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A MODEL FOR THE DESIGN OF HYPOLIMNETIC AERATORS

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Abstract—Diffusor depth, air flow rates, rise velocity and cross-sectional area of the riser tube are the major variables considered in the simple empirical model presented for use in the design of hypolimnetic aerators. Water flow values predicted by the model were correlated with those observed in twenty published field experiments ($r = 0.893$). The model determined that some aerators are inefficient and their design could be improved. A discussion of required oxygen input during aeration is presented in which the problems of hypolimnetic oxygen depletion rates and oxygen transfer efficiencies (observed and absolute) are considered.

INTRODUCTION

There are numerous documented research projects which deal with aeration as applied to the restoration of small lakes and reservoirs (see Toetz *et al.*, 1972; Dunst *et al.*, 1974), a few involve deep water oxygen injection (Fast *et al.*, 1975a; Fast *et al.*, 1977; Bianucci & Bianucci, 1979) and some involve air lift hypolimnetic aeration. Bernhardt (1967) published the first account of an *in situ* hypolimnetic aerator operating as an air lift pump (see also Bernhardt, 1974, 1978; Bernhardt & Wilhelms, 1975), and similar experiments soon followed (Fast, 1971a, b; Fast *et al.*, 1973; Fast *et al.*, 1975b; Ohle, 1974; Bengtsson & Gelin, 1975; Smith *et al.*, 1975; Wirth *et al.*, 1975). There are also two more recent studies (Taggart, 1980; Taggart & McQueen, 1981; and Ashby and Northcote, Personal Communication). Air lift pump hypolimnetic aerators operate by the release of compressed air from a diffusor at the bottom open end of a cylindrical riser tube. An air-water jet is formed in the enclosed riser, and as water rises to the surface it is oxygenated and stripped gases (e.g. H_2S) are vented to the atmosphere at the surface. The bubble-free oxygenated water is then returned to the hypolimnion by gravity flow and head pressure via return manifold tubes.

Most studies to date have yielded positive results with respect to lake restoration: (1) in stratified lakes the thermocline remains stable and, therefore, the hypolimnion remains cold and intact while being aerated; (2) dissolved oxygen concentration (DO) is usually elevated in the hypolimnion; and (3) concentrations of phosphorus, nitrogen and hydrogen sulfide have been shown to decrease in the hypolimnion. However, the design of hypolimnetic aerators has received little attention, and as a result there exist several different designs which display various efficiencies (Table 1). Design models have been developed for destratification or circulation aeration (Ivakhenko & Gulyan, 1972; Karasik *et al.*, 1972; Karasik & Stovbun, 1974; Smith *et al.*, 1975; Lorenzen & Fast, 1977; Carr & Martin, 1978; Shell & Stein, 1978). The hydrodynamics and oxygenation capacity of bubble plumes in stratified waters and bubble-water uncoupling (which allows thermal stratification to be maintained) has been modelled and tested by Rayyan & Speece (1977). Lorenzen and Fast (1977) in their extensive review of aeration described a hypolimnetic aerator sizing model which may be needlessly complex, and which does not fit the data presented in this paper.

To augment the existing literature, and in an attempt to provide a straightforward analysis of the dynamics of hypolimnetic aeration, the following paper develops a simple, empirically derived model for use in aerator design for biologists, limnologists, and environmentalists. It does not attempt to consider all of the engineering, pneumatic and hydrodynamic aspects of aerator function, as many of the parameters for such analysis are impossible to obtain without sophisticated equipment generally unavailable to field biologists. There are two major sets of problems that must be considered when designing an aerator: (1) In order to determine the capacity of the air compressor to be used in a particular lake it is necessary to calculate (a) the volume of the hypolimnion; (b) the oxygen depletion rate during summer stagnation, and (c) the desired hypolimnion DO. Lorenzen and Fast (1977) considered this subject and we will review the problems involved in the discussion. (2) After compressor capacity is known, the aerator design requires calculation of (a) the length and cross-sectional area of the riser tube, and (b) the cross-sectional area of the return manifold tubes. These are considered in the model outlined below.

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Key words: lake restoration, aeration, hypolimnion, aerator design, dissolved oxygen.

