REAERATION[1/]

James F. LaBounty and Danny L. King[2/]

Introduction

Hundreds, perhaps thousands, of reservoirs and lakes in the United States suffer poor water quality due to the low amounts or complete lack of dissolved oxygen in the hypolimnion or deep layers during periods of peak stratification. Decay of organic material consumes great amounts of dissolved oxygen so that in a matter of weeks, the bottom layer of the lake or reservoir may become severely oxygen-deficient. Within the bottom sediments of lakes are various amounts of heavy metals. When dissolved oxygen is present, these metals remain in the particulate form and are almost always harmless to aquatic life. When the condition exists where dissolved oxygen is lacking, it usually means that metals such as copper, zinc, and lead exist in the soluble or toxic form and all aquatic life suffers. In addition, when such metals as manganese and iron exist in the soluble form, release and use of these waters result in offensive tastes, odors, and discolorations. Anaerobic conditions can exist during both summer and winter periods of stratification. The purpose of reaeration is to prevent the formation of an anaerobic state.

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2/ Research Biologist and Chief, Hydraulics Branch, U.S. Bureau of Reclamation, Engineering and Research Center, Denver, Colorado 80225.

Methodology

Reaeration is applied to small lakes of a few hectares as well as those of several hundred thousand hectares to improve or prevent poor water quality for municipal use and fisheries. There are two basic types of aeration techniques, those that destratify the lake and those that merely add oxygen to the hypolimnetic area. Each of these types is accomplished by a number of methods.

Destratification is the most commonly used method of reaeration. Besides the desired effect of preventing any portion of a body of water from becoming anaerobic, there are other benefits to destratification. There is the possibility that nuisance algae will be reduced. Evaporation may be slightly reduced because the average temperature of the surface water is reduced. There is also the desired effect of increasing fishery habitat because of the additional space in the water column containing sufficient dissolved oxygen.

There are also some disadvantages to destratification. The cold water resource is destroyed and there will be an overall increase in the heat budget of the reservoir. A trout fishery in the reservoir outflow that depends on cold water releases could be damaged or destroyed because the water temperature will be higher. Also, if the destratifier is too near the bottom, materials could be resuspended. The most important disadvantage is the very low efficiency in using destratification technology. Efficiency is defined as the ratio of the change of reservoir stability to the energy used by the destratification device. To date, efficiencies of 1 to 2 percent are common.

There are three alternative methods of destratification: diffused air, mechanical pumps, and hydraulic guns. Diffused air is the most commonly used method of destratification. The use of any method which allows bubbles to move through the entire depth will affect stratification by initiating vertical mixing through the drag between bubbles and water. This method employs air compressors which supply air through pipes to the desired depth of a body of water. With diffused air, over 90 percent of the oxygen transfer occurs at the reservoir surface.

Results from experiences at Casitas Reservoir in California have been favorable. Diffused air has been used for over 8 years to maintain partial destratification of this 2700-surface-acre (1093-ha), 250-foot (76.2-m) deep reservoir. Besides reducing the extent of low D.O. in the hypolimnion, which previous to aeration resulted in severe taste and odor problems, a trophy rainbow trout fishery has been created because of the destratifier. The cost of this operation has been approximately $20,000 per year, just for electrical energy. Research is underway with the objective of significantly reducing these costs. It is operated from April to October.

Much of the experience with mechanical pumps has been on small impoundments. The Garton pump, named after the developer at Oklahoma State

University, has been proven for small lakes of less than 100 acres (40 ha) and 30 to 50 feet (9 to 15 m) deep. However, it is still in the developmental stage for large lakes and reservoirs. The Garton pump is simply a motor-driven propeller, mounted on an anchored raft, which pushes water downward. Tests for the past 4 years at Ham's Lake, a 100-acre (40-ha) 930-acre-foot (1.2- x 10^6-m^3) impoundment near Stillwater, Oklahoma, have been very successful. Tests of a scaled-up model at Lake-of-the Arbuckles, a 2350-acre (950-ha), 72 400-acre-foot (89- x 10^6-m^3) impoundment in southeastern Oklahoma, have been partially successful, and tests are continuing. The efficiencies of the Garton pump are much higher than other methods.

