UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 450

Design of an Aeration System to Enhance Trout Habitat in Holland Lake, MN

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Omid Mohseni, Greg Graske, Richard Donovan,
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Prepared for

MINNESOTA DEPARTMENT OF NATURAL RESOURCES
Metro region Fisheries, St. Paul, Minnesota

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Abstract

Holland Lake, a small but deep mesotrophic lake in the Twin Cities Metropolitan Area, has been considered by the Minnesota Department of Natural Resources, Division of Fisheries, for stocking with brown trout. Holland Lake, with a surface area of 0.14 km^2 (35 acres) and a maximum depth of about 18.8 m (61 ft) consists of two shallow bays covered with rooted macrophytes and a deep main basin. The deep basin is thermally suitable for brown trout. However, due to a high oxygen depletion rate in summer, the lake becomes anoxic below the surface mixed layer from late June to early July. The rate of oxygen depletion below the surface mixed layer, based on field measurements, was estimated to be about 0.47 $mg l^{-1} day^{-1}$. Field studies conducted in the summers of 1999 and 2000 indicated that only horizontal advection processes could explain the observed high dissolved oxygen (DO) depletion rates. Density currents transport low DO water with high BOD into the deep basin metalimnion. These currents from the shallow bays were attributed to the temperature regimes of the shallow bays and groundwater flow through the lake.

To improve brown trout habitat in Holland Lake, an aeration system has been designed based on the observed summer conditions. The aeration system comprises two bubble curtains along the border of the shallow bays to enhance mixing in the shallow bays and one metalimnetic aerator in the deep basin. The bubble curtains deepen the surface mixed layer down to 4 m, and prevent the formation of density currents from the shallow bays into the deep basin.

The metalimnetic is 10 m (32.8 ft) high and installed 1.5 m (4.9 ft) below the lake surface. The riser tube diameter is 2.3 m (7.5 ft), and the outflow tube diameter is 3.3 m (10.8 ft). It aerates and mixes the metalimnion from 4 to 9 m (13 to 30 ft).

The overall cost of the aeration system is estimated to be in the order of $100,000. The bubble curtains represent about 10% of the total cost of the system including the metalimnetic aerator, compressors, air pipelines, accessories and a shelter for the compressors.

Acknowledgements

The work reported herein was supported by the Minnesota Department of Natural Resources, Metro Region Fisheries. Mr. Gerald Johnson was the project officer. We would like to thank Tom Johnson for his constructive comments and for information on previously built hypolimnetic aerators.

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I. Problem Description

The Division of Fisheries of the Minnesota Department of Natural Resources (MNDNR) has considered Holland Lake, located at the southern fringes of the Minneapolis/St. Paul Metropolitan Area (Figure 1), for stocking with brown trout. Holland Lake is considered suitable for this purpose because it is exceptionally deep in comparison to other small lakes in the Metro Area and has relatively good water quality. The lake can provide extensive cold-water habitat during the summer stratification period. However, low concentrations or absence of dissolved oxygen (DO) in the lake metalimnion and hypolimnion in summer, adversely affect the stocking of the lake with brown trout. In summer, water temperature in the surface mixed layer (epilimnion) exceeds the maximum temperature tolerance of brown trout (21 °C according to the *MNDNR* [1978]), which forces brown trout to find suitable habitat (between 10 °C to 20 °C) in deeper layers of the lake. However, in early summer, the upper metalimnion regularly becomes anoxic and the lower metalimnion loses its oxygen a few weeks later. The hypolimnion is anoxic for the summer.

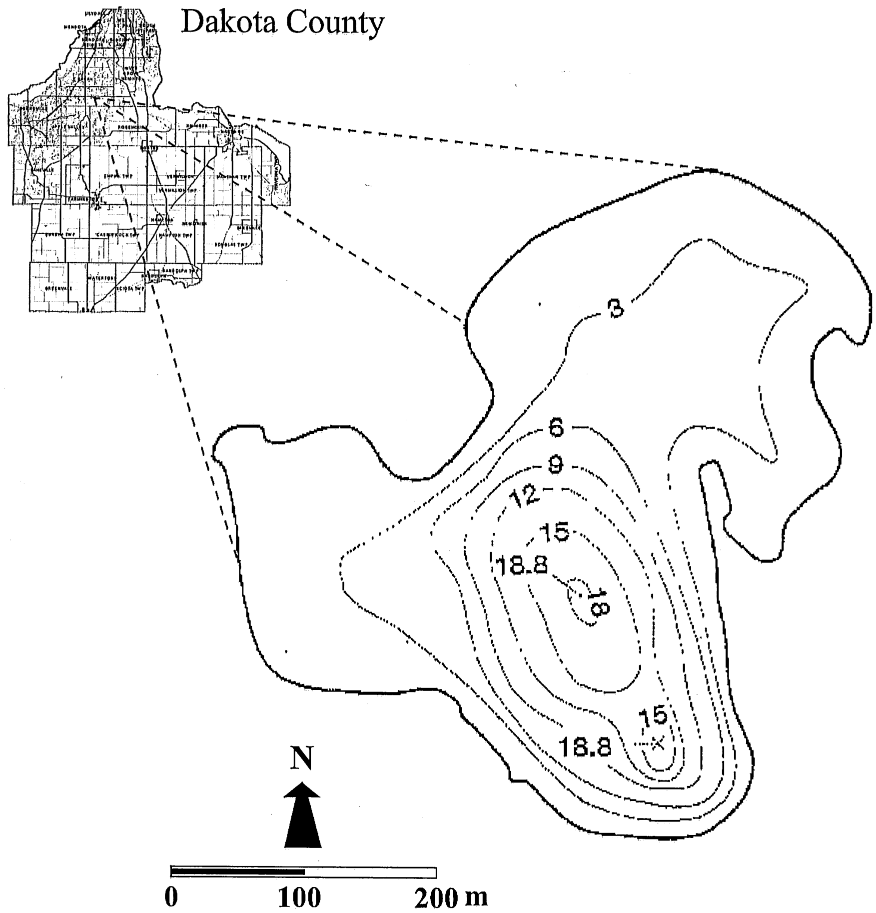
Figures 2a and 2b are examples of water temperature and dissolved oxygen profiles measured by the Twin Cities Metropolitan Council in 1983 and 1984 showing the development of an anoxic layer in the upper metalimnion of Holland Lake (For more examples see *Mohseni and Stefan* [2000]). The data collected in 1999 by the Minnesota Department of Natural Resources (MNDNR), the Metropolitan Council Environmental Services (MCES) and the St. Anthony Falls Laboratory (SAFL) have been compiled and used to plot the threshold isotherm of 21 °C, and the threshold DO isopleth of 5 mgl^{-1} in Figure 3. The two regions bounded by the 21 °C isotherm and 5 mgl^{-1} isopleth illustrate where and when brown trout would be under temperature or DO stresses according to the *MNDNR* [1978] trout habitat criteria. Brown trout would be under both or either stresses everywhere in the lake from July to mid-September.

A field study conducted by *Mohseni and Stefan* [2000] in the summer of 1999 showed that the shallow bays of Holland Lake with substantial macrophyte beds (Figure 1) exhibit significant temperature stratification in July and August. A comparison of water temperatures in the eastern shallow bay with those in the deep main basin, provided evidence that there should be significant exchange flows between the two water bodies. In July and August, water near the bottom (e.g. at 3.4 – 3.7 m) of the eastern shallow bay was about 3 to 5 °C colder and hence denser than water at the same depth in the deep main basin. This temperature difference can be expected to cause an intrusive water flow from the deeper part of the bay into the deep main basin. The bed slope in the shallow bays is toward the deep main basin (Figure 4), which facilitates this intrusive flow. This intrusion can transport oxygen-depleted water and substantial amounts of dissolved and suspended organic materials into the metalimnion of the deep main basin. This material ultimately causes the observed high DO depletion rate in the metalimnion.

The field studies conducted in the summers of 1999 and 2000 in Holland Lake gave an average estimate of 8,500 to 9,800 m^{3}day^{-1} for groundwater flow through Holland Lake. The results also suggest that any subsurface inflows to the shallow bays of Holland Lake are either intermittent near surface flows (caused after rainfall events) or from a shallow aquifer possibly connected to other lakes in the area, or from both

[*Mohseni and Stefan*, 2001]. The temperature stratification observed in the eastern shallow bay during the summer of 1999, is mainly due to shading by macrophytes, the suppressed turbulent mixing caused by dense macrophyte beds, and strong wind sheltering by trees and hills around the lake, rather than the groundwater inflow.

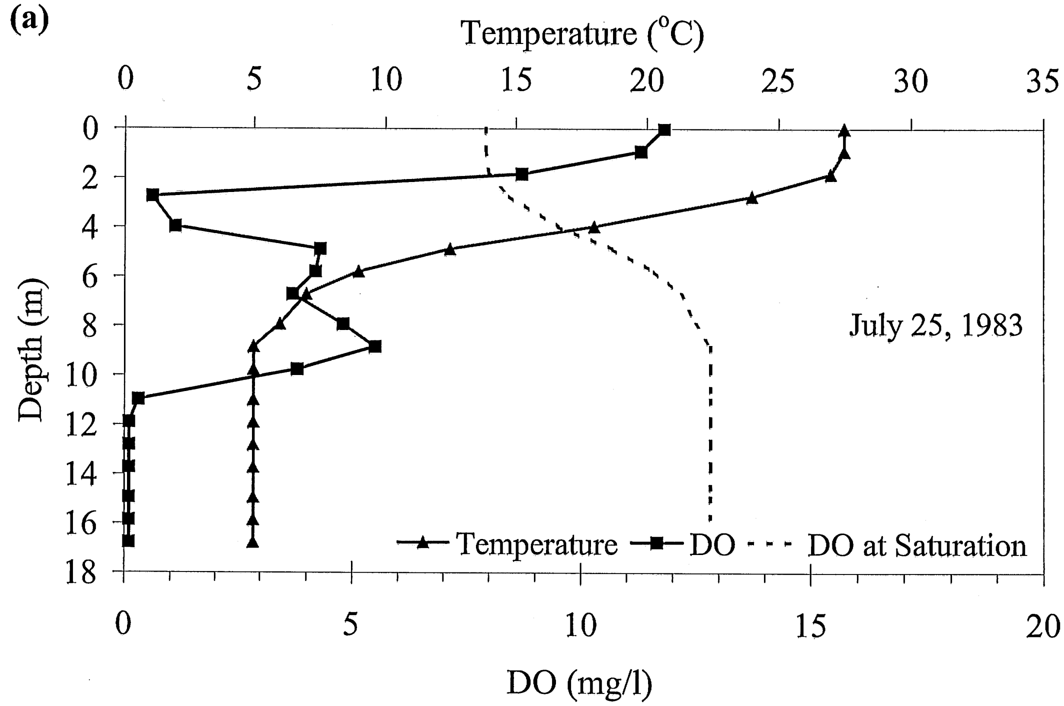
In order to sustain a suitable summer trout habitat (DO> 5 mgl^{-1} and $10<T<21$ °C) in Holland Lake, either the DO concentration in the metalimnion must be raised or the summer temperature of the well-oxygenated surface mixed layer must be lowered. To improve the DO level up to 5 mgl^{-1}, the DO sinks either need to be reduced, or additional DO need to be supplied or both. Since, rooted macrophyte beds form detrital material after senescence and death, oxygen demand is high in the bays, and can significantly affect the depletion of oxygen in the deep basin. Therefore, harvesting of the macrophytes by mechanical means or dredging the sediments in the shallow bays may seem a solution to the problem. Unfortunately, both dredging and harvesting are temporary solutions and would disturb or even destroy the lake ecosystem. Furthermore, the cost of dredging and harvesting is high. It varies from $\$0.24\ m^{-3}$ to $\$14\ m^{-3}$ of dredged material and is affected by many different variables, e.g., the project size, availability of a disposal site, the density of the material being removed, and the distance to the disposal area [*Cooke et al.*, 1993]. In this report, the authors focus on other means of creating and sustaining a trout habitat in Holland Lake. The report describes options, which would help lower the temperature of surface mixed layer or supply the DO required for trout habitat in the metalimnion.



All contours in meters

Figure 1. Location and plan view of Holland Lake, MN.

(a)



(b)

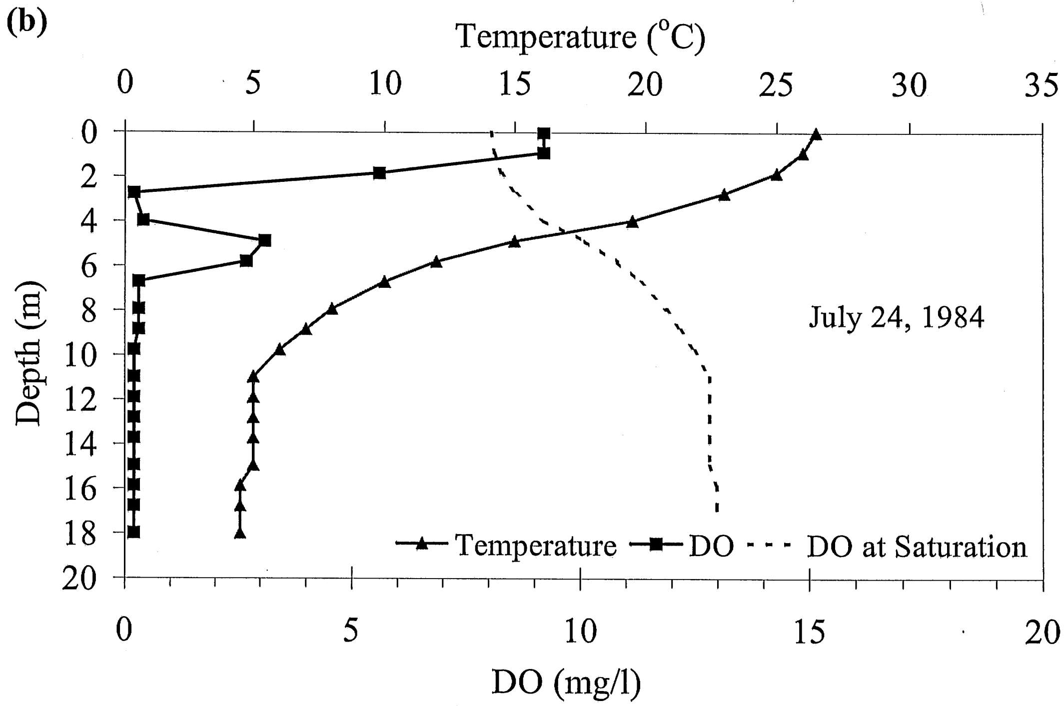


Figure 2. Temperature and DO profile measured, and the saturation DO estimated in the deep main basin of Holland Lake in the summers of (a) 1983 and (b) 1984. The data were collected by the Twin Cities Metropolitan Council.

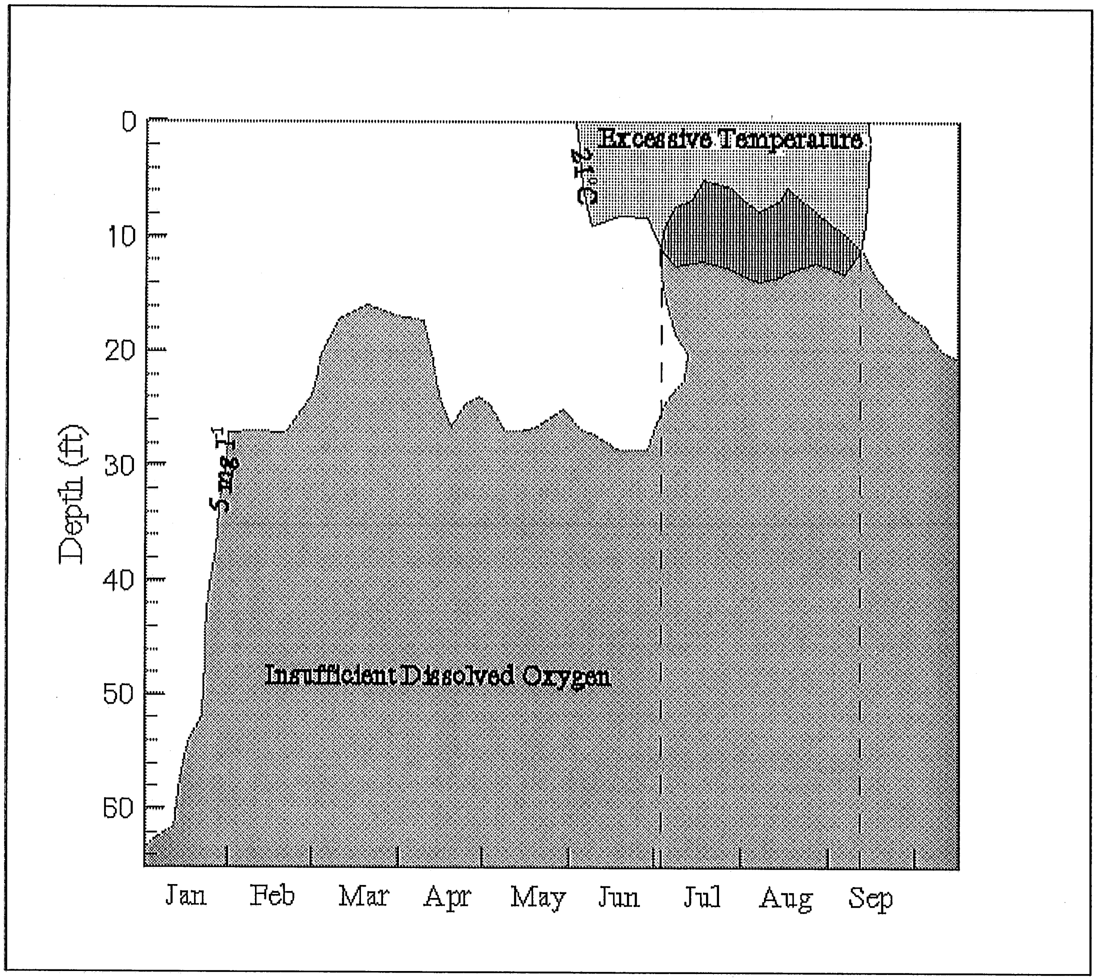


Figure 3. Projected temperature and dissolved oxygen threshold isopleths (21 °C and 5 mgl^{-1}, respectively) for brown trout habitat in Holland Lake. The figure is plotted using the temperature profiles measured by the MNDNR, the MCES and the SAFL in 1999 [*Mohseni and Stefan,* 2000]. One foot is 0.3 m.