Table 1. Observed and theoretical values of several variables in hypolimnetic aeration studies. Z = rise distance of air water jet; F_a = air flow, F_w = water flow; r = radius of the riser tube; O_2 refers to increase in O_2 concentration up the riser; O_2 t.e. is observed transfer efficiency of oxygen (uptake/supply). Theoretical values calculated from the model (see text) are underscored

Lake	Z (m)	F_a (l s^{-1})	F_w (l s^{-1})	$\frac{F_w}{F_a}$	r	O_2 (mg l^{-1})	O_2 t.e. (%)
Wahnbach (Bernhardt 1967)	21.3	67.0	1927.5 1036.2	28.8 15.5	1.0 0.85	5	50
(Bernhardt 1974)	42.0	116.7	3611.1 3288.5	30.9 28.2	1.0 1.51	5	50
(Bernhardt 1978)	42.0	48.3	2472.2 1836.9	51.2 38.0	1.0 1.13	—	—
	42.0	75.0	2833.3 2456.1	37.8 32.8	1.0 1.30	—	—
	42.0	76.7	2916.7 2492.7	38.0 32.5	1.0 1.31	—	—
	42.0	115.0	3527.7 3256.8	30.7 28.3	1.0 1.50	4	45
Hemlock (Fast, 1971; Fast *et al*., 1973)	14.5	46.7	590.3 522.4	12.5 11.2	0.69 0.60	—	—
	14.5	58.3	677.1 604.8	11.5 10.4	0.69 0.65	—	—
	14.5	70.0	723.4 682.4	10.4 9.8	0.69 0.69	—	—
Silver (Wirth *et al*., 1975)	12.2	13.3	178.0 186.5	13.4 14.0	0.23 0.36	5–6	22–27
	12.2	15.6	238.0 207.3	15.3 13.3	0.23 0.38	—	—
	12.2	19.0	190.0 236.1	10.0 12.4	0.23 0.40	—	—
Mirror (Wirth *et al*., 1975)	12.2	8.0	120.0 133.4	15.0 16.7	0.23 0.30	3.9	20*
Pure O_2	12.2	4.5	70.0 91.2	15.6 20.3	0.23 0.25	13.4	16*
Air and O_2 Mixture	12.2	10.6	150.0 160.6	14.2 15.2	0.23 0.33	8.6	23*
Larson (Wirth *et al*., 1975)	12.2	8.0	80.0 133.4	10.0 16.7	0.23 0.30	2.8	9*
	12.2	8.0	120.0 133.4	15.0 16.7	0.23 0.30	2–2.6	12–14*
Waccabuc (Fast *et al*., 1975b)	3.8	65.8	252.5 138.3	3.8 2.1	0.58 0.31	8	10.6*
Järlasjön (Bengtsson & Gelin, 1975)	20.0	380.0	883.3 3028.8	2.3 8.0	0.30 1.45	—	10.3†
Tory (Taggart, 1980; Taggart & McQueen, 1981)	8.5	3.4	55.9 49.8	16.4 14.7	0.29 0.19	1.8–4.5	10.3–25.8

* After Smith *et al*. (1975).
† After Lorenzen & Fast (1977).

THE MODEL

General design

The hypolimnetic aerator we describe results from modifications of designs by Bernhardt (1967, 1978), Fast *et al*. (1973), Bengtsson & Gelin (1975), Smith *et al*. (1975) and Wirth *et al*. (1975). The system we recommend (Fig. 1) includes a weighted intake collar which is suspended from a flexible polyvinyl coated nylon riser tube suspended from a head collar. Wirth (Personal Communication) attempted the use of a flexible riser tube but he found that it oscillated violently during aerator operation which led to rapid deterioration of the riser. Lorenzen & Fast (1977) mention that the riser should be rigid or it will collapse during operation. However, two aerators using flexible riser tubes have since been successfully used with no apparent violent oscillations or collapse (Taggart & McQueen, 1981; McQueen, unpublished). A draw string below the head col-

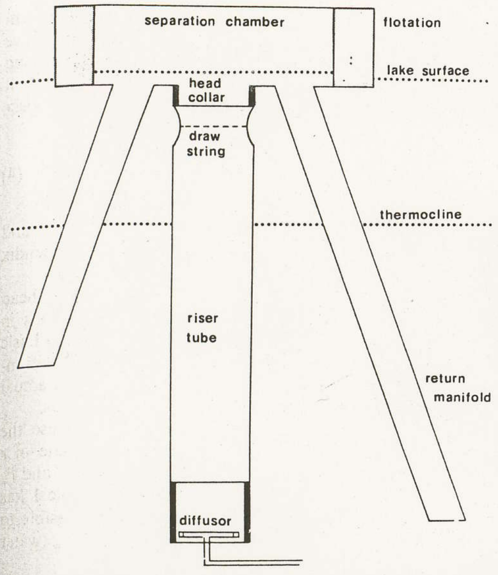

Fig. 1. General design for a floating hypolimnetic aerator with a flexible polyvinyl riser tube. Dimensions depend upon design calculations which are given in the text.

