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Study of the efficiency of hypolimnetic aeration process on the preservation of the thermal stratification

Mostefa Gafsi[a,*], Ahmed Kettab[b], Abdelkader Djehiche[a], Khadidja Goteicha[a]

[a]*Research Laboratory of Civil Engineering: RLCE, Research Team Water Resources, University of Ammar Telidji Laghouat, Laghouat, Algeria, emails: msgafsi@yahoo.fr, m.gafsi@mail.lagh-univ.dz (M. Gafsi), a.djehiche@mail.lagh-univ.dz, djehichea@yahoo.fr (A. Djehiche), hamidoz83@yahoo.fr (K. Goteicha)*

[b]*Laboratory Research in Water Science, LRW-Water/ENP National Polytechnic School, El Harrach, Algeria, email: kettab@yahoo.fr, lrseau@netcourrier.com*

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ABSTRACT

Lake eutrophication has proven to be a stubborn environmental problem. Depletion of dissolved oxygen (O_2) in the deep layer (hypolimnion) of lakes during stratification and its deleterious effect on fish stocks have been observed and analyzed for more than 100 years. Although it has taken only 60 years for humans to turn many freshwater lakes eutrophic, studies estimate that their recovery may take 1,000 years under the best circumstances. In deeper (thermally stratified) lakes, the stabilization can involve several factors, including biogeochemistry of the deep layer of water (hypolimnion), temperature of the hypolimnion, shape of the lake basin, abundance of rooted plants, and food web structure. The main purpose of this study was to show the efficiency of hypolimnetic aeration process on the preservation of the thermal stratification, the increasing the amount of oxygen dissolved, and the reduction in phosphorus in the depths of the lake. The 10.3 km^2 of the water of Hallwil Lake is an important tourist center for the Canton Aargau (Switzerland). In fact, fishing and water sports are practiced. Before its restoration in the winter of the year 1985/1986, this lake's eutrophication showed significant disruption of aquatic activities, and pollution damage due to its various uses, and thus inhibited the development of tourism in the region. In order to address the eutrophication of Hallwil Lake, the Canton Aargau put into service in the winter of 1985/1986, an installation of a aeration system in two alternate modes of aeration namely by a aeration system in winter destratification and aeration hypolimnetic in summer (air/pure oxygen). As a result, the values of the concentrations of dissolved oxygen during the aeration are as follows: $[O_2]_{min} \geq 4.5\ g/m^3$ in the spatial variation and $5\ g/m^3$ in the temporal variation. Also, the heating of the hypolimnion has not attained the thermocline, and as a result, the thermal stratification is preserved.

Keywords: Hypolimnetic aeration; Dissolved oxygen; Thermal stratification; Phosphorus; Hypolimnion; Temperature

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*Corresponding author.

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1. Introduction

Eutrophication arises from the oversupply of nutrients, inducing explosive growth of plants and algae. When such organisms die, they consume the oxygen in the body of water, thereby creating the state of hypoxia [1]. Lake eutrophication has proven to be a stubborn environmental problem [2,3]. Depletion of dissolved oxygen (O_2) in the hypolimnion of lakes during stratification and its deleterious effect on fish stocks have been observed and analyzed for more than 100 years [4]. The amount of dissolved oxygen is essential for fish and insects, and influences many different biological and chemical processes in lakes and streams [5].

Although it has taken only 60 years for humans to turn many freshwater lakes eutrophic, studies suggest their recovery may take 1,000 years under the best circumstances [6]. Although sewage, agriculture, and factories all increase nutrient input in watersheds, the amount of input varies according to the types and amounts of human activity occurring to each watershed [7]. Industrial wastes and domestic sewage are the major urban sources of nutrient overload, responsible for 50% of the total amount of phosphorus unloaded into lakes from human settlements [8]. Other sources that contribute to cultural eutrophication include the use of fertilizers, faulty septic systems, and erosion into the lake. Industrial agriculture, with its reliance on phosphate-rich fertilizers, is the primary source of phosphorus excess responsible for degrading lakes [9]. In order to control eutrophication and restore water quality, it is necessary to check and restrict phosphorus inputs, reduce soil erosion, and develop new technologies to limit phosphorus content of overenriched soils [6]. This development and control of freshwater eutrophication by phosphorus loads is ubiquitous and well documented [7,10,11]. Conversely, phosphorus loading restrictions have led to rapid recovery from eutrophication in many lakes [12]. In deeper (thermally stratified) lakes, the stabilization can involve several factors, including biogeochemistry of the deep layer of water (hypolimnion), temperature of the hypolimnion, shape of the lake basin, abundance of rooted plants, and food web structure [13].