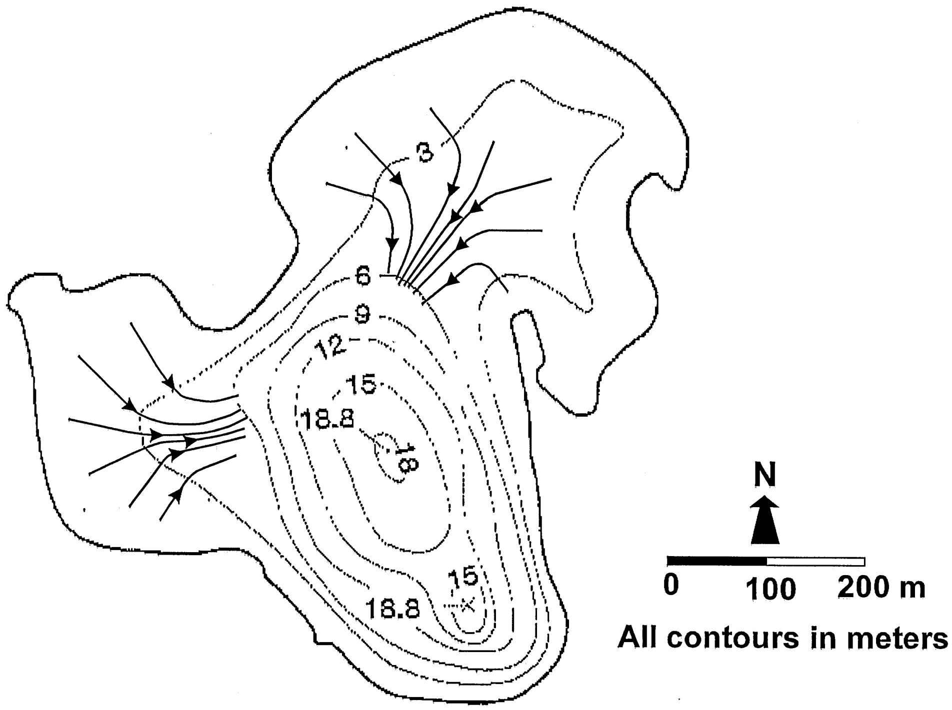


Figure 4. Schematic of intrusive flow from the bottom of the shallow bays into the deep basin.

II. Design Options

In order to provide summer habitat for brown trout in Holland Lake, we consider three design options.

(1) To deepen the surface mixed layer down to the bottom of the metalimnion and take advantage of natural surface aeration to provide the oxygen.

(2) To mix and aerate the entire lake.

(3) To aerate layers below the surface mixed layer of the lake selectively.

II.1. Deepening the Surface Mixed Layer

Deepening of the surface mixed layer exploits natural surface aeration to provide the minimum DO for the brown trout habitat. This can be achieved using air bubble systems, hydraulic jet mixing and even mechanical mixing. The main disadvantage of this method is the potential increase of the surface mixed layer temperature. Before we attempt to focus on the design parameters and techniques of this option, we first examine the attainable water temperature when the mixed layer is deepened.

The metalimnion extends down to about 9 m (30 ft) depth in summer. Assuming approximately 10,000 m^3day^{-1} of groundwater inflow [*Mohseni and Stefan*, 2000 and 2001], and weather forcing at the surface, one can use the heat budget of the deepened mixed layer to estimate its daily temperature. There are two unknown parameters, however, which need to be quantified to make the computations: the groundwater temperature, and the wind speed over the lake.

Deep groundwater is about 1 to 2 °C warmer than the mean annual temperature of a region [*Todd*, 1980]. The mean annual air temperature in the Twin Cities Metro area is about 7 °C. The field studies done by *Mohseni and Stefan* in 1999 and 2000 did not give any indication of such a low groundwater temperature. In the first attempt, a 10 °C will be assumed as the groundwater temperature. Subsequently, the sensitivity of the deepened mixed layer temperature to higher groundwater temperatures will be checked.

Wind affects the heat exchange across the air-water interface through sensible heat and evaporative heat fluxes; therefore, it plays an important role in the heat budget of the lake. Unfortunately, there are no records of wind speeds over Holland Lake. Due to the presence of trees around the lake, and the land use and the topography of the region, wind speed over the lake may differ significantly from the measured wind speed at the Minneapolis-St. Paul International Airport. Wind speeds measured over Lake McCarrons in Roseville, MN, which has a larger surface area, but relatively similar land use around the lake, are about 1/3 of the wind speeds measured at the airport [*Mohseni and Stefan*, 2001]. To remedy the lack of information on wind speeds, we will incorporate wind speeds measured at Lake McCarrons as the lower bound, and those measured at the airport as the upper bound.

The lake bathymetry gives 602,000 m^3 for the volume of the deepened surface mixed layer of 9 m depth (Figure 5). The results of the heat budget computations for the deepened surface mixed layer under the weather forcing from June to October of 1999 are shown in Figures 6a to 6c for three scenarios. In Figure 6a, the groundwater temperature is set at 10 °C, and the wind speeds are those estimated* at 2 m elevation over Lake McCarrons. The simulated daily temperatures exceed 21 °C, the maximum lethal temperature of brown trout, from June 10 to October 15. By late July, the simulated daily water temperatures reach 35 °C. The high water temperatures are due to the small wind speed, and consequently, weak evaporative cooling. In Figure 6b, the wind speeds measured at the airport are utilized, and therefore, lower water temperatures are projected. Nonetheless, the water temperature would exceed 21 °C from June 20 to mid-August. Since, the lower bound of the groundwater temperature gave very warm surface temperature, a warmer groundwater temperature would definitely give higher values for the surface mixed layer. If the groundwater inflow estimated is twice as much as *Mohseni and Stefan*'s [2001] estimates, then the deepened surface mixed layer temperature will be lower, as shown in Figure 6c. The last scenario shows that for a month and a half, from July to mid-August, water temperature exceeds the maximum temperature tolerance of brown trout by 2 to 5 °C. The heat budget components are given in Appendix B. Figure 7 shows the surface mixed layer temperatures under the same scenario for 1981-1990. The simulations are from April to October. As it is evident, there are at least one or two months per year that the deepened surface mixed layer is 2 to 6 °C warmer than the maximum temperature tolerance of brown trout, even if the groundwater inflow is assumed 20,000 $m^3 day^{-1}$.

In the heat budget computations, the heat losses of the deepened mixed layer to the metalimnion or the lake sediment, and the heat fluxes from power input of the aeration system are not taken into account. However, these heat losses are small due to the presence of diffusion barriers, and the aeration power input would not contribute significantly to the overall temperature of the surface mixed layer [*Sedory and Stenstrom*, 1995]. Therefore, deepening the surface mixed layer down to 9 m depth may provide the desirable DO concentration, but the water temperature will exceed the maximum temperature tolerance of brown trout. Consequently, this option is not viable.

II.2. Whole Lake Aeration

In the previous section, deepening of the surface mixed layer down to 9 m required mixing a volume of 602,000 m^3. For the whole lake aeration option, it would require to mix 726,000 m^3 (Figure 5), which is only 124,000 m^3 more than the previous option. This extra 124,000 m^3 will not increase the water body thermal inertia enough to lower its temperature. Consequently, under the whole lake aeration scenario, lake temperatures will be too high in July and August. Therefore, whole lake aeration also cannot provide a solution for sustaining a trout habitat in Holland Lake.

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* Wind speeds were estimated for the 2 m elevation from those measured at 1 m elevation.

II.3. Selective Layer Aeration

The DO and temperature profiles measured by the MNDNR, the MCES and the SAFL [*Mohseni and Stefan*, 2000] suggest that summer water temperatures at depths greater than 4 m are suitable for trout habitat (see Figure 3). Therefore, if only layers between 3 and 9 m depth are aerated, then both suitable temperatures and DO for brown trout can be achieved. The basic concept is illustrated in Figure 8. Metalimnetic aeration creates an aerobic cool, isothermal layer bounded by two thermoclines, which are strong barriers to vertical diffusion. Metalimnetic aerators have been used in other lakes, e.g. Mulberry Reservoir in CT, and are shown to be more cost effective than whole lake aerators or the hypolimnetic aerators [*Kortmann et al.*, 1988]. A listing of several lake/reservoir destratification/aerator systems is given in Appendix A.

In the 1999 field study conducted in Holland Lake, the thermocline, defined as the steepest water temperature gradient and measured in °C/m, was at 3.6 to 4.8 m depth for most of the summer. In July, the surface mixed layer in the main basin was about 2.4 m deep at night and became 0.6 to 1.2 m deep during daytime. The seasonal surface mixed layer deepened to 3.6 m by mid-August and stayed at 3.6 m until early September. By early October, the seasonal surface mixed layer became 6 m deep with a temperature of about 15 °C.

By early July, the upper metalimnion, from 3 to 4.8 m depth, had become anoxic while the lower stratum of the metalimnion, from 6 to 8.4 m depth, still contained up to 7 mg DO l^{-1}. Apparently, the oxygen depletion rate was lower in this layer than in the upper metalimnion. By mid-August, DO was less than 2 mg l^{-1} below the 4 m depth and water temperature was warmer than 20 °C above the 4 m depth. By late August, the entire metalimnion became anoxic and a clinograde oxygen profile was formed in the lake. Similar DO and temperature profiles have been observed in previous years. The metalimnion temperature varied from 6 °C to 22 °C. For selective aeration, the strata from 3 to 9 need to be aerated.

Although the shallow bays are less than 4.5 m deep, they exhibit significant temperature stratification in July and August and become anoxic below the 2 m depth (see Appendix D in *Mohseni and Stefan* [2000]). If selective aeration is applied to layers between 3 to 9 m, stratification due to the presence of macrophytes or due to daytime solar heating would still cause the development of an anoxic layer above the selected aerated strata, i.e. between 1 to 3 m depths. This low DO layer may impose stresses on brown trout any time they travel into the surface layer, e.g. for feeding on perch. Therefore, better selective aeration can be accomplished if simultaneously the surface mixed layer is maintained down to the depth where selective aeration begins.

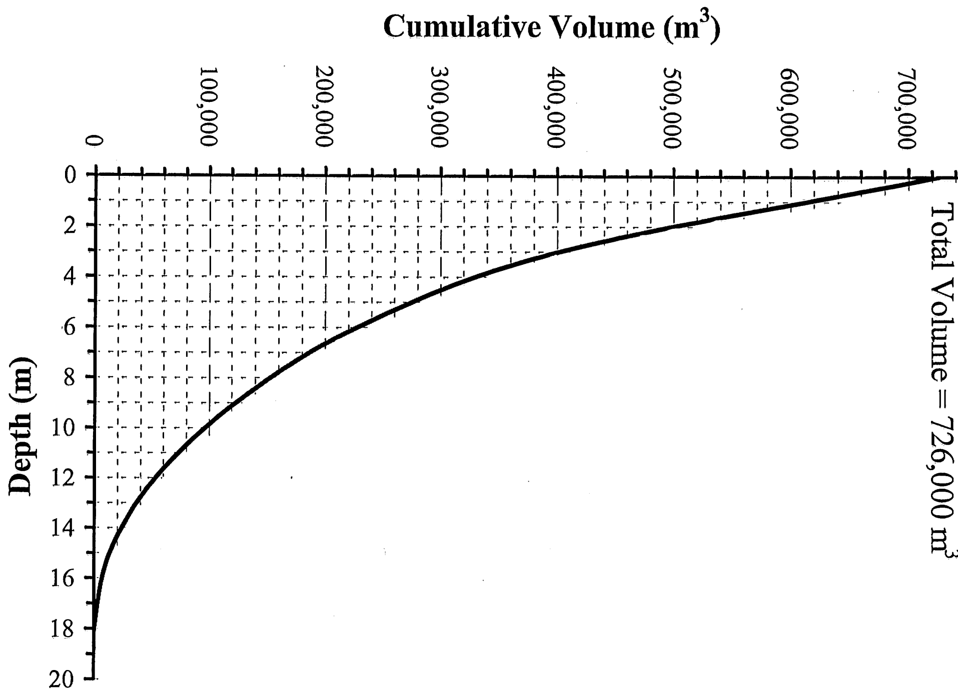


Figure 5. Cumulative volume versus depth for Holland Lake. The information has been obtained from the lake bathymetry (Figure 1).

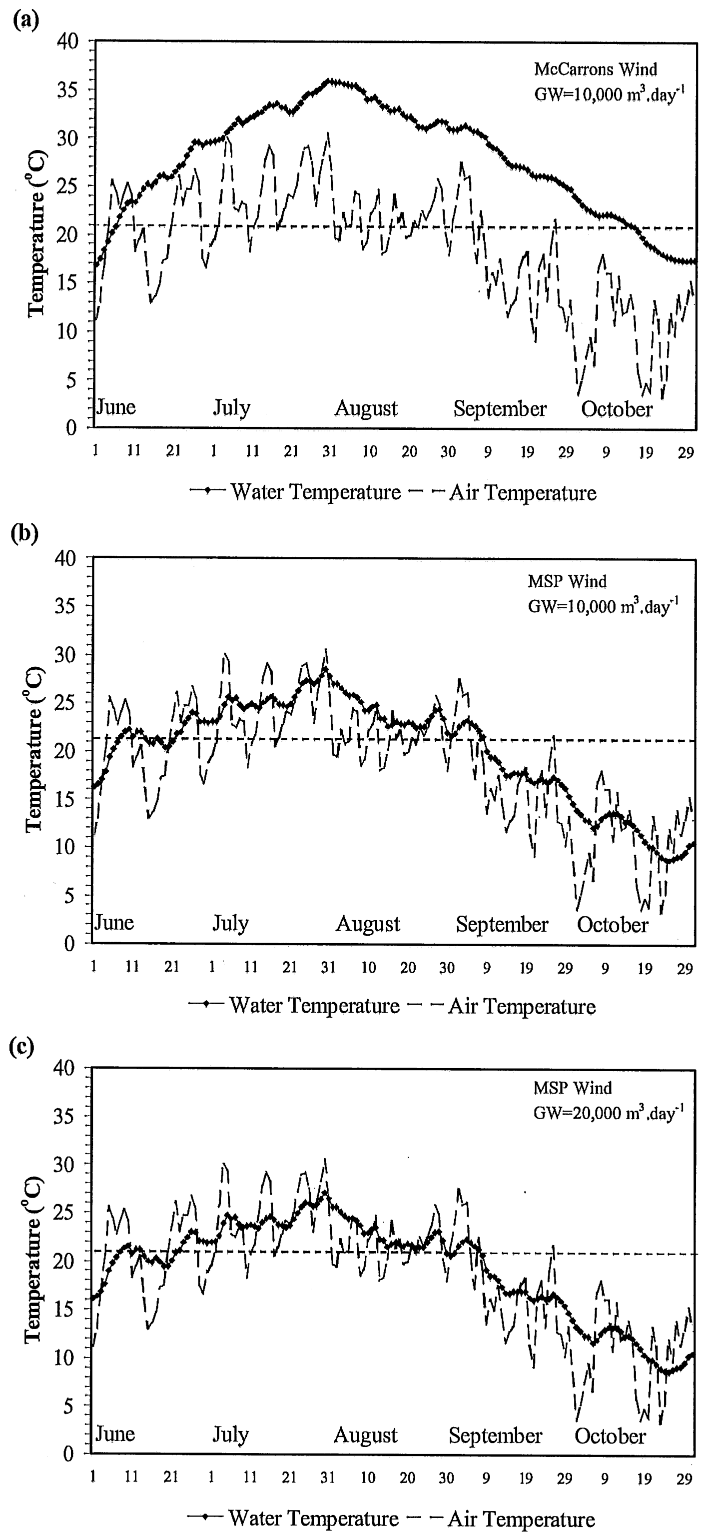


Figure 6. Estimated surface mixed layer temperatures (from surface to 9 m depth) in Holland Lake and air temperatures, from June to October 1999, under three scenarios.

