Sheldrake Lake Hypolimnetic Aeration Project

A Technical Overview of the Proposed Sheldrake Lake Hypolimnetic Aeration Project

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Disclaimer

While every effort has been made to provide the correct general specifications, materials, operating procedures and sizing procedures, it must be emphasized that lake restoration is a relatively new field of study. This proposed hypolimnetic aeration system has been reviewed to the best of my ability, using information collected from many scientific articles, and 21 years of experience with hypolimnetic aeration. The specifications and procedures are a general guide, and input from experienced limnologists, machinists and engineers should be encouraged. This design is constantly evolving towards a better design, and it is this process that will eventually reduce the uncertainties currently present in the field of hypolimnetic aeration.

Summary

Sheldrake Lake is a small (13.1 ha), shallow (max. depth = 7 m) mid-mesotrophic lake located near St. Margaret's Bay, Nova Scotia, within the municipal boundaries of Metro Halifax. Sheldrake Lake is dystrophic and dimictic, exhibits seasonal anoxia during summer and winter stratification and is at or very near the lower limit for hypolimnetic aeration. Low pH and alkalinity may be impediments to restoring the salmonid population. Two estimates of hypolimnetic volume were used in estimating hypolimnetic oxygen depletion: a 3-7.5 m estimate of 92,822 m^3, and a 4-7.5 m estimate of 45,972 m^3. A plot of hypolimnetic oxygen content vs. time indicates linear oxygen depletion for the period from May 3 to June 28, 1992 with a correlation coefficient (i.e., r^2) of 0.99. The maximum calculated depletion rate was 0.15 mg L^{-1} d^{-1} for both the 3-7.5 m and 4-7.5 m hypolimnetic volumes. This rate was increased to 0.2 mg L^{-1} d^{-1} to allow for expected increased oxygen consumption during actual aeration. The required daily oxygen input for a hypolimnetic aeration system ranged from 6.90 to 18.56 kg O_2 day^{-1}. A high efficiency full lift Bernhardt design hypolimnetic aeration system is recommended, and on-site generation of high purity oxygen via Pressure Swing Adsorption technology should be used to maximize the oxygen transfer capabilities of the system. A review of existing Sheldrake Lake equipment indicates the current oxygen generator is undersized, and additional equipment should be upgraded to ensure the PSA oxygen generator receives clean feed air and delivers oxygen efficiently. Protocols to govern the use of hypolimnetic aeration techniques are discussed and advice on development of criteria to screen other lakes is presented to determine those suitable for remediation using hypolimnetic aeration. Advice is given on the development of appropriate analytical methodologies to measure before and after water quality parameters that can be monitored at reasonable cost in order to gauge the success of hypolimnetic aeration. A list of selected publications on hypolimnetic aeration is provided.

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1. Introduction

This report is designed to assist the Woodens River Environmental Organization (WRWEO) conduct a pilot lake restoration project in Sheldrake Lake, Nova Scotia. Hypolimnetic aeration was selected by WRWEO, based on a report submitted to the Nova Scotia Department of Environment in 1994 recommending hypolimnetic aeration as a lake restoration technique that would improve the water quality of Sheldrake Lake (Mandaville, 1994). The author was contacted by Capt. Frank Hope on September 4, 2000 and requested to provide technical assistance and guidance with the project. It is intended that the successful restoration of Sheldrake Lake via hypolimnetic aeration will set a precedent for the aeration of several other lakes in the municipality and possibly some 70 other lakes across the Province, in addition to raising public and government awareness of the need to protect and restore the water quality of Nova Scotia's lakes.

2. Limnology of Sheldrake Lake

Sheldrake Lake (44° 40' Lat., 63° 48' Long.) is located near St. Margaret's Bay, Nova Scotia, within the municipal boundaries of Metro Halifax. The lake is 13.1 ha in surface area, with a maximum depth of 7 m. Selected morphometric features of Sheldrake Lake are listed in Table 1.

Table 1. Selected morphometric features of Sheldrake Lake.

Elevation (m A.S.L.)	**Surface area (ha)**	**Max. depth (m)**	**Mean depth (m)**	**Watershed area (ha)**	**Flushing rate (#/yr)**
76	13.1	7.0	2.7	514	11.2

Sheldrake Lake is at or very near the lower limit for hypolimnetic aeration. Shallow depths decrease the effectiveness of hypolimnetic aeration systems as it reduces the hydrostatic pressure available for oxygen transfer and increases the risk of unintentional destratification. To compensate for the shallow depth, it is recommended that a high efficiency aeration system be designed and installed in Sheldrake Lake, and that on-site generation of high purity oxygen via Pressure Swing Adsorption technology is used to maximize the oxygen transfer capabilities of the system.

Sheldrake Lake is classified as mid-mesotrophic. Limnological data collected in 1991-92 indicates Secchi depths ranged from 1.0 m in October, 1991 to 2.2 m in August, 1992, with a mean value of 1.7 m. The mean volume weighted euphotic zone chlorophyll *a* value for this period was 4.4 $\mu g\ L^{-1}$ while the volume weighted total phosphorus concentration was 22 $\mu g\ L^{-1}$. The lake is quite high in colour (69 Rel. units), suggesting humic staining and a dystrophic nature (Mandaville, 1994).

Sheldrake Lake is dimictic, experiencing complete fall and spring circulation, and oxygen concentrations appear to be near saturation prior to formation of winter ice cover (Mandaville, 2001). The fact that Sheldrake Lake exhibits seasonal anoxia during summer and winter corroborates the trophic classification of mid-eutrophic, and exhibits a significant hypolimnetic oxygen demand. Salmonids inhabiting Sheldrake Lake will have minimal thermal refuge volume during summer months, and the fishery is likely showing signs of stress.

Two anomalies were noted in the Sheldrake Lake data file that may influence the effectiveness of hypolimnetic aeration for restoring salmonid habitat. Firstly, the pH of Sheldrake Lake is usually low, with a mean of 4.9, and a minimum of 4.5 in Oct, 1991 and January, 1992 (Mandaville, 2001). Secondly, alkalinity values (as $CaCO_3$) were reported as negative on several occasions (Mandaville, 2001). Alkalinity is the sum of the titratable bases in the lake, and tends to shift pH towards the alkaline side of neutrality and buffer against acidification. Low pH and alkalinity suggests the lake is receiving acidic runoff or direct acidic deposition, and is near the lower limit for salmonid survival. Low pH values also increase the toxicity of certain metals, and the high aluminum content of Sheldrake Lake may also be an impediment to restoring the salmonid population. Sheldrake Lake may require liming, in addition to hypolimnetic aeration, if pH levels continue to decrease.

3. Sheldrake Lake hypolimnetic oxygen demand

One of the most important steps in properly sizing a hypolimnetic aeration system is estimating the hypolimnetic oxygen depletion rate. This process begins with an estimate of the hypolimnetic volume. This can be determined from an accurate bathymetric map and a series of summer temperature profiles. One must be careful to obtain the largest estimate of hypolimnetic volume to avoid undersizing the aeration system.

In this case, the morphometric information was obtained from a Provincial Government lake survey file on Sheldrake Lake (Figure 1). The file indicated the survey was conducted on July 5, 1992. The volumes of 1 m strata for Sheldrake Lake are as follows (Table 2):

Table 2. Volume of Sheldrake Lake in 1 m intervals.

Strata	**Volume**	**Depth**
M	**m^3**	**m**
0-1	114,294	0
1-2	85,718	1
2-3	64,210	2
3-4	46,850	3
4-5	26,663	4
5-6	12,522	5
6-7	6,287	6
7-7.5	500	7
		7.5
Total vol. =	357,044	
Total vol. =	45,972	4 – 7.5 m
Total vol. =	92,822	3 – 7.5 m

A small volume of 500 m^3 was added to the 7 to 7.5 m depth strata to facilitate calculation of the hypolimnetic oxygen demand. Thermocline depth is then used to define the volume of the hypolimnion to be oxygenated. The 1991 and 1992 oxygen-temperature data supplied for Sheldrake Lake indicates the hypolimnion is usually confined to the 5-7.5 meter strata during the summer months. However, since hypolimnetic volumes invariably increase during hypolimnetic aeration due to hypolimnetic mixing, two larger estimates of hypolimnetic volume were used in the aerator sizing procedure: a 3-7.5 m estimate of 92,822 m^3, and a 4-7.5 m estimate of 45,972 m^3. This ensures a conservative estimate and reduces the probability of undersizing the hypolimnetic aeration system.

A volume weighted mass of oxygen was then calculated for the whole lake, each lake strata and the hypolimnion on a spreadsheet program. The calculations were done using the 3-7.5 m (92,822 m^3) and 4-7.5 m (45,972 m^3) hypolimnion volumes to examine the difference between the two estimates of hypolimnetic volume. The spreadsheet calculations are shown in Appendix 1.

The hypolimnetic oxygen demand was estimated by calculating the rate of oxygen depletion following spring circulation. The spring circulation period is preferable to inverse winter stratification as spring oxygen and temperature conditions will approximate those encountered during actual aeration. The total hypolimnetic oxygen content was plotted against time, and the depletion rate in mg L^{-1} day^{-1} was calculated from the maximum slope of the regression line.

