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HYPOLIMNETIC AERATION: FIELD TEST OF THE EMPIRICAL SIZING METHOD

KENNETH IAN ASHLEY[1], SHAWN HAY[2] and GEORGE H. SCHOLTEN[2]
[1]Fisheries Research and Technical Service Section, Fisheries Branch, Ministry of Environment 2204 Main Mall, University of British Columbia, Vancouver, British Columbia, Canada V6T 1W5 and [2]Fish and Wildlife, Ministry of Environment, 2569 Kenworth Road, Nanaimo, British Columbia, Canada V9T 4P7

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Abstract—A hypolimnetic aeration system was recently installed in a small (16 ha S_a) eutrophic lake and a comparison made between measured performance and predicted performance from an empirical sizing method. The design variables used to size the system were: hypolimnetic volume 451,600 m^3; maximum hypolimnetic oxygen consumption 0.2 mg l^{-1} d^{-1}; aerator input rate 2 mg l^{-1}; water velocity 0.76 m s^{-1} and depth of air release 12.2 m. A 3.7 kW compressor (0.57 m^3 min^{-1}) generated a water velocity of 0.46 m s^{-1}, a water flow of 17.7 m^3 min^{-1} and a theoretical hypolimnetic circulation period of 18 days. Dissolved oxygen increased by an average of 1.6 mg l^{-1} on each cycle through the aerator, and aerator input rates ranged from 0.6 to 2.6 mg l^{-1}. Hypolimnetic oxygen consumption averaged 0.12 mg l^{-1} d^{-1} and ranged between 0.02 and 0.21 mg l^{-1} d^{-1}. The aeration system was unable to meet the daily oxygen demand (90 kg) as the water velocity was slower than expected (0.46 m s^{-1}). To avoid undersizing future aeration installations the following recommendations should be considered when using the empirical sizing formula: (1) estimates of oxygen consumption should be annual maximums from aerobic hypolimnia; (2) aerator input rates should be conservative (e.g. 1–4 mg l^{-1}) and increase with depth; (3) water velocity of 0.45–0.50 m s^{-1} should initially be used when no information on actual bubble size or velocity is available; (4) aeration start-up should be timed to avoid periods of accumulated oxygen demands.

Key words—hypolimnetic aeration, empirical sizing method, water velocity, transfer efficiency, aerator design

NOMENCLATURE

g = acceleration of gravity (m s^{-2})
S_a = lake surface area (ha)
u = bubble terminal rise velocity (m s^{-1})
r_e = equivalent bubble radius (m)
Z_m = lake maximum depth (m).

INTRODUCTION

In a recent *Water Research* paper, Ashley (1985) proposed an empirical sizing formula for full lift hypolimnetic aeration using hypolimnetic volume, hypolimnetic oxygen consumption, water flow, air flow and inflow tube radius as design criteria.

Following this publication, the British Columbia Fish and Wildlife Branch (Ministry of Environment) designed and installed hypolimnetic aeration systems in two eutrophic coastal lakes; Glen Lake (S_a = 16 ha) near Victoria, B.C. and St. Mary Lake (S_a = 182 ha) on Saltspring Island, B.C.

The purpose of this paper is to report on the first full-scale test of the empirical sizing formula, and compare measured vs predicted performance from the empirical sizing method.

Study area and site description

Glen Lake is a eutrophic urban lake located (elevation 69 m, 48°26′20″ N, 123°31′15″ W) in the Insular Lowland limnological region of British Columbia (Northcote and Larkin, 1956). Lakes in this region usually experience high summer surface temperatures and severe oxygen depletion in the deeper layers. Glen Lake (Z_m = 13 m) is typical with July surface temperatures approaching 25°C and < 1 mg l^{-1} O$_2$ below 6 m.

Glen Lake's present trophic status is a result of natural succession and human activity in the watershed. The entire lake is surrounded by residential buildings on septic tanks and tile fields. Based on its value as a recreational fishery, declining survival and catch of stocked rainbow trout (*Salmo gairdneri*) and low oxygen concentrations, Glen Lake was selected as the first site to test the empirical sizing formula for hypolimnetic aeration.