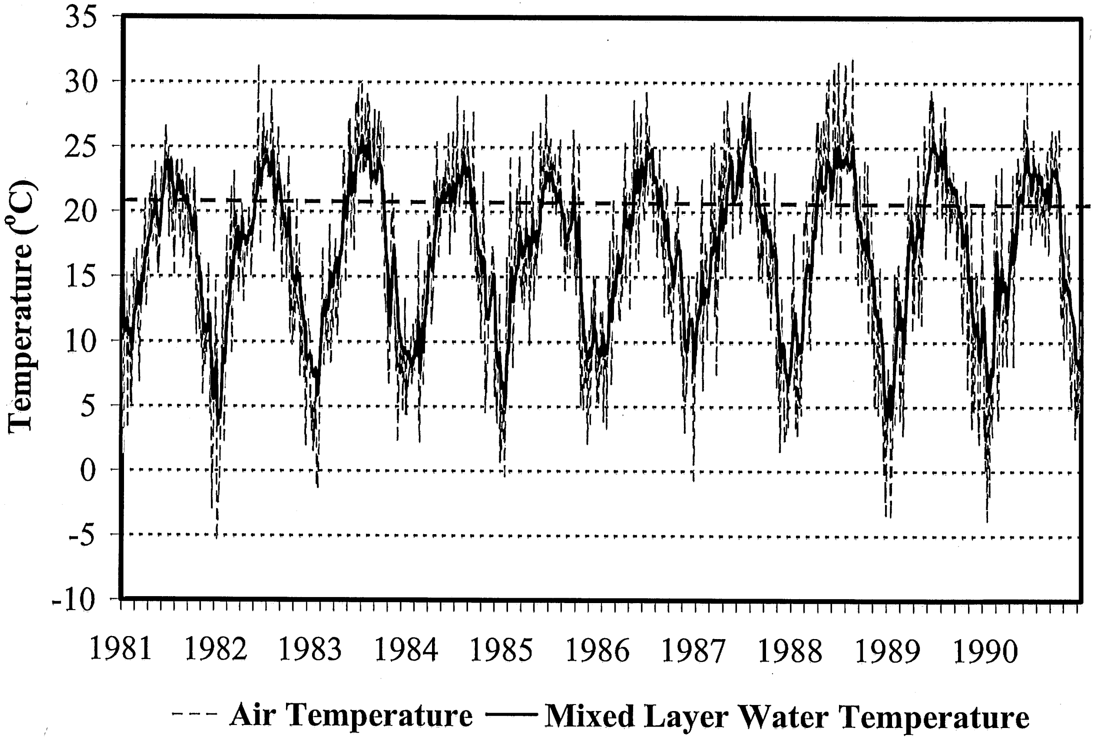


Figure 7. Estimated water temperatures of the deepened surface mixed layer (9 m depth) and air temperatures for April to October of 1981-1990. The groundwater inflow is set to 20,000 m^3 day^{-1} and the wind speeds are those measured at the St. Paul-Minneapolis Airport.

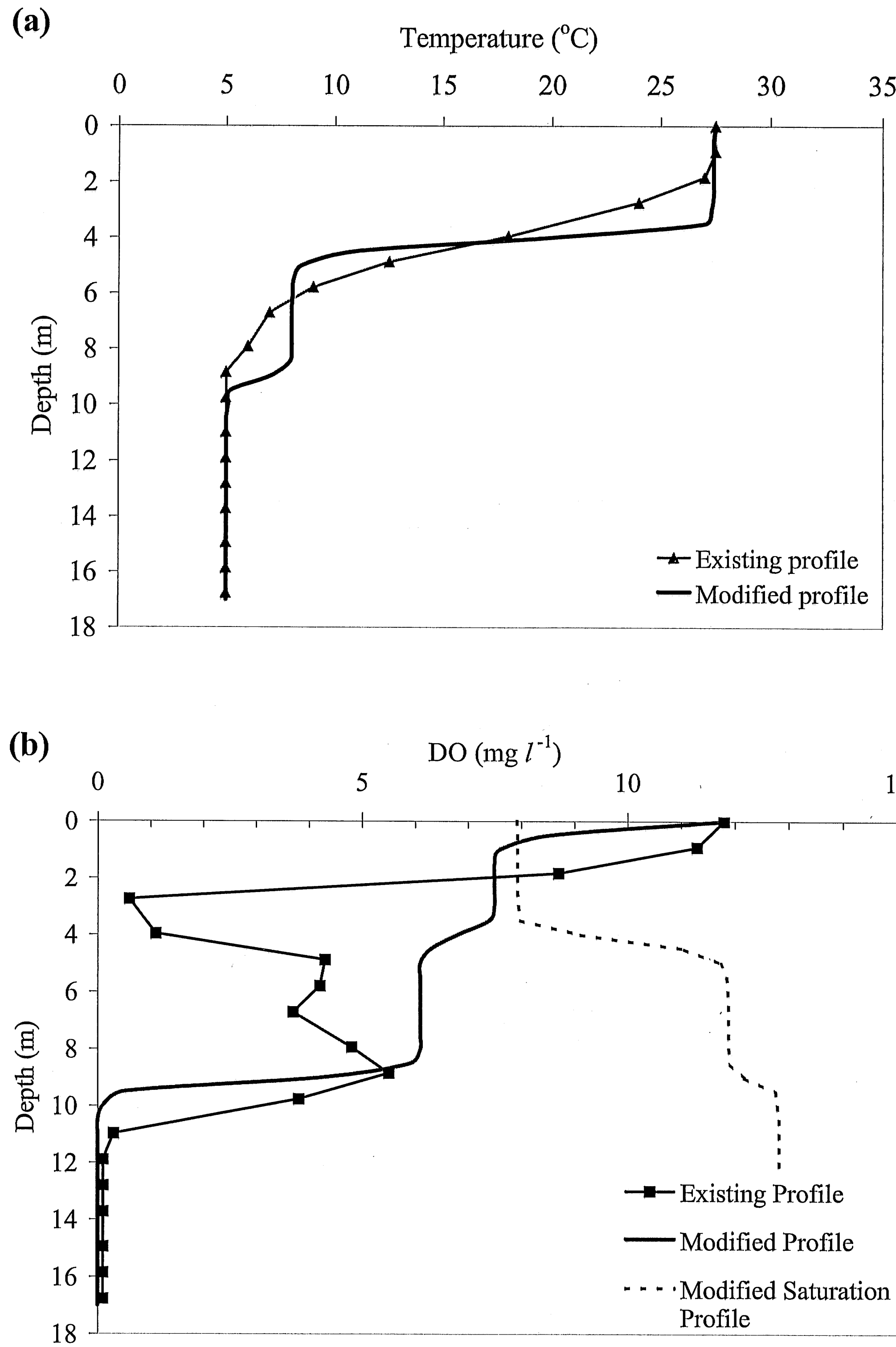


Figure 8. Schematic of (a) water temperature profiles and (b) dissolved oxygen profiles before and after installation of air bubble curtains and the metalimnetic aerator.

III. Design Parameters

III.1. Temperature and DO Criteria

Based on the MNDNR criteria [*MNDNR*, 1978], the minimum DO concentration required to sustain a suitable habitat for brown trout is 5 mgl^{-1}, and its maximum temperature tolerance is 21 °C. The isothermal layer developed by the metalimnetic aerator should meet these criteria.

III.2. Dissolved Oxygen Depletion Rates

The DO concentrations measured at weekly or biweekly intervals in the summer of 1999 can be used to estimate current DO depletion rates. Values are shown in Figure 9. A maximum DO depletion rate of about 0.47 mg l^{-1}day^{-1} occurred in the upper stratum of the metalimnion in late June and early July.

The 0.47 mg l^{-1}day^{-1} net depletion rate is calculated using measurements at the beginning and the end of a two-week period. This value, therefore, is a weekly average net depletion rate of DO. This rate is the highest measured DO depletion rate in 1999. Unfortunately, there are not enough measurements in previous years to confirm this rate. Some measurements of DO profiles were taken by the MCES in 1983, 84 and 85. From those data, the maximum net depletion rates have been estimated to be 0.24, 0.18 and 0.15 mg l^{-1} day^{-1}, respectively. However, the time intervals between two consecutive DO measurements were often more than two weeks. None of these estimated DO depletion rates represent daily rates.

The design DO depletion rates determined for normal conditions, i.e. before aeration starts, often do not meet the actual DO depletion rates when aerators are operating [*Smith et al.*, 1975; *Ashley et al.*, 1987; *Stefan et al.*, 1987]. There are several factors affecting such discrepancy when aerators are in operation: (1) Water circulation increases, thus water velocity near the sediment bed increases. Since sedimentary oxygen uptake is linearly proportional to water velocity [*Mackenthun and Stefan*, 1998], the DO depletion rate increases. (2) Aerators enhance mixing, thus, increasing the water temperature of the lower layers. Increased temperatures enhance respiration and decomposition rates of organic materials. (3) The estimated depletion rates are obtained from limited data. *Lorenzen and Fast* [1977] have recommended a 30% increase of the measured respiration rates as a safety factor for the estimation of the DO depletion design rate. However, *Smith et al.* [1975] found that the consumption rate in Larson Lake, during aeration, was as much as three to four times as great as the normal depletion rate.

Therefore, a large safety factor needs to be applied to the maximum measured net DO depletion rate (0.47 mg l^{-1} day^{-1}) before use as the aerator design rate. This safety factor has not been formally established by those involved with lakes and reservoirs management. Based on the observations mentioned above, a factor of 2.5 will be applied to the maximum observed depletion rate of DO to obtain the design rate for the Holland Lake aerator. The design rate becomes 1.2 mg l^{-1}day^{-1}.

III.3. Hydraulic Renewal Time

To size the aerator, the water flow through the aerator must be estimated. While the water flow is a function of the air flow rate, it must also meet the requirements for efficiently mixing the entire metalimnion. If hydraulic resident times are several days or more, it is quite likely that the metalimnion will exhibit stratification instead of being fully mixed. This would result in diffusion barriers and insufficient supply of DO to the entire metalimnion, i.e., slower than the DO depletion rate.

Very short resident times, i.e., less than a day will increase the size of the aerator and, accordingly, the cost. Therefore, a resident time of one to three days will be considered for the aerator sizing.

III.4. Layer Volume and Depth

The metalimnion is more or less located between depths of 3 to 9 m. The volume of this layer (Figure 5) is 270,000 m^3. The volume, however, changes throughout the season. If the surface mixed layer is kept at a specific elevation, then it is not only possible to avoid anoxic layers above the aerated metalimnion, but one can also somewhat downsize the metalimnion, e.g., from 4 to 9 m with a volume of 210,000 m^3 (Figure 5), for a more cost effective system.

III.5. Proposed Aeration System

It is therefore recommended to install and operate two systems (Figure 10):

1. Two air bubble curtains installed at a depth of 4 m between the shallow bays and the deep basin.
2. A metalimnetic aerator installed between 4 and 9 m depth in the deep basin.

The air bubble curtain is a device to maintain a well-oxygenated surface mixed layer of about 4 m depth. It is an inexpensive complement to the metalimnetic aerator. In conjunction with the metalimnetic aerator, it will serve to maintain a three-layer system in the lake (Figure 8). The two top layers (surface mixed layer and metalimnion) would be well oxygenated. The hypolimnion would be anoxic.

By installing the air bubble curtains, a strong temperature gradient acting as diffusion barrier between the metalimnion and the surface mixed layer will be aerated. It is also expected that aeration of the shallow bays to the near bottom will reduce the influx of organic dissolved and suspended detrital materials to the deep basin metalimnion, thus reducing the oxygen demand in the 4 m to 9 m layer, where brown trout will find suitable DO and temperature conditions. The surface mixed layer and the metalimnion will both meet the DO criteria for the brown trout, but only the metalimnion will meet the temperature criteria.

As the bubble curtains enhance mixing in the surface mixed layer, they may increase the nutrients concentrations by drawing them from sediments, and consequently may change the phytoplankton/macrophyte dynamics in the shallow bays, e.g. by increasing the phytoplankton concentration and decreasing the area covered by macrophytes, or changing the distribution and heights of the macrophytes. This may eventually increase the phytoplankton concentration, decrease the water clarity, and change its color. The airflow rates must be adjusted to minimize the effects of enhanced mixing on the lake productivity while providing a 4 m deep mixed layer.

The metalimnetic aeration will replenish DO lost to biochemical oxygen demand (microbial respiration and chemical oxidation). An objective of the metalimnetic aerator design is to minimize loss of the injected DO by diffusion into adjacent layers and by biochemical uptake (BOD and SOD). Therefore, water circulation induced by the metalimnetic aerator must be gentle enough to minimize flow velocities over the sediments and diffusion across the thermocline, but strong enough to keep the metalimnion layer relatively well mixed.

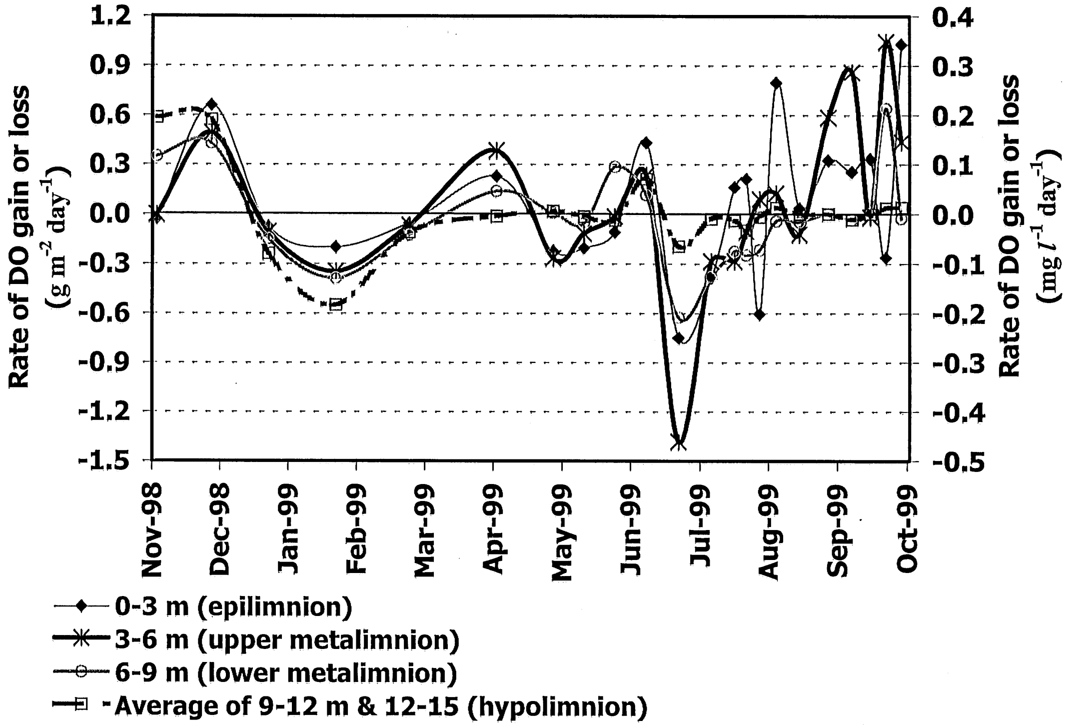


Figure 9. Rates of dissolved oxygen (DO) gain or loss in different strata of Holland Lake from November 1998 to October 1999. The maximum rate of DO depletion is 0.47 mg l^{-1} day^{-1} in late June.

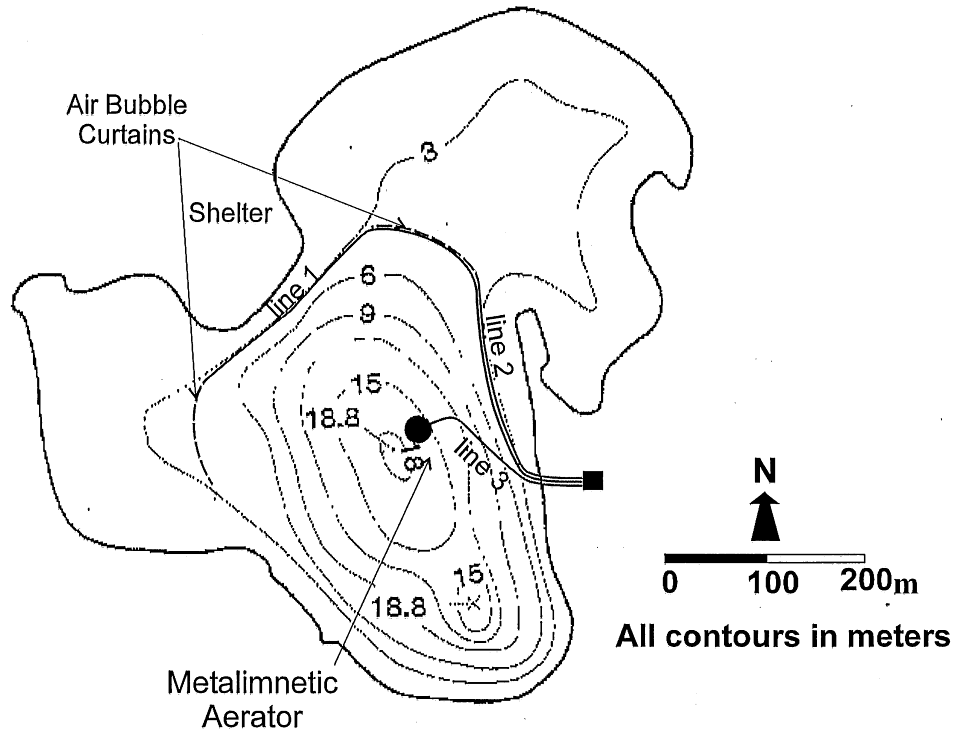


Figure 10. Proposed locations of the shelter for blowers and compressors, and the main pipes for the two bubble curtains, the metalimnetic aerator, and associated air supply lines.

IV. Design Procedure and Results

IV.1. Air Bubble Curtain

IV.1.1. Purpose

The air bubble curtain is a device to maintain a constant surface mixed layer depth. Air bubble diffusers are a good means to achieve this goal. They do not affect the aquatic environment as severely as mechanical mixers and hydraulic jet mixers do.

In addition to maintaining the depth of the surface mixed layer, the air bubble diffusers are also intended to prevent intrusive flows from the shallow bays into the deep basin. To be effective, they must be installed as bubble curtains between the shallow bays and the deep basin. Figure 10 schematically displays the location of the bubble curtains. It is proposed to install the diffusers at 4 m depth. Maintaining a surface mixed layer of 4 m depth instead of 2 or 3 m will reduce the volume of water to be aerated by the metalimnetic aerator.

