking water concerns include taste, odor and color as well as possible presence of algal toxins.

System Description and Application

- DDP circulation system installed to mix water to below the depth of intake, but not necessarily to keep the entire water column mixed.

- DDP unit consists of a flotation platform supporting a solar powered electric motor that turns an impeller that forces surface water down a flexible draft tube of 13.5 feet diameter with a discharge point at 33 feet depth.

- DDP unit capacity, about 48,000 gallons per minute or about 210 ac-ft per day.

- Target area was about 80 acres with a volume of about 2,070 ac-ft moved about once every 10 days, or at a rate of 10% per day.

- System operated continuously all year.

Results

The results listed below are for the primary reservoir described above and operated by the utility.

- DDP system did not de-stratify the reservoir, but rather, created a deeper and very stable upper layer, minimizing influence from the lower layer until fall turnover.

- Within the target volume (area, ~80 acres; average depth, ~26 feet; volume, ~2,070 ac-ft) oxygen increased by 20 to 45%, turbidity and color levels decreased by 60 to 80%, and iron and manganese concentrations decreased by 60 to 90%. Noticeable decrease in cyanobacteria was also cited.

- Water deeper than the lowest used intake formed a separate layer and declined in quality. This was a brief problem for the supply due to turnover, but by moving oxygen rich surface water downward, risks of moving oxygen poor bottom water with associated water quality problems upward were minimized.

- DDP system aided natural stratification processes to create a deeper and more stable upper layer with better water quality as a result of continuous operation of the system.

In a separate reservoir operated by this utility, a larger DDP circulator system was unable to alter the frequency or severity of cyanobacteria blooms over a 10 year period of operation. Problems preventing effective operation such as system undersize or other factors is unknown. In recent years, alteration to partial mixing from the top down is reported to have improved results.

Findings

- DDP circulation system was used to create a deeper and more stable upper water layer than would have occurred otherwise, improving the quality of water used for drinking supply.

- Quality of deep water declined during stratification, but that water did not substantially interact with the water used for supply during the period of stratification.

- Additional DDP units in conjunction with more power might have allowed complete mixing of the reservoir, but the current system was deemed sufficient to meet water quality goals.

Case Study OC-67

Background

- Water supply reservoir located in Illinois was first filled in 1942.

- Approximately 36 acres in size with an average depth of 6 feet (approximate volume, 227 ac-ft), and a maximum depth of 18 feet.

- Watershed (1,700 acre) is drained by one major and two minor tributaries.

- Land use is dominated by agricultural uses, specifically crops.

- Sedimentary geology is overlain by moderately permeable sandy loam soils.

Water Quality Concerns/Issues

- Reservoir intermittently experiences thermal stratification at about 12 feet and anoxia can occur as shallow as 6.3 feet, indicating a very strong oxygen demand.

- Cyanobacteria blooms and elevated levels of manganese and iron from low oxygen levels.

- Drinking water concerns also included disinfection by-product precursors and taste and odor at the intakes.

System Description and Application

- Custom made mechanical circulation system was installed in the reservoir with the goal of increasing oxygen in the deeper reservoir waters to reduce the release of iron and manganese levels and the frequency and severity of cyanobacteria blooms.

- Custom made system is made of a 1.5 hp (horse power) engine mounted horizontally on 90 degree gear reduction box (50:1) with six variable angle (14-30 degrees) blades on a vertical shaft. It can either push water down or pull water up, but was mostly used as a downdraft pump (DDP) system.

- Unit was positioned in a small, deep portion of the reservoir, but the target was the whole reservoir volume of 227 ac-ft.

- System operated from the time when stratification would be expected to start in the spring to the time when it would be expected to break down in the autumn. Also, as a 1980s operation, most aspects functioned by trial-and-error for its 7 years of operation.

Results

- Stated goals of oxygen >2 mg/L at the bottom and >4 mg/L as a water column average were mostly achieved; occasionally oxygen dipped below 2 mg/L near the bottom, but anoxic conditions were rare and iron and manganese were reduced by >95%.

- Cyanobacteria blooms were reduced in frequency and severity, but algae levels required copper treatment in multiple years. However, intense blooms of green algae occurred in one year, and turbidity varied considerably over time, but cyanobacteria were substantially decreased.

