Oxygenation and Circulation to Aid Water Supply Reservoir Management [Project #4222c]

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OBJECTIVES

This study is one of three parts of a larger project aimed at exploring enhancement of water supply reservoir operations and maintenance strategies. The previous reports examined water quality modeling techniques and rapid monitoring approaches to support reservoir management, with the titles of *Water Quality Modeling to Aid Water Supply Reservoir Management* (project #4222a) and *Rapid Water Quality Monitoring to Aid Water Supply Reservoir Management* (project #4222b), respectively. This element of the overall project, *Oxygenation and Circulation Techniques to Aid Water Supply Reservoir Management*, evaluates available techniques for adding oxygen and/or mixing reservoir waters and their use in reservoir water quality management.

This study accomplishes the following:

- provides background on oxygenation and circulation from literature and experience in a format comprehensible to water supply managers
- offers direction for selecting appropriate techniques to address water quality issues and examines the use of related equipment in the water supply industry through case studies and analysis of general trends.
- summarizes what has been learned through oxygenation and circulation projects over the last two decades, and provides key lessons learned that can be applied by water suppliers

Overall, this project will help water supply managers better employ oxygenation and circulation approaches to benefit water supply, both in terms of cost control and finished water quality.

BACKGROUND

Management of reservoirs that store and supply source water that is treated and distributed to the public has assumed increasing importance in light of the connection between source water quality and treatment costs, finished water quality, and ultimately human health. Years of research have documented the impact of water quality on public health, and utilities are seeking ways to improve source water quality to reduce treatment needs. Oxygenation and circulation are techniques that can be applied in reservoirs to improve source water quality.

Oxygenation and circulation encompass multiple and often overlapping techniques. Circulation is the movement of water to increase atmospheric interaction that oxygenates, homogenizes water quality, and disrupts algal growth. Oxygenation is defined here as the addition of oxygen to deeper water in a thermally stratified reservoir without disrupting that stratification. Circulation can be applied to any portion of a reservoir from the surface to any chosen depth, above or below any point of natural stratification. Oxygenation can be applied to any area within a reservoir, but usually targets the deep zone.

Available equipment and approaches can be divided into four forms of oxygenation and three forms of circulation. Diffused oxygen is the release of oxygen gas directly into the reservoir. Hypolimnetic aeration employs submerged chambers into which air is released and oxygen is transferred from the air bubbles to water moving through the chamber. Downflow bubble contact systems inject oxygen into water being pumped downward in a chamber, most commonly the Speece cone, with most of the oxygen absorbed by the water before being discharged to a target zone. Side stream supersaturation adds oxygen to a shore-based pressurized container to produce a supersaturated solution that is then discharged into a target zone. Circulation methods include releasing diffused air directly into the lake at a rate that will mix the water above the bubble plume and upward and downward pumping systems.

APPROACH

A wide range of applications of oxygenation and circulation techniques were examined. Case studies of oxygenation and circulation, most from the water supply industry, were collected and summarized, and a database of information was established to examine trends and key features of oxygenation and circulation systems. These findings have been summarized into a set of conclusions and recommendations.

While oxygenation and circulation involve commercial equipment acquired from vendors in most cases, the use of trade names has been minimized to the extent practical, taking no stand on which brand of equipment is least expensive or most effective. The use of available tools is more consequential than the brand, but potential buyers should carefully evaluate options. Important features of oxygenation and circulation systems have been highlighted, and brand names are sometimes used in a factual manner, especially where no alternative exists.

The focus here is on what can be done and how reliable the results can be with current technology, not who makes what and how effective their marketing campaigns might be. Some vendors did supply case history leads or even the data for case histories, but all cases were independently reviewed and were included only when there were sufficient corroborating data.

The approach is to document successes and failures, not to promote or dissuade. It is expected that potential users of oxygenation and circulation approaches will gain insights from this evaluation, but will be guided in specific equipment selection by their own experience, connections, and critical review of product information.

RESULTS/CONCLUSIONS

Circulation and/or oxygenation have the potential to enhance water quality in reservoirs, but there are many possible pitfalls that can lead to suboptimal performance. Achievement of all goals all the time in a cost-effective manner has been elusive. Many lessons learned have been incorporated in various sections of this report, and summarized in the Conclusions and Recommendations section. While those considering oxygenation or circulation systems are encouraged to examine the entire report, key conclusions are provided here.