IV.1.2. Capacity and Dimensions

The volume of the lake above the 4 m depth is 393,000 m^3 (Figure 5). The blowers needed for the air bubble curtain need to be placed in a shelter on the east side of the deep basin (Figure 10), where the MNDNR has provided a power line.. Table 1 gives the approximate dimensions of the air lines. Two separate air lines are needed to have more control over the mixing in both shallow bays. Line 1 supplies air to the western shallow bay and line 2 for the eastern shallow bay. The other alternative for line 1 would be through the southern part of the deep basin, which gives the same total length. Therefore, to minimize the chance of pulling the air lines by fishing hooks, it is proposed to place both lines next to each other.

Table 1. Dimensions of the bubble curtains

Location	Total pipe lengths (m)	Sections with orifices (m)	Diameter in m (inches)	Orifice size in mm (inches)	Orifice spacing in m (ft)
Western shallow bay, line 1	520	80	0.051 (2")	1 (0.04)	2 (6.6)
Eastern shallow bay, line 2	250	100	0.051 (2")	1 (0.04)	1.5 (5)

The required capacity of the blowers is dependent upon the amount of water that needs to be moved to maintain a surface mixed layer. To minimize stratification in the mixed layer, the renewal time for the mixed later volume must be set at less than a day. A very short renewal time is, however, associated with high water velocities, which may activate the benthic community for higher rates of oxygen uptake. Since the cost for the bubble curtain will be about 10% of the overall cost, the system can be designed for high flow rates with the capability of adjusting for lower flow rates to provide a balance between complete mixing from the surface to 4 m depth, and oxygen demand. Therefore, we propose a renewal time of 12 hours. With a layer volume of 393,000 m^3, the required water flow rate becomes 9.1 m^3 sec^{-1}.

The airflow rate required to move 9.1 m^3 sec^{-1} (3.73 m^3 sec^{-1} for line 1 and 5.37 m^3 sec^{-1} for line 2) water can be estimated using the hydrodynamics of plumes [*Wüest et al.*, 1992; *McGinnis et al.*, 2001]. There are also empirical methods relating the water flows to the airflows and the submergence depth of diffusers. *Fujie* [1992] determined that the rising speed of water U_w induced by diffusers in a parallel-piped tank is proportional to the diffuser depth of submergence H and the n = 1/3 or 1/2 power of airflow rate Q_a.

$$U_w \propto H\, Q_a^n \tag{1}$$

Goossens [1979] found that total water flow at the surface as a result of entrainment of an axisymmetric bubble plume could be expressed as

$$Q_w = 0.47 Q_a^{1/3} H^{4/3} \tag{2}$$

In equation 2, Q is in m^3 sec^{-1} under standard conditions, and H is in m. If the orifices in the air line are closely spaced, the aeration system behaves as a line source rather than a series of point sources. For the line source, the water flow can be approximated by [*Carey*, 1983]

$$Q_w = 2.28 Q_a^{1/2} H^{0.813} L_p^{\ 1/2} \tag{3}$$

where L_p is the length of the line source. The diffusers behave as a line source if the orifices are less than half of the depth of submergence apart from each other [*Carey*, 1983], i.e., less than 2 m for the bubble curtains considered in Holland Lake.

Using equation 3, the airflow rates become 3.5 $l\text{sec}^{-1}$ (7.4 SCFM†) and 5.8 $l\text{sec}^{-1}$ (12.3 SCFM) for the western and eastern shallow bays, respectively (Appendix C). The estimated water flow rate induced by this airflow rate is in general agreement with estimates given by *McCord et al.* [2000]. The total airflow rate divided by the total water volume of the deepened mix layer will be 1.4 SCMM‡/($10^6 m^3$), which is comparable to lakes and reservoirs where bubble diffusers have been successfully used for complete mixing, e.g. Kezar Lake, NH, Lake Roberts, NM [*Lorenzen and Fast*, 1977]. A listing of several major lake/reservoir aeration systems is given in Appendix A. To maintain a relatively uniform flow rate through the orifices, the pressure head loss through each orifice should be quite large, i.e. the orifice should be quite small. Therefore, size of the orifices were set equal to 1 mm for both bubble curtains, with 2 m spacing for the western shallow bay and 1.5 m spacing for the eastern shallow bay. The theoretical bubble size forming at the outlet of the orifice, assuming a spherical shape, can be obtained by setting the sum of the bubble weight and the surface tension force equal to the buoyant force as follows [*Deronzier* et al., 1998]

$$d_B = \sqrt[3]{\frac{6\sigma_s d_o}{g(\rho_w - \rho_a)}} \tag{4}$$

† SCFM = Standard cubic feet per minute

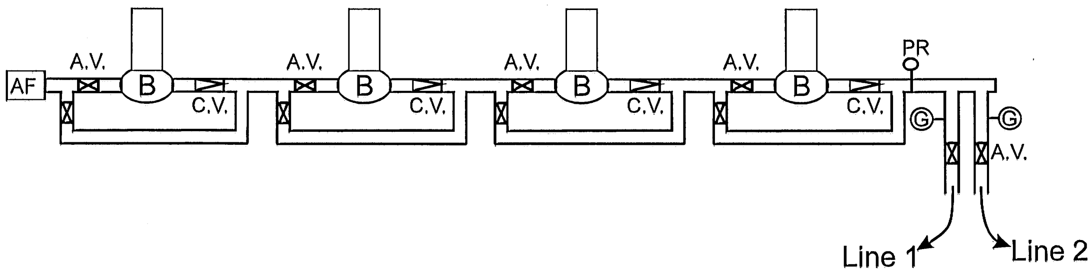
‡ SCMM = Standard cubic meter per minute

where d_B is the bubble diameter, d_o is the orifice size, ρ_w and ρ_a are the water and air density, respectively, g is gravitational acceleration and σ_s is surface tension. Based on ambient temperatures (10 to 30 °C), the theoretical bubble size at the outlet of the orifices will be about 3.5 mm, which is in general agreement with sizes measured in the laboratory by *Ashley et al.* [1992].

The flow rate and working pressure for the bubble curtains are 0.56 SCMM and 53 kPa (20 SCFM and 8 psi), respectively (see Appendix C for calculations). Such low pressure can be easily obtained by using blowers (not compressors) either single or in series. The required air can be provided using three R6 series GAST regenerative blowers in series (with operating points of 20 SCFM at 3.6 psi (100 inches of water pressure)). Figure 11 shows a schematic of the blower layout. The blower characteristics are given in Appendix C. The forth blower in Figure 11 represents a 33% standby. It will be utilized when any of the three main blowers requires repair or maintenance.

It is likely that mixing will not be complete in the remote areas of the shallow bays due to short-circuiting of the flow around the bubble curtain (Figures 12a and 12b), and the damping of turbulence by rooted macrophytes in the bays. This will not cause any problem in the performance of the bubble curtains because the mixed layer will be as deep as 4 m in the deep basin, and the flow field around the bubble curtains will not allow intrusion currents into the metalimnion (Figure 12c).

Oxygen transfer from the air bubbles to the water will not be significant in summer given that the saturated DO is low at high water temperatures and the 4 m depth makes travel time too short for oxygen to diffuse from the bubbles into the water column. However, surface film renewal will be enhanced by the plume action on the lake surface and that effect will increase the lake reaeration coefficient.



AF Air Filter
AV Air Valve
B Blower
CV Check Valve
G Flow Meter
PR Pressure Relief

Figure 11. Schematic of the blower layout for the bubble curtains.

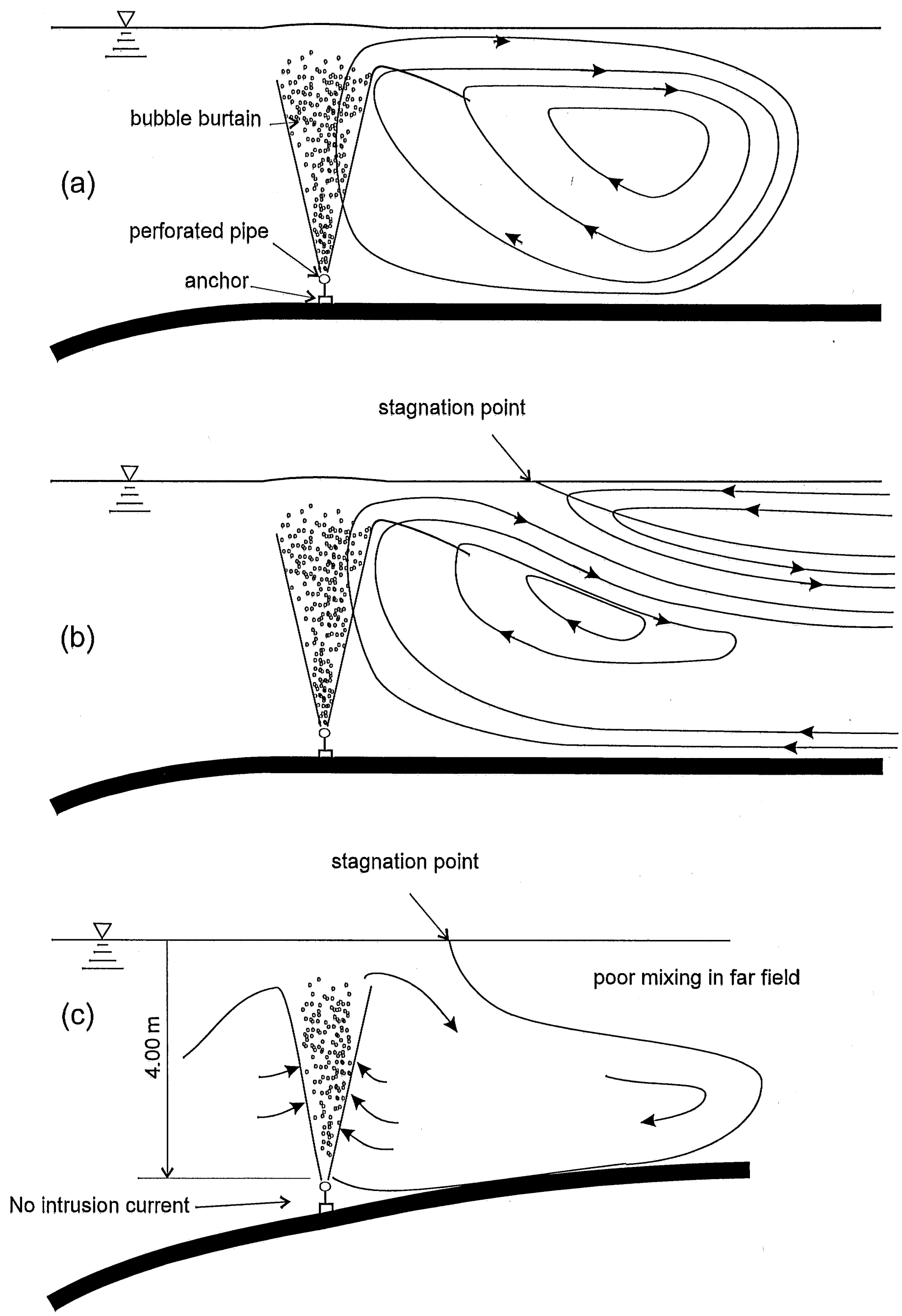


Figure 12. Flow field induced by the bubble curtains. (a) Flow field in the shallow bays under isothermal conditions, (b) flow field in the shallow bays under stratified conditions (after Goossens, 1979), and (c) how the induced flow field prevents intrusion currents from the shallow bays to the deep basin.

IV.2. Metalimnetic Aerator

IV.2.1. Concept

Over the last 40 years, a variety of techniques has been developed and applied for lake and reservoir aeration. Most common techniques have been either aerating the entire water column and destroying the thermal stratification, or aerating the hypolimnion. As shown earlier, full lake aeration has the adverse effect of increasing the water temperature, which eliminates the cold-water habitat. Hypolimnetic aeration, on the other hand, conserves the thermal stratification, but often activates chemical and biological processes by increasing circulation. Therefore, hypolimnetic aeration introduces uncertainties in the kinetic rates of chemical and biological processes. In addition, hypolimnetic aeration may require substantial power due to high pressure at the outlet of diffusers, especially in deep lakes.

A third technique is metalimnetic aeration. This technique has previously been explored by limnologists to create a daphnia refuge in a stratified lake [*Stefan et al.*, 1987]. In metalimnetic aeration, the thermal stratification is maintained, and a smaller portion of the lake is chemically and biologically activated than in whole lake or hypolimnetic aeration. The cost of metalimnetic aeration is lower due to smaller aerated water volumes and lower required pressures.

In metalimnetic aeration, water is extracted from the metalimnion, aerated and then returned to the metalimnion. The actual aeration (oxygen transfer) can be done in a cascade on-shore [*Ellis and Stefan*, 1990] or large vertical tube submerged in the lake. If aeration is in cascade water has to be pumped out from the lake to the cascade. The required intake screen would be prone to clogging by plant material and floating object. The cascade requires substantial construction in the park, and the placement of the intake and outlet of the water flow system requires construction in the lake. For these reasons a vertical tube aerator that requires only an air supply line is proposed in this report. Inside the riser tube, air or oxygen is injected at the bottom and allowed to rise (Figure 13). Water is entrained into the riser tube, and the drag force on the rising bubbles provides the force to lift the water up the column. The water withdrawn near the bottom is lower in oxygen than the water discharged near the top.

IV.2.2. Capacity and Dimensions

It is proposed to place a metalimnetic aerator in the deep basin to aerate the layer from 4 to 9 m. The volume of this layer is about 210,000 m^3 (Figure 5). The water flow rates required for one- and two-day renewal of the metalimnetic layer are 2.43 and 1.21 m^3sec^{-1}, respectively.

The design DO depletion rate was previously established at 1.2 mg $l^{-1}day^{-1}$. The oxygen transfer efficiency (OTE) of the aerator, which is the percentage of the supplied oxygen dissolved in water, depends on the submergence depth of diffusers, the bubble sizes, the density of diffusers [*Wagner and Pöpel*, 1998], the DO content of the water column, the saturation limit of the water column and the air flow rate. There have been many studies to quantify OTE as a function of these parameters, but the problem is not yet fully solved. It is well known that by increasing the depth, OTE increases due to an increase in the travel time, which allows more time for oxygen in the air bubbles to dissolve in the water column [*EPA*, 1989; *Wagner and Pöpel*, 1998]. With membrane diffusers OTE decreases as flow rate increases, because the openings of the membrane become wider, which produce larger bubbles [*Deronzier* et al., 1998]. Unfortunately, diffuser manufacturers give the OTEs based on standard conditions [*ASCE*, 1984], which often cannot be met in lake aeration systems.

Figure 14 [*Dryden Aqua*] gives a relationship between OTE and depth in terms of partial pressure of oxygen in the solution, i.e., the ratio of the DO concentration to the DO concentration at saturation. The dissolved oxygen concentration at saturation, DO_s, in mg l^{-1} can be well approximated as a function of water temperature, T_w, in °C as follows [*EPA*, 1997].

$$DO_s = \frac{468}{31.6 + T_w} \tag{5}$$

Using equation 5, and taking the metalimnetic temperature range before aeration (6 to 20 °C), the DO concentration at saturation will vary from 12 to 9 mg l^{-1}. We set the intake pipes at 9 m depth, and the diffusers at 11.5 m depth, with a 10 m travel distance for the bubbles. When the initial DO is 5 mg l^{-1}, the OTE will vary from 27% to 22% (Figure 14). Some time after the aerator starts operating, DO and water temperature increase in the metalimnion, which will cause a decrease in OTE. Therefore, we assume a 20% OTE for sizing the aerator.

Assuming 21% of air is oxygen, the total air needed for the metalimnetic aeration becomes 59 l sec^{-1} (125 SCFM) or 6,000 kg day^{-1}. Using the empirical relationship developed by *Taggart and McQueen* [1982] from about 10 studies on vertical tube hypolimnetic aerators such as shown in Figure 13, water flow rate can be estimated from

$$Q_w = 5.14\, H^{0.698}\, Q_a^{\;0.459}\, 5.75^{D/2} \tag{6}$$

In equation 6, H and D are the height and diameter of the riser tube in m, respectively, and Q_w and Q_a are flow rates of water and air in $l$sec^{-1}. In hypolimnetic aerators, the water flow Q_w is dependent upon the riser tube diameter, D. For a given air flow rate, as D increases, it is expected that the effect of D disappears, and the flow resembles unconfined bubble plumes (equation 2). However, in equation 6, water flow increases indefinitely with D. Therefore, equation 6, which is based on 10 studies of operating hypolimnetic aerators, must have upper and lower limits. To determine the applicability of equation 6, it was plotted for our case with a riser tube height of 10 m and for different diameters in Figure 15. In addition, equation 2 [*Goossens*, 1979] and equation 3 are also plotted on the same graph for comparison. The line with square markers represents equation 2. Equation 2 has a milder slope because the exponent of airflow is smaller in equation 2 than in equations 3 and 6. The solid lines represent unconfined line sources for lengths from 0.1 m (4 inches) to 3 m (10 ft). The dashed lines represent equation 6 for different riser tube diameters. One would expect the Goossens equation (equation 2) to give a limit for equation 6. Therefore, for the case of H = 10 m, riser tube diameters larger than 3.5 m do not seem reasonable.

