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LAYER AERATION: A FIFTEEN YEAR STUDY OF SOURCE WATER QUALITY IMPROVEMENTS

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INTRODUCTION

Water supply quality has historically been addressed almost exclusively by the design of Water Treatment Plants**.** “Source of supply considerations” dealt with water *quantity*, with very little consideration of water quality effects in watersheds, diversions, storage and distribution reservoirs. Source water facilities were designed to supply adequate quantities to the WTP to meet demands.

Water supply quality goals and regulations are changing. Prechlorination steps are being eliminated to reduce DBPs. Existing coagulation-flocculation systems (originally designed for turbidity removal) are being “enhanced” to remove natural organic matter prior to disinfection. Alternative coagulants, operational pH, disinfectants, and oxidizing and buffering agents are being changed. Utilities are seeking methods to provide higher quality finished water (to reduce DBPs, avoid protozoan cysts, control corrosion, reduce taste and odor, etc.), often by modified processes within existing WTP facilities. Often the existing WTP infrastructure and process sequence limitS options (e.g. EBCT for retrofit activated carbon, and CxT for adequate disinfection).

With the increased demand for higher quality finished water has come a renewed need to improve source raw water quality. Management of the “source system” can provide a consistent source of higher quality raw water with lower concentrations of DBP precursors, lower risk of taste and odor episodes, reduced turbidity and color, and reduced risk of a pathogen breakthrough. Indeed, several supply water quality regulations are directly related to the source waters. For example, enhanced coagulation uses a raw water TOC-Alkalinity matrix to establish guidelines for %TOC removal.

Watershed Management: Non-Point Source Controls, and Best Management Practices for a variety of land-uses, are essential for long-term protection of water supplies. Comprehensive and quantitative “Resource Allocation Techniques” are available for guiding effective watershed protection programs.

Tributaries and Diversions: In many source systems the timing, withdrawal/discharge location, and treatments of supply diversions can avoid raw water quality impacts. Improvements to tributary streams, such as low-head reaeration weirs, nutrient inactivation, and wetland enhancement/creation, can improve water quality en-route to a reservoir.

Storage Reservoirs: Many source systems have storage reservoirs (designed for water quantity) which can be operated in a manner which improves raw water quality. Methods such as depth-selective release, reservoir sequencing and blending, aeration technologies, nutrient inactivation, and biomanipulation can be very cost-effective in storage reservoirs.

Terminal Reservoirs: The terminal surface water supply reservoir provides an opportunity to manage raw water quality immediately prior to treatment. Although other "upstream" source components warrant management consideration, water in the terminal reservoir has a direct relationship to WTP processes. In a very real sense, the "terminal reservoir" is the first "treatment chamber" of a water treatment plant. Raw water quality control techniques for terminal reservoirs include *Physical, Chemical, and Biological Methods*.

Physical Methods: Deep Releases and Depth-Selective Withdrawal, Flow Routing, Artificial Circulation, Hypolimnetic Aeration, and Depth-Discrete Layer Aeration.

Chemical Methods: Nutrient Inactivation, Alternative Algicides, Focused Algicide Applications, Buffering System Management, Enhanced Decalcification.

Biological Methods: Biomanipulation, Habitat Management for Water Quality.

As the supply of organic matter to a reservoir increases (for example due to increasing weed and algae growth in response to "eutrophication"), respiration in the lake increases. As respiration increases the demand for terminal electron acceptors (oxygen in aerobic organisms) in respiration pathways increases. The ultimate result in a thermally stratified reservoir is oxygen loss, the accumulation of nutrients, iron, manganese, hydrogen sulfide, etc. Raw water quality becomes poor, and leads to a variety of water treatment problems, including: taste and odor episodes, shortened filter runs and increased backwash volume, shortened GAC substrate longevity, increased TOC and chlorine demand (hence higher DBP formation potential), increased turbidity, increased sludge production, and potentially toxic substances if certain genera of Cyanobacteria become dominant. Recent studies suggest that some DBP precursors (particularly HAA precursors) increase as anaerobic respiration intensifies.

Warm water is less dense than cold water. Hence, warm water floats on colder water. This is why a reservoir is warm at the surface and cold at the bottom during the summer. Thermal stratification limits the input of atmospheric oxygen to deep waters; respiration consumes oxygen faster than it is replenished. Oxygen loss results, followed by anaerobic respiration which leads to nutrient build-up, and the accumulation of anaerobic respiration products (carbon dioxide, iron, manganese, sulfide). In order to remedy these "consequences of eutrophication" a variety of aeration methods have been developed to increase the aerobic respiration capacity of a lake or reservoir. The aeration technologies available today are described below.

