93-02

Environment Canada

Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau

Environnement Canada

Eutrophication Management in Hamilton Harbour:
Hypolimnion Oxygen

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NWRI Contribution # 93-02

13-02

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January 13, 1993

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Management Perspective

Eutrophication Management in Hamilton Harbour: Hypolimnion Oxygen

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January 8, 1993

Hamilton Harbour is one of the 17 Areas of Concern in Canada designated by the International Joint Commission as requiring a Remedial Action Plan. This position paper was written in response to a proposal to artificially aerate the hypolimnion of Hamilton Harbour. The causes of eutrophication problems and the causes of hypolimnion oxygen depletion are reviewed. The priority of oxygen depletion as a problem to be repaired specifically is examined and found to be low. Interactions between nutrient and contaminant issues exist but their importance is likely small compared to benefits to be derived from better wastewater treatment. The plan of increasingly stringent sewage treatment and/or diversion is supported. Artificial aeration does not seem likely to solve any problems.

1 Introduction

Hamilton Harbour is one of the seventeen Areas of Concern designated by the International Joint Commission which are required to develop Remedial Action Plans (RAPs) according to the Great Lakes Water Quality Agreement (GLWQA) between Canada and the U.S.A.. The Harbour has aesthetic problems caused by sewage loading. There are small areas of highly toxic sediment. Fish and wildlife habitats have been destroyed or degraded. The bottom waters of the Harbour develop low dissolved oxygen concentrations for about 2 months in the summer of each year. In the fall of 1992, an unsolicited proposal for the purpose of artificially aerating the harbour was received by Hamilton Wentworth Municipal Regional Municipality. In addition to aerating the harbour, the proposal alleged other ancillary benefits all at a very attractive cost compared to other recommendations in the RAP. At the request of the Region, written opinions on the proposal were solicited. This report is provided to add some perspective to the issue of managing the dissolved oxygen situation in Hamilton Harbour.

2 The Causes of Water Quality Problems

Water flowing into Hamilton Harbour is about equally divided between stream flow and municipal sewage. During summer, nearshore water from Lake Ontario flows into the bottom of the Harbour. Most of the sewage volume represents water which is pumped from Lake Ontario for domestic use and ends up as sewage in the Harbour. In dry months much of the flow into the surface waters may be sewage. Sewage contains nitrogen and phosphorus which are nutrients that stimulate plant growth. The sewage is discharged with a phosphorus concentration of 300-1000 micrograms per litre (ug/L). A desirable phosphorus concentration in the water is 10 ug/l (Lake Ontario goal) but 20 ug/L may be more practical for the Harbour. The streams contain urban and agricultural runoff which also have nutrients. If the streams had no nutrients the mean incoming phosphorus concentration in all the water flowing to the Harbour would be, say, 250 ug/l. We see, however, that the concentration in the open waters is about 50 ug/L (enough to cause excessive algae). Excessive algal populations are one symptom of advanced eutrophication, the process of enrichment with nutrients.

The Harbour copes with the phosphorus load through discharge to Lake Ontario and through sedimentation in the Harbour. The large difference between the incoming high concentration of phosphorus and lower open water concentration is the reason to believe that good water quality can result from further management of wastewater discharges. At present the phosphorus load from treated sewage is excessive. Even though the majority of sewage phosphorus is removed, the effluent from STPs is biologically available and this causes problems. Compared to the situation of the 1950s, work carried out under the GLWQA has resulted in overall better conditions. For example, phosphorus concentrations in open Lake Ontario have been reduced to 1/2 of former levels. Even so, the relatively high concentration of phosphorus in sewage discharged near shore causes local problems especially in embayments such as Hamilton Harbour.

Another source of sewage pollution in Hamilton Harbour is combined sewer overflows. Overflows occur when rainwater fills the combined storm/sanitary sewers to capacity. The excess water, contaminated with sewage, then has to overflow, mainly into the Hamilton side of the Harbour without treatment. The well-being and usability of the Harbour are threatened by the added nutrients, pathogenic bacteria, and the numbers of floating personal products. These signal the presence of raw sewage and completely undermine the aspirations for public use. Fortunately, construction is well underway on a system of holding tanks which will contain the excess flows and allow them to be treated at the sewage plant after the rain passes.

Sewage plants at Dundas, Waterdown, Burlington, and Hamilton discharge directly to, or into tributaries to, the Harbour. The obvious idea of solving quality problems in the Harbour by diverting sewage from Hamilton and Burlington was rejected during the RAP process.

