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# Comparative studies of the different mechanical oxygenation systems used in the restoration of lakes and reservoirs

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## Abstract
The techniques used for the restoration of lakes or to prevent eutrophication are numerous (chemical, biologic, mechanical, etc). Due to their excessive costs and the relatively insignificant outcomes of some of these techniques, the process of artificial aeration is one of the most promising methods. Four strategic techniques for the control of nutrients are selected for this study: artificial destratification by the bubble plume, partial (or total) lift hypolimnetic aerator, bubble plume oxygenation and Speece cone oxygenation. Each of these methods has both advantages and disadvantages. Technical and economic analyses established by different researchers reveal that hypolimnetic oxygenation is most favorable for nutrient control. In hypolimnetic aeration systems, the bubble plume appears to be most economical and perhaps most simple among the systems proposed for Standley Lake (Colorado, USA), even as other researches selected the Speece cone aeration system in other applications. Based on existing hypolimnetic aeration research, this study provides a synthesis of a number of issues related to the aeration in lakes and reservoirs, including the advantages and disadvantages of these aeration systems. This study also concentrates on the economic and technical aspects associated with these aeration systems. We found that the use of oxygen limits the nitrogen saturation and in contrast with using air. We demonstrate that the most efficient hypolimnetic aeration system is the bubble plume diffuser, although accidental destratification may occur. The destratification can be used in winter because the temperature of the lake is not modified. However, the hypolimnetic aeration is used in summer in order to avoid the homogenization of the lake temperature during this period.

***Key words:*** Aeration, eutrophication, destratification, hypolimnetic aeration, temperature, dissolved oxygen, pollution, thermal stratification, restoration techniques, lake.

## Introduction

The problems of water quality are related to a decrease in the dissolved oxygen (DO) content, particularly in the lower layers [1], which may deteriorate significantly if the DO consumed in biochemical processes is not renewed by surface aeration or photosynthesis [2]. The concentration of DO is one measure of the water quality [1]. The amount of DO in water is an indication of the level of microbiological activity, the amount of decaying organic matter present and level of reaeration. In addition, DO is probably the most significant factor relating to the sustainability of fish habitat [3]. The artificial mixing of stratified lakes with aerators prevents thermal stratification from becoming established and increases the DO throughout the water column [1, 4]. It also prevents the surface of rivers or lakes from freezing over [5, 7], creates barriers against saltwater intrusion into rivers and lakes [5, 8] and retards ice formation in harbors and inland waterways [9]. The artificial mixing helps to produce surface currents to protect harbor areas against high amplitude waves [9, 10] to avoid oil slicks from spreading after oil tanker accidents [5,11] and to bring about an almost complete compensation of the oxygen deficit resulting from metabolic activity [12].

The artificial aeration of oxygen-depleted lake waters is one of many methods used for remediation [13]. It is undoubtedly the most frequently used technique [13, 14] due to its relatively low cost and ease of deployment [13]. There are two main types of artificial aeration of lakes: destratification and hypolimnetic aeration [15]. In the first case, the entire lake is mixed, usually by the release of compressed air from a perforated air line laid along the bottom of the lake. In the second case, the objective is to maintain thermal stratification, while oxygenating the hypolimnion [16]. These restoration techniques can be used separately or in combination [17]. In the case of separately used systems [17], an artificial mixing of the water column during the cold season and an input of oxygen into the hypolimnion during summer in order to preserve the stratification are assured. Combined systems can be switched between mixing mode using coarse air bubbles and hypolimnetic oxygenation or aeration mode using fine oxygen or air bubbles. Every diffuser is operated using air or oxygen during the summer and air during the winter [18]. Each one of these methods has its advantages and disadvantages.

The work presented in this paper is a review of aeration techniques and their impacts on water reservoirs. This study will enable us to choose the most efficient technique for use in our future project.

## Aeration Systems

***Destratification aeration:*** Destratification using aeration was first reported by Scott and Foley [46]. Using this method, destratification is commonly achieved by injecting air through a single air diffuser (Fig. 1) [19, 20].

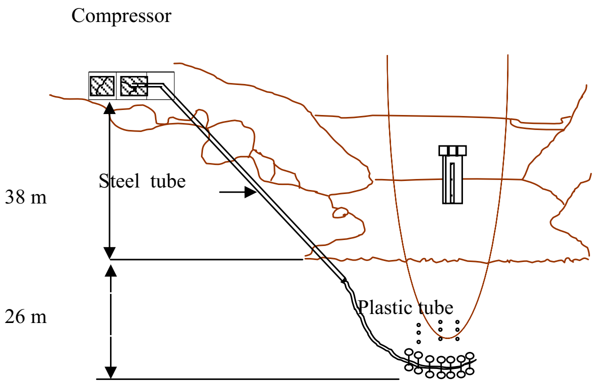


***Figure 1.*** A simple lake destratification system [19, 20].

Other techniques include mechanically pumping bottom water to the surface and mechanically pumping surface water to the bottom [19]. Steinberger and Zimmermann [21] compared two methods of destratification, intermittent and permanent destratification, in Lake Fischkaltersee to demonstrate that certain physical actions (i.e. mixing) can be applied successfully to lake remediation. Futhermore, they wanted to show that lake remediation measures, which include these physical actions, can serve as a rather effective and rapid manipulation tool in managing cyanobacterial blooms in lakes, mostly independent of the nutrient pool. These two remediations started in April 1980 and April 1985. They demonstrated that intermittent destratification has some advantages over permanent destratification. The authors concluded that intermittent destratification provides very rapid remediation and also appears to be applicable in relatively shallow lakes (‹15 m), whereas permanent destratification methods appear risky in shallower waters [21].

