

SUMMARY

LIMNOLOGICAL PRINCIPLES AND POSSIBILITIES WITHIN LAKE RESTORATION

In this paper lake restoration, reasoned by irreversible damages caused by far-gone eutrophication, is introduced as a basically ecological problem. The possible measures available for fighting the eutrophication are divided into two main categories:

1. Preventive measures in the watershed area
2. Corrective measures in the lake

The word "lake restoration" only includes the corrective measures in a lake. Preventive measures in the watershed area or, in other words, lake protection are therefore not discussed in this paper.

Although the restoration of a lake is carried out by technical means, the lake restoration problem is essentially ecological. Therefore it is necessary to begin by outlining the general pattern of thought presumed when approaching this question.

According to conventional usage the lakes are classified into eutrophic ones and oligotrophic ones. These terms, originally introduced for the classification of marshes, were applied to limnological practice by Naumann. He based his typological classification on the nutrient content of lake water, and this has been the basis of many pioneering limnologists, of whom here Thienemann, Naumann and Järnefelt before others may be mentioned. Naumann's original classification based upon the observation that there is abundant plankton growth in eutrophic waters and scanty growth in oligotrophic waters.

After the developing of the C14 method for direct measurement of primary production by Steeman Nielsen and the application of this method for limnological purposes by Rodhe one had already come closer to what we really mean by a stage of trophic.

When besides Rigler has shown the remarkable rapidity of phosphorus turnover in eutrophic waters it had become obvious that, instead of the abundance of plankton, parameters describing the intensity of production should be used when determining the trophic stage of a lake.

It must be pointed out that according to what is said above, the trophic stage of a lake has been determined on the basis of water characteristics. If we take the term, say, eutrophication, it thus means increasing primary productivity of the water. In a narrow limnological interpretation this, of course, is correct. However, if we take the perspective of lake restoration, the problems must be scrutinized on a broader basis.

The dependence of a lake's nature on the quality of the surrounding watershed area has been understood in an early stage of limnology. As early as 1929 Järnefelt emphasized the difference between the influences of a primary and a secondary watershed area. This quite obvious fact has been neglected in many calculations as regards the nutrient load of a lake.

An inevitable conclusion is that a lake, as an object of restoration, does not consist a separate ecosystem. The lake and its watershed area form an ecosystem complex, in which the lake itself is the lowest part gathering influences from all parts of the watershed area. This ecosystem complex again influences upon lower similar systems only through the effluent of the lake. (Here we may pay no attention to such factors as creatures moving over from one watershed area to another and the transfer of substances conveyed by the wind.)

The nutrients, at least the phosphorus, can leave the lake only through its effluent. The difference between nutrient income and nutrient outflow settles to the bottom and deposits on the bottom sediments. However, it has not left the lake. The bottom sediment thus forms a potential nutrient source for primary producers and so an eutrophication hazard as well. This means that there is no such thing as the self-purification of a lake, although this term may be used with great discretion as regards the water phase. (Here again we must generalize a little, "forgetting", for instance, the denitrification). The importance of bottom sediments is one of the central problems of limnology and, as far as there is a question of lake restoration, the key point.

Referring to what has been stated in the foregoing it is quite clear that before commencing a lake restoration project, all possible preventive measures in the watershed area must be carried out. Although the preventive measures in the watershed area are not the subject of this paper, they may be listed as follows:

1. Control and restriction of the amount of wastes transported to or created in the watershed area. This includes also the enrichment of soil with nutrients and the problem of waste reuse.
2. Purification of sewage and waste water.
3. Allocation of the sewer outlets aiming at minimal consequences in the recipient lake.
4. Organizing the waste disposal problem of scattered dwellings, holiday cottages, camping places, tourist centers etc.
5. Attempts to limit the agricultural sources of eutrophication. These include among other things animal wastes, silage juice and artificial fertilizers.
6. Control of the influence of forest management and forest fertilizing.
7. Limiting the use of pesticides in the watershed area. 8. Allocation of dumping places.
8. Allocation of dumping places.
9. Removal of possible snow dumping places out of lakes, where they usually are situated.
10. Limiting the density of holiday cottaging.
11. Limiting the motor boat traffic on small lakes.
12. Paying attention to possible consequences of highway traffic.
13. Protecting the lake by means of shore regulations.

Lake restoration includes all such measures that aim at the improving of a lake's condition by directing the measures to the lake itself. The significance of such measures to the improving of a lake's condition varies greatly depending on methods.

The lake restoration methods are as follows:

1. Altering of water level or surface area of a lake
 - raising of water level
 - lowering of water level

- isolation of parts of a lake by means of dams or embankments
2. Changing of water balance or flowing directions in a lake
 - dilution of lake water and reduction of the retention time by leading additional pure water from other watershed areas
 - diverting of flood water
 - directing the flows in a lake
 - water level regulation for the augmentation of minimum effluences
 3. Aeration or oxygenation of lake waters
 - artificial destratification
 - hypolimnion aeration
 - other aeration methods
 4. Depletion of certain water layers from a lake
 - hypolimnion depletion
 - epilimnion depletion
 5. Removal of the biomass
 - removal of higher aquatic plants
 - phytoplankton harvesting
 - fishery as means of removing biomass - additional possibilities
 6. Precipitation of phosphorus in a lake
 7. Management of sediments
 - sediment removing
 - sediment isolation
 - sediment compressing
 - sediment aeration
 8. Other possibilities

In the following we study the most important means of restoration on the basis of publications. The Finnish text includes scrupulous references to the original sources, listed in the bibliography. Special attention is paid to the various methods' possibilities of application in the conditions in Finland.

