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FINAL REPORT

A LITERATURE REVIEW AND FEASIBILITY ANALYSIS ASSESSING MICROBIAL DECOMPOSITION AS A TECHNIQUE FOR RESTORING LAKE APOPKA

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INTRODUCTION

As part of the effort to improve water quality in Lake Apopka, International Science & Technology, Inc. (IS&T) has conducted a literature review and preliminary feasibility analysis assessing in situ sediment decomposition as a technique for oxidizing organic lake sediments and decreasing sediment nutrient loading to the water column. This technique applies biochemical or chemical processes, or a combination of both, and has its origins in wastewater treatment technology.

Four specific techniques for sediment decomposition were investigated: microbial inoculation, denitrification, hydrogen peroxide addition, and ozonation. Thorough investigation of research and field applications of sediment oxidation techniques required a review of the peer-reviewed and "grey" literature, as well as interviews with scientists and lake managers with experience in this field and commercial vendors of these technologies.

BACKGROUND

Decreasing the organic content of sediments has the potential for improving water quality in eutrophic lakes by decreasing the oxygen demand of the sediments on the water column, inhibiting nutrient cycling from the sediments to the water column, and increasing the depth of the water column through sediment consolidation.

Natural systems accumulate excess organic material when biological productivity exceeds the capacity to decompose this material. This can be the result of nutrient limitation, the presence of toxins, or other adverse environmental conditions that constrain decomposition. Sediment treatment research focuses on accelerating decay processes through combinations of chemical, mechanical, and biological intervention.

The sediments in Lake Apopka are moderately organic and subject to "intense microbial activity and anaerobic conditions" (Reddy et al. 1988). Anaerobic conditions are reflected in extremely high ammonium concentrations. Active denitrification is indicated by very low nitrate concentrations. The sediment has undergone significant microbial degradation, but the remaining degradable organic material in the sediments appears to be far from depleted, as reflected by the anaerobic conditions and high concentrations of ammonia. In addition, anaerobic conditions in the sediments may be sustained by the continual deposition of dead algal cells and allochthonous organic material. Sediment accretion rates average approximately 1 cm/year (Pollman, pers. comm.).

BIOCHEMICAL OXIDATION TECHNIQUES

There are two technologies that attempt to induce microbial sediment oxidation. The first relies on the introduction of non-native microorganisms to both aerobic and anaerobic sediment environments. The second relies on native bacterial populations stimulated by introduced nitrate to oxidize sediments by denitrification under anaerobic conditions.

Introduced Microorganisms. Non-native microorganisms are introduced into eutrophic lakes with the intention of removing particulate and dissolved organic material from the water column and sediments through enhanced aerobic and anaerobic bacterial activity, including denitrification. The products are composed of mixtures of bacterial species that are reported to be free of Salmonella and related pathogens. Most manufacturers of microbial treatments claim that their products work under both aerobic and anaerobic conditions, but that aerobic conditions are preferable and can be induced through mechanical aeration.

Hanson (1981) conducted the most extensive investigation to date of in situ sediment digestion techniques, including aeration and microbial inoculation. The results indicated no detectable difference between sediments inoculated with the commercial product and the untreated controls. The author concluded that inoculating sediments with the correct mix of aerobes that have already developed the specific decay mechanisms required "may be very difficult, if it is possible at all." Other researchers have reported similar negative results in evaluating the effectiveness of microbial inoculations (Jewell and McCarty, 1970; Foree and McCarty, 1971; Boyd et al., 1984; Tucker and Lloyd, 1986; Muller, 1987; Palmer et al., 1987; Blouin et al., 1988;)

The technology of microbial inoculation to improve water quality is based on highly controversial scientific theories. Controversy centers on the principal that if it is environmentally possible for a substrate to be used as an energy source, mechanisms will have developed over time to efficiently use that substrate. Given the general capability of native microbial populations to adapt to complex substrate types, the presence of excessive substrate (accumulated organic material) indicates that accretion rates are greater than the processing rates of the microbial population. This could be caused by nutrient limitation or toxicity (Jewell and McCarty, 1971). Either of these conditions would also limit the effectiveness of introduced microorganisms (unless toxins to native populations were non-toxic to introduced microbes).

The most compelling argument against the efficacy of commercial microbial products is the absence of published accounts of success in applying these products to eutrophic lakes. No support for the use of microbial inoculation as a lake restoration method can be found in the peer reviewed scientific literature. The few refereed journal articles documenting microbial inoculation conclude that the treatment is ineffective and theoretically unsound (Boyd et al., 1984; Hanson, 1981). Without exception, the professional limnologists and aquatic scientists contacted during this investigation expressed the opinion that the addition of microbial products to promote sediment decomposition and lake restoration has little theoretical basis and no credible evidence to substantiate the claims made by the manufacturers. It was concluded that further investigation regarding the application of commercial microbial products to the restoration of Lake Apopka is not warranted.

The cost of microbial inoculation can vary considerably, depending on whether mechanical aeration is included in the project design. Based on manufacturers' recommended doses, areal costs range from $6 to $25 per hectare. These costs include only the purchase of the microbial product. Costs associated with application, environmental monitoring, or additional water conditioning, such as aeration or treatment with chemical precipitants, are not included.

Nitrate Application. Lake restoration techniques involving nitrate application rely on the stimulation of biochemical denitrification. The principal objective is to inactivate sediment phosphorus through nitrate-induced reactions, but a related effect of the treatment is anaerobic sediment oxidation through denitrification. The mechanism of phosphorus inactivation is the sorption of phosphate onto insoluble ferric, Fe(III), oxides and hydroxides under oxidizing conditions. Cooke et al. (1986) observed that in shallow lakes with high pH and temperature, iron redox reactions may not control phosphate release. In such systems nitrate application may not inactivate phosphate, although sediment oxidation would still occur under reducing conditions.

Laboratory studies by Hanson (1981) and Szewczyk (1984) examined the effectiveness of nitrate application in oxidizing organic sediments and found nitrate application to be a promising technology, concluding that readily-degradable organic material was effectively decomposed without adverse impact to the water column. Neither investigator reported any reduction in sediment volume at any nitrate dose. Unfortunately, neither study examined the efficiency of denitrification or inhibition of phosphorus recycling. There are mixed, but generally positive reports of the success of nitrate addition treatments (Forsberg, 1987; Lingren, 1986; Ripl, 1979; Willenbring, et al., 1984; Verner, 1985; Ripl, 1985; Foy, 1986).

The success of nitrate application appears to be related to site specific conditions, including sediment chemical characteristics. It is evident that denitrification occurs intensely in the sediments in Lake Apopka. Thus, there may be substantial oxidation of organic material occurring routinely in the upper sediments of the lake. Conditions in the lake appear to be suitable for nitrate application; a shallow, sub-tropical system with a productive, aerobic, well-mixed water overlying the sediments. The capability for this technology to control phosphorus release in the highly productive environment of Lake Apopka is uncertain. Field investigations will be required to assess the efficacy of the technique.

Ripl (1985) developed application technology and equipment, known as RIPLOX, to inactivate phosphorus and oxidize organic sediments through the addition of calcium nitrate in conjunction with lime and ferric chloride. This technology is marketed in the United States by Aqua Technique, distributor of the RIPLOX technology. Aqua Technique provides the mechanical apparatus for injecting calcium nitrate into lake sediments and the technical expertise in developing treatment designs for specific projects. Application costs for nitrate treatment depend on the specific dose of calcium nitrate needed and on whether additional chemicals, such as lime or ferric chloride are required. Treatment costs reported in the literature range from \$0.74/m^2 to \$1.33/m^2.

CHEMICAL OXIDATION TECHNOLOGY

Organic sediments can be decomposed by reactions involving chemical free radicals which form from compounds with highly reactive oxygen groups. The two chemical oxidants examined in this study, hydrogen peroxide and ozone, have been applied for both water treatment and lake sediment oxidation. Application of either technology would require isolating a several hectare area of lake and introducing either liquid or gas into the flocculant sediments.

Hydrogen Peroxide. Hydrogen peroxide (H_2O_2) is commonly used in wastewater pretreatment for BOD, odor, and solids removal (Cole et al. 1974, 1976, Weber 1972). Research in the use of H_2O_2 for lake management has been conducted in field experiments by Barroin (1980) and laboratory experiments by Barroin and Feuillade (1986), Hanson (1981), Soares (1980), and Szewczyk (1984).

Soares (1980) conducted laboratory studies on the biological effects of H_2O_2 application to eutrophic lake sediments. H_2O_2 treatments resulted in the complete elimination of benthic macrofauna, and possibly microflora as well, with subsequent recolonization by sulfur-reducing bacteria. Mortality resulted from oxidation by the H_2O_2, but also by H_2O_2 reaction products such as sulfide, ammonium, and copper. Following oxidation, the onset of reducing conditions was observed, presumably brought on by the renewed activity of reducing bacteria. The H_2O_2 application was effective in removing 30 percent of the COD.

Hanson (1981) and Szewczyk (1984) included hydrogen peroxide treatment in their studies of in situ sediment consolidation techniques. Hanson reported highly efficient oxidation of organic sediments with increases in concentrations of dissolved carbon, phosphorus, and nitrogen and pH depression in the water column. He concluded that H_2O_2 treatment was the most effective method tested. The author recommended a post-treatment lime application to adjust pH, and a final treatment for uptake of soluble nutrients and organic carbon, using either nitrate or aeration combined with microbial inoculation. Szewczyk (1984) concluded that while the sediment oxidation capacity of H_2O_2 was great, the high cost and adverse environmental impacts render the technology impractical.

The effectiveness of chemical oxidation in lakes is offset to some extent by the profound impact of reaction by-products on overlying water quality. Follow-up treatment is necessary to precipitate nutrients from the water column. The choice of potentially applicable precipitants includes lime, alum, and ferric chloride, all of which are widely used in water treatment and lake management. Another secondary effect of chemical oxidation is a post-treatment pH decrease of 2 to 4 units. In-lake treatment operations (experimental or full-scale), will require a substantial secondary treatment program applying lime, or some other neutralizing agent to adjust the water column pH. It may be possible to use lime for both pH adjustment and precipitation. The extent of the treatment necessary will depend on iron concentrations in the sediment relative to the quantity of nutrients suspended. The cost of this additional treatment could easily equal or exceed the cost of initial oxidant application.

The application of H_2O_2 on an operational scale would be logistically complex and labor intensive. Liquid hydrogen peroxide is available in bulk as a 35 or 70 percent solution. The 35 percent solution has a cost of $0.107/kg, not including delivery. Cost for treatment is approximately $48/m^2. Additional costs would include product delivery, application equipment costs, and labor.

Ozone. Ozone (O_3), like H_2O_2, is used in water treatment for its powerful oxidizing capability but is poorly documented as a lake management technology. Other than a project report (Water Management, Inc.), Hanson (1981) provides the only known report of ozone application to oxidize lake sediments. Oxidation of organic material was significantly lower than H_2O_2 treatments and was comparable to removal observed in nitrate treatments. Sediment volume decreased significantly. The response of the water column to sediment ozonation is analogous to that of H_2O_2 treatments, and the secondary treatment requirements are identical.

Ozonation would probably be highly effective in decomposing the UCF and CF sediment fractions in Lake Apopka. Additionally, organic material in the water column would be oxidized, including phytoplankton cells. Secondary treatment with a chemical precipitant would remove the resulting soluble nutrients from the water column and seal the sediments with a relatively insoluble surface layer. The result would be a deeper water column with a more consolidated lake bottom, and environmental conditions conducive to the establishment of rooted macrophytes.

Implementing an effective ozonation program on Lake Apopka would be logistically complex. Ozone can be generated on-site, eliminating the problem of bulk shipping highly corrosive liquids (e.g., H_2O_2). The nature of the treatment would require that confined areas be treated sequentially as batch reactors. An enclosure in the lake would be required to hydraulically contain the area being treated. Following initial treatment with the chemical oxidant, the water would undergo treatment to remove dissolved nutrients and suspended residual organic material. After completion of the treatment, the enclosure would be moved to a new area and the process would be repeated.

Traditionally, cost has been the limiting factor in applying ozonation as a treatment technology. Recent advances in ultraviolet (UV) light technology have resulted in the development of a relatively inexpensive method of generating a "highly reactive ionized oxygen gas plasma," known as "activated oxygen," and commercially produced under the trademark "PHOTOZONE" (Water Management, Inc.). The manufacturer claims that PHOTOZONE generation requires 3 to 5 kw-hours to produce one pound of ozone, in comparison with 8 to 12 kw-hours to produce one pound of ozone using conventional methods. PHOTOZONE has been used in lake management. Interestingly, the PHOTOZONE representative contacted for this study stated that PHOTOZONE no longer markets their product for lake management projects.

Energy consumption will be the most expensive aspect of ozonation. Considering literature values of approximately 5 kw-hr to generate 1 pound of ozone, Hanson's (1981) ozone dose of 75 g O_3/l of sediment, and energy costs of $0.041/kw-hr (supplied by Florida Power and Light), energy costs to oxidize the UCF and CF sediments in Lake Apopka would be approximately $ 3 billion.

PUBLIC HEALTH IMPLICATIONS

None of the biological or chemical products considered in this study appear to present a human health hazard. Genetically engineered organisms were specifically excluded.

A possible public health risk indirectly related to any remediation efforts is the release from the sediments (and consequent activation) of the pathogenic amoeba, Neaglaria fowleri. This organism has been demonstrated to cause disease and death in humans in subtropical waters including lakes in central Florida. Generally the organism exists as a non-pathogenic encysted form in sediments until water temperatures exceed approximately 32 °C, whereupon it converts to a free-living form and can enter the human body through mucous membranes. The existence of this organism in Lake Apopka has not been investigated for this study. However, prior to implementation of in-lake restoration activities, population studies are recommended to determine initial densities and, more importantly, to determine what, if any, effects may result from large-scale disturbance of the organic sediments that may harbor the dormant cysts of this organism.

CONCLUSIONS AND RECOMMENDATIONS

Of the technologies examined in this study, nitrate application and ozonation exhibited potential for immediate field testing in Lake Apopka. Chemical oxidation technologies would be substantially more costly than nitrate application (Table E-1). The cost of initial application alone to Lake Apopka would probably exceed $3 billion for ozonation and $7 billion for hydrogen peroxide application, and extensive secondary treatment would be required in addition to that cost for water quality mitigation. Nitrate application, was therefore selected as the most economical and technically feasible in situ lake restoration technique. Specific conclusions and recommendations regarding each technology are provided below.

The theoretical framework that describes the mechanisms by which microbial inoculation should work is not supported by experimental data and is highly controversial. There is no evidence to indicate that application of this technology to Lake Apopka would bring about the desired responses of sediment decomposition or suppressed nutrient cycling. The technology of microbial inoculation currently provides a very low probability of success in field applications. Field tests of this technology are not recommended.

The injection of calcium nitrate into anaerobic sediments has been demonstrated to oxidize organic sediments through denitrification and inactivate phosphorus through co-precipitation with ferric hydroxide. The chemistry and biochemistry of the processes involved in this technology have been established through field and laboratory experimentation. Thus, there is adequate theoretical and practical information available to develop reasonable designs for field trials of the technology. Field evaluation of this technology is recommended.

TABLE E-1. ANTICIPATED TREATMENT COSTS FOR IN SITU LAKE RESTORATION.

Technology	Material Costs ($ million)	Cost Considerations
Microbial Inoculation	0.3	• Cost for single application. As many as 3 applications per month may be necessary for the duration of the restoration program. • Application and labor costs are not included. • Mechanical aeration was not included in cost estimates.
Nitrate Application	790	• Cost averaged from total treatment costs referenced in case studies (Section 3.2.4). • Application depth of 1.2 m assumed. Typical application depth is approximately 0.2 m, therefore unit surface area costs from case studies was multiplied by 1.2/0.2.
Hydrogen Peroxide	7,000	• Cost includes bulk material only. Transportation, application, and labor costs not included. • In addition to primary treatment, secondary treatment to mitigate water quality will be necessary at a cost comparable to nitrate application or alum application. • The area being treated requires hydraulic isolation from the remaining water column. Costs for engineering, construction, and maintenance of the enclosures are not included.
Ozonation	3,000	• Cost is based on energy requirements for ozone generation only. Capital costs for equipment or labor costs are not included. • In addition to primary treatment, secondary treatment to mitigate water quality will be necessary at a cost comparable to nitrate application or alum application. • The area being treated requires hydraulic isolation from the remaining water column. Costs for engineering, construction, and maintenance of the enclosures are not included.

Note: Material costs reflect estimates for treatment of 1.2 m of organic sediment over 12,500 ha in Lake Apopka.

Published reports of field and laboratory experiments using H_2O_2 and ozone show them to be highly effective in oxidizing organic sediments. Any application of chemical oxidation technology must be followed by treatment to inactivate dissolved nutrients and residual particulate organic material.

It is recommended that H_2O_2 and ozonation not be considered for field tests, because of excessive treatment costs and the logistic implications of large-scale treatment operations (e.g., bulk H_2O_2 or ozone generation requirements).

EXPERIMENTAL DESIGN

The objective of in situ treatment experiments will be to develop performance estimates that are representative of large-scale applications. The results of these field investigations will provide a basis for extrapolating the probable effects of large-scale applications of either nitrate addition or chemical oxidation. The next step in the evaluation of the applicability of these techniques to Lake Apopka should be field experiments in "limno-corrals" or similar enclosures placed in Lake Apopka. These experiments should be performed on as large a scale as practical to maximize representativeness.

The recommended field experiments will involve nitrate application in enclosures located in the lake. Monitoring should be conducted before and after the treatment applications to evaluate chemical and biological changes that result from the applications and quantify the effectiveness of the treatments in reducing sediment nutrient release and water column nutrient concentrations. Data collection should include physical, chemical and biological parameters. Gravimetric and chemical analyses will provide a quantitative indication of the degradation of particulate and dissolved organic pollutants over periods of weeks to months. The monitoring design will also document changes in the physical, chemical, and biological parameters that may result from the treatments. In addition, toxicity testing should be conducted using native plants, zooplankton, and fish.

After application of the treatments, monitoring should be conducted for a period of approximately six (6) months. Monthly evaluation of the data should be conducted to allow mid-course changes in treatment, such as reapplication, or in monitoring design.

IMPLEMENTATION SCHEDULE AND COSTS

A minimum of 16 months should be allowed for conducting recommended experiments and evaluating the resulting data. It is estimated that the investigation can be completed for a total cost of approximately $250,000, including construction, labor, and laboratory chemical analyses. Some savings may be realized by modifying the sampling frequency and limiting the number of parameters measured; approximately 40 percent of the total estimated cost is attributable to laboratory analyses.

FURTHER DEVELOPMENT

The results from the suggested experiments will allow the District to assess the applicability of the investigated treatments to the restoration and management of Lake Apopka. Assuming that one of the treatments proves successful and practical, the next step should be an optimization effort, the objective of which will be to develop specific dose and application criteria for full-scale application to the lake.

SECTION 1. INTRODUCTION

The water quality of Lake Apopka, Florida, has been progressively impaired by the effects of eutrophication, a lake condition typically induced through excessive nutrient loading and resulting in increased productivity and decreased diversity in lake biota. The St. John's River Water Management District (District) is attempting to improve water quality in Lake Apopka by identifying and mitigating nutrient loading sources to the lake. As part of this effort International Science & Technology, Inc. (IS&T) has conducted a literature review and preliminary feasibility analysis assessing in situ sediment decomposition as a technique for oxidizing organic lake sediments and decreasing sediment nutrient loading to the water column. The technology associated with in situ sediment decomposition applies biochemical or chemical processes, or a combination of both, and has its origins in wastewater treatment technology. This is not an established science; there is a limited amount of scientifically rigorous published literature documenting design criteria or even successful applications of this technology in lake management.

This study compiles and evaluates available information regarding in situ sediment decomposition, provides a preliminary assessment of the feasibility of the technology, and presents recommendations on further research and assessment activities in this area. Four specific techniques for sediment decomposition were investigated: microbial inoculation, nitrate application, hydrogen peroxide addition, and ozonation. The screening criteria that led to the selection of these four technologies are summarized below.