***Hypolimnetic oxygenation:*** This method introduces oxygen into the hypolimnion of a lake or reservoir without disturbing the temperature gradient [12, 22, 23]. It is particularly suitable for improving the DO in drinking water reservoirs when the hypolimnion extends for more than 10 m and the ratio,

$$\frac{V_{epi}}{V_{hyp}} \leq 2$$

where $V_{epi}$ and $V_{hyp}$ are the epilimnion and the hypolimnion volumes respectively [6].

Fast [19] invented an aeration system for fisheries which can be used with air or oxygen. The system is a vertical pipe where water is raised either by air compression or by mechanical means. The natural stripping by this method restores not only the lake but also the fish population [19, 24]. These systems showed great potential for use in eutrophic stratified lakes or reservoirs and can be used in marine water and in the isothermal conditions [19].

Bernhardt and Clasen [12] reported results of 15 years hypolimnetic aeration in the Wahnbach Dam (Germany) ($Vol_{epi}$ = 20.10$^6$ m$^3$, $Vol_{hyp}$ = 16.10$^6$ m$^3$, depth = 45 m), using a hypolimnetic aerator developed by the Wahnbach Reservoir Association. They proved that, despite the huge development of occasional algae, the consumption of DO at the sediment-water interface is compensated during the stratification [12]. No anaerobic condition has been produced on the bottom of the lake (DO was maintained at > 4 mg/l). In addition, the iron and manganese concentrations are suppressed in the hypolimnion and treatment to remove the manganese is not necessary. The release of orthophosphate from sediments remains insignificant (internal load) and consequently prevents a rapid renewal of the eutrophication. During the stratification, the hypolimnion conserves a temperature less than or equal to 10°C for the month of October and stays within acceptable limits for drinking water.

Another hypolimnetic oxygenation technique involves drawing water to the shore, injecting it with pure oxygen gas under high pressure and then returning it to the hypolimnion. This is known as side-stream pumping or side-stream supersaturation and is one of the earliest reported oxygenation systems (Fig. 2).

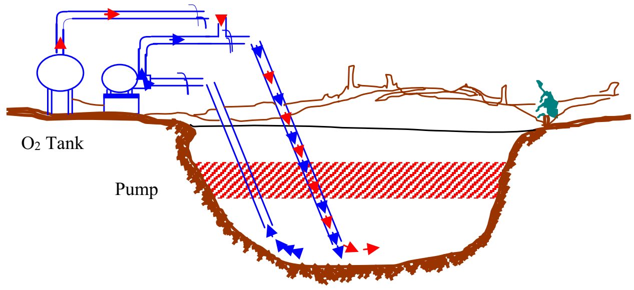


***Figure 2.*** Side-stream pumping (S.S.P) [19, 25].

Three types of oxygen input devices are commonly used for hypolimnetic aeration (Fig. 3) [26-28].

*Airlift hypolimnetic aerator* (Fig. 3a): Full-lift hypolimnetic aerators typically consist of a vertical riser tube, a diffuser inside the bottom of the tube, an air air-water separation chamber at the top of the riser and one or two return pipes, called downcomers [26, 27].

*Bubble-plume oxygenator* (Fig. 3b): Bubble-plume diffusers are generally linear or circular and inject either air or oxygen at relatively low gas flow rates [27]. These systems are most suitable for deep lakes where the bulk of the bubbles dissolve in the hypolimnion and the momentum generated by the plume is low enough to prevent significant erosion of the thermocline [26, 27].

*Speece cone oxygenator* (Fig. 3c): The system consists of a source of oxygen gas, a conical bubble contact chamber, a submersible pump and a diffuser that disperses highly oxygenated water into the hypolimnion [26, 29, 30].

Typically, pure oxygen is used in Speece cones, air is used in partial-lift hypolimnetic aerators [22, 26] and bubble-plumes use oxygen or air [26]. Pure oxygen is used for hypolimnetic oxygenation to prevent the accumulation of molecular nitrogen which can be