One implication of sewage discharge to the Harbour is that extraordinary treatment will be required before it is required in other municipalities. With regard to the RAP goal of swimming in appropriate areas, a further implication is that there is no place free from sewage in the Harbour. The movement of

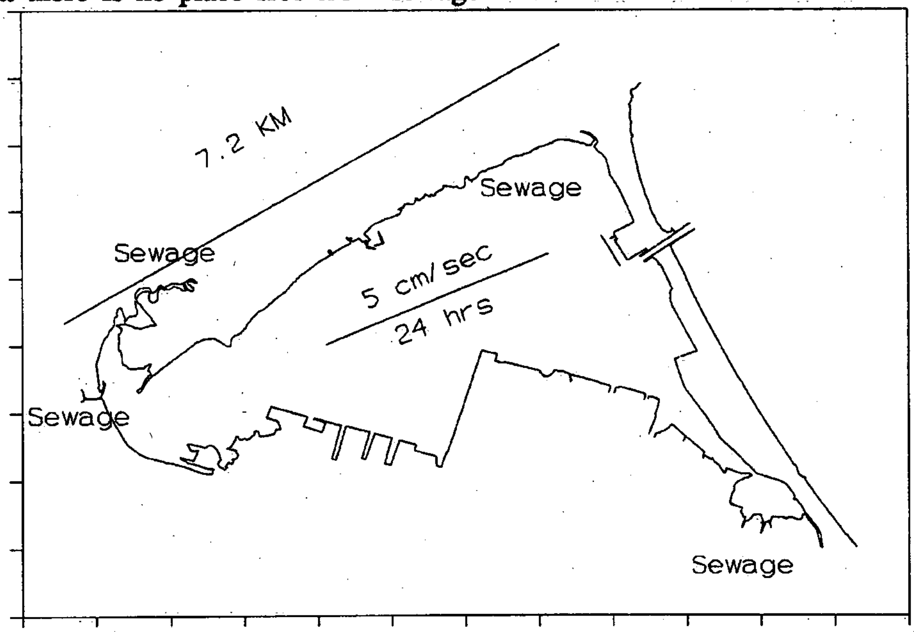

Figure 1: Location of sewage inputs and potential distance a patch of water can travel in one day.

patches of water has been studied by following the path of drogues (Boyce and Chiocchio 1992). A typical speed is 5 centimetres per second. Over 24 hours a patch of water would travel a distance equal to about 1/2 the length of the Harbour. Of course, some days would have much less movement and some days much more and the actual paths are not straight lines. Nevertheless, considering that sewage is discharged 24 hours per day the horizontal mixing will distribute it everywhere. Thus, a great deal of public relations may be necessary to convince the public of the swimmability of proposed swimming areas in the RAP unless combined sewer overflows are prevented and sewage treatment is radically improved.

3 The Causes of Oxygen Depletion

In the spring when lakes are no longer ice covered the water is cold and usually circulating from top to bottom. Eventually, with the increase in sunlight and overall moderating wind speeds, a thin layer of warm water can develop on the surface. If wind speeds stay low, the warm layer can increase in temperature and thickness. Because an increase in temperature causes a decrease in density, the warm layer floats on the cold layer much like oil on water. The upper warm layer is called the **Epilimnion**, the cold lower layer is called the **Hypolimnion** and the transition zone between them is called the **Thermocline.**

This stratified condition can last about 4 months. The living organisms, both in the water and in the sediment, consume oxygen. The epilimnion circulates in contact with the air and therefore oxygen is normally maintained at high concentrations. For the duration of the stratified period, however, the hypolimnion water cannot circulate up to the surface to pick up replacement oxygen from the air. Therefore, the consumption of the organisms causes a **depletion of oxygen** in the hypolimnion just like people breathing in a closed room. This happens in all stratified lakes and is a natural process that occurs