The critical aspect of determining oxygen depletion rates is to obtain the maximum slope of the regression line. Hypolimnetic oxygen consumption rates typically increase during hypolimnetic aeration (Smith et al., 1975; Ashley, 1983, McQueen et al., 1984). This results from several factors including suspension of sestonic material and hypolimnetic warming. Therefore, the regression slopes were limited to those periods of when oxygen consumption was not limited by low oxygen concentrations. A plot of hypolimnetic oxygen content vs. time indicates the depletion rates decrease in July, 1992 (Figure 2), therefore, the only data period suitable for oxygen depletion rate estimation was during May and June, 1992. A plot of the May 3, 1992 to June 28, 1992 (Julian days 123 to 179) hypolimnetic oxygen content vs. time data indicates linear oxygen depletion (Figure 3) with a r^2 of 0.999, indicating an excellent fit of the data. The resulting depletion rate estimates, and regression equations are as follows (Table 3):

Table 3. Hypolimnetic oxygen depletion rate estimates.

	Hypolimnetic volume	**Hypolimnetic volume**
	4-7.5 m (45,972 m^3)	3-7.5 m (92,822 m^3)
Regression equation	y = -0.1545x + 30.626	y = -0.1531x + 31.469
r^2 (correlation coefficient)	0.9982	0.9995
Julian days	123 to 179	123 to 179
Period (days)	56	56
Depletion rate (mg L^{-1} day^{-1})	0.1545	0.1531

4. Estimated oxygen input requirements

The maximum calculated depletion rate for the period from May 3 to June 28, 1992 was 0.15 mg L^{-1} d^{-1} for both the 3-7.5 m and 4-7.5 m hypolimnetic volumes. This rate was increased to 0.2 mg L^{-1} d^{-1} to allow for expected increased oxygen consumption during actual aeration. The required daily oxygen input for a hypolimnetic aeration system therefore ranges from 6.90 to 18.56 kg O_2 day^{-1} (Table 4).

Table 4. Estimates of daily hypolimnetic oxygen input required for Sheldrake Lake.

	Hypolimnetic volume	**Hypolimnetic volume**
	4-7.5 m (45,972 m^3)	3-7.5 m (92,822 m^3)
Depletion rate @ 0.15 mg L^{-1} day^{-1}	6.90 kg O_2 day^{-1}	13.92 kg O_2 day^{-1}
Depletion rate @ 0.20 mg L^{-1} day^{-1}	9.19 kg O_2 day^{-1}	18.56 kg O_2 day^{-1}

5. Review of Sheldrake Lake equipment

The following section is a review of the proposed equipment list for the Sheldrake Lake hypolimnetic aeration project, with comments and suggestions where appropriate:

a. Model Pro4 Oxygen Generator. Oxygen output flow of 32 SCFH. Output pressure of 45-50 psig. Oxygen purity of 94% +/- 2%. I believe the Model Pro4 oxygen generator is **undersized** for the Sheldrake Lake project. My calculations indicate an oxygen generator with an output capacity of 50 SCFH is the absolute minimum size required, and preferably a 75 SCFH unit is required to provide an adequate safety margin, and to allow use on other lakes which may have a greater hypolimnetic oxygen demand than Sheldrake. An OGSI (Oxygen Generating Systems Inc.) Model OG-75, rated at 75 SCFH is recommended;

b. Model RU-S Hydrovane rotary vane air compressor. Power is 575/3/60 or 220/3/60. It is not possible to determine the size of compressor from this information, as Hydrovane manufactures a variety of compressors in the PURS line, from 2 to 10 hp. Hydrovane compressors are a good choice for this project, as they are designed to operate 24 hrs per day, and are among the most reliable of the small, rotary vane compressors. My calculations indicate a 5 hp unit is required, Model 25 PUAS. The model 25 PURS includes a receiver tank which is not necessary, as the oxygen generator should have an oxygen receiver tank. The motor should be a 3-phase unit, and the voltage can be specified as to the voltage of electricity available at the site, so either 575/3/60 or 220/3/60 choices would be satisfactory. Single phase motor units are acceptable, however the cost of the electric motor generally increases relative to 3 phase, and the maximum single phase electric motor size is typically limited to 7.5 hp. The Model 25 PUAS includes an air blast aftercooler and autodrain, as all moisture must be removed from the compressed air prior to entering the PSA oxygen generating unit. Allowing warm, moist air to enter the oxygen generating system may void the warranty on the system, and will decrease the effective life of the zeolite beds used to generate oxygen. Used aftercoolers are typically available from compressor suppliers for relatively low costs (e.g., $300), and this option should be explored if the 25 PUAS compressor option is too expensive. If an add-on aftercooler can be obtained, then a Model 25 PUTS compressor would be satisfactory, as this model is the basic compressor with motor, tripod stand and starter;

c. Wilkerson Model M16-04-FOO, 1.5" NPT, coalescing filter, c/w auto drain. This unit may not have sufficient filtration capacity. It is strongly recommended that the air from the aftercooler should be routed through a Wilkerson 5.0 μ particulate and oil/water filter with autodrain, then a Wilkerson 0.01 μ MICROalescer™ particulate filter and oil/water filter with autodrain. Pressure Swing Adsorption molecular sieves are very sensitive to contamination so it was imperative that no moisture, particulates or compressor oil reaches the synthetic zeolite adsorbent beds. The inlet and outlet diameters of the filters should be ¾" to match the air line diameter;

d. One reel of ½" inside diameter PVC braided hose, P/N PVC-128-500, length 500 ft. This type of hose is not recommended for hypolimnetic aeration installations. Standard rubber compressed air hose is the recommended hose for this application. This type of hose has a normal working strength of 100 psig, and a burst strength of 400 psig, and is designed specifically to be used with compressed air applications. Non-compressed air hoses may react with the lubricating oil carried over from the compressor, and degrade the interior lining of the hose. In this case, the upstream filtration by the 5.0 μ and 0.01 μ filters will remove all compressor oils, however, the strength and durability of standard rubber compressed air hose is high, and it will last indefinitely underwater. The diameter should be ¾" minimum inside diameter to minimize frictional resistance and to match the filter sizes, and of sufficient length to reach from the deepest section of the lake to the compressor shed, with 2-3 meters left over which can be coiled inside the compressor shed;

e. An assortment of fittings, 2 ball valves, and a pressure switch to indicate if no oxygen is flowing, and a discharge regulator. This appears acceptable, and should be standardized in ¾" NPT to match the rest of the system;

f. One diffuser manifold with ½" NPT and 4 x ½" diffuser tubes, and black flow check valve. There is insufficient information to determine the acceptability of the diffuser design. A diffuser design similar to the one shown in Figure 4 should be manufactured out of aluminum or stainless steel. The diffuser system is one of the most important design parameters of the hypolimnetic aeration system. The object of the diffuser is to create as many small bubbles as possible, with an ideal bubble size of 2.5 mm diameter (Ashley, Mavinic and Hall, 1990). This maximizes the oxygen transfer process by creating as much bubble surface area, without running into diffuser and orifice clogging problems. The diffuser design sketch is shown in Figure 4 is constructed of 2" ID aluminum tubing with a series of 3/4" male to 1/2" female brass reducing fittings. The air stones are gently screwed into each fitting. The air stones are available from Aquatic Ecosystems Ltd., Apopka, Florida, phone (407) 886-3939 and are 1.5" x 1.5" x 6.0" in size. The model number of this diffuser is ALR 15. These air stones have a maximum pore size of 140 μ, create bubbles in the correct diameter range to achieve high oxygen transfer (Ashley and Hall, 1990), are relatively inexpensive, and are fairly durable. This type of diffuser system has been installed in lakes in British Columbia and operated for several years with no clogging or breakage problems;

g. Compressor shed and pad – the compressor shed should be a minimum of 8' x 8', and preferably 10' x 10' to allow arrange of the PSA unit, aftercooler (if separate), air compressor, tools, oil containers and sampling equipment. The door should be large enough to allow the compressor and the PSA unit be installed and removed without removing the door. The two main concerns with the compressor shed are noise and heat generation. The shed should be located on a concrete pad, of suitable thickness (~4-6") to support the building and weight of the aeration equipment. The shed should be lined with fibreglass and/or acoustic tiling to prevent compressor noise from escaping, particularly in urban areas. Significant heat buildup occurs due to the heat of compression from the air compressor, and heat released from the aftercooler. A minimum of a 1' x 4' vent should be located near the floor, and another near the ceiling to allow convention currents to dissipate the heat. The shed should be wired to have 2 x 110 volt outlets to allow operation of miscellaneous equipment, plus a standard 100 watt light fixture in the centre of the shed to provide lighting during winter and evenings. In case a power failure occurs during winter when temperatures are below freezing, a portable 110 volt heater (1500 watt max.) will be needed to heat the compressor so that it doesn't start up with oil that is below freezing, as this could damage the oil seals in the compressor.