Raising of the water level

Consequences of the raising of water level can be compared with those occurring in a newly filled artificial reservoir, although in a minor scale. If the level of a lake has been lowered, the new shoreline has usually had time enough to settle and to develop an ecological balance. The immediate disadvantages of the lowering have ceased and the lake has reached a natural balance. Furthermore, the shoreland has often been used for agricultural purposes. Thus a reraising of the water level may result in increased washingout of nutrients which again causes an increase of plankton biomass with all the resulting drawbacks.

As a result of the raising of the water level the quality of the lake water does not change in principle, but the increasing of the water volume also prolongs the average retention time. This again means an improvement of the net sedimentation and an enrichment of the sediments with organic substances and nutrients. Thus the raising of the water level may theoretically increase the eutrophication potentiality of a lake.

The total effect of the raising of water level essentially depends on the condition and steepness of the banks. A special problem - and certainly not the easiest one - is made up by holiday cottages built next to water, which as a result of the raising may suffer considerable damage and which seldom can be removed. Although it is not possible on the basis of what has been said above to properly affect the quality of water in a lake by raising the water level, the general condition of the lake can in certain cases be decisively improved by the raising. This concerns above all those lakes which have been lowered previously and are for that reason becoming over grassed as well as those lakes the usability of which has decreased owing to lowering. The raising of water level can be considered profitable and recommendable in the following cases:

1. The lake is becoming over grassed owing to shallowness.
2. Improving of landscape. E.g. the shore zone of a lowered lake spoils the landscape.
3. Increasing of the shore zone's recreational value.
4. Increasing of the lake's economic value for fishery.
5. Increasing of the amount of oxygen in low-volume hypolimnion where the increase in volume indicates improvement in the critical oxygen conditions.

The most probable instance of the use of the raising of water level as a measure contributing to the restoration of a lake obviously consists of the prevention of the lake becoming over grassed. Becoming over grassed is caused, except for shallowness as such, also by the fact that light may intensely enough penetrate the water mass down to the bottom. There are remarkable differences in the maximum depths where different species of aquatic plants are found. This leads us to a conclusion, according to which how much the water level has to be raised is determined on the basis of the water's transparency and species of aquatic plants. It does seem, however, that some of the most difficult species, particularly *Elodea canadensis* and *Potamogeton perfoliatus*, need quite a considerable depth to die out. In polyhumic lakes, where the Secchi disk transparency is less than 125 cm, the maximum depths where aquatic plants are found may owing to limited illumination obviously be smaller than average, in which case the minimum depth needed in combating them decreases correspondingly. We may point out, however, that the desirable depth of water is around 3 m in areas occupied by aquatic plants.

The maximum of the raising of water level is as a rule determined by the use of the shore and the limitations set by it. Excessive increasing of the depth is, however, harmful in the limnological sense, too.

Need for the raising of water level is brought about by shallowness, and for this reason thermal stratification is not likely to occur in the lake subject to raising, not at least when the lake is not covered by ice. By increasing the depth excessively the forming of hypolimnion becomes possible and this has to be regarded as a factor jeopardizing the general condition of the lake. The depth needed before stratification becomes relevant depends on a number of factors. Of these we may mention at least the shape of the basin, the position, the steepness of the banks, the type of the surrounding vegetation and in general all the factors contributing to the possibilities of wind to mix water masses. In some stratified small lakes the epilimnion is only 4 m thick. The thermocline stratum being higher than this can be considered rare. We may say that the stratification risk, which is inversely proportional to the lakes area, can be considered actual as the maximum depth exceeds 4 m.

The stratification of a hollow having a small area is not very dangerous as such, if in return for example boating or bathing becomes possible. No general rule can be given, but the result must be weighed separately in each case.

On the basis of what has been said above we may establish that, when endeavoring by the raising of the water level to prevent a lake from becoming over grassed, a minimum depth of approx. 3 m has to be reached on the bottom area occupied by aquatic plants. On the other hand the water level must not be raised so high as to during an ice-free period cause thermal stratification, which involves a maximum depth of at least 4 m, in a lake not stratified before.

How the shore to be covered by water as a result of the raising should be treated prior to raising is a question not to be forgotten. If the shore area to be covered mainly consists of cliff or soil consisting of mineral matter, it is not of any great significance to the quality of water. The significance increases as the soils organic matter content becomes higher and may lead to the forming of remarkable damage showing up as the color of the water, plankton turbidity and consumption of oxygen. Land areas bound by the roots of plants may even rise to the surface after raising, for the prevention of which such a cover may be punched and torn before raising.

From the shore zone to be left under water trees, stumps, barks, litter and soil containing humus must, unless the zone is considered insignificant, be removed in the extent it is possible within the costs. The effect of the organic soil may well be decreased also by covering it by a layer at least 30 cm thick of humusless soil containing mineral matter. Among other substances manganese, which is to be regarded as one of the most harmful from the point of view of water being used in households, dissolves in water of the litters and other remnants of plants left under water. If the lake serves as a crude water basin, it is of special importance to clean the shores properly before raising. Aquatic plants must be removed mechanically before raising.