A "hydraulic gun," designed by the Bureau's Southwest Region, pumps water upward through a 2-foot (610-mm) diameter pipe with large bubbles of air. The raft-mounted "gun" circulates water at an estimated rate of 30 ft^3/s (0.85 m^3/s) and has drawn water from a depth of about 57 feet (17 m). Thus, more of the reservoir water is exposed to the atmosphere for reaeration, and ciculation is achieved. Preliminary tests of this device at Lake-of-the-Arbuckles, Oklahoma, have shown very limited success because of inadequate size of the device. Further use of the "gun" is contemplated in a smaller impoundment. Efficiencies of this device seem to be similar to other destratifiers.

Hypolimnion reaeration is the second category of reservoir aeration. The concept of hypolimnion aeration is to complete all or most of the oxygen transfer within the bottom layer, thus maintaining stratification. The cold water resource is maintained and if a two-story fishery exists in the lake or reservoir, it will not be affected. In fact, the fishery will in some cases be restored by the addition of oxygen. Another advantage of this method is nutrients are not upwelled into the epilimnion where they may promote algal growth. Cold, well-aerated water is produced by hypolimnion aeration, whereas only warm, well-aerated water is produced by destratification. A major disadvantage of this method is the relatively high cost when using pure oxygen. If air is used, there is a potential for dissolved gas supersaturation.

There are four alternative methods of hypolimnetic reaeration. Diffusion of molecular oxygen is the most commonly used. The concept is to complete all or most of the oxygen transfer within the bottom layer by releasing very fine bubbles slowly from diffusers near the bottom. By the time the bubbles reach the thermocline, the gas transfer is complete and no bubbles remain. The bureau is presently researching this technique at Twin Lakes, Colorado, in an attemt to prevent winter anoxia. Gas produced from liquid oxygen passes through tubing and a series of diffusers mounted about 65 feet (20 m) below the ice and 3 feet (1 m) above the bottom. During the most severe winters (heavy snow, low runoff, long ice cover) the bottom 3 to 10 feet (1 to 3 m) may become anaerobic, allowing a reduction state to exist. Thus, toxic concentrations of heavy metals that are in the bottom sediments permeate the reservoir, resulting in a die-off of aquatic life preceding and during spring turnover periods. The winter of 1976-77 is the first time this operation has been tested, using four diffusers. To this point, results are positive. However, due to the lack of snow cover on the ice, limited data are availalbe as to the amounts of oxygen actually added by the apparatus. If this method is shown to be economically practical, a full system may be designed for Twin Lakes and potential application exists for many other lakes and reservoirs.

Other methods of hypolimnion reaeration include Bernhardt's device, downflow-bubble-contact aeration, and the bypass system. Bernhardt (1967) and Fast (1971) proposed a method that includes an open-ended vertical pipe which extends from near the bottom of the reservoir to above the water surface. Air is introduced through a diffuser at the bottom of the pipe. Four distribution pipes, branching from the vertical pipe, are located just below the thermocline. Water is drawn in behind a rising column of air bubbles in a vertical stock open at the surface and either leaves the stack at the top of the hypolimnion or is forced down again in the space between the stack and a jacket around the stack and out near the inlet (Toetz, et al, 1972). The stack allows undissolved air to escape to the atmosphere and extends far enough above the surface so that water is unable to overflow at the top.

Speece (1971), while at the University of Texas, developed the downflow-bubble-contact aerator. Bubbles of pure oxygen are diffused into a mass of water flowing downward in an inverted cone. During descent, the oxygen diffuses into the water and nitrogen from the water diffuses into the bubble (Speece, Madrid, and Nudhain, 1970). This concept can be designed for 100 percent transfer efficiency.

The bypass system removes water from the hypolimnion, oxygenates it, and then returns it to the hypolimnion. Fast, et al. (1975), proposed a modified system of hypolimnetic oxygenation called side stream pumping (SSP), which is similar to the bypass system. The SSP system uses liquid oxygen and a conventional water pump. A small volume of water is diverted from the mainstream, oxygenated, and then returned to the mainstream. As a result, the oxygen concentration of the mainstream is elevated to a desired concentration while a relatively small volume of water is pumped. The SSP system has also been used to increase the dissolved oxygen concentration in well water used for fish rearing and in discharge through the dam penstocks in large reservoirs (L. L. Kelley and C. P. Kester, pers. comm., 1974, as reported in Fast et al., 1975).

An overall comparison of reaeration methods is in tables 1, 2, and 3, which is from King (1970). In summary, the data on these tables indicate that hypolimnion aeration using molecular oxygen is the most efficient method of reaeration. However, it also is the most costly.