6. Advice on development of generic technical specifications to govern the design and selection of appropriate hypolimnetic aeration plants

Hypolimnetic aeration systems are available in a wide variety of designs, ranging from full-lift to partial-lift designs (Fast & Lorenzen, 1976). However, several of these designs have not been subjected to full scale testing and their performance characteristics are not well known. The type of hypolimnetic aerator recommended for Sheldrake Lake is known as a full-lift Bernhardt design (Figure 5). Heinz Bernhardt was among the first designers of hypolimnetic aerators (Bernhardt, 1967), and has considerable experience with reservoir aeration (Bernhardt, 1974).

The rationale for selecting the full-lift Bernhardt design was fourfold:

a. Performance - The full-lift Bernhardt design hypolimnetic aerator has a high performance rating in terms of oxygen transfer efficiency (i.e., percent oxygen absorbed / percent oxygen supplied), oxygenation capacity (i.e., kg oxygen absorbed per kilowatt-hour of energy used) and water:air ratio (i.e., induced water flow per unit air flow) (Lorenzen and Fast, 1977);

b. Low Technology - This type of hypolimnetic aerator is technically very simple, and can be constructed out of standard materials available in most industrialized countries. As a result, the cost of the units is relatively low, and the units are simple to build and operate. The separator box is typically made of fibreglass coated plywood, or 100% fibreglass. The separator box could be manufactured out of aluminum. Steel is not recommended due to the higher weight and corrosion. The bottom and sides of the separator box should be lined with stryrofoam insulation, minimum 2.5 cm thick, to insulate the hypolimnetic water from the warmer epilimnetic water. The surface of the separator box should be covered with a hinged lid of expanded metal decking or equivalent, so that the lid can be locked down in place to ensure that no liability issues will emerge from persons potentially falling into the separator box, and possibly being swept down the outlet tube. The inlet and outlet tubes can be made of any material that is strong, lightweight, and can withstand years of submergence without experiencing corrosion or structural failure. Common construction materials include spiral wound aluminum or galvanized steel tubing, similar to ventilation ducts in large buildings, and fibreglass tubes. Conventional PVC sewer pipe and large diameter water pipe are not recommended due to their high cost and weight. Iron and steel pipe is too heavy and expensive, and subject to corrosion. The inlet and outlet tubes should be insulated with sprayed foam that is acceptable for underwater use. Polyethylene heavy mil wrapping can be used over the foam to ensure the foam remains attached to the inlet and outlet tubes. The insulation prevents heat transfer across the inlet and outlet tubing, and minimizes hypolimnetic warming, which can lead to unintentional destratification.

c. Accessibility - An important advantage of this design is its accessibility. The unit floats above the water surface, and can be boarded to measure its operating performance. One of the main problems with submerged partial-lift hypolimnetic aeration systems is the difficulty in measuring current velocity and oxygen input as SCUBA divers are required. The performance of a full-lift design can be determined by a single person with an oxygen-temperature meter and a current meter;

d. Experience - There are a number of Bernhardt design hypolimnetic aeration systems throughout Europe and North America (Bernhardt, 1967; Bernhardt, 1974; Gemza, 1997; Smith et. al., 1975; LaBaugh, 1980; McQueen and Lean, 1986). The author has 21 years experience with the full-lift design (Ashley, 1983; Ashley, 1985; Ashley et al. 1987). As a result, reasonable estimates of its performance characteristics are available. Partial lift hypolimnetic aerators have not experienced the widespread application of full lift systems, although the concept is sound (Figure 6). One reason may be the commercial "overselling" of their capabilities relative to other designs of hypolimnetic aerators;

e. Maintenance - The submerged design approach is particularly useful in high boat traffic areas and ice-prone regions, but it is more difficult to conduct routine inspections and performance monitoring. In extreme cases, undersized partial lift system may have to be replaced, as they are less amenable to retrofitting than the more accessible full lift designs. This was the unfortunate situation in Medical Lake, Washington where a fabric design partial lift hypolimnetic aeration system with a coarse bubble diffuser was unable to meet the hypolimnetic oxygen demand. After retrofitting with a smaller 600 μ orifice diameter diffuser and a higher output compressor, the partial lift unit was still undersized and then experienced complete structural failure. It was replaced with two Bernhardt style full lift hypolimnetic aerators which successfully oxygenated the hypolimnion and significantly improved lake water quality (Soltero et. al., 1994).

The two main problems with hypolimnetic aeration are (1) estimating the oxygen demand of the lake and (2) estimating the oxygen input capacity of the aeration system (Ashley and Hall, 1990). By using a proven design with several years of operating experience, the errors in estimating oxygen input capacity can be minimized.

7. Advice on development of protocols to govern the use of hypolimnetic aeration techniques

The operating procedure for the hypolimnetic aerator is quite simple. The system should be turned on when the hypolimnetic oxygen concentration in the deepest section of the lake has declined to 4 mg L^{-1} following spring circulation and the onset of summer stratification. By starting the aeration system at this time, the oxygen demand of the lake will be relatively low and the system should start oxygenating the hypolimnion. If the system is not turned on until the hypolimnion is anoxic, the accumulated chemical and biochemical oxygen demand can exceed the oxygenation capacity of the aeration system and the hypolimnion may remain anoxic.

The ballast tanks positioned in the end walls of the separator box are used to balance the aeration unit when the compressor is running. The air flowing up the inflow tube tends to raise that end of the aerator slightly. By adding ballast water to the inflow end tank, the separator box can be leveled out so the unit is resting level in the water.

During spring and fall months the aeration system should not be operated. The limited oxygen and temperature profiles for Sheldrake Lake indicate the lake experiences complete spring and fall circulation, and operation of the aeration system will have minimal benefit on the lake, and place unnecessary operating hours on the compressor and PSA unit, and increase annual operating costs.

During winter months the aeration system should be operated once oxygen concentrations decrease to less than 4 mg L^{-1}. Winter oxygen concentrations in Sheldrake Lake are below saturation levels, and the aeration system will assist in the whole-lake circulation during inverse winter stratification. After a few years of operation, winter operation may be reduced as the trophic condition of the lake gradually decreases. The separator box should freeze into the ice surface, and thus be approachable by walking on the ice surface. However, extreme caution should be exhibited near the separator box as stray bubbles form the outlet tube may cause localized weak areas in the ice surface, and with a light covering of snow or cold night, these areas may not be visible the following day and could collapse underfoot. Also, the plume of water discharged from the outlet tube of the aerator may travel some distance to the adjacent shoreline and create a thin ice area near shore some distance from the aerator. Therefore, warning signs should be posted near the lake to warn of these potential dangers to ensure no accidents occur and ensure that WRWEO is protected from potential civil liability. The law is very clear in this regard:

Criminal Code of Canada, Section 263: "Duty to safeguard opening in ice – Excavations on land – Offences: 263 (1) Everyone who makes or causes to be made an opening in ice that is open to or frequented by the public is under legal duty to guard it in a manner that is adequate to prevent persons by falling in by accident and is adequate to warn them that the opening exists."

"Every one who fails to perform duty imposed by subsection (1) is guilty of manslaughter, if the death of any person results therefrom; (b) an offence under Section 269, if bodily harm to any person results therefrom."

8. Advice on development of criteria to screen other lakes to determine those suitable for remediation using hypolimnetic aeration techniques

A selection criteria to screen lakes suitable for remediation by hypolimnetic aeration is as follows:

a. Depth – the lake must be sufficiently deep to allow installation of a hypolimnetic aeration system. In addition, the lake must thermally stratify during the summer. At present, the lower limit for hypolimnetic aeration is ~7 m, any lake shallower than this is not suitable for hypolimnetic aeration with the current technology;

b. Trophic status – the lake must be deficient in dissolved oxygen in the hypolimnion such that cold water fish species are excluded from the hypolimnion. The normally accepted criteria for cold water fish is ~5 mg L^{-1} of dissolved oxygen. Hence, if the hypolimnetic dissolved oxygen concentration does not decrease below 5 mg L^{-1}, then consideration of a hypolimnetic aeration system is not warranted. Consequently, oligotrophic lakes by definition will not require hypolimnetic aeration; mesotrophic lakes may depending on their degree of hypolimnetic oxygen depletion, and most eutrophic lakes would be suitable for hypolimnetic aeration;

c. External nutrient loading – external nutrient loading from point and non-point sources should be minimized in order to increase the success of a hypolimnetic aeration system at increasing the concentration of dissolved oxygen in the hypolimnion. If the lake continues to receive excessive amounts of limiting macronutrients, primarily phosphorus and nitrogen from external sources, this will often overwhelm the capacity of the aeration system, and negate the benefit of the hypolimnetic aeration system. Where possible, a complete watershed restoration program should be implemented that reduces external inputs of nutrients to the lake in question. It is permissible to install a hypolimnetic aeration system in advance of longer term watershed activities to reduce nutrient loading, as this will allow some early benefits to be realized from the funds being spent on watershed nutrient control;

d. Contaminant loading - the lake should not be receiving any contaminant loading from any industrial or agricultural operation that would adversely affect the biota in the lake (e.g., pesticide runoff). In this case, the beneficial effect of hypolimnetic aeration would be negated by the toxic effects of industrial or agricultural runoff;

e. Power supply – electric power should be available at the lake under consideration for hypolimnetic aeration. A variety of alternate power sources have been examined for hypolimnetic aeration, including wind, solar, diesel and propane, however, the only power option that was cost-effective and reliable over the long term was electricity. This may change in the future with the development of fuel cells, however, it is unlikely the energy required for hypolimnetic aeration could be cost-effectively supplied by wind or solar power until the $/kW of these energy sources decreases considerably (Ashley and Nordin, 1999);

f. Lake size – there are no firm rules regarding the minimum and maximum size of lakes suitable for hypolimnetic aeration. Lakes as small as 1 ha in surface area are suitable for hypolimnetic aeration, if the community or agency involved believes aeration is warranted. The general rule of thumb is that the unit cost per hectare aerated increases with smaller lakes, however, the overall cost declines because of the reduced size of equipment (Ashley, 1987). The maximum size of lake that can be aerated is simply a question of funds, the unit cost per hectare decreases as economy of scale come into play, however, the total cost of the project increases with lake size, and at some point, exceeds most available budgets for lake restoration.