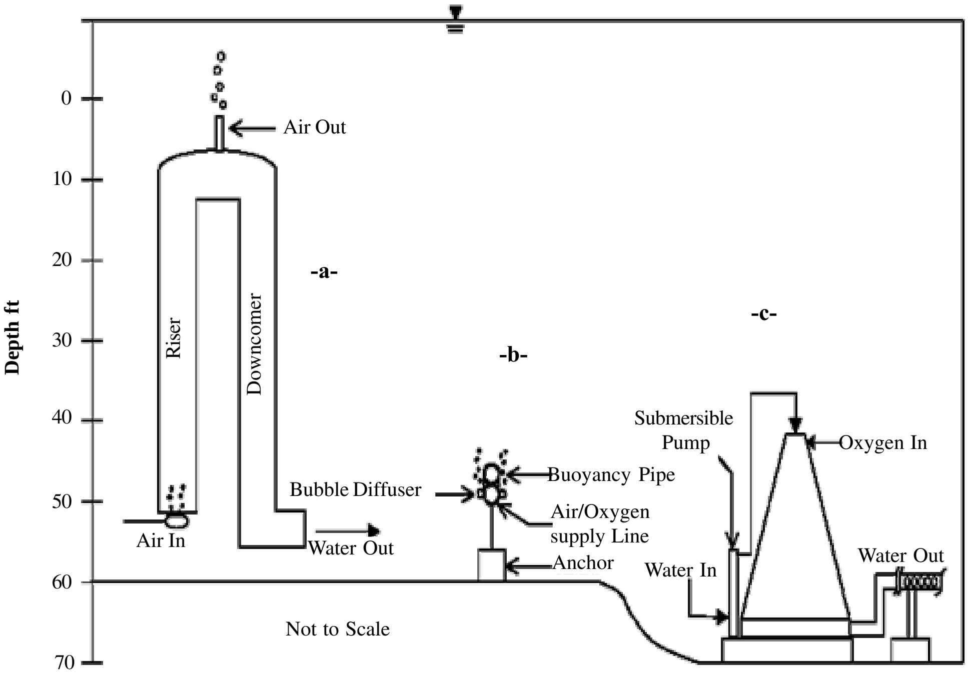


***Figure 3.*** Schematic representation of three oxygen input devices [26, 31].

toxic to fish [17]. Air aeration also leads to elevated levels of turbulence within the hypolimnion which may increase sediment oxygen demand or results in an accidental destratification [32]. Airlift aerators are installed most frequently during the early years of hypolimnetic aeration and oxygenation [27].

### Comparison of Aeration Systems

***Hypolimnetic aeration systems:*** Fast [19] proposed a comparative study of the three systems of hypolimnetic aeration [19, 33]: Side-stream pumping (SSP), the partial airlift hypolimnetic aerator and the full airlift hypolimnetic aerator. This latter system is typically operated at pressures higher than 3 atm and water temperatures of 10°C or less. The efficiency of this system is based on the greater solubility of pure oxygen and its pressure injection in the water [19, 33].

Several authors compared the costs of three types of hypolimnion aerators and found that the full airlift hypolimnetic aerator has the lowest usage cost and the highest efficiency. The SSP has a much smaller capital cost [19, 33]. Kortmann [34] reported that the earliest aerators utilized a full airlift pumping practice. However, lately the partial airlift hypolimnetic aerators are most commonly used; even though oxygen transfer efficiencies are higher in the full-airlift systems [34].

Oxygen absorption efficiencies for the bubble plumes and Speece cones were evaluated by Speece [35]. He showed that in impoundments and shallow reservoirs with depths less than 30 m the fine bubble diffusers require a rise height of about 30 m within the hypolimnion to ensure efficient oxygen transfer to the hypolimnion. He highlighted that the bubbles must be maintained in contact with the water for approximately 100 seconds to accomplish oxygen absorption efficiencies more than 80%. An example of an oxygen transfer device is the downflow bubble contact oxygenator Speece cone, or Speece cone, developed by the author. Water is introduced downward at the tip of the cone with an adequate rate such that oxygen bubbles are trapped and the bubble swarm cannot collapse. In cases where the cone cross-section increases, the downward water velocity decreases to where it is less than the Buoyant velocity of the bubbles. Consequently, very efficient oxygen transfer can be achieved. The author [35] concluded that free rising bubble plumes are to be avoided in order to maintain stratification and illustrated the advantage of hypolimnetic oxygenation in two lakes. Newman Lake has an average depth of 10 m and is about 3 km long in its major axis. During two years, the system has successfully maintained oxic conditions without eliminating the weak stratification and has prevented phosphorus recycling from the sediment.

In the case of Comanche Reservoir, the impoundment has variable depth, increasing to 40 m at the dam. During a drought, the water depth decreases to 8 m, and in mid-June the DO is frequently less than 7 mg/l. During July or early August, anaerobic conditions are established at the bottom of the hypolimnion where the discharge is located. The author concluded that the ammonium concentration in the impoundment decreased and the phosphorus concentration declined to 25% of the original value after the aeration systems were started.

Based on a study of Standley Lake (Colorado, USA), McGinnis and Little [26] described a technical and economic analysis of these three systems (Fig. 3) in order to select the most appropriate aeration mechanism for a specific lake, thus optimizing both the design and operation to ensure the greatest oxygen transfer efficiency (see Tables 1-3) [26].

McGinnis and Little [26] showed that the bubble plume diffuser is the most economic system as well as being most simple of these three systems. Their conclusions were based on the following: in the partial-lift hypolimnetic aerator, the efficiency of oxygen transfer is lowest (16%). For the Speece cone and the bubble plume, the efficiency of oxygen transfer is very similar (94 and 93% respectively). In addition, a high value of the water velocity

**Table 1.** Partial-lift hypolimnetic aerator [26, 36].

| Variable and predicted performances | Value |
|---|---|
| -Air flow ($Nm^3/s$) | 0.12 |
| -Height of ascending tube (m) | 12.2 |
| -Diameter of ascending tube (m) | 3.10 |
| -Flow of drained water ($m^3/s$) | 1.17 |
| -Increase in oxygen concentration ($g/m^3$) | 4.60 |
| -Efficiency in oxygen transfer (%) | 16 |
| -Total oxygen transfer (16 aerators) (kg/day) | 464 |
| - Oxygen transfer by aerator (kg/day) | 7400 |