- With system adjustment, copper use declined, and the operation was considered successful in all 7 years. Particularly, the homogenization of water quality was cited as an advantage for water supply treatment.

Findings

- Reduction in iron and manganese was the major benefit of the circulation system.

- Given this early system, control of cyanobacteria was not complete, and inter annual variability represented operational challenges but improved performance was noted.

- Project suggests that copper or other algaecides may be necessary to back up circulations systems.

- Increased capacity to maximize performance during warm summers is advised; any period of low DO will result in a rapid decline of water quality, and it is essential to prevent anoxia to achieve maximum success.

<u>Case Study OC-68</u>

Background

- Australian drinking water reservoir first filled in 1942.

- Approximately 617 acres in size with an average depth of 40 feet (approximate volume, 24,680 ac-ft), and a maximum depth of 138 feet.

- Watershed (27,000 acres) is drained by one major and four minor tributaries.

- Vegetation consists of shrubs and grassland close to the reservoir and mostly eucalyptus groves farther away.

- Land use is largely natural eucalyptus forests and includes cattle grazing lands.

- Igneous geologic setting overlain by limited permeability silty loam soils.

Water Quality Concerns/Issues

- The reservoir is thermally stratified and experienced anoxia below 18 feet.
- Cyanobacteria and elevated manganese and iron levels linked to low dissolved oxygen concentrations that allow metals and nutrients to be released from sediments.
- Drinking water concerns also include taste and odor as well as possible presence of algal toxins.
- Variability of conditions is an impediment to consistent water treatment.

System Description and Application

- Adjacent installation of two DDP units in October of 2001 (start of Australian summer season).
- Each DDP unit includes a flotation platform supporting a flexible draft tube of almost 17 feet diameter and an electrical motor that turns an impeller to pump water down. The pumped water is released at depths >50 feet.
- Each DDP unit capacity, about 80,000 gallons per minute or about 350 ac-ft per day. With two units running, up to about 700 ac-ft can be moved per day.
- Target zone is nearly 150 acres, about 25% of the reservoir area that is located in the downstream dendritic section of the reservoir which is also the reservoir's deepest part and results in a target volume of about 6,113 ac-ft.
- Target reservoir volume of water (~6,113 ac-ft) is moved about once every 9 days, or at a rate of nearly 11% per day during summertime peak operations of both the units. Rate can be scaled back over the winter, when less energy is required to mix the target volume of the reservoir.

Results

- The DDP system has operated nearly continuously for over 12 years and its operation is ongoing, and have generally been considered successful.

- The DDP circulation system can maintain completely mixed conditions from top to bottom during fall, winter and spring, but only reduces the vertical thermal gradient and anoxia during summer.

- Operated from before stratification commencement, the system is reported to be able to minimize the thermal gradient from top to bottom and prevent anoxia except during periods of extreme weather. Even after stratification had already begun in 2001 and oxygen was depressed in water <50 feet deep, the DDP system gradually mixed the water column to a depth of about 80 ft and raised oxygen to near 4 mg/L in water <50 feet deep.

- Iron and manganese were reported to have been greatly reduced and all intake depths produced water of acceptable and consistent quality.

- Circulation expanded and improved fish habitat.

- Mixing had variable impact on algae composition and levels.

- Potentially toxic cyanobacteria were kept below alert levels most of the time, but algae levels were not always low.

- Variability in weather in particular droughts and floods was considered a confounding influence, especially since the DDP system only influenced a portion (about 25%) of the whole reservoir.

Findings

- Homogenization of water quality in the vicinity of the intake through mixing of the water column in a large enough area and volume of the reservoir.

Case Study OC-69

Background

- Australian drinking water reservoir first filled in 1962.
- Approximately 325 acres in size with an average depth of 44 feet (approximate volume, 14,300 ac-ft), and a maximum depth of about 82 feet.
- Watershed (44,000 acre) has one major and one minor tributary.
- Land use is dominated by natural uses (90%) with grassland as the main vegetation.
- Sedimentary geology is overlain by soils of moderately permeable sandy loams.