Improving of landscape and increasing of the shore zones recreational value are proper reasons for the raising of water level when the set goal is truly reached. The trimming of the shore zone to be left under water must in these cases be considered extremely important.

It is also possible to increase the economic value for fishing by raising the water level. The main advantage then obviously consists of the increased oxygen content in the greater volumes of water, particularly with consideration to winter conditions. As a question of nutrients and living space among other things the elongation of the litoral zone, the formation of a potential profundal zone or a bottom area outside higher aquatic vegetation, changes in the aquatic vegetation and bottom creatures as well as the changes in the primary productivity form together with the basic type of the lake a complicated complex of problems, in which all factors are not necessarily advantageous from the piscatorial point of view. Closer studying of the matter goes beyond the scope of this elucidation. Cleaning of shores by for instance removing the trees and stumps is inevitable in this case, too, because remnants of this kind may impede fishing and break tackles.

Leading of additional water for the shortening of the retention and flushing of the lake

There are at least three mechanisms contributing to the improvement of the condition of a lake accomplished by the leading of additional water:

1. Direct decrease in the content of basic nutrients.
2. Decreasing of the content of some trace element or elements to a content in which it/they become a minimum factor.
3. The flushing speed of phytoplankton through effluence in relation to the reproduction of phytoplankton gets a value higher than before, which contributes to the decreasing of the lakes phytoplankton amount.

In the application of the system at least the following viewpoints must be considered:

1. The required amount of additional water is in principle high. This automatically confines the system to small or medium-sized lakes, the volume being more decisive than the area. The need for additional water is eventually determined by the volume of hypolimnion.
2. The nutrient content of the additional water must be lower than that of the water in the lake.
3. Additional water must be continuously available, if the basin to be restored is eutrophic by nature. One may conclude that a lake which is oligotrophic by its basic nature and eutrophicated by waste waters can be restored by temporary leading of additional water applied for a certain period of time, supposing the sources of waste water can be eliminated.
4. In the comparison of the quality of the water in the lake and that of the additional water the prediction of the result of the dilution must be based upon biotests carried out by using water from the lake, the additional water and the different mixtures of these waters.

With conditions in Finland in mind we may examine the matter as follows:

1. The method deducts nutrients from the lake and thus decreases its potential eutrophicity. This makes the method recommendable.
2. Finland's lakes are mostly small, particularly by their volume. This limits the amount of necessary additional water.
3. The high number of water systems in Finland make the supply of additional water possible. On the basis of the foregoing it pays to clear up the possibility of flushing a lake by means of additional water, as one begins to plan the restoration of a lake. This is particularly needful, if sediments are removed from the lake, whereat part of the nutrients in the sediments easily get in water.

Diversion of flood water

In a number of studies it has been noticed that the amounts of nutrient conveyed by flowing water are greatly dependant on the amounts of water. The flows of substances (flow multiplied by content) are at their most during large flows. This is partly due to the increasing of flushing of the ground and the increasing of erosion, but partly also to the fact that during large flows water flushes off from the bed matters that have been sedimentized on the bottom during small flows. This raises easily a question of to what extent the nutrients conveyed by flood load lakes and what is gained with regard to the condition of the lake, if the floods are diverted away from the lake.

When considering the possibility of improving the condition of a lake by diverting floods away from the lake, the viewpoints of greatest importance may be crystallized as follows:

1. The nutrient concentrations of a circulating lake and of flood water discharging into it must be compared with each other, taking into consideration what is known about the biological activity of erosion phosphorus. The best method of comparison is probably the algal test. The effect of a flood is to such an extent dependant on hydrographic and chemical differences between it and lake water, determined by regional factors, that there is no general regularity in the effect of the "new water" brought in by flood upon the productivity of the "old water" in the lake.
2. The bulk of the flood evidently passes through the lake without, owing to a "hydraulic short circuit", considerably affecting the quality of the water in it. The effect is in any case smaller than what is shown by the dilution values obtained on the basis of water quantities.
3. If flood water is diverted away from a lake, the lake basins flood balancing effect will be omitted. This may result in serious hazards caused by floods lower down the water system.

4. The quality of the flood is in the first place dependant on the soil factors and the use of the soil in the remote areas. If a lake situated in oligotrophic close surroundings receives its additional water from cultivated areas, or if the water in the river is laden with wastes, the diverting of the flood water away from the lake may be advantageous. Otherwise the method seems quite questionable.

Aeration or oxygenation of water mass

General

The basic problem of eutrophication with regard to the condition of a lake consist of the consumption of oxygen caused by biomass produced in the water. This is particularly distinct when the water mass is in a state not in connection with the atmosphere. In summer the existence of such a mass presupposes thermal stratification, when oxygen is consumed in hypolimnion. In winter the consumption of oxygen may be prevalent in the entire water mass. The shortage of oxygen in hypolimnion in summer may at least in cases where restoration is required be regarded as a consequence of the dissolving of the autoctonic organic matter, the biomass, whereas the shortage of oxygen in winter is often caused by the dissolving of an alloctonic organic matter in the lake. During the past decade various attempts have been made to improve the condition of fully or partially deoxygenated lakes by aerating or oxygenating them.