Monitoring of Environmental Effects

The effect of reaeration upon the environment, and synecological (studies of individual organisms or individual species) and antecological (studies of groups of organisms associated as a unit) aspects of the aquatic system must be evaluated. This evaluation should be made on all reaeration devices, structures, and related features so that the influence of this alteration on the aquatic environment can be documented and any alterations in the system that will achieve the desired goals as well as improve the environment can be made. Two aspects of the evaluation that should be considered are: (1) the rate and magnitude of changes, and (2) the relationship between physical, chemical, and biological factors.

Since it is vital to the evaluation to have substantial background data, the collection of data should occur as long as possible prior to operation, then during operation. The following are parameters that should be measured.

1. Physical Factors. -

a. Temperature. - It is essential to measure temperature profiles near and away from the reaeration device to learn the effectiveness of the operation. A minimum of twice a week profiles are desirable. As a general rule, a minimum of one sampling station per 600 acres (250 ha) of surface area should be used. However, where topography varies, the number of sampling stations should be increased.

b. Transparency. - This can be measured simply with a Secchi disk or a limnophotometer may be used. Transparency is measured for two reasons; it indicates the degree of phytoplankton growth as well as whether or not the device is increasing the turbidity of the body of water by stirring bottom sediments.

c. Turbidity. - This is measured generally with some sort of turbidity meter. One that reads in Jackson units is most convenient. The purpose of measuring turbidity is to learn what influence the reaeration device is having on bottom sediments. It is desirable to measure turbidity both on the surface and near the bottom.

d. Hydrodynamics. - It is desirable to obtain some information on the internal currents within the lake reservoir especially as they are influenced by the reaeration device. However, this may be precluded because of the expense of instrumentation and the large amount of data required to adequately define the complex currents in a lake or reservoir.

2. Chemical Factors. -

a. Dissolved oxygen. - This, along with temperature, is essential to the monitoring program since they are the two primary indicators of successful operation.

b. Routine chemical analyses. - It is desirable to perform, at selected times of the year, routine chemical analyses to measure the amounts of the major cations and anions. Alkalinity and pH should be measured in the field while the cations and anions can be measured from a collected water sample in the laboratory. The elements causing problems should be monitored closely. For example, if taste and odor problems exist due to the presence of iron and manganese, these two elements should be monitored, especially within the hypolimnion. ONe chemical parameter that recently is becoming more and more used is oxidation-reduction potential (ORP). It is measured most easily with a probe and is a good indicator of conditions within the hypolimnion during stratification. That is, as the ORP drops within the hypolimnion, it is an indication that a deterioration of conditions because of stagnation is leading to a net loss of dissolved oxygen and a lowering of pH, resulting finally in the presence in noxious concentrations of heavy metals such as iron, manganese, copper, zinc, lead, etc., in the dissolved form. When the ORP becomes low enough, one by one these metals present in the particulate form in the bottom sediments become available in the ionic or dissolved form, which is toxic to aquatic life as well as causing taste, odor, and health problems to humans.

c. Biochemical oxygen demand (BOD). - This is a good test to perform, especially during the critical time of the year - at the first signs of formation of summer stratification. It is essential in estimating the change in dissolved oxygen due to reaeration.

3. Biological factors. - If the body of water of concern is a fishery or proposed to be a fishery, it is essential that some indication of the condition of the fishery be monitored. In addition, the monitoring of algae populations, both kind and abundance, is essential to any municipal water supply, especially if there is no treatment plant downstream. Reaeration does have a very positive influence, in most cases, on a fishery. Manipulation of the system or selection of the type of system can have profound influence on a fishery. Therefore, careful monitoring of the food chain as well as the fish species and abundance is important if the fishery is of concern. In general, it is desirable to include in the monitoring program the following:

a. Benthic. - Collection and straining of bottom mud samples will provide information not only on the trophic condition of the bottom of a lake or reservoir, but also, since many benthic animals are sensitive to anaerobic conditions, the recent past chemical conditions near the bottom will be indicated. Following straining of bottom muds, the sample should be counted and identified, then a diversity index can be calculated. From this, because some benthic fauna are more tolerant than others to anaerobic conditions, conclusions can be made regarding the conditions within the hypolimnion.

b. Zooplankton. - The collection of zooplankton is desirable since they are the food of some fish and are important especially to the forage species. Collections are made either with a towed or a thrown net. It is primarily important to determine quantitatively the species present and secondarily the abundance of each.

c. Phytoplankton productivity. - An index of the phytoplankton productivity should be incorporated into the program. Phytoplankton productivity is most easily measured by chlorophyll analysis. Known volumes of water from selected depths are collected and filtered. Chlorophyll productivity is expressed in mg/m^3 of volume. In an aquatic system where eutrophication is a problem, the amount of chlorophyll is a good indication of water quality conditions. As stated earlier, reaeration has been found to reduce algae production.

d. Fish. - Abundance, species composition, and distribution of fish are important to know if a body of water is being used as a fishery. Preoperational data on the above should be collected so that the changes in the fishery resulting from reaeration can be documented.