**Table 2.** Bubble plume [26, 36].

| Variable and predicted performances | Value |
|---|---|
| -Oxygen flow ($Nm^3/s$) | 0.069 |
| -Initial diameter of bubbles (mm) | 2.5 |
| -Length of the diffuser (m) | 2.500 |
| -Initial speed of the plume (m/s) | 0.038 |
| -Height of the plume rise | 1.5 |
| -Efficiency in oxygen transfer (%) | 93 |
| -Total oxygen transfer (kg/day) | 7400 |

**Table 3.** Speece cone [26,36].

| Variable and predicted performances | Value |
|---|---|
| -Oxygen flow ($Nm^3/s$) | 0.068 |
| -Initial diameter of bubbles (mm) | 2.0 |
| -Imposed water flow ($m^3/s$) | 1.3 |
| -Detention time of bubble (min) | 2.0 |
| -Increase in oxygen concentration ($g/m^3$) | 66 |
| -Total oxygen transfer (kg/day) | 7400 |
| -Efficiency in oxygen transfer (%) | 94 |

must be maintained in the Speece cone in order to ensure that the bubbles would not reach equilibrium with the water which may lead to accumulation of bubbles and coalescence in the cone leading to a decrease in the total efficiency.

Mobley [37] described a proficient and economical aeration diffuser design, developed by the Tennessee Valley Authority (TVA), which operated successfully. By spreading the gas bubbles over a very large area in the reservoir, the oxygen is rapidly transferred, and temperature destratification and sediment disturbance are minimized [37, 38]. The reservoir water displayed significant increases of dissolved oxygen in the hypolimnion and no substantial disruption of thermal stratification (Fig. 4). Finally, the author mentioned that TVA line diffuser can represent a beneficial resolution for meeting difficult dissolved oxygen requirements at hydropower projects. Because of the high oxygen transfer efficiency and operational ease, ensure costs are reduced.

Beutel [32] published a comparison between the hypolimnetic aeration systems. He focused on the associated costs and the effect on water quality. Table 4 shows the costs as well as the advantages and the disadvantages of the different oxygenation systems.

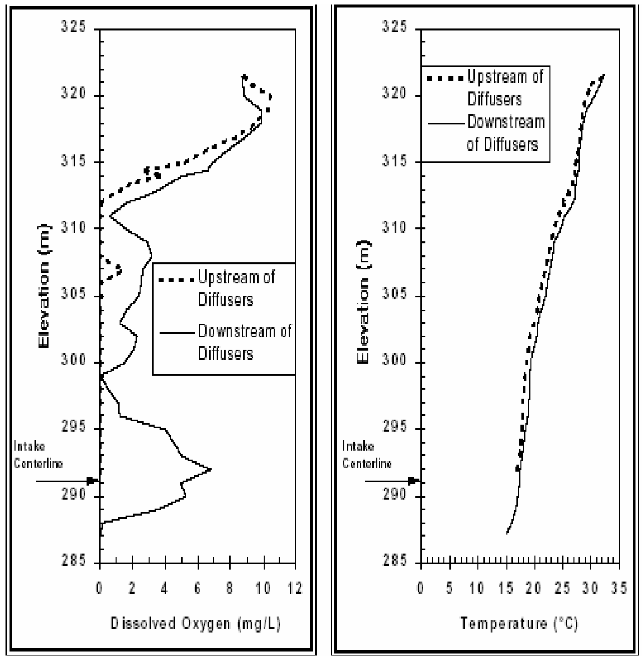


***Figure 4.*** Reservoir profiles at Cherokee Dam, August 14, 1995 [37].

***Destratification and hypolimnetic aeration systems:*** Ruane and his co-workers [39] compared two methods of aeration (Table 5) applied to the Patrick Henry Dam (south of Holston River, USA). They reported that destratification and hypolimnetic aeration are not applicable to the Patrick Henry Dam. They explained that the first method could increase the water temperature and consequently lead to ominous effects on the pisciculture, since the dam is classified as a coldwater fishery. In addition, the hypolimnetic aeration with air causes nitrogen supersaturation, and the aeration with oxygen is not promising due the high cost of oxygen [39]. The published results of the effect of oxygenation on the nitrogen concentration are not consistent. The total nitrogen and total ammonium diminish in some surveys, but increase in others [40].

In order to increase the oxygen content in the hypolimnion, oxygen gas can be used instead of air. The advantage of using oxygen gas is that a compressor is not necessary and oversaturation with nitrogen is avoided [39].

Steinberg *et al.* [21] studied hypolimnetic aeration during the summer months and tried to ensure continual thermal gradients. To allow dead algae to settle and minimize internal mixing, whole lake mixing in spring and autumn was proposed to provide maximum oxygen transfer and optimal nitrification at all depths. The authors emphasized that hypolimnetic aeration is 10 times more costly than intermittent destratification. Hypolimnetic aeration possibly will amplify the production by enhancing eddy diffusion [21].