There are many decisive differences of principle in the methods, determined by the intermediary goal by means of which one tries to reach the ultimate goal, i.e. aerobic state of water mass. The methods may thus be classified as follows:

- A. Destratification either by pumping air in hypolimnion, hypolimnion water to the surface or epilimnion in hypolimnion.
- B. Hypolimnion aeration without destratification.
- C. Other methods of aeration and oxygenation, such as dissolution of oxygen from air or oxygen pumped in water, pumping of water on ice for aeration and prevention of freezing as well as aeration by generating surface current.

Prevention of stratification or destratification

a) Pumping of compressed air in hypolimnion

Scrutiny of the method:

The effectiveness of aeration as a destratificator can be described by comparing the change in the stability of water mass with the amount of energy used. The destratification efficiency, DE, indicating this is obtained by calculating the reduction of stability, given in kilowatt hours, in percentages of the total amount of energy used.

Another possibility to describe the effectiveness of aeration is the oxygenation capacity, OC, which is obtained by dividing the increase in a lakes oxygen amount during a certain period of time by the total amount of energy used.

The observations of precedents may be crystallized as follows:

1. Hypolimnion may definitely be put in an aerobic state by pumping air in it.
2. Aeration is based on destratification and artificial maintaining of circulation. Dissolution of oxygen from pumped air is of little importance compared with this.

3. Aeration is the more efficient, the smaller the bubbles are and the lower the overpressure needed to circulate the water mass. On page 32 we see the "influence of hole diameter and overpressure on ability of air to move water, according to Knoppert & al. 1970"
4. The "bubble screen" obtained through holed pipe is more efficient as a circulator of water than aeration concentrated on one point.
5. Destratification involves the entire basin, though aeration takes place in just one spot. This does not, of course, concern isolated hollows.
6. Destratification has led to essential elimination of the harmful effects of manganese.
7. Cooling of the surface stratum caused by destratification lessens evaporation from the lake. This fact is hardly of any major importance in Finland's climate, although it may be meaningful in countries where the climate is dry and warm. From the recreational point of view the cooling of epilimnion is a harmful phenomenon. In crude water basins on the other hand, the warming up of hypolimnion is harmful from the point of view of using the water as drinking water.
8. The amount of plankton biomass has not in general increased owing to destratification. This danger is, however, apparent at least during an ice free period in connection with realized destratification.
9. The increased living space for fish and the increased area inhabited by lake bottom creatures as a consequence of the oxygenated state of the water mass is a phenomenon advantageous to fish. It is no wonder that one has noted an increase in the rate of growing of fish after the commencement of destratification. A change in water's thermal condition may bring changes in the selection of species in the stock of fish.
10. The prevention of harmful smells in crude water basins by destratification has always been successful.

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Figure 1 on page 37 shows the principle of a waste water aerator developed in Finland by Oy Nokia Ab. A destratification and aeration experiment is presently being carried out with it at Lake Tuusulanjärvi.

Table 2 on page 38 includes a comparison of efficiencies of different destratification experiments as collected from different publications (Bernhard 1967 table 4, Symons & al. 1967 c table 4 and Symons & al. 1970 table 2).

Table 3 on pages 39-40 presents the advantages and disadvantages of destratification and aeration of reservoirs according to Teerink & Martin 1969.

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b) Pumping of hypolimnion and mixing it with epilimnion

The pumping of hypolimnion and mixing it with epilimnion can in the light of examples be seen crystallized as follows:

1. Destratification can be realized by using a sufficient amount of energy. It seems, however, that it is advantageous to restrict the methods to lakes smaller than 10 ha as blowing of compressed air to hypolimnion is used. In Lake Pfäffikersee, having an area of over 300 ha, an unstable condition has been developed leading to an interruption of the experiment and finding that the object was not reached. On the other hand the circulation of the 43 ha Lake Vesuvius has succeeded by this method.

2. The need for energy is greater than in cases in which pumping of air has been applied and which have ended up in a corresponding result. This is particularly evident in the case of Boltz Lake, where both the systems have been tested.
3. Nutrients, concentrated in hypolimnion, have in many cases after coming in touch with epilimnion caused increased amounts of plankton. The result may, however, be contrary too, as is shown e.g. by the case of Stewart Hollow Lake.
4. As a result of the application of the method it has been possible to bring bottom areas previously within an oxygenless stratum of water back into living space for lake bottom creatures. From the stock of fish point of view the effect has been positive.

Picture 2 on page 44 shows a device, according to Irwing & al. 1966, used for upward pumping of hypolimnion in eastern Ohio, U.S.A.-Table 4 of the same source on page 45 shows the morfological features and pumping data of four lakes in eastern Ohio when the pumping device in picture no. 2 is used.

c) Aeration of hypolimnion

Aeration of hypolimnion without destratification is in principle a better method than aeration aiming at destratification or aeration by which destratification can be carried out.

Aeration experiments using several well-known methods have been carried out since summer 1971 in the Hasselfelde crude water basin at Rappbodevorsperre in Germany, aiming at decreasing of manganese and iron content, improving of phosphorus retention ability and increasing of living space for fish. A method not including destratification proved the most efficient method or deep lake aeration.