1. Engineered organisms (any organisms developed through gene-splicing technology) were not considered.

2. Technologies were limited to those intended to consolidate sediments through oxidation of the organic constituents. Techniques such as phosphorus inactivation were not considered,

per se, unless they resulted in sediment oxidation. A thorough investigation of the literature regarding phosphorus inactivation can be found in Baird and Bateman (1987).

3. Mechanical aeration was not specifically investigated as a treatment technology. However, the theory supporting mechanical aeration to decompose organic sediments is analogous to aerobic microbial decomposition, which is addressed in this study.

4. Mechanical dredging and drawdown were not considered in this study. Drawdown to effect sediment consolidation is addressed in Wedepohl et al. (1983).

In situ sediment decomposition technologies are not well documented in the peer-reviewed scientific literature (Hanson 1981, Crisman et al. 1984). Thorough investigation of research and field applications of sediment oxidation techniques required a review of the peer-reviewed and "grey" literature, as well as interviews with scientists and lake managers with experience in this field and commercial vendors of these technologies.

The following sections document the findings of this study. Section 2 describes the major decomposition processes of concern and characterizes the sediments in Lake Apopka in terms of these processes. Sections 3 and 4 provide a detailed explanation of the state-of-the-technology in biochemical and chemical sediment oxidation techniques, respectively. Section 5 describes the environmental and public health impacts of in situ sediment decomposition technologies. Section 6 provides a discussion and technical evaluation of the information presented in Sections 3 through 5. Section 7 consists of conclusions and recommendations for further investigation; and Section 8 provides an experimental design to implement the recommendations presented in Section 7.

The appendices provide access to the raw information used in developing this study. Appendix A is an annotated bibliography of the relevant literature. Appendix B lists all individuals interviewed for this project. Appendix C provides a listing of all commercial vendors interviewed and includes information regarding their product lines. Appendix D contains abstracts of relevant in situ sediment decomposition field studies. The information presented in Appendices A through D has been organized into an IBM-PC data base using dBASE III Plus. A description of this data base appears in Appendix E. Appendix F provides data summaries from the research results of relevant scientific studies.

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SECTION 2. BACKGROUND

Natural systems accumulate excess organic material when biological productivity exceeds the capacity to decompose this material. This can be the result of nutrient limitation, the presence of toxins, or other adverse environmental conditions that constrain decomposition. Attempts have been made to accelerate decay processes through combinations of chemical, mechanical, and biological intervention.

Technologies designed to enhance or induce the decomposition of organic sediments in lakes are critically examined in this report. Decreasing the organic content of sediments has the potential for improving water quality in eutrophic lakes by decreasing the oxygen demand of the sediments on the water column, inhibiting nutrient cycling from the sediments to the water column, and increasing the depth of the water column through sediment consolidation. This section describes decomposition processes in eutrophic lakes and characterizes the water quality and sediment conditions in Lake Apopka.

2.1 DECOMPOSITION PROCESSES

Organic material decomposes in natural systems through microbial activity under both aerobic and anaerobic conditions. The rates and specific mechanisms of decomposition depend on environmental conditions in the water column and sediments. Organic carbon in lakes is composed primarily of particulate and dissolved fractions originating from outside the lake (allochthonous) and of algae and macrophytes from within the lake (autochthonous). A large portion of the allochthonous organic material has already undergone microbial decomposition of the more labile, or easily reactive, compounds by the time it reaches the lake water column. Residual organic materials are relatively resistant to microbial decomposition (Wetzel 1975). Autochthonous organic material, primarily dead algae and macrophytes, decays rapidly in the water column. The initial decomposition is of the cellular contents of the plants. The cell walls are more resistant to decomposition (Wetzel 1975). Particulate organic material decomposes to varying degrees in the water column as it settles to the lake bottom. The organic content of the lake sediments, therefore, is governed by organic loading to the lake, organic production within the lake, and the capacity of the water column to decompose organic material.

In productive lakes that are capable of assimilating allochthonous and autochthonous organic material, labile organic compounds are decomposed in the water column, with the remaining, recalcitrant organic material deposited as relatively inert sediment. Productive lakes that are less efficient at processing labile compounds in the water column have sediments of higher organic content with greater potential for decomposition.

Organic carbon compounds that are resistant to decomposition, termed refractory or recalcitrant material, are composed primarily of cell structural material, such as cellulose, lignin, or chitin, and of other cellular compounds, such as tannins and melanins. These substances can be degraded by bacteria and fungi that possess specific mechanisms of substrate utilization. Thus, a wide variety of microbes may be necessary to effectively degrade refractory organic material in lake sediments (Hartenstein 1981).

Decomposition of organic material can occur under aerobic or anaerobic conditions. Under aerobic conditions, bacteria use oxygen as a terminal electron acceptor to process organic substrate as an energy source. An example is the common reaction that results in the aerobic oxidation of glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2$$

Aerobic microbial decomposition relies on oxygen as the hydrogen acceptor. Anaerobic decomposition involves complex processes providing organic hydrogen acceptors in the absence of oxygen. Methane fermentation is the predominate mechanism of anaerobic decomposition, by which organic material is converted quantitatively to methane and carbon dioxide in 2 stages. In the first stage, obligate anaerobic bacteria convert proteins, carbohydrates, and fats into fatty acids by hydrolysis and fermentation. The process is completed as methane-producing bacteria convert the organic acids to methane and carbon dioxide (Wetzel 1975).

Other anaerobic decomposition processes rely on the reduction of inorganic hydrogen acceptors, such as sulfate, nitrate, and nitrite. Sulfate reducing bacteria of the genera Desulfovibrio and Desulfotomaculum are obligate anaerobes and derive oxygen from sulfate for the oxidation of organic material. An example is the glucose reaction

$$C_6H_{12}O_6 + H_2SO_4 \longrightarrow 6CO_2 + 2H_2O + H_2S$$

which yields hydrogen sulfide, carbon dioxide, and water. Facultative anaerobic bacteria, such as Nitrosomonas or Nitrosococcus, perform the same initial degradation step by reducing nitrate and oxidizing organic substrate to nitrites, carbon dioxide, and water:

$$C_6H_{12}O_6 + 12NO_3 \longrightarrow 12NO_2 + 6CO_2 + 6H_2O$$

Nitrites are subsequently reduced to nitrogen gas through the following reaction:

$$C_6H_{12}O_6 + 6\ NO_2 \longrightarrow 3N_2 + 6CO_2 + 6H_2O$$

Because relatively inert nitrogen gas is the reaction product in complete denitrification, rather than potentially toxic methane or hydrogen sulfide gas, denitrification is a more desireable anaerobic decomposition process for lake restoration.

Denitrification has been observed to occur intensely in anaerobic environments and is frequently limited by the availability of nitrate (Chen et al. 1972, 1979). Nitrate can be generated through nitrification, the oxidation of ammonium to nitrate under aerobic conditions:

$$NH_3 \longrightarrow NO_2 \longrightarrow NO_3$$

Ammonia is formed in the water column and in flooded sediments through the deamination of proteins, amino acids, and urea (Wetzel 1975). Ammonia is converted to nitrate in the presence of oxygen and nitrifying bacteria. Consequently, anaerobic sediments frequently store high concentrations of ammonia.

2.2 LAKE APOPKA

Lake Apopka occupies 12,500 ha and has a mean depth of approximately 2 m. As part of a survey to assess the internal nutrient budget of Lake Apopka, Reddy et al. (1988) conducted an extensive monitoring program to characterize sediment and water column conditions in the lake. Sampling was conducted during the summer of 1987. Selected water and sediment quality and quantity observations from that investigation are summarized below as background information for this study.

Lake Apopka is considered highly eutrophic with dense, persistent phytoplankton communities. Reddy et al. (1988) reported chlorophyll a concentrations in excess of 150 ug/l, mean total phosphorus (TP) concentrations of 0.22 mg/l, and mean total Kjeldahl nitrogen concentrations of 4.92 mg/l in 1987.

Anaerobic conditions prevail in the sediments, although the loosely consolidated upper sediments are intermittently subject to aerobic conditions under the influence of mechanical wind mixing. Sediments may be divided into six categories: unconsolidated floc (UCF), consolidated floc (CF), peat (P), sand (S), clay (C), and marl (M). Of relevance to this study are the UCF and CF horizons. The UCF horizon represents loosely consolidated sediment composed primarily of dead algal cells and allochthonous particulate organic material and is "actively involved in resuspension and nutrient release during wave currents" (Reddy et al. 1988). The CF horizon consists of approximately the same material as the UCF horizon, but has a higher bulk density (is more compact) and contains more fiberous material. The average depths of the UCF and CF fractions were approximately 35 cm and 82 cm, respectively in 1987.

The sediments in Lake Apopka are moderately organic, averaging approximately 55 percent volatile solids (VS) in the UCF fraction and 59 percent VS in the CF fraction. Nitrogen analyses of sediment porewater indicate that the sediments are subject to "intense microbial activity and anaerobic conditions" (Reddy et al. 1988). Anaerobic conditions are indicated by extremely high ammonium concentrations, ranging from 3 to 110 mg N/l in the UCF fraction and 6 to 178 mg N/l in the CF fraction. Nitrate concentrations were at detection-limit concentrations, indicating active denitrification.

Organic constituents of the sediments were determined using acid detergent fiber (ADF) analysis. ADF is expressed as a percent of total organic carbon and identifies the organic carbon constituents that are most resistant to degradation. ADF can be further fractionated into the organic components cellulose/hemicellulose and lignin, the recalcitrant cell structural material. ADF concentrations in Lake Apopka ranged from 62 to 76 percent for the UCF fraction and 67 to 94 percent for the CF fraction. Cellulose/hemicellulose ranged from 19 to 40 percent in the UCF and 8 to 45 percent in the CF fractions. Lignin content was lower, ranging from 11 to 19 percent in the UCF and 8 to 21 percent in the CF fractions.

The ADF content in Lake Apopka is high, indicating the sediment has undergone significant microbial degradation. Degradable organic material in the sediments appears to be far from depleted, however, as reflected by the anaerobic conditions and high concentrations of ammonia. High ADF content may represent the residue of microbial degradation through nitrification-denitrification resulting from the intermittent aeration of ammonia-rich sediments. Reducing conditions in the sediments may be sustained by the continual deposition of dead algal cells and allochthonous organic material. Sediment accretion rates in Lake Apopka average approximately 1 cm/year (Pollman, pers. comm.).

Specific interactions at the sediment/water interface, particularly nutrient cycling to the water column and decomposition rates within the sediments are being investigated to support nutrient budget studies for Lake Apopka. Once the relative influence of the sediments on the water column has been determined, the potential impact of management alternatives, such as in situ sediment decomposition, can be further assessed.

SECTION 3. BIOCHEMICAL OXIDATION TECHNIQUES

Microbial degradation of organic sediments can be induced in aerobic or anaerobic environments. This section describes research and field applications of two technologies that attempt to induce microbial sediment oxidation. The first relies on the introduction of non-native microorganisms to both aerobic and anaerobic sediment environments. The second relies on native bacterial populations stimulated by introduced nitrate to oxidize sediments by denitrification under anaerobic conditions.

3.1 INTRODUCED MICROORGANISMS

Non-native microorganisms are introduced into eutrophic lakes with the intention of inducing water quality improvements that would not normally occur without such external intervention. Typically, proprietary microbial products are used in conjunction with lake restoration programs that include mechanical aeration and, occasionally, the addition of inorganic compounds that precipitate particulate organic matter. The products are intended to remove particulate and dissolved organic material from the water column and sediments through aerobic and anaerobic bacterial activity, including denitrification. Commercial suppliers report that the products are composed of mixtures of bacterial species, principally Bacillus, Rumenococcus, Arthrobacter, and related, non-pathogenic species. The products are reported to be free of Salmonella and related pathogens as prescribed by the U.S. Department of Agriculture. Moreover, concentrations of the potentially opportunistic pathogenic species of Pseudomonas spp. are reported to be less than 10^6 cells per gram of product. Total bacterial cell density in the product is stated to be 8×10^{10} colony forming units per gram (based on representative data from LaMonte Environmental Technology).

The theoretical foundation for water quality improvements through microbial inoculation is highly controversial and generally unsupported in the scientific literature. Manufacturers of such products claim that proprietary microbial products are designed to be added to the water column at concentrations sufficient for the introduced bacteria to outcompete the naturally occurring problem phytoplankton for dissolved nutrients (ammonium, nitrite, nitrate, phosphate, etc.) and thus improve water clarity in the water column. Increases in water clarity create conditions conducive to re-establishment of rooted aquatic plants.

3.1.1 Relevant Research

Lake restoration techniques that rely on introduced microorganisms are not well documented in the scientific literature. Documentation consists primarily of reports and case studies frequently prepared by, or in collaboration with, the producers of commercial microbial products. Of the available literature, very little has been published in peer-reviewed professional journals, or is of adequate quality for publication in the scientific literature.

The application of non-native microorganisms to improve water quality is often conducted in conjunction with mechanical aeration to oxygenate anaerobic bottom waters and promote circulation. Most manufacturers of microbial products claim that their products work under both aerobic and anaerobic conditions, as their products are composed of facultative microorganisms, but that aerobic conditions are preferable and can be induced through mechanical aeration.

Case studies documenting combined aeration and microbial inoculation have not established treatment or monitoring designs capable of distinguishing between the relative effects of mechanical aeration and microbial inoculation. It is therefore appropriate to examine laboratory studies that make such comparisons, field studies that apply mechanical aeration with microbial inoculation, and field studies that apply either microbial inoculation or aeration alone.

LABORATORY INVESTIGATIONS

Laboratory research has been conducted to quantify the effects of microbial inoculation on water quality and sediment composition. Of the available studies, only the investigation of Hanson (1981) specifically addressed sediment oxidation. In that study, eight in situ sediment digestion techniques were evaluated, including aeration and microbial inoculation. Organic sediments were collected from four eutrophic Wisconsin lakes. A summary of the chemical characteristics of the lake sediments appears in Appendix F. Sediment samples were placed in containers with lake water and subjected to a total of ten treatments (Table 1).

Treatments with introduced microorganisms were designed based on the manufacturer's instructions for product application. Where the manufacturer's recommendations were not followed, a control was run to determine the effect of deviating from the recommendations. Four variations on treatments with introduced microorganisms were tested, along with four additional controls (Table 2). These experiments were performed in duplicate, with one set receiving water column aeration and the other receiving both sediment and water column aeration (Hanson 1981).

The results of the five-week test run (Figure 1 and Appendix F) indicate that the treatments and controls were virtually identical in composition to the original sediments. Hanson (1981) presented three possible explanations for the lack of response of the microorganisms: (1) the microorganisms capable of using oxygen as an electron acceptor were not present, (2) the system was nitrogen or phosphorus limited, or (3) the system was carbon limited due to biochemical toxins inhibiting the microbes, or the microbes present were not able to decompose certain chemical structures. Because of the experimental design, Hanson (1981) considered the first and second possibilities unlikely. In support of the third possibility Jewell and McCarty (1971) observed that certain derivatives of chlorophyll are antibacterial and that the pigment melanin is a controlling factor in the decomposition of certain fungi. Hanson (1981) speculated that, with the onset of aerobic conditions, certain obstacles, such as the toxins described above, prevented effective use of available substrate (organic sediments) by microbial populations, even under favorable environmental conditions.

Hanson (1981) cited the observation of Hartenstein (1981) that a wide variety of bacteria may be necessary to decompose recalcitrant molecules because of the diversity of bond types. Similarly, the efficient aerobic

TABLE 1. TREATMENTS TESTED IN HANSON'S (1981) SCREENING STUDY OF EIGHT IN SITU SEDIMENT OXIDATION TECHNOLOGIES

Treatment	Description	
Bio Chemical	Electron Acceptor	Microbiological Population
1	Oxygen introduced into the sediment column	Native
2	Oxygen introduced into the water column	Native and proprietary microorganisms with nutrients adjusted
3	Oxygen introduced into the water column	Native and proprietary microorganisms without nutrients adjusted
4	Oxygen introduced into the sediment column	Native and proprietary microorganisms with nutrients adjusted
5	Oxygen introduced into the sediment column	Native and proprietary microorganisms without nutrients adjusted
6	Nitrate added to sediments which were first stabilized using two weeks of aeration	Native
7	Nitrate	Native
Chemical		
8	Hydrogen peroxide	
9	Ozone introduced into sediments which were first stabilized using two weeks of aeration	
10	Ozone	

Note: Proprietary microorganisms were supplied by Clean-Flo Laboratories, Inc.

TABLE 2. TREATMENTS AND CONTROLS FOR MICROBIAL INOCULATION TESTS FOR HANSON'S (1981) STUDY

	Treatment Description
Treatments:	
CF-1	Water column was aerated, nutrient adjustment was performed, and proprietary microorganisms were added.
CF-2	Water column was aerated, and proprietary microorganisms were added.
CF-3	Both the sediment column and the water column were aerated, nutrient adjustment was performed, and proprietary microorganisms were added.
CF-4	Both the sediment column and water column were aerated, and proprietary microorganisms were added.
Controls:	
CF Cont.-1	Water column was aerated, nutrient adjustment was performed, sediment was electrically grounded, proprietary microorganisms were added, and a variety of benthic organisms was added.
CF Cont.-2	Water column was aerated, nutrient adjustment was performed, sediment was electrically grounded, and proprietary microorganisms were added.
CF Cont.-3	Water column was aerated, nutrient adjustment was performed, sediment was electrically grounded, and a variety of benthic organisms was added.
CF Cont.-4	Water column was aerated, nutrient adjustment was performed, and sediment was electrically grounded.

Note: Electrical grounding was recommended by the supplier of the microbial product (Clean-Flo Laboratories, Inc.).

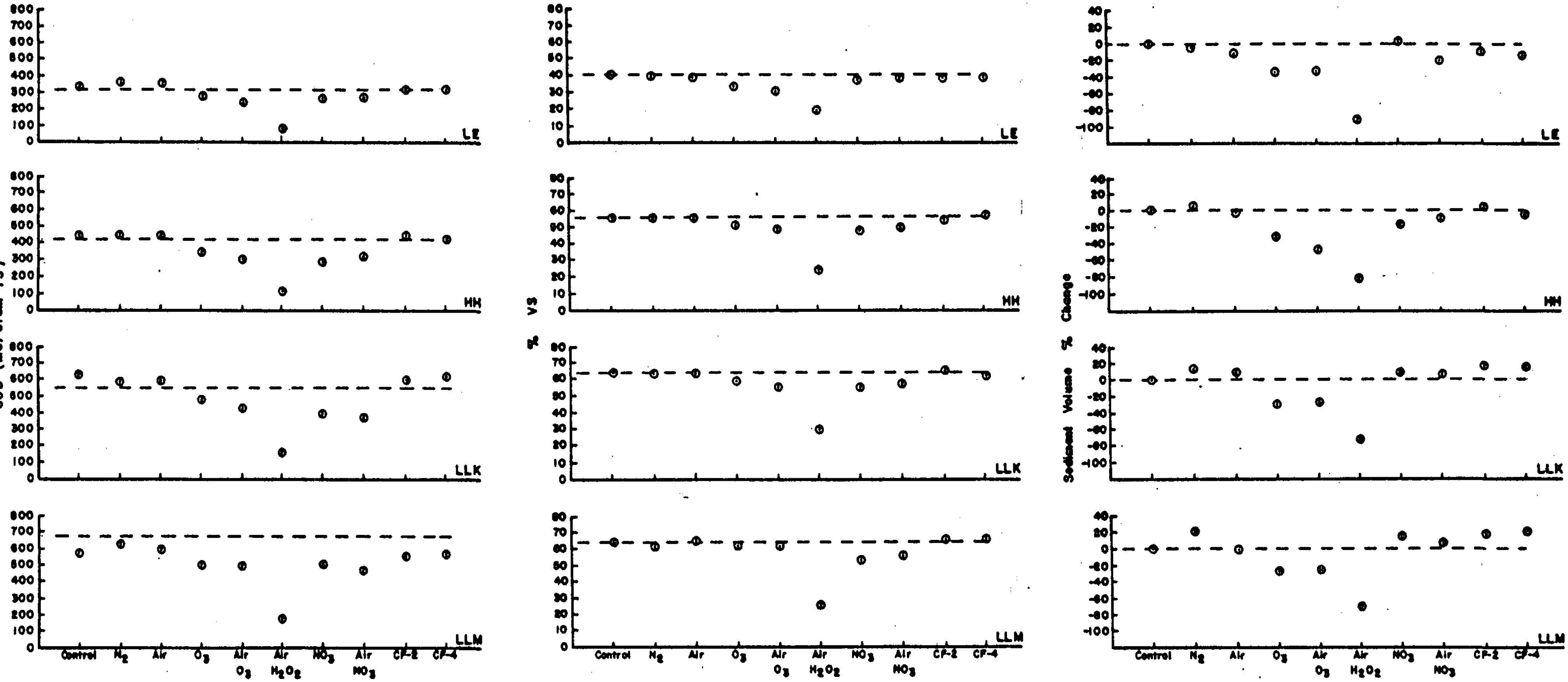

Figure 1. Results of Hanson's (1981) screening study of in situ sediment oxidation techniques. Removal of chemical oxygen demand (COD), percent volatile solids (%VS), and sediment volume change is plotted for each lake and treatment. Treatments are described in Tables 1 and 2.

decomposition of organic sediments requires the development of a diverse complement of microorganisms and decay mechanisms (enzymes, etc.). Hanson (1981) concluded that inoculating sediments with the correct mix of aerobes that have already developed these mechanisms "may be very difficult, if it is possible at all."