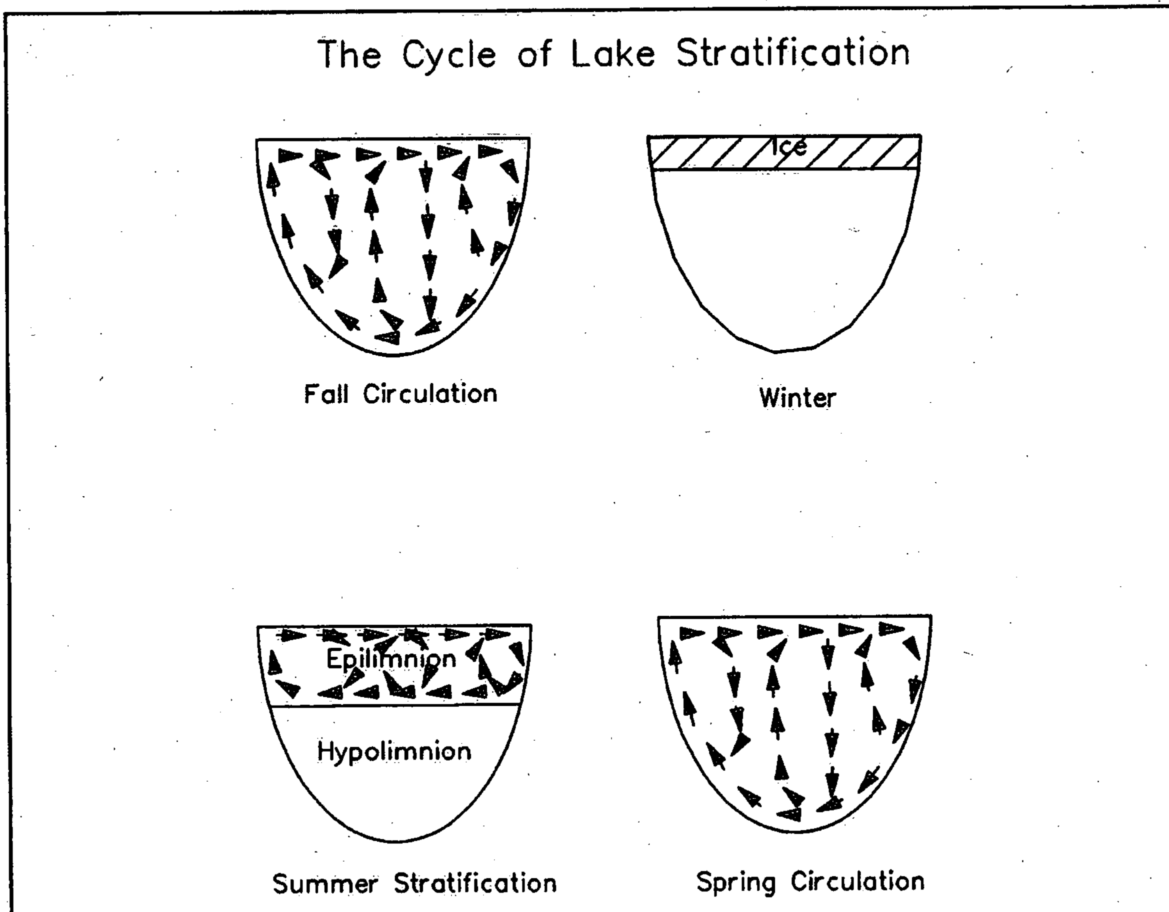

Figure 2 Simplified cycle of lake stratification; vertical scale has been multiplied by 300000, bottom slopes are actually quite flat.

even when the surface water quality is good.

Oxygen depletion rate is related to the amount of algae, the temperature, and the thickness of the hypolimnion. Lakes with a thin hypolimnion tend to have higher temperature hypolimnion water. This causes faster oxygen depletion because the organisms consume oxygen faster at higher temperatures. The thickness is also important because oxygen consumed by sediment is taken from a smaller reservoir when the hypolimnion is thin. Again, this is similar to people breathing in smaller unventilated rooms. We cannot do anything about the temperature or the thickness of the hypolimnion. We can, in some cases, do something about