MATERIALS AND METHODS

Aeration system

The hypolimnetic aerator we built was a free-floating full lift design with equivalent diameter inflow and outflow tubes attached to the bottom of an insulated separator box. The separator box (3.7 × 1.8 × 1.2 m) was constructed of fiberglass and foam-core stiffness with a laminate composition of 1.73 kg m^{-2} fiberglass and 4.03 kg m^{-2} resin. Permanent flotation (2133 kg) was built into the separator box using foam-core construction, and 320 kg of extra flotation was available using adjustable end tanks. The inflow and outflow tubes (0.9 m dia) were constructed of 1.6 mm spiral wound galvanized sheet metal and attached to the separator box floor with 4.7 mm sheet metal suspension plates. A perforated pipe air diffusor was installed 0.5 m inside the bottom edge of the inflow tube. The outflow tube was fitted with two 90° elbows to prevent recirculation of aerated water. The entire unit weighed approx. 2000 kg and was securely anchored above the 13 m contour. Two 3.7 kW rotary vane compressors (Hydrovane SR 1700, rated 0.57 $m^3 min^{-1}$ each free air delivery at 7.0 kg m^{-2}) were installed in a below-ground concrete shed near the shoreline and connected to the aerator by a weighted airline (382 m × 3.81 cm i.d.).

Design variables

The design variables used to size the Glen Lake system were as follows: hypolimnetic volume—451,600 m^3; maximum hypolimnetic O_2 consumption—0.2 mg $l^{-1} d^{-1}$; aerator input rate—2 mg l^{-1}; water velocity—0.76 m s^{-1}; and depth of air release—12.2 m. Water velocity and aerator input rate were estimated from a survey of literature values. The maximum hypolimnetic oxygen consumption was calculated from spring 1983 oxygen profiles (Ashley, unpubl.). The calculated value (0.05 mg $l^{-1} d^{-1}$) was increased to 0.2 mg $l^{-1} d^{-1}$ as the spring 1983 data were collected from a partially oxygen-deficient hypolimnion. Lakes in the Insular Lowland area often experience maximum hypolimnetic oxygen depletion rates of 0.2 mg $l^{-1} d^{-1}$, and we felt this value was realistic for sizing the Glen Lake system. The aerator was sized using the Appendix equations from Ashley (1985).

Sampling

Dissolved oxygen and temperature were measured at 1 m intervals with an air-calibrated oxygen temperature meter (YSI 54 ARC). The data were collected every two weeks at two sampling stations, one 15 m from the aerator at right angles to the outflow elbows and another approx. 300 m from the separator box. Dissolved oxygen and temperature were also measured at 10 m inside the outflow tube for input rate calculations. Water velocity was measured at 3 m in the outflow tube with a current meter (General Oceanics No. 2035). Both compressors (i.e. 2 × 3.7 kW) were briefly operated (1-h) on 21 June 1985 to assess the effect of increased air flow on aerator performance.

Oxygen calculations

Hypolimnetic oxygen depletion rates between two sampling dates were calculated by standard limnological methods (e.g. Lorenzen and Fast, 1977). Hypolimnetic depletion rates calculated during aeration included the daily oxygen input of the aerator (i.e. input rate × daily water flow). No attempt was made at measuring oxygen diffusion across the thermocline, and all oxygen increases in the hypolimnion were attributed to the aeration system.

RESULTS

Field results

Aeration started on 1 June 1985 with one compressor providing the air supply. Water velocity was measured at 0.46 m s^{-1} (30-min average), which generated a water flow of 17.7 $m^3 min^{-1}$ and a theoretical hypolimnetic circulation period (hypolimnion volume = 451,600 m^3) of 18 days. Thermal stratification was not influenced by the aeration process; however, a slight degree of hypolimnetic warming (2–3°C) occurred during the aeration period.

Hypolimnetic aeration increased dissolved oxygen by an average of 1.6 mg l^{-1} ($n = 6$) on each cycle through the aerator, and aerator input rates ranged from 0.6 to 2.6 mg l^{-1} per cycle (Table 1). Water flow through the aerator was constant (25,590 $m^3 d^{-1}$); therefore, a range of 15.4–66.5 kg $O_2 d^{-1}$ was added to the hypolimnion (Table 1). Hypolimnetic oxygen concentrations remained well below saturation, but remained above 1.0 mg l^{-1} during the summer (Fig. 1) and prevented anaerobic conditions from developing.