Water Quality Concerns/Issues

- Reservoir thermally stratifies below 26 feet and could go anoxic below about 33 feet.
- Primary water quality concerns include cyanobacteria blooms and accumulation of reduced compounds, especially manganese, in deeper water with low DO levels.
- Associated issues also include taste and odor as well as possible toxicity.
- Flooding is also a problem at this reservoir.

System Description and Application

- DDP system installed near the center of the reservoir (midpoint based on volume).
- DDP consists of a pontoon mounted platform supporting an electric motor that powers an impeller that forces surface water down a nearly 17 foot diameter flexible draft tube to a depth of about 50 feet.

- The DDP unit can pump up to 80,000 gallons per minute or about 350 ac-ft per day.

- Target reservoir volume of water (~7,040 ac-ft) which is nearly half of the reservoir volume is moved about once every 20 days, or at a rate of 5% per day.

- System operates at all times unless under repair or power supply is interrupted.

Results

- DDP has been in operation for 10 years, and continues to operate.

- Improved water quality has been obtained in terms of the goal to increase oxygen to at least 2 mg/L everywhere in the reservoir.

- Toxin forming cyanobacteria has not been reported and DO goals were achieved. However, elevated manganese in surface waters at times was reported.

- No obvious algal blooms identified from aerial images over the last decade but flooding issues have been noted and the water is murky at times likely due to suspended sediments.

Findings

- Although water quality is not optimal at all times, the mixing function of the DDP unit helps homogenize water entering the intake, and consistency of water quality is valued in treatment.

- Mixing after a period of stagnation may cause temporary increases in undesirable substances such as manganese, and operator experience was noted as important to optimal operation of the DDP system.

<u>Case Study OC-70</u>

Background

- Australian drinking water reservoir.

- Approximately 47 acres in size with an average depth of 19 feet (approximate volume, 900 ac-ft), and a maximum depth of about 46 feet.
- Watershed (5,000 acre) is drained by one major tributary.
- Land use consists mainly of natural (50%) and agricultural (38%) uses. The vegetation is mixed.
- Igneous geology is overlain by limited permeability silty loam type soils.

Water Quality Concerns/Issues

- Reservoir thermally stratifies and experiences anoxia below 16 feet.
- Low DO in deeper water leads to cyanobacteria blooms, and elevated levels of manganese and iron.
- Drinking water concerns include taste and odor as well as possible presence of algal toxins.

System Description and Application

- DDP unit consists of a flotation platform supporting an electric motor that turns an impeller that forces surface water down a flexible draft tube of 13.5 feet diameter. The discharge point is at about 30 feet, which is below the thermocline.
- Pumping capacity of system, 48,000 gallons per minute or about 210 ac-ft per day.
- All the water in the reservoir can be moved in just over 4 days. However, DDP unit runs at half capacity, so it is expected to move the target volume which is the entire reservoir volume of ~900 ac-ft once every 8.5 days, a rate of 11.8% per day.
- The DDP system operates continuously all year long.

Results

- The DDP system operation has been ongoing even after 15 years of service and suggests some degree of success in controlling cyanobacteria and dissolved metals levels.

- Well mixed conditions to a depth of 30 feet and oxygen >2 mg/L has been reported. This should minimize iron and manganese within the water layer from which supply water is drawn.

- Prior to DDP operation weekly to monthly use of copper sulphate treatments were needed to control algae.

Findings

- Reduced cyanobacteria levels and apparently reduced overall algae levels, have been maintained for 15 years.

- Complete and continued circulation of this reservoir is likely attributed to having reversed a long-term decline in water quality and overall reservoir condition.

- Enhanced ecological conditions were noted as a benefit.

<u>Case Study OC-09</u>

Background

- Reservoir located in Tennessee and was first filled in 1941.

- Reservoir used mainly for power production, but provides habitat and recreation, and is part of a river system that provides water supply for domestic and industrial purposes.

- Approximately 31,000 acres in size with an average depth of 50 feet (approximate volume, 1.55 million ac-ft), and a maximum depth of about 154 feet.

- Watershed (1.0 million acres) drains to the reservoir through one major and two minor tributaries.