Jewell and McCarty (1970) observed an increase in decomposition rates of algae cultures inoculated with selected microorganisms under aerobic conditions. But Foree and McCarty (1971) found no significant differences in anaerobic algal decay in cultures with wide variation in bacterial inoculation. The authors provide no explanation for the difference in responses between aerobic and anaerobic cultures.

Tucker and Lloyd (1985) conducted an unpublished laboratory evaluation comparing the effectiveness of a commercial microbial product (Aqua-Bacta-Aid) in improving water quality in catfish-culture ponds in Mississippi. Tucker (pers. comm.) created sediment/water column microcosms using plastic tanks. Sediment organic content was approximately 3 percent volatile solids, which is considered typical of catfish-culture facilities. Treatments consisted of aerated and unaerated tanks inoculated with the microbial product, and aerated and unaerated controls. No difference was observed with application of the microbial product in any of the chemical parameters monitored, including sediment organic content, nutrients, biochemical oxygen demand (BOD), dissolved oxygen (DO), and turbidity. A field trial of the same product produced similar results (Tucker and Lloyd, 1985).

Blouin et al. (1988) examined the aerobic biodegradation of organic matter in swine waste using both inoculated and natural microbial populations. Swine waste supernatant was inoculated with selected microbial strains extracted from treated waste or activated sludge under aerobic conditions. No change was observed in the degradation of organic matter among inoculated and non-inoculated samples subjected to similar conditions. It should be noted that because the substrate was composed entirely of animal waste, specific degradation processes may not be typical of those occurring in Lake Apopka.

FIELD STUDIES: MECHANICAL AERATION

It is not strictly within the scope of this study to address mechanical aeration as a lake restoration technique. However, the majority of case studies documenting microbial inoculation use mechanical aeration to maintain aerobic conditions in the sediments and water column. Two studies attempted to quantify sediment removal associated with aeration: Little Muskego Lake, Minnesota and Lake Brooker, Florida. The former is currently underway and the latter has been completed and documented.

Little Muskego Lake in Muskego, Wisconsin, is being restored by mechanical aeration and circulation. Little Muskego Lake is eutrophic with summer phytoplankton blooms that impair uses of the lake. Nutrient loading from runoff and nutrient release from sediments have been identified as the forces driving eutrophication in the lake. The Little Muskego Lake Association contracted Clean-Flo Laboratories, Inc. (Appendix C) to install and maintain 72 aerators in the lake with the intention of improving water quality by disrupting summer stratification and supplying oxygen to the lower water column and organic sediments. It was the specific intention of the project to increase lake depth by decomposing organic sediments. The Wisconsin Department of Natural Resources, which has authority over lake restoration projects in that state, issued a permit for restoration of the lake through the use of mechanical aerators with the stipulation that water quality and sediment depth be monitored using reliable, repeatable techniques.

With the assistance of the USGS, which includes Little Muskego Lake in its water quality monitoring network, monthly samples are collected. Semi-weekly sampling is conducted during summer months. The water quality response to aeration in the first (1987) summer season was obscured by heavy rainfall, resulting in high levels of nutrient loading to the system. Data from the second (1988) summer season indicate decreases in nutrient concentrations. It is believed that these decreases are due primarily to drought conditions during that summer, which resulted in diminished nutrient loading from the watershed (Stephen Field, pers. comm.). Dissolved oxygen concentrations are reported to have increased, but consistent summer oxygenation to the lake bottom has not been observed (Mark Wolf, pers. comm.).

To map sediment depths, a sampling pattern was established with 18 cross-sections forming a grid with 400 ft. between nodes. To date, pre-treatment and post-treatment data have not been compared. This project is unique in its rigorous approach to sediment mapping. The final results are expected to provide reliable documentation of the sediment oxidation and consolidation performance of mechanical aeration.

Crisman et al. (1984) monitored the long-term response of anaerobic sediments in Lake Brooker (10.5 ha surface area, 4.0 m mean depth), near Tampa, Florida (Appendix D), to aeration. A monitoring program was conducted for one year before aeration and two years during aeration. The monitoring program included enumeration of sediment bacteria and analysis for sediment organic content, percent water, and adenosine triphosphate (ATP). ATP occurs at approximately the same proportion relative to carbon in all living cells and degrades rapidly after cell death. Thus sediment ATP provides an estimate of combined autotrophic-heterotrophic biomass and activity.

Assuming no nutrient limitation, and based on Hanson's (1981) premise that efficient mechanisms of substrate use will develop over time, a progressive increase is expected in the efficiency in the oxidation of organic sediments following aeration. Crisman et al. (1984) observed that there was no discernable response to aeration in sediment bacterial numbers, ATP, or organic content. There was no explanation for this phenomenon. Although microorganisms were not introduced into Lake Brooker, Crisman (pers. comm.) reported that bacteria were present at concentrations of 10^6/ml to 10^7/ml prior to, and throughout the study.

Crisman et al. (1984) attempted to quantify the volume of sediments oxidized in Lake Brooker, but could not develop a reliable method to measure sediment depth. Ideally, a marker horizon could be located in sediment cores and the depth of that horizon could be monitored during the restoration project. Such a marker was found in one area of the lake and comparisons of cores before and two years after aeration actually demonstrated an increase in the flocculent uppermost centimeters of sediment (Crisman et al., 1984), possibly due to sediment migration and disruption induced by water circulation.

Concurrent with the work of Crisman et al. (1984), Cowell et al. (1984, 1987) monitored other physical, chemical, and biological aspects of the Lake Brooker restoration effort, primarily oriented toward water column responses. It was concluded that many of the undesirable features of eutrophication were eliminated, but that the trophic state was not improved. Moreover, to sustain the beneficial effects of mechanical aeration, multiple years of treatment may be necessary (Cowell et al., 1987).

Gachter (1987) agreed with Cowell et al. (1987) with regard to the long-term response of hypereutrophic lakes to mechanical aeration and circulation. Lakes Baldegg and Sempach, two hypereutrophic Swiss lakes, were subjected to mechanical aeration and circulation. Gachter (1987) concluded that it is technically possible to improve redox conditions at the sediment-water interface, thereby inhibiting phosphorus release. The improvement in hypolimnetic redox conditions may accelerate the rate of recovery of a hypereutrophic lake restored by reduction of external phosphorus loading, but "oxygenation per se will hardly be able to cause a reduction of trophic state" (Gachter, 1987).

FIELD STUDIES: MICROBIAL INOCULATION

Field studies documenting the application of non-native microorganisms to eutrophic lakes have been conducted in both the presence and absence of mechanical aeration. None of the completed studies, however, reliably quantifies sediment oxidation. Muller (1987) is currently conducting and monitoring the restoration of Highland Lake (6 ha surface area, less than 1 m mean depth), Minnesota. Restoration consisted of diverting wastewater treatment plant effluent from the lake. In situ treatment consisted of mechanical aeration and the addition of proprietary microbial and inorganic (buffered alum) products. Aeration and microbial and chemical treatments began during the 1987 summer. Sediment and water column data collected before and during treatment are inconclusive. Sediment analyses for percent water, percent volatile solids, and percent ash weight for four sampling stations provide no consistent indication of organic material removal. Changes in lake depth were measured along one transect using a sonar chart recorder. The accuracy and precision of this method are considered inadequate to measure sediment oxidation. A report summarizing monitoring data for 1988 is currently under preparation (Muller, pers. comm.).

Mechanical aeration and microbial inoculation were conducted on Lake Theresa (6.5 ha surface area, 1.4 m mean depth), in Orlando, Florida to assess the sediment oxidation capability of a commercial microbial product (Palmer et al., 1987). Sediments in the lake were characterized as "black, gelatinous, unconsolidated sludge" before treatment and as "reddish in color and contained fragments of plant fiber" at the end of treatment. Sediment chemistry data were collected, but are not available. Sediment depth was measured at six stations in the lake using graduated stakes. At the end of the study, only two of the original six stakes could be located. Other than observations of the appearance of the sediments, no conclusions could be drawn regarding the effectiveness of the treatments with respect to sediment quality. Water column nutrients increased during treatment, but other water quality indicators improved: Secchi transparency increased and algal cell counts decreased (Palmer et al., 1987).

Laing (1979) reported that sediment oxidation in Lake Maggiore (160 ha surface area, 1.4 m mean depth), in St. Petersburg, Florida occurred as a result of mechanical aeration and application of a proprietary microbial product supplied by Clean-Flo Laboratories, Inc. Laing (1979) measured sediment thickness using a marked plastic tube. The tube was lowered into the water column until mild resistance was perceived and that depth was recorded as the top of the organic sediment layer. The tube was then pushed into the sediments as far as human exertion permitted. That depth was considered to be the top of the original lake bed material. This technique was performed at 9 stations on a total of 19 sampling dates. The original thickness of organic sediments averaged 1.4 m. A linear regression of organic sediment depth (measured as described above) over time was used to estimate sediment removal at each site. The resultant slopes (depth change/time) for each station were averaged by arithmetic mean to determine an overall sediment removal rate for the lake, reported to be 67 cm in 19 months (Laing 1979). This removal rate can be considered unreliable for several reasons. The method of measurement of organic sediment depth was arbitrary and not referenced to a known sediment horizon or other horizontal datum. Laing (1979) conceded that the measurement technique was unreliable because of inconsistencies in the amount of force necessary to push the marked tube to the proper sediment depths. Hanson's (1981) analysis of the Lake Maggiore data concludes that the linear regression technique applied by Laing (1979) was inappropriate because it failed to recognize that "the sediment surface topography is a dynamic three-dimensional system," and that linear regression analysis did not adequately account for sediment migration due to the circulation induced by the aeration process.

One lake restoration project is currently underway that applies a commercial microbial product without the assistance of mechanical aeration. Organic Research, Inc. (Appendix C) is conducting a pilot restoration study to assess the effectiveness of their proprietary microbial product in decomposing a portion of the organic sediment layer in Lake Effie (40 ha surface area, less than 1 m mean depth), in Polk County, Florida. Lake Effie is hypereutrophic with observed concentrations of total phosphorus (TP), total nitrogen (TN), and chlorophyll a of 1.5 mg/l, 10.5 mg/l, and 532 ug/l, respectively. Organic sediments in excess of 3 m and a maximum water depth of 1 m are present. The primary source of nutrient loading, effluent from a 1 million gallon per day treatment plant, was diverted from the lake in 1987.

The Lake Effie study will be conducted in 4 test chambers placed in the lake. The chambers are constructed of stainless steel pipes 2 m in diameter and long enough to be placed upright and extend from above the water line through a significant portion of the organic sediment layer. Organisms will be introduced, without aeration, to 3 of the 4 chambers; the remaining chamber will be used as a control. Water and sediment quality and sediment depth will be monitored for the duration of the study.

Field application of microbial products has been attempted in catfish culture ponds in the south (Boyd et al., 1984; Tucker and Lloyd, 1985). Boyd et al. (1984) treated four catfish ponds in Alabama with a commercial microbial product (Aqua-Bacta-Aid) and used four similar ponds as controls. The objective of the study was to verify the claims of the producer that their product would prevent off-flavor in fish; compete with blue-green algae; reduce nitrate, nitrite, and ammonia concentrations; lower phosphorus concentrations; and increase dissolved oxygen and rates of decomposition of organic matter. No significant difference was observed in concentrations of nitrate, nitrite, ammonia, TP, chemical oxygen demand (COD), or five-day biochemical oxygen demand (BOD_5), although it was noted that variability in these parameters was extremely high within treatments. There were no significant differences observed between treatments in the numbers of bacteria or phytoplankton. For bacterial enumeration, plate counts were used, which may be selective for certain strains of bacteria (Crisman et al., 1984). Thus, shifts in bacterial populations were not necessarily detectable. Significant differences were detected in DO on three sampling dates during the 150 day experimental period. These differences were not observed immediately following application of the microbial product. Treated ponds had significantly higher morning DO on those dates.

Tucker and Lloyd (1985) conducted a similar study on catfish ponds in Mississippi using the same microbial product (Aqua-Bacta-Aid). The results of the study were similar. No significant differences in water quality parameters could be detected.

Results of studies conducted in catfish-culture ponds cannot be readily extrapolated to Lake Apopka, because of differences in environmental conditions. Typically, catfish ponds are highly productive, yet maintain low quantities of particulate and dissolved organic material. The volatile solids (VS) content of sediments in such ponds ordinarily remains below 10 percent (Tucker, pers. comm.), while VS in Lake Apopka sediments average approximately 55 percent in the uppermost centimeters (Reddy et al., 1988).

3.1.2 Ancillary Effects

The potential public health effects associated with the application of microbial products to the water column are discussed in Section 5. Specific water column responses to microbial inoculation are not well documented. Commercial producers of microbial products claim that application results in substantial water quality improvements, as previously discussed, but these results have not been substantiated by reliable experimental data. Case studies documenting water quality improvement following the application of microbial products almost exclusively employ mechanical aeration as an adjunct to the treatment process, thus obscuring the relative effects of the product and aeration. Although there is no clear evidence that microbial inoculation improves water quality, there is no indication that application of microbial products impairs water quality.

3.1.3 Commercial Producers

Table 3 summarizes the commercial producers of microbial products commonly used in lake restoration. Other producers exist, but the companies listed in Table 3 represent those most active in lake restoration. Representatives of these companies were interviewed by Dr. Robert Hodson, Professor of Microbiology at University of Georgia. Interviews with technical representatives of each of these companies and a summary of product characteristics is provided in Appendix C.

3.1.4 Cost

The cost of microbial inoculation can vary considerably, depending on whether mechanical aeration is included in the project design. Water Quality Science, Inc. markets the product Aqua-Bacta-Aid S-1, which costs \$5/liter. At the manufacturer's recommended dose, the cost of the product would be \$15/ha. The microbial product C-Flo, marketed by Clean Flo Laboratories, costs \$52/kg; or \$6/ha at the recommended dose. The microbial product marketed by Bio-Treat Company costs \$25/ha. Extrapolated to Lake Apopka, material costs for treating the entire 12,500 ha surface area of the lake would range from \$75,000 to \$188,000.

TABLE 3. COMMERCIAL SUPPLIERS OF MICROBIAL PRODUCTS

LaMonte Environmental Technology, Inc.
Bio-Treatment Company
Clean-Flo Laboratories, Inc.
Creative Sales West
Organic Research, Inc.
Water Quality Sciences, Inc.

The costs provided above represent only one application of the product. As many as two or three applications per month may be required for an indefinite period for restoration operations. Additionally, the above costs include only the purchase of the microbial product. Costs associated with application, environmental monitoring, or additional water conditioning, such as aeration or treatment with chemical precipitants, are not included.

3.2 NITRATE APPLICATION

Lake restoration techniques involving nitrate application rely on the stimulation of biochemical denitrification. Typically, the principal objective in such restoration projects is to inactivate sediment phosphorus through nitrate-induced reactions, but a related effect of the treatment is anaerobic sediment oxidation through denitrification. This section examines these techniques and the potential for denitrification induced specifically for sediment oxidation.

3.2.1 Relevant Research

Manipulation of the nitrogen cycle has been proposed and attempted for lake restoration projects, typically to alter nutrient release at the sediment/water interface. Specifically, increasing rates of nitrification-denitrification can bring about nitrogen loss to the system and result in oxidation of organic material, as described in Section 2.1. Chen et al. (1979) investigated the possibility of aerating anaerobic sediments containing high concentrations of ammonia. In principal, aeration would induce nitrification of ammonia to nitrate. Removal of aeration would then allow the sediments to become anaerobic again. Under anaerobic conditions, nitrate was expected to be converted to nitrogen gas (N_2) through denitrification. Laboratory tests using eutrophic lake sediments indicated rapid and complete ammonia conversion to nitrate under aerobic conditions. However, denitrification of the evolved nitrate was not complete; up to 60 percent of the nitrate was converted to organic nitrogen rather than denitrified (Chen et al., 1979). While denitrification occurs most efficiently under anaerobic conditions, it has been observed to occur in the presence of oxygen, presumably due to facultative conversion at anaerobic microsites (Nakajima et al., 1984; Oleszkiewicz, 1986).

The studies of Chen et al. (1972, 1979) considered lake restoration through removal of bioavailable nitrogen. Other researchers attempted to immobilize phosphorus through nitrate addition, notably Ripl (1979, 1985, 1986) and Foy (1986). The mechanism of phosphorus inactivation is the sorption of phosphate onto insoluble ferric, Fe(III), oxides and hydroxides under oxidizing conditions. Particulate phosphorus and other organic material are removed through physical entrapment in the ferric hydroxide matrix (Cooke et al., 1986), as with aluminum sulfate (alum) treatment. The onset of anaerobic conditions reduces the ferric iron, to soluble ferrous iron, Fe(II). Ferric hydroxide compounds disassociate, releasing sorbed and sequestered phosphorus. The iron reaction is completed as ferrous iron combines with reduced sulfur (sulfide). Thus, the phosphorus binding capacity of iron degrades under anaerobic, or reducing, conditions as ferric iron converts to ferrous iron.

Nitrate is used to alter these reactions in several ways. The nitrate provides a mechanism for denitrification. Excess nitrate is added to oxidize organic material in sediments through denitrification, thereby decreasing the oxygen demand exerted in the sediments and favoring oxidizing conditions in the sediments. Additionally, nitrate reduction causes iron sulfides to convert to ferric iron and elemental sulfur. The ferric iron is then able to form iron hydroxide compounds and co-precipitate additional phosphorus. Essentially, this process can be reversed if oxygen and nitrate are exhausted. In that case, anaerobic facultative bacteria will use sulfate as the terminal electron acceptor and produce sulfide, and ferric hydroxide compounds will disassociate, releasing phosphate.

In some lakes, it may not be possible to inactivate sediment phosphate with calcium nitrate application. Cooke et al. (1986) observed that in shallow lakes with high pH and temperature, iron redox reactions may not control phosphate release. In such systems calcium nitrate application may not inactivate phosphate, although sediment oxidation would still occur under reducing conditions.

Ripl (1985) developed application technology and equipment, known as RIPLOX, to inactivate phosphorus and oxidize organic sediments using the reactions described above. Through laboratory tests, Ripl (1979) discovered that lake sediments may not contain adequate concentrations of certain chemical constituents to complete the necessary reactions. As a result Ripl conducts chemical and physical analyses of lake sediments for a broad range of parameters to determine appropriate treatment chemicals and doses (Geney, pers. comm.).