g. Water elevation changes – lakes and reservoirs that are subject to large changes in elevation complicate the design and operation of a hypolimnetic aeration system. Most natural lakes fluctuate ~1-3 m annually, and hypolimnetic aeration systems are sized physically to provide minimum clearances from the lake bottom, and to deliver sufficient oxygen to exceed the hypolimnetic oxygen demand. Some reservoirs may fluctuate up to 20-30 m annually, and this wide variation in depth and hypolimnetic volume requires variable length inlet and outlet tubes, and design oversizing, in order to compensate for the range in depth and hypolimnetic volume.

h. Remoteness – very remote lakes are less suitable for hypolimnetic aeration as they typically do not have access to hydroelectric power, which at present is the most reliable and cost effective power source for hypolimnetic aeration. In addition, remote locations reduce the frequency of maintenance visits and limnological sampling which are required to ensure the equipment is in proper working condition, and the aeration system are adequately functioning properly.

9. Advice on development of appropriate analytical methodologies to measure before and after trophic states as well as identification of WQ parameters which can be monitored at reasonable cost in order to gauge the success of hypolimnetic aeration

The water quality parameters which can be monitored at reasonable cost to gauge the success of the hypolimnetic aeration system are as follows:

a. Dissolved oxygen concentration. The presence of dissolved oxygen in the hypolimnion at a time of year when oxygen was not formerly present is a clear measure of success. Dissolved oxygen monitoring should be done bi-weekly throughout the ice-free period, and on monthly or 3 week intervals during winter. Dissolved oxygen can be measured with a chemical Hach™ kits, or Winkler titration; however, it is recommended that a portable oxygen-temperature meter be purchased. This type of meter, usually a polarographic probe design (e.g., YSI Instruments) are very reliable, and will give years of service. It is important to change the electrolyte in the probe, and inspect the probe membrane at regular intervals, calibrate the meter each time it is used by a simple air-saturation calibration, and to keep the meter indoors and not let it freeze as this can damage the probe;

b. Temperature. Temperature measurements are required to confirm that the hypolimnion remains colder than the epilimnion, and has not been unintentionally destratified by operating the system incorrectly. Hypolimnetic aeration typically causes a temperature increase in the lower strata of the hypolimnion by simple dilutional mixing with the layers situated immediately above the lowermost and coldest layers. This cannot be avoided, and is usually not a problem as the temperature differential in the hypolimnion is minimal. Hypolimnetic warming can also be caused by heat transfer across the inlet and outlet tubes during summer operation. Metal conducts heat quite efficiently, and the large surface area of the inlet and outlet tubes, combined with the high volume of water flowing through the tubes, can result in significant hypolimnetic warming if the tubes and separator box are not insulated with a thermal lining (see Section 6);

c. The oxidation state of nitrogen species in the hypolimnion is a key measure of success. Ammonia nitrogen (NH_3-N) tends to predominate in anoxic or anaerobic hypolimnia, whereas nitrate nitrogen (NO_3-N) dominates in aerobic hypolimnia. Routine water sampling during aeration should show a decrease in the concentration of hypolimnetic ammonia nitrogen, and an increase in the concentration of hypolimnetic nitrate nitrogen. This process is typically bacterially mediated by *Nitrosomas* and *Nitrobacter* sp. bacteria, and the bacteria prefer slightly alkaline conditions, hence the acidic pH of Sheldrake Lake may slow the process of bacterial oxidation of ammonia nitrogen to nitrate nitrogen (Wetzel, 1975; Perrin et. al., 2000);

d. The oxidation state of key metals in the hypolimnion is also a measure of success of a hypolimnetic aeration project. Under anaerobic or anoxic conditions, manganese and iron exist in their reduced states, i.e., Mn^{+2} and Fe^{+2}. These metals are completely dissolved when present in their reduced *manganous* or *ferrous* oxidation states. As the oxidation-reduction potential increases in the hypolimnion due to the presence of oxygen, the dissolved the metals are oxidized to their oxidized state, *manganic* manganese (Mn^{+4}) and *ferric* iron (Fe^{+3}). Both manganic and ferric iron exist in a particulate form, and will gradually settle out of the hypolimnion as their specific density is greater than water, hence the concentration of total iron and total manganese in the hypolimnion will decrease. In some cases, the separator box may develop an orange rust coloured coating from the precipitation of the ferric iron, and a black sand-like material may be found in the separator box, which is the manganic manganese. Another indicator of success is the ratio of dissolved to particulate manganese and iron, but this means that water samples must be taken, and field filtered through a 0.45 µ filter, and preserved with nitric acid to prevent the metals from oxidizing or plating out on the sampling bottle. However, if a regular water sampling program is to be carried out on Sheldrake Lake, analysis for total metals should be done. If additional laboratory funds are available, it is interesting to plot the decline in the concentration of dissolved (i.e., reduced metals), the temporary increase in particulate (i.e., oxidized) metals, and then the eventual precipitation, which allows you to observe the oxidation and precipitation process;

e. The concentration of hydrogen sulfide (H_2S) is the hypolimnion is a very sensitive indicator of success. This reduced gas can be present in anaerobic environments only, and as soon the oxygen is introduced into the hypolimnion, H_2S is oxidized to sulfates (SO_4^{-2}), or simply vented from the lake. A strong odour of rotten eggs may be noted initially around the separator box as hydrogen sulfide is vented from the hypolimnion. Hydrogen sulfide is very toxic to aquatic life, and must be removed if the hypolimnion is to be recolonized by aerobic organisms. The water chemistry test for H_2S is not particularly reliable, and is typically sensitive only to 0.5 mg L^{-1}, hence the most cost-effective test is to sniff the odour of the separator box. If hydrogen sulfide is present, the human nose will easily detect it;

f. The concentration and type of phosphorous in the hypolimnion is another key measure of success. Under anoxic and anaerobic conditions, the reduced inorganic phosphate ion (i.e., PO_4^{-3}, or orthophosphate ion) tends to be present, along with variable concentrations of total dissolved phosphorus and total phosphorus. As the hypolimnion becomes oxidized, the concentration of the inorganic phosphate ion should decrease as it oxidizes and co-precipitates with manganic manganese or ferric iron. The concentration of total dissolved and total P may not change as much, hence they are not as sensitive a measure of success as inorganic phosphate ion, although they are valuable in tracking the longer term response of the system to changes in external or internal nutrient loading;

g. The turbidity in the hypolimnion is an index worth tracking, however, it is not a sensitive indicator of success. The hypolimnia of lakes tends to be quiescent under normal conditions, and hypolimnetic current velocities are rather slow relative to wind induced current in the epilimnion which typically approximate 3% of surface wind velocity (Lawrence et. al., 1995). Hypolimnetic aeration induced currents in the hypolimnion are significantly greater than the pre-aeration conditions, and this often increases the turbidity of the hypolimnion, and may be responsible for the observed increase in hypolimnetic oxygen demand which is observed during the initial stages of hypolimnetic aeration. Turbidity measurements are a relatively inexpensive test at most commercial laboratories, and can also be measured with inexpensive field instruments.

It is important to note that most of the aforementioned oxidation-reduction sensitive water quality parameters can show a significant improvement in water quality, without any free dissolved oxygen being detected in the hypolimnion. These reactions are oxidation-reduction mediated, and as oxygen is introduced into the hypolimnion it may be immediately used such that free oxygen is not detected, yet ammonia is being oxidized to nitrate, manganous manganese and ferrous iron are being transformed to their oxidized states, and hydrogen sulfide is being vented. Thus it is possible, during the early stages of operating a hypolimnetic aeration system, that the system appears undersized as the oxygen meter, or other oxygen measuring procedure, is not measuring any free oxygen in the hypolimnion. Under these circumstances, one should just wait for a few weeks as the accumulated oxygen deficit is reduced, then free dissolved oxygen should start being detected in the hypolimnion.

Standard trophic state indices, such as the OECD index, Carlson Trophic State Index, and Dillon-Rigler models will not be very useful as indicators of tropic state change in the *short term* as it will likely take at least one summer to effect significant changes in the ecology of Sheldrake Lake. In the *longer term*, any of the published trophic state indices should be a useful tool for demonstrating a change in the trophic status of Sheldrake Lake. It is recommended that the aforementioned water quality parameters be used to determine the measure of success of the hypolimnetic aeration project, as they are more sensitive, and will show changes within a few days of starting the aeration system.