- Watershed land is mainly in agricultural use, and vegetation generally consists of agricultural fields and deciduous trees.

- Geologic setting is sedimentary.

Water Quality Concerns/Issues

- Reservoir thermally stratifies at 25 feet and experiences anoxia in much of the area below this depth.

- Low dissolved oxygen levels in the tail waters of the reservoir affect the downstream warm water fishery and are also a concern for downstream water suppliers.

System Description and Application

- The DDP system is one element of a three element oxygenation and circulation system.

- When oxygen in the deep intake zone exhibits a distinct decline, the DDP system is started to push oxygenated surface water into the deep zone near the water intakes for power production.

- The system consists of 9 DDP units with each unit mounted on a floating platform and includes a 30 kW electric motor and gear reduction drive that spins a 15 ft stainless steel impeller at up to 24 revolutions per minute.

- The pumps are designed to move 530 cfs downward, and that water can represent up to 30% of the discharge water volume.

- DDP system is only run for a couple of months per year.

Results

- The DDP system can increase the oxygen content in discharge water only slightly even when all 9 units are in operation.

- Once the reservoir stratifies, the DDP system becomes much less effective for mixing near the dam, and as it operates over only a small area, it cannot prevent stratification from occurring.

Findings

- This case demonstrates the potential for a multi-element system to meet oxygen goals, although the entire reservoir is not addressed in this largely power-related case.

- The utility runs the turbine vents first (add about 1.5 mg/L of oxygen), followed by the DDP system (add about 0.5 mg/L of oxygen) and finally the diffused oxygen system (add about 2 mg/L of oxygen). The goal is to maintain tail water oxygen >4 mg/L.

In terms of overall finding from the nine DDP system case studies, it was shown to be successful in 5 cases and partially successful in 4 cases. Most of the DDP system cases reported by Wagner (2015) are in the context of water supply reservoirs in Australia. Where the overall goal in practically all cases was to increase DO such that cyanobacteria was reduced and levels of iron and manganese were diminished. Though algae were still abundant.

Wagner (2015) also point out that the DDP systems for which case histories were developed were not oversold, and each was part of an overall management and treatment program, often involving other steps to maximize raw water quality. Moving substantial quantities of targeted water volume each day was noted to be critical. Partial successes resulted mainly from a limited number of installed units to address the portion of the reservoir capable of influencing intake water quality or inability of the system to counter the heat input from the extended periods of high summertime temperatures. In a few cases, where the inflow into the reservoir system was flashy and if flooding occurred, the DDP system was generally unable to meet its design goals.

Finally, from the Australian case studies referenced in Wagner (2015) and summarized here, it appears, all of the installed DDP systems are based off the commercial WEARS system from Australia. Though the summary here provides an overview of this system, and its general performance; additional information of the WEARS Australia system is available from the WEARS Australia website (http://www.wears.com.au/), and in the paper by Elliott (2009).

The WEARS Australia website provides the different DDP products lines such as the ResMix™ systems. Elliott (2009) questions both the practicability and the value of the conventional concept of destratification driven by meteorological processes. Elliott (2009) argues the need for artificial means to destratify reservoirs and to improve DO distribution throughout the water column. The approach discussed by Elliott (2009) is the use of downward pumping to destratify.

In the following section the key advantages and limitations of the top-down mixing system are presented based on the reviews presented in this section.

3. Advantages and Limitations of Top-Down Mixers

Based on the literature review and discussions presented in the previous section it can be inferred that top-down mixers can effectively improve specific water quality related issues in water storage systems. Top-down mixers move oxygenated water from surface layers to depth to improve water quality of releases. Increasing release of dissolved oxygen (DO) concentrations at a mid- or lower-level dam outlet would be a typical application for a top-down mixer. Top-down mixers have also been used to improve taste and odor problems of intake water due to cyanobacteria bloom and elevated levels of iron and manganese.

The key advantages and limitations of the top-down mixing systems are presented here based on the DDP case-studies summarized in the previous section from Wagner (2015).

<u>Advantages</u>

- Improved and generally homogenized water quality for water intake structures.
- Localized area of treatment.
- Enhanced ecological conditions.
- Can be used complimentary to other oxygenation and circulation systems.