Hypolimnetic oxygen consumption averaged 0.12 mg $l^{-1} d^{-1}$ and ranged between 0.02 and 0.21 mg $l^{-1} d^{-1}$ (Table 1). Although the average hypolimnetic oxygen consumption (0.12 mg $l^{-1} d^{-1}$) exceeded the average input (0.09 mg $l^{-1} d^{-1}$), daily input was greater than daily consumption on a few occasions (e.g. 2–16 July, 30 July–15 August) (Table 1). As a result, hypolimnetic oxygen content gradually increased during the aeration period and nearly twice as much oxygen was present on 15 August, 1985 (891 kg) as compared to 2 July, 1985 (469 kg) (Table 1). Hypolimnetic oxygen content increased more than the aerator input rate between 17 September and 1 October, indicating oxygen was being entrained from the epilimnion and the lake was beginning to destratify. The aeration system was turned off on 3 October, 1985 for the winter season.

Comparison with model based predictions

Most of the measured values were similar to the expected values except for water velocity, water flow and daily oxygen input (Table 2). The maximum hypolimnetic oxygen consumption (0.21 mg $l^{-1} d^{-1}$) was similar to the expected value (0.20 mg $l^{-1} d^{-1}$), confirming our suspicion that the calculated pre-aeration rate of 0.05 mg $l^{-1} d^{-1}$ was too low, and that 0.20 mg $l^{-1} d^{-1}$ is representative of Insular Lowland area lakes.

Table 1. Hypolimnetic (5–12 m) oxygen content, consumption, aerator input and daily input for Glen Lake

Period	Aerator input rate (mg l^{-1})	Daily oxygen input from aerator (mg $l^{-1} d^{-1}$)	Daily oxygen input from aerator (kg)	Total hypolimnetic oxygen content (kg)	Hypolimnetic oxygen consumption (mg $l^{-1} d^{-1}$)
6–17 Jun	0.6	0.03	15.4	773	0.02
17–21 Jun	1.3	0.07	33.3	517	0.21
21 Jun–2 Jul	2.1	0.12	53.7	469	0.13
2–16 Jul	2.2	0.13	56.3	921	0.05
16–30 Jul	2.4	0.14	61.4	857	0.15
30 Jul–15 Aug	2.6	0.15	66.5	891	0.14
15 Aug–17 Sep	0.6	0.03	15.4	381	0.07
17 Sep–1 Oct	0.6	0.03	15.4	738	−0.06

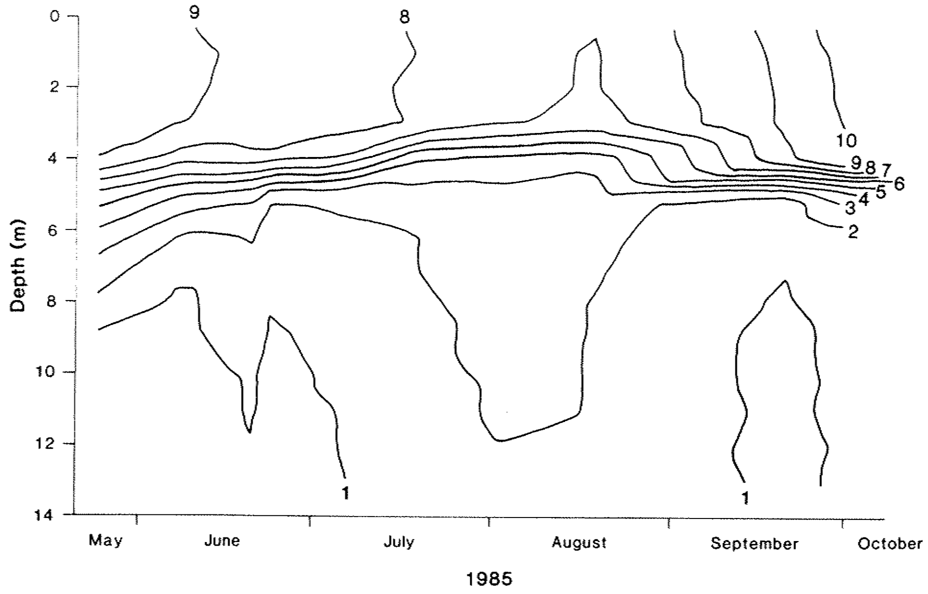

Fig. 1. Oxygen isopleths (mg l^{-1}) for Glen Lake during 1985 aeration period.