## Positive Results of Hypolimnetic Aeration and Destratification Aeration

***Destratification aeration systems:*** Destratification is generally effective, especially when the presence of hydrogen sulphide, iron and manganese and other conditions associated with anaerobic water are problematic [19]. Destratification may limit the proliferation of algae, if the mixing is total and the lake has sufficient

**Table 4.** Oxygenation systems [32].

| System (reference) | Capital cost | Operational cost | Advantage | Disadvantage |
|---|---|---|---|---|
| Pure oxygen submerged chamber | $1 million | $ 850 | Very high oxygen transfer efficiency. Oxygen discharged horizontally over sediment-water interface. System efficiency independent on lake depth | Need for a submerged pump and chamber. |
| Deep pure oxygen U -tube | Not reported | $ 1.000 | Low operating cost compared to on shore chamber. System efficiency independent on lake depth. | Need to construct 175-foot deep U-tube. Pumping involved. |
| Diffuse deep-water oxygenation | $1 million | $ 1.000 | No pumping. Good horizontal distribution of oxygen. | Oxygen release above and away from sediment-water interface. System efficiency decreases with lake depth. May impact thermal stratification. |
| Shallow pure oxygen U-tube | Not reported | $ 1.200 | Tube only 20-30 feet deep. System efficiency independent of lake depth. | Pumping involved. Compared to deep U-tube, less oxygen delivered per unit flow through the system. |
| Bubble plume oxygenation | Not reported | Not reported | By pumping air through the diffusers, it can also be as destratification system. | System efficiency decreases with lake depth. Oxygen released above and away from sediment-water interface. System can impact thermal stratification. |
| Pure oxygen on shore pressurized chamber | Not reported | $ 3.000 | Most facilities on shore. System efficiency independent on lake depth. | High pumping cost. |

**Table 5.** Application domain of the aeration methods for the Patrick Henry Dam [28, 39].

| Conditions under which the aeration technique must be applied | Destratification | | Hypolimnetic aeration with diffusion | |
|---|---|---|---|---|
| | Mechanical pumping | Air diffusion | Air | Oxygen |
| Cold water | - | - | + | + |
| Strong increase in DO | - | - | ? | ? |
| Minimal effect on the production of energy | + | + | + | + |
| Minimal increase in the dissolved nitrogen | ? | ? | ? | + |
| Small cost | + | + | - | - |

+ a positive effect on the particular aeration method, - a negative effect on the particular aeration method, ? an unknown effect for the shown condition

depth in its euphotic region [19]. Many studies showed a substantial increase in the distribution of fish depth associated with destratification [19]. In winter, the destratification system can prevent the fish killing by ice covering the lakes [19, 41]. Sometimes, the destratification can increase the fish production by bringing to the surface the nutritional elements regenerated from the hypolimnion, which are not precipitated by the increase of the reduction-oxidation potential or by the $CaCO_3$ [16]. Destratification using the bubble plume system may have some effect on the water quality, because these plumes can occupy the whole water column or compartmentalize this water column by a plume cascade. This has a large impact on the water quality. For instance, a high concentration of nutrients from the lake sediments can be transferred rapidly to the photic region by a bubble plume that occupies the whole water column. In contrast, a plume cascade should have a small transfer capacity of nutritional elements. Also, in some circumstances, a plume cascade may be undesirable, although the mixing efficiency is small [42].

***Hypolimnetic aeration systems:*** The hypolimnetic aeration has many advantages over the destratification system. The nutrients (nitrogen and phosphorus) are not transported to the epilimnion where they can stimulate algae growth, and the process can preserve a cold water habitat for fishes such as salmon and trout[43]. The advantage of hypolimnetic aeration is the potential to re-supply dissolved oxygen while preserving the thermal stratification [22]. McQueen and Lean [18] concluded that a well conceived oxygenation system can maintain the stratification and need not significantly increase the temperature of the hypolimnion water [18]; the level of hypolimnion oxygen increases [44]; the concentrations of iron, manganese, hydrogen sulphide and methane decrease [18, 44]; the population of zooplankton is not affected in general [18]; the concentrations in chlorophyll A are typically not changed [18]; the depth distribution of cold water fish populations is increased [18] and hypolimnetic aeration has no effect on the depth distribution of algae.

The most promising means by which the hypolimnetic aeration may affect the algae density are the modification of the nutrient cycle and creation of a change in the composition of species and the zooplankton density, the benthic fauna and other trophic levels[19].

Hypolimnetic aeration can increase the diversity of species by the creation of an adequate habitat for coldwater fishes [19]. Sometimes, hypolimnetic aeration is preferred over destratification in the management of fisheries and in the supply of domestic and industrial water, since the total mixing may promote an increase of algae [16, 19].

Fast [19] reported that hypolimnetic aeration creates an adequate habitat for coldwater fishes in different lakes where no previous aeration has been carried out. Hypolimnetic aeration can also be used to prevent winter fish death. The application of this system during the summer yields the oxidation of organic materials and subsequently reduces the oxygen demand in winter [19]. Other advantage of hypolimnetic oxygenation [32] is weak rate of water recycling minimizing the turbulence in the hypolimnion thus reducing SOD and limiting accidental destratification. It maintains a high level of DO during the whole period of stratification, and energy cost is low.

### Negative Results of Aeration Systems

It has been reported that the aeration using air compression raises the nitrogen gas concentration and consequently may cause fish death [22, 43]. However, McQueen and Lean found no unfavorable effect on the fish population [43]. The concentration of hypolimnetic nitrogen in Waccabuc Lake increased to 150% of saturation for 80 days during continuous hypolimnetic aeration (Fig. 5) [19]. The use of oxygen injection helps to avoid problems related to nitrogen oversaturation [32]. Also, the destratification system could increase the water temperature, while the air hypolimnetic aeration may cause the problem of nitrogen oversaturation [35, 39]. The destratification system is less effective in the reduction of algae[19].