Aeration Strategies

Over the past 50 years, a variety of aeration methods have been employed for lake management. The first method used was artificial circulation by diffused air-lift pumping (Fast, 1977), mechanical pumping (Hooper et al., 1953; Ridley et al. 1966; Symons et al., 1967) and other means (Ridley et al., 1966; see: Fast, 1977). The principle of artificial circulation is to destroy or prevent the development of thermal stratification. This strategy works best in nutrient-rich lakes, where nutrient control is not feasible, when oxygen depletion is a threat to warm water fisheries, and for control of metals accumulation in storage reservoirs (Cooke, et al. 1986). Lake temperature is homogenized which adversely impacts coldwater fishery habitat and zooplankton refugia (Kortmann et al., 1988; Kortmann and Henry, 1987). In over 50 percent of reported case studies water clarity declined following artificial circulation (Pastorak, et al. 1982). Artificial circulation eliminates the use of depth-selective supply withdrawal for optimizing raw water quality from distribution reservoirs (Kortmann et al. 1988; Kortmann, 1989; Cooke and Carlson, 1989). The benthic flux of dissolved constituents from sediment-interstitial to overlying waters is driven by Fickean Diffusion and is a function of the concentration gradient across the sediment interface (Kortmann, 1980; Kortmann, 1981). Perhaps the most important, and least well known, effect of artificial circulation is the intensification of concentration differential at the benthic interface and consequential benthic flux of a variety of pore-water constituents. Epilimnetic expansion may accomplish management goals in some cases while reducing adverse impact potential (Kortmann, 1991).

> *"Artificial aeration, probably more than any other restoration process, directly effects almost all aspects of the lake ecosystem -- nutrient cycling, water chemistry, the heat budget, bacteria, phytoplankton, zooplankton, zoobenthos, and the fish. It directly effects distribution of these things as well as their rates of changes."* Arlo W. Fast (1977)

The second aeration approach to be developed was hypolimnetic aeration. The principle of hypolimnetic aeration is to aerate the cold isothermal hypolimnion to avoid perturbation of the thermal-density structure of the metalimnion. A variety of methods and apparatus have been used. The first aerators utilized a full airlift pumping process (Fast, 1976; Bernhardt, 1967). Pumped, side stream systems have been used with air or liquid oxygen (Fast et al., 1975b). Partial airlift (submerged) hypolimnetic aerators (Fast et al., 1975) have become the most commonly used hypolimnetic aerators in recent years (Cooke et al. 1986); even though oxygen transfer efficiencies are greater in full-airlift systems (Fast 1975a; 1976; Kortmann et al., 1988).

Hypolimnetic aeration offers many aeration benefits while reducing, or eliminating, perturbation of the thermal-density structure of a stratified lake and the biological communities related to that physical structure. Hypolimnetic aeration has, in some cases, been effective at improving hypolimnetic oxygen content, cold water habitat, reducing sediment-P release, and controlling the accumulation of anaerobic respiration products (Fe, Mn, S=), and amino acid deamination (NH4+) (Bernhardt, 1967; Garrell et al. 1978; McQueen and Story, 1986; Lean et al., 1986; McQueen and Lean, 1984; 1986; Kortmann et al. 1988; Kortmann, 1989). However, hypolimnetic aeration has been less effective at reducing phytoplankton abundance, dominance by Cyanobacteria, and phosphorus availability in surface waters than originally expected. In some cases, epilimnetic and metalimnetic phosphorus, phytoplankton biomass, and Cyanobacteria dominance increased (Steinberg and Arzet, 1984). High rates of oxygen consumption often result in anoxic metalimnia. Increased diffusion across the thermocline, metalimnetic anoxia, and related effects on phosphorus availability and habitat refugia appear to be the main limitations of hypolimnetic aeration (Cooke et al. 1986; Kortmann, 1988). A review of hypolimnetic aeration suggests that the method is most appropriate where the aerobic-anaerobic interface remains below the thermocline (i.e. metalimnion remains oxic), and where sufficient iron is available to bind phosphorus. When reduced ferrous iron is removed as insoluble ferrous sulfide, phosphorus binding capacity diminishes. When the ferric-ferrous iron couple dominates benthic detrital electron flux (Wetzel and Rich, 1973; Kortmann 1980; 1981), effects on phosphorus control by hypolimnetic aeration are more predictable.

Layer Aeration

During the early 1980's Layer Aeration was developed to manage aerobic respiration capacity of a supply reservoir and related water quality relationships. Unlike the previous two methods which are very dependant on the "mechanical" oxygen input, Layer Aeration uses biological oxygen sources in addition to compressed air gas phase transfer. Oxygen produced by photosynthesis is used to help meet respiratory oxygen demand in deeper waters. The method is very useful for cost-effective water supply quality improvement, especially when several vertical supply intake gates are available for supply withdrawal. This paper presents results of a fifteen-year Layer Aeration program at a water supply reservoir in Connecticut.

Site Description

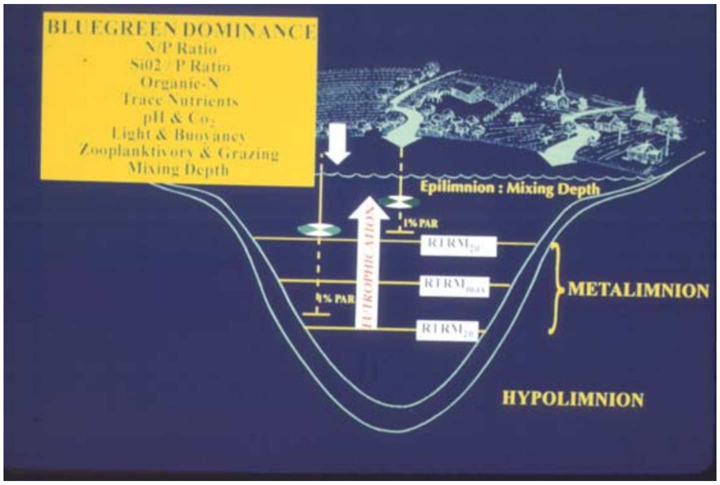
During the early 1980's, Lake Shenipsit regularly exhibited bluegreen algae blooms including *Anabaena sp.* (shown at left) and *Aphanizomenon sp.* which resulted in summer taste and odor episodes and shortened GAC substrate longevity.