<u>Limitations</u>

- Literature primarily points to applications related to increasing dam release dissolved oxygen concentrations, controlling cyanobacteria growth, algal growth and managing levels of iron and manganese for drinking water purposes with practically limited to no discussion of other water quality parameters.

- Performance varies depending on reservoir configuration including reservoir size, depth, and geometry (e.g., dendritic, elongated, etc.).

- Design issues including the number of required units to move targeted volumes of water is variable.

- Flooding can lead to murky water due to suspended sediments impacting DDP performance.

- Variability in weather patterns is likely to have an impact on DDP circulation system results.

4. Summary and Applicability to Grand Lake

4.1 Summary

A review of available literature on top-down mixing systems also referred to as Garton pumps or down draft pumps (DDP) was presented here.

Examples of use of this technology from the United States appears to be limited in the literature and standalone application is mostly restricted to relatively small drinking water supplies (see Wagner (2015) case study OC-67 summary above; ~227 ac-ft reservoir in Illinois). In another application (see Wagner (2015) case study OC-09 summary above; hydropower operation in Tennessee) this technology was used to compliment a multi-element system to improve DO conditions.

The majority of the applications reviewed and presented here from Wagner (2015) were for water supply reservoirs in Australia spanning a wide range of reservoir sizes and configurations. However, in all cases, the focus of the DDP technology application was essentially the same. The goal was to improve DO in the water column to increase dissolved oxygen concentrations in low-level dam releases, to reduce cyanobacteria, reduce algae growth, and reduce levels of iron and manganese in the source water. At least these case studies to what could be inferred from Wagner (2015) did not consider any additional water quality parameters.

Additional research is likely needed to test the performance of the top-down mixing technology to control water quality parameters that are site specific. Reservoir site location, geometry and unique characteristics will likely play an important role in such performance testing. To that end, Elliot (2009) discusses the need for modeling flow patterns and presents discussions from numerical modeling experiments.

4.2 Applicability to Grand Lake

Grand Lake is a natural lake approximately 515 acres in surface area located at nearly 8,300 feet above mean sea level with a capacity of 68,600 ac-ft of water and a maximum depth of about 265 feet. It is located in the headwaters of the Colorado River along with nearby Shadow Mountain Reservoir and Granby Reservoir in Grand County, Colorado. The three water bodies are collectively known as the Three Lakes System. The Colorado-Big Thompson Project, which is owned by Reclamation and operated jointly with Northern Colorado Water Conservancy District, collects water from the headwaters of the Colorado River and uses the Three Lakes System as a conveyance system, pumping water from Granby Reservoir into Shadow Mountain Reservoir which then can be pulled through Grand Lake into the Alva B. Adams Tunnel as a means to transfer water from west to east slope of Colorado (Figure 3). Water quality/clarity in the Three Lakes has been a local concern for decades. Clear water enters Shadow Mountain Reservoir and clouded water enters Grand Lake. Based on the limited availability of documented studies, it would be difficult to hypothesize that installation of a top-down mixing system (or DDP) in Grand Lake would improve water clarity.

Additional study and modeling will likely be required before using a top-down mixing system to vertically mix a deep mountain lake in the unique setting of windy high-elevation environment that has a large river of pumped water flowing over the surface toward a shallow surface release spill-off.

Based on the literature review, considerations for additional analysis to test the hypothesis that DDP systems can improve Grand Lake clarity will likely need to include the following.

- Size, geometry, depth and physical setting of Grand Lake.
- Highly fluxing hydrology, extreme weather including wind conditions at the site.
- C-BT project operation controls on Grand Lake's level fluctuation (typically one vertical foot or less).

Based on the literature review, this technology can have potential application to improve dissolved oxygen concentrations in the Shadow Mountain Reservoir.