Hypolimnion aeration has among other things the following advantages:

1. Water temperature does not rise.
2. Nutrients in dissolved form in hypolimnion do not return to the productive stratum thus causing no algal production.
3. The amount of water to be aerated is small in relation to the basins total volume, because the epilimnion is not treated.
4. The need for aeration becomes even less, if reducing gases are dispelled from the water before aeration. This is particularly true when the Vyrecip method developed in Finland is used.
5. The bearability of ice does not diminish in the aeration of hypolimnion, which in Finland's winter conditions may be meaningful.

In connection with hypolimnion aeration feeding of a chemical precipitating phosphorus might be worthy of being experimented with in a suitable situation.

From what has been said above it is apparent that hypolimnion aeration has plenty of advantageous effects. On the other hand nowhere have abvious disadvantageous effects been noted. As regards costs this is not a cheap method, but considering the factors diminishing the need for total aeration, characteristic of the method, it is, with regard to the result obtained, hardly any more expensive than leading of compressed air to hypolimnion.

Picture 3 on page 50 shows a hypolimnion aerator by Bernhardt.

Picture 4 page 52 shows a "Limnox" hypolimnion aerator developed in Sweden. Data of this aerator's need of energy and capacity of oxygenation as given by the manufacturer Atlas Copco Ab are found at the bottom of-page 51.

Figure 5 on page 52 shows the principle of operation of the "Vyrecip" hypolimnion aerator developed in Finland by Suomen Porakaivo Oy. Data of the power and capacity of oxygenation of the aerator as given by the manufacturer are found in a table on page 53.

Picture 6 page 54 shows a Speece's U-tube hypolimnion aerator (Speece 1971).

Picture 7 page 55 shows an Electrolux hypolimnion aerator. Data of the aerator's capacity of oxygenation as given by the manufacturer are found at the middle of page 56.

Picture 8 page 57 shows a Speece's Downflow Bubble Contact Aerator, DBCA.

On page 59 there is a table in which the capacities of oxygenation of the different hypolimnion aeration methods are compared. Some data are based upon theoretical calculations and information from manufacturers, in addition to which the effect of aeration depth and water's oxygen content on the capacity of oxygenation have to be taken into consideration.

General review of aeration methods

1. Aeration of water mass does not in principle remove the cause of the phenomenon that has made aeration necessary, but the question is of a method by which one may more or less temporarily affect the condition of a lake.

Hypolimnion aeration outside a lake by a special aerator in accordance with the Vyrecip method also causes reduced gases to escape. To some extent this is probably true with other methods of hypolimnion aeration, too. 2. According to what has been said above, aeration of a lake can, as a means of restoration, in the first place be applied to the following instances:

- One wants to expedite a spoilt lakes rate of restoration in cases where the discharge of waste waters is finishing. With a view to the return of recreational use there are many years that can be won back, especially in lakes of slow water renewal.
- Artificial lakes during the first years as the nutrient washout from lake basin is decreasing.
- One wants, e.g. because of smell or manganese damage, to improve the quality of water in a crude water basin serving drinking and household water purposes. Even continuous use of the method may be considered in a case like this, because there is an apparent criterion of necessity associated with the continuity of the waters usability.
- One wants to prevent fish kill caused by lack of oxygen developed during an exceptionally severe or long winter.

3. In the choice of an aeration method attention must be paid to the size of the lake. The general rule seems to be that the smaller the basin in question is, the less meaningful the method used is with view to the reaching of the result. E.g. a recommendation or restriction of method as shown below seems feasible to compile:

Size of lake	Methods
Less than 10 ha	Destratification, hypolimnion aeration, in catastrophe cases different types of epilimnion aeration, pumping of water on ice, developing of surface current.

-"- 100 " Destratification, hypolimnion aeration.

More than 100 ha Hypolimnion aeration.

4. Mixing of hypolimnion with epilimnion may lead to increased nutrient content in epilimnion and, with it, an increase in the amount of plan',,ton. This can be avoided, if only hypolimnion is aerated.

5. It is advantageous to start aeration at the beginning of thermal stratification,when a better result is reached by regular intermittent aeration periods with smaller consumption of energy than by trying to destratify the developed stratification. Hereupon the damage referred to above, resulting from reduced water mass getting to circulation, is also avoided.

6. If aeration is applied for the remedying of winter conditions in particular, the importance of ice cover's bearability to fishery, traffic and outdoor life must be clarified.

Depletion of certain stratum of water

Hypolimnion depletion

The concentration of nutrients as a result of decomposition of organic matter settling from epilimnion to a stratified lake's hypolimnion and dissolution from silt forms one of the basic phenomena in a lake's nutrient circulation.. If the water mass above silt is as a result of increased loading of the lake oxygenless on large areas, the amount of nutrients in hypolimnion may while being mixed with epilimnion during a circulation period contain such an amount of additional loading as to significantly accelerate eutrophication. The often strongly reducing compounds in oxygenless hypolimnion may on the other hand when mixed with epilimnion cause a real catastrophe with regard to oxygen.

Depletion of hypolimnion is indeed one of the most obvious possible measures in cases of lake restoration. When examining the means of lake restoration, Thomas points out that depletion of hypolimnion is obviously the best way to improve the condition of a lake.