Environmental Effects of Reaeration

The effects of the different reaeration devices vary from one type of environment to another. An ecosystem will respond differently to destratification than it will to hypolimnion aeration. Also, a eutrophic system will respond differently than an oligotrophic system. Artificial destratification will accelerate many of the cemical reactions involving sorption with sediments or particulate matter because of the changing of such physical factors as temperature, redox potential, pH, and mixing rates. At the onset of destratification, the first effect is a lowering of the thermocline. Then, complete mixing occurs, assuming adequate energy imput. The long-term effect is that the heat budget becomes higher on a seasonal basis. The mixed water prevents insulation of water at lower depths and lower surface temperatures allow more heat transfer into the reservoir. However, during hypolimnion aeration, the thermocline is maintained and there are no changes in temperature.

The purpose of most reaeration systems is to maintain or enhance the dissolved oxygen content somewhere in the water column, generally in the hypolimnion. However, with destratification, D.O. may decrease in the epiliminion. Furthermore, an increase in hypolimnetic temperature should accelerate the use of oxygen there. Hypolimnion aeration will merely increase the D.O. within the hypolimnion while maintaining stratification.

Changes in the concentration of organic matter as a result of reaeration are largely unknown. However, it has been found that densities of particulate organic carbon (POC) and dissolved organic carbon (DOC) increased following the onset of destratification. Reasons for the increase in these are stirring of the bottom for POC and an increase in phytoplankton for DOC.

Following the commencement of operation of a destratification device, an immediate decrease in the pH of surface and an increase of pH of bottom waters have been noted. Transparency of the water immediately increases when blue-green algae is present because it tends to float to the surface. Some investigators found a decrease in transparency resulting from an increase in algae density, presumably not of the blue-green group. In an oligotrophic lake, transparency especially decreases largely due to an increase in the amount of debris, detritus, etc.

Destratification has been found to uniformly redistribute ions throughout the water column, thus the specific conductance increases at the surface and decreases near the bottom. In an oligotrophic lake, there is also a decrease in alkalinity and specific conductance near the bottom. This is attributed to calcium and magnesium precipitating as carbon dioxide and being lost from the system. Hydrogen sulfide (H_2S) tends to disappear from the hypolimnion upon aeration. However, sulfates (SO_4) show little change. The presence of manganese and iron in water is of concern especially if the water is to be used as a domestic source. These two elements are the first to go into solution as the D.O. becomes used up and the redox potential drops. Therefore, they are of first concern. Increasing the D.O. either by mixing or hypolimnion aeration results in iron and manganese gradually decreasing in concentration.

Destratification changes many factors that are important in determining the rate and direction of chemical reactions. Destratification leads to a loss of CO_2, H_2S, and NH_4 to the atmosphere. However, data are scanty on its effect on many elements or compounds. In any case, mixing may merely redistribute things, in most cases.

It has already been stated that blue-green algae is affected by mixing. There is a decrease in its biomass. Destratification may eliminate some species of algae that have unique distributions in stratified lakes. However, overall, the primary production has been found to increase during destratification because materials are more available. Destratification accelerates both the rate of energy flow and the rate of nutrient cycling in the ecosystem.

As is true with nutrients, phytoplankton, etc., destratification and the mixing that results from it causes the vertical distribution of zooplankton to be altered. Generally, the vertical distribution is increased because of the increase in space. However, the species composition and density of zooplankton may be altered and the standing crop decreased. The species that are characteristic of oligotrophic lakes may disappear.

The benthic fauna of a lake is a good indicator of the lake's condition since some benthic fauna are extremely sensitive to anaerobic conditions. In general, low dissolved oxygen levels reduce the diversity of the benthic community. In eutrophic lakes, population numbers of chironomid larvae and oligochaetes are greatly increased after aeration - up to 65 percent. This is due to the fact that following aeration of a eutrophic lake, certain species invaded the hypolimnion. In contrast, destratification resulted in reduction of standing crops of benthic fauna of oligotrophic lakes.