An example is the comparative success of RIPLOX treatment in Lake Lillesjon (4.2 ha surface area, 2.0 m mean depth) and failure in Lake Trekanten (13.4 ha surface area, 3.9 m mean depth), both in Sweden. Lake Trekanten was treated with calcium nitrate injected into the sediments. Low concentrations of iron were present in the sediments; and following treatment no improvements in hypolimnetic oxygen or phosphorus were observed (Forsberg, 1987; Lingren, 1986). In contrast, Lake Lillesjon (Ripl, 1979, 1985) was initially treated with 146 g Fe/m^2 ferric chloride ($FeCl_3$) to co-precipitate phosphorus. Slaked lime ($Ca(OH)_2$) was then added at a concentration of 180 g Ca/m^2 to offset acidity created by ferric chloride dissolution. Finally calcium nitrate ($Ca(NO_3)_2$) was added at a dose of 141 g N/m^2 (Ripl 1986). All chemicals were injected directly into the sediments at a depth of 15 to 20 cm below the sediment surface using a harrow device specifically designed for this purpose. The treatment was considered successful. Hypolimnetic TP and BOD decreased significantly. Denitrification in the sediments was calculated to occur at 3.2 g N/m^2/day, or in oxygen equivalents, 14.1 g O_2/m^2/day. Water column and interstital nitrate was removed to detection-limit concentrations within weeks following treatment (Ripl, 1986).

The RIPLOX treatment system has been applied in the United States on Long Lake, Minnesota (Willenbring, et al., 1984; Verner, 1985). The south basin of Long Lake (48.0 ha surface area, 3.0 m mean depth) was treated with $Ca(NO_3)_2$ to inhibit phosphorus release from anaerobic sediments. Tank studies indicated an optimum dose of 105 g N/m^2. Additional ferric iron was determined to be unnecessary (Willenbring et al., 1984). The response of Long Lake to treatment was an initial reduction in TP in the first year after treatment, with a deterioration in water quality to pre-treatment conditions in subsequent years (Noonan, Larson, pers. comm.). It is believed that external nutrient loading was responsible for the decline in water quality. In retrospect, the USA distributers of RIPLOX technology believe this response could have been predicted through a more thorough examination of the lake and watershed, resulting in either a different dosing plan or a recommendation that RIPLOX technology would be inappropriate for that lake (Geney, pers. comm.).

Ripl (1985) modified the RIPLOX approach to nitrate application for the restoration of the estuary Schlei (2,000 ha surface area, 2.5 m mean depth) in West Germany. Instead of direct injection of calcium nitrate into the sediments, diversion of nitrate-rich effluent from a tertiary wastewater treatment plant to the estuary basin was proposed. To develop a nitrate dose, denitrification studies were conducted in six in-lake enclosures (3 m x 3 m) installed in the estuary to a depth of 30 to 40 cm below the sediment surface and filled with water from the estuary. Synthetic effluent was introduced into the enclosures and sediment and water quality was monitored. Experimental results indicated that average denitrification rates varied with influent dose from 0.42 to 0.80 g $N/m^2/day$ for doses ranging from 5 to 15 mg NO_3-N/l, respectively. Ripl (1985) extrapolated these results to the entire estuary and concluded that an existing treatment plant was capable of inducing sufficient denitrification to oxidize organic material at a rate equalling or exceeding the rate of organic accretion in the Schlei. Ripl (1985) recommended that effluents from the treatment plant undergo "polishing" to remove phosphorus to a level 0.3 mg P/l or less and to nitrify the effluent to convert ammonia to nitrate.

Nitrate application to suppress sediment phosphorus release from anaerobic sediments was conducted on White Lough (7.4 ha surface area, 7.2 m mean depth) in Northern Ireland (Foy 1986). Laboratory experiments were initially conducted using sediment cores from White Lough to assist in dose determination. In the experiments, calcium nitrate ($Ca(NO_3)_2$) was injected into the top 20 mm of the sediment at doses ranging from 6.2 to 61.7 g N/m^2. Sediment and water quality was monitored. Test results indicated that phosphorus release decreased with increasing dose over a 200 day study period and that a nitrate dose of 30 to 60 g N/m^2 was necessary to prevent phosphorus release from the sediments.

The dose applied to White Lough was 23.7 g N/m^2, injected into the sediments early in the seasonal stratification period (May). Immediate post-treatment increases in hypolimnetic calcium and nitrate concentrations indicated that 25 percent of the calcium and 15 percent of the nitrate applied to the sediments escaped to the water column. The water quality response to treatment was a reduction in magnitude and delay in the seasonal hypolimnetic increase in phosphorus and iron concentrations, although phosphorus release from the sediments and hypolimnetic deoxygenation were clearly not eliminated. By the end of summer stratification, nitrate had virtually disappeared from the hypolimnion. Increases in ammonia concentrations following treatment indicate the reduction of nitrate to ammonium, although denitrification to elemental nitrogen was considered to be the dominant reaction (Foy 1986). Foy (1986) concluded that the treatment was not successful in eliminating phosphorus release due to inadequate nitrate dose.

The majority of research conducted on nitrate application considers denitrification and resultant sediment oxidation as a means of decreasing sediment oxygen demand. Laboratory studies by Hanson (1981) and Szewczyk (1984) specifically examined the effectiveness of nitrate application in oxidizing organic sediments. Hanson (1981) evaluated eight in situ sediment oxidation techniques that included nitrate application (Section 3.1.1). The experimental design consisted of two treatments. In the first treatment, sediments were aerated for a two week period; and in the second treatment, the sediments were allowed to remain quiescent for the same two week period. Nitrate was then applied to both treatments and the sediments remained quiescent for the remaining five weeks of the test (Hanson 1981). The dose was based on the amount of nitrate needed to satisfy the theoretical oxygen demand of the sediments as measured by COD. The following reaction predicts that a dose of 2.86 mg $Ca(NO_2)_2.4H_2O$ is required for every mg COD:

$$NO_3^- + 6H^+ + 5e^- \longrightarrow 0.5N_2 + 3H_2O.$$

The results of Hanson's (1981) study are summarized in Appendix F. Unfortunately, no determination of nitrate concentration or denitrification rate was conducted, so comparison with other studies or evaluation of completeness of denitrification can be made. Of the four lake sediments examined, three exhibited COD removal in the range of 32 to 37 percent for both treatments, volatile solids removal ranging from 10 to 14 percent, and sediment volume reduction ranging from -16 to +17 percent. The other lake sediment demonstrated substantially lower COD, VS, and sediment volume reduction at 11, 2, and 1 percent, respectively. The evident increase in sediment volume has been observed in other laboratory studies and is believed to result from the expansion of the flocculent inorganic residue of denitrification (Willenbring et al., 1984).

In comparison with aeration or inoculation with microbial products, Hanson (1981) found nitrate application to be a promising technology and concluded that readily-degradable organic material was effectively decomposed without adverse impact to the water column. Although sediment oxidation occurred, as indicated by changes in COD and VS, sediment consolidation did not occur. In two of four sediments tested, sediment volume actually increased and in all four sediments total solids increased, presumably due to generation of loose inorganic floc formed as a residue of denitrification. Willenbring et al. (1984) observed such a loosely consolidated floc in laboratory experiments applying calcium nitrate to organic sediments.

Hanson's (1981) investigation of in situ sediment oxidation technologies was followed by the research of Szewczyk (1984). Szewczyk performed laboratory studies of sediment from two of Hanson's sites and examined treatment combinations applying calcium nitrate, hydrogen peroxide, and mechanical aeration. Szewczyk's experimental design included calcium nitrate injection at three doses and three controls: no treatment, aeration, and ammonium application. The nitrate doses applied were 57, 113 and 170 g $Ca(NO_2)_2.4H_2O$ per 4 l sediment. The high

(170 g) dose corresponds to Hanson's (1981) stoichiometric dose calculation based on theoretical oxygen demand. The other doses, 57 and 113 g represent one third and two thirds of the high dose, respectively. All treatments and controls were conducted in duplicate. The ammonium control was established to determine whether effects of nitrate treatments were due to addition of nitrate as a deficient nutrient in the sediment, or to its oxidation properties (Szewczyk 1984). As with Hanson's study Szewczyk placed 4 l of sediment in 10 l jars, added 4 l deionized water, and allowed the sediment to stabilize for two weeks prior to initiation of the experimental run, 93 days in length.

The results of Szewczyk's (1984) study appear in Appendix F. The author reported no significant changes in water column parameters in the no-treatment control jars (Appendix F). Similarly, virtually no sediment degradation occurred in no-treatment jars and reduction in organic material was significantly higher in all treatments than in any controls, including the aerated control. With regard to the ammonium control, it was concluded that the sediment response to nitrate addition was not due to nutrient deficiency, because ammonia nitrogen was essentially unaltered at the end of the test period, while nitrate concentrations in the calcium nitrate treatments decreased through denitrification.

Analysis of variance indicated no significant difference in COD, VS, or sediment volume response to varying nitrate doses. Szewczyk (1984) concluded that the lowest nitrate dose applied, 57 g $Ca(NO_2)_2.4H_2O$ per 4 l sediment was optimal for both lakes. Neither Hanson (1981) nor Szewczyk (1984) reported any reduction in sediment volume at any nitrate dose for either lake sediment. While decreases in sediment volume were not evident, the organic content of the sediment decreased. COD removal ranged from 17 to 54 percent.

While Szewczyk's (1984) and Hanson's (1981) studies are unique in addressing the sediment oxidation capabilities of in situ treatments, they do not analyze the response to more common lake management objectives, such as efficiency of denitrification or inhibition of phosphorus recycling.

3.2.2 Ancillary Effects

Potential public health impacts of in situ sediment decomposition technologies are discussed in Section 5. Nitrate application causes little adverse impact on water column quality. The biological processes that are induced result in mineralized nutrient forms or nitrogen gas. In the case of induced denitrification through treatments using combinations of ferric chlorides, calcium nitrate, and other chemical conditioners, toxicity to fish has not been detected. In bioassays Willenbring et al. (1983) determined that a calcium nitrate dose of 140 g N/m^2, applied to Long Lake, MN, exhibited no adverse effects on fathead minnows. An LC50 of a 66 percent solution of $Ca(NO_2)_2 \cdot 4H_2O$ was determined to be 0.78 g N/m^2.

Nitrate application can lead to improved water quality conditions. If sediment phosphorus loading is controlled by iron redox reactions (Section 3.2.1), then phosphate release to the water column should decrease significantly following nitrate treatment (Cooke et al., 1986). If ferric chloride is applied as a component of that treatment, water column phosphorus should decrease in concentration through co-precipitation as ferric hydroxide is formed. The chemical matrix formed by ferric hydroxide should also sequester particulate organic material, including phytoplankton cells and inorganic particulate material, resulting in increased water column transparency.

3.2.3 Commercial Vendors

Calcium nitrate application technology is marketed in the United States by Aqua Technique. Aqua Technique distributes the RIPLOX technology, which includes the mechanical apparatus for injecting calcium nitrate into lake sediments. Aqua Technique also provides technical expertise and laboratory analytical support in developing treatment designs for specific projects. Further information is provided in Appendix C.

3.2.4 Cost

Application costs for nitrate treatment depend on the specific dose of calcium nitrate needed and on whether additional chemicals, such as lime or ferric chloride are required. Treatment operations on Lake Lillesjon used RIPLOX application equipment to apply calcium nitrate, lime, and ferric chloride. The resulting application cost was $\$1.33/m^2$ in 1980 dollars. RIPLOX treatment on Long Lake, MN, where only calcium nitrate was applied, cost $\$1.10/m^2$. Nitrate treatment was considered for Green Lake, in Seattle, WA., where the projected cost was estimated to be $\$0.74/m^2$.

Typically RIPLOX applications treat approximately the top 20 cm of organic sediment. Because the UCF and CF sediments in Lake Apopka are approximately 120 cm deep on average, scaling up the costs listed above will not reflect the alterations in technology required to treat sediments that deep, nor will it reflect the large surface area to be treated. However, applying linear scaling of the average treatment cost listed above, and assuming a surface area of 12,500 ha and 1.2 m of sediment depth, the treatment cost would be approximately $790 million.

SECTION 4. CHEMICAL OXIDATION TECHNOLOGY

Organic sediments can be decomposed by reactions involving chemical free radicals. These free radicals form from compounds with highly reactive oxygen groups. The two chemical oxidants examined in this study, hydrogen peroxide and ozone, have been applied for both water treatment and lake sediment oxidation.

4.1 HYDROGEN PEROXIDE

4.1.1 Relevant Research

Hydrogen peroxide (H_2O_2) is commonly used in wastewater pretreatment for BOD, odor, and solids removal (Cole et al. 1974, 1976; Weber 1972). In natural systems, fungi use H_2O_2 with the enzyme pyroxidase to degrade humic substances (Hartenstein 1981). Research in the use of H_2O_2 for lake management has been conducted in field experiments by Barroin (1980) and laboratory experiments by Barroin and Feuillade (1986), Hanson (1981), Soares (1980), and Szewczyk (1984).

Barroin (1980) applied H_2O_2 to the anaerobic hypolimnion of lac du Morillon (0.4 ha surface area, 2.7 m mean depth) specifically to eliminate sulfide production and concentration in the lake. It was predicted that sulfide removal would occur by three mechanisms: direct oxidation of H_2S to elemental sulfur or sulfites to sulfates, oxygen evolution by the H_2O_2 under oxidizing conditions, and direct oxidation of the sulfur-reducing bacteria. To determine the approximate H_2O_2 dose, Barroin (1980) assumed that only sulfide oxidation consumed H_2O_2, and H_2O_2 uptake by the sediments would be negligible. The final dose for lac du Morillon was 457 kg of 35 percent liquid H_2O_2 to oxidize 150 kg of sulfide-sulfur, applied at depths of 1.5 m (280 kg) and 4 m (175 kg). To monitor the chemical reactions occurring in the water column, Barroin (1980) employed a simple but ingenious technique demonstrated by Hayes et al. (1958); a rusty iron rod was placed vertically in the water column and experienced changes in visible characteristics depending on the chemical reactions taking place (Table 4).

TABLE 4. SURFACE APPEARANCE AND CORRESPONDING COMPOUNDS SHOWN BY AN IRON ROD PLACED IN DIFFERENT PHYSICO-CHEMICAL ENVIRONMENTS (HAYES ET AL., 1958)

Surface Appearance	Compound
Rusty, gelatinous	Ferric hydroxide
Blackish, gelatinous, turning fast rusty exposed to air	Ferro-ferric hydroxide
Black, porous, even exposed to the air	Iron sulfide
Cleaned metal	Elemental iron
Yellow-green, spotted	Elemental sulfur

Lac du Morillon responded to treatment with an immediate 82 percent decrease in sulfide and a 38 percent increase in dissolved oxygen. Since the dose was designed to remove 100 percent of the available sulfide, Barroin (1980) speculated that a fraction of the H_2O_2 descended to the lake sediments before reacting with sulfide. Concentrations of sulfide increased to pre-treatment levels within one week of treatment. It was concluded that the sulfur-reducing bacteria residing in the sediments were not destroyed by the treatment and resumed sulfide production as soon as the H_2O_2 dose had been exhaused and reducing conditions returned to the sediments.

Soares (1980) conducted laboratory studies on the biological effects of H_2O_2 application to eutrophic lake sediments. H_2O_2 treatments resulted in the complete elimination of benthic macrofauna, and possibly microflora as well, with subsequent recolonization by sulfur-reducing bacteria. Mortality resulted from oxidation by the H_2O_2, but also by H_2O_2 reaction products. Toxic concentrations of ammonium, sulfide, and copper ion were released through the oxidation of organic material. Following oxidation, Soares (1980) observed the onset of reducing conditions, presumably brought on by the renewed activity of reducing bacteria. The H_2O_2 application was effective in removing 30 percent COD (Soares, 1980).

Hanson (1980) and Szewczyk (1984) included hydrogen peroxide treatment in their laboratory studies of in situ sediment consolidation techniques (Sections 3.1.1 and 3.2.1). Hanson (1981) treated four eutrophic Wisconsin lake sediments with 30 percent liquid H_2O_2 (applied directly to the sediments). The H_2O_2 dose was determined from theoretical oxygen demand. The equation

$$H_2O_2 \rightarrow O_2 + 2H^+ + 2e^-$$

predicts that 2.1 mg H_2O_2 are required to produce 1 mg O_2. Thus, the H_2O_2 dose for the four lake sediments ranged from 143 to 176 grams H_2O_2 per 4 l sediment (Hanson, 1981).

The results of Hanson's (1981) study (Figure 1 and Appendix F) indicate highly efficient oxidation of organic sediments. COD decreased by 69 to 74 percent, VS decreased by 54 to 58 percent, and sediment volume decreased by 72 to 89 percent. Of the eight in situ sediment consolidation technologies examined by Hanson (1981), H_2O_2 treatment was, by far, the most effective at removing organic material.

Water column quality, however, was seriously impaired. Dissolved carbon, phosphorus, and nitrogen concentrations in the water column greatly increased and pH decreased by 2 to 4 pH units. Detrimental water quality effects aside, Hanson (1981) considered H_2O_2 treatment to be the most effective method tested and recommended further investigation using H_2O_2 as a "sediment conditioner" to degrade recalcitrant organic material. Hanson (1981) recommended a post-treatment lime application to adjust pH, and a final treatment for uptake of soluble nutrients and organic carbon, using either nitrate or aeration combined with microbial inoculation.

Szewczyk (1984) continued Hanson's (1981) research by conducting experiments on sediments from two of Hanson's (1981) sites (identified as LE and LLM). Four treatments were established. All treatments included a dose of 205 g of liquid H_2O_2 per 4 l sediment. Five days after H_2O_2 treatment, pH was adjusted to pH-neutral conditions with lime ($Ca(OH)_2$). Treatment 1 consisted of H_2O_2 addition and pH adjustment only; Treatment 2 included aeration following pH adjustment for the remainder of the 93 day experimental run; Treatment 3 included aeration and inoculation of 100 ml activated sludge following pH adjustment; and Treatment 4 was similar to Treatment 3 with the addition of 170 g of calcium nitrate ($Ca(NO_3)_2$).

Experimental results are presented in Figure 1 and Appendix F. Decreases in COD ranged from 32 to 76 percent, VS decreases ranged from 40 to 55 percent and sediment volume decreased from 52 to 79 percent. All H_2O_2 treatments were highly efficient in oxidizing lignin and cellulose. Removal of lignin ranged from 60 to 77 percent and cellulose removal ranged from 59 to 84 percent. The objective in Treatments 2, 3, and 4 was to protect overlying water quality. Although Treatments 2, 3, and 4 did affect final sediment and water quality, water column nutrient and organic carbon concentrations were clearly excessive. Szewczyk (1984) concluded that while the sediment oxidation capacity of H_2O_2 was great, the high cost and adverse environmental impacts render the technology impractical.

4.1.2 Ancillary Effects

Chemical oxidation techniques can severely impair water quality. The strong oxidants injected into the sediments (H_2O_2 or ozone) react directly with carbon constituents of complex organic molecules resulting in the solubilization of nutrients and organic carbon and consequently producing elevated dissolved nutrient concentrations. Soares (1980) observed high concentrations of organic carbon, nitrogen, ammonium, sulfite, and copper ion following H_2O_2 application in a laboratory experiment. That same experiment revealed 96 to 100 percent mortality of benthic macrofauna and the same response by microflora. Benthic macrofaunal mortality was caused by direct oxidation, as well as the liberation of toxic concentrations of sulfide, ammonium, and copper.

The laboratory experiments of Hanson (1981) and Szewczyk (1984) indicated a dramatic increase in water column nutrients as well as pH depressions of 2 to 4 pH units following H_2O_2 and ozone treatment. The pH depression could not be explained, but occurred in all treatments. Fish toxicity resulting from the application of chemical oxidants in lake restoration efforts has not been documented in the literature.

4.1.3 Commercial Producers

Liquid hydrogen peroxide is available in bulk from DuPont Chemical Company and Degussa Chemicals, among others. DuPont's H_2O_2 product line, known as ALBONE 35, a liquid hydrogen peroxide product delivered as a 35 percent solution. DuPont has another product, ALBONE 70, a 70 percent H_2O_2 solution. ALBONE 70 may present safety problems, because of its high concentration of H_2O_2.