The water flow and airflow requirements for a metalimnetic aerator in Holland Lake are also shown in Figure 15. A one-day renewal time requires a 3.1 m riser tube, while a two-day renewal time requires 2.3 m. Adding an outer tube to a 3.1 m (10.2 ft) riser tube would give a final structure uncomfortably large for construction, transportation and installation.

Using two aerators, each supplying half the air needed and a renewal time of two days, would require a 1.85 m diameter for each riser tube. The cost of one 2.3 m aerator, however, is approximately 30% less than two 1.85 m aerators. Since a 2.3 m riser tube is not considered excessively large for construction and installation, it is chosen for the proposed selective layer aeration system (see Appendix D for calculations). This metalimnetic aerator has a water flow rate of 1.25 $m^3 sec^{-1}$. For a metalimnetic layer volume of 210,000 m^3, the water renewal time becomes 1.9 days. Based on 20% efficiency, the DO added to the water on each pass through the tube has to be 2.4 mg l^{-1}.

Figure 16 gives the dimensions for the riser, inlets, and outlets. The aerator will be placed 1.5 m (5 ft) below the water surface with only a short ventilation tube to prevent any damages due to moving ice in spring. The 1.5 m is based on the natural variability of the lake stage and an average ice thickness of about 70 cm (28 inches).

The flow rate and working pressure for the metalimnetic aerator are 1.6 CMM and 122 kPa (57 CFM and 18 psi), respectively (see Appendix D for calculations). To provide this pressure several small compressors in parallel and series can be used. It is recommended to use oil-less rotary-vane compressors. The advantages of rotary-vane compressors are vibration-free operation, few moving parts, and a non-pulsating air supply. Figure 17 shows a schematic of the compressor layout if AQ63 oil-less vane compressors are used. In this design, six compressors are considered of which two are stand by. The operating point of each AQ63 compressor is 50.5 CFM at 10 psi. If other compressors with higher working pressures, thus occupying less space in the shelter, are available on the market, a 50% standby is recommended. The amount of oxygen transferred to the water per unit work effort would be 1.2 kg O_2 per kWh. Literature values range from 0.2 to 1.1 kg O_2 per kWh.

The metalimnetic aerator with a 2.3 m diameter has enough width to place 36 FlexAir 9-inch fine bubble disc diffusers (Figure 18). Normal airflow range of each diffuser is 0 to 5 SCFM. The air supply line from the compressors to the aerator will be a 0.064 m (2.5 inches) polyethylene pipe. The disc diffusers will be mounted on a mesh of steel bars and connected to the header line through 6-way manifolds.

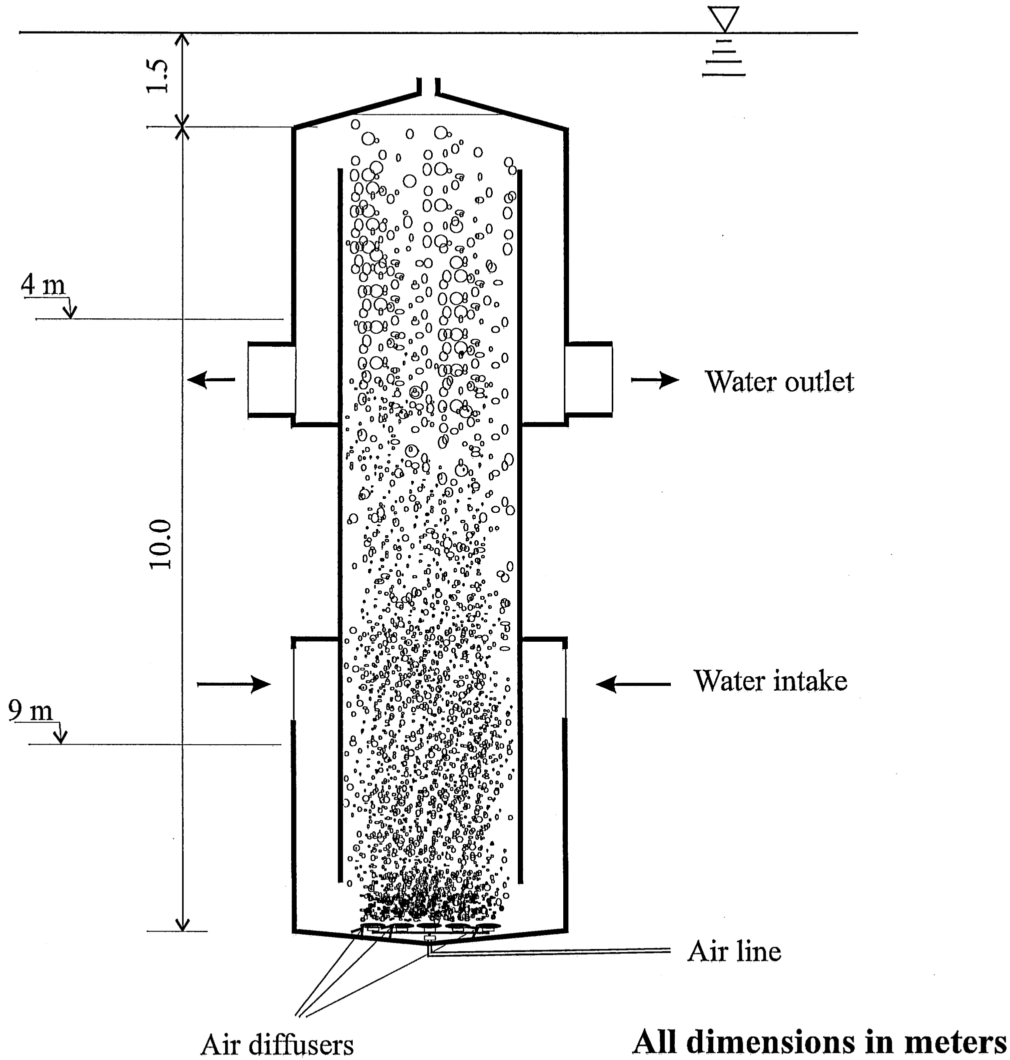


Figure 13. Schematic of the metalimnetic aerator.

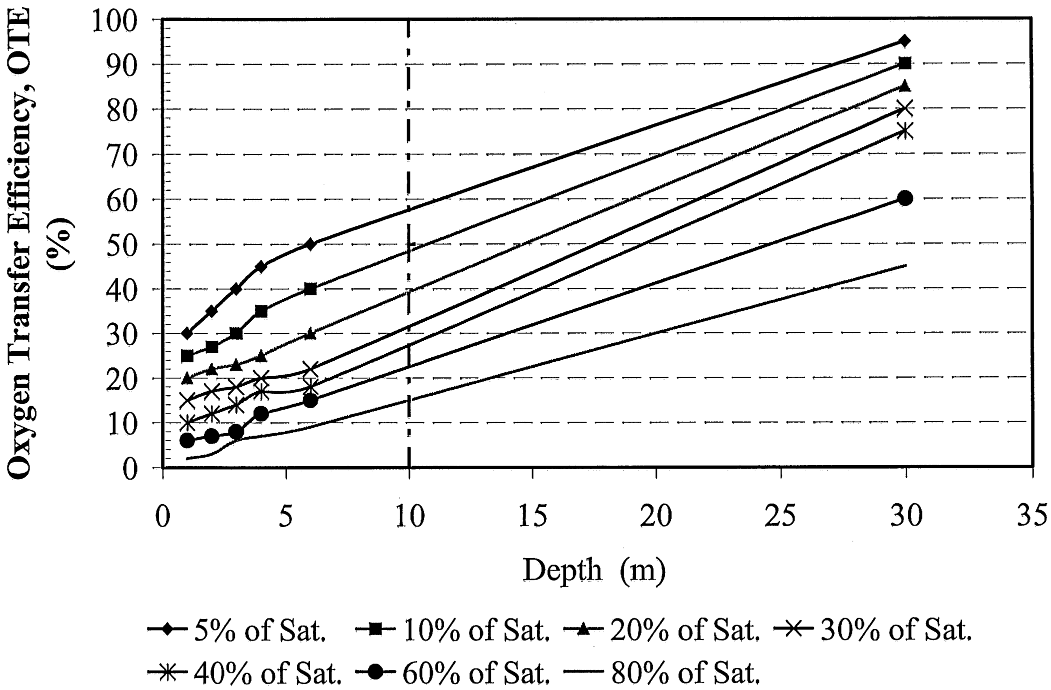


Figure 14. Typical oxygen transfer efficiencies (OTE) of fine bubble diffusers, for different water depths against the partial pressure of oxygen in solution (after Dryden Aqua).

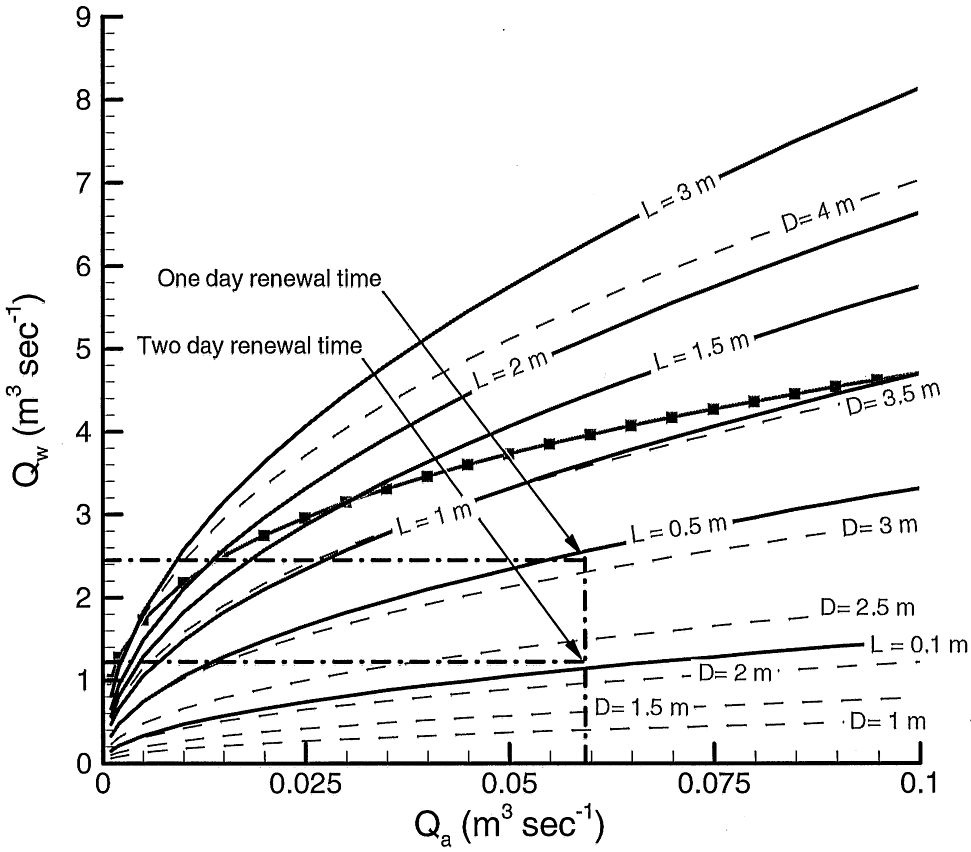


Figure 15. Water flow versus airflow using equation 2 (axisymmetric plume) shown with square markers, using equation 3 (line source) for different lengths shown with solid lines, and using equation 6 (Taggart and McQueen) for different riser tube diameters using dashed lines. The curves are plotted assuming a 10 m lift for all bubble plumes.

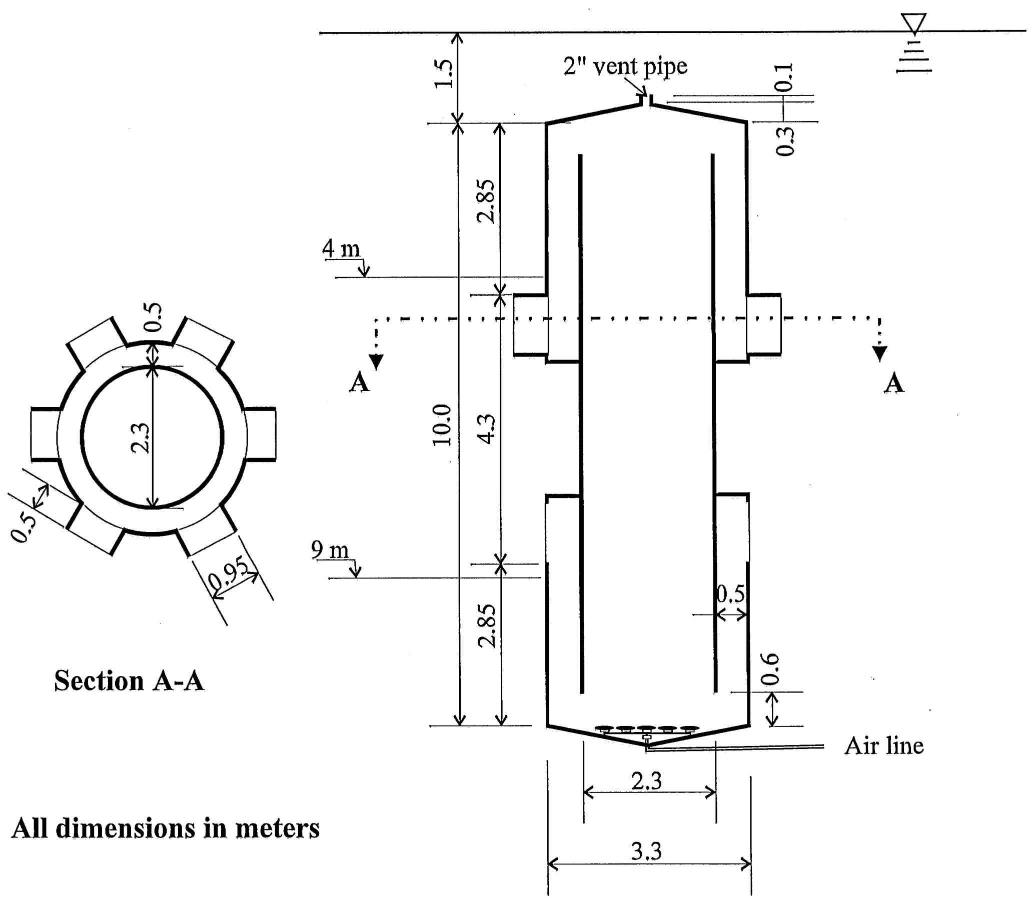
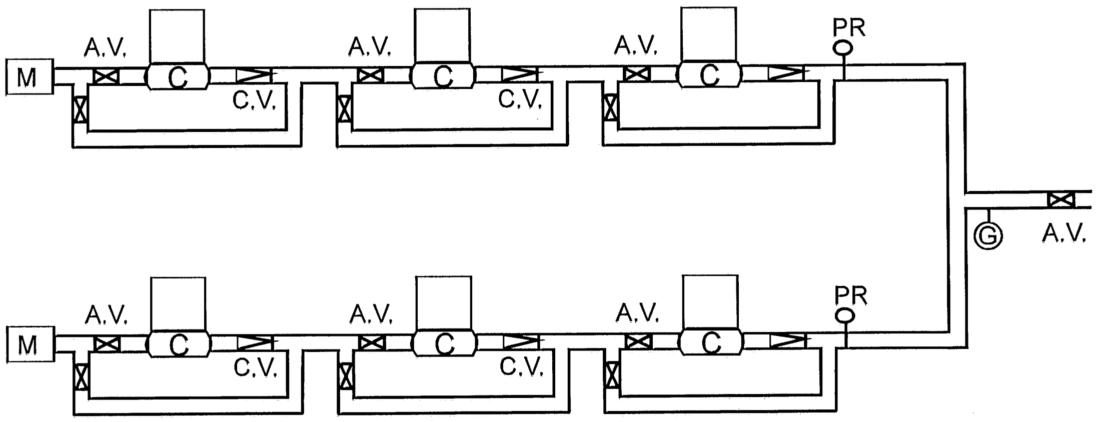
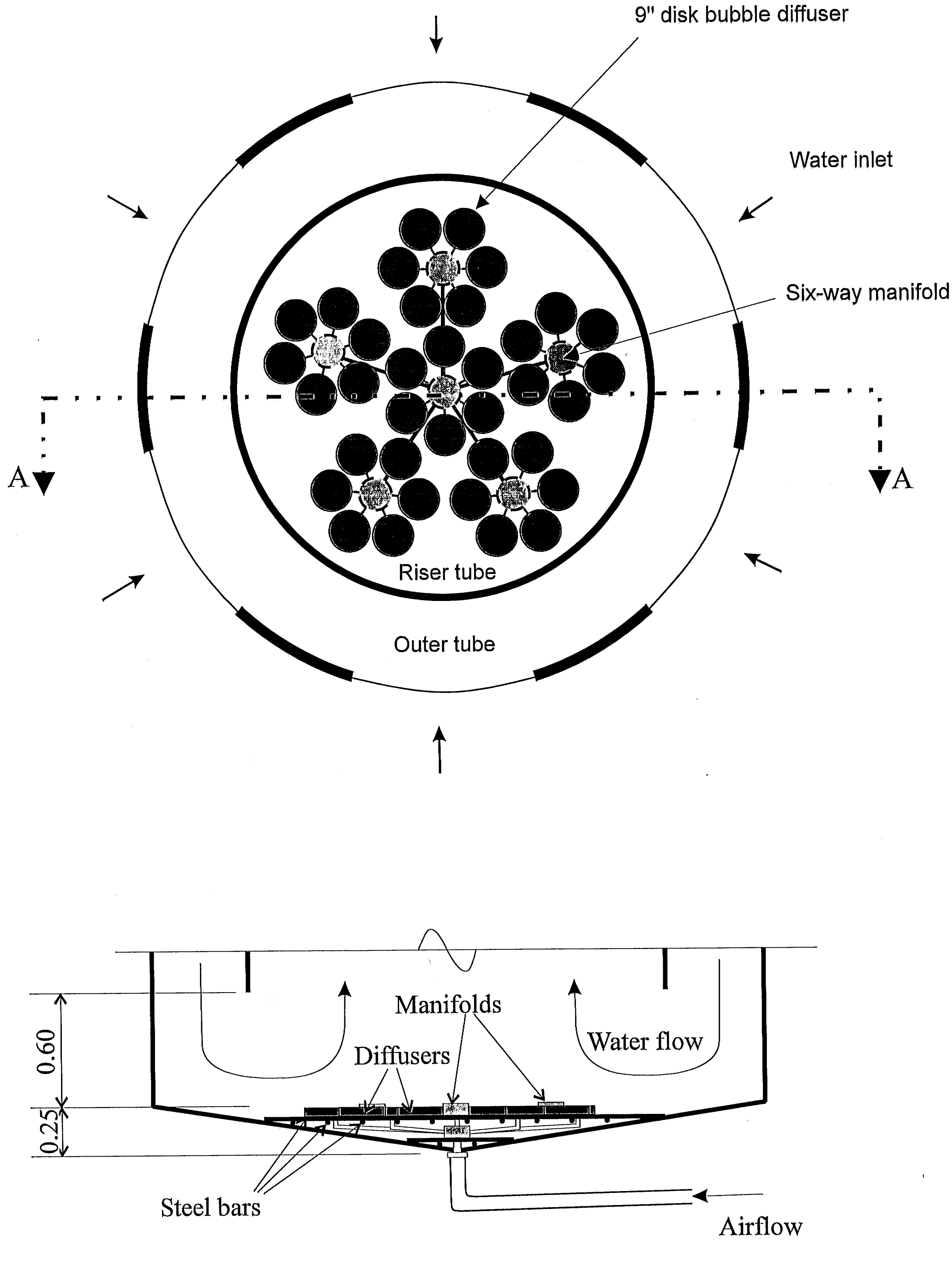


Figure 16. Schematic of the vertical and horizontal cross-sections and the dimensions of the metalimnetic aerator.