Epilimnion depletion

The shortage of oxygen developed in a lake's hypolimnion during summer stratification is mainly due to the consumption of oxygen occurring in connection with the decomposition of organic matter, above all phytoplankton, settling from epilimnion. For this reason the idea of depleting as much plankton as possible with epilimnion water before settling to hypolimnion seems almost realistic.As early as in the first written systematic review of lake restoration means Thomas presents in 1944 that, albeit the amount of dissolved nutrients depleted through effluence is small, as the most important nutrients are tied together with plankton becoming minimum factors, a remarkable amount of nutrients is depleted from effluence tied together with plankton biomass.

Hummel proposes that contrary to the earlier practice of leading the required minimum amount of water from valley dam basins serving as water reservoirs through a gate on the bottom this amount of water by special arrangements be taken from warm epilimnion rich in plankton.

Depletion of epilimnion is in all of our natural waters the solution realized by nature itself. When maintaining artificial lakes one may often, however, choose from what depth water is depleted. In cases of this kind it is advisable to work out, if the depletion of water from epilimnion at certain times, e.g. during the plankton maximum in spring, is more advantageous from the condition of the

lake point of view than depletion of deep water. Likewise this question merits attention, if one sets out to flush a lake by using additional water taken from elsewhere.

Scrutiny of the method

The improving of a lakes condition by depleting a desired stratum of water accelerating harmful development in the lake seems in the light of examples and theoretical examination to present viewpoints as follows:

1. The method contributes to the disappearing of factors which have caused the unfavorable development in the lake and is thus in principle highly recommendable.
2. Depletion of hypolimnion presupposes, unless one wants to use pumping energy, that the effluence or some other part of the lake has a difference of level great enough available for the functioning of a siphon. Distance from the hollow to the outlet of the siphon must similarly be short enough to keep the costs of conduction within boundaries of possible realization. In most cases one may without doubt conclude that there are no qualifications for the realization of the method.
3. The effect of the depletion of hypolimnion is dependant on the volume of hypolimnion and the water conducting capacity of the pipe employed, which on the other hand is affected by the available difference of level, diameter of the pipe and in some degree the length of the pipe, too.
4. The improving of a lakes condition caused by depletion of hypolimnion seems in principle to progress slowly, unless hypolimnion with a very low volume is in question.
5. Improving in a lakes condition caused by depletion of hypolimnion may only be expected after all sources of waste water discharged into the lake have been eliminated.
6. Periodical depletion of a lakes epilimnion instead of hypolimnion may in some cases be advantageous. Depletion of epilimnion during the algal maximum in spring before oxygenlessness, is developed in hypolimnion should then be considered in the first place.
7. If the hypolimnion to be depleted is oxygenless and has a large area owing to the shape of the basin, it may be useful to deplete it step by step in such a way that very large areas in the bottom will not be within the reach of circulating water simultaneously. This is how large doses of nutrients are avoided from suddenly getting within the reach of primary producers from silt still in an anaerobic state.

Removal of biomass

The binding of nutrients causing eutrophication in a lake system with the biomass in the various stages of the production chain presents a way of eliminating part of these nutrients by certain kind of harvesting. As for basic productivity it is the removal of aquatic plants and algae and as for the late stages of the production chain it is in the first place the removal of fish that come into question. Let us emphasize that it is not the destruction of these groups of living organism that is in question but specifically the mechanical removal of excessive production mass from a lake.

Removal and control of aquatic plants

The removal of aquatic plants as a means of lake restoration is based upon the nutrients combined to them being liberated back to water as the plants wither away in the fall. For instance aquatic

plants with roots, above all helophytes, relinquish their nutrients with increased yield, because they are capable of taking nutrients even from silt. A research on a small river in Central Sweden showed that the aquatic vegetation of a river is meaningless as a retainer of nutrients, unless it is removed as the period of growth comes to an end. The dissolution of dead aquatic plants is a phenomenon about twice as slow as the mineralization of sewage water.

In pond experiments carried out with the water hyacinth (*Eichornia crassipes*) researchers have found out that the productivity decreased in the ponds where the harvest was not returned as compared with the ponds where the removed plants were thrown back into the water.

The removal of aquatic plants may in principle only be carried out mechanically. The biological and chemical methods are means of controlling, realizable without the removal of biomass from a lake system. From the lake restoration point of view removal - as pointed out here several times in various connections - shall be regarded as the primary object.

The methods of removal and controlling of aquatic plants are divided into physical, biological, chemical and mechanical ones. The following may briefly be said about them:

Physical methods of control

These include the temporary lowering of the water level so that plants and their roots dry and die and the limiting of light by means of a black plastic cover or by dyeing the water black. Sawyer has called the limiting of light - as well as the limiting of the availability of nutrients - ecological control. Fruh mentions about the application of carbon black to exclude light in small wind-shielded crude water basins.

Biological methods of control

The main principle of this method consists of fighting biology with biology. By this method the control of aquatic plants is carried out through diseases, competition between species, herbivorous fish, snails, insects and mammals.

Chemical methods of control

By chemical methods we mean the poisoning of aquatic plants. It is highly questionable, whether the application of poison to a lake can be regarded as a means of restoration at all, quite irrespectively of what the purpose of the poisoning is. For this reason the chemical methods of controlling aquatic plants may in this connection be passed with just a brief mention.