lar at the point of riser attachment prevents air and water from leaking around the head collar. The air-water separation chamber must have enough flotation to support the system when under full operation and the manifold tubes should return water to different depths within the hypolimnion to facilitate mixing of hypolimnetic water. The floating design permits the system to rise and fall with natural fluctuations in lake level and allows for portability of the entire system.

Pneumatics

All air compressors are rated by the manufacturer to deliver specific volumes at fixed temperatures and pressures; but the specifications are invariably given "at the compressor" and do not consider the fact that the compressor must deliver air through a pipe from the shore-based compressor to the air diffusor located at some depth in the lake. To estimate the amount of air actually delivered, the formula of Horton (1959) may be used:

$$F_a = 58\left(\frac{p \cdot d^5}{WL}\right)^{1/2} \qquad (1)$$

where F_a = air flow (ft^3 min^{-1}); p = pressure drop along delivery pipe (lb in^{-2}); W = weight (lb) of 1 ft^3 of entering air at ambient temperature; L = length of delivery pipe (ft) and d = diameter of delivery pipe (in.). The effect of couplings, restrictions and bends can also be incorporated into the calculation of F_a (see Horton 1959). An example of the use of (1) above is given in the Appendix.

Hydraulics

The amount of water that will flow through the aerator depends on air flow and length (or depth) of the riser tube. An estimate can be made using the proportionality equapion of Baines (1961):

$$F_w \propto Z^{1.5} \cdot F_a^{0.666} \qquad (2)$$

where F_w = water flow (l s^{-1}); Z = rise distance of the air water jet (m) and F_a = air flow (l s^{-1}). This relationship determines that for any fixed F_a; F_w increases with Z (Fig. 2), and flow efficiency of the bubbler system F_w/F_a increase also with Z (a result of increasing bubble size and buoyancy with decreasing hydrostatic pressure during rise). However, for any fixed Z, F_w/F_a decreases with increasing F_a (Fig. 3). These above relationships suggest that the riser tube should be as long as possible, and that small systems are more efficient than large ones.

Using equation (2) above, we calculated the theoretical F_w and F_w/F_a for each of the 20 experiments listed in Table 1. We also used a step-wise regression of Z (depth of riser tube in meters) and F_a (air flow in l s^{-1}) on F_w (water flow in l s^{-1}) to produce the equation:

$$F_w = (Z^{1.16})(F_a^{0.66})(1.85) \qquad (3)$$

with a multiple correlation coefficient of 0.963. The resulting values are listed in Table 1. A sample calculation appears in the Appendix. It is interesting to note the similarity in exponents between this equation and the formula (2) derived empirically by Baines (1961).

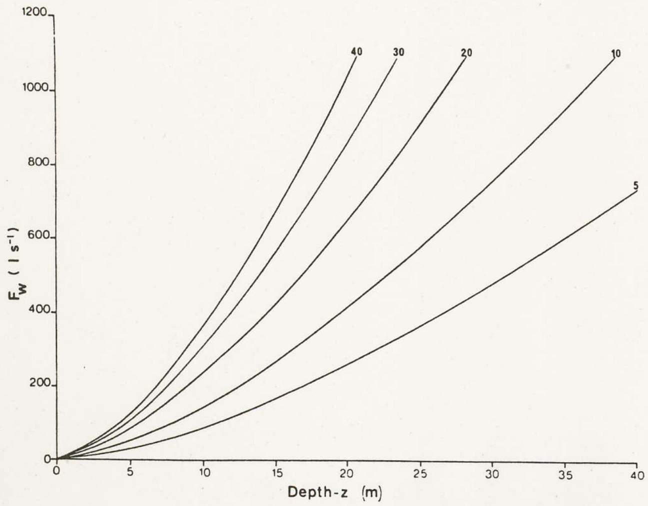

Fig. 2. Theoretical water flow (F_w) with respect to depth of riser tube (Z) at various air flow rates (5, 10, 20, 30 and 40 l s^{-1}).