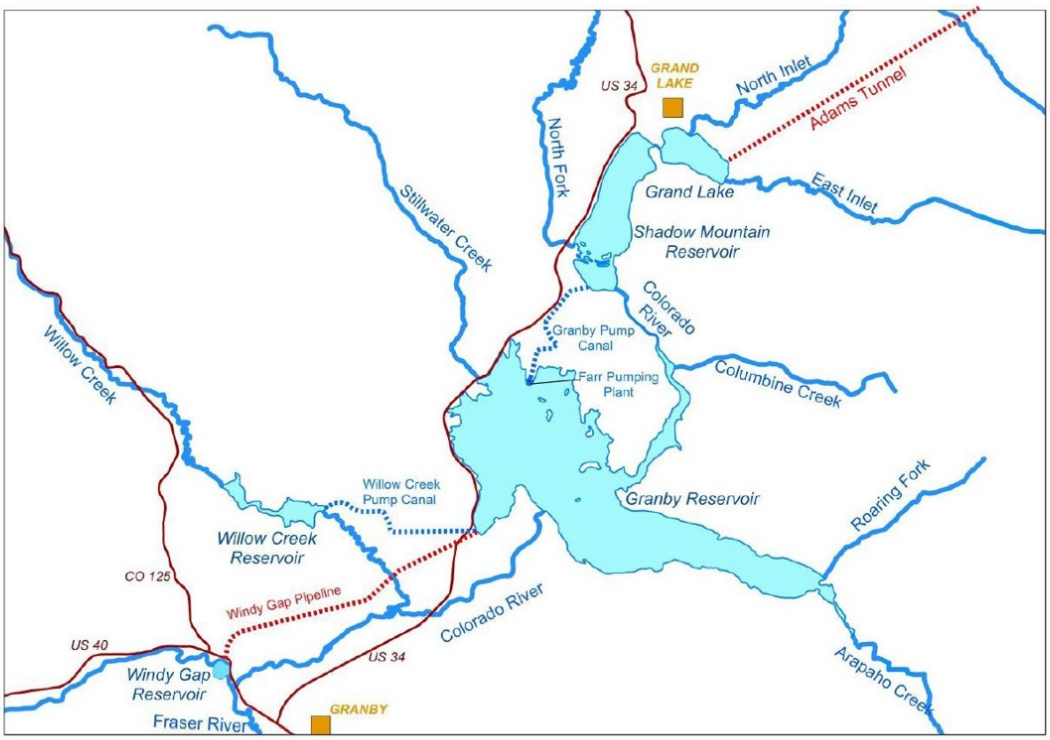

Figure 3. Grand Lake, Shadow Mountain and Granby Reservoir in the Colorado Big-Thompson (C-BT) project.

5. References

Dortch, M.S., and S.C. Wilhelms, 1978, “Enhancement of Releases From a Stratified Impoundment by Localized Mixing, Okatibbee Lake, Mississippi.” USACE, Army Engineer Waterways Experiment Station, Hydraulics Laboratory, Vicksburg, Mississippi. http://acwc.sdp.sirsi.net/client/search/asset/1034702; accessed September 25, 2016.

Elliott, S., 2009, “Pumping Down to Destratify: A Different Approach to Controlling Phosphorus, Metals and Cyanobacteria,” prepared for WEARS Australia 2009. http://www.wears.com.au/wp-content/uploads/2013/09/WEARSDOC070813-pumping-down.pdf; accessed September 25, 2016.

Garton, J. E. and H.R. Jarrell, 1976, “Demonstration of Water Quality Enhancement Through the Use of the Garton Pump.” Supplement to the Technical Completion Report, C-5228, Oklahoma Water Rresources Research Institute.

Holland, J. P., 1983, “Enhancement of Reservoir Release Quality with Localized Mixing.” Proceedings of the Third Annual Conference, North American Lake Management Society, October 18-20, 1993, Knoxville, TN, pp. 552-554.

Mobley, M., W. Tyson, J. Webb, and G. Brock, 1995, “Surface water pumps to improve dissolved oxygen content of hydropower releases,” http://mobleyengineering.com/images/pub_SWPumps_MHM_WP95.pdf; accessed, September 25, 2016.

Quintero, J.E., and J.E. Garton, 1973, “A Low Energy Lake Destratifier.” Trans. Am. Soc. Ag. Engr., Vol. 16, No. 5, pp. 973-976.

Wagner, K.W., 2015, “Oxygenation and Circulation to Aid Water Supply Reservoir Management.” Report #4222c, Water Research Foundation, Denver, CO, 322p.