4.1.4 Cost

DuPont's ALBONE 35 can be delivered in bulk as a 35 percent solution at a cost of \$0.107/kg, not including delivery. The dose applied by Hanson (1981) was 54 kg H_2O_2/m^2, assuming a treatment depth of 120 cm. The resultant cost product cost for treatment would be approximately \$48/m^2. Additional costs would include product delivery, application equipment costs, and labor. Extrapolating to the entire 12,500 ha surface area of Lake Apopka, material costs would be approximately \$7 billion.

4.2 OZONATION

4.2.1 Relevant Research

Ozone (O_3), like H_2O_2, is used in water treatment for its powerful oxidizing capability. Ozonation is virtually unknown as a lake management technology. Other than a project report (Water Management, Inc.), Hanson (1981) provides the only known documentation of ozone application to oxidize lake sediments. Historically, ozone has not been used in lake management because ozone generation equipment is expensive, relatively immobile, and requires a source of pure oxygen gas. The ozonation unit used by Hanson (1981) produced 2 percent O_3 gas in a carrier gas of 98 percent O_2. Ozone application was included in this study because recent advances in ozone generation technology have made ozone a more accessible oxidant (Section 4.2.3).

Hanson's (1981) experimental design consisted of two treatments consisting of 4 l lake sediment with 4 l deionized water. Treatment 1 was aerated for 4 weeks prior to ozonation and Treatment 2 remained quiescent for 4 weeks. Ozone treatment lasted approximately 3 days for both treatments, followed by approximately 4 days of quiescent conditions. As with Hanson's other experiments (Sections 3.1.1, 3.2.1, 4.2.1) the ozone dose applied was based on the theoretical oxygen demand of the sediments, predicted by the equation

$$O_3 + 2H^+ + 2e^- \longrightarrow O_2 + H_2O$$

which indicates that 2 mg ozone is required for each 1 mg oxygen demand (Hanson 1981).

Hanson's experimental results appear in Appendix F. Decreases in COD ranged from 10 to 25 percent; VS decreases ranged from 0 to 17 percent; and sediment volume decreases ranged from 27 to 33 percent. Oxidation of organic material was significantly lower than any of Hanson's H_2O_2 treatments (Section 4.1.1) and was comparable to removal observed in his nitrate treatments (Section 3.2.1). Hanson (1981) speculated that ozone attacked different organic constituents than nitrate. While COD and VS decreases were similar among ozone and nitrate treatments, sediment volume decreased significantly in ozone treatments relative to nitrate treatments, possibly indicating removal of cell structural material, such as lignin. However it does not seem likely that ozone would oxidize recalcitrant substances without also oxidizing the more easily degradable material attributed to oxidation by denitrification. The response of the water column to sediment ozonation is analogous to that of H_2O_2 treatments. Following ozonation, water column concentrations of phosphate and TKN increased significantly and pH decreased by 2 to 4 units. Hanson (1981) concluded that the excessive cost of ozone generation and the adverse impact of ozone treatment on water quality made this technology inappropriate for use in lake management.

4.2.2 Ancillary Effects

The water quality response of applying chemical oxidants to organic sediments is described above in Section 4.1.2. Public health implications are discussed in Section 5.

4.2.3 Commercial Vendors

Recent discoveries in ultraviolet (UV) light technology resulted in the development of an inexpensive method of generating a "highly reactive ionized oxygen gas plasma," known as "activated oxygen," and commercially produced under the trademark "PHOTOZONE" (Water Management, Inc.).

Commercial literature indicates that PHOTOZONE is composed of ozone, hydroxyl radical (OH), hydrogen dioxide (HO_2), H_2O_2, atomic oxygen (O), and other oxidants (Table 5). The manufacturer, Water Management, Inc., claims that PHOTOZONE generation requires 3 to 5 kw-hours to produce one pound of ozone, in comparison with 8 to 12 kw-hours to produce one pound of ozone using conventional methods. PHOTOZONE is generated using a patented process whereby air is passed through a cylindrical treatment cell and exposed to UV radiation. In the case of sediment oxidation, the treated air would then be pumped into the organic sediment zone.

PHOTOZONE units are typically installed in water systems that are highly sensitive to biological growth, such as water supply treatment plants, air stripping towers, and swimming pools. A PHOTOZONE system was used in the 1.6 MGal McDonalds olympic swimming pool for the Los Angeles Olympics in 1984. The system operated in place of chlorine disinfection units. PHOTOZONE has been used in lake management. Appendix C includes a project report documenting its installation. Interestingly, the PHOTOZONE representative contacted for this study stated that PHOTOZONE no longer markets their product for lake management projects.

4.2.4 Costs

Representative equipment and energy costs for ozonation may be derived from the literature distributed by the manufacturer of PHOTOZONE units. PHOTOZONE generators are available in a wide range of sizes, depending on the requirements of the specific application. The smallest units (single bulb) are capable of treating in excess of 2,000 gallons per day and cost approximately $5,000. Units suitable for continuous application (e.g., in reservoir aeration systems) utilize up to 10 proprietary UV bulbs and cost approximately $20,000. Energy requirements for these particular units are modest, ranging from 100 to 600 watts.

Energy consumption will be the most expensive aspect of ozonation. Considering literature values of approximately 5 kw-hr to generate 1 pound of ozone, Hanson's (1981) ozone dose of 75 g O_3/l of sediment, and energy costs of $0.041/kw-hr (supplied by Florida Power and Light),

TABLE 5. THE COMPOSITION OF PHOTOZONE ACTIVATED OXYGEN (WATER MANAGEMENT, INC.)

Constituent	Percent
Ozone	66.7
Hydroxyl radical, OH	14.7
Hydrogen dioxide, HO_2	6.3
Hydrogen peroxide, H_2O_2	5.9
Atomic oxygen, O	4.4
Other oxidants	2.0
Nitrogen oxides, NO_x	0.1

energy costs to oxidize the UCF and CF sediments in Lake Apopka would be approximately $3 billion.

Additional costs are incurred in construction of enclosures, procurement and operation of a barge or similar platform for the ozonator and compressor plants, and electrical power generation on-site (e.g., generator). Capital costs for a continuous aeration system in a 3,000 acre-ft. reservoir was estimated by Water Management, Inc. to be $167,000, with an annual operating cost of approximately $36,000. It is not possible to project large-scale treatment costs for Lake Apopka until the performance characteristics of this technology are quantified for the specific conditions found in the lake.

SECTION 5. PUBLIC HEALTH IMPLICATIONS

During lake treatment operations, risk to public health could occur during the application process, where concentrations of chemicals and/or microorganisms are highest, or after application has been completed as a result of chemical or biological transformations in the sediments or water column. None of the biological or chemical products considered in this study appear to present a human health hazard. Genetically engineered organisms were specifically excluded.

Based on data available at this time, it is not anticipated that the bacteria in commercially available microbial products present major public health risks. This conclusion is based on the fact that most commercial microbial products have received fairly wide use in treating aquaculture ponds and raceways without noticeable adverse effects on the health of the fish (or shrimp, etc.) or the human consumers of the fish. Most commercial microbial products have been approved for use in U.S. Department of Agriculture inspected plants and the sludge left by some products after degradation reportedly has been pressed and sold as cattle feed (W. Fuller, Bio-Treat Company, pers. comm.).

The products are claimed to be free of coliforms and other bacteria pathogenic to humans. Regular independent monitoring for the presence of Salmonella, Pseudomonas, etc. would not be difficult to conduct, if one of the products were selected for large-scale treatment of Lake Apopka. Natural turnover of the bacterial population of the water column would result in the removal of added bacteria in a period of days or weeks via grazing by zooplankton.

Care needs to be taken to minimize exposure of humans to high concentrations of bacteria during treatment operations. Possible sources of exposure include aerosolization of droplets from the water surface during product application. Additionally, monitoring would be necessary to assess the physical (e.g., current mixing) conditions in areas under treatment to insure adequate dilution and dispersal of the microorganisms and prevent exposure to high, undiluted concentrations. Procedures for such a monitoring program can be developed and optimized as actual cell densities needed to treat various areas of the lake are determined.

A possible public health risk indirectly related to remediation efforts, whether microbiological, chemical, or physical, is the release from the sediments (and consequent activation) of the pathogenic amoeba, Neaglaria fowleri. This organism has been demonstrated to cause disease (though rare) and death in humans in subtropical waters including lakes in central Florida. The problem is especially troublesome in small lakes and lakes that have extensive areas of shallow water. Generally the organism exists as a non-pathogenic encysted form in sediments until water temperatures exceed approximately 32 °C, whereupon it converts to a free-living form and can enter the human body through mucous membranes. In cases of infection, prognosis is generally poor and death can result in as little as six days, especially in children and other immunologically compromised individuals. In studies at a new reservoir on the Savannah River Plant facility in South Carolina, potentially dangerous concentrations of this organism were found in the water column during the first two years after the reservoir was filled, particularly during warm summer months and when water temperature was elevated by effluents from a nuclear reactor (Dr. Robert Hodson, University of Georgia Department of Microbiology, pers. comm.).

The existence of this organism in Lake Apopka has not been investigated for this study. However, prior to implementation of in-lake restoration activities, population studies are recommended to determine initial densities and, more importantly, to determine what, if any, effects may result from large-scale disturbance of the organic sediments that may harbor the dormant cysts of this organism.

Public health risk associated with other treatment technologies considered in this study are probably limited to safety issues associated with the application process. Chemicals that may be handled in bulk include calcium nitrate, calcium oxide, ferric chloride, hydrogen peroxide, and ozone. These chemicals are routinely handled for industrial processes. In the interest of safety during field application operations, the development of project-specific safety plans is recommended. Safety plans should conform, at a minimum, to Occupational Safety and Health Act (OSHA) standards and clearly explain safety precautions and appropriate responses to emergency situations. Additionally, a safety officer should be assigned to each project with the responsibility of assuring that workers conform to safety standards. This will include announced and unannounced safety inspections at the worksite.

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SECTION 6. DISCUSSION

This project assesses the technology of in situ oxidation of organic lake sediments. Four technologies were examined: microbial inoculation, nitrate application, hydrogen peroxide addition, and ozone addition. Information was collected primarily by searching the peer reviewed literature, academic theses, project reports, and unpublished data and interviewing experts and commercial suppliers. Results were presented in Sections 3, 4, and 5. This section discusses the results in terms of the demonstrated success of the technology, the soundness of the theoretical basis for the technology, and the expected feasibility and economy of application to Lake Apopka.

6.1 MICROBIAL INOCULATION

The technology of microbial inoculation to improve water quality is based on highly controversial scientific theories. Commercial microbial products are claimed to improve water quality and degrade particulate organic material in the water column and sediments. In the water column, the products are intended to be added at sufficiently high concentrations to outcompete phytoplankton for dissolved nutrients (ammonium, nitrite, nitrate, phosphate, etc.), resulting in a decrease in algal concentrations and turbidity in the water column. Improved water clarity, in principal, would lead to re-establishment of rooted aquatic plants. The introduced microorganisms would also remove organic material through heterotrophic bacterial activity, including denitrification.

In eutrophic lake systems that undergo no perturbation other than microbial inoculation, the product added must compete with the native bacteria and phytoplankton that have adapted to the lake environment. Controversy regarding the efficacy of microbial inoculation is based on the principal that if it is environmentally possible for a substrate to be used as an energy source, mechanisms will have developed over time to efficiently use that substrate. In eutrophic lake systems that are mechanically aerated and augmented by microbial inoculation (which is typically the case if microbial products are applied), the same fundamental premise applies. Aerobes will quickly replace anaerobic bacteria and oxidation processes will proceed under aerobic conditions (Dunst et al., 1974; Fast, 1971).

Degradation of particulate organic material requires a diverse complement of microorganisms and decay mechanisms (enzymes, etc.) to decompose the diversity of bond types present (Hartenstein 1981). Hanson (1981) conducted the most rigorous known laboratory study assessing the effectiveness of introduced microbial products in decomposing organic sediments. Testing four microcosm treatments conducted in duplicate, with sediment aeration and with water column aeration only (Section 3.1.1), the author could discern no difference in sediment quality among treatments and controls. It was concluded that it would be very difficult, and maybe impossible, to inoculate sediments with the specific and correct mix of microbes that have developed decay mechanisms specifically suited to the lake conditions.

Given the general capability of native microbial populations to adapt to complex substrate types, the presence of excessive substrate (accumulated organic material) indicates that accretion rates are greater than the processing rates of the microbial population. This could be caused by nutrient limitation or toxicity (Jewell and McCarty, 1971). Either of these conditions would also limit the effectiveness of introduced microorganisms (unless toxins to native populations were non-toxic to introduced microbes).

Proponents of microbial inoculation contend that the function of inoculation is not simply to augment native microbial communities to induce specific decomposition functions that could not otherwise occur. Rather, microbial inoculation is effective because the numbers of active bacteria and enzymes introduced to the system are orders of magnitude higher than ambient native populations. As a result, the system undergoes a transient period of intense bacterial activity as these bacteria consume substrate (dissolved nutrients, organic carbon, etc.).

An implicit assumption is that this intense level of activity is not sustainable, which is why re-application is necessary with all commercial microbial products. Following application, microbial populations decrease to a level sustainable by the system. It is the pulse of bacterial activity immediately following application that brings about changes in the system. Commercial suppliers of these products claim that, while the effects are temporary, with sufficient re-application they will result in the establishment of a more stable ecosystem (e.g., development of rooted macrophytes in place of phytoplankton).

The contention that microbial inoculation is effective because it creates a transient pulse of bacterial activity is vulnerable to several arguments. Assuming that introduced bacteria were capable of outcompeting phytoplankton for dissolved nutrients, bacterial biomass would be produced in place of phytoplankton biomass, presumably causing levels of turbidity similar to the phytoplankton. Additionally, replacing phytoplankton with bacteria removes an important source of oxygen in eutrophic lakes. In eutrophic lakes the cycle of oxygen production during daylight hours and consumptive respiration during low-light conditions frequently results in a net oxygen gain, commonly causing oxygen saturation or super-saturation (Wetzel, 1975). As bacteria outcompete phytoplankton, oxygen consumption may exceed oxygen production, resulting in anaerobic conditions in the water column.

Introduced microorganisms would also be subject to the same substrate-use limitations as the native microbial population. Nutrient limitation or the presence of toxics, described above, would affect the success of inoculation. An example of substrate limitation is denitrification. Eutrophic lake sediments are commonly anaerobic and microbial activity by native microorganisms will maintain nitrate at low concentrations (Wetzel, 1975). In such cases, inoculation with facultative anaerobic bacteria cannot result in additional denitrification because of nitrate limitation.

Certain conditions, however, may favor substrate uptake by the introduced microbes that would not ordinarily occur with native populations. In an untreated natural system, total numbers of native microorganisms may be limited by zooplankton grazers. The application of high concentrations of active microbes may then allow additional substrate uptake associated with the temporarily elevated microbial numbers. However, zooplankton populations will quickly increase in number in response to the increased microbial population.

The theory that microbial products contain sufficient concentrations of bacteria to outcompete phytoplankton for nutrients (or native bacteria for substrate) has been questioned by Boyd et al. (1984). In that study, the authors determined that dilution of a commercial microbial product (Aqua-Bacta-Aid) at the manufacturer's recommended dose in a test pond resulted in an insignificant increase in bacterial numbers compared to the native population. Crisman et al. (1984) concluded that microbial inoculation of a lake being mechanically aerated would have no beneficial effect because bacterial numbers were normally present at high concentrations (10^6/ml to 10^7/ml) during aeration. As an example of typical dosage for the microbial products, Creative Sales West recommends a 1 ppm application dose for their Clear-Pond product. This corresponds to an increase in cell numbers of approximately 10^3 cells/ml. The other reviewed products may be expected to yield cell increases within one or two orders of magnitude of this value. This clearly represents an insignificant increase in the total number of organisms.

The most compelling argument against the efficacy of commercial microbial products is the absence of published accounts of success in applying these products to eutrophic lakes. No support for the use of microbial inoculation as a lake restoration method can be found in the peer reviewed scientific literature. One of the few refereed journal articles documenting microbial inoculation concluded that the treatment was ineffective and theoretically unsound (Boyd et al., 1984). The only scientifically rigorous laboratory study assessing the effectiveness of commercial microbial products found that no discernable effects to organic sediments occurred as a result of inoculation (Hanson, 1981).

Qualitative, frequently anecdotal, reports of improved water quality and changes in sediment characteristics are common in project reports and promotional literature produced by commercial suppliers of microbial products. The projects reported consist almost exclusively of mechanical aeration augmented by microbial inoculation. In part because these are typically small-scale operational projects, thorough data collection and separation of the relative effects of aeration and inoculation have not been conducted.

Without exception, the professional limnologists and aquatic scientists contacted during this investigation (Appendix B) expressed the opinion that the addition of microbial products to promote sediment decomposition and lake restoration has little theoretical basis and no credible evidence to substantiate the claims made by the manufacturers.

Theories advocating the use of microbial products for lake restoration are controversial and speculative. The use of these products is not supported by experimental data published in the peer-reviewed literature or independent case studies. Therefore, it is concluded that further investigation regarding the application of commercial microbial products to the restoration of Lake Apopka is not warranted.

6.2 NITRATE APPLICATION

Nitrate application has been conducted in lake restoration projects to inactivate sediment phosphorus release and oxidize organic sediments. Specifically, nitrate is introduced to anaerobic lake sediments to stimulate denitrification, which results in the oxidation of organic material and the reduction of nitrate to nitrogen gas.

Phosphorus inactivation techniques using nitrate application rely on controlling denitrification in anaerobic sediments to manipulate iron redox reactions. Ripl (1979) refined a process of phosphorus co-precipitation with ferric hydroxides known as RIPLOX, which may include applications of ferric chloride and lime ($Ca(OH)_2$) depending on site-specific environmental conditions. Denitrification is necessary for phosphorus inactivation to prevent sulfate reduction to sulfite and to degrade organic material. Inhibition of sulfite production is necessary, because ferric hydroxide compounds that sequester phosphorus will disassociate in the presence of sulfite. Degradation of organic material decreases sediment oxygen demand and promotes oxidizing conditions in the sediments required for phosphorus inactivation.

Nitrate application to bring about phosphorus inactivation is well documented in the scientific literature. Ripl (1986) reported success in treating Lake Lillesjon in Sweden with ferric chloride, lime, and calcium nitrate. Other applications of this technology were considered unsuccessful. Lake Trekanten, Sweden returned to pre-treatment conditions following nitrate application, because iron concentrations in the sediments were too low for the necessary reactions to occur (Forsberg 1987). It is believed that Long Lake, Minnesota did not respond to nitrate application because of continued and excessive external phosphorus loading and persistent reducing conditions in the sediments (Larson, pers. comm.). Calcium nitrate application in White Lough, Northern Ireland (Foy, 1986) induced denitrification, but the dose applied was believed to be too low to maintain oxidizing conditions in the sediments.

While RIPLOX technology has met with mixed success, denitrification occurred as anticipated in all cases and produced the desired reactions. Projects that were unsuccessful did not recognize certain environmental limitations. For example, in the case of Lake Trekanten, supplementing the calcium nitrate dose with ferric chloride and lime pre-treatment may have created the necessary environment to co-precipitate the phosphorus (Forsberg, 1987).

Laboratory studies designed to assess in situ sediment oxidation technologies observed that calcium nitrate treatment was effective in removing COD and VS, but that sediment consolidation did not occur (Hanson, 1981; Szewczyk, 1984). Results indicated that the more easily degradable fraction of organic sediments were decomposed by denitrification, but the cell wall materials (lignocellulose) were more resistant to decay. The fraction that decomposed formed a loosely flocculated residual material. Willenbring et al. (1984) observed a similar floc in laboratory studies and noted that in an open-water environment this flocculent material would be easily mobilized by water currents.

Conditions in Lake Apopka appear to be suitable for nitrate application. The UCF and CF sediments contain high concentrations of ammonium (mean = 29.3 mg/l) and "negligible" nitrate nitrogen indicating anaerobic conditions with active denitrification (Reddy et al., 1988). Sediments are organic, but contain a relatively high fraction of acid detergent fiber (approximately 70 percent in the UCF zone), indicating that a significant fraction of the organic sediments is resistant to microbial degradation.