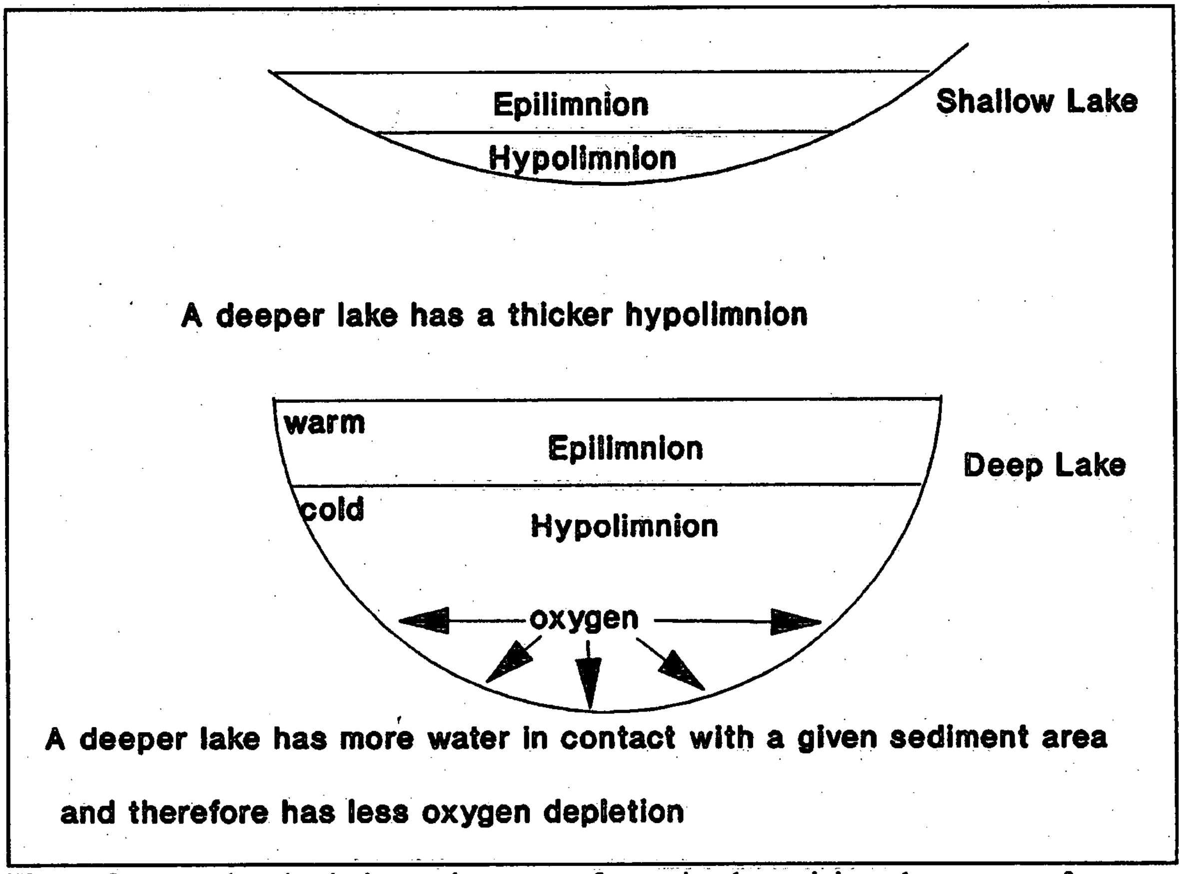

Figure 3 Lake depth is an important factor in determining the extent of oxygen depletion.

the amount of algae (the number of people, to pursue the analogy) in the water. Another type of organism that consumes oxygen is bacteria. These do not need light to live, instead, most of them only need oxygen and some organic material provided by algae and sewage treatment plants (STPs). Finally, the duration of stratification determines whether or not the other factors will add up to consume all the oxygen within the period when the hypolimnion exists.

4 Prognosis for Oxygen in Hamilton Harbour

The three main factors of amount of algae, water temperature, and hypolimnion thickness have been combined in a general relationship which can predict oxygen in the Great Lakes (Charlton 1980). By taking into account the duration of stratification, the relationship can be used to predict the worst (lowest oxygen) conditions at the end of the summer.

Figure 4 shows the end of summer predicted oxygen as a function of "Chlorophyll" which is a measure of the amount of algae. In Fig.4, the thickness