An appropriate sampling design should be implemented to track the effect of the hypolimnetic aeration program. A single sampling station near the deepest section of the lake would be adequate for a lake the size of Sheldrake. A standard sampling program would be as follows:

Dissolved oxygen and temperature vertical profile monitoring should be done bi-weekly at 1 meter intervals throughout the ice-free period, 3 week intervals during spring and fall circulation and 1 month intervals during winter;

Secchi depth should be monitored bi-weekly throughout the ice-free period.

Water chemistry (general ions), metals and nutrients (NH_3-N, NO_3-N, SRP, TP, and TDP) should be analyzed from a composite epilimnetic sample and a composite hypolimnetic sample collected bi-weekly throughout the ice-free period, 3 week intervals during spring and fall circulation and 1 month intervals during winter;

Phytoplankton should be collected from a composite epilimnetic sample collected bi-weekly throughout the ice-free period, and analyzed for chlorophyll *a*. Actual species identification may be conducted later if an adequate sampling budget is arranged;

Zooplankton sampling is optional, at the same frequency and location as the phytoplankton sampling. The samples can be stored for later analysis if adequate funding can be arranged. An option is to simply measure the zooplankton as dried weight.

The samples should be analyzed at a credible private water chemistry laboratory, Government laboratory, or at an educational institution such as Dalhousie University. Advice on this topic is best obtained from a local limnologist.

10. Reference material

Several key reports have been published on hypolimnetic aeration, in addition to numerous scientific journal publications. Copies of the following ten key references are provided with this report, and should be reviewed to gain an appreciation of the issues involved with hypolimnetic aeration.

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Bernhardt, H. 1967. Aeration of Wahnback Reservoir without Changing the Temperature Profile. J. Am. Water Works Assn. 59: 943-963.

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Perrin, C.J., K.I. Ashley and G.A. Larkin. 2000. Effect of Drawdown on Ammonium and Iron Concentrations in a Coastal Mountain Reservoir. Water Qual. Res. J. Canada 35: 231-244.

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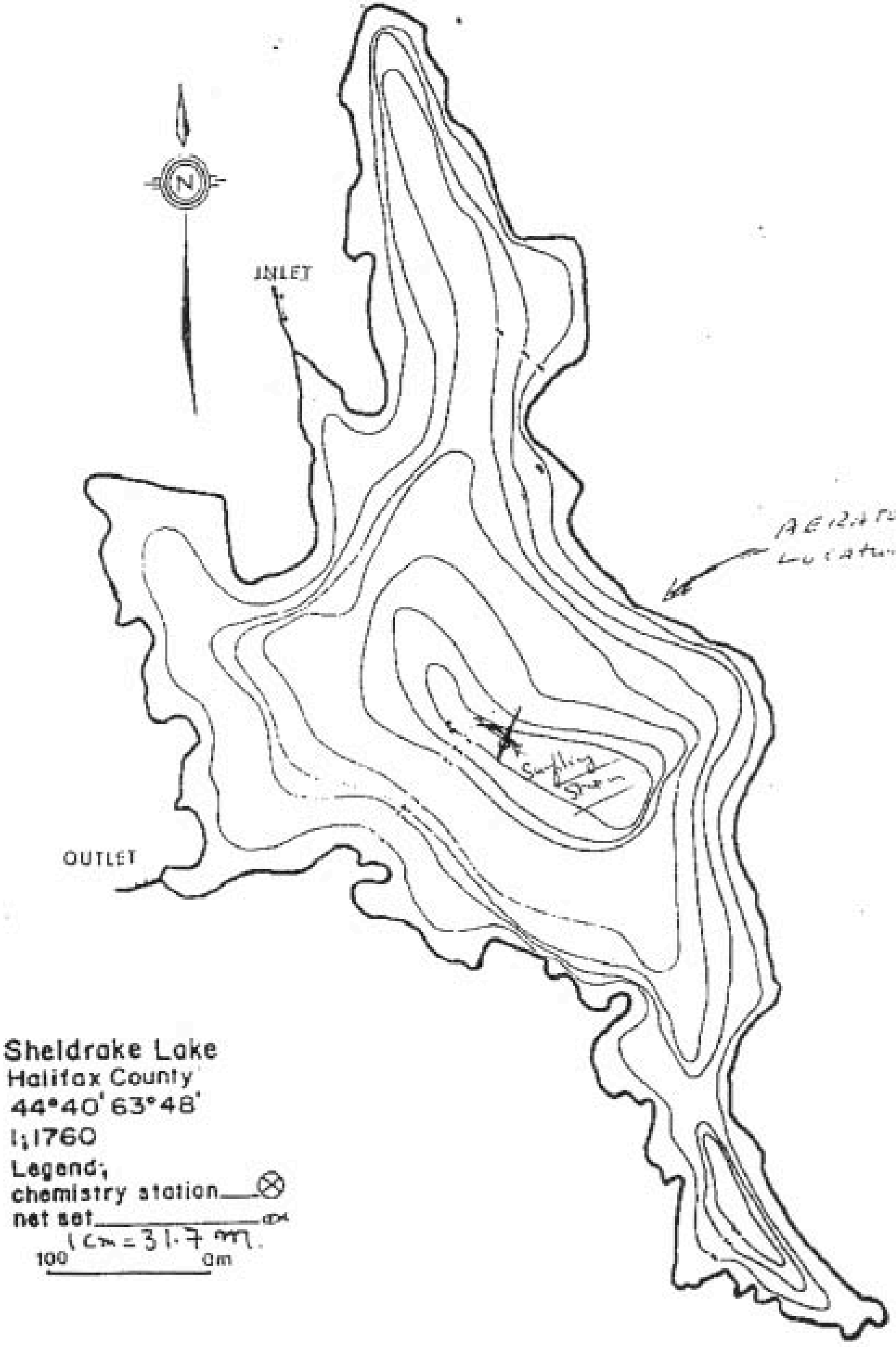
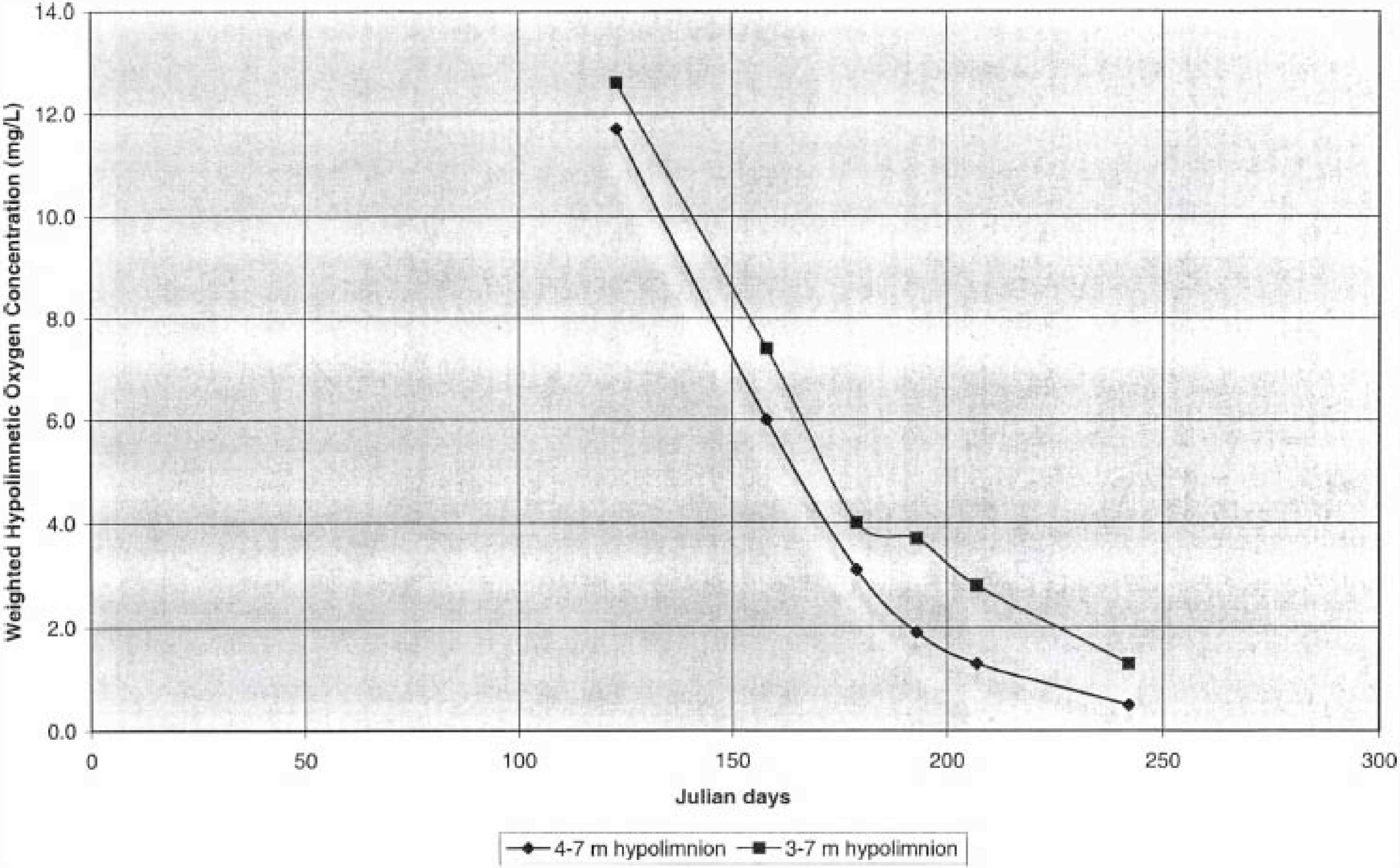
Figure 1. Sheldrake Lake morphometry