The artificial mixing help producing surface currents, which protect harbor areas against high amplitude waves [14,15]; and avoids oil slicks from spreading after oil tanker accident, that consequently or protect coastal habitats against damage from oil [15,16]. Also, the artificial mixing affects the composition of the algal population, the total possible number of algae, and the algal growth rate [16,17].

In order to remediate the eutrophication of the Hallwil Lake, the Canton Aargau (Switzerland) has implemented in the winter 1985/1986, an installation of alternate aeration system in two aeration modes [18,19]:

(1) An aeration by a destratification system in winter period,
(2) Hypolimnetic aeration in summer period (air/pure oxygen).

The main purpose of this study was to show the efficiency of hypolimnetic aeration process in the preservation of the stratification, increasing the concentration of oxygen dissolved, and reduction in phosphorus in the depths of the lake.

2. Materials and methods

Since 1986, recovering Hallwil Lake is supported by an aeration system. In Seezopf Meisterschwanden, there is a building with compressors and systems to deliver oxygen. Six lines are leading from the shore to the middle of the lake. The six diffusers eject air or oxygen required in the deep water at 45 m (Fig. 1) [18,19].

This operation uses a circular feather bubbles diffuser (Fig. 2) and ejects air or oxygen. These systems are more suitable for deep lakes where the charge of dissolved bubbles in the hypolimnion and the momentum generated by the feathers are sufficiently weak to avoid a significant erosion of the thermocline.

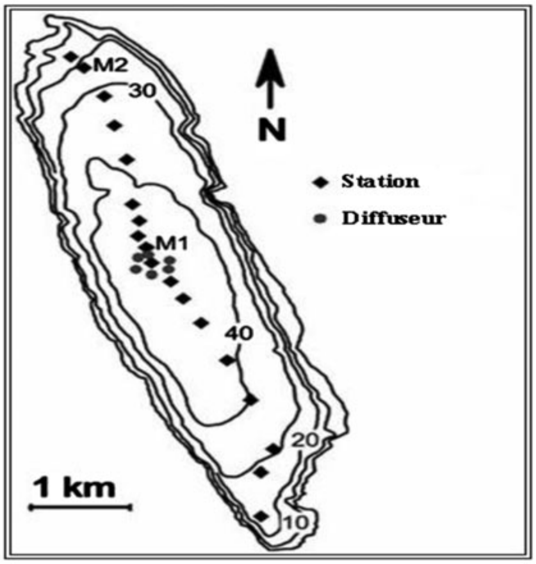

Fig. 1. Lake Hallwil bathymetry [18,19].

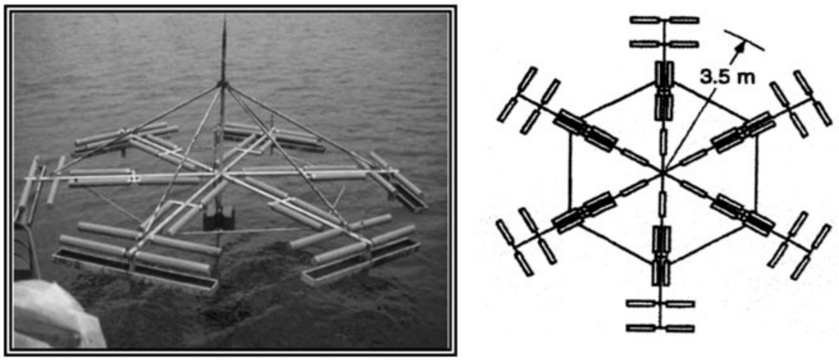

Fig. 2. One of the six diffusers of Tanytarsus that has a diameter 6.5 m [18,19].

The six diffusers (Fig. 2) have a diameter of 6.5 m each, and are located in a circular configuration of 3 m diameter near the middle of the lake (Fig. 2 and Table 1). Every diffuser uses air or oxygen during summer season for the hypolimnetic aeration mode and air during the cold season for the destratification aeration mode [18,19].

Table 1 shows the characteristics of the lake as well as the system of the diffuser that has been installed in the Hallwil Lake, when the destratification and the aeration or the hypolimnetic oxygenation is set.