Several factors distinguish Lake Apopka from other lakes treated with nitrate. Documented case studies of calcium nitrate application have typically been conducted on temperate lakes with distinct summer stratification and the development of an anoxic hypolimnion. Lake Apopka is a shallow, subtropical system with a productive, aerobic, well-mixed water overlying the sediments.

Reddy et al. (1988) report that wind mixing frequently re-suspends the unconsolidated sediments in the top centimeters of the lake bottom. Wind mixing temporarily aerates a portion of the sediment zone, resulting in nitrification of ammonia to nitrate. As anaerobic conditions return, or as nitrate is diffused into underlying sediments (Reddy et al., 1988) denitrification occurs. Thus, some degree of sediment oxidation takes place through nitrification of ammonia present in the sediments followed by denitrification.

The phenomenon of the formation of a loosely consolidated flocculent material following nitrate application has particular significance to Lake Apopka. Wind mixing would undoubtedly disperse this material throughout the water column, resulting in increased mineral turbidity and reduced light transmission. This scenario represents the present conditions in Lake Apopka: an unconsolidated flocculent sediment layer overlain by a water column with significant mineral turbidity.

It is possible that wind mixing introduces sufficient oxygen to the sediments that significant nitrification of ammonia to nitrate occurs. It is evident that denitrification occurs intensely in the sediments. Thus, there may be substantial oxidation of organic material occurring routinely in the upper sediments of Lake Apopka. The high content of acid detergent fiber in the UCF and CF fractions indicates relatively low percentages of easily degradable organics, possibly through the opportunistic denitrification of nitrate produced by nitrification of ammonia.

The capability for nitrate application technology to control phosphorus release in the highly productive environment of Lake Apopka is uncertain. Field investigations will be required to assess the efficacy of the technique. This technology has been demonstrated to be feasible and successful in laboratory and field experiments that are documented in the peer-reviewed literature.

6.3 CHEMICAL OXIDATION

Research in the application of hydrogen peroxide (H_2O_2) and ozone (O_3) for sediment oxidation was investigated. Both chemicals are strong oxidants that are commonly used in wastewater pre-treatment and water purification. The responses of these products are similar, although there are differences in application techniques and ancillary effects.

Generally, the documented performance of these chemicals in oxidizing sediment was exemplary. In all studies that were evaluated, H_2O_2 and ozone were found to be effective in oxidizing organic material and reduced chemical compounds. A secondary effect of treatment was, however, severe impairment to water quality, in the form of elevated concentrations of soluble nutrients, pH depression, and mortality among organisms directly exposed to the oxidizing agents.

Laboratory studies to assess the capability of H_2O_2 and ozone to oxidize sediment (Hanson, 1981; Szewczyk, 1984) determined that both agents were effective in significantly decreasing COD, VS, and sediment volume. The chemical oxidants were the only in situ treatments tested in these studies that produced significant reductions in sediment volume. Szewczyk's (1984) experiments indicated that cellulose removal ranged from 59 to 84 percent and lignin removal ranged from 60 to 77 percent.

Comparing the relative effectiveness of H_2O_2 and ozone, Hanson (1981) considered the former to be clearly superior to ozone, because removal efficiency for H_2O_2 was substantially higher in laboratory experiments. Ozone, with an oxidation potential of 2.07 volts, is substantially more reactive than H_2O_2, with an oxidation potential of 1.77 volts. It would be expected that the ozone treatments would be at least as effective as the H_2O_2 treatments. Hanson (1981) also found H_2O_2 to be a more practical oxidant to apply. The equipment used to generate ozone for Hanson's (1981) study was a Welsbach Laboratory Ozonator (Model T-816) that generated a gas composed of 2 percent O_3 and 98 percent O_2; an instrument clearly unsuited to field environments.

The application of H_2O_2 on an operational scale would be logistically complex and labor intensive. Unless it could be generated on-site, liquid H_2O_2 would be delivered in bulk trucks to shore sites, where it would need to be pumped or towed by barge to work sites. Ozone could be generated on-site, at probably a significantly lower cost than bulk H_2O_2. In either case, application would require introduction of a liquid or compressed gas stream into the unconsolidated flocculent sediment layer. Liquid injection would use a harrow or rake system similar to those used for applying nitrate, alum, and lime to lake sediments. An aeration system would be employed to apply ozone.

The effectiveness of chemical oxidation in lakes is offset to some extent by the profound impact of reaction by-products on overlying water quality. Oxidation of organic molecules results in the dissolution of constituent nutrients into the water column. Hanson (1981) and Szewczyk (1984) observed significant increases in dissolved nutrients following ozone and H_2O_2 treatments. Soares (1980) observed that H_2O_2 was toxic to the benthic macrofauna and microflora through direct oxidation as well as through liberation of toxic concentrations of ammonium, sulfite and copper.

Another secondary effect of chemical oxidation observed by Hanson (1981) and Szewczyk (1984) was a post-treatment pH decrease of 2 to 4 units. Hanson (1981) was unable to provide an explanation for this decrease; the sediments and overlying water were taken from a well-buffered natural system (sediment alkalinity ranged from 231 to 893 mg/l $CaCO_3$). Szewczyk (1984) continued Hanson's (1981) research, and observed the same drop in pH following oxidation, although the experimental design was slightly different. The overlying water used for the experiment was deionized water (Hanson used lake water). Thus, Szewczyk's treatments were relatively poorly buffered because of the negligible alkalinity of the overlying water, but the alkalinity of the sediments should have provided adequate buffering. If the pH depression is a real phenomenon, in-lake treatment operations (experimental or full-scale), will require a substantial secondary treatment program applying lime ($CaCO_3$), or some other neutralizing agent to adjust the water column pH. The cost of this additional treatment could easily equal or exceed the cost of initial oxidant application.

Regardless of the pH response to oxidation, further treatment would be necessary to precipitate nutrients from the water column. The choice of potentially applicable precipitants includes lime, alum, and ferric chloride, all of which are widely used in water treatment and lake management. It may be possible to use lime for both pH adjustment and precipitation. The extent of the treatment necessary will depend on iron concentrations in the sediment relative to the quantity of nutrients suspended. Iron redox reactions, described previously, will co-precipitate some of the nutrients suspended by the treatment. Some level of chemical precipitation will be required to remove water column nutrients.

Chemical oxidation would probably be highly effective in decomposing the UCF and CF sediment fractions in Lake Apopka. Oxidation would degrade the easily decomposable organic sediments as well as a significant fraction of the cellulose and lignin present in the sediments. Additionally, organic material in the water column would be oxidized, including phytoplankton cells. Secondary treatment with a chemical precipitant would remove the resulting soluble nutrients from the water column and seal the sediments with a relatively insoluble surface layer. The result would be a deeper water column with a more consolidated lake bottom, and environmental conditions conducive to the establishment of rooted macrophytes.

Implementing an effective chemical oxidation program on Lake Apopka would, however, be logistically complex. The nature of the treatment would require that confined areas be treated sequentially as batch reactors. An enclosure in the lake would be required to hydraulically contain the area being treated. As described above, following initial treatment with the chemical oxidant, the water would undergo treatment to remove dissolved nutrients and suspended residual organic material. After completion of the treatment, the enclosure would be moved to a new area and the process would be repeated.

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SECTION 7. CONCLUSIONS AND RECOMMENDATIONS

In situ sediment decomposition techniques are intended to oxidize organic lake sediments and suppress internal nutrient cycling. Regardless of the mechanism or effectiveness of the treatment, internal nutrient cycling will become re-established and intensify unless external loading is abated. If external loading cannot be mitigated, or if mitigation occurs slowly over a long period of time, in-lake treatment technologies can be re-applied to protect water quality, but the effects will be temporary.

The treatment technologies considered for this study were microbial inoculation, induced denitrification, and application of the chemical oxidants hydrogen peroxide and ozone. Of these technologies, nitrate application and ozonation exhibited potential for immediate field testing in Lake Apopka. Chemical oxidation technologies would be substantially more costly than nitrate application (Table 6). The cost of initial application alone to Lake Apopka would probably exceed $3 billion for ozonation and $7 billion for hydrogen peroxide application, and extensive secondary treatment would be required in addition to that cost for water quality mitigation. Nitrate application, was therefore selected as the most economical and technically feasible in situ lake restoration technique. Specific conclusions and recommendations regarding each technology are provided below.

MICROBIAL DECOMPOSITION

The theoretical framework that describes the mechanisms by which microbial inoculation should work is not supported by experimental data and is highly controversial. Although the efficacy of microbial inoculation has not been categorically invalidated, there is no evidence to indicate that application of this technology to Lake Apopka would bring about the desired responses of sediment decomposition or suppressed nutrient cycling. It is concluded that the technology of microbial inoculation currently provides a very low probability of success in field applications. Field tests of this technology are not recommended.

TABLE 6. ANTICIPATED TREATMENT COSTS FOR IN SITU LAKE RESTORATION.

Technology	Material Costs ($ million)	Cost Considerations
Microbial Inoculation	0.3	• Cost for single application. As many as 3 applications per month may be necessary for the duration of the restoration program. • Application and labor costs are not included. • Mechanical aeration was not included in cost estimates.
Nitrate Application	790	• Cost averaged from total treatment costs referenced in case studies (Section 3.2.4). • Application depth of 1.2 m assumed. Typical application depth is approximately 0.2 m, therefore unit surface area costs from case studies was multiplied by 1.2/0.2.
Hydrogen Peroxide	7,000	• Cost includes bulk material only. Transportation, application, and labor costs not included. • In addition to primary treatment, secondary treatment to mitigate water quality will be necessary at a cost comparable to nitrate application or alum application. • The area being treated requires hydraulic isolation from the remaining water column. Costs for engineering, construction, and maintenance of the enclosures are not included.
Ozonation	3,000	• Cost is based on energy requirements for ozone generation only. Capital costs for equipment or labor costs are not included. • In addition to primary treatment, secondary treatment to mitigate water quality will be necessary at a cost comparable to nitrate application or alum application. • The area being treated requires hydraulic isolation from the remaining water column. Costs for engineering, construction, and maintenance of the enclosures are not included.

Note: Material costs reflect estimates for treatment of 1.2 m of organic sediment over 12,500 ha in Lake Apopka.

NITRATE APPLICATION

The injection of calcium nitrate into anaerobic sediments has been demonstrated to oxidize organic sediments through denitrification and inactivate phosphorus through co-precipitation with ferric hydroxide. The chemistry and biochemistry of the processes involved in this technology have been established through field and laboratory experimentation. Thus, there is adequate theoretical and practical information available to develop reasonable designs for field trials of the technology. Specific recommendations for field evaluation of this technology are presented in Section 8.

CHEMICAL OXIDANTS

Published reports of field and laboratory experiments using H_2O_2 and ozone show them to be highly effective in oxidizing organic sediments. The application of strong oxidants to decompose organic material, however, creates severe water quality impairment in overlying waters. Any application of chemical oxidation technology must be followed by treatment to inactivate dissolved nutrients and residual particulate organic material.

It is recommended that neither H_2O_2 nor ozonation be considered for field tests because of the cost of the oxidants and the logistic implications of large-scale treatment operations (e.g., supplying bulk H_2O_2 or ozone generation requirements).

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SECTION 8. EXPERIMENTAL DESIGN

The preceding discussions have presented analyses of the available in situ technologies that may be applicable to Lake Apopka, and identified nitrate addition as the most promising technique. This section presents recommendations for further investigation and experiments that should be conducted to build upon the findings of the feasibility study and quantitatively evaluate the performance of nitrate application under the specific physical, chemical, and biological conditions of Lake Apopka. The results of this investigation will provide a basis for extrapolating the probable effects of large-scale applications of either nitrate addition or chemical oxidation.

8.1 SELECTION OF SCALE

Experimental evaluation of in situ treatment technologies may be conducted on a range of scales, from the smallest bench-scale reactor to a whole-lake application. Small-scale laboratory investigations are useful in examining fundamental processes in a highly controlled situation, but necessarily exclude many potentially influential factors that exist in the lake environment (e.g., hydraulic circulation, benthic fauna, fishes, etc.). In contrast, in-lake experiments generally allow the inclusion of the myriad factors that characterize the natural system.

The objective of in situ treatment experiments will be to develop performance estimates that are representative of large-scale applications. This objective places the investigation in the realm of engineering evaluation, rather than basic scientific research. It has been assumed that the District is interested in evaluating technologies with proven records of successful application, and not conducting research into potentially useful, but unproven processes. Successful applications of the subject technologies have been documented. Accordingly, the next step in the evaluation of the applicability of these techniques to Lake Apopka should be field experiments in "limno-corrals" or similar enclosures placed in Lake Apopka. These experiments should be performed on as large a scale as practical to maximize representativeness. Small-scale jar tests are recommended for developing dosage estimates prior to conducting the suggested field experiments.

8.2 EXPERIMENTAL DESIGN

The structure of the recommended field experiments involves application of the treatment (i.e., nitrate addition) in enclosures containing lake water and underlying sediments. Monitoring should be conducted before and after the treatment applications to evaluate chemical and biological changes that result from the applications and quantify the effectiveness of the treatments in reducing sediment nutrient release and water column nutrient concentrations.

8.2.1 Field Enclosure Design

The design of the field enclosures should be such that a well defined column of lake water and underlying sediment is effectively isolated from the surrounding lake while being open at the top and exposed to the same meteorological conditions. These enclosures may be either circular or square, and should be approximately 10 meters across. This size will be large enough to allow inclusion of representative pelagic and benthic communities, and minimize the potential effects of spatial variability. Moreover, 10 meter enclosures will permit certain sampling that would be impractical in smaller areas.

The walls of the enclosures must be impervious and anchored securely in the lake bottom to prevent exchange with the surrounding lake water and sediments. The anchoring system must be designed to withstand the currents and wave action that are characteristic of Lake Apopka.

8.2.2 Treatment Design

One treatment and one control should be investigated in the experiments: a nitrate application treatment and a control within an enclosure. Three replicates are recommended for the treatment and control, for a total of six enclosures. The enclosures should be arranged in a two by three grid with the treatments and controls randomly assigned to each cell.

Nitrate doses should be derived from stoichiometric relationships and available analytical data characterizing Lake Apopka sediment and water quality. To confirm the validity of these values, jar tests should be conducted using various doses on sediment and water samples from the lake. Jar tests will also indicate the necessity of any additional chemical treatment, such as supplemental iron. Controls will be left undisturbed, except for the collection of samples and measurements as required in the monitoring design (Section 8.2.4).

8.2.3 Site Selection and Installation

The site for the experiments should be chosen based on representativeness and logistics. It is critical that the test site be representative of lake conditions such as depth, sediment composition, and circulatory patterns. The site should be accessible for installation and maintenance of the test enclosure systems throughout the duration of the study.

Certain permits may be required by the U.S. Army Corps of Engineers and the Florida Department of Environmental Regulation in conjunction with constructing the enclosures and conducting the experiments. Investigation of required permits and submittal of applications should be initiated as soon as possible to ensure that the time required for permit issuance does not delay the implementation.

Enclosures should be installed with minimal disruption of the bottom sediments being contained. To ensure representativeness of all biological components, stocking of organisms may be required to achieve densities and community structures found in the surrounding waters.

8.2.4 Monitoring Design

Data collection should include physical, chemical and biological parameters. Table 7 lists the recommended parameters, along with suggested sampling intervals. The gravimetric and chemical analyses will provide a quantitative indication of the degradation of particulate and

TABLE 7. SUGGESTED PARAMETERS TO BE MONITORED DURING FIELD EXPERIMENTS

Parameter	Sampling Interval
Physical:	
Sediment depth	Monthly
Sediment density	Monthly
Water column turbidity	Daily*
Water temperature	Daily*
Water Quality:	
Dissolved ammonium, nitrite, nitrate	Daily*
Dissolved phosphate	Daily*
Total phosphorus	Daily*
Dissolved oxygen	Daily*
Suspended particulate organic carbon	Daily*
Biochemical oxygen demand	Daily*
Chlorophyll a	Daily*
Sediment Chemistry:	
Leachable organic matter content	Bi-weekly
Cellulose and hemicellulose content	Bi-weekly
Lignin content	Bi-weekly
Sediment ATP	Bi-weekly
Sediment nutrient regeneration	Bi-weekly
Redox potential	Daily*
Biological:	
Total bacterial numbers (Water & sediment)	Weekly
Productivity	Bi-weekly
Zooplankton (Abundance and composition)	Bi-weekly
Phytoplankton (Abundance and composition)	Bi-weekly
Benthic Invertebrates (Abundance and composition)	Bi-weekly
Fish (Abundance and composition)	Monthly

* Daily for two weeks after treatment and weekly thereafter.

dissolved organic pollutants over periods of weeks to months. Central to these studies would be chemical analyses of the flocculent sediments and peat to determine what total percentage has been degraded in a given time period, as well as which specific components have been removed and which components are refractory to the treatments tested.

The monitoring design will also document changes in the physical, chemical, and biological parameters that may result from the treatments. In addition, the structure of the enclosures will allow toxicity testing on native plants, zooplankton, and fish.

Monitoring should begin upon installation of the enclosures. After installation, the enclosures should be allowed to acclimate for a period of no less than two weeks prior to application of the treatments. Monitoring data collected during this period will provide a basis for evaluating the similarity of the water and sediment systems contained in each of the cells. This information will be useful in interpreting the final study results.

After application of the treatments, monitoring should be conducted for a period of approximately 6 months. Monthly evaluation of the data should be conducted to allow mid-course changes in treatment such as re-application or monitoring design.

8.3 IMPLEMENTATION SCHEDULE AND COSTS

The following implementation schedule is recommended for the field experiments:

Task	Month after project initiation 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Research Plan	XXXX
Quality Assurance Plan	XXXX
Dosage Determinations	XX
Site Selection	XXXX
Permit Application	XXXXXX
Installation	XXXXXX
Treatment	X
Monitoring	XXXXXXXXXXXXXXXX
Data Evaluation	............X..X..X..XXXXXXXXXXXXXXX
Report	XXXXXX

It is estimated that the described investigation can be completed for a total cost of approximately $250,000, including construction ($50,000), labor ($100,000), and laboratory chemical analyses ($100,000). Some savings may be realized by reducing the sampling frequency and limiting the number of parameters measured; approximately 40 percent of the total estimated cost is attributable to laboratory analyses.

8.4 FURTHER DEVELOPMENT

The results from the suggested experiments will allow the District to assess the applicability of the investigated treatments to the restoration and management of Lake Apopka. Assuming that one of the treatments proves successful and practical, the next step should be an optimization effort. The objective of this optimization will be to develop specific dose and application criteria for full-scale application to the lake. The field experiments will provide information on the general practicality of the treatment, while the optimization will use that information and build upon it to generate an operational plan. Optimization also will involve application of a range of nitrate doses to identify the specific application strategy that is most effective and efficient.

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Strategies of Lake Sanitation.
Schweiz. Z. Hydrol., 49(2):202-219.

Effective lake restoration requires limitation of external phosphorus loading. Biological interactions involving phosphorus and local loading conditions must be considered in evaluating strategies for lake restoration. The limits and effectiveness of technical and administrative control measures are presented with regard to the source of phosphorus loading.

Blouin, M., J.G. Bisaillon, R. Beaudet, and M. Ishaque, 1988.
Aerobic biodegradation of organic matter of swine waste.
Biological Wastes, 25:127-139.

Degradation of organic material in swine waste is dependent on the metabolic activity of the indigenous microorganisms. The time required by the indigenous mesophillic microflora for the stabilization chemical oxygen demand (COD) in the waste was a function of the initial COD concentration. The inoculation of selected strains isolated from treated waste or activated sludge to swine waste did not accelerate the degradation of organic material. Samples from different environments were inoculated in stabilized waste and after incubation of these cultures dominant bacterial strains were isolated. When inoculated in stabilized waste, these strains reduced only slightly the remaining COD. Optimization of degradation of organic material of swine waste supernatant is possible, but appears to be limited by the presence of substances of low degradability.