Lake Shenipsit covers 212 ha (523 acres) to mean and maximum depths of 9.9m (32 ft) and 20.7m (68 ft), respectively. Lake Shenipsit exhibits a limited littoral zone where rooted aquatic vegetation can establish. Only 8% of lake area is less than two meters deep. The volume:sediment contact area ratio between 6 and 12 meters is disproportionately large (metalimnetic depth range). This was one reason for selection of a layer aeration strategy.

The watershed drainage basin was divided into ten subbasin units, and land-use fractions were computer digitized from areal photographs. Total annual external phosphorus loading was estimated at 1002 kg TP yr^{-1} (475 mg m^{-2} yr^{-1}). This estimate was used to design a tributary sampling program on a storm event, flowstage schedule, and to focus watershed management efforts in subbasins with the highest areal TP export rates. All loading estimates indicate that Lake Shenipsit is eutrophic.

Lake Shenipsit provides water for a large distribution area (12 towns; 60,000 customers). The water treatment plant is a conventional system with coagulation, flocculation, and filtration. The original anthracite-sand filters were replaced with retrofit granulated activated carbon (GAC) filters to control taste and odor episodes related to summer Cyanobacteria, and fall-winter-spring chrysophyte and diatom blooms. Although GAC substrate longevity was designed at 3 years based on empty bed contact time, during the most intense bloom years in the early 1980's substrate changes were done on a 9 month cycle. The premature breakthrough of the GAC beds was caused, in part, by organic loadings from *Synura sp.*, *Anabaena sp.*, *Aphanizomenon sp.*, and *Asterionella sp.* blooms.

The anaerobic respiration system is dominated by the use of iron as an alternate terminal electron acceptor. Much of the lake bottom, throughout the metalimnetic and hypolimnetic depth ranges, became anaerobic. That resulted in reduction of the oxidized microzone at the sediment surface (shown at left), and the release of phosphorus to the water column. Internal P loading was a significant factor which caused bluegreen blooms.



BLUEGREEN DOMINANCE
N/P Ratio
Si02 / P Ratio
Organic-N
Trace Nutrients
pH & Co$_2$
Light & Buoyancy
Zooplanktivory & Grazing
Mixing Depth

There are a number of “theories and hypotheses” regarding why bluegreen algae become the dominant phytoplankton, including the N:P ratio, silica depletion, light penetration, organic N, inorganic carbon source, food web dynamics, etc. Many of these hypotheses relate to the structure of thermal stratification, fluxes across the metalimnion, and light penetration to the thermocline (illustrated above right).

Raw water intakes are located at 3.5 m (12 ft.) and 6.7 m (22 ft.) below spillway. Although supply:demand variation does not result in significant fluctuation in pool elevation, intentional releases of epilimnetic waters lower lake level by approximately 1 to 1.5 m in August (prior to hurricane season). Hence, intake depth ranges used to establish design criteria were 2.5-3.5 m (upper intake) and 5.7 - 6.7 m (deep intake).

Methods

Aeration Process

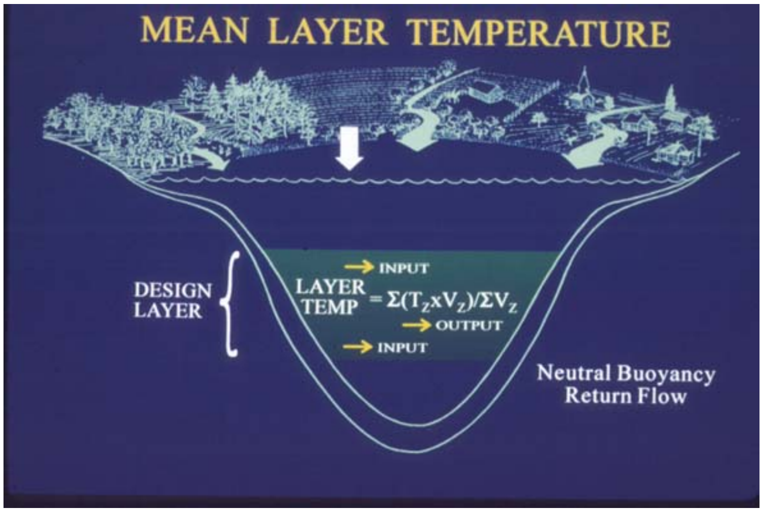
In an effort to alleviate in-lake nutrient loading (as evidenced by spring to fall TP increase) and unsatisfactory raw water quality, an aeration system was designed specifically for Lake Shenipsit, to take advantage of its natural properties (oxygen availability and demands, heat distribution, stratification structure, compensation depth, and vertical intake depths). Three Layer Aerators with selective depth inflows and outflows were used to aerate and circulate waters from 4.7m to 10.7m. The layer aeration depth range was selected based on iterative computer simulation modeling of heat and available dissolved oxygen mass, volume-sediment contact area ratios, thermal resistance to mixing as a function of temperature, and supply intake depth ranges. The following were the main objectives and design criteria:

1. Facilitate selection of the supply intake depth to avoid buoyancy controlled Cyanobacteria (e.g. *Anabaena sp.*) if bloom episodes persisted.
2. Use of neutrally buoyant aerator return flow to optimize reservoir-wide effects.
3. Use of photosynthetic oxygen production and downward diffusional transport as oxygen sources, reducing dependence on gas-solute phase transfer..
4. Maintenance of cold layer temperatures and strong thermal resistance to mixing at the top and bottom of the layer; reducing the area and volume of the high DO demand hypolimnion.
5. Two small hypolimnetic aerators were installed to divert excess airflow (when not needed in the layer) to the now smaller hypolimnion for "anaerobic aeration" (operating the bottom in the nitrogen cycle to prevent P release, despite anoxia). It was not the intent to accomplish measurable DO in the deep strata. Rather, it was intended to raise redox potential, enhance nitrification and subsequent denitrification, and reduce sulfide production which could lead to reduced P binding capacity (via ferrous sulfide).
6. Layer temperature and oxygen criteria were established in relation to brown trout and *Daphnia sp.* habitat suitability requirements to provide habitat not isolated from the epilimnion by metalimnetic anoxia. These criteria were established to accommodate future biomanipulation efforts.

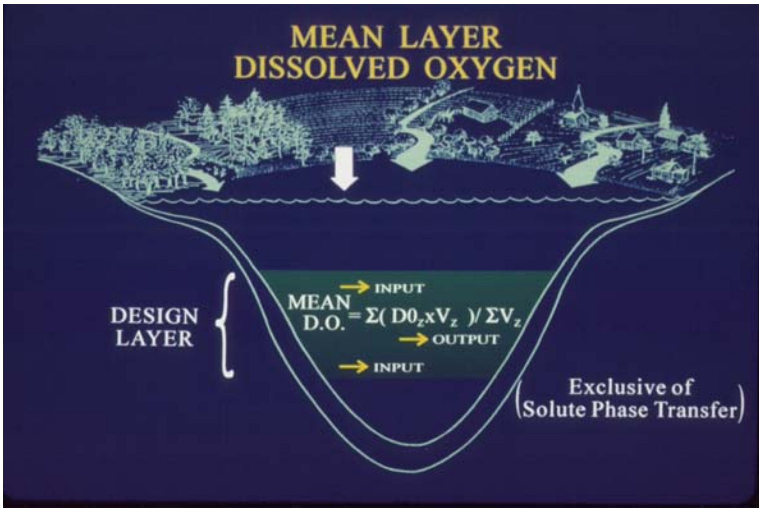
In addition to these main objectives and features, a complete destratification system was integrated into the system (total capacity = 1.5 x $10^6 m^3 d^{-1}$; 400 MGD) for temporal use (spring, fall, winter thermal treatment).

The Layer Aeration System has been operated each summer (approximately May 1 through October 15) each year since it was installed in 1987.

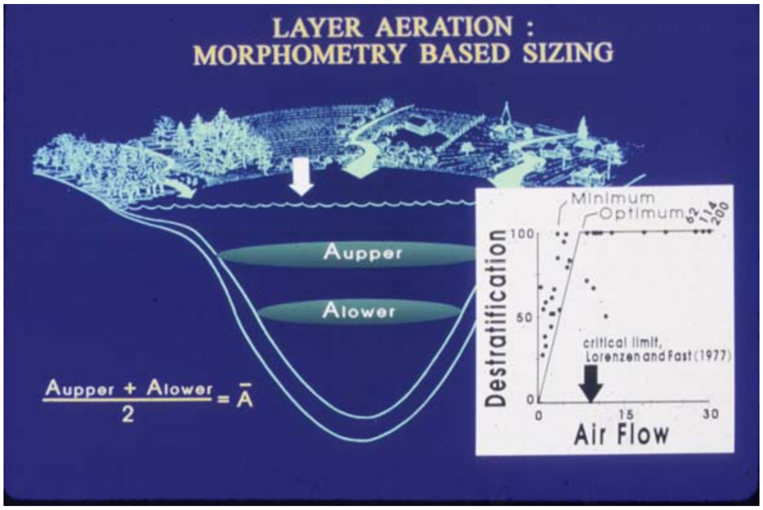
Layer Aeration – Principles and System Components



In Layer Aeration, a mixed layer is created in the middle depths of the water column, with thermoclines above and below the layer. The mean Layer temperature can be estimated by a detailed heat budget within the Layer design depth range. Thermocline strength can then be forcast using temperature differentials above and below the layer.