From April to October, many tons of oxygen are introduced in the form of fine bubbles diffused on the lake bottom and dissolved in the water with an amount required of 1–4 tons per day. Thus, the oxygenation in deep water is maintained throughout the year. The annual required oxygenation has varied between 200–800 tons (Fig. 3) depending on the development of algae [20].

Table 1
Special characteristics of the Hallwil Lake and the system of the diffuser [18,19]

Parameters	Value
Maximum depth (m)	46.5
Average depth (m)	28.9
Surface (m)	9.9×10^6
Total volume of water (m^3)	285
Geometry of diffusers	Circular
Number of diffusers	6
Diameter of diffusers (m)	6.5
Average depth of diffusers (m)	46
Gas flow of all diffusers ($Nm^3 H^{-1}$)	46–148 (O_2) 180 (air)

Notes: The gas pressure is 1 bar; temperature is 0°C.

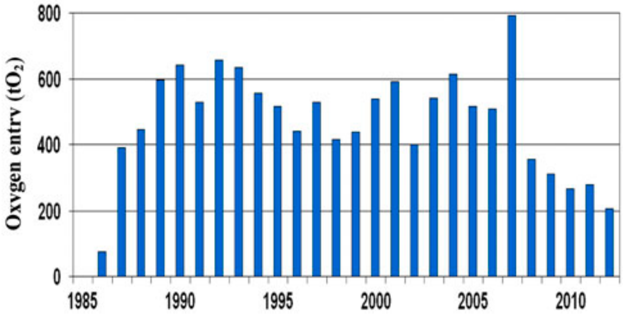

Fig. 3. Oxygen transfer by aeration in summer [20].

3. Results and discussion

3.1. Spatial variation

3.1.1. Oxygenation

In the years 1973, 1979, and 1982 and before the aeration (Fig. 4) the profiles of oxygen had a similar tendency, e.g. maximum values of oxygen concentration in the surface reaching 13 g/m^3 (July 1982) and minimum values in the depth that are the same 0.01 g/m^3. The oxygen concentration was lost beginning at an average depth of 8 m leading to minimum values at the bottom of the lake.

During the aeration, the profiles of the oxygen concentration at the surface (in the three years test) are comparable to those observed in the non-aerated period, but they differ from the other profiles beyond a depth of 13 m, which explains that the oxygenation has been limited to the depth and particularly in the hypolimnion layer.

The values of the highest oxygen concentration in the lower layer of the lake are 7, 5.8 and 8 g/m^3 in 2000, 2001, and 2002, respectively. However, an approximate value of 0.01 g/m^3 is recorded in 1973,

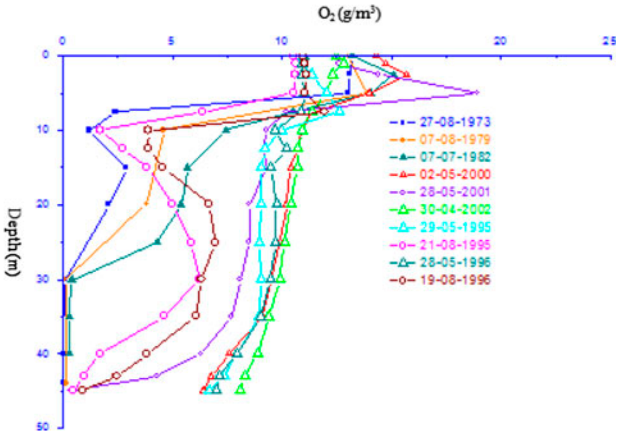

Fig. 4. Profiles of oxygen concentration dissolved with respect to the depth of the lake before and during the hypolimnetic aeration [19].

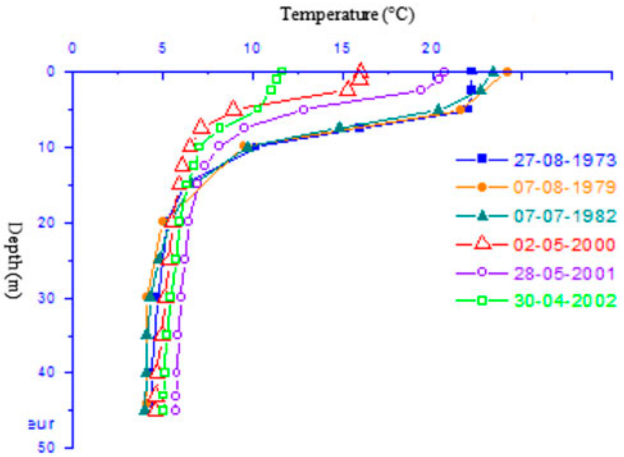

Fig. 5. Profiles of temperature according to the depth before and during hypolimnetic aeration [19].