Boyd, Claude E., William D. Hollerman, John A. Plumb, and Mohamed Saeed, 1984.
Effect of treatment with a commercial bacterial suspension on water quality in channel catfish ponds.
Prog. Fish Cult., 46(1):36-40.

To assess the effectiveness of commercial microbial products in improving water quality in eutrophic systems, four channel catfish ponds were treated with a commercial bacterial suspension (Aqua-Bacta-Aid) and four ponds served as controls. Concentrations of nitrogen and phosphorus forms, chemical and five-day biochemical oxygen demand, chlorophyll a, bacterial numbers, and other parameters were monitored daily for a five-month sampling period (June through October). The microbial product was applied four times during the study. Results indicated that bacterial numbers never changed significantly during the study. Comparisons of water quality parameters of treatments to controls were obscured by high variability in all parameters, but the treatments exhibited no distinct improvement in water quality. The singular exception were three discrete days during which dissolved oxygen was significantly higher in treated lakes. Boyd et al. concluded that the bacterial suspension demonstrated little promise for improving water quality.

Carr, Joseph E. and Dean F. Martin, 1978.
Aeration efficiency as a means of comparing devices for lake restoration.
J. Environ. Sci. Health, A13(1):73-85.

Methods of evaluating the efficiency of mechanical aeration devices for lake restoration are considered. The oxygen transfer coefficient, K_La, may be used, but the values depend on the size of the lake and other factors that are not always specified in the literature. Comparisons based on aeration efficiency, P, the weight of oxygen transferred per 67it power (horsepower-hour) are superior to K_La values for rating efficiency of aeration devices.

Chen, R.L., D.R. Keeney, D.A. Graetz, and A.J. Holding, 1972.
Denitrification and nitrate reduction in Wisconsin lake sediments.
J. Environ. Qual., 1(2):158-162.

The fate of ^{15}N labelled nitrate in Wisconsin lake sediment-water systems was investigated in laboratory and field experiments. In the laboratory, approximately 90 percent of the added nitrate disappeared from a calcareous sediment (Lake Mendota) compared to approximately 40 percent for a non-calcareous sediment (Trout Lake). In a field investigation, $^{15}NO_3$-N added to Lake Mendota sediments disappeared within 4 days. Approximately 37 percent was converted to organic nitrogen and the remaining 63 percent was believed to have been denitrified. Chen et al. concluded that denitrification and nitrate reduction in sediments receiving nitrate in ground waters must be evaluated in calculating nitrogen budgets of seepage lakes.

Chen, R.L., D.R. Keeney, and L.J. Sikora, 1979.
Effects of hypolimnetic aeration on nitrogen transformations in simulated lake sediment-water systems.
J. Env. Qual., 8(3):429-433.

Manipulation of hypolimnetic aeration of lakes was investigated as a method of inducing nitrification-denitrification to bring about nitrogen loss to the system. Aeration of NH_4 enriched hypolimnion should lead to nitrification of ammonium to nitrate. If the sediment had a high oxygen demand, reducing conditions should return, resulting in denitrification of the nitrate to nitrogen gas. This hypothesis was investigated in simulated sediment-water environments. Results indicated that nitrate formation under aerobic conditions was limited by depletion of NH_4. Although nitrate was observed to disappear from lake sediments, 60 to 65 percent was converted to NH_4 and organic nitrogen.

Cooke, G. Dennis, Eugene B. Welch, Spencer A. Peterson, and Peter R. Newroth, 1986.
Sediment oxidation.
In: Lake and Reservoir Restoration, Butterworth Publishers, Stoneham, MA, p. 133-138.

The application of nitrate to lake sediments to inactivate phosphorus cycling using RIPLOX technology was reviewed. Descriptions of the chemical processes, equipment and application rates, case studies, costs, and related effects were provided.

Cowell, Bruce C., and Clinton J. Dawes, 1984.
Algal studies of eutrophic Florida Lakes: the influence of aeration on the limnology of a central Florida lake [Lake Brooker].
Report Submitted by the Department of Biology, University of South Florida, Tampa, FL 33620. Submitted to the Florida Department of Natural Resources, Tallahassee, FL, 299 pp.

Restoration efforts in Lake Brooker, Florida were reported. Lake Brooker was treated using Clean-Flo Laboratories aeration equipment to aerate and circulate the water column. Cowell et al. observed decreases in dissolved gases (carbon dioxide, hydrogen sulfide, and ammonia) and reduced forms of iron and manganese and thermal stratification was eroded. Improvements in water quality during the first year of aeration were evidently masked by high external loading during the second year. Primary production and chlorophyll a concentrations did not change with aeration, but phytoplankton cell volumes decreased markedly. Blue-green algae blooms were eliminated and green algae became dominant. Cowell et al. concluded that aeration was successful in improving water quality, but may be necessary for multiple years to achieve lasting results.

Cowell, Bruce C., Clinton J. Dawes, William E. Gardiner, and Sandra M. Scheda, 1987.
The influence of whole lake aeration on the limnology of a hypereutrophic lake in central Florida.
Hydrobiol., 148(3-24).

Water quality monitoring associated with restoration activities on Lake Brooker, Florida, was reported. The water quality response to aeration using Clean-Flo Laboratories equipment was investigated. Cowell et al. concluded that the aeration system successfully eliminated many of the undesirable effects of eutrophication (e.g., oxygen depletion, blue-green algae blooms, low benthic diversity), but did not change the trophic state. Aeration of hypereutrophic lakes for multiple years may be necessary to maintain desired conditions.

Crisman, Thomas L., P.R. Scheurman, A. Keller, U.A.M. Crisman, D.J. Medina, J.S. Bays, J.R. Beaver, and M.J. Binford, 1984.
Algal management through lake aeration: final project report.
Prepared by the Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611. Submitted to the Bureau of Aquatic Plant Research and Control, Florida Department of Natural Resources, Tallahassee, FL.

Monitoring to detect microbial responses to restoration activities on Lake Brooker, Florida, were investigated. Restoration consisted of aeration using Clean-Flo Laboratories equipment. The sampling program included enumeration of water column and sediment bacteria by flourescence microscopy and analysis for sediment adenosine triphosphate (ATP), composition, and thickness. One year of pre-aeration data and two years of aeration data were collected. Crisman et al. concluded that water column aeration did not appear to have an impact on either water column or sediment microbial communities. Sediment microbial biomass, as estimated from ATP concentrations, did not change significantly as a result of aeration. Sediment thickness remained unchanged, and in the deeper areas of both pools, there was a tendency for the thickness of the surficial flocculent sediment zone to increase.

Drabkova, G., 1983.
Bacterial decomposition of organic matter in lake sediments.
Hydrobiol., 103:99-102.

Decomposition of organic material in sediments of lakes situated in the forest zone and forest-steppe of the USSR was investigated. Accumulation of organic matrial in the sediments was closely related to producton and decomposition processes in the trophogenic layer. Processes of organic material transformation were found to be most active in the uppermost sediment. The quantity of bacteria demonstrated no correlation with the organic material content of the sediment. Increases in organic material, up to 80 percent dry weight, was often accompanied with a decrease in bottom bacteria. The intensity of aerobic decomposition of the labile organic material can be judged from the oxygen demand of the sediments, however, it is important to differentiate between chemical and biological oxidation processes.

Foree, Edward G. and Perry L. McCarty, 1970.
Anaerobic decomposition of algae.
Env. Sci. & Tech., 4(10):842-849.

The rate and extent of algal degradation under simulated natural conditions were investigated. Decomposition of heterogeneous and unialgal cultures was studied under dark, anaerobic, constant-temperture laboratory conditions. Effects of high sulfate concentration, bacterial inoculation, temperature, pH, and cell composition on the rate and extent of degradation were evaluated. In cultures with wide variation in bacterial inoculation, no significant differences were observed in either the rate or extent of reduction in particulate matter or in the long term extent of total chemical oxygen demand stabilization.

Forsberg, Curt, 1987.
Evaluation of lake restoration in Sweden.
Schweiz. Z. Hydrol., 49(2):260-273.

The objectives and results of the Swedish lake restoration program during the last 20 years are discussed and evaluated. Specifically, restoration projects involving the mitigation of the effects of acidity and eutrophication are discussed. Mitigation of acidity included external measures (reducing acidifying emissions) and internal measures (lake liming). Eutrophication control consisted of reducing point and non-point sources of external loading and mechanical and biological methods to control internal loading.

Foy, R.H., 1986.
Suppression of phosphorus release from lake sediments by the addition of nitrate.
Water Res., 20(11):1345-1351.

Nitrate application to control phosphorus release from anoxic sediments in White Lough, Northern Ireland was investigated. The addition of 24 g N/m^2 of nitrate to the sediments resulted in a delay and reduction of phosphorus release similar to that observed in laboratory experiments. Ammonium release rates in the laboratory and in whole-lake treatments did not vary with nitrate input. Comparing the costs of using nitrate or iron/aluminum salts to suppress sediment phosphorus release indicated that the nitrate method was at least 80 percent more effective.

Gachter, Rene, 1987.
Lake restoration. Why oxygenation and artificial mixing cannot substitute for a decrease in the external phosphorus loading.
Schweiz. Z. Hydrol., 49(2):170-185.

Data collected from Lakes Baldegg and Sempach, two artifically mixed and oxygenated lakes, demonstrated that it is technically possible to significantly improve redox conditions, even in large eutrophic lakes. Gachter concluded that improvement of hypolimnetic redox conditions by internal measures such as aeration or oxygenation may accelerate the rate of recovery induced by a reduction of the external phosphorus loading, but that oxygenation per se will not be able to cause a reduction in the trophic state.

Geller, Annette, 1986.
Comparison of mechanisms enhancing biodegradability of refractory lake water constituents.
Limnol. Oceanogr., 31(4):755-764.

Bacterial degradation of macromolecular dissolved organic material, aged under weakly photolytic conditions, was compared to that of the original compounds before and after provision of a cosubstrate. Bacteria, *Pseudomonas* sp., *Flavobacterium* sp., and *Erwinia* sp., and macromolecules were isolated from the same lake water samples, one taken in winter and one taken in summer. The degradable portions of the original and aged macromolecules were consumed within the first week of incubation and the remainder was persistent. Provision of a nutrient pulse did not result in the production of enzymes that might have enabled to bacteria to assimilate the refractory remainder.

Hanson, Adrian T., 1981.
A screening test for eight proposed in-situ sediment digestion techniques.
Master's thesis, University of Wisconsin-Madison.

Hanson conducted a laboratory experiment to screen eight potential in situ sediment oxidation techniques. Sediments and water from four eutrophic Wisconsin lakes was used. Techniques tested were microbial inoculation, nitrate addition, hydrogen peroxide treatment, and ozonation. Results indicated no response from microbial inoculation treatments. The three other techniques demonstrated removal of chemical oxygen demand and volatile solids to varying degrees. Nitrate application resulted in a sediment volume increase. Hydrogen peroxide treatment and ozonation resulted in significant sediment volume decreases, but severe water quality impairment. Hanson recommended further investigation of hydrogen peroxide treatment with secondary treatment to improve water quality.

Horsfall, Frank L., III and Barton Gilbert, 1976.
Method for rendering bacteria dormant and the product produced thereby.
United States Patent Office, patent no. 3,963,576, Washington, DC, 8 columns.

A method of rendering bacteria dormant is provided which includes the steps of growing bacteria under aerobic conditions in an aqueous medium. The bacteria produced include at least one species of _Pseudomonas_ bacteria, which is capable of enzymatically reducing nitrate to nitrogen and one species of _Rhodopseudomonas_ bacteria which is capable of photosynthetically forming red pigment.

Jewell, William J. and Perry L. McCarty, 1971.
Aerobic decomposition of algae.
Env. Sci. & Tech., 5(10):1023-1031.

The rate and extent of decomposition of both axenic algal cultures and mixed cultures of algae, bacteria, and zooplankton are described. Culture ages ranged from a few days to seven months, and the growth media from a synthetic freshwater to seawater. The decomposition of pure cultures followed second-order kinetics during initial stages of decomposition, but subsequent decomposition could be adequately described with first-order kinetics.

Kaleel, Raymond T. and Andrew E. Gabor, 1978.
Lake Weston Restorative Evaluation.
Orange County Pollution Control Department, Orlando, Florida.

Lake Weston (11.3 ha surface area, 15 m maximum depth), in Orlando, Florida, was treated using Clean-Flo aeration and inorganic (buffered alum) chemical treatments. Water quality impairment originated from sewage effluent loading that was subsequently diverted from the lake.

Laing, Robert L., 1974.
A non-toxic lake management program.
Hyacinth Contol J., 12:41-43.

Restoration activities on several lakes using Clean-Flo Laboratories aeration systems and application of inorganic chemicals (Clean-Flo Lake Cleanser) are described. The chemical applied was an alum product buffered with calcium designed to precipitate nutrients.

Laing, Robert L., 1979.
Organic sediment removal through multiple inversion.
Internal document, Clean-Flo Laboratories, Inc., 4342 Shady Oak Rd., Hopkins, MN 55343.

The oxidation of organic lake sediments using Clean-Flo Laboratories mechanical aeration systems is discussed. Restoration efforts on Lake Maggiore, Florida, are described. Laing reports substantial degradation of organic sediments resulting from aeration, but the methods of analysis of sediment depth cannot be considered replicable.

Laing, Robert L., 1979.
The use of multiple inversion and Clean-Flo lake cleanser in controlling aquatic plants.
J. Aquat. Plant Manage., 17:33-38.

Laing reported that prior to the use of Clean-Flo Lake Cleanser $(CaSO_4{:}Al_2(SO_4{:}H_3BO_3))$, in three Minnesota lakes the water was pre-conditioned using Clean-Flo Laboratories aeration systems to remove carbon dioxide and bottom acids. This process was reported to be effective in controlling aquatic macrophytes.

Muller, Virgil, 1987.
Restoration and water quality management interim report for Anoka County on Highland Lake, Kordiak Park, Columbia Heights, Minnesota.
Muller Engineering, 10100 Morgan Ave., S., Bloomington, MN 55431.

The restoration of Highland Lake, Minnesota, is currently underway and consists of aeration using Clean-Flo Laboratories mechanical aeration equipment; the addition of Clean-Flo Lake Cleanser, an inorganic buffered alum product; and C-Flo Living Organisms, a microbial inoculum.

Nakajima, Mitsutoshi, Teruyoshi Hayamizu, and Hajime Nishimura, 1984.
Effect of oxygen concentration on the rates of denitrification and denitritification in the sediments of an eutrophic lake.
Water Res., 18(3):335-338.

The effect of oxygen concentration on the rates of denitrification was investigated under complete anaerobic conditions for wide ranges of nitrate and nitrite concentrations using sediments sampled from a highly eutrophic lake. Rates of conversion of nitrate to nitrite (denitratification) were found to be a decreasing function of the oxygen concentration below 60 uM O_2. Approximately the same rate was observed for conversion of nitrite to nitrogen gas (denitritification) below 30 uM O_2. Above 30 uM O_2, this rate dropped to half of the maximum and remained almost constant until a critical oxygen concentration was attained. The critical concentration, above which denitritification was suppressed thoroughly, depended on nitrite concentration.

Oleszkiewicz, Jan A., 1986.
Nitrogen transformations in an aerated lagoon treating piggery wastes.
Agricultural Wastes, 16(3):171-181.

Effluents from anaerobic lagoons were treated in two parallel aerated lagoons at variable organic load and hydraulic residence time. The removal of total Kjeldahl nitrogen (TKN) was found to increase rapidly at higher TKN food to microorganisms (F/M) ratios. At lower F/M ratios nitrification manifested itself through accumulation of oxidized forms of nitrogen. The apparent decrease in denitrification, evidenced by nitrites and nitrates present at these loads, can be attributed to an inadequate supply of easily available carbon as electron donor. Accumulation of nitrites at lower loads (higher residence times) may have been due to free nitrous acid toxicity to the Nitrobacter species.

Palmer, Carla N., Michael Claycomb, Michael Palmer, and Harry Stolmack, 1987.
Biological augmentation for sediment reduction at Lake Theresa.
Unpublished report, Dyer, Riddle, Mills, & Precourt, Orlando, FL, 12 pp.

The effectiveness of a freeze-dried biological product, supplied by LaMonte Environmental Technology, Inc, applied in conjunction with mechanical aeration, supplied by Aire-O_2, was assessed in Lake Theresa, in Orlando, Florida. Response to water column chemical, physical, and biological parameters was monitored. Attempts were made to quantify the oxidation in organic sediment thickness.

Ripl, W., 1979.
Sediment manipulation and oxidation with nitrate.
In: Bjork, Sven, et al. Lake management studies and results at the Institute of Limnology in Lund. Arch. Hydrobiol. Beih. Ergebn. Limnol., 13:31-55, p. 48-55.

The chemical reactions and biochemical processes related to calcium nitrate application for sediment phosphorus inactivation are developed. Restoration activities on Lake Lillesjon are summarized and descriptions of application techniques are provided.

Ripl, W., 1985.
Oxidation of sapropelic sediments by nitrified effluents from a treatment plant.
Lake & Reserv. Manage., (NALMS) 153-156.

In situ experimentation to determine the effectiveness of nitrate application for phosphorus inactivation in the estuary Schlei, West Germany, is described. Effluent from an advanced wastewater treatment plant is proposed to be diverted directly into the organic sediments of the Schlei. Ripl used in-lake enclosures to determine the effectiveness of varying doses of nitrate-rich synthetic wastewater effluent. Ripl concluded that it would be possible to oxidize sediments using wastewater effluent at a rate equalling the deposition rate of organic sediment in the estuary.

Ripl, W., 1986.
Biochemical oxidation of polluted lake sediment with nitrate -- a new restoration method.
Ambio., 5(3):132-135.

Restoration activities in Lake Lillesjon and the RIPLOX technology are discussed. Ripl reports the following phenomena associated with nitrate application: (1) rapid oxidation of the sediment layer to the depth of calcium nitrate injection, (2) decreased sediment oxygen demand, (3) general suppression of the exchange reactions of phosphorus and iron, and (4) almost immediate denitrification.

Soares, L.F., 1980.
Le traitment au perhydrol (H2O2) d'un sediment reduit; une approche de laboratoire de son impact sur la macrofaune endobenthique (tubificides).
Doctoral thesis. L'Universite Claude Bernard, Lyon.

The impact of hydrogen peroxide (H_2O_2) treatments on benthic endofauna was studied in laboratory experiments. Treatments consisted of application of hydrogen peroxide to oxidize the upper 40 mm of lake sediment. Immediately following treatment, intense solubilization of NH_4, SO_4, and Cu were obsererved along with 96 to 100 percent mortality of the endofauna. Approximately 30 days after treatment, reducing conditions returned to the sediments, presumably due to activity of surviving sulfur reducing bacteria.

Szewczyk (Shefchek), Joseph E., 1984.
Screening tests of sediment oxidation techniques for lake rehabilitation. Master's thesis. University of Wisconsin-Madison.

Szewczyk continued the research of Hanson (1981) and investigated in situ sediment oxidation through nitrate application and hydrogen peroxide treatment. Szewczyk used lake sediments from two eutrophic Wisconsin lakes. Results were similar to those of Hanson (1981). Both nitrate and hydrogen peroxide application resulted in decreased sediment chemical oxygen demand and volatile solids. Nitrate treatments resulted in increased sediment volume and hydrogen peroxide treatments resulted in impaired water quality. Variations on hydrogen peroxide treatments attempted to mitigate the adverse impacts of treatment. These variations consisted of secondary treatment with combinations of lime, aeration, microbial inoculation (with activated sludge), and nitrate application.

Tucker, Craig S. and Claude E. Boyd, 1977.
Relationships between potassium permanganate treatment and water quality. Trans. Am. Fish. Soc., 106(5):481-488.