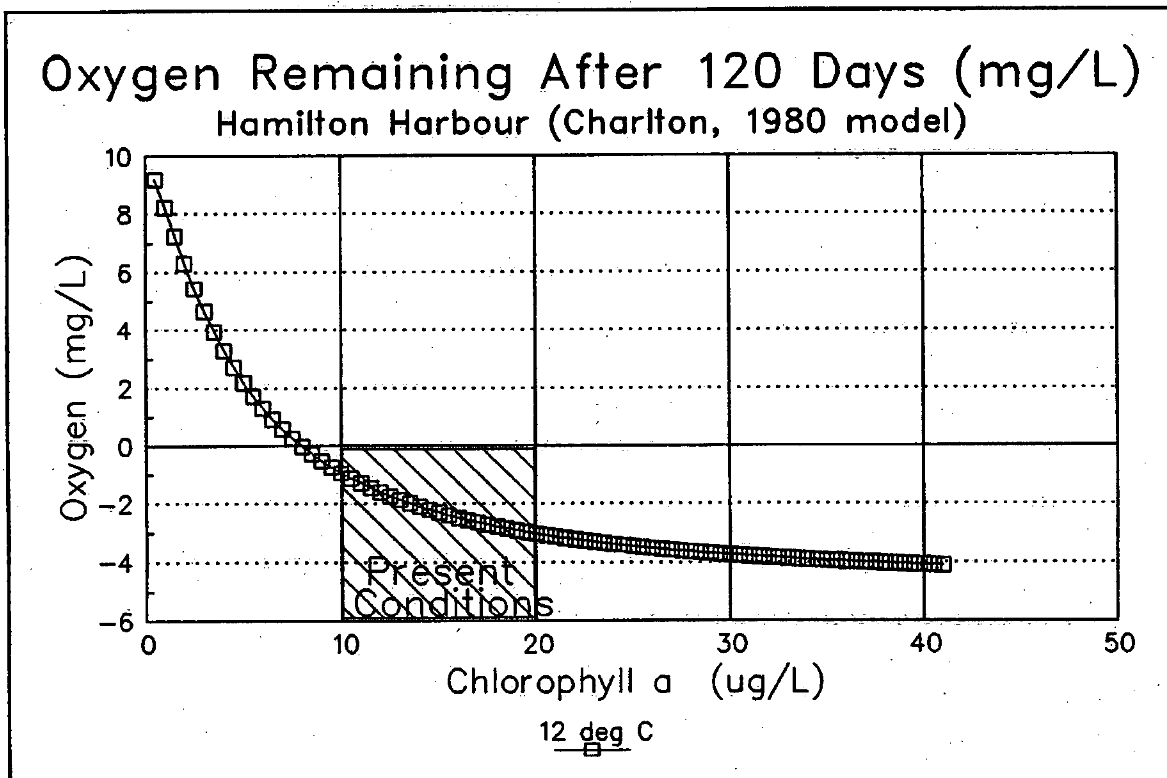

Figure 4 Relationship between oxygen depletion and hypolimnion thickness, temperature, and algae (chlorophyll) used to predict oxygen at the end of stratification as it depends on chlorophyll.

and the temperature have been held constant so all the differences are caused by algae. This has been done because the algae represent the effect of STPs which are candidates for improved controls. Despite the unusual conditions such as direct discharge of STPs, water exchange with Lake Ontario, and, sewer overflows, Fig.4 depicts the oxygen regime in the Harbour hypolimnion well.

Oxygen is depleted fast enough to reach zero well before the end of the summer. and concentrations would remain at zero if the summer inflows from Lake Ontario did not occur. The situation is likely to respond strongly to decreases in algae so that at half the present algal level a good oxygen concentration of about 4 milligrams per litre may be expected.

Until now the sewage loads have been so great that hardly any improvement in oxygen has occurred. This was predicted from the flat right hand side of the curve in Fig.4. Since sewage loads are a main factor in algae levels, controlling the sewage further should improve the oxygen as suggested by Fig.4.

4 Is Oxygen a Problem in Hamilton Harbour?

The oxygen depletion phenomenon occurs each year in Hamilton Harbour during the months of June, July, August, and September. About half of the Harbour volume is affected. The oxygen concentration decreases from about 10 mg/L to about 2 mg/L by mid summer. By then, the organisms either migrate out or slow down their metabolism due to lack of oxygen. Also, water coming into the Harbour from Lake Ontario through the ship canal is cooler and better oxygenated. This water tends to be trapped in the hypolimnion and actually helps maintain oxygen supplies. For much of the summer, the oxygen concentration on the bottom varies from 0 to 2 mg/L. Occasionally, statements are made to the effect that "Hamilton Harbour is anoxic" (without oxygen). This type of statement ignores the fact that there is plenty of oxygen in most of the Harbour most of the time and anoxia is rare.

By mid-summer the hypolimnion oxygen concentration is too low for fish. Fish need about 4 mg/L or more. The cold water fish in lakes with little hypolimnetic oxygen are able to find tolerable conditions in the thermocline which in the

Harbour is several metres thick. The cold-water fish of the Harbour have access to excellent habitat in Lake Ontario. The absence of fish kills during the low oxygen period means that either the cold species are in the thermocline or that they have already migrated out. There are about 60 kinds of fish in the Harbour and about 50 of these appear to be spawning there. Cold water Whitefish and Salmon types cannot utilize the hypolimnion for 2 months each year in its present condition. Balancing this is the abundance of cold water habitat nearby in Lake Ontario. The organisms in the hypolimnion are mostly limited to low oxygen tolerant worms in the sediment and the oxygen consuming algae and bacteria in the water. Again, this situation is found in a great many lakes and is not necessarily a symptom of excessive pollution. In Hamilton Harbour the sewage pollution causes aesthetic surface water problems and these cause lower hypolimnetic oxygen concentrations than would otherwise occur.

In some lakes, hypolimnion anoxia causes the nutrient phosphorus to dissolve out of the sediment where it is normally buried in the form of iron-phosphorus compounds. Very high concentrations of phosphorus can develop in the hypolimnion which then diffuse upward and re-pollute the epilimnion. Fortunately, the water coming through the ship canal prevents severe anoxia so this phosphorus release is not important in the Harbour.