The aerator O_2 input rate of 1.6 mg l^{-1} was similar to the expected value of 2.0 mg l^{-1}. The expected value was based on the data of Smith *et al.* (1975) who used a similar depth of air injection, compressor size, and aerator design.

The measured water velocity in the outflow tube (0.46 m s^{-1}) was slower than the expected value (0.76 m s^{-1}). As a result, water flow and daily oxygen input were less than expected and the system was undersized with respect to daily oxygen input. This conclusion is substantiated by the hypolimnetic oxygen concentrations which remained well below saturation all summer. When the second 3.7 kW compressor was briefly operated (1-h) on 21 June, 1985, the extra airflow increased the aerator input rate to 2.2 mg l^{-1} and water velocity to 0.65 m s^{-1}.

DISCUSSION

Increased oxygen consumption during hypolimnetic aeration has been documented by a number of researchers (Smith *et al.*, 1975; Ashley, 1983; McQueen *et al.*, 1984), and results from a variety of factors including continued suspension of sestonic material and increased sediment oxygen demand. An allowance for induced oxygen demand should be included in the estimate of maximum hypolimnetic oxygen consumption if the data was collection from

Table 2. Comparison of measured values using one and two compressors and values predicted from the empirical sizing formula

Parameter	Predicted	One compressor	Two compressors (1-h test)
Max. hypolimn. O_2 consump. (mg l^{-1} d^{-1})	0.20	0.21	0.21
Aerator input rate (mg l^{-1})	2.0	1.6	2.2
Water flow (l s^{-1})	523.0	296.0	427.0
Water velocity (m s^{-1})	0.76	0.46	0.65
Tube diameter (m)	0.94	0.91	0.91
Depth of air release (m)	12.2	11.7	11.7
Calculated air flow (m^3 min^{-1})	0.41	0.57	1.14
Output pressure required (kg cm^{-2})	3.4	7.0	7.0
Separator box size (m) L:	3.0	3.7	3.7
W:	1.5	1.8	1.8
H:	1.1	1.2	1.2
Electric motor size (kW)	3.0	3.7	7.4
Daily oxygen input (kg)	90.3	15.4–66.5	81.0

an oxygen-deficient hypolimnion. The most accurate estimates of maximum hypolimnetic oxygen consumption are obtained near the onset of thermal stratification when hypolimnetic metabolism is not restricted by lack of oxygen (Lorenzen and Fast, 1977).

Aerator input rates published in the literature, range between 0.7 and 9.0 mg l^{-1}, and are very difficult to predict (Taggart and McQueen, 1982). The observed variation in input rate (0.6–2.6 mg l^{-1}) was expected, and presumably reflects changes in the immediate dissolved oxygen demand (IDOD), resulting from rapid oxidation of reduced inorganics (e.g. Mn^{2+}, Fe^{2+}). Taggart and McQueen (1982) also observed wide ranges in oxygen transfer efficiency and concluded it was due to IDOD and not to variations in hypolimnetic biochemical oxygen demand (BOD). Given that most oxygen transfer occurs in the lower half of the inflow tube (Bernhardt, 1967; Smith *et al.*, 1975) and that co-current bubble-water transport becomes progressively less efficient at oxygen transfer at shallow depths (Speece, 1974), the logical conclusion is that input rates will usually be greater in deeper systems (Taggart and McQueen, 1982). However, due to variable immediate dissolved oxygen demands, measured values may underestimate actual input rates and caution must be used when estimating this parameter.

Water velocity can be estimated as bubble rise velocity is related to bubble size and shape (Andeen, 1974). For small bubbles (<0.025 cm radius) water viscosity is the most important factor determining the rate of rise; however, large bubbles (>0.5–0.7 cm radius) rise independently of water properties and their velocity can be described by:

$$u = 1.02\sqrt{gr_e}$$

where

u = terminal rise velocity (m s^{-1})
g = acceleration of gravity (9.8 m s^{-2})
r_e = equivalent radius of a bubble (m), i.e. radius of a sphere of equal volume (Haberman and Morton, 1959).