Sheldrake Lake
Halifax County
44°40' 63°48'
1:1760
Legend:
chemistry station ⊗
net set
1 cm = 31.7 m.
100 0m

Figure 2. Plot of Sheldrake Lake hypolimnetic oxygen content vs. time



Sheldrake Lake Hypolimnetic Oxygen Content - 1992

Figure 3. Linear plot of Sheldrake Lake hypolimnetic oxygen content vs. time

Sheldrake Lake Hypolimnetic Oxygen Content - 1992

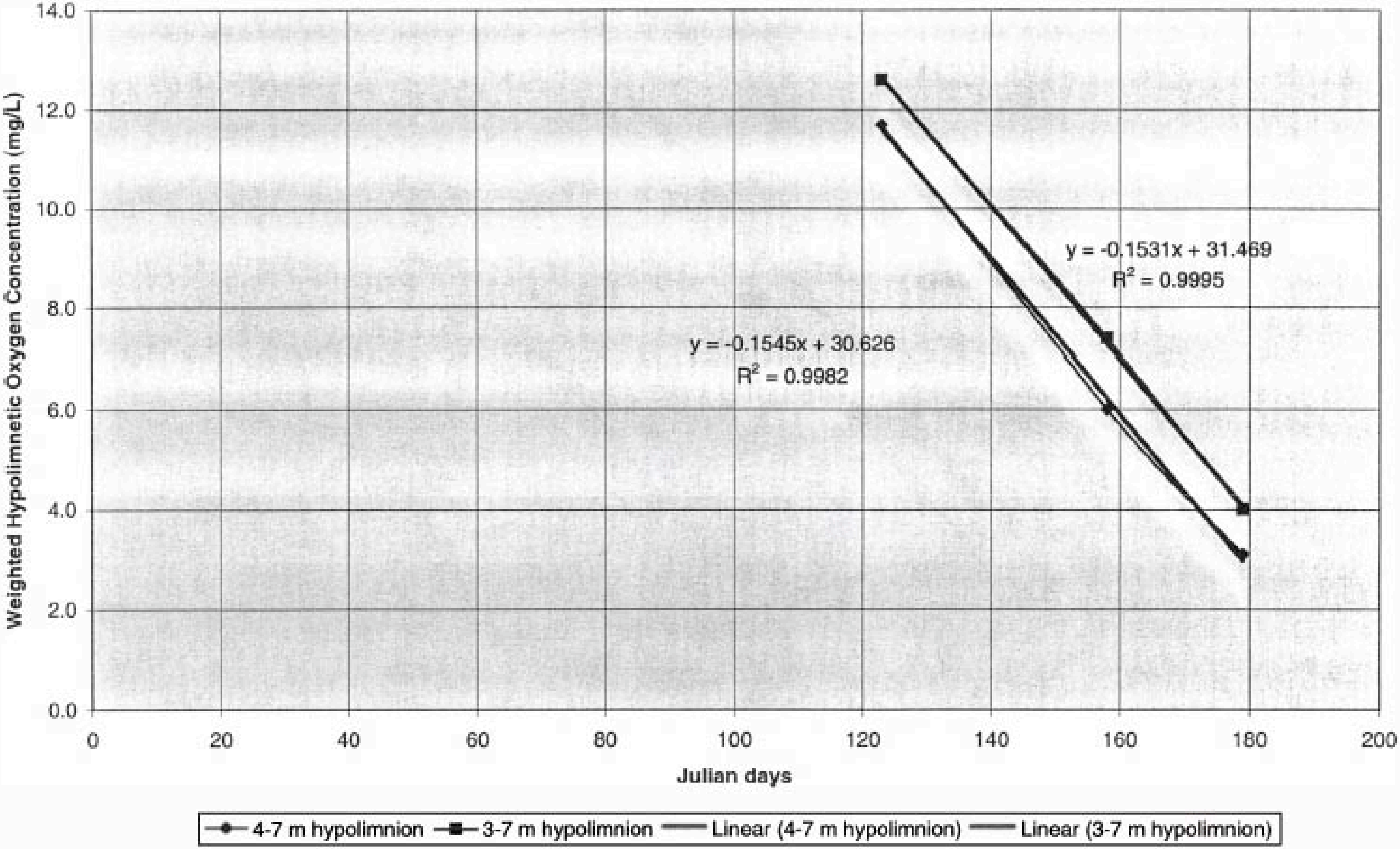
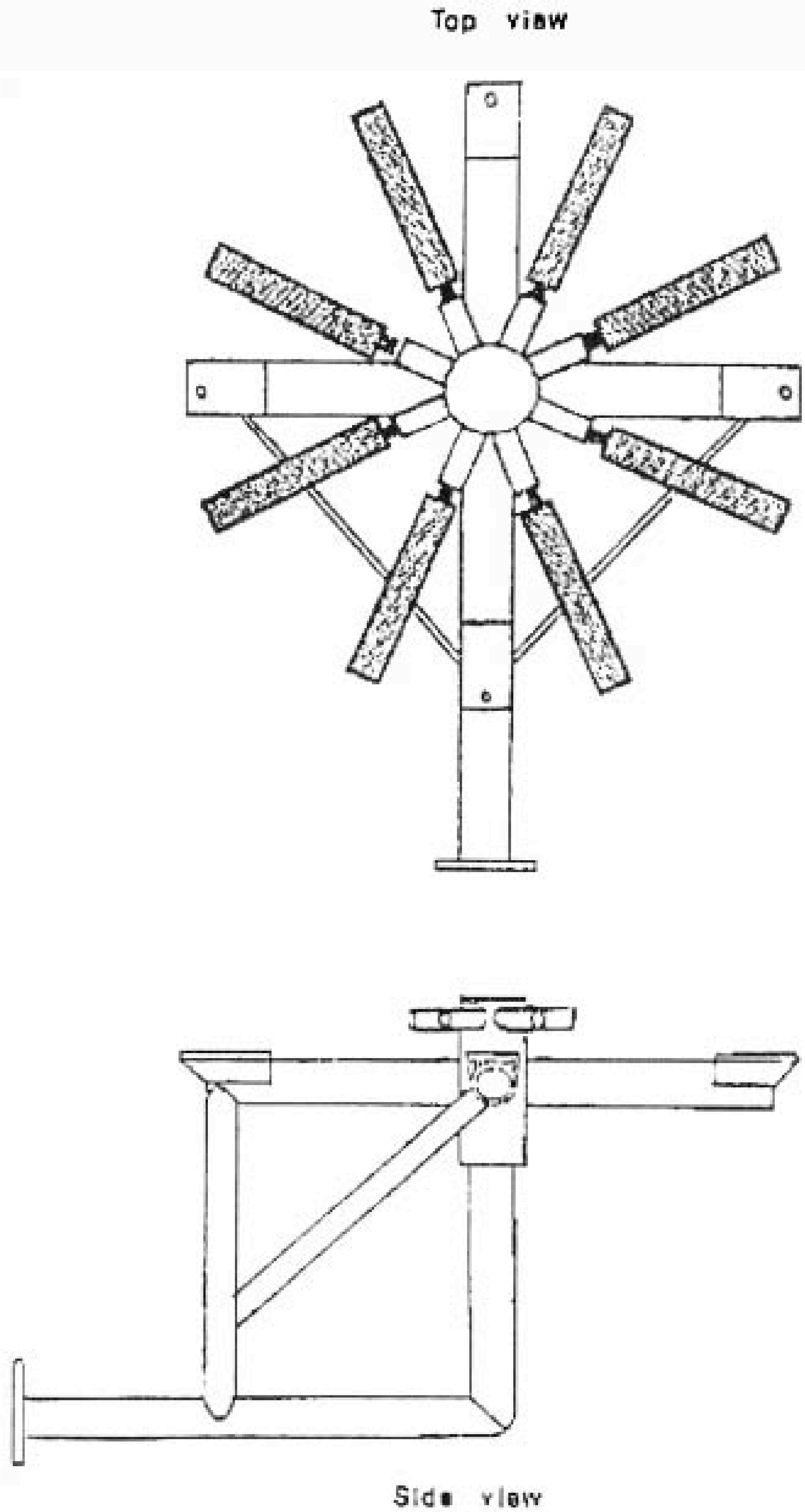


Figure 4. Fine bubble diffuser design



Scale 1" = 9"

DIFFUSER ASSEMBLY.