Hypolimnion oxygen in Hamilton Harbour is a problem in that present conditions do not meet specifications in the GLWQA. There are no data showing, however, that these specifications were ever met. Even computer models such as Fig.3 show only general tendencies; the combined looseness of their underlying relationships preclude guarantees of any one oxygen concentration. The GLWQA objective of hypolimnion oxygen suitable for fish may be quite impractical for Hamilton Harbour. Certainly, the intent was to achieve good oxygen levels by natural processes aided by nutrient controls; artificial means were not considered.

Slavish adherence to the GLWQA specification may make it impossible to delist Hamilton Harbour as an area of concern. A valid judgement would be that the disruption in fish ecology caused by present oxygen conditions is a problem that warrants artificial and specific maintenance aeration. The author's judgement is that oxygen will probably respond, possibly to specifications, in response to aggressive sewage treatment and that residual oxygen depletion would be a tolerable condition not a problem.

Hypolimnion oxygen is a complicated phenomenon but it is strongly related to surface water quality. Achievement of acceptable surface water quality in Hamilton Harbour would be an outstanding and overriding accomplishment whether or not hypolimnion oxygen responded enough to meet the possibly unrealistic specifications.

5 Nutrient and Contaminant Interactions

One of the facets of the "Ecosystem Concept" way of environmental management is that the various issues should be coordinated so that one aspect is not damaged while another is being repaired. In the past, the eutrophication issue and the contaminants issue were seen as two unrelated problems. Now, several links are apparent. For example, the trophic status of water controls the number of organisms likely to be contaminated. Harbour sediments contain metals and organic chemicals which are dangerous to water organisms at high enough doses. The eutrophication of the Harbour helps control the exposure of organisms to the chemicals by affecting, for example, the distribution of the fish.

There is a potential disadvantage of higher oxygen levels in the summer hypolimnion. The idea is that fish would be able to eat food chain organisms in the sediments and would thereby accumulate more persistent organic toxic chemicals. Uptake of sediment contaminants by insects and fish does occur in laboratory experiments (Krantzberg and Boyd, 1992) but the real question is whether the biota would be significantly worse. The extent of extra uptake may be minimal because the fish already have access to the full bottom area for 9 months every year and the affected area is only half the total bottom area. Moreover, the particles floating in the water which now form the basis of the food chain are about as contaminated as the surface sediments. The most likely fish inhabitants of a high oxygen hypolimnion would be cold water types which, coming from Lake Ontario, are already contaminated. We know these fish appear in the Harbour but are able to leave in order to escape the critical low oxygen period. Therefore, we do not know whether attaining merely adequate oxygen conditions would be sufficient to entice the fish to stay in the Harbour. Clearly, this concern cannot be rejected out of hand but the importance, if it occurs, is completely unknown. The author perceives no basis to predict a large change in the contaminant status of the general fish population due to better oxygen conditions in the hypolimnion. Neither does the author perceive any reason to delay any improvement in surface water quality, through better wastewater treatment, that may indirectly cause improved hypolimnion oxygen.

It is difficult to demonstrate that elevated levels of metals and organic contaminants in most Hamilton Harbour sediments are toxic because most organisms are excluded due to the periodic low oxygen conditions in the overlying water. The periodic low oxygen concentrations help the sediment build up naturally occurring sulphide and ammonia which may cause positive toxicity tests with organisms under artificial laboratory conditions (T.P. Murphy, NWRI, personal communication). In published results, tests on sediment representing a wide area of the harbour indicate the sediment is not very toxic under oxygenated conditions. For example, 81% of the test insects survived but when the test was repeated with a different sample from the same place all survived; control sediment from Honey Harbour killed 7% of the animals. Most sediments were not toxic to minnows in these 21 day tests (Krantzberg and Boyd, 1992). The majority of the animals living in hypolimnion sediment are worms which tolerate low oxygen and are not preyed upon during the growing season. During non-stratified periods, animals requiring oxygen are sometimes found in or on the sediment which in summer only supports worms. Thus, there is some evidence that the sediment is habitable by a more diverse community of benthic animals. Indeed, there is a much more diverse benthic community in most of the epilimnion sediment areas. Although there are introduced toxic materials in the sediment, it is not be clear whether they are having toxic effects unless oxygen conditions allow animals to live in or on the hypolimnion sediment year round. Since oxygen conditions are likely to respond to eutrophication controls the author perceives no reason at this time to address the condition of the benthic community by artificial aeration.