1979, and 1982 (non-aerated period). This shows clearly a very appreciable augmentation of oxygen concentration in the deep layer during the operation of the aeration.

The average content of dissolved oxygen in the hypolimnion is maintained at higher than 3 g/m^3 during the summer season, without disruption of the existing thermal stratification. The dissolved oxygen concentration is kept over a threshold that is necessary and that is equal to 3 g/m^3, this may entertain a convenient habitat for cold water fish living. This result has been confirmed by McCord et al. [21].

The oxygen profiles before and during the hypolimnic aeration of Hallwil Lake, are comparable to the profiles of Fast [22], to profiles of Wüest et al. [23], to the profiles of Mobley [24], and to the profiles of McGinnis et al. [25], for the respectively the restoration of the Waccabuc Lake, the restoration of de Baldegg Lake, the aeration of blue Ridge Reservoir, and the restoration of Spring Hollow reservoir. In the summer season, the dissolved oxygen concentration increases during the hypolimnetic aeration of the Hallwil Lake as well as in the lakes studied by the authors mentioned previously. Therefore, the hypolimnetic aeration yields to an augmentation of dissolved oxygen which involves an eutrophization of the water [22].

3.1.2. Temperature

Fig. 5 shows the evolution of daily water temperatures vs. to the depth of the lake before and during the hypolimnetic aeration. The lake is stratified normally during the years 1973, 1979, and 1982. The thermocline is characterized by a temperature gradient that increases from 9 to 13 m in August 1973, from 8 to 13 m in August 1979, and from 7 to 13 m in July 1982. These results show that the surface of the hypolimnion begins on average at 12 m. The temperatures taken and stored during the years 1973, 1979, and 1982 are, respectively, 22, 23, and 24°C at the surface and 5.2, 5.1, and 5°C at the bottom of the lake. During the aeration of the lake, the temperature profiles exhibit similar patterns as those observed in medium prior to the aeration of the lake.

In July 2001, the temperature profile perfectly fits the profiles of the years when the lake is not aerated. The temperature differences between the surface and the bottom are 17°C (August 1973), 19°C (August 1979), and 18°C (July 1982), thus indicating that the lake is indeed thermally stratified during aeration. The temperature differences between surface and bottom are 11.1°C (May 2000), 15°C (July 2001), and 5.5°C (April 2002), indicating that during aeration of the lake, thermal stratification is well maintained and is more significant in the warmer months in May and July 2000 and 2001, respectively.

Temperature profiles before and during hypolimnetic aeration of Hallwil Lake, are comparable to the profiles of McGinnis et al. [25] when restoring Lake Spring Hollow, the profiles of Wüest et al. [23] during the Aeration of Lake Baldegg, and the profiles of Fast [22] in the aeration of Lake Waccabuc, NY.

The temperature increases during the hypolimnetic aeration of Hallwil Lake and in the lakes studied by the authors mentioned above [19].

3.1.3. Total phosphorous

The daily evolution of the concentration of the total phosphorus vs. to the depth of the lake before and during hypolimnetic aeration is shown in Fig. 6.

Before the aeration of the lake, the three curves of the variation of phosphorus show a net increase from the surface to the bottom of the lake. A minimum concentration of phosphorus is observed at the surface with a value of 0.01 g/m^3 (August 1973) and a maximum value of 0.04 g/m^3 (July 1978). In the bottom of lake, the minimum value of 0.4 g/m^3 is observed on (July 1978–1982) and a maximum value of 0.5 g/m^3 is recorded on August 1973.

During the aeration, the profiles mentioned previously have a generally uniform variation from the surface to the bottom of the lake. A clear decrease in phosphorus concentration is more visible during the restoration at any depth. In terms of values, the surface concentrations of phosphorus have values closer to 0.0 (May 1997), 0.02 (April 2000), and 0.07 g/m^3 (May 2001), while the background values are 0.05 (May 1997), 0.04 (April 2000), and 0.15 g/m^3 (May 2001). In addition, the average value of the amount of phosphorus in the depth of the lake remains below 0.20 g/m^3 [19].