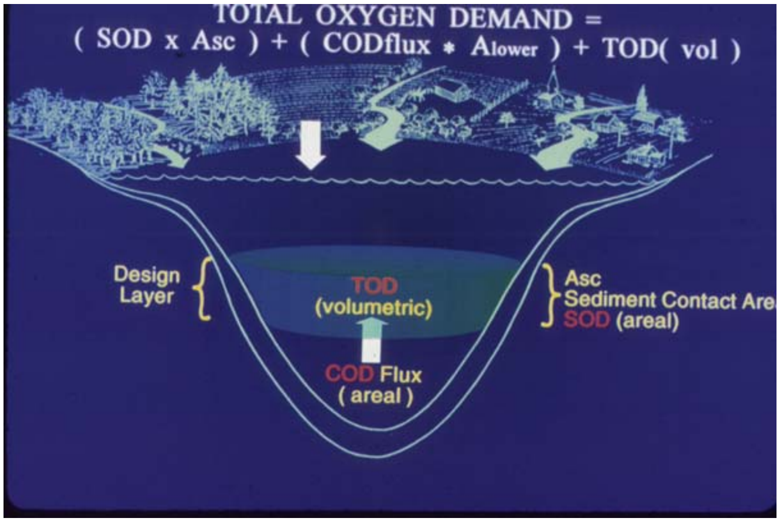
Layer aeration takes advantage of available ambient dissolved oxygen sources rather than relying solely on gas-solute phase transfer. A detailed DO mass computation through the Layer depth range can be used to estimate the oxygen redistribution function of Layer Aeration.



LAYER AERATION : MORPHOMETRY BASED SIZING

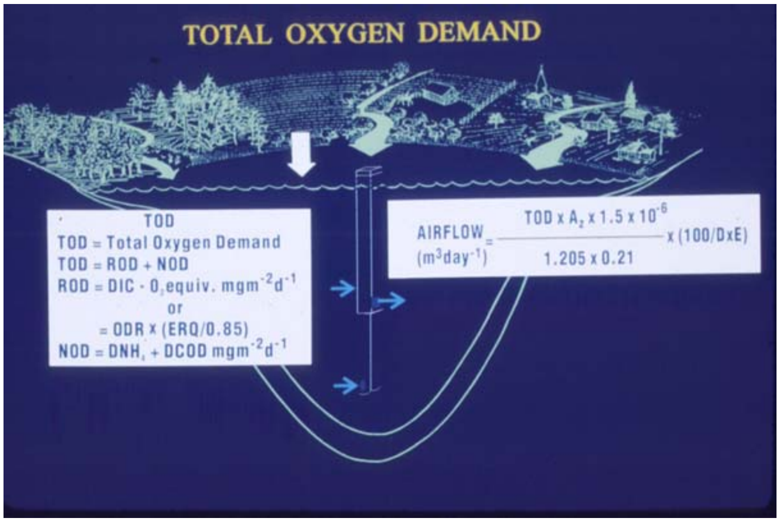
$$\frac{A_{upper} + A_{lower}}{2} = \bar{A}$$

Because Layer Aeration is analogous to "destratifying a discrete depth range" the first sizing estimate is from research on destratification systems (only using the area at the depth of the layer rather than the entire surface area). This provides an initial estimate of SCFM airflow requirements.



TOTAL OXYGEN DEMAND = (SOD x Asc) + (CODflux * Alower) + TOD(vol)

Sources of oxygen demand then need to be computed, including sediment oxygen demand (layer sediment contact area), upward flux of bottom generalte constituents, and volumetric demand within the layer volume.



TOTAL OXYGEN DEMAND

TOD

TOD = Total Oxygen Demand

TOD = ROD + NOD

ROD = DIC - O_2 equiv. $mgm^{-2}d^{-1}$

or

= ODR x (ERQ/0.85)

NOD = DNH_4 + DCOD $mgm^{-2}d^{-1}$

$$\underset{(m^3day^{-1})}{AIRFLOW} = \frac{TOD \times A_z \times 1.5 \times 10^{-6}}{1.205 \times 0.21} \times (100/D \times E)$$

Once the Total Oxygen Demand has been computed, determining airflow capacity becomes an exercise in the application of gas laws and aerator efficiency terms.

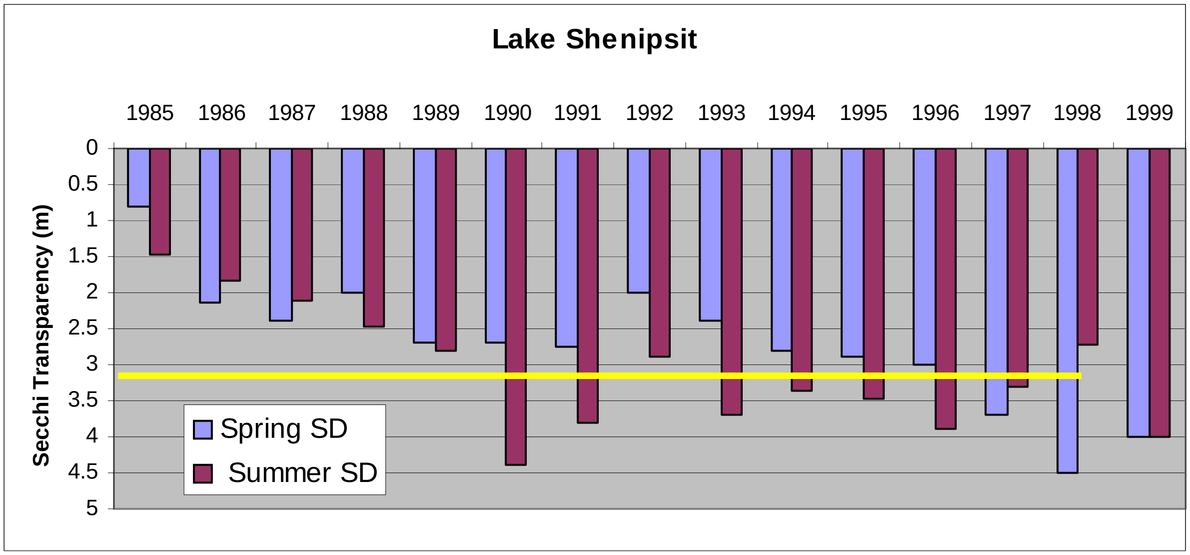
The Layer Aeration System at Lake Shenipsit is driven by two 30HP rotary screw compressors. The compressors were installed in the treatment building (for long-term operation convenience), and compressed air is conveyed through several miles of piping to five aeration stations.