Figure 5. Full-lift Bernhardt design hypolimnetic aerator

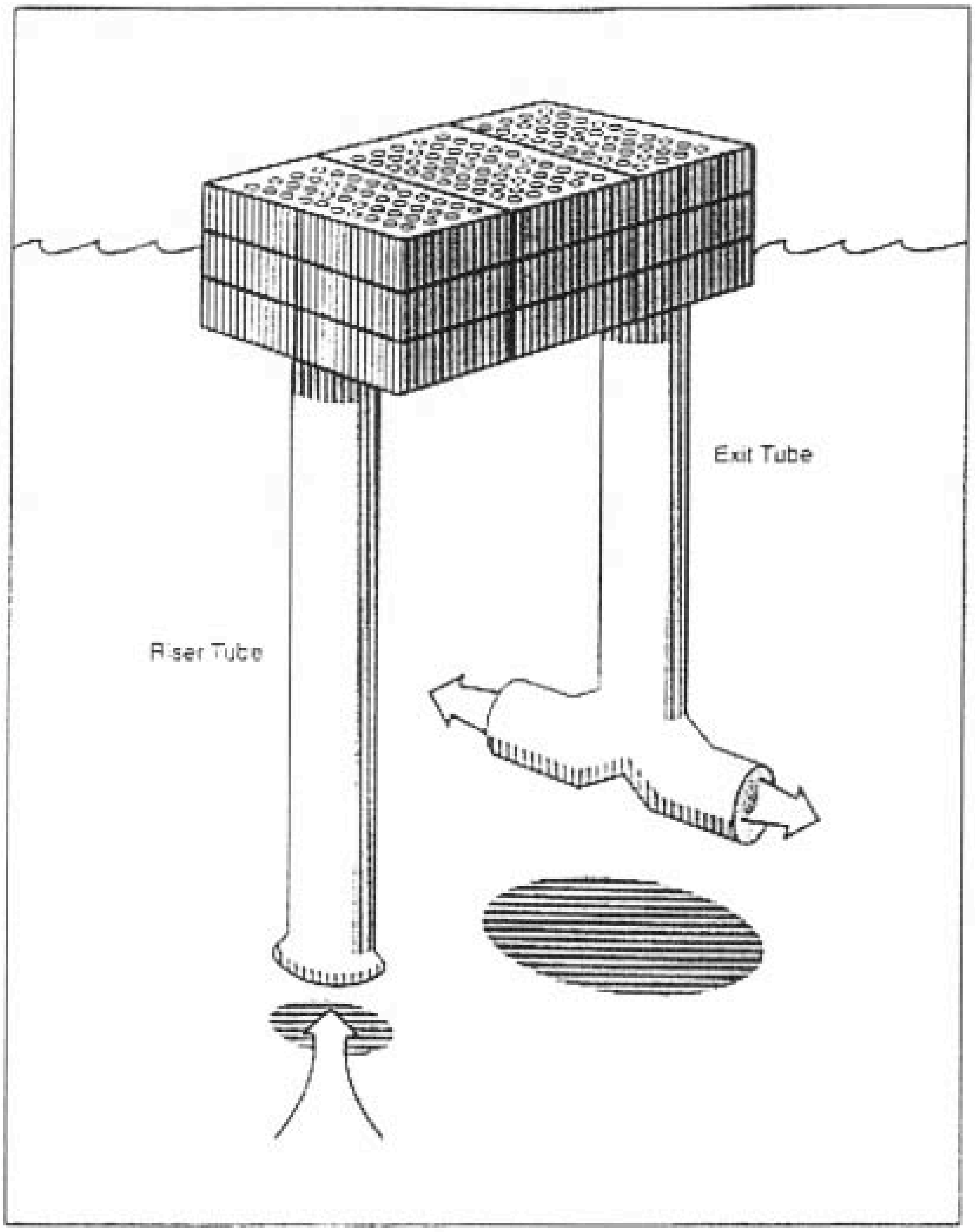
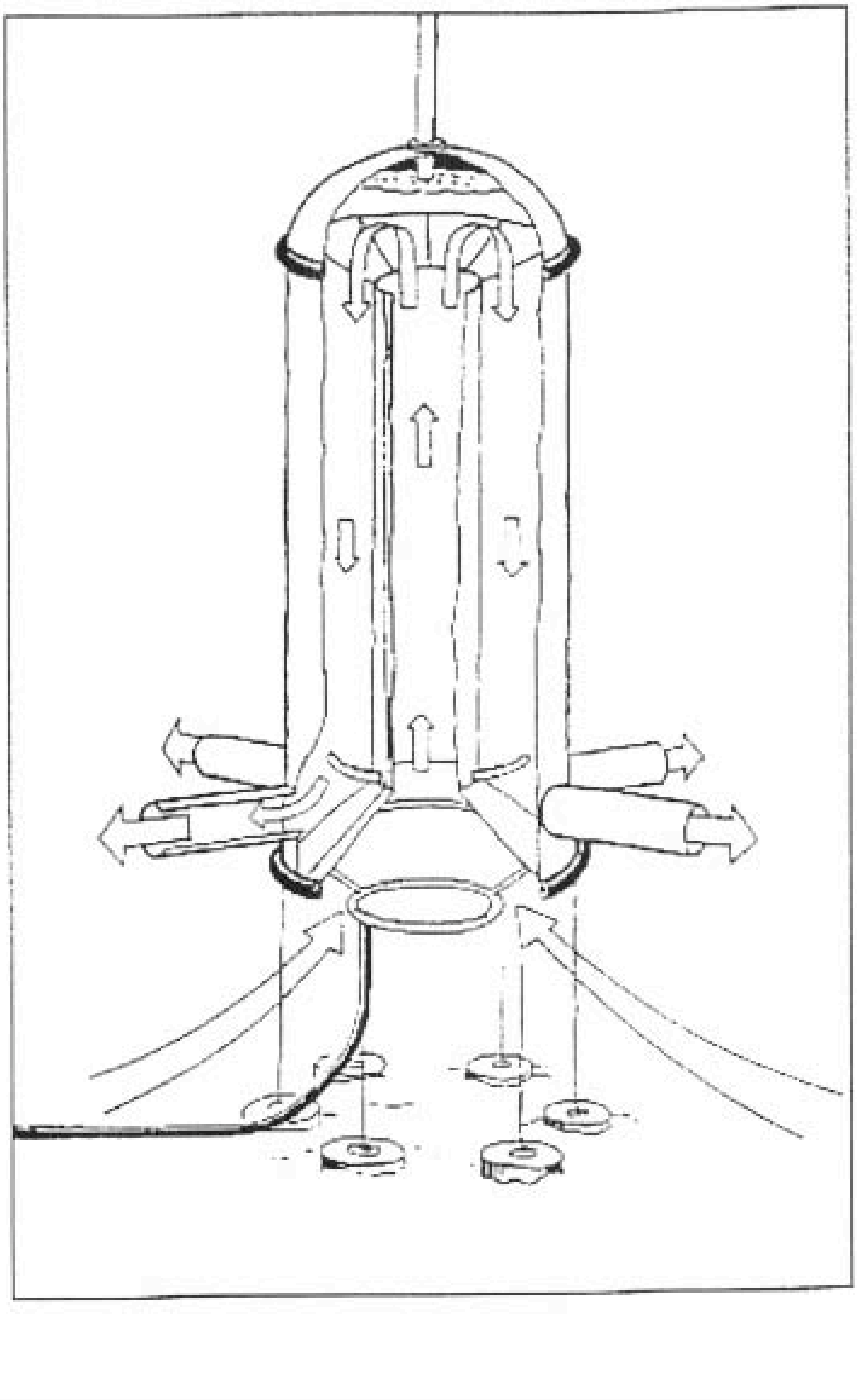

Exit Tube
Riser Tube

Figure 6. Partial lift hypolimnetic aerator



12. Appendix

Sheldrake Lake oxygen depletion rates

Date	Strata (m)	Volume	Depth	DO conc.	Av. DO	Mass	Weighted
July 28/91	m	m3	m	mg/L	mg/L	kg	av. (mg/L)
	0-1	114,294	0	6.6	6.3	720.1	
	1-2	85,718	1	6.0	5.9	505.7	
	2-3	64,210	2	5.8	3.9	247.2	
	3-4	46,850	3	1.9	1.0	44.5	
	4-5	26,663	4	0.0	0.0	0.0	
	5-6	12,522	5	0.0	0.0	0.0	
	6-7	6,287	6	0.0	0.0	0.0	
	7-7.5	500	7	0.0	0.0	0.0	
			7.5	0.0			
	Total vol. =	357,044			Whole Lake	1517.5	4.3
	Total vol. =	45,972		4 - 7 m	Hypolimnion	0.0	0.0
	Total vol. =	92,822		3 - 7 m	Hypolimnion	44.5	0.5
Date	Strata (m)	Volume	Depth	DO conc.	Av. DO	Mass	Weighted
Sept 14/91	m	m3	m	mg/L	mg/L	kg	av. (mg/L)
	0-1	114,294	0	8.4	8.2	937.2	
	1-2	85,718	1	8.0	8.0	685.7	
	2-3	64,210	2	8.0	7.9	507.3	
	3-4	46,850	3	7.8	7.6	356.1	
	4-5	26,663	4	7.4	7.2	192.0	
	5-6	12,522	5	7.0	3.7	45.7	
	6-7	6,287	6	0.3	0.2	0.9	
	7-7.5	500	7	0.0	0.0	0.0	
			7.5	0.0			
	Total vol. =	357,044			Whole Lake	2724.9	7.6
	Total vol. =	45,972		4 - 7 m	Hypolimnion	238.6	5.2
	Total vol. =	92,822		3 - 7 m	Hypolimnion	594.7	6.4
Date	Strata (m)	Volume	Depth	DO conc.	Av. DO	Mass	Weighted
Oct 12/91	m	m3	m	mg/L	mg/L	kg	av. (mg/L)
	0-1	114,294	0	9.4	9.3	1057.2	
	1-2	85,718	1	9.1	9.1	775.7	
	2-3	64,210	2	9.0	9.0	574.7	
	3-4	46,850	3	8.9	8.8	409.9	
	4-5	26,663	4	8.6	7.9	209.3	
	5-6	12,522	5	7.1	6.9	85.8	
	6-7	6,287	6	6.6	6.2	39.0	
	7-7.5	500	7	5.8	5.2	2.6	
			7.5	4.6			
	Total vol. =	357,044			Whole Lake	3154.2	8.8