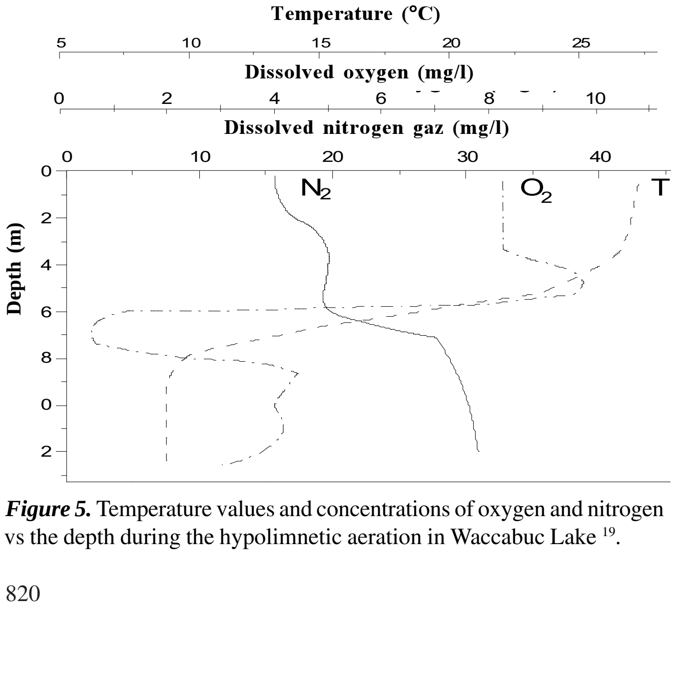


*Figure 5.* Temperature values and concentrations of oxygen and nitrogen vs the depth during the hypolimnetic aeration in Waccabuc Lake [19].

Destratification increases the sediment temperature as well as the water flow on the sediments, which would increase the phosphorus exchange rate with the sediments [19]. Destratification can increase the growth of nutritional elements in the eutrophic region and hence stimulate algae growth [19].

When the lake is strongly eutrophied and contains an active mud layer, hypolimnetic aeration cannot by itself maintain a production of respiratory equilibrium and cannot even limit this equilibrium. The circulation of the hypolimnion in small lakes causes the movement of nutrients (phosphate) by eddy diffusion from the hypolimnion to the metalimnion, where the phytoplankton biomass (principally the blue green algae) is significantly increased[12].

The artificial destratification in Casistas Calif Lake (San Diego, USA) caused excess oversaturation of nitrogen to about 140% relative to the surface pressure (Fig. 6) [19]. Fast [19] mentioned that all the parameters affecting the nitrogen concentration during the destratification with air compression are unknown. He concluded that they include probably the mixing level, the air bubble density, the plume's vertical speeds, the depth of the air injection, the quotient of the water total volume to the total injected air volume and finally the water oxygen content.

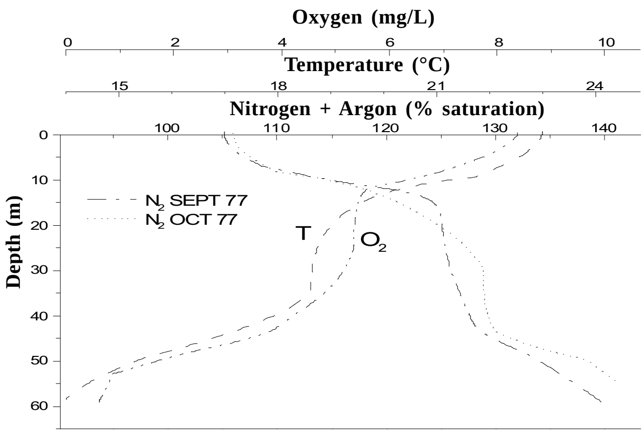


*Figure 6.* Concentrations of oxygen, nitrogen and temperature values vs the depth during the destratification aeration in Casistas Calif Lake [19].

Aeration by destratification may result in numerous harmful impacts on the lake. These systems give rise to a microthermal stratification near to the surface, which may result in an increase in algal growth [19, 24].They provoke a temperature rise in the lake during the summer, eradicating cold water species such as trout and salmon [15, 19, 35]. The change in some chemical properties as the concentration of nitrogen and phosphorus could present a problem for the distribution of fishes, zooplankton, benthic fauna and other biota [19].

According to Kirke and El Gezawy [45], the method of destratification has three problems. 1) It consumes a lot of energy: The compressors use power range of 37 to 100 kW, and they can be ineffectual for large reservoirs. 2) A plume thrust is not able to penetrate a thick thermocline and the destratification is achieved only by the friction process of air bubbles, with ineffective mixing.

3) Introduction near the lake floor of high energy can increase the turbidity and hence disturb the sediments and release of nutrients.

## Conclusions

It has been shown in the studies described above that all the mechanical aeration techniques have both advantages and disadvantages. For the restoration of a lake or a reservoir, a system must satisfy both technical and economic aspects. Aeration by destratification is a simple technique which needs less means compared to hypolimnetic aeration, but at the same time remains inefficient in the conservation of the thermal equilibrium of lakes. Technically, hypolimnetic oxygenation is most efficient but is more costly.

This study allows us to conclude that the aeration by oxygen limits the nitrogen saturation; in contrast the aeration by air creates it. The most efficient hypolimnetic aeration system is the bubble plume diffuser; although an accidental destratification may occur. In shallow reservoirs, these systems should be avoided, because it can entrain the colder, hypolimnion water and carry it through the thermocline into the epilimnion and to the surface by the momentum induced by the bubble plume. Destratification can be used in winter because the temperature of the lake is not modified. However, the hypolimnetic aeration is used in summer in order to avoid the homogenization of the lake temperature during this period. For reservoirs and dams, summer destratification is not profitable due to the warming-up of the reservoir water which can be a problem.