A set of three Layer Aerators, and two aerators which aerate the deeper hypolimnion (reduced area and volume) are located in the lake.

Results

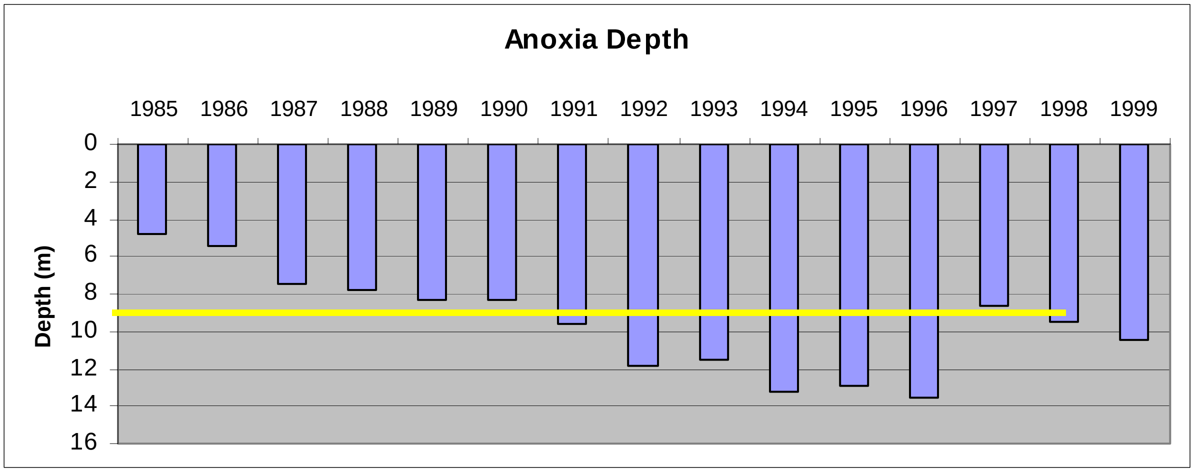
Physical Response

Complete response to aeration required several years due to effects on almost all aspects of the reservoir ecosystem. Layer aeration at Lake Shenipsit resulted in immediate deepening of the aerobic-anaerobic interface. That descent of anoxia exposed a disproportionately large sediment area to oxygen for a longer duration. The anoxic factor (Nurnberg, 1987) decreased from 40 before layer aeration, to less than 8 during the first years of layer aeration. Anoxia never ascended above the lower metalimnetic boundary (RTRM20) during aeration. A cumulative annual response occurred for the first five years of layer aeration. Depth of anoxia, light penetration, and compensation depth continued to deepen. An abrupt improvement in water clarity occurred the third year of Layer Aeration, when the compensation depth descended to the hypolimnion. This phenomenon may have been the result of a shift in zooplankton community structure in response to restored habitat conditions.



Secchi Disk (SD) transparency depth since initiation of Layer Aeration in 1987.

Since 1990, Lake Shenipsit has exhibited a minimum of 2.5 x $10^6 m^3$ (2000 acre-ft) of water which meets brown trout habitat criteria (Raleigh et al., 1986), and an additional 1.6 x $10^6 m^3$ (1300 acre-ft) of metalimnetic water immediately below it which exceeds 1.5 mg/*l* DO. Large-bodied (>0.8mm) *Daphnia sp.* became the dominant zooplankton species in 1990, and has persisted since. Hence, improved metalimnetic habitat (refugia) and the zooplankton community shift to *Daphnia sp.* may have contributed to the abrupt transparency increase in 1990 (Wright and Shapiro, 1990). Daphnia are very efficient grazers on algae, and are beneficial in a water supply reservoir.