6 Hypolimnetic Aeration

Artificial aeration has been used many times to increase the oxygen content of the hypolimnion in eutrophic lakes. On the other hand, there is evidence that surface water quality problems of eutrophic lakes such as excessive algae are not eliminated by aeration (Cooke et al. 1986; McQueen et al. 1986). The best aeration technique contains the aerating bubbles in a vertical column which extends to the surface. The apparatus is constructed to return the water uprising with the bubbles to the hypolimnion while the bubbles escape at the surface. In this way the stratification of a lake can be maintained while aerating. Another method is bubbling with oxygen gas (Murphy 1990). Technically, if enough funds are available almost any body of water can be aerated. For example, aeration is a cornerstone of sewage treatment. The main questions are whether aeration is necessary in the Harbour, whether risk of loss due to ship movements is tolerable, whether other means of attacking the source of the problems are more desirable, and whether the effects to be obtained are worthy of the expenditures.

In Europe, many pollution problems are more intense than ours. Contrary to Canadian experience, many Polish lakes become worse the more their tributary streams flow. Instead of flushing out nutrients the streams are so contaminated they bring in more! The lakes begin to function as giant cesspools. In desperation, aeration can be used to supply the oxygen needed to allow the bacteria to break down the waste. In Canada, we prefer to conduct this aeration in our sewage plants.

Claims of success for aeration seem to revolve around both the installation/operation of the devices and improved water quality. The first category is irrelevant because the purpose of expenditures is to achieve an objective not to develop equipment. The author's impression is that, beyond increased oxygen, claims of water quality improvements should be closely examined. For example, a reduction in hypolimnion phosphorus regeneration is claimed. This reduction does occur but in many cases the reduction is from very, very high concentrations to very high concentrations. This effect is quickly reversible because the iron-phosphorus compounds formed and precipitated in the presence of oxygen will dissolve again should low oxygen conditions redevelop. This sort of reversible effect tends to be called a success even though objectives for surface water are not attained. This dubious benefit is irrelevant because anoxic hypolimnion phosphorus regeneration is not a problem in Hamilton Harbour.

Similarly, the author is unconvinced that any worthwhile change in surface water quality would result from aeration of the hypolimnion in Hamilton Harbour. The sewage is introduced in the surface water and appears to mix well there as algae are stimulated. Use of apparatus to induce general circulation from top to bottom in naturally unstratified periods would seem inappropriate because there is usually plenty of oxygen there naturally. Often in the summer the bacteria concentrations in the Harbour are close to or below levels required for swimming. Elevated bacteria occur after rain episodes. It is difficult to accept that more aeration in the open waters would increase public safety or public confidence. Furthermore, in order to determine the effects of various stages of ongoing STP improvements, it is important not to confuse the assessments with add-on techniques such as lake aeration.

Oxidation of sediments is claimed as a benefit of hypolimnion aeration. Sediment is reduced (a chemical term meaning that elements have been stripped of any oxygen) naturally in typical lake deposits. The main reason is that decomposition of organic material such as leaves or algal detritus consumes all the oxygen and the diffusion rate from water to sediment is too slow to replace the oxygen. Anaerobic processes prevail in most lake sediment. Even in Lake Superior, the least polluted of the Great Lakes, oxygen penetrates only about two centimetres into the sediment (Carlton et al. 1989). Since there is oxygen near the sediment in the Harbour most of the time it is difficult to understand how providing a little more oxygen to the sediment would be constructive. The author has observed a small shallow lake with no hypolimnion before and after a wind storm. Before the storm there was a high oxygen concentration in the whole water column. After the storm the oxygen concentration was much lower due to stirring of the reduced sediments. Thus, fully oxygenated water does not prevent the formation of reduced sediment even though a thin surface layer may be oxidized. Again, it seems that most lakes have anoxic or reduced sediments. In Hamilton Harbour, it is important not to attempt to oxidize sediment by aeration as this would require stirring which would cause concern about contaminants which are now buried. Oxygen in the water is the issue - not oxygen in sediment which will be mostly reduced regardless of the level of dissolved oxygen in the water above the sediment. Oxidizing sediments does not seem to be a worthwhile goal to the author.

Navigation difficulties in a shipping harbour are only clear after an accident occurs. Our experience is with scientific apparatus properly marked and reported in "Notices to Mariners". Occasionally, an installation is destroyed by a ship in Hamilton Harbour. As a general rule, our apparatus is susceptible to loss at any depth less than 10 metres. Hypolimnion aeration equipment must extend to the surface so there is some risk of loss which will increase with the number of units installed. In addition, aeration equipment needs air compressors on shore with connecting air lines or anchored barges to contain the compressors. These present additional risk due to collisions or fouling by ship and boat anchors.