Nevertheless, some experiments showed that the mechanical aeration is not lasting for the following reasons. Duct pipes are frequently plugged by algae and, consequently, become difficult to use. When the mechanical aeration is stopped, the lake rapidly becomes eutrophic. Mechanical aeration equipment is generally placed about 7 cm above the lake floor. This does not allow restoring the region below and therefore leads to the hypoxia and disappearance of fishes living near the lake floor.

Consequently and according to the depth and dimension of the exploitations, we can distinguish two kinds of restorations: the restoration by destratification appears to be most adaptable during the cold months and to shallow lakes or reservoirs whose use is exclusively agricultural. Hypolimnetic aeration suits deep lakes or reservoirs that have different uses (feeding, irrigation, leisure, etc...), allowing the amortization of the invested fees for the system. However, it should be noted that in the case of lakes or reservoirs used for fish farming, the hypolimnetic oxygenation limits the amount of nitrogen introduced as compared with systems that aerate using air, and guarantees the preservation of the fish.

## References


[1]Davis, J. M. 1980. Destratification of reservoirs - A design approach for perforated-pipe compressed-air systems. Water Serv. **84**:497-505.

[2]Zic, K., Stefan, H.G. and Ellis, C. 1992. Laboratory study of water destratification by a bubble plume. J. Hydraul. Res. **30**(1):7-27

[3]Steinberger, N. and Hondzon, M. 1999. Diffusional mass transfer at sediment-water interface. Journal Environmental Engineering **125**(2):192-200.

[4]Chen, M.H, and Cardoso, S.S.S. 2000. The mixing of liquids by a plume of low-Reynolds number bubble. Chemical Engineering Sciences **55**:2585-2594.

[5]Kobus, H.E. 1968. Analysis of the flow induced by an air-bubble system. In Proc. 11th Conf. Coastal Eng., London, ASCE, pp. 1016-1031.

[6]Aseada, T. and Imberger, J. 1993. Structure of bubble plumes in linearly stratified environments. J. Fluid Mech. **249**:35-57.

[7]Baines, W.D. and Leitch, A.M. 1992. Destruction of stratification by a bubble plume. J. Hydraul. Eng. ASCE **118**:559-577.

[8]Wen, J. and Torrest, R.S. 1987. Aeration-induced circulation from line sources. I: Channel flows. J. Environ. Eng. **113**(1):82-98.

[9]Wilkinson, D.L.1979. Two-dimensional bubble plumes. Journal of Hydraulic Division ASCE, **105**(2):139-154.

[10]Brevik, I. and Kristiansen, Ø. 2002. The flow in and around air-bubble plumes. Int. J. Multiphase Flow **28**(4):617-634.

[11]Hussain, N. A. and Narang, B.S. 1984. Simplified analysis of air-bubble plumes in moderately stratified environments. Journal of Heat Transfer ASME C **106**:543-551.

[12]Bernhardt, H. and Clasen, J. 1985. Recent developments and perspectives of restoration for artificial basin used for water supply. Intern. Congr. on Lake Pollution and Recovery, pp. 213-227.

[13]Janczak, J. and Kowalik, A. 2001. Assessment of the efficiency of artificial aeration in the restoration of Lake Goplo. Limnogical Review **1**:151-158.

[14]Brzozowska, R., Gawronska, H. and Grochowska, J. 2001. Nutrient release from the bottom sediments of artificially aerated Lake Dlugie. Limnogical Review **1**:25-32.

[15]McGinnis, D.F., Little, J.C. and Wuest, A. 2001. Hypolimnetic oxygenation: Coupling bubble-plume and reservoir models. Proceedings of Asian WATERQUAL 2001, IWA Regional Conference, Fukuoka, Japan.

[16]Fast, A.W., Moss, B. and Wetzel, R. G. 1973. Effets of artificial aeration on the chemistry and algae of two Michigan Lakes. Water Resources Research **9**:624-647.

[17]Wuest, A., Brooks, N.H. and Imboden, D.M. 1992. Bubble plume modelling for lake restoration. Water Resources Research **28**(12):3235-3250.

[18]McGinnis, D.F., Lorke, A., Wuest, A., Stockli, A. and Little, J.C. 2004. Interaction between a bubble plume and the near field in a stratified lake. Water Resources Research **40**(10):W10206, doi:10.1029/2004WR003038.

[19]Fast, A.W. 1978. Artificial aeration as a lake restoration technique. Proceedings of National Conf. on Lake Restoration, pp. 121-131.

[20]Gafsi, M., Kettab, A., Benmamar, S. and Benziada, S. 2005. Etat de Connaissance sur les différents systèmes mécaniques impliqués dans la restauration des lacs et réservoirs. Congrès International sous le Thème: De l'Eau pour le Développement Durable dans le Bassin Méditerranéen, LRS-EAU/RMEI, le 21-22-23 Mai, 2005, Alger, Algérie. Algerian Journal of Technologie (AJOT), Special Issue, pp. 363-373.

[21]Steinberger, C. and Zimmermann, G. M. 1988. Intermittent destratification: A therapy measure against Cyanobacteria in lakes. Environmental Technologie Letters **9**:337-350.