1. Oxygenation and circulation have been applied to drinking water reservoirs for about five decades, but this area of reservoir management is not yet a mature applied science. Further improvements can be expected. Each type of system has advantages and drawbacks, and no one system is ideal for all reservoirs.
2. Problems addressed by oxygenation or circulation are related to low oxygen and associated water quality impairment or excessive algae. Increasing oxygen levels is beneficial to virtually all aspects of water quality for water supply. Maintaining oxygen levels is more beneficial than restoring oxygen after it has become depleted.
3. Circulation systems mix water and include diffused air circulation, updraft pumps, and downdraft pumps. Circulation can act over any portion of the reservoir from the surface to any chosen depth. The mixing of water can oxygenate deeper water, but also provides possible advantages in water quality homogenization and algae control that are independent of oxygenation functions. No single system type is ideal for all applications.
4. Oxygenation systems add oxygen to deeper water without disrupting major thermal stratification when present. The lower water layer often experiences low oxygen and the addition of oxygen can counter oxygen loss to maintain enough oxygen to avoid water quality problems. Oxygenation systems include diffused oxygen, hypolimnetic aeration chambers, downflow bubble contact chambers, and side stream supersaturation systems. No single system type is ideal for all applications.
5. Knowledge of the thermal regime over time and space, including variability, is important to successful design and operation. Breaking stratification after it occurs requires much more energy than preventing it, so circulation systems should be designed and operated to minimize temperature differences. However, it is difficult to mix the water column all the way to the sediment-water interface in deep water without disturbing sediment, and most circulation systems leave a thin unmixed zone at the bottom that can experience anoxic conditions and impaired water quality.
6. The more water moved by a circulation system, the better the results are likely to be, but assessment of case histories did not reveal clear thresholds for water movement for successful projects. Cost and site-specific features will be important factors in design.
7. Existing guidance to provide at least 1.3 cubic feet per minute per acre (9.2 cubic meters per minute per square kilometer) of air in circulation systems using diffused air is upheld as a threshold for success, although less air should be adequate for winter circulation and other factors influence success when enough air is provided. Distribution of the air is as important as the quantity added.
8. Circulation can provide algae control by moving algae into darker zones to create a light limitation, but this tends not to work well where the water depth is <33 feet (10 m). In most cases, algal biomass has not decreased as a function of circulation, and may increase where

nutrient limitation is removed by mixing without imposing light limitation. Circulation does favor some types of algae and is likely to shift the algae community, often but not always to a more desirable composition.

9. Circulation systems are usually inadequate to counter the heat input from an extended summer period of sunny days, and cyanobacteria blooms and impaired water quality are more likely to occur in late summer. Yet undesirable water quality is less common and more transient when a circulation system is in place.
10. Oxygenation systems must add enough oxygen to the target zone to maintain the desired dissolved oxygen concentration, usually >2 mg/L for water supply purposes and >4 to 6 mg/L for habitat support, depending on the species of interest. Estimation of oxygen demand is important but difficult, leading to uncertainty in the design process and the need to adjust systems after installation.
11. Algae control through oxygenation is possible through reduced internal loading of phosphorus, but many reservoirs receive elevated loads of nutrients from their watersheds, overshadowing the importance of internal loading. In those cases, oxygenation may influence types of algae, but will not prevent algae blooms.
12. Oxygenating or circulating only part of a reservoir may reduce costs but increases the risk of water quality impairment from the unaddressed portion of the reservoir. Careful consideration of tradeoffs is warranted during design. It may be possible to expand a system to address more of the reservoir later, but effectiveness and cost may not be proportional.
13. Evaluation of oxygenation and/or circulation case histories indicated almost 90% of systems provided measurable benefits, but only about half met all goals. Suboptimal performance was most often linked to inadequate capacity to meet the oxygen demand or to overcome thermal gradients and/or to operational problems such as frequent compressor shutdown or intentional partial day operation. Success is a matter of appropriate design, adequate budget, and competent system management supported by a sufficient monitoring program.
14. The cost of oxygenation and circulation systems is highly variable and economies of scale limit the value of standardizing values per unit area or volume. Costs of a suite of systems employing all four oxygenation methods overlapped to a degree that suggests site-specific costing will be necessary to determine the lowest cost option. The situation is similar for the three methods of circulation.
15. Limited data on cost savings by utilities applying oxygenation and/or circulation techniques to reservoirs suggest that reduced treatment costs usually offset operation costs for oxygenation and circulation systems, but that many years of successful operation would be necessary to recover capital costs. More often, utilities cite avoidance of more expensive treatment as a result of oxygenation and circulation, allowing the utility to provide better finished water quality and meet regulatory compliance needs and consumer expectations without major treatment cost increases.