3.2. Temporal variation

3.2.1. Oxygenation

Fig. 7 shows the evolution of the average concentration of dissolved oxygen at the surface, 15 and 30 m, and the bottom (45 m) of the lake before and during the period of hypolimnetic aeration of May–September 1982 and May–September 1987.

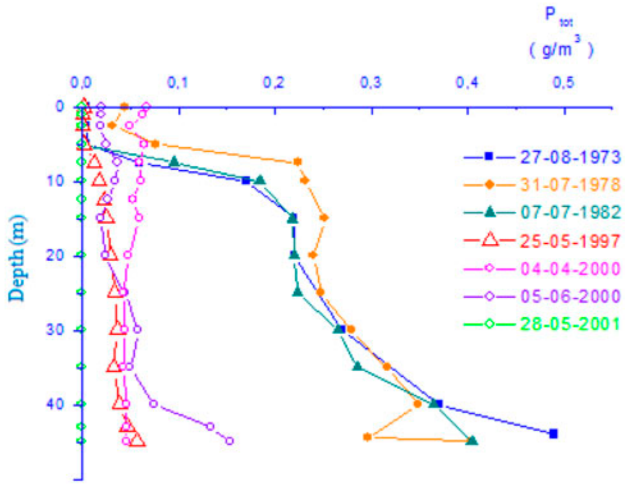

Fig. 6. Profiles of the concentration of total phosphorus according to the depth of the lake before and during hypolimnetic aeration [19,26].

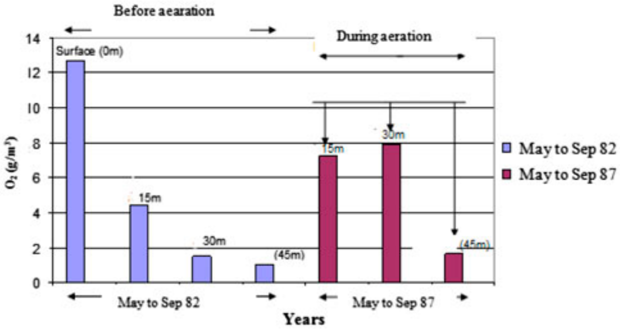

Fig. 7. Evolution of the average concentration of dissolved oxygen from the surface, 15 m, 30 m, and the bottom before and during hypolimnetic aeration from May to September 1982 and from May to September 1987 [19,26].

A decrease in mean summer concentration of dissolved oxygen before hypolimnetic aeration of 12.6 g/m^3 at the surface, 1.51 g/m^3 in 30 m, and 1.05 g/m^3 at the lake bottom. The increase in the average concentration of dissolved oxygen in hypolimnetic aeration of 7.2 g/m^3 in 15 m, 7.9 g/m^3 in 30 m, and 1.6 g/m^3 in the bottom. The increase in dissolved oxygen induces the reduction of eutrophication. During aeration, the amount of oxygen increased appreciably, especially at 15 and 30 m.

3.2.2. Temperature

Fig. 8 shows the evolution of the average temperature between the surface, 15 m, 30 m, and the bottom (45 m) of the lake before and during the period of hypolimnetic aeration.

A decrease in mean summer temperature from 20.81 ℃ at the surface to 4 ℃ at the bottom before

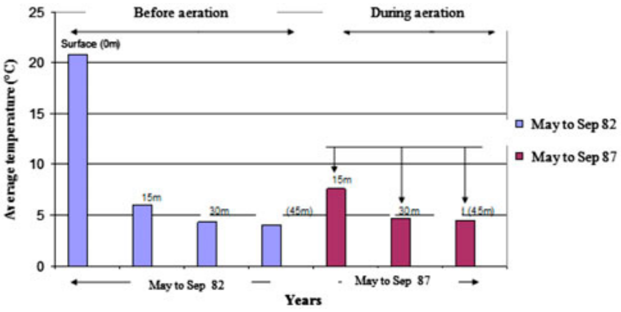

Fig. 8. Evolution of the average temperature between the surface (0 m), 15 m, 30 m, and the bottom before and during hypolimnetic aeration from May to September 1982 and from May to September 1987 [19,26].