	Total vol. =	45,972		4 - 7 m	Hypolimnion	336.7	7.3
	Total vol. =	92,822		3 - 7 m	Hypolimnion	746.6	8.0
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
Nov 17/91	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	11.8	11.7	1331.5	
	1-2	85,718	1	11.5	11.5	981.5	
	2-3	64,210	2	11.4	11.3	725.6	
	3-4	46,850	3	11.2	11.2	522.4	
	4-5	26,663	4	11.1	11.1	294.6	
	5-6	12,522	5	11.0	11.0	137.7	
	6-7	6,287	6	11.0	11.0	68.8	
	7-7.5	500	7	10.9	8.2	4.1	
			7.5	*5.5*			
	Total vol. =	357,044			Whole Lake	4066.2	11.4
	Total vol. =	45,972		4 - 7 m	Hypolimnion	505.3	11.0
	Total vol. =	92,822		3 - 7 m	Hypolimnion	1027.7	11.1
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
Jan 26/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	13.0	11.5	1314.4	
	1-2	85,718	1	10.0	8.5	728.6	
	2-3	64,210	2	7.0	6.6	423.8	
	3-4	46,850	3	6.2	6.0	281.1	
	4-5	26,663	4	5.8	5.5	146.6	
	5-6	12,522	5	5.2	3.9	48.8	
	6-7	6,287	6	*2.6*	2.0	12.3	
	7-7.5	500	7	*1.3*	1.0	0.5	
			7.5	*0.7*			
	Total vol. =	357,044			Whole Lake	2956.1	8.3
	Total vol. =	45,972		4 - 7 m	Hypolimnion	208.2	4.5
	Total vol. =	92,822		3 - 7 m	Hypolimnion	489.3	5.3
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
March 7/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	12.8	12.1	1377.2	
	1-2	85,718	1	11.3	9.1	775.7	
	2-3	64,210	2	6.8	6.7	430.2	
	3-4	46,850	3	6.6	6.7	313.9	
	4-5	26,663	4	6.8	6.6	174.6	
	5-6	12,522	5	6.3	6.3	78.9	
	6-7	6,287	6	6.3	5.3	33.0	
	7-7.5	500	7	4.2	3.2	1.6	
			7.5	*2.1*			

	Total vol. =	357,044			Whole Lake	3185.2	8.9
	Total vol. =	45,972		4 - 7 m	Hypolimnion	288.1	6.3
	Total vol. =	92,822		3 - 7 m	Hypolimnion	602.0	6.5
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
May 3/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	14.1	14.0	1594.4	
	1-2	85,718	1	13.8	13.7	1174.3	
	2-3	64,210	2	13.6	13.6	870.0	
	3-4	46,850	3	13.5	13.4	627.8	
	4-5	26,663	4	13.3	13.2	350.6	
	5-6	12,522	5	13.0	11.8	147.8	
	6-7	6,287	6	10.6	6.4	40.2	
	7-7.5	500	7	2.2	1.7	0.8	
			7.5	*1.1*			
	Total vol. =	357,044			Whole Lake	4806.0	13.5
	Total vol. =	45,972		4 - 7 m	Hypolimnion	539.4	11.7
	Total vol. =	92,822		3 - 7 m	Hypolimnion	1167.2	12.6
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
June 7/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	10.2	10.2	1165.8	
	1-2	85,718	1	10.2	10.2	874.3	
	2-3	64,210	2	10.2	9.7	622.8	
	3-4	46,850	3	9.2	8.8	412.3	
	4-5	26,663	4	8.4	7.2	190.6	
	5-6	12,522	5	5.9	4.9	61.4	
	6-7	6,287	6	3.9	3.4	21.1	
	7-7.5	500	7	2.8	2.1	1.1	
			7.5	*1.4*			
	Total vol. =	357,044			Whole Lake	3349.3	9.4
	Total vol. =	45,972		4 - 7 m	Hypolimnion	274.1	6.0
	Total vol. =	92,822		3 - 7 m	Hypolimnion	686.4	7.4
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
June 28/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	10.2	10.0	1137.2	
	1-2	85,718	1	9.7	9.1	775.7	
	2-3	64,210	2	8.4	6.7	430.2	
	3-4	46,850	3	5.0	4.9	229.6	
	4-5	26,663	4	4.8	4.0	106.7	
	5-6	12,522	5	3.2	2.4	30.1	
	6-7	6,287	6	*1.6*	1.2	7.5	
	7-7.5	500	7	*0.8*	0.6	0.3	

			7.5	*0.4*			
	Total vol. =	357,044			Whole Lake	2717.3	7.6
	Total vol. =	45,972		4 - 7 m	Hypolimnion	144.5	3.1
	Total vol. =	92,822		3 - 7 m	Hypolimnion	374.1	4.0
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
July 12/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	9.0	8.9	1017.2	
	1-2	85,718	1	8.8	8.5	728.6	
	2-3	64,210	2	8.2	8.0	510.5	
	3-4	46,850	3	7.7	5.4	253.0	
	4-5	26,663	4	3.1	2.6	68.0	
	5-6	12,522	5	2.0	1.3	15.7	
	6-7	6,287	6	0.5	0.5	2.8	
	7-7.5	500	7	0.4	0.3	0.2	
			7.5	*0.2*			
	Total vol. =	357,044			Whole Lake	2595.9	7.3
	Total vol. =	45,972		4 - 7 m	Hypolimnion	86.6	1.9
	Total vol. =	92,822		3 - 7 m	Hypolimnion	339.6	3.7
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
July 26/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	9.4	9.2	1045.8	
	1-2	85,718	1	8.9	8.5	724.3	
	2-3	64,210	2	8.0	7.2	462.3	
	3-4	46,850	3	6.4	4.3	201.5	
	4-5	26,663	4	2.2	1.7	45.3	
	5-6	12,522	5	1.2	0.9	10.6	
	6-7	6,287	6	0.5	0.5	2.8	
	7-7.5	500	7	0.4	0.3	0.2	
			7.5	*0.2*			
	Total vol. =	357,044			Whole Lake	2492.8	7.0
	Total vol. =	45,972		4 - 7 m	Hypolimnion	58.9	1.3
	Total vol. =	92,822		3 - 7 m	Hypolimnion	260.4	2.8
Date	**Strata (m)**	**Volume**	**Depth**	**DO conc.**	**Av. DO**	**Mass**	**Weighted**
Aug 30/92	**m**	**m3**	**m**	**mg/L**	**mg/L**	**kg**	**av. (mg/L)**
	0-1	114,294	0	8.7	8.6	982.9	
	1-2	85,718	1	8.5	7.6	651.5	
	2-3	64,210	2	6.7	5.3	337.1	
	3-4	46,850	3	3.8	2.2	103.1	
	4-5	26,663	4	0.6	0.5	13.3	
	5-6	12,522	5	0.4	0.4	5.0	

	6-7	6,287	6	0.4	0.4	2.5		
	7-7.5	500	7	0.4	0.3	0.2		
			7.5	*0.2*				
	Total vol. =	357,044			Whole Lake	2095.6	5.9	
	Total vol. =	45,972		4 - 7 m	Hypolimnion	21.0	0.5	
	Total vol. =	92,822		3 - 7 m	Hypolimnion	124.1	1.3	

			Depl. Rate			Depl. Rate
Date	**Julian day**	**4 - 7 m**	**mg/L/D**	**Julian day**	**3 - 7 m**	**mg/L/D**
July 28/91	209	0.0		209	0.5	
Sept 14/91	257	5.2		257	6.4	
Oct 12/91	285	7.3		285	8.0	
Nov 17/91	321	11.0	0.09	321	11.1	0.08
Jan 26/92	26	4.5		26	5.3	
March 7/92	66	6.3		66	6.5	
May 3/92	123	11.7	0.16	123	12.6	0.15
June 7/92	158	6.0	0.14	158	7.4	0.16
June 28/92	179	3.1	0.09	179	4.0	0.02
July 12/92	193	1.9	0.04	193	3.7	0.06
July 26/92	207	1.3	0.02	207	2.8	0.04
Aug 30/92	242	0.5		242	1.3	