Fish are often detrimentally affected because of reduced volume of fish habitat when stratification occurs. Below a certain depth, the amount of D.O. is limited, and above a certain depth too high temperatures are limiting. Aeration is extremely beneficial to fish except where a two-story fishery is thriving and destratification is destroyed. This is very rare since if aeration is necessary, the hypolimnion is suffering low D.O. levels, too low for most fish to survive. The following benefits to a fishery may occur:

1. Prevention of summer kill because of the maintenance of adequate D.O. both for fish survival and survival of food for fish
2. Increasing the rate of organic decomposition which prevents later utilization of D.O. and results in a reversal of the eutroptrication process
3. Enhancement of favorable trophic conditions for fish by expanding fish habitat
4. Prevention of winter kill by either preventing ice formation or aerating the hypolimnion

Artificial destrat fication has been found to increase fish habitat, increase fish production, and increase the production of macroinvertebrates.

In summary, when applied with adequate planning and forecast of results, aeration, no matter what the method, is beneficial to a lake's productivity as well as its water quality. Destratification is, in most cases, more practical because of the expense of hypolimnion aeration. However, for small lakes where it is desirable to maintain stratification, hypolimnion aeration may be practical.

Table 1

EFFICIENCIES OF SEVERAL REAERATION DEVICES

Method	Efficiency (lb/kwhr)
Diffused air, mixing	*0.3-4.3
Mechanical turbine aerators	1.3-5.6
Mechanical pump, mixing	1.0
Aerohydraulic gun	1.4
Hypolimnion aeration and mixing	2.1

*Transport of water to surface allows atmospheric reaeration in addition to oxygen transfer from bubbles.

Table 2

OVERALL COMPARISON OF REAERATION METHODS

Device	Efficiency	Advantages	Disadvantages
Diffusers (including reservoir mixing)	2-8 percent (Est. 1-3 lb/kwhr)	Many types available.	Clogging. Requires filtering of air. Relatively low transfer efficiency. High first cost.
Mechanical aerators	2-5 lb/kwhr	Many types available. Natural or forced-air admission. Valves, piping, blowers, etc., are not required.	Swimming hazard. Obstructs channel. High first cost.
Turbine injection	2-6 lb/kwhr (with admission by natural draft)	Natural or forced-air admission. Large discharges. Low first cost, low maintenance cost.	Possible power loss and adverse effects on turbine performance. Restricted to sites with hydroplants.
Venturi tubes	2-3 lb/kwhr	Natural or forced-air admission.	Head loss. Small discharges.
Cascades	Determined from empirical formula (Low, see Table 4).	Maintenance free. Often associated with energy dissipation. Large discharges. No auxiliary equipment required.	Head loss may not be allowable. High first cost. Low transfer efficiency.
U-tubes	1-5 lb/kwhr	Natural or forced air admission. Low maintenance cost. High surface transfer, longer contact time, increased deficit due to pressurization. Can be used in channel.	Not yet proven for large discharges. Possible plugging with debris or ice.
Hydraulic guns	≈2 lb/kwhr	Efficient mixing, high surface currents, surface boil.	Primarily for mixing. Large bubble size, low transfer efficiency.
Pressure injection	No data available.		Small volumes
Fixed-cone valves	No power use or loss is involved.	Associated with required energy dissipation. Large volumes. No auxiliary equipment required.	Requires reservoir releases, which may not be possible.
Mechanical pump mixing	< 1 lb/kwhr	Simple equipment. Minimal maintenance.	Primarily for mixing. Low transfer efficiency. Verified only for relatively small volumes.
Hypolimnion reaeration and mixing	> 2 lb/kwhr	Allows stratification to remain undisturbed.	Relatively low transfer efficiency.
Molecular oxygen	14-55 percent	Can be used with various types of contact devices. High transfer efficiency. No dissolved nitrogen.	High cost of molecular oxygen.

Table 3 [From Ref (T-15)]

ANNUAL COSTS OF REAERATION*

Type of cost	Cost for diffused-air aeration ($)	Cost for turbine aeration ($)	Cost for cascade aeration ($)	Cost for mechanical aeration ($)
Capital cost	39,000	3,000	30,000	50,000
Per year	3,130	240	2,400	4,000
Annual operating cost	5,150	2,570	–	4,500
TOTAL	8,280	2,810	2,400	8,500

*Conditions for computation are: 10,000 lb oxygen/day/1,000 cfs (16 kg/day/100 cu m/sec) or 1.86 mg/l, for 90 days.