APPLICATIONS/RECOMMENDATIONS

This report should serve as a guide to water supply reservoir managers considering the application of oxygenation or circulation in reservoir management. It provides a review of available techniques that will help when considering options for increasing oxygen levels or mixing raw water and includes 70 case studies, itemizing lessons learned from those cases and the available literature. It provides insights that should help utilities understand the processes involved, possible benefits, and encountered constraints. While costs for oxygenation and circulation systems vary widely, a general sense of what it costs to undertake various forms of oxygenation and circulation is provided.

There are many recommendations embodied in the lessons learned from oxygenation and circulation of water supplies over the past two decades. Those considering installation of oxygenation or circulation systems are encouraged to examine the entire report, but key recommendations and advice are provided here.

1. Utility staff should be part of the design team for any oxygenation or circulation system, involved in setting clear goals and gaining an understanding of the potential and limits of each system under consideration. Utility staff should be involved in decisions relating to any trade-offs between capacity and cost, recognizing the resulting total cost of providing safe drinking water. Careful cost-benefit analysis is warranted.
2. The choice between oxygenation and circulation as a strategy for improving oxygen near the sediment-water interface and associated water quality at intake or discharge points depends on multiple factors and should be considered on a case-by-case basis. In general, reservoirs that do not strongly stratify or have a very thin bottom layer are better candidates for circulation. Stratified reservoirs with substantial bottom water layer volumes and thickness can be circulated, but oxygenation without disrupting stratification is usually preferred, especially if there are intakes at multiple depths.
3. Additional guidance on the selection of oxygenation or circulation techniques is provided in the form of flow charts to aid decisions when source water quality, algae control, or habitat support is a goal. Site-specific factors and costs will be important to decisions, but the flow charts provide general guidance on which techniques are appropriate under what circumstances.
4. While variation in needs is recognized, it is recommended that circulation systems be designed to circulate at least 20% of the target volume per day. Additional capacity may be needed where oxygen demand is higher than typical or the target zone is only a small portion of the reservoir, possibly as much or more than the entire target volume each day. Calculation of water movement from gas addition should not be relied on too heavily, as available equations have many sources of error. The well-established target of 1.3 cfm/ac (9.2 $m^3/min/km^2$) of air remains an appropriate initial design standard.
5. It is strongly recommended that temperature profiles be used to assess circulation system performance under field conditions. Avoid assumed water movement based on pump specifications or conversion of air flow to water flow. Maintain temperature differences <3 C^o in vertical profiles within the target area for best results.
6. To maximize the probability of success, oxygenation systems should be designed to allow delivery of air at a level that represents at least five times the background oxygen demand or pure oxygen at a level at least twice the background oxygen demand. This level of apparent excess capacity may be needed to counter oxygen demand induced by gas addition and related water movement near the sediment surface. Modular systems that allow partial installation and testing to assess performance are favored until a reliable means for measuring induced oxygen demand is developed.
7. Frequent assessment of oxygen profiles is strongly advised to track performance of oxygenation systems; best water quality will be obtained by maintaining oxygen in the target

zone, rather than by restoring it, and knowledge of oxygen trends can aid adaptive management.

8. Be prepared to make field adjustments over a year or more. Very few cases examined in this project had completely acceptable results immediately upon installation. Uncertainty about oxygen demand or thermal regime necessitated modifications in nearly all cases to optimize system performance. Utilities seeking to contract for services should be aware of the iterative nature of most circulation and oxygenation projects and structure contracts accordingly.

PARTICIPANTS

The following utilities, government entities, consulting firms, and equipment suppliers directly participated in this project, all contributing in-kind services and information critical to its completion.

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