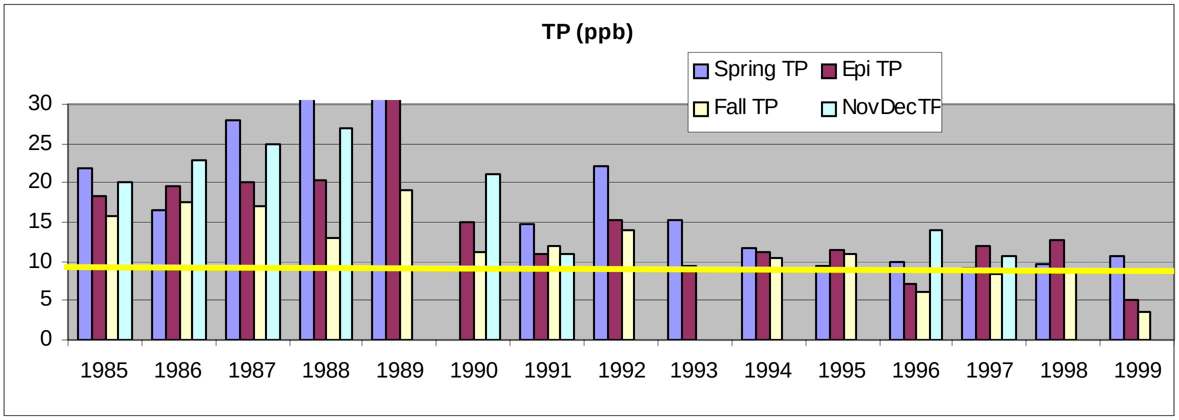


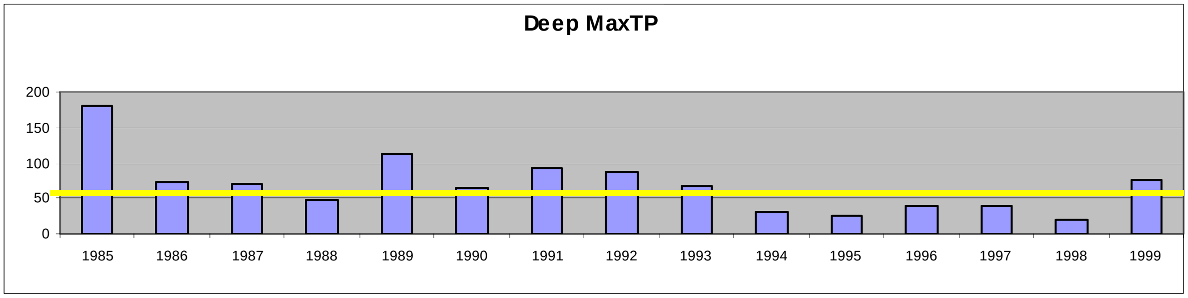
A strong thermocline persisted above the design layer (RTRMmax = 150 at 4m), while a second functional thermocline developed below the aerated layer (RTRM = 31 at 10m). ΣRTRM indicated little change in overall stratification stability of Lake Shenipsit during layer aeration. Total stratification stability, as measured by ΣRTRM, may have been strengthened slightly (ΔΣRTRM = 51), but this was probably a function of annual variability of mixing dynamics. The total RTRM between 5m and 10m decreased from Σ RTRM = 230 to ΣRTRM = 130. The difference (100 RTRM units) approximately equals the increased ΣRTRM immediately above and below the aerated layer. Layer aeration has not weakened thermal stratification, but has focused resistance to mixing immediately above and below the aerated layer. Since resistance to mixing between the hypolimnion and epilimnion remained unchanged, and hypolimnetic nutrient concentrations decreased, diffusional transport of nutrients was not a problem during layer aeration.

Metabolic-Chemical Response

DO concentration remained above 3 mg/liter to the bottom of the aerated layer, with low DO conditions to 15m in 1991. Oxidation-reduction potential was field measured using a platinum probe in 1991 (not available from 1985). Although field oxidation-reduction potential measurements were reproducible, they did not compare well with lab measurements, perhaps due to lack of equilibrium conditions. Hence, we report field-measured oxidation-reduction potentials as apparent redox potential (ARP). In 1991, ARP remained positive to the bottom of the lake despite oxygen loss below the aerated layer. It is interesting to note that ARP did not drop sharply for several meters below the anoxic boundary. That indicates that the lake bottom in the depth range was operating above the ferric-ferrous redox couple.

Spring total phosphorous concentration decreased by about 25%. Summer TP revealed similar, or greater decreases. A sharp decrease in NH4-N concentrations occurred following layer aeration, presumably due to enhanced nitrification and subsequent denitrification.