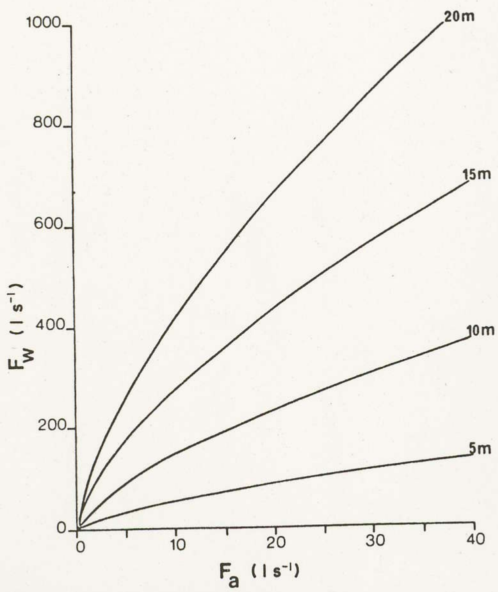

Fig. 3. Theoretical water flow (F_w) with respect to air flow (F_a) at various riser tube depths (5, 10, 15 and 20 m).

Riser tube cross-sectional area

Having estimated F_a and F_w on the basis of compressor capacity and depth, the cross-sectional area of the riser tube must be determined. The ascending velocity of a freely rising air-water plume varies with bubble size. Bubbles with a diameter of 2–8 cm have a range in terminal rise velocity between 30 and 60 cm s^{-1} (Ippen & Carver, 1954; Andeen, 1974). Baines (1961) has stated that at an air flow of 0.005 l s^{-1} or more, bubbles issue from an orifice as a heterogeneous mixture of sizes which are independent of the size of the orifice. The bubbles range in size from 0.16 to 2.5 cm dia. and reach an average rise velocity of 49 cm s^{-1} at 1.5 m above a diffusor releasing air at 0.47 l s^{-1}. We observed bubbles ranging from 0.75 to 8 cm dia. in the Tory Lake aerator. For our model we have chosen a median bubble velocity of 0.46 m s^{-1}. Assuming that bubble velocity determines maximum water velocity, it is possible to solve for the optimum radius of the riser tube:

$$r = \left(\frac{F_w}{\pi v}\right)^{1/2} \tag{4}$$

where r = radius of the riser tube; $v = 0.46$ m s^{-1} and F_w = water flow determined from (3) above (see Appendix for sample calculation).

Because of friction, changes in bubble size and head pressure it is impossible to make precise calculations in advance of aerator design. However, with respect to basic designs, it can be seen in Table 1 that the above relationship establishes a general sizing criterion in that the actual radius need not be greater than the calculated radius.

The approach outlined above is necessary because the model is designed to produce an optimum estimate of r (radius) based on known measurements of Z (depth) and F_a (air flow). However, the data set presented in Table 1 has observed values for Z, F_a and r. It is therefore possible to do a stepwise regression of these three values on F_w (water flow). The resulting equation is:

$$F_w = (5.75^r)(F_a^{0.459})(Z^{0.698})(5.14) \tag{5}$$

with a multiple correlation coefficient of 0.993. The proportion of variance reduced by r alone is 84.6%. This clearly demonstrates that once air flow and depth have been established, r becomes a critical parameter in determining water flow rates.

Water return manifold tube sizing

Once the radius of the riser tube has been calculated it remains to determine the cross-sectional area of the water return tubes. We experimented with various water flow rates (F_w) and various total areas (M) of the manifold tubes and measured the head (h) of water in the air-water separation chamber of the Tory Lake aerator. Figure 4 indicates that as F_w/M (velocity) increases, h (height of water in chamber above lake level) increases, and clearly when $F_w = 0$ or when M becomes very large, h approaches 0.

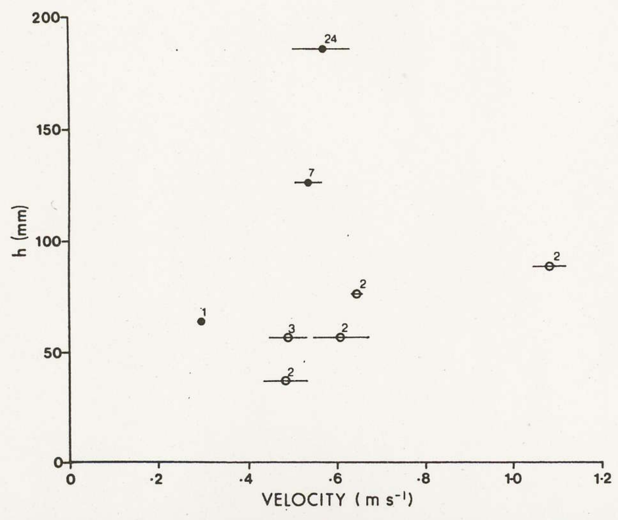

Fig. 4. Height of head (h) with respect to velocity (F_w/M) of water flow (±1 SD) in the Tory Lake aerator. The solid points represent data collected with manifold area (M) set and air flow altered, open points with air flow set and M altered. Superscripts are the number of measurement taken.