M Muffler
AV Air Valve
C Compressor
CV Check Valve
G Flow Meter
PR Pressure Relief

Figure 17. Schematic of compressor layout for the metalimnetic aerator.



SECTION A-A

Figure 18. Horizontal and vertical cross sections of the bottom of the metalimnetic aerator showing the arrangement of 36 fine disc bubble diffusers.

V. Recommended Implementation

V.1. Materials/Equipments

- Polyethylene pipes are recommended in water. Metal tubing (galvanized steel pipe) is recommended outside the lake.
- To anchor the air curtain pipes on the lake bottom, 0.10 m (4 inch) concrete blocks (2.3 kg or 5 lbs), at 0.5 m (20 inches) spacing, or weighted diffuser tubing are required to overcome buoyancy. To anchor the 2.5" header line of the metalimnetic aerator, 0.125 m (5 inch) concrete blocks at 0.5 m (20 inches) spacing are required.
- The metalimnetic aerators tubes (inner and outer tube) can be made from fiberglass or polypropylene, reinforced with angle profiles. Eye loops for anchoring are needed at the bottom and placed where angles are attached to the body.
- The noise level of blowers and compressors should not be excessive.
- To facilitate cleaning of the diffusers in spring, and for flexibility of the system operation, blower and compressor capacities at the required pressure are recommended to be higher than required. Lower flow rates can be achieved by throttling of the system.
- If air tanks are deemed necessary, they should be installed in the shelter on the main supply lines.

Table 2. List of the materials

Item	Specifications	Dimensions, sizes, weight	Type or material	Amount or number
Pipes	-	2"	Galvanized steel	100 ft (30 m)
Pipes	Heavy duty	2"	Polyethylene	2500 ft (740 m)
Pipes	Heavy duty	2.5"	Polyethylene	660 ft (200 m)
Blowers	3 phase, 2" inlet/outlet FNPT	120 lbs	R6 GAST	4
Compressors	Oil-less vane, 3 phase, 5 hp	155 lbs	AQ63	6
Check valves	-	2"	-	4
Check valves	-	2.5"	-	6
Air valves	-	2"	-	12
Air valves	-	2.5"	-	13
Flow meter	-	-	-	3
Pressure relief	-	-	-	2
Pressure gauge	-	-	-	10
Diffusers	Fine bubble disc diffuser with membrane, normal airflow of 0-5 SCFM	9"	FlexAir	36
Ceiling crane	300 lbs	-	-	-
Shelter	Concrete floor with ventilation	13' × 13'	-	1

V.2. Construction

- Before placing any purchase order for the materials, transects in the vicinity of pipeline and aerator locations should be surveyed and mapped. Historical records of the lake stage need to be assembled. It is noteworthy that the lake stage has changed from the early 1980s and is different from the 1969 map on the MNDNR website.

  After the survey is completed, design parameters, e.g. required tubing lengths, need to be matched to the actual terrain.

- It is recommended to construct and install the system in two stages. First, a shelter with a concrete floor should be built to install the blowers and the bubble curtain air lines. Before and during this period, lake water quality parameters such as temperature profiles, DO profiles and TOC profiles need to be measured in the bays and the deep basin. The bubble curtains should be operated before any further action for the construction of the aerator is taken. While the bubble curtains are operating, DO, TOC and temperature profiles need to be taken at the same spots in the lake to estimate the effect of the bubble curtains on the DO depletion rates in the metalimnion and the nutrients levels in the bays. If the DO depletion rate and TOC are significantly changed, the working pressure and flow rate need to be adjusted, and compressors should be selected based on the new rates.

  If the DO depletion rate and/or the nutrients levels are increased, the airflow rate through the bubble curtains must be adjusted to reduce further oxidation of organic materials, while the surface mixed layer is maintained.

- Air pipes need to be sloped downward towards the lake and in the lake such that the lowest point of the air line will be the end of line. The air line for the metalimnetic aerator must eventually run on the 9 or 10 m contour and then be connected to the bottom of the aerator. The diffuser mount under the bottom of the metalimnetic aerator must be the lowest point in the pipeline.

- Piping in the shelter is recommended to be sloping towards accessible drain points. Air outlets should be taken from the top of the main line so that possible moisture will not enter the outlet.

- The bottom of the aerator tube must be kept closed, because it is 2.5 m (8 ft) into the hypolimnion. The inlets are positioned at the 8.23 m depth.

- A 1.0 m (3 ft) door should be placed in the lowest part of the aerator for access to the diffusers by scuba divers.

- Floatation devices need to be mounted outside the upper part of the aerator tube. The floatation devices must be designed for the period that the air is not operating. The dimensions of the floatation devices depend on the aerator material and thickness. For 10 mm thick fiberglass, ten 1.0 m × 0.55 m × 1.0 m (3.3 ft × 1.8 ft × 3.3 ft) Styrofoam pads are needed. Anchoring devices must be designed for the period when diffusers are operating at the maximum airflow during the diffuser cleaning period. If concrete blocks are used, 2.6 m^3 of concrete is needed (twenty four 0.8 m × 0.5 m × 0.30 m).

- A shelter for compressor and blowers is proposed. The shelter area should be designed based on the selection of compressors and blowers. It is estimated that 16 m^2 (170 ft^2) of floor space will be sufficient.
- The shelter should be ventilated.
- A ceiling crane, with 300 lbs capacity, should be considered in the shelter.
- If prolonged droughts are a major concern for the future operation of the aerator, then the aerator need to be designed to meet those conditions. Adding another 0.6 m to the submergence depth of the aerator (a total of 2.1 m) could provide a high safety factor for the aerator to stay submerged before the winter ice cover period starts. It is noteworthy that a 1.5 m drop in the lake stage may theoretically occur over a 2-year rainless period.

  Figure 19 displays schematically an aerator installation for prolonged drought conditions. In Figure 19, the main dimensions have not changed; only the positions of the outlets and inlets have changed. Therefore, the travel length for air bubbles inside the aerator has remained the same, and consequently the oxygen transfer efficiency will not change under the new design. The main change will be in the working pressure of the compressors, which has increased by 0.6 m of water (0.85 psi). Therefore, if it is decided to use the schematic of the aerator shown in Figure 19 instead of Figure 16, the compressors must be operated under the new working pressure.

V.3. Operation

- Water temperature, DO and BOD profiles must be measured in the deep basin and the bays (three spots) before the bubble curtains start operating.
- It is recommended to monitor the lake, especially the surface mixed layer, when the bubble curtains start operating. Monitoring the water quality of the lake is recommended for fine-tuning the airflow rate to prevent any excessive increase of the shallow bay productivity. Since the effects of nutrient increase are not immediate, it is recommended to start operating the bubble curtains immediately after installation and to take water samples in the bays and the deep basin once every two weeks to monitor the nutrient concentrations before and during the operation.
- System must run for three to four months, from late May to early September. DO must be monitored from early May. Before the DO concentration falls below 5 mgl^{-1} anywhere in the metalimnion, the aerator should be started.
- There is no need to remove any part of the system for winter.
- In spring, the discs can be cleaned with higher airflow rates before the normal operation starts. If they are not cleaned by airflow, then, a scuba diver is needed for *in situ* cleaning or changing the discs.

V.4. Some Considerations for Winter Operation

To prevent winterkill, ice-covered lakes are often artificially aerated. To provide a suitable habitat for fishes in winter, the metalimnetic aerator can also be operated during the ice cover period. The high DO content in the vicinity of the aerator will provide a refuge for the fishes. Since, there is no need to provide a surface mixed layer for the upper 4 m depth of the lake, there will be no need to operate the bubble curtains.

Winter lake aeration degrades the ice cover, creating a hazard to winter lake users. Air bubblers have been used to melt ice in harbors and navigation channels. Bubblers transfer heat stored in the water to the underside of the ice cover. The heat is likely to melt the ice above the plume completely, creating an open water area. Therefore, if the aerator operates in winter, thin ice warning signs must be posted around the area. The diameter of the plume, D_p (m), striking the underside of the ice can be obtained from the following equation [*Carey et al.*, 1983]

$$D_p = 0.364\,(H + 0.8)\left(Q_a/L\right)^{0.15} \tag{7}$$

In equation 7, Q_a is the airflow rate under standard conditions in m^3sec^{-1}, L is the length of the line source in m, and H is the depth of the diffusers in m. If the airflow rate recommended for the summer operation is supplied in winter, the width of the plume becomes about 0.9 m (3 ft). This would be approximately the width of the opening in the ice created by the rising bubbles. Thin ice will extend on the sides. Warning signs should be posted at a radius of 5 m (17 ft) around the aerator.

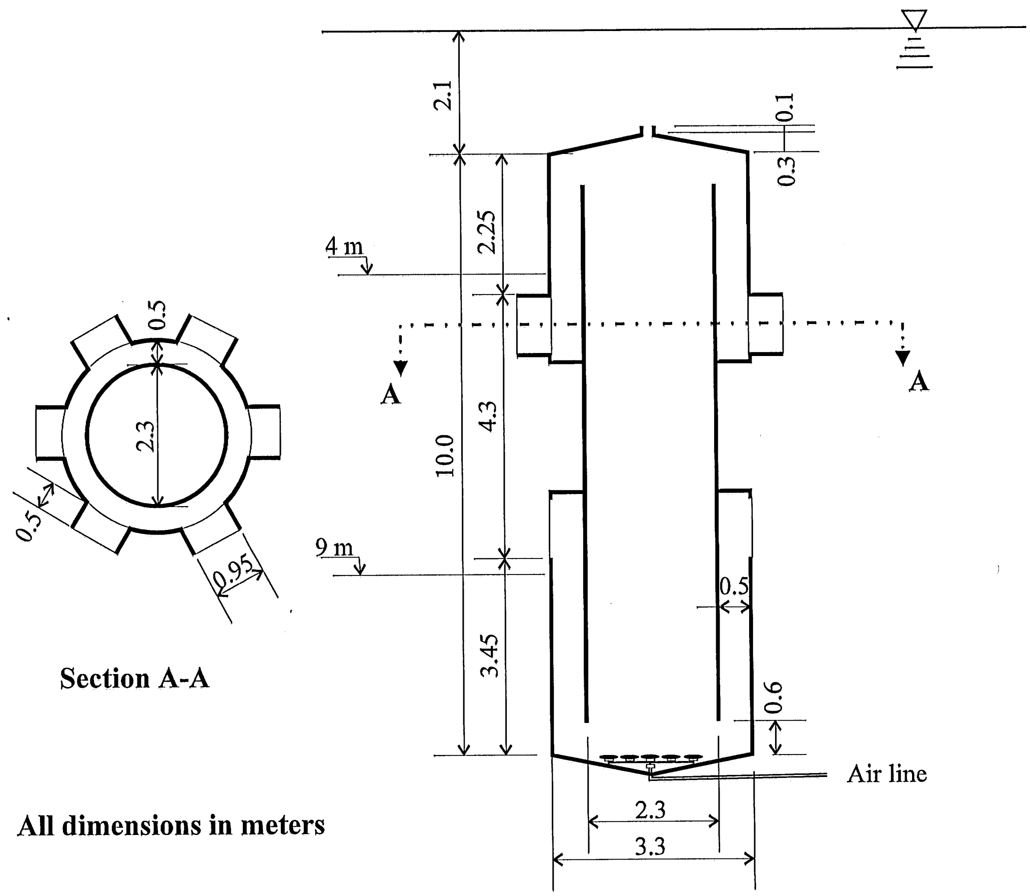


Figure 19. Schematic of the vertical and horizontal cross-sections and the dimensions of the alternative metalimnetic aerator considering prolonged drought in the future.

VI. Cost Estimates

VI.1. Construction

Bubble Curtains:

Items	Number	Price per unit	Cost, $
• Blowers (R6 GAST)	4	1000	4,000
• Inlet filter	1	130	130
• Pressure switch	1	30	30
• Heat dissipating pipe/flange	2	120	240
• Pressure relief	1	200	200
• Check valves	4	100	400
• Pressure gauges	4	10	40
• Flow gauges	2	60	120
• Air valves	12	20	240
• Polyethylene pipe, 2" (770 m)	13 coils	180	2340
• Miscellaneous			560
• Installation			2,200
		Total	10,500

The air supply system for the metalimnetic aerator:

Items	Number	Price per unit	Cost, $
• Compressors (AQ63)	6	2,000	12,000
• Single valve outlet	6	80	480
• Inlet Muffler assembly	2	110	220
• Pressure switch	2	30	60
• Heat dissipating pipe/flange	1	120	120
• Pressure relief	1	50	200
• Check valves	6	100	300
• Pressure gauges	6	10	60
• Flow gauges	1	60	60
• Air valves	13	20	260
• Rubber coupler	6	65	390
• Polyethylene pipe, 2.5" (200 m)	4 coils	250	1,000
• Miscellaneous			1,000
• Installation			3,350
		Total	19,500

Metalimnetic aerator and diffusers:

Items	Number	Price per unit	Cost, $
• Fiberglass tubes 155 m^2 (1670 ft^2)		30/ft^2	50,100
• Angles, stainless steel rings, anchors and floatation devices			1,200
• Diffusers/Discs	36	15	540
• 6 way manifolds	6	25	150
• Miscellaneous			510
• Labor/Installation			7000
		Total	59,500

Shelter:

The area of the shelter depends upon the type and number of compressors and blowers selected. Based on the compressors and blowers selected above, at least 170 ft^2 is needed. Including a ceiling crane, shelter would cost about $12,000.