Bubble size at Glen Lake was visually estimated at 0.5–5 cm dia which predicts a theoretical rise velocity of 0.16–0.50 m s^{-1}. Ippen and Carver (1954) measured terminal rise velocities of 2–8 cm dia bubbles at 0.3–0.6 m s^{-1}, and Baines (1961) recorded an average rise velocity of 0.49 m s^{-1} from 0.16–2.5 cm dia bubbles. Therefore, a median velocity of 0.45–0.50 m s^{-1} should be adequate for initial estimates when no data on bubble size or velocity is available (e.g. Taggart and McQueen, 1982).

As previously mentioned, the system was undersized when running on one compressor. However, a number of additional factors contributed to overload the aeration system. Aeration was not started until 1 June, 1985, well after stratification and hypolimnetic oxygen depletion had occurred. When starting this late the aeration system must oxidize a number of reduced compounds (e.g. H_2S, CH_4, Mn^{2+}, Fe^{2+}) in addition to meeting a possible increase in aerobic oxygen consumption. This often overloads the aerator and low oxygen concentrations persist (e.g. Smith *et al.*, 1975; Steinberg and Arzet, 1984). Aeration should be timed to coincide with natural circulation periods to minimize accumulated chemical oxygen demands (CODs).

The transfer efficiency (% oxygen absorbed)/(% oxygen supplied) of the aerator was 18%. Although this is an improvement from the Black Lake system (6%; Ashley, 1983), it is less than the 25–50% transfer efficiencies recorded at a number of installations (Lorenzen and Fast, 1977). We believe or low transfer efficiency was partially due to the coarse bubble perforated pipe diffusor (3 mm orifice dia) and large bubbles (0.5–5 cm dia) in the inflow tube. The influence of bubble size on oxygen transfer is a complex phenomenon involving several factors (e.g. air flow rate, diffusor depth, water temperature, transfer coefficient) (Bewtra and Mavinic, 1978). Perforated pipe diffusors are generally less efficient at oxygen tranfer than porous filter diffusors (Markofsky, 1979).

In addition, the relatively small surface area of hypolimnetic aerator separator boxes places additional constraints on oxygen transfer. Nielson (1974) examined the relative contribution of each stage of oxygen transfer (bubble formation, bubble rise, bubble bursting and natural surface aeration) and concluded only 6–12% of the total oxygen transfer originated from bubble formation, rise and bursting. Therefore, diffusor design and bubble size are critical design parameters for hypolimnetic aeration and more emphasis is required on how to maximize oxygen transfer within the confines of the aerator tubes and separator box.

The data from Table 2 suggest that with both 3.7 kW compressors operating the aeration system was capable of increasing the daily oxygen input to 81 kg, very near the required input of 90 kg O_2 day^{-1}. Since the aeration system was designed to operate on a single 3.7 kW compressor, this implies the sizing procedure underestimated compressor power by approx. 100%. A single 3.7 kW compressor may eventually provide sufficient oxygen as the oxygen demand may decline after several years aeration (McQueen *et al.*, 1984); however, during the initial phases of aeration the system was definitely undersized.

The compressor motor and air flow were sized to the design specifications. The output pressure we obtained was approximately double the design specifications (7.0 vs 3.4 kg cm^{-2}); however, the sizing formula simply establishes a general pressure requirement for a given installation and indicates whether a low pressure blower, single stage compressor or two-stage compressor is required.

In summary, the measured and expected values from the empirical sizing formula were similar except for water velocity, water flow and daily oxygen input. To meet these requirements two compressors were needed indicating that the system was undersized with one compressor operating. To avoid undersizing future aeration installations, the following recommendations should be considered when using the empirical sizing formula:

(1) Estimates of hypolimnetic oxygen depletion should be calculated from well oxygenated hypolimnia in spring months to ensure that maximum depletion rates are obtained.

(2) Aerator input rates should be conservative (e.g. 1–4 mg l^{-1}) and increase with depth.