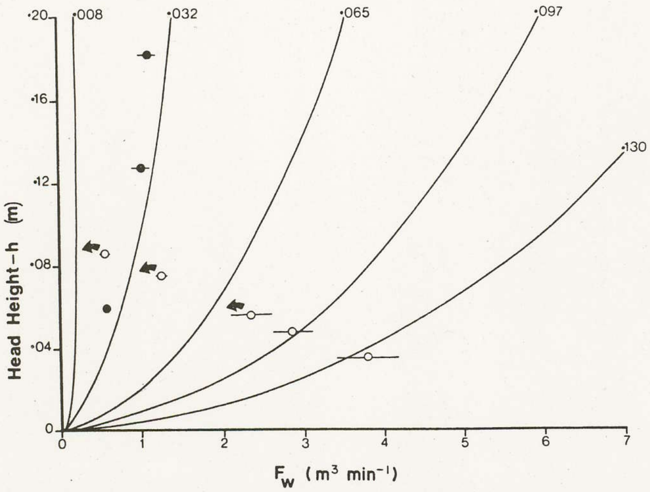

Fig. 5. Theoretical and observed relationship between height of head (h) and water flow in the Tory Lake aerator. The solid points (± 1 SD) were obtained with a constant manifold area (M) and various air flows (F_a), and the open points with constant F_a and various M. Line superscripts are values of M. Number of measurements taken for each point are given in Fig. 4.

It can be shown that F_w depends upon h and the return tube diameter and length. These are related by a transformed formulation after Horton (1959):

$$h = \frac{(v/c)^2(L_t + 16.46D)}{D} \tag{6}$$

where h = head (m); D = return manifold diameter (m); L_t = length of manifold tube and v = velocity of flow (m s^{-1}). Where more than one return tube is considered an equivalent value of D can be derived from the total area (M) of the tubes (m^2):

$$D = 2\left(\frac{M}{\pi}\right)^{1/2}. \tag{7}$$

and velocity (m s^{-1}) is calculated from:

$$v = \frac{F_w}{\pi(D/2)^2} \tag{8}$$

c in (6) above is a constant derived from Horton (1959) where:

$$c = [(\log_{10}D)(-7.98)] + 18.74. \tag{9}$$

For the values of M and L_t (9.6 m) in the Tory Lake aerator the relationship between F_w and h was determined (Fig. 5). During 1978 M was held at 0.032 m^2 while F_a (and therefore F_w) was altered. The result was a substantial increase in head which was close to that predicted in (6) above. In the second year F_a (and so F_w) was held constant while M was altered. As M decreased h increased in a manner close to that predicted. The above explains the relationship between F_w, M and h, but it does not define the optimum value of M. A linear regression was performed on the h and M data from 1979 and Fig. 6 shows that the regression line intercepts the x-axis (manifold tube area) at M = 0.23 m^2. This is only slightly smaller than the cross-sectional area of the riser tube of the Tory Lake aerator (0.26 m^2), and so not surprisingly the conclusion is that the total cross-sectional area of the return manifold tubes should not be less than the cross-sectional area of the riser tube.

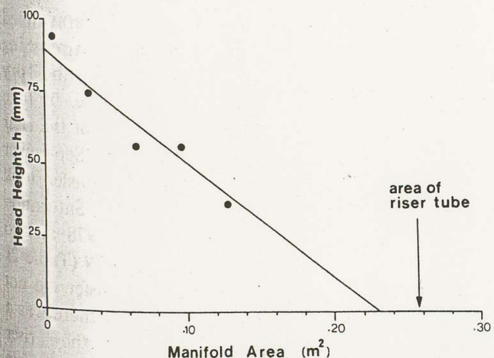

Fig. 6. The relationship between height of head (h) and increasing manifold area (M) in the Tory Lake aerator under constant air flow. Regression line has an r^2 value of 0.94.