Mechanical removal

Removing aquatic plants by mechanical means is absolutely the most recommendable way of lessening biomass formed by aquatic vegetation. A variety of different machines and devices have been developed for the purpose, enabling the realization of not only small but also very extensive measures.

Only a temporary improvement is reached by the removal of aquatic plants, unless other methods of restoration, such as raising of the water level, are realized in the same connection. Cut aquatic plants are apt to grow faster, for which reason the keeping of aquatic plants in order by cutting apparently requires several repeated cuttings. Regrowth may be decelerated by tearing plants' roots into pieces.

The utilization of vegetation removed from water is one of the problems connected with the method. Research has been carried out among other things of using water plants as fodder, compost or raw material for industry. If plants are destroyed by burning, this may not be done on the shore, from where the ashes may be washed back into a lake. Upon the whole it is obvious that plants removed from water have to be conveyed to a place where nutrients liberated as plants dissolve cannot get back into a lake.

The removing of aquatic plants often involves the remaining of nutrients, which otherwise would have been bound with aquatic plants, for being used by plankton algae. Occurrence of algae in masses is often the result particularly when aquatic plant mass is not removed after it having been controlled.

Precipitation of phosphorus in a lake

One of the methods still at an experimental stage involves the thorough lowering of a lakes nutrient level by precipitating the phosphorus directly in the lake. Aluminum sulfate has been tested for the purpose. In the instance most carefully studied so far, viz. Lake Lingsjön in Sweden, amounts of aluminum sulfate have twice, both times corresponding to a content of 50 g/m³, been added to the lake.

Precipitation of phosphorus in a lake is still a new method and comparatively few experiments have been carried out with it. The oldest test results date two years back, and they do not quite indisputably indicate that the improvement in the situation be lasting. Phosphorus accumulated in sediment has neither escaped from a lake nor does the length of time used in the experiments yet entitle one to regard precipitated phosphorus in all conditions remaining in sediment as being certain. Gas generation in reduced black silt mixes precipitated silt with unprecipitated silt at greater depths, and dissolved phosphorus in interstitial water may return to free water. The method in question is, however, evidently worthy of consideration, the usability of which ought to be experimented with in Finnish conditions as well. Especially in cases where in connection with the putting of sediment in motion for one reason or another a great deal of phosphorus in sediment has gotten to water chemical precipitation may be a useful measure. One may also think of precipitating phosphorus on the bottom just before sediment is removed when the removal of sediment is applied.

Removal, isolation or other treatment of sediment

Removal of sediment as a means of lake restoration was introduced by Björk of Sweden. The principle is briefly as follows:

Because the aging of a lake is due to the basin gradually becoming full of sediment, the lake may be rejuvenated by removing sediment layers. The change of matter between sediment and water disturbed because of eutrophication can thus be returned to natural state by selecting the sediment generated in "harmonic" surroundings maybe 2000...3000 years ago as the contact surface of sediment and water. The topmost layers of sediment can easily be removed by pumping and the silt may by spraying be spread on suitable tilled land areas, forests or other expedient places in the surroundings of the lake.

Observations of the compression of land occurring in connection with drainage give an intimation of the fact that, when a lake to be restored can temporarily be drained, silt becomes compressed and concentrated solely through waiting. The following questions should, however, be answered:

- must the compressed silt be removed or is it possible after a certain period of time allow water upon it again

- is it possible or necessary to bind the silt by suitable vegetation in such a way that it remains dense under water, too
- does the silt, proper ditching provided, become so dense that it can bear the weight of the equipment used for the removal of soil in the event that the silt has to be removed
- how long is it necessary to keep the lake dry to produce adequate depression of silt.

It is thinkable that in cases where the problem where the silt to be removed should be placed cannot be solved for instance owing to settlement around the lake concentration of silt by draining the lake temporarily be tried. If the result of mans continued heedless action can be corrected by waiting, say, 3...4 years, the length of that period should not obstruct the measure from being carried out.

Scrutiny of methods applied to sediment

Sediments are the visible ultimate result of a lake's biological phenomena and dynamic development. The quality of a lakes water is reflected in the structure of sediment, and the quality of sediment on the other hand affects the quality of water. For example Ohle has found out that four lakes in Northern Germany have direct dependency between the volume of silts nutrient supply and the plankton basic productivity. According to the opinion of several researchers, silt, and especially the interstitial water found in silt, forms the most important, or in any case a very important, supply of nutrients in a lake.

In aerobic state silt in a lake is an extremely efficient retainer of phosphorus. After oxygen content in water above silt has decreased to 1-2 mg/l silt begins, however, to affect the quality of water, for the redox potential decreases at silts uppermost millimeters to a level enabling the dissolution of sedimented matters such as manganese, iron and phosphorus. It has been shown by radioactive phosphorus isotope p32 that phosphorus moves with ease in silt and for instance phosphate placed in silt at a depth of 4 cm has moved upward all the way to water.