(3) Water velocity of 0.45–0.50 m s^{-1} should be used when no information on actual bubble size and velocity is available;

(4) Aeration start-up should be timed to avoid periods of accumulated oxygen demands.

In retrospect, the most direct approach to meeting the daily oxygen demand would have been a more accurate estimate of water velocity and a larger diameter tube to handle the extra water flow. However, once a system has been built, installed and found to be undersized, there are only three solutions to increase oxygen input.

The first method (the one we used) is to supply additional air to the system. This generally increases the aerator input rate and water velocity to the point where daily oxygen requirements are achieved. This approach is more capital intensive (i.e. compressor and operating costs) and should only be used up to a void fraction (air volume)/(water volume) of 10% at which point air-lift pump efficiency declines (Andeen, 1974). This approach provides the flexibility and reliability of having a backup compressor on hand.

A second approach is to inject pure oxygen or a mixture of compressed air and oxygen into the aeration system (e.g. Smith *et al.*, 1975). This method is expensive and may be impractical for remote areas or for large lakes.

The third approach is to increase the oxygen transfer efficiency of the existing system. For example, if the aerator input rate of the Glen Lake system increased from 1.6 to 3.4 mg l^{-1}, the daily oxygen demand would be satisfied by one 3.7 kW compressor. This is the most cost effective solution, and given the amount of oxygen transfer information in the sanitary engineering literature, we believe this is a straightforward technology transfer problem.

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REFERENCES

Andeen G. B. (1974) Bubble pumps. *Compress. Air Mag.* **79,** 16–19.

Ashley K. I. (1983) Hypolimnetic aeration of a naturally eutrophic lake: physical and chemical effects. *Can. J. Fish. Aquat. Sci.* **40,** 1343–1359.

Ashley K. I. (1985) Hypolimnetic aeration: practical design and application. *Wat. Res.* **19,** 735–740.

Baines W. D. (1961) The principles of operation of bubbling systems. In *Proceedings of the Symposium on Air Bubbling*. National Research Council, Associate Committee on Soil and Snow Mechanics. Tech. Mem. No. 70, Ottawa, Canada.

Bernhardt H. (1967) Aeration of Wahnbach Reservoir without changing the temperature profile. *J. Am. Wat. Wks Ass.* **59,** 943–963.

Bewtra J. K. and Mavinic D. S. (1978) Diffused aeration systems from theory to design. *Can. J. civ. Engng* **5,** 32–41.

Haberman W. L. and Morton R. K. (1954) An experimental study of bubbles moving in liquids. *Proc. Am. Soc. civ. Engrs* **80,** 379–429.

Ippen A. T. and Carver C. E. (1954) Basic factors of oxygen transfer in aeration systems. *Sewage ind. Wastes* **26,** 813–829.

Lorenzen M. and Fast A. W. (1977) *A Guide to Aeration/Circulation Techniques for Lake Management.* U.S. Environmental Protection Agency, 600/3-77-004.

McQueen D. J., Rao S. S. and Lean D. R. S. (1984) Hypolimnetic aeration: changes in bacterial populations and oxygen demand. *Arch. Hydrobiol.* **99,** 498–514.

Markofsky M. (1979) On the re-oxygenation efficiency of diffused air aeration. *Wat. Res.* **13,** 1339–1346.

Neilson B. J. (1974) Reaeration dynamics of reservoir destratification. *J. Am. Wat. Wks Ass.* **66,** 617–620.

Northcote T. G. and Larkin P. A. (1956) Indices of productivity in British Columbia lakes. *J. Fish. Res. Bd Can.* **13,** 515–540.

Smith S. A., Knauer D. R. and Wirth T. (1975) Aeration as a lake management technique. Wisconsin Department of Natural Resources, Technical Bulletin No. 87.

Speece R. A. (1974) Ten years' experience of reservoir aeration: reply to H. Bernhardt. *Prog. Wat. Technol.* **7,** 483–495.

Steinberg C. and Arzet K. (1984) Impact of hypolimnetic aeration on abiotic and biotic conditions in a small kettle lake. *Envir. Technol. Lett.* **5,** 151–162.

Taggart C. T. and McQueen D. J. (1982) A model for the design of hypolimnetic aerators. *Wat. Res.* **16,** 949–956.