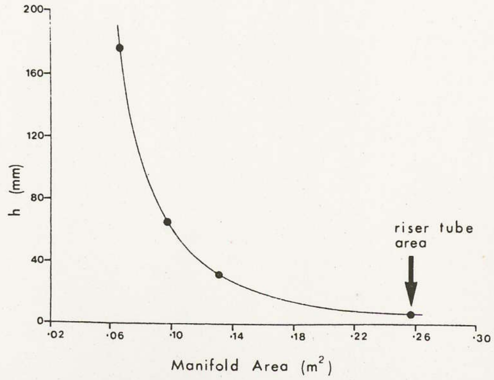

Fig. 7. Theoretical relationship between head height (h) and manifold area assuming a fixed air flow rate of 3.4 l s^{-1}.

The relationship is not precise as the model shows that for any fixed value of F_w there is always some head, regardless of how large M may be. However, when F_w remains constant (e.g. 3.35 m^3 min^{-1} in the Tory Lake aerator during 1979) it can be seen that h approaches a minimum when M is equal to riser tube cross-sectional area (Fig. 7).

DISCUSSION

The observed and predicted flow rates are highly correlated (Fig. 8). Bernhardt's (1978) Wahnbach aerator displayed the greatest flow efficiency (28.8–51.4%); with the highest value corresponding to the lowest air flow used, as predicted by the model. The Wahnbach aerator also had the greatest observed oxygen transfer efficiency (45–50%). Both of these observations are no doubt related to the large value of Z and hence a relatively longer bubble-water contact time which increases oxygen transfer. Most other aerators, notably those used in Hemlock, Silver, Mirror, Larson and Tory Lakes have observed flow efficiencies of between 10.0 and 16.4% and predicted values of between 9.8 and 16.7% which are not significantly different from the observed ($n = 12$, $\alpha = 0.05$, Students' t-paired difference test).

The Järlasjön aerator (Bengtsson & Gelin, 1975) had the lowest observed flow efficiency value (2.3%). This is a result of two factors: (1) the air flow (380 l s^{-1}) was too large as we have shown that at any fixed depth F_w/F_a decreases with increasing F_a (Fig. 3); and (2) the cross-sectional area of the riser was undersized and restricted flow. The actual area was 0.283 m^2 ($r = 0.3$ m), but our model determined that an area of 6.6 m^2 ($r = 1.45$ m) was required for an estimated F_w of 3029 l s^{-1}. The small size of the riser resulted in a 1.8 m high plume of water above the lake surface during aerator operation (Lorenzen & Fast, 1977).

It is worth noting that in Fig. 8, when Järlasjön is included in the data set, the correlation between observed flow and measured flow is $r = 0.893$ and the relationship is described by the equation $FW = 124.7 + 0.840\,FWO$ where FW = predicted flow and FWO is measured flow. When Järlasjön is omitted from the data set r becomes 0.987 and the regression line becomes $FW = -4.9 + 0.855\,FWO$.

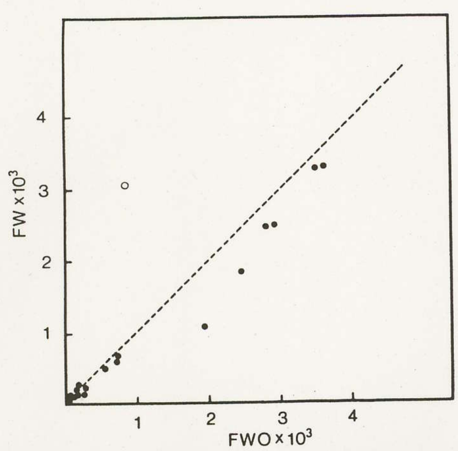

Fig. 8. Correlation between observed flow (FWO) and flow predicted by the model (FW). The correlation coefficient $r = 0.893$. The open point is for the Järlasjön aerator.

The second lowest flow efficiency (3.8) recorded was that of the LIMNO aerator (Atlas Copco, AB, Stockholm; Fast *et al.*, 1975b). This is a result of the short rise distance ($Z = 3.8$ m) which was permitted by aerator design, a factor which has been noted by others (Bernhardt, 1978). The observed water flow induced is more than twice that predicted by the model and is most likely related to jet or pressure flow induced by a large air flow (65.8 l s^{-1}) which would be greater than that induced by passive flow (freely rising bubbles). Bengtsson & Gelin (1975, p. 321) have stated that the LIMNO aerator is advantageous because "by not lifting water to the lake surface, energy is saved and higher efficiency is achieved". Clearly, once energy has been used to compress air for release at depth, what happens to that air after release is irrelevant, as far as energy consumption is concerned. Furthermore, flow efficiency *can* be increased by allowing for a greater rise distance. This would not only increase flow efficiency but it would also result in a longer period of bubble-water contact and, therefore, increase oxygen transfer and subsequently DO in the upwelling water.