On the basis of what has been said above we may conclude that a lake with a long-lasting eutrophicated state and slow water circulation will because of silt's nutrient supplies long remain in a eutrophicated state after the elimination of the basic reason for eutrophication. It is only if the loading of waste water has not lasted long that a lake's condition may return quickly in a lake of long retention without measures applied to sediment. As a rule the situation can only be corrected by breaking off the direct contact between silt and water, which can be done by removing the silt or by isolating it. Not even keeping hypolimnion artificially in an aerobic state does prevent phosphorus from passing from silt to water, for but an extremely thin layer in silt's surface can thus be made aerobic, and, besides, phosphorus is transferred to water from aerobic silt, too. Measures applied to sediment, particularly the removal of silt, are in fact among the most radical and effective means of lake restoration. Above everything else specifically in cases of this description all potential sources of nutrients must be eliminated before any action is taken, because if the productivity of organic matter remains high in a lake after sediment has been removed, a new stratum of silt rich in nutrients is soon formed on the bottom and the situation goes back to the former state.

Shaking of the topmost stratum of sediment, even if pumping is carried out with care, may be hard to avoid. As a result thereof nutrients in sediment may to some degree get to water. To diminish the harm resulting from this chemical precipitation of phosphorus may especially in basins of slow renewal be considered for use in connection with removal of silt as pointed out above.

The greatest difficulty in removing sediment consists of the placing of silt in the surroundings of a lake. In this respect no universal rule can be given, since the question must in each case be solved separately by taking into account the various factors relative to soil, objectives set for the use of the land, land's proprietary relationships as well as available capital.

Recommendations

Owing to factors depending among other things on the shape and location of a basin, factors relative to the soil of the close and remote vicinity as well as cultural features of the watershed area every lake's behavior is, as is well known, different in the limnological sense. Thence the method of restoration must also in each case be chosen so as to meet the lake's special features, and no universal forms can be followed blindly. If something is to be said we have to confine ourselves to presenting some general lines of what kind of means of restoration in the first place probably will come into question in different cases most frequently in question. Then we end up in the following recommendations:

Problem	Possible solution
<p>Excessive eutrophication and, succeeding it, strong turbidness by the plankton resulting in an anaerobic hypolimnion during stratification.</p>	<ol style="list-style-type: none"> 1. Aeration of hypolimnion. Applicable also in an unstratified lake in winter. 2. Depletion of hypolimnion in a stratified lake. Depletion of epilimnion during algae maximum in early summer before the hypolimnion becomes oxygen-devoid. 3. Chemical precipitation of phosphorus. Worthy of consideration particularly in an unstratified lake. 4. Removal or isolation of sediment in extremely serious cases.
<p>Fish kill through suffocation.</p>	<ol style="list-style-type: none"> 1. Under catastrophe conditions in winter any aeration of water stratum next to ice in such a way that mixing with deep water or silt is avoided. Pumping of compressed air under ice is the method most easily realizable, but it involves a greater risk than e.g. the generation of surface current or aeration in which reducing gases are expelled in connection with aeration and water returned to its original depth. 2. Kill through suffocation during a circulation period can only be avoided by advance prevention. This has to be performed in such a way that hypolimnion is aerated prior to a circulation period. The mean value of water column's oxygen content, in which direct consumption of oxygen has been considered as "negative" content, surpassing the boundary value of fish kill through suffocation must be assumed as the objective.
<p>Problems with oxygen in a new artificial lake.</p>	<ol style="list-style-type: none"> 1. Removal of organic matter as completely as possible prior to the filling of the basin. Clearing of banks from humus matters and remnants of plants. 2. Depletion of hypolimnion. 3. Passing of additional water through the basin in the first years. This possibility is probably more or less theoretical, because artificial

	lakes are as a rule formed in areas with little water.
Becoming totally grassed.	4. Gradual filling of the basin in such a way that all the water is replaced several times during the first phase of the filling while the amount of water is small and its concentration highest.
Problems with manganese in a crude water basin.	1. Mechanical removal of aquatic plants. 2. Raising of water level. 3. Removal of sediment.
Smell and taste troubles caused by plankton in a crude water basin.	1. Artificial destratification. 2. Depletion of hypolimnion. 3. Aeration of hypolimnion.
Tidying of a bathing beach on a shore with a muddy or sludgy bottom.	1. Chemical precipitation of phosphorus. 2. Copper sulfate treatment just after harmful population has begun to increase. 3. Aeration or depletion of hypolimnion.
Spreading of heavy waste water to an undesired direction.	1. Covering of sediment regionally by plastic sheet and/or sand. It is advantageous to remove the topmost layer of loose mud or sludge from the area to be covered. 2. Bottom dam. 3. Regulation in such a way that the flow of water to the undesired direction is as little as possible.

The order in which the means have been presented is not the order in which they are recommended, but the solution presented shall in each case be weighed as equal alternatives, of which many may come into question at the same time. As emphasized above, all possibilities - including those not given as examples of solutions - shall be taken into consideration at the starting of restoration before the means are chosen.

Whatever the method chosen is, it is, however, essential that before measures are taken to get a lake restored everything possible be done to minimize a lake's nutrient loading, in other words a through renovation is carried out.

Lake restoration is a measure requiring versatile application of technical, ecological, biological, social and economic knowledge. Without cooperation between representatives of these fields restoration is unrealizable. If cooperation between technicians and biologists had been settled earlier, many misunderstandings could have been avoided. The direct benefit of the reckless exploitation of natural sources would then have been weighed by economically realistic calculations which take into account the great and long-lasting harmful effects manifesting themselves ecologically. Now that the indifference pointed at water protection in the previous years and the realized incorrect solutions have made lake restoration a current problem in Finland, too, we ought to be able to benefit from the experiences attained elsewhere.