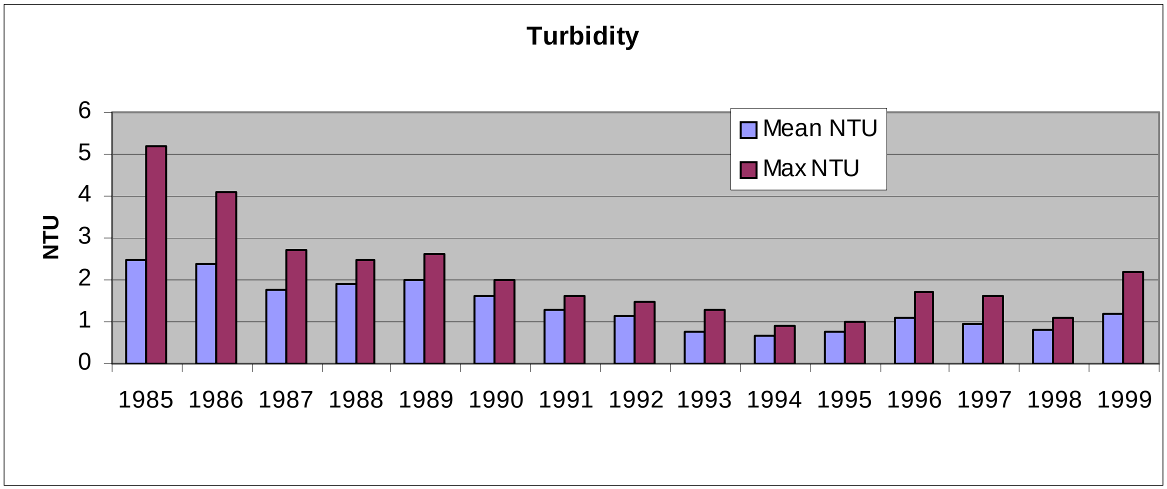


Biological Response: An immediate decrease in summer Cyanobacteria (bluegreen algae) abundance was observed. Blooms of buoyant Cyanobacteria (*Anabaena sp.*, *Aphanizomenon sp.*), decreased from > 17,000 cells/ml pre-aeration to < 500 cells/ml following two layer aeration seasons. Percent composition of the phytoplankton community shifted from Cyanobacteria (>80% pre-aeration) to mostly nannoplankton; i.e. small-celled Chlorophyta (50%) and Diatomacea (40%).

Numbers of zooplankton increased following layer aeration. This was most pronounced for rotifers and small cyclopoid copepods in spring. Cladocera with greater than 0.8 mm carapace (*Daphnia sp.*) represented a larger fraction of the summer zooplankton community following two years of layer aeration. In 1989-1990 Cladocera comprised 60% of the zooplankton community (animals liter^{-1}). Improved metalimnetic DO may have contributed to the shift in zooplankton community composition. Increased abundance of grazer zooplankton (e.g. *Daphnia sp).* relative to those organisms which primarily perform bactivory (e.g. *Bosmina sp.*) is a possible cause of the abrupt increase in transparency in 1990, two years after initiating layer aeration.

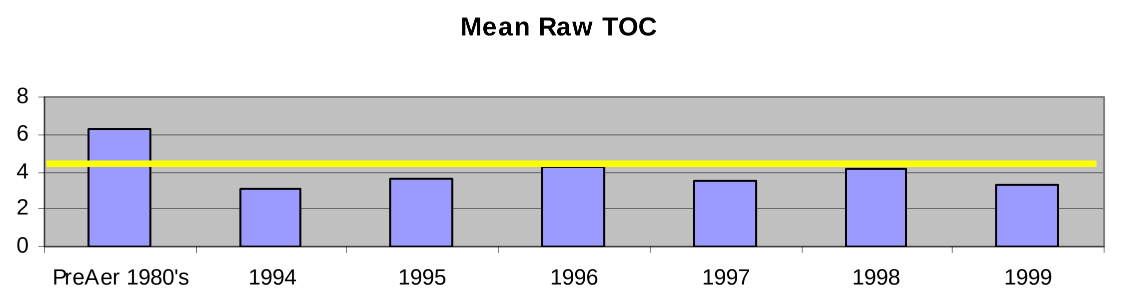
Water Supply

Significant decreases in the iron content, turbidity, and color of withdrawn raw water were observed at the treatment plant. Surface intake turbidity declined sharply. *Synura sp.* episodes during fall-winter-spring persisted for two years, then declined sharply in 1989-90. The turbidity decline appears to be a function of decreased Cyanobacteria blooms during and following summer stratification. Color decreased at the surface intake, especially during the summer. The summer decrease in surface water color may be a function of reduced phytoplankton abundance (esp. Cyanobacteria), greater light penetration, and photodegradation of DOC.



Raw water turbidity (annual mean) since initiating Layer Aeration in 1987.

Improved raw water quality has benefited the treatment process. Prechlorination was eliminated, which is particularly advantageous prior to GAC filtration due to selective adsorption-desorption of chlorinated organics by GAC media, and potential disinfection byproduct and taste-odor effects (Voudrias et al., 1986). GAC media has recently been changed every 18-24 months, doubling its longevity. This is attributed to decreased Cyanobacteria blooms during the summer and decreased chrysophytes and diatom abundance during fall-winter-spring. Annual average raw water TOC decreased significantly.



Conclusions

All oxygen loss does not need to be eliminated for aeration to be effective. Both coldwater fish and zooplankton refuge habitat can be restored in middepth strata while deepest waters are aerated only to raise Eh, enhance nitrification-denitrification, and reduce sediment-P release.

The response to aeration involves all aspects of the lake ecosystem -- biotic and abiotic, internal and external. TOD is the sum of respiratory and nitrogenous demands and is dependent on allochthonous, as well as autochthonous, matter.

Layer aeration provides a cost-effective aeration alternative, especially in stratified eutrophic reservoirs with anoxic metalimnia and depth-selective supply withdrawal capability. It provides a mechanical means for reversing the ascent of compensation depth which occurred during eutrophication. Layer aeration uses available ambient DO sources (as in artificial circulation) while maintaining desirable temperatures and stratification stability. Hence, layer aeration takes advantage of the air-lift function for depth-discrete mixing (like destratification) as well as the oxygen transfer from bubble to water (like hypolimnetic aeration). As a result, consequences of eutrophication (increased respiratory demand, internal loading, habitat degradation) can be managed using smaller compressed air systems. Raw water quality benefits included avoidance of bluegreen bloom dominance (and related taste and odor), prolonged GAC substrate effectiveness, reduced turbidity, and reduced metals.

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