Oxygen transfer efficiency is a major problem in hypolimnetic aeration. From Table 1 it can be seen that observed efficiencies range from 9% (Larson Lake) to 50% (Wahnbach Reservoir). Efficiencies are calculated as the ratio of the mass of oxgyen supplied (O_{2s}) to the observed DO increase up the riser tube (ΔDO), expressed as a percentage. This calculation neglects the possible effect of instantaneous oxygen demand (IOD). Furthermore, no measurements of the O_2 content in the air vented (O_{2v}) from aerators have been made, which would enable the calculation of IOD as follows:

$$\mathrm{IOD} = O_{2s} - \Delta\mathrm{DO} - O_{2v}.$$

A similar problem is encountered when it is assumed that upwelling water will be saturated upon reaching the top of the riser tube. Our observations in the Tory Lake aerator show that this is not the case. In June and September 1978 the water at the top of the riser was near saturation (Table 2), and in September approx. 60% of the observed oxygen transfer took place within the first meter of rise (Fig. 9). Saturation dropped to less than 60% in October 1978 and to below 25% for most of the summer of 1979 (Table 2). At the same time the greatest rate of transfer did not take place at greater depth. In June 1979 there was a substantial increase in DO up the riser (4.4–8.9 mg l^{-1}), but the greatest transfer rate occurred between 3 and 1 m (Fig. 9). In August 1979 the greatest transfer occurred between 6 and 5 m but this was followed by a decrease in DO between 5 and

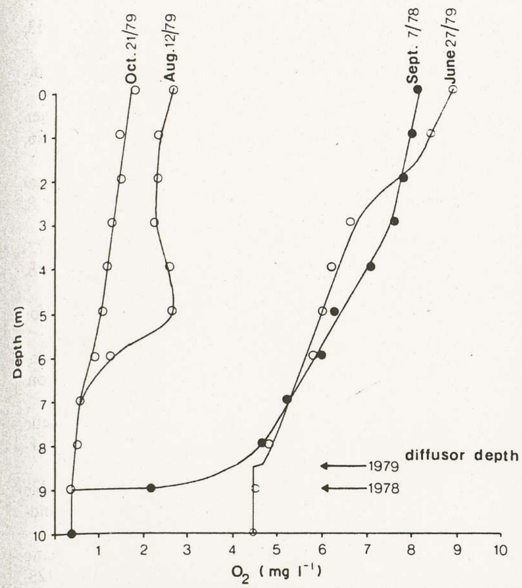

Fig. 9. The relationship between dissolved oxygen concentration in upwelling water and depth in the Tory Lake aerator riser tube on four occasions in 1978 and 1979.

3 m. In October the rate of transfer was almost linear with respect to depth. These data suggest that oxygen was being used instantaneously and, therefore, DO measurements may be seriously underestimating absolute oxygen transfer. These changes in observed oxygen transfer appeared not to be related to hypolimnetic biochemical oxygen demand (BOD). Although we did not monitor hypolimnetic BOD_5 (5 day, 20°C) for most of the summer of 1978, we did measure BOD from September through to the end of the study. The maximum value recorded during the fall of 1978 was 9.0 ± 0.5 SD (n = 3) mg l^{-1} on September 21, 1978. This can be compared to the maximum BOD measured during all of 1979 which was 10.5 ± 0.9 SD (n = 5) mg l^{-1} on August 29. Although there is a significant difference (α = 0.05) between mean maximum BOD in 1978 and 1979 amounting to 1.5 mg l^{-1}, we do not believe that it sufficiently explains the observation that during 1978 the oxygen saturation of water at the top of the riser tube was >50%, while the saturation of the water at the top of the riser was <30% during the fall of 1979 (Table 2, Fig. 9). This means that it may be very difficult to predict in advance the amount of oxygen required to successfully aerate a given lake. This has been attempted by Lorenzen & Fast (1977) who have presented an extensive discussion of aerator design with respect to required (or desired) oxygen input to the hypolimnion predicted from oxygen depletion rates. Those authors also pointed out that oxygen depletion rates often underestimate (e.g. by 30% in Lake Waccabuc) depletion rates that are observed during aeration and they refer to Smith *et al.* (1975) who found that depletion rates were 3–4-fold greater during aeration experiments in Larson Lake. Disturbance of the sediment–water interface during aeration may be responsible for increased depletion rates, but there is no evidence that supports this conclusion, and furthermore, while one might expect increased metabolic activity of hypolimnetic bacteria populations during aeration, preliminary experiments suggest that hypolimnetic aeration decreases the percent respiring bacteria (McQueen, unpublished).