Items	Cost, $
• Bubble curtains	10,500
• The air supply system for the metalimnetic aerator	19,500
• Metalimnetic aerator and diffusers	59,500
• Shelter with a ceiling crane	12,000
Total	101,500

VI.2. Operation

Items	Cost, $
• Energy cost for 10 kWh at ¢7.3 for 3 months	1,600
• Half of a day per week of a person to check on the blowers and compressors, and taking DO and temperature and probably TOC profiles	1,200
Total per year based on 2001	2,800

VI.3. Maintenance

Items	Cost, $
• Parts (vane set, filters, diffusers, valves)	1,000
• Labor for diffuser cleaning and start up	500
Total per year based on 2001	1,500

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Appendix A: Examples of Destratification Systems [*Lorenzen and Fast*, 1977]

Lake	Location	Air release depth (m)	Mean depth (m)	Volume (10^6 m^3)	Area (10^6 m^2)	Qair (SCMM)	SCMM / (10^6 m^3)	SCMM / (10^6 m^2)	Comment
Clines Pond	Corvallis, OR	5	2	0.0028	0.0014	0.028	10	20	Good mixing
University Lake	NC	9	3	2.6	0.81	0.4	0.15	0.49	DO depletion
Eufaula Reservoir	OK	28	16	703.0	43.5	34	0.05	0.78	Central pool 125 psig 1-2 °C
Kezar Lake	NH	8	3	2.2	0.71	3	1.3	4.2	15 psig, good mixing
Lake Roberts	NM	9	4	1.2	0.28	2.8	2.3	10	
El Captain	CA, 1970	21	10	18.0	1.84	6.1	0.34	3.3	Did not mix algae
	CA, 1971	28	10	21.0	2.22	6.1	0.29	2.7	
Test Lake 1	Boltz, KY	19	9	3.6	0.39	3.2	0.89	8.2	
Test Lake 2	Falmouth, KY	13	6	5.5	0.91	3.3	0.59	3.6	
Section Four Lake	MI	18	10	0.11	0.011	2.2	20	200	Compressor run only 8 hrs a day
Ottoville Quarry	OH, 1970	17	9	0.062	0.0071	0.91	14.5	128	Non-continuous compressor operation
	OH, 1971	17	9	0.062	0.0071	2.2	35	310	
Casitas Reservoir	CA, 1972	43-49	26	248.9	9.61	18	0.07	1.9	Air injected about 25-30 m off the bottom
	CA, 1973	43-49	28	294.8	10.6	18	0.06	1.7	
Buchanan Lake	Ontario, Canada	13	5	0.42	0.086	0.28	0.67	3.3	
Valen Lake	Ontario, Canada	5	2	1.2	0.61	0.28	0.24	0.46	
Parvin Lake	CO	10	4	0.85	0.19	2.1	2.5	11	Helixor[R]
Lake Wohlford	CA	14	6	3.09	0.53	5.9	1.9	11	Compressor run 9hr/day
Cox Hollow	WI	9	4	1.48	0.39	2	1.4	5.1	Aero-hydraulic cannons
Wahnbach Reservoir	W. Germany, 1961-62	43	19	41.6	2.14	2	0.05	0.93	
	W. Germany, 1964	43	19	41.6	2.14	5.9	0.14	2.8	
Hyrum Reservoir	UT	21	11	16.6	1.77	2.8	0.17	1.6	Did not mix algae

Appendix B: Heat Budget Components

The heat budget components across the air-water interface in Holland Lake were estimated using the weather data measured at the St. Paul-Minneapolis International Airport and are displayed in Figure B-1 for three different scenarios. The heat budget components are denoted in the figure as follows:

Hs = solar radiation

Hla = atmospheric long wave radiation

Hlb = back radiation from the surface

Hc = sensible heat flux

He = evaporative heat flux

Hp = heat flux due to rain

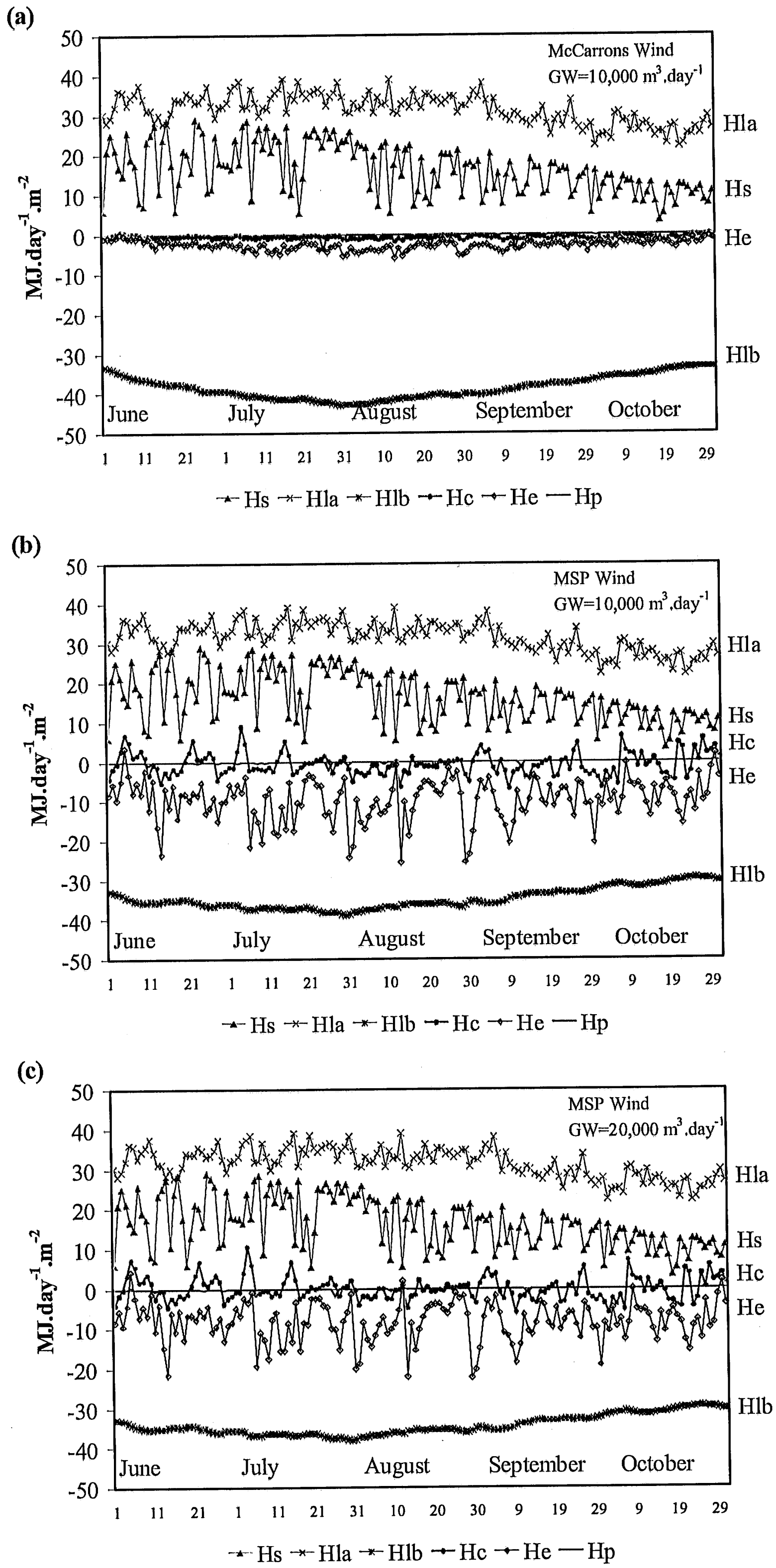

Figure B-1. Estimated heat budget components across the air/water interface in Holland Lake, from June to October 1999, under three scenarios.

Appendix C: Bubble Plume Calculations

C.1. Air Supply Line

The water flow/air flow rate relationship (equation 3) can be rearranged as follows

$$Q_a = \left(\frac{Q_W}{2.28 H^{0.813} L_p^{\ 1/2}} \right)^2 \quad \text{(C-1)}$$

Distributing the required airflow between the two bays based on their volumes (44,000 m^3 for the western shallow bay and 118,000 m^3 for the eastern shallow bay) and assuming each bubble curtain mixes half the deep basin (115,500 m^3), the water flow rate for a 12-hour renewal time (9.1 $m^3\ sec^{-1}$) for each line would be

$Q_{w,W}$=9.1*0.41=3.73 $m^3\ sec^{-1}$

$Q_{w,E}$=9.1*0.59=5.37 $m^3\ sec^{-1}$

From equation C-1, Q_as, under standard conditions, in the western and eastern shallow bays become 0.0035 and 0.0058 $m^3\ sec^{-1}$, respectively.

C.1.1. Line 1

For line 1 (Figure 9), the total length L = 520 m, and the length of the perforated section *Lp* = 80 m. We assume a diameter of 0.051 m (2") polyethylene pipe for this line.

Required working pressure at the blower (P)= hydrostatic pressure, (P_w) + air line head loss (P_l) + minor losses (P_{lm}) + the orifice head loss (ΔP_o).

The head loss ΔP_o across the orifices depends strongly on orifice diameter. This head loss should be made large enough to assure that all orifices discharge about equal airflow rates even if the line is not perfectly aligned resulting in variable hydrostatic back pressure at variable depths of submergence. To maintain a relatively uniform airflow through orifices, the pressure head loss through each orifice should be quite large in comparison to air line friction loss and minor losses, which are no more than 0.3 m of water. Therefore, assuming a 2 m of water pressure loss, we estimate the orifice size from equation C-2.

$$d_o = 2 \left(\frac{Q_a}{\pi C_d \sqrt{\frac{2\,\Delta P_o}{\rho_a}}} \right)^{1/2} \quad \text{(C-2)}$$

In equation C-2, d_o is the orifice diameter, C_d is the flow coefficient of the orifice and is about 0.65, and ρ_a is the density of air, which would be 1.9 kg/m^3 at about 6 m head of water. At a pressure of 6 m of water, airflow Q_a would contract to 0.0022 $m^3\ sec^{-1}$. With 40 orifices for line 1, with 2 m spacing to maintain a line source, the orifice size from equation C-2 becomes 0.87 mm. Drilling 1 mm orifice in the pipe at 2 m intervals, the velocity through orifice would become 70 m/sec, and the pressure head loss through the orifice from

$$\Delta P_o = \tfrac{1}{2}\, \rho_a\, V_o^2/C_d^2 \qquad \text{(C-3)}$$

would become 11018 Pa.

The air line friction loss can be estimated from the Darcy Weisbach equation as follows

$$P_l/\gamma_a = f\, L\, V^2/(2g\, D) \qquad \text{(C-4)}$$

For a kinematic air viscosity of $2.045*10^{-5}$ m^2/sec and a Reynolds number of 2700 gives a friction factor of 0.044 for a smooth pipe and a friction head loss of 68 m of air. The minor head losses would be estimated from

$$P_{lm}/\gamma_a = \Sigma\, (K_i\, V_i^2/2g) \qquad \text{(C-5)}$$

Minor losses occur at air valves, check valves, bends, and junctions (see Figure 11). The total minor losses are estimated to be P_{lm}/γ_a = 25 m of air.

P = 4*9810 + (68 + 25)*1.9*9.81 + 11018 = 51991 Pa or 52 kPa or 7.5 psi

SCMM = 0.0035 * 60 = 0.21, or 7.4 SCFM

CMM = 0.21 * 101/(101 + 52) = 0.14, or 4.9 CFM

C.1.2. Line 2

For line 2 (Figure 9), the total length L = 250 m, and the length of the perforated section *Lp* = 100 m. We assume a diameter of 0.051 m (2") polyethylene pipe for this line as well.

At the same pressure as line 1 (52 kPa), the airflow rate would be compressed from 0.0058 to 0.0039 m^3 sec^{-1}. Assuming 1 mm orifice size, the spacing would be 1.5 m. For a kinematic air viscosity of $2.045*10^{-5}$ m^2/sec and a Reynolds number of 4700 gives a friction factor of 0.038 for a smooth pipe and a friction head loss of 35 m of air.

The total minor losses are estimated to be P_{lm}/γ_a = 35 m of air, and the pressure head loss through the orifice would be 12728 kPa.

P = 4*9810 + (35 + 35)*1.9*9.81 + 12728 = 53273 Pa or 53 kPa or 8 psi

SCMM = 0.0058 * 60 = 0.35 or 12.3 SCFM

CMM = 0.35 * 101/(101 + 53) = 0.23 or 8.0 CFM

Therefore, the operating point for the blowers would be 13 CFM at 8 psi.

Power = PQ/η where η is the efficiency or the power factor of the electric motor. For fully loaded electric motor is about 0.9 but it goes down with partially loaded motor. We assume an η of 0.6.

Power = 53* (0.0039 + 0.0022) / 0.6 = 0.55 kW

Based on the type of blower, the kW may exceed this value. For three R6 GAST blowers, the required power would be 1.0 kW (see figure C-2). For operation cost estimates, we will use one kW for the blowers.

C.2. Bubble sizes

Using equation 4 to estimate the bubble sizes for different orifice size

$$d_B = \sqrt[3]{\frac{6\sigma_s d_o}{g(\rho_w - \rho_a)}}$$

Surface tension at the air-water interface σ_s varies with temperature. It is 0.0742 and 0.0712 N/m at 10 °C and 30 °C, respectively. The density of air ρ_a would be about 1.9 kg/m^3 at the outlet of the orifices. ρ_w the density of water would be 1000 and 996 kg/m^3 at 10 °C and 30 °C, respectively. The difference between the bubble sizes at these two temperatures will not be significant.

The theoretical bubble sizes at the outlet of the orifices obtained from equation 4 are listed in Table C-1. The bubble size increases as it rises to the surface due to a decrease in pressure and subsequently a decrease in the air density.

Table C-1. Theoretical bubble sizes at the outlet of orifices

Orifice size in mm	Bubble size in mm
0.5	2.8
0.8	3.3
1	3.5
2	4.5

C.3. Anchoring the pipe line

Anchors are needed to counter balance the buoyant forces on the air lines. If we assume that 0.1 m × 0.1 m × 0.1 m (4" × 4" × 4") concrete blocks are attached to the pipe, and setting the weight of a concrete block in water equal to the buoyant force exerted on the pipe (neglecting the weight of the pipe), then spacing would be obtained as follows.

For D = 0.051 m (2" diameter)

$F_{B,p} = s * \pi * 0.051^2/4*1 = 0.002s$ t. The parameter s is spacing between the blocks in meters.

Volume of each concrete block is 0.001 m^3. The spacing between the concrete blocks would be $s = (2.3 - 1.0)*0.001/0.002 = 0.65$ m.

To provide a safety factor, a 0.5 m spacing of the blocks is recommended for the 2" pipes. The weight of each block is 2.3 kgf (5 lbs). For the section where the two pipe lines are next to each other (Figure 10), the pipes can be attached together to 0.125 m × 0.125 m × 0.125 m (5" × 5" × 5") concrete blocks with 0.5 m spacing.

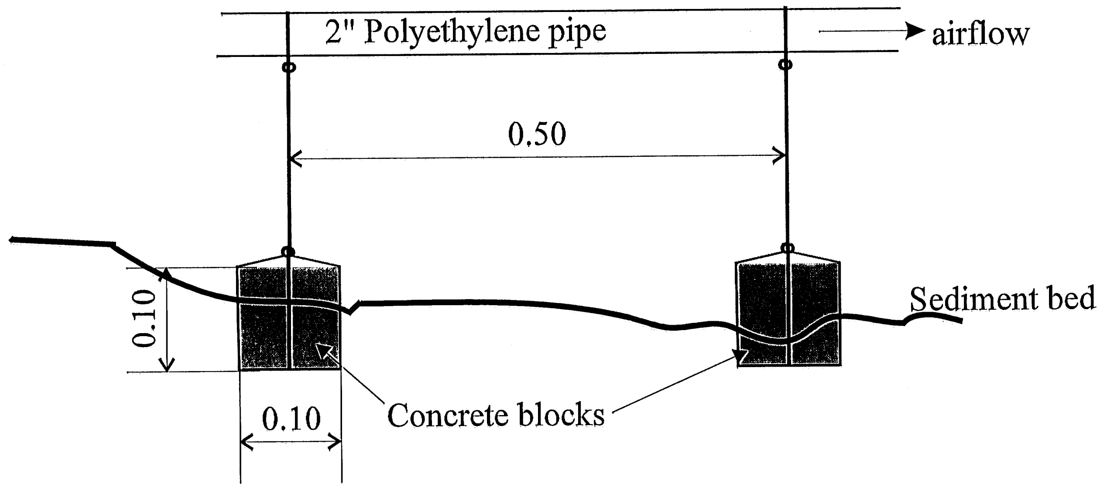

Figure C-1. Layout of the anchoring blocks for the air pipes. All dimensions are in meters.

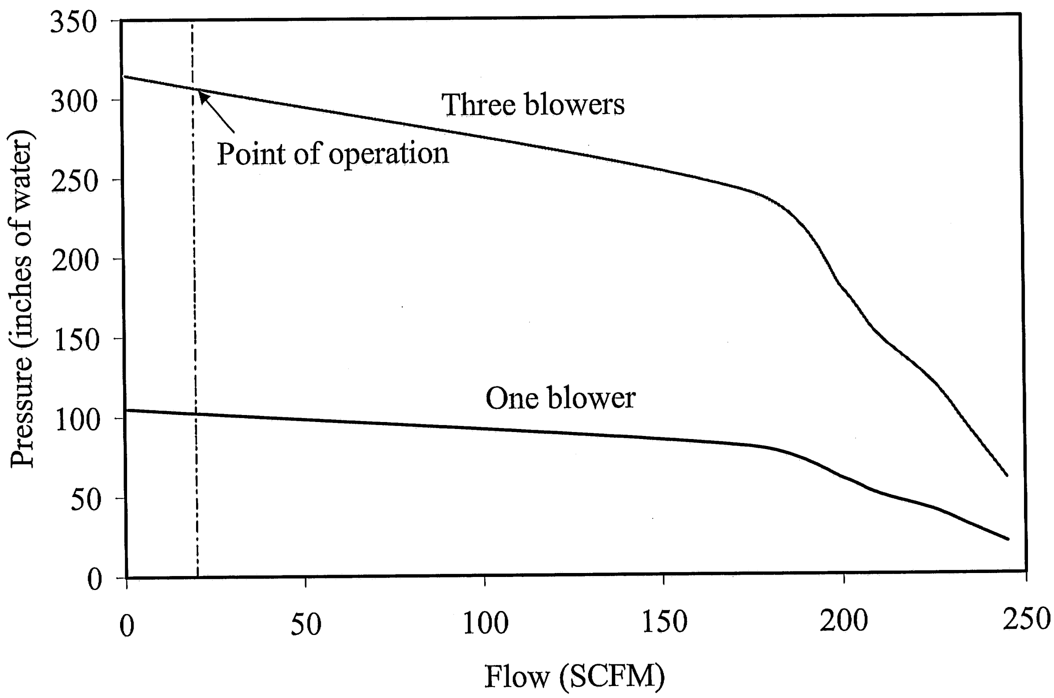

Figure C-2. The R6 GAST blower characteristics and the point of operation for the bubble curtains.