[22]McGinnis, D.F. and Little, J.C. 2002. Predicting diffused-bubble oxygen transfer rate using the discrete-bubble model. Water Research **36**:4627-4635.

[23]Singleton, V., Gantzer, L.P. and Little, J.C. 2007. Linear bubble plume model for hypolimnetic oxygenation: Full-scale validation and sensitivity analysis. Water Resour. Res. **43**(2):W02405.

[24]McDougall, T. J. 1978. Bubble plumes in stratified environments. J. Fluid Mech. **85**(4):655-672.

[25]Fast, A.W., Overholtz, W. J. and Tubb, R. A. 1975. Hypolimnetic oxygenation using liquid oxygen. Water Resources Research **II**:294-299.

[26]McGinnis, D.F. and Little, J.C. 1997. Nutrient control in Standley Lake: Evaluation of three oxygen transfer devices. Proceedings of the IAWQ/IWSA Joint Specialist Conference Reservoir Management and Water Supply - An Integrated System, Prague, Czech Republic.

[27]Singleton, V. L. and Little, J.C. 2006. Designing hypolimnetic aeration and oxygenation systems. Environmental Sciences and Technology **40**(20):7512-7520.

[28]Gafsi, M., Kettab, A., Benmamar, S. and Benziada, S. 2006. L'eutrophisation dans les eaux de surface; causes, effects et luttes. Third International Conference on Water Resources in Meditererranean Basin, Watmed 3, Tripoli, Lebanon, pp. 1-3.

[29]McGinnis, D.F. and Little, J.C. 1998. Bubble dynamics and oxygen transfer in Speece cone. Proceedings of the IAWQ/IWSA Joint Specialist Conference, Reservoir Management and Water Supply- An Integrated System, Prague, Czech Republic.

[30]Singleton, V. L. and Little, J.C. 2006. Designing hypolimnetic aeration and oxygenation systems. Environmental Sciences and Technology **40**(20):7512-7520.

[31]Gafsi, M., Kettab, A., Benmamar, S. and Benziada, S. 2007. L'aération artificielle et ses effets sur le contrôle de la pollution dans les réserves. Acte du 9[ime] Symposium International de Cannes, France.

[32]Beutel, M. 2002. Improving Raw Water Quality with Hypolimnetic Oxygenation. AWWA 2002 Annual Conference Marc Beutel, Brown and Caldwell Environmental and Consulting 201 North Civic Drive, Walnut Creek, CA 94596 925-210-2844

[33]Gafsi, M., Kettab, A., Benmamar, S. and Benziada, S. 2004a. L'eutrophisation dans les eaux de surface: Effets comparés des systèmes d'aérations. Proceedings Séminaire International sur l'Eau dans le Contexte Saharien. Université de Laghouat, Algeria.

[34]Kortmann, R.W., Knoecklein, G.W. and Bonnell, C. H. 1994. Aeration of stratified lakes: Theory and practice. Lake and Reserv. Manage. **8**(2):99-120.

[35]Speece, R. E. 1994. Lateral thinking solves stratification problems. Water Quality WQI **3**:12-15.

[36]Kettab, M., Gafsi, M., Benmamar, S. and Benziada, S. 2005. Etudes comparatives des différents systèmes mécaniques impliques dans la restauration des lacs et réservoirs. Proceedings 6[th] International Conference, Menton, "Sharing a Common Vision for Our Water Resources".

[37]Mobley, M.H. 1997. TVA Reservoir Aeration Diffuser System. Technical Paper 97-3 Presented at WaterPower 97, August 5-8, 1997, Atlanta, Georgia.

[38]Mobley, M.H. and Proctor, W.D. 1997. Richard B. Russell Forebay Aeration Using Line Diffusers: Cost Comparison with Existing System. Tenessee Valley Authority Resource Group, Engineering Services, Engeneering Laboratory, Norris, Tenessee.

[39]Ruane, R. J., Vigander, S. and Nicholas, W. R. 1977. Aearation of hydro releases at Ft. Patrick Henry Dam. Proceedings of American Society of Civil Engineers **103**(HY10):1135-1145.

[40]Burris, V. L., McGinnis, D. F. and Little, J.C. 2002. Predicting oxygen transfer and water flow rate in airlift aerators. Water Research **36**:4605-4615.

[41]McCord, S. A., Schladow, S. G. and Miller, T. G. 2000. Modeling artificial aeration kinetics in ice-covered lakes. Journal of Environmental Engineering **126**(1):21-31.

[42]Schladow, S.G. 1992. Bubble plume dynamics in stratified medium and the implications for water quality amelioration in lakes. Water Resources Research **28**(2):313-321.

[43]Burris, V.L., McGinnis, D. F. and Little, J. C. 2002. Predicting oxygen transfer and water flow rate in airlift aerators. Water Research **36**:4605-4615.

[44]Little, J.C. and McGinnis, D.F. 2000. Hypolimnetic oxygenation: Predicting performance using a discrete-bubble model. Proceedings of 1[st] World Water Congress, International Water Association (IWA), Paris, France.

[45]Kirke, B. and El Gezawy, A. 1997. Design and model tests for an efficient mechanical circulator/aerator for lakes and reservoirs. Water Research **31**(6):1283-1290.

[46]Scott, W. and Foley, A.L. 1921. A method of direct aeration of stored water. Proc. Ind. Acad. Sci. **1919**:71-73.