The most suitable method for predicting oxygen depletion rates in the hypolimnion may be that of Cornett & Rigler (1979) who have shown that areal hypolimnetic oxygen deficit (AHOD) is a function of the average thickness and temperature of the hypolimnion during summer stagnation and lake phosphorus retention (see also Cornett & Rigler, 1980; Charleton, 1980). These models could be used in determining hypolimnetic oxygen deficit which could be used to assess necessary oxygen input by aeration. But this will only solve half of the problem because the few observations that have been made indicate that it may be very difficult to predict the absolute transfer efficiencies up the riser tube. Clearly more work is required before this process will be properly understood.

We have presented here an empirically derived model for use in designing hypolimnetic aerators which ensures maximum flow efficiency but may not maximize oxygen transfer efficiency. However, until absolute oxygen transfer during aeration is measured and made predictable, we suggest that our design con-

Table 2. Dissolved oxygen concentration (mg l^{-1}), at the bottom of the riser tube, and at the top of the riser tube of the Tory Lake aerator. Temperature is that of the upwelling water. Saturation is that of the top water

Date	Temperature (°C)	Bottom DO (mg l^{-1})	Top DO (mg l^{-1})	Oxygen uptake (mg l^{-1})	Oxygen saturation (%)
June 15 1978	9.5	3.80	9.60	5.80	85
Sept. 1 1978	14.5	0.00	8.00	8.00	79
Sept. 7 1978	13.5	0.40	8.10	7.70	78
Oct. 19 1978	10.0	3.35	6.60	3.25	59
June 27 1979	7.7	4.40	8.90	4.50	75
Aug. 12 1979	9.2	0.40	2.80	2.40	25
Sept. 27 1979	10.2	0.55	2.30	1.75	21
Oct. 29 1979	10.0	0.45	2.65	2.20	24

siderations can improve the efficiencies of hypolimnetic aerators.

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APPENDIX

An example of use of the design model described in the text is outlined below using equations (1), (3) and (4) and data collected from the Tory Lake aeration system.

The compressor used at Tory Lake (Taggart and McQueen 1981) was rated to deliver 12 $ft^3\ min^{-1}$ at 100 $lb\ in^{-2}$ gauge pressure (0.34 $m^3\ min^{-1}$ at 7.03 $kg\ cm^{-2}$); however, delivery of compressed air through more than 1000 ft (305 m) of pipe resulted in reduced air flow and pressure drop. On 5 November 1979, the ambient air temperature was 6°C and so W [used in equation (1)] was 0.791 $lb\ ft^{-3}$ (*p.* 1927, Horton, 1959). Gauge pressure at the compressor was 17.5 $lb\ in^{-2}$ and gauge pressure at the aerator was equivalent to hydrostatic pressure at diffusor depth (8.5 m) and was 12.42 $lb\ in^{-2}$. Therefore $p = 17.50 - 12.42 = 5.08\ lb\ in^{-2}$. The diameter ($d$) of the delivery pipe was 0.75 in and length (L) was 1018.7 ft. Solving (1) yields $F_a = 7.09\ ft^3\ min^{-1}$ or 0.20 $m^3\ min^{-1}$, which is only 60% of compressor capacity. Air flow measured by volume displacement at the aerator was 0.221 $m^3\ min^{-1}$.

The rise distance (Z) of the air-water jet was 8.5 m. At an air flow (F_a) of 3.39 $l\ s^{-1}$ (average F_a in 1979), the solution to (3) yields $F_w = 49.8\ l\ s^{-1}$. Actual F_w was 55.9 $l\ s^{-1}$.

With an expected F_w of 0.0498 $m^3\ s^{-1}$ and assuming a rise velocity of 0.46 $m\ s^{-1}$ the value of r can be estimated with (4) and yields $r = 0.19$ m. The actual radius of the Tory Lake riser was 0.29 m.