In general, artificial aeration seems to be a treatment in search of a problem. The presence of the treatment tends to make the observations of low oxygen an issue when in fact the priority is low. Undeniably, aeration is worthwhile in cesspools, sewage plants, and lakes grossly polluted with raw sewage which are very much different than Hamilton Harbour. Effects of aeration are likely reversible and therefore aeration offers no solution to any problem.

7 The Linwold Proposal

This section refers to the "Proposal For The Recultivation Of The Waters Of Hamilton Harbour Of Lake Ontario, Canada" presented to the Environmental Services Committee, Regional Municipality of Hamilton Wentworth, 9 September, 1992 by a company named Linwold Wastewater Systems, Islington, Ontario.

The equipment described is a concentric up and down tube hypolimnetic aerator. This apparatus should be fully capable of aerating any lake if enough of them are used.

The proposal does not contain a rationale for statements such as: "*The patented design of the Ekoflox system aerates and mixes the bottom sediments without stirring up the bottom sediments.*" or "*Recultivation and bringing the water back to its normal biological process will eliminate phosphorus by 90%, prevent bacterial contamination and allow restoration of the normal wildlife and swimming with no risk.*" Without explanation, these statements seem contrary to expectations based on theory and practice.

Sizing of aeration apparatus is an inexact art. For example, after making detailed calculations of the amount of oxygen required, the advice in Cooke et al. (1986) is to simply double the estimate to account for unmeasured factors! Unfortunately, a rationale for sizing was not included in the proposal. The following rationale and calculations may provide a perspective on the scale of apparatus needed.

Following stratification the oxygen concentration in the hypolimnetic water declines at a rate of about 0.15 mg/L/day. This rate incorporates all the natural effects such as sediment oxygen consumption before concentrations become low enough to limit the rate of uptake. This approach is simple, it does not require detailed information on all the sources and sinks of oxygen. Over the 120 day stratified period we wish the processes to deplete the oxygen no more than to 4 mg/L from an initial concentration of 10 mg/L. Thus, the required depletion rate is about 6/120 = 0.05 mg/L/day and an aeration scheme would have to supply the difference of about 0.10 mg/L/day.

Amount of Oxygen Required:
$0.10 mg/L/d = 0.1 g/m^3/d \times \text{Volume } 1.4 \times 10^8 m^3 = 14 \times 10^6 g/d$

The molecular weight of Oxygen is 32 g and the volume occupied by 32 g is 22.4 L and air is 21% oxygen therefore $((14 \times 10^6 g/d)/32) \times 22.4 L/0.21 = 47 \times 10^6$ L air/day. The volume of air required is at least $47x10^3m^3$/day. Similar results were obtained using methods in Cooke et al. (1986).

According to the proposal, three compressors of $600m^3$/hour would be pumping 600x3x24 = $43x10^3m^3$ of air per day. Thus, the compressor scheme would almost supply the oxygen required if the safety factor of 2 is not used and if the transfer of oxygen to water is 100%.

According to the proposal each aeration unit would supply a minimum of 14 Kg oxygen per hour. Thus, one unit would supply 14 x 24 = 0.336 x 10^6g oxygen per day. Using these figures, 14/0.336 = 42 units would be required compared to the 9 units specified in the proposal.

The calculations above simply compare figures in the proposal with facts known about the Harbour. The comparison indicates the proposal is undersized. The comparison questions the number of compressors and more importantly the number of aeration units to be installed in the water.

8 Conclusions

Calculations herein indicate the Linwold Wastewater Systems proposal is undersized.

The degree of hypolimnion oxygen depletion is a natural tertiary effect of nutrient loads which are partly controllable. More important water quality problems occur in surface waters visible to the public. The surface water quality problems should be addressed by aggressive sewage treatment to the best standards and/or by sewage diversion. Oxygen depletion remaining after the best sewage treatment should be accepted.

Artificial aeration in Hamilton Harbour is unnecessary. Most of the benefits claimed, in general, for aeration are of doubtful validity and/or irrelevant to the situation in Hamilton Harbour. These include:

a) any useful reduction in surface water phosphorus concentrations
b) any useful reduction in surface water algal concentrations
c) any useful improvement in surface water clarity
d) any useful effect on effects of sediment contaminants
e) any useful reduction in hypolimnion phosphorus concentrations

Interactions of nutrient and contaminant issues do not provide reasons to delay improvements in wastewater treatment.

There is little or no reason to artificially improve hypolimnion oxygen in advance of improvements in surface water quality. Furthermore, in order to determine the effects of various stages of ongoing STP improvements, it is important not to confuse the assessments with add-on techniques such as aeration.

The author concludes that the Linwold proposal is inadvisable.

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