Appendix D: Metalimnetic Aerator Calculations

D.1. Aerator

The water flow/air flow rate relationship (equation 6) can be rearranged as follows

$$D_r = 1.143\, ln\left(\frac{Q_w}{5.14\, H^{0.698}\, Q_a^{\;0.459}}\right) \tag{D-1}$$

Airflow rate Q_a is 59 l sec^{-1} and water flow rates Q_w for one- and two-day renewal periods are 2430 and 1215 l sec^{-1}, respectively. With these values and H = 10 m, equation D-1 gives inner tube diameters D_r = 3.1 and 2.3 m, respectively. Choosing the two-day renewal time, D_r = 2.3 m. The outer tube diameter for inflow and outflow can be obtained from the equation

$$D_o = \sqrt{2} D_r \tag{D-2}$$

Equation D-2 is obtained by equating the cross sectional area of the inner (riser) tube with the area in the annulus between the outer and inner tubes. Equation D-2 gives D_o=3.3 m for the outer tube diameter for the two-day renewal time. Assuming 6 inlet and 6 outlet pipes, perpendicular to the outer tube with the same average flow velocity, their diameters would be 0.95 m. These dimensions are shown in Figure 16.

D.2. Air supply line

According to Figure 9, the length of the air supply line L is approximately 200 m. We propose a 0.064 m (2.5") diameter polyethylene pipe for the air supply.

Required total working pressure of the compressors (P)= hydrostatic back pressure (P_w) + air line friction loss (P_l) + minor (local) losses (P_{lm}) + diffuser head loss (ΔP_d).

P_w = 11.5 m of water.

Accounting for compression the airflow rate out of the diffuser Q_a = 28 l sec^{-1}. The air flow velocity in the 2.5" diameter supply line is V = 8.8 m/sec, which is within the typical range of air velocities in air supply pipes.

The adiabatic temperature rise due to compression can be obtained from the equation

$$\Delta T = \frac{T}{e}\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right] \tag{D-3}$$

In equation D-3, e is the efficiency of the compressor, T is the absolute temperature, and P_1 and P_2 are the absolute pressures of the atmosphere and in the pipe line, respectively. At a temperature of T = 5 °C, ΔT would be 98°C. The actual temperature of the compressed air will be less than this due to heat loss in the lake. Neglecting the heat loss, for a kinematic viscosity ν of $2.3*10^{-5}$ m^2/sec, and a Reynolds number of $2.8*10^4$, the Moody diagram gives a friction factor of 0.023 for smooth pipes. The head loss due to friction in the pipe therefore becomes 243 m of compressed air or 0.54 m of water (Equation C-4). Local (minor) losses occur in the air filter (K = 5), air valves (K = 5), check valves (K = 2.5), pipe junctions and elbows (K = 0.5) and are calculated from equation C-5 to be 107 m of compressed air or 0.18 m of water.

The pressure loss in the diffuser discs is 0.5 psi or 3.5 kPa. Then, the total required working pressure must be equal or larger than

P = 11.5*9810 + (243 + 107)*1.7*9.81 + 3500 = 122152 Pa, or 122 kPa or 18 psi.

SCMM = 0.059 * 60 = 3.54, or 125 SCFM

CMM = 3.54 * 101/(101 + 122) = 1.6, or 57 CFM

Therefore, the operating point for the system of compressors is 57 CFM at 18 psi. As mentioned in Appendix C, Power = PQ/η. Therefore, the required power is then

Power = 122* 0.027 / 0.7 = 4.7 kW

The compressors must supply a minimum of 56 CFM at a minimum of 18 psi working pressure. Therefore, based on the selection of compressors, the power may exceed 4.7 kW. For two sets of two AQ63 compressors in series (Figure 17) to provide the airflow at the required pressure, the power would be about 9 kW. It is important to select compressors, which meet the operation point of the system closely.

D.3. Heat gain from power input

Heat input from the metalimnetic aeration systems into the water body depends upon the air compression. The air temperature increases under adiabatic conditions when air is compressed (see equation D-3). A portion of the heat is transferred from the air to the water during the transport of air from the compressors to the diffusers. The heat transfer is by combined convective and conductive heat transport through the pipe walls. The remaining portion of the heat transfer from air to water resulting in a temperature increase of the water occurs as air bubbles expand and rise to the surface. To make an order of magnitude estimate we assume that all the compressors' power becomes heat input to the metalimnion (from 4 to 9 m). The temperature increase in the well-mixed metalimnion due to the compressors' power input can be conservatively approximated by

$$\rho_w c_p \forall \frac{dT}{dt} = P \qquad \text{(D-4)}$$

In equation D-4, c_p is the specific heat of water, T is water temperature, $\forall$ is the volume of the metalimnion and P is the power of compressors. Using 9 kW for P, the heat input will increase the temperature of 210,000 m^3 of water by about 0.0009 °C per day. Over a 100-day period of operation, the water temperature increase would be less than 0.1 °C. Therefore, the heat input from the compressors is insignificant for the entire metalimnion. For winter operation, the volume affected by the heat input will be significantly larger. Therefore, water temperature increase will be even less than 0.1 °C in winter.

D.4. Checking the water flow rate

To obtain a rough estimate of the water flow rate through the aerator as designed, three different methods can be used:

1) Energy equation,
2) Water flow velocity equation developed by *Taggart and McQueen* [1982],
3) Using the air bubble velocity as the flow velocity.

The energy equation between inlet and outlet pipes of the aerator (Figure D-1) can be expressed as

$$\frac{P_1}{\gamma_w} + Z_1 + \frac{V_1^2}{2g} + E_{Diffusers} = \frac{P_2}{\gamma_w} + Z_2 + \frac{V_2^2}{2g} + h_l + h_m \qquad \text{(D-5)}$$

The sum of pressure and potential heads ($P/\gamma_w + Z$) at points 1 and 2 are equal, and the velocity heads $V^2/2g$ at points 1 and 2 are negligible. By taking friction losses and minor losses at the inlet, bends (90° and 180°) and the outlet into account, and expressing the energy input from the diffusers similar to the power input from a pump ($\gamma_w H Q_a$) driving the water flow Q_w with efficiency η, equation D-5 can be rewritten as

$$\frac{\eta H Q_a}{Q_w} = \left(f\frac{L}{D} + K_e + 2K_{b,90} + 2K_{b,180} + K_o \right) \frac{Q_w^{\,2}}{2gA^2} \qquad \text{(D-6)}$$

Equation D-6 can be rearranged in terms of Q_w as a function of H and Q_a as follows

$$Q_w = C H^{1/3} Q_a^{1/3} \qquad \text{(D-7)}$$

where

$$C = \left(\frac{2g\eta A^2}{\left(f\frac{L}{D} + K_e + 2K_{b,90} + 2K_{b,180} + K_o \right)} \right)^{1/3} \qquad \text{(D-8)}$$

Equation D-7 is similar to equation 2 proposed by *Goossens* [1979] for unconfined axisymmetric bubble plumes. The main difference between equation 2 and D-7 is the power of H, which is 4/3 in equation 2 and 1/3 in equation D-7, and Q_a, which is at standard conditions in equation 2 and is the compressed air flow at the outlet of the diffusers in equation D-7 Assigning values of 0.014 for the friction factor f, 0.5 for the entrance loss coefficient K_e, 1 for the 90° elbow loss coefficient $K_{b,90}$, 2 for the 180° elbow loss coefficient $K_{b,180}$, and 1 for the exit loss coefficient K_o, the constant C will become 2.08 $m^{5/3}$ $sec^{-2/3}$. For H = 11.5 m and Q_a = 0.028 m sec^{-1}, and assuming diffusers being 20% efficient in moving the water, the water flow becomes 1.4 m sec^{-1}, which is more than the estimate given by equation 6. The uncertainties associated with the energy equation are the amount of energy used to move the water in the rising tube.

The second method is based on the correlation between superficial velocities[§] of air and water in the aerator.

$$V_w = 0.70 V_a^{0.53} L^{0.56} \quad \text{(D-9)}$$

In equation D-9, V_w is the superficial water velocity (m sec^{-1}), V_a is the air superficial velocity derived from the volumetric airflow rate at standard conditions (m sec^{-1}), and L is the height of the rising tube (m). Equation D-9 correlates the observed data to within ±30%. The validity of equation D-9 was checked by *Prein and Bernhardt* [1989]. Based on their data, equation D-9 tends to underestimate the water flow velocities.

Using equation D-9, with V_a = 0.014 m sec^{-1}, and L = 10 m, gives V_w = 0.27 m sec^{-1} in the aerator, which corresponds to 1.1 m^3 sec^{-1} water flow rate through the aerator. This is in general agreement with the two-day renewal time.

In the third method, we try to estimate the average rising velocity of bubbles U_B = dZ/dt, where Z is the vertical distance from the bottom of the aerator. According to the perfect gas law, the air bubble volume $\forall$ at any distance Z m from the bottom of the aerator is related to the absolute pressure as

$$\forall = \forall_0 \frac{Pa + 11.5\gamma_w}{Pa + (11.5 - Z)\gamma_w} \quad \text{(D-10)}$$

where Pa is the atmospheric pressure, $\forall_0$ is the bubble volume at the outlet of the diffuser and γ_w is the specific weight of water. Assuming spherical shape for all bubbles, equation D-10 can be rearranged in terms of the bubble size as

$$d_B = d_{B0}\left(\frac{Pa + 11.5\gamma_w}{Pa + (11.5 - Z)\gamma_w}\right)^{1/3} = d_{B0}\left(\frac{213.8}{213.8 - 9.81Z}\right)^{1/3} \quad \text{(D-11)}$$

In equation D-11, d_{B0} is the bubble size at the outlet of the diffuser, which is about 3 mm for our case.

By equating the buoyant force exerted on a bubble to the drag force working against the bubble's upward move, the terminal velocity of a bubble in terms of the bubble size is found to be

$$U_B = \left[\frac{4(\rho_w - \rho_a)g}{3\rho_w C_D} d_B\right]^{1/2} \quad \text{(D-12)}$$

In equation D-12, C_D is the drag coefficient, which depends on the Reynolds number, hence, it changes with velocity and will not be constant along the tube length. For this case, it varies from 0.6 to 0.8. We assume C_D = 0.7. By plugging equation D-11 into equation D-12, the bubble velocity becomes

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[§] Superficial velocity means the velocity obtained by dividing the flow rate by the cross sectional area of the riser tube.

$$U_B = \frac{dZ}{dt} = 3.61\left(C_D d_{B0}\right)^{1/2}\left(\frac{213.8}{213.8-9.81Z}\right)^{1/6} \qquad \text{(D-13)}$$

By integrating equation D-13 for Z values from 0 to 10 m, the bubble travel time in the tube would be about 53 seconds and average bubble velocity would then be 0.19 m sec^{-1}. Assuming the average water velocity in the inner tube is equal to the average bubble velocity (no slip velocity), the water flow rate becomes 0.78 m^3 sec^{-1}, which is about 65% of the value given by equation 6.

The three methods give water flow rates from 0.78 to 1.4 m^3 sec^{-1} corresponding to 1.7 to 3.1 days renewal time.

D.5. Depth of intake and outlets

To avoid interfacial mixing between metalimnion and hypolimnion, the intake pipes need to be installed at some height above the metalimnion/hypolimnion interface. This height can be estimated using the following equation [*Harleman*, 1961]

$$Z_o = \left(\frac{V D_{in}^{\ 2}}{3.25\sqrt{g'}}\right)^{0.4} \qquad \text{(D-14)}$$

where Z_o is the distance between the centerline of the intake pipe and the metalimnion/hypolimnion interface, D_{in} is the diameter of the intake pipes, V is the water flow velocity of the intake pipes, and g is the reduced gravitational acceleration and is equal to $g' = g\Delta\rho/\rho$. The height Z_o is estimated to be 0.8 m. Therefore, the invert of the intake pipe would be at 8.65 m below the surface. A same clearance is assumed for the crown of the outlet pipe, i.e., the crown of the outlet pipe need to be at 4.35 m.

D.6. Floatation devices

It is assumed that the aerator tubes will be built from fiberglass.

Total area of the fiberglass = π*2.3*8.8 + 2(2.85+1.0) *π *3.3 – 12*π*0.95^2/4 +2*π*3.3^2/4 + 2*π*(3.3^2-2.3^2)/4 = 161 m^2

The thickness of the fiberglass will be determined by the manufacturer. Assuming 10 mm thickness and 2.5 t m^{-3} specific weight for fiberglass

W = 2.5*0.01*161 = 4.03 t

Assuming about 0.35 t weight for angles and enforcement rings, the required floatation force would be

F_B = 4.03 + 0.35 - 0.01*161*1.0 = 2.77 t

Including a small safety factor, F_B will become 3 t. The specific weight of Styrofoam is γ_S = 0.433 t/m^3, therefore, the required volume of Styrofoam becomes

V_S= 3/(1.0-0.433) = 5.3 m^3

The perimeter of the outer tube is π*3.3 = 10.37 m

Assuming 10 pieces of Styrofoam, each piece will have dimensions of 1.0 m (length) × 0.55 m (width) × 1.0 m (height). This gives 3.7 cm (about 1½") space between the floatation devices.

D.7. Anchoring

The anchors have to equal or exceed the buoyant forces exerted by the bubbles on the aerator. With Q_a = 0.059 m^3/sec and a 53 seconds for the bubbles resident time, the air bubble volume in the inner tube becomes 3.127 m^3, assuming 0% air is dissolved in water.

The force is = 3.127*1.0= 3.127 t

Weight of the concrete blocks in the water should exceed the sum of 3.127 t and the safety factor considered for the floatation devices (0.23 t). Then, the required volume of concrete is

$$Vc = (3.127+0.23) / (2.3 - 1) = 2.6 \text{ m}^3$$

If 24 concrete blocks connected to eye loops (two between every two outlet pipes) are considered for the aerator, then each block should be 0.8 m × 0.5 m × 0.3 m. Each block will weight 280 kg above water.

To anchor the air pipe, 0.125 m × 0.125 m × 0.125 m (5" × 5" × 5") concrete blocks with 0.5 m spacing are required.

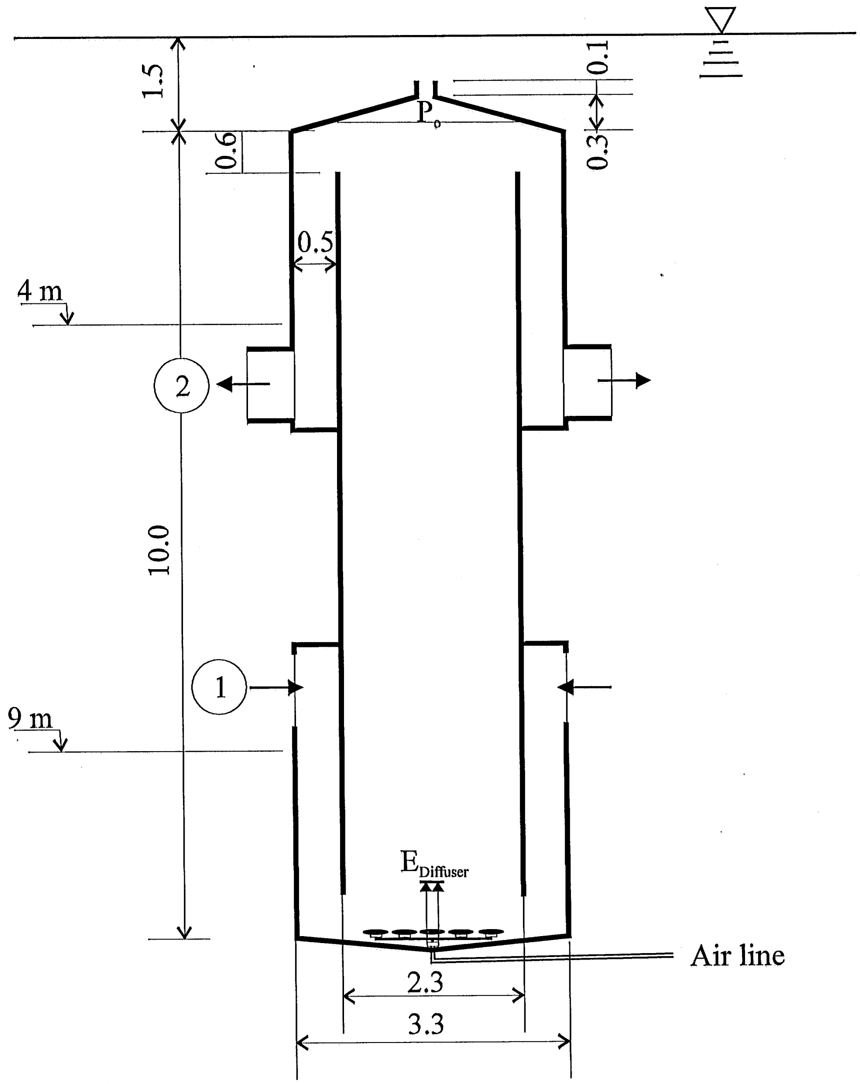
D.8. Dimensions of the separator box

In the aerator, water is lifted to an intermediate elevation, where the air separates from the water and is vented to the surface usually through a vent assembly (Figure D-1). If the separation occurs before the water enters the outer tube, then the aerator cannot function. Therefore, enough space must be considered for the separated air in the aerator.

The pressure at the air/water interface must be large enough to help the airflow out of the aerator. If this pressure is denoted by P_o then

$$\frac{P_o}{\gamma_a} = (1+K)\frac{V_a^2}{2g} + H \qquad \text{(D-15)}$$

where H is the pressure head in terms of column of air over the vent pipe (Figure D-1). Assigning a 2-inch vent pipe, and assuming all air being exhausted from the vent pipe, and 1.1 m of water column over the pipe, i.e. H = 1.1 γ_w/γ_a, equation D-15 gives a pressure of 9,680 m of air, or 1.18 m of water. Therefore, most of the vent pipe will be filled with air. This will not interfere with the water flow into the outer tube.



All dimensions in meters

Figure D-1. Schematic of the metalimnetic aerator.