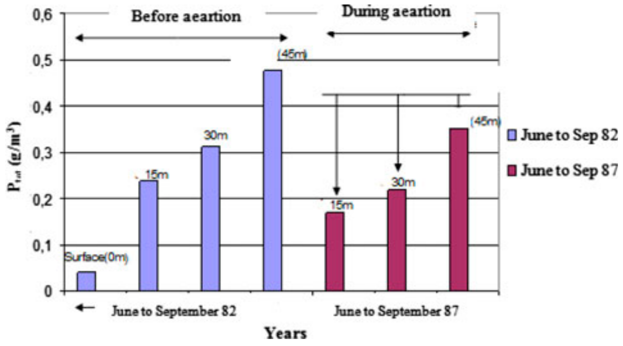

Fig. 9. Evolution of the average concentration of total phosphorus from the surface (0 m), 15m, 30 m, and the bottom before and during hypolimnetic aeration from June to September 1982 and from June to September 1987 [19,26].

hypolimnetic aeration was observed. A low rise in the average temperature during the hypolimnetic aeration from 6 to 7.59°C is recorded at 15 m level. In all other layers (30–45 m), there is almost a conservation of temperature.

Before and during the aeration, the temperature differences between the same levels are 1°C for 15 m level and approximately 0.3°C for 30 and 45 m levels. This shows that during the aeration, the temperature in the layer of the hypolimnion has not changed, and therefore, the thermal stratification is preserved.

3.2.3. Total phosphorous

Fig. 9 shows the evolution of the average concentration of total phosphorus at the surface, 15 m, 30 m, and the bottom (45 m) of the lake before and during the period of hypolimnetic aeration.

The evolution of the average concentration of the total phosphorus before hypolimnetic aeration shows an increase of 0.04 g/m^3 at the surface, 0.23 g/m^3 at 15 m, 0.31 g/m^3 at 30 m, and 0.47 g/m^3 at the lake bottom. During hypolimnetic aeration, an average concentration of total phosphorus of 0.16 g/m^3 is observed at 15 m, 0.21 g/m^3 at 30 m, and 0.35 g/m^3 at the lake bottom.

Therefore, the average concentration of the total phosphorus has decreased during hypolimnetic aeration, leading to a decrease in the eutrophication of the lake [19].

4. Conclusions

The operation of the installation of hypolimnetic aeration system during the summer years of experimental records has yielded the following results:

(1) During the restoration, the average concentrations of oxygen exceeded 4.5 g/m^3 in the summer season (in spatial variation).
(2) The average value of the content in this component is greater than 5.5 g/m^3 (in chronological variation).
(3) In the hypolimnetic aeration mode, the heating of the hypolimnion has not reached the thermocline and thus, the thermal stratification is preserved.
(4) The average values for oxygen and phosphorous concentrations are both within the range of the allowed values (in spatial variation):
    (a) Summer season (30 m ≥ H ≥ 15 m): $[O_2]_{\min} \geq 4.5\ g/m^3$; $[P_2]_{\max} \leq 0.\ 20\ g/m^3$.

This allows to conclude that the lake is out of the eutrophication stage.

In the region of hypolimnetic layer, the content of dissolved oxygen is maintained over a suitable value that is necessary for the survival when the brewing is on. Moreover, the conservation of the thermal stratification creates a suitable habitat for the maintaining of a favorable temperature for the cold water fishes. Accordingly, the temperature as well as the oxygen profiles confirms this fact.

The hypolimnetic aeration mode has significantly allowed the minimization of the phosphorus amount. The maximum content of this component dissolved in the lake is within the acceptance interval. This is being well validated for a long period by the evolution of phosphorus in this mode of aeration.

Acknowledgement

This work is a continuation and application of a work, which I have published on a study of two methods of aeration: the hypolimnetic aeration and destratification. The study published is as follows: "Comparative Studies of the Mechanical Different Oxygenation Systems Used in the Restoration of Lakes and reservoirs." Int. J. Food, Agriculture and Environ., Vol 7 JFAE. (2)-2009. This study has been reviewed by Prof. Alfred Wuest, Prof. John Little, Madam Prof. Little, and Dr Dan McGinnis of Department of Surface Waters Research and Management Federal Institute for Planning the Treatment and Water Protection (EAWAG) in Lucerne (Switzerland). The assistance and encouragement of these Professors is gratefully acknowledged. Also, I gratefully acknowledge Dr Arno Stöckli for his help during the preparation of

this study. The work presented here is subject to analysis and commentary of experimental measurements made on the Hallwil Lake. Such data are collected from the Department of Surface Waters Research and Management Federal Institute for Planning the Treatment and Water Protection (EAWAG) in Lucerne (Switzerland).

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