The effect of potassium permanganate ($KMnO_4$) on some factors regulating dissolved oxygen concentrations in fish ponds was evaluated. Addition of 2, 4, and 8 mg/l $KMnO_4$ slightly decreased the chemical oxygen demand of pond water samples. Treatment of samples with 4 and 8 mg/l $KMnO_4$ decreased the biochemical oxygen demand, but did not prevent depletion of dissolved oxygen within the 4 day test period. Potassium permanganate was highly toxic to bacteria in laboratory studies. However, pond waters often contain large amounts of organic matter that express a $KMnO_4$ demand, rendering the chemical less effective as a bactericide. This implies that in treating bacterial fish diseases, enough $KMnO_4$ should be added to satisfy the $KMnO_4$ demand plus a bactericidal residual.

Tucker, Craig S., 1985.
Evaluation of a commercial bacterial amendment for improving water quality in channel catfish ponds.
Mississippi Agricultural & Forestry Experiment Station Research Report, 10(9), Mississippi State, MS 39672.

Field experiments were conducted in eight catfish culture ponds to assess the effectiveness of a commercial microbial product (Aqua-Bacta-Aid) in improving water quality. Tucker found no significant changes in water quality attributable to application of the microbial product and noted that the quantity of bacteria applied in routine treatment is insignificant compared to the bacterial populations already present in eutrophic environments.

URS Corporation, 1987.
Green Lake water quality improvement plan; Green Lake restoration program phase 2a.
Report prepared for the City of Seattle Parks and Recreation Department. Prepared by URS Corporation, 3131 Elliot Ave., Suite 300, Seattle, WA 98121, p. 27-30.

As a component of the Green Lake Water Quality Improvement Plan, the RIPLOX method of calcium nitrate treatment was investigated for potential application to Green Lake to inactivate internal phosphorus loading. The report concluded that while RIPLOX is technically feasible, the application costs exceed those of alum treatment.

Verner, Bo, 1985.
Biochemical oxidation of lake sediment with nitrate: two case stories, Lake Schlei, Germany, and Long Lake, Minnesota.
Lake & Reserv. Manage., (NALMS) 149-152.

Application technology and costs for two lake restoration projects using RIPLOX technology were documented in detail: Lake Schlei, West Germany, and Long Lake, Minnesota. RIPLOX treatments in Lakes Lillesjon and Trekanten in Sweden are also discussed.

Wedepohl, Richard E., Adrian Hanson, and Joseph Szewczyk, 1983.
Lake deepening using in situ techniques.
Lake & Reserv. Manage., (NALMS) 41-45.

Studies were conducted to evaluate alternatives to dredging, both for lake deepening and sediment treatment. Sediment consolidation by draw-down is the physical lake deepening technique examined. Sediment digestion using aeration, nitrate, hydrogen peroxide, ozone, and proprietary microorganisms was evaluated in a laboratory scale study. Although hydrogen peroxide and ozone have the most dramatic effects on sediment volume reduction, degradation of the overlying water column may limit their usefulness.

Willenbring, Peter R., Mark S. Miller, and William D. Weidenbacher, 1984. Reducing sediment phosphorus release rates in Long Lake through the use of calcium nitrate.
Lake & Resv. Manage., (NALMS) 118-121.

The effect of injecting different doses of calcium nitrate into the bottom sediments of Long Lake, Minnesota, was observed in a laboratory study. The purpose of the study was to determine the minimum dosage necessary to reduce phosphorus release rates from the sediments. The study concluded that at least for the short term (90 days), injection of calcium nitrate could virtually eliminate all phosphorus release from sediments.

APPENDIX B. INDIVIDUALS INTERVIEWED

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Sacramento, CA 94236-0001
TELEPHONE NUMBER: (916) 324 - 2189
DATE CONTACTED: 11 / 8 / 88

NAME: Mr. Richard Pugh
ADDRESS: Florida Department
of Environmental Regulation
4520 Oak Fair Blvd.
Tampa, FL 33610
TELEPHONE NUMBER: (813) 623 - 5561
DATE CONTACTED: 9 / 13 / 88 and 11 / 7 / 88

NAME: Mr. Kurt Pollman
ADDRESS: KBN Engineering
5700 S.W.34th St.
Gainesville, FL 32604
TELEPHONE NUMBER: (904) 375 - 8000
DATE CONTACTED: 11 / 7 / 88

NAME: Dr. Ronald Rashke
ADDRESS: U.S. EPA Athens Laboratory
College Station Road
Athens, GA 30613-7799
TELEPHONE NUMBER: (404) 546 - 2207
DATE CONTACTED: 11 / 7 / 88

NAME: Mr. John Reuter
ADDRESS: University of California at Davis
Limnology Laboratory
Davis, CA 95616
TELEPHONE NUMBER: (916) 758 - 3327
DATE CONTACTED: 11 / 8 / 88

NAME: Mr. Gary Ritter
ADDRESS: South Florida Water Management District
Okeechobee Field Office
1000 NE 40th St.
Okeechobee, FL 34972
TELEPHONE NUMBER: (813) 763 - 3776
DATE CONTACTED: 11 / 7 / 88

NAME: Mr. Donald Roberts
ADDRESS: U.S. EPA Region V
29 W 175 Oak Grove
West Chicago, IL 60185
TELEPHONE NUMBER: (312) 886 - 0134
DATE CONTACTED: 11 / 7 / 88

NAME: Mr. John Rogers
ADDRESS: U.S. EPA Athens Laboratory
College Station Road
Athens, GA 30613-7799
TELEPHONE NUMBER: (404) 546 - 3592
DATE CONTACTED: 11 / 7 / 88

NAME: Mr. Charles Stark
ADDRESS: Atlantic Environmental Services Group
P.O. Box 660002
Miami Springs, FL 33266
TELEPHONE NUMBER: (305) 884 - 1637
DATE CONTACTED: 11 / 8 / 88

NAME: Dr. Louis Semprini
ADDRESS: Civil Engineering Department
Stanford University
Stanford, CA 94305-4020
TELEPHONE NUMBER: (415) 723 - 0861
DATE CONTACTED: 9 / 7 / 88

NAME: Dr. Joseph Shapiro
ADDRESS: Limnological Research Center
University of Minnisota
3205 W. Owasso Blvd.
St. Paul, MN 55126
TELEPHONE NUMBER: (612) 624 - 0596
DATE CONTACTED: 10 / 6 / 88

NAME: Mr. Joseph Shefchek (Szewczyk)
ADDRESS: Wisconsin Power and Light
222 W. Washington Ave.
Madison, WI 53701
TELEPHONE NUMBER: (608) 252 - 3132
DATE CONTACTED: 10 / 18 / 88

NAME: Dr. Andrew Sharpley
ADDRESS: USDA-ARS
Water Quality and Watershed
Research Laboratory
P.O. Box 1430e
Durant, OK 74702
TELEPHONE NUMBER: (405) 924 - 5066
DATE CONTACTED: 10 / 14 / 88

NAME:	Mr. Wendell Smith
ADDRESS:	U.S. EPA Region IX 215 Fremont St. Mail Code W-3 San Fransisco, CA 94608
TELEPHONE NUMBER:	(415) 974 - 0828
DATE CONTACTED:	11 / 7 / 88

NAME:	Mr. Jeff Spence
ADDRESS:	Polk County Department of Environmental Services Water Resources Division P.O. Box 798 Bartow, FL 33830
TELEPHONE NUMBER:	(813) 533 - 2151
DATE CONTACTED:	9 / 7 / 88

NAME:	Ms. Judy Taggart
ADDRESS:	North American Lakes Management Society 1000 Connecticut Ave., NW Suite 202 Washington, DC 20036
TELEPHONE NUMBER:	(202) 466 - 8550
DATE CONTACTED:	9 / 9 / 88

NAME:	Mr. Mark Thomasek
ADDRESS:	Minnesota Pollution Control Agency Program Development Sector Water Quality Division 520 Lafayette Road St. Paul, MN 55126
TELEPHONE NUMBER:	(612) 296 - 7756
DATE CONTACTED:	9 / 7 / 88

NAME: Dr. Craig Tucker
ADDRESS: Delta Branch Experiment Station
Stoneville, MS 38776
TELEPHONE NUMBER: (601) 686 - 9311
DATE CONTACTED: 10 / 6 / 88 and 11 / 7 / 88

NAME: Mr. Randy Waite
ADDRESS: U.S. EPA Region III
841 Chestnut Bldg.
Mail Code 3WM12
Philadelphia, PA 19107
TELEPHONE NUMBER: (215) 597 - 3425
DATE CONTACTED: 11 / 7 / 88

NAME: Dr. Richard Wedepohl
ADDRESS: Wisconsin Department of
Natural Resources
P.O. Box 7921
Madison, WI 53707
TELEPHONE NUMBER: (608) 267 - 7513
DATE CONTACTED: 9 / 2 / 88

NAME: Dr. Eugene Welch
ADDRESS: University of Washington
Civil Engineering Department
FX10
Seattle, WA 98195
TELEPHONE NUMBER: (206) 543 - 2632
DATE CONTACTED: 9 / 7 / 88

NAME: Mr. Mark Wolf
ADDRESS: Little Muskego Lake District
W179 S6891 Muskego Drive
Muskego, WI 53150
TELEPHONE NUMBER: (414) 481 - 9018
DATE CONTACTED: 10 / 6 / 88

APPENDIX C. COMMERCIAL SUPPLIERS

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COMPANY

AquaTechniques
447 Rt. 10, Suite 14
Randolph, NJ 07869
(201) 361 - 1116

SALES REPRESENTATIVE

Richard Geney
(201) 361 - 1116

TECHNICAL REPRESENTATIVE

Richard Geney
(201) 361 - 1116

PRODUCT

RIPLOX Technology

MECHANISM OF REMOVAL

Oxidation of organic sediments through denitrification under anaerobic conditions by native microbial populations.

PRODUCT TECHNICAL DESCRIPTION

RIPLOX is the trade name for the technology and specialized application equipment for injecting calcium nitrate into lake sediments. The treatment technology was developed by Dr. W. Ripl as a method to inactivate internal phosphorus cycling by co-precipitating phosphorus in the chemical formation of iron hydroxides under oxidizing conditions. Calcium nitrate is intended to promote oxidizing conditions by removing the sediment oxygen demand exerted by organic sediments.

RIPLOX technology has been applied to Lakes Trekanten and Lillesjon, Sweden and Long Lake, Minnesota. Treatment was considered successful in Lake Lillesjon, but unsuccessful in Lake Trekanten and Long Lake. The chemical reactions predicted by theory occurred in all lake applications, but external loading is believed to have caused treatment failures in Lake Trekanten and Long Lake.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of RIPLOX as a result of public health, environmental, or other concerns.

COMPANY

Bio-Treat Company
1726 Travelers Palm Drive
Edgewater, FL 32032
(904) 428 - 9648

SALES REPRESENTATIVE

Woody Fuller
(904) 428 - 9648

TECHNICAL REPRESENTATIVE

Jerry Chen, Microbiologist
(512) 837 - 1145

PRODUCT

MICRO-BAC

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

MICRO-BAC works as a facultatively anaerobic mixed population derived from growth on extracts of grain and other organic products. Technical data provided by the Bio-Treat Company indicates that the product has been tested and found to be resistant to high concentrations of a wide range of organic pollutants and inorganic toxicants. It is claimed to have high biological degradative capability for carbohydrates, lipids, and proteins. In addition to the live bacteria, the product has a range of extracellular enzymes that also add to the overall degradative capacity of the inoculum, although these may not remain active for long time periods under lake conditions.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of MICRO-BAC as a result of public health, environmental, or other concerns.

COMPANY

Clean-Flo Laboratories, Inc.
4342 Shady Oak Road
Hopkins, MN 55343
(612) 935 - 2137

SALES REPRESENTATIVE

Robert Laing
(612) 935 - 2137

TECHNICAL REPRESENTATIVE

Robert Laing
(612) 935 - 2137

PRODUCT

C-Flo Living Organisms

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic, but primarily aerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

Clean-Flo Laboratories, Inc. specializes in lake treatments involving a mechanical aeration process known in promotional literature as "inversion oxygenation." Microporous air diffusers placed on the lake bottom act as air-lift pumps circulating and oxygenating hypolimnetic water. Inversion treatments may be augmented by "Clean-Flo Lake Cleanser," an inorganic alum product buffered with calcium, or C-Flo Living Organisms. Clean-Flo stated that the C-Flo product is specifically adapted to decompose particular substances of interest, cellulose, for example.

As with other microbial products, C-Flo is claimed to be free of pathogens such as Salmonella and is effective under aerobic or anaerobic conditions, although more efficient under aerobic conditions. The company stated that the aeration is critical to success in lake treatments and acknowledges that the natural bacteria of the lake would perform "nearly as well" as the C-Flo inoculum if the lake were naturally aerobic down to the sediments. The inoculum is claimed to enrich the bacterial population in the needed aerobes which would be inactive in the anaerobic sediments.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of C-Flo as a result of public health, environmental, or other concerns.

COMPANY

Creative Sales West
Bio Science Division
P.O. Box 768
Oxnard, CA 93032
(805) 644 - 0620

SALES REPRESENTATIVE

Robert Friedman
(805) 644 - 0620

TECHNICAL REPRESENTATIVE

Robert Friedman
(805) 644 - 0620

PRODUCT

CLEAR-POND

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

The product line marketed by Creative Sales West includes microbiological additives to decompose organic sediments and enhance denitrification and nitrification primarily in aquaculture systems. Products claimed to consist of natural and "mutated" micro-organisms. Specific products include:

ZOO-MIX
CLEAR-POND LIQUID
CLEAR-POND NITRI-QUICK LIQUID
NITRI-QUICK MARINE
CLEAR-POND DRY
CLEAR-POND DRY SUPER-X
CLEAR-POND DRY MARINE
CHLORAMINE BUSTER

These products are claimed to be effective in aerobic or anaerobic environments, although a typical treatment includes mechanical aeration using air diffusers similar to aquarium air stones or air blowers that set propellors in motion. Microbial products are claimed to be free of pathogenic bacteria and have been tested by the EPA and USDA. These products are claimed to have been widely used (1.5 million treatments sold) in fish ponds, fish farms, and lakes up to approximately 20 acres.

Company representatives predict that, with Lake Apopka sediments, the organic sediment layer may be removed at a rate of 2 to 5 inches in 60 days. Creative Sales West is currently treating a lake on the MGM movie lot in Culver City, California. Company representatives claim that three to four months were required to break down the leaves accumulated on the lake bottom to just the "fingers," the more highly lignified components of the leaf lignocellulose. Application involves an initial inoculation followed by another application after one week and subsequent monthly treatments. The company has recently introduced "mutants" of bacteria and specific fungi that are stated to be highly active in the degradation of cellulosic organic material.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of CLEAR-POND as a result of public health, environmental, or other concerns.

COMPANY

LaMonte Environmental Technology, Inc.
P.O. Box 340482
Tampa, FL 33694
(813) 962 - 3143

SALES REPRESENTATIVE

Steven LaMonte
(813) 962 - 3143

TECHNICAL REPRESENTATIVE

Michael Clacomb
Florida Environmental Associates
129 W. Packwood Ave.
Maitland, FL 32751
(407) 628 - 5134

PRODUCT

AG-DC-50 Concentrated Microbial Cell Paste

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

AG-DC-50 is composed of bacterial and enzyme products intended for application in aerobic or anaerobic environments. Product technical information claims that AG-DC-50 is composed of saprophytic-vegetative bacteria including Rumenococcus and Arthrobacter cultured through laboratory fermentation processes. Test results cited by the producer indicate that the product contains no Salmonella or other known pathogens and has a Pseudomonas concentration of less than 10^6 colony forming units per gram. This viable bacterial count may be sustained for up to 30 days under refrigerated conditions or 7 days at room temperature.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of AG-DC-50 as a result of public health, environmental, or other concerns.

COMPANY

Organic Research, Inc.
1100 Main Street
Suite 1870
Kansas City, MO 64105
(816) 346 - 4838

SALES REPRESENTATIVE

Gib Bourke
(816) 346 - 4838

TECHNICAL REPRESENTATIVE

Barbara Novotny
(816) 346 - 4838

PRODUCT

Proprietary microbial product.

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

The proprietary microorganisms marketed by Organic Research, Inc. are known as "lacto-bacilli," bacteria and enzymes cultured through lactic acid fermentation processes. As with other commercial suppliers of microbial products, Organic Research, Inc. stated that their product is effective under aerobic or anaerobic conditions. Unlike other suppliers, however, the product is claimed to perform equally well under anaerobic conditions. A field test currently underway in Lake Effie, Florida (Appendix D) is being conducted under anaerobic conditions. Specific information regarding the composition of the product is unavailable.

RESTRICTIONS ON APPLICATION

Although the product is claimed to contain no genetically altered microorganisms, permits were required to apply the product to Lake Effie, Florida. Concern was expressed regarding the introduction of "exotic" organisms into Florida waters. As a result, permits from the Florida Department of Environmental Regulation, U.S. Army Corps of Engineers, and Florida Department of Natural Resources restricted the application of the product to confined test chambers. Test results may lead to less restrictive whole-lake tests.

COMPANY

Water Management, Inc.
P.O. Box 2552
825 N. Andreasen Drive, Suite B
Escondido, CA 92025
(619) 745 - 0762 (Tel.)
(619) 745 - 0763 (FAX)

SALES REPRESENTATIVE

Diane Race
(619) 745 - 0762

TECHNICAL REPRESENTATIVE

Diane Race
(619) 745 - 0762

PRODUCT

PHOTOZONE

MECHANISM OF REMOVAL

Chemical oxidation by direct application of oxygen free radicals, primarily ozone, to oxidize sediments.

PRODUCT TECHNICAL DESCRIPTION

PHOTOZONE is the trade name for an ozone-based gas produced through a patented photochemical process using ultraviolet (UV) light. The product gas, termed "activated oxygen," is claimed to be composed primarily of ozone (O_3, 67 percent) and hydroxyl radical (OH, 15 percent) with lesser concentrations of hydrogen dioxide (HO_2), hydrogen peroxide (H_2O_2), atomic oxygen (O), and other oxidants.

The PHOTOZONE gas is bubbled through the substrate to be oxidized. Energy requirements for PHOTOZONE production are claimed to be significantly lower than for conventional ozonation methods. PHOTOZONE requires 3 to 5 Kw-hours to produce 1 pound of ozone, while more conventional methods require 8 to 12 Kw-hours to generate 1 pound of ozone.

Typical PHOTOZONE applications are in water disinfection and wastewater treatment. A PHOTOZONE system was used in the 1.6 million gallon McDonalds olympic swimming pool for the 1984 Los Angeles Olympic Games. PHOTOZONE has been used in lake management, but Water Management, Inc. representative Diane Race stated that PHOTOZONE products are no longer marketed for lake management.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of PHOTOZONE as a result of public health, environmental, or other concerns.

COMPANY

Water Quality Science, Inc.
P.O. Box 532
Bolivar, MO 65613
(417) 326 - 8225

SALES REPRESENTATIVE

Granville Watson, President
(417) 326 - 8225

TECHNICAL REPRESENTATIVE

Granville Watson, President
(417) 326 - 8225

PRODUCT

AQUA - BACTA - AID: S1

MECHANISM OF REMOVAL

Microbial decomposition of organic material using facultative anaerobic bacteria.

PRODUCT TECHNICAL DESCRIPTION

Aqua-Bacta-Aid (A-B-A) is marketed for use in treating aquaculture ponds, raceways, fish hatchery tanks, and biological filters. A-B-A-S1 is recommended for treatment of aquaculture systems with heavy organic loading. A-B-A-S1 is claimed to contain bacteria including Aerobacter aerogenes, Bacillus subtillis, Cellulomonas biazotea, Nitrosomonas sp., Nitrobacter winogradskyi, Pseudomonas denitrificans, Pseudomonas stutzeri, and Rhodopseudomonas palustris. Thus the product contains both aerobic and anaerobic bacteria, as well as both heterotrophs (using organic carbon for energy) and autotrophs that oxidize toxic nitrogen compounds (ammonium and nitrite) to nitrate. Additionally, there are denitrifiers that can, under anaerobic conditions, convert nitrate to N_2 gas. Also present are purple non-sulfur bacteria that use light energy to oxidize organic matter in the absence of oxygen. Together these organisms are stated to complement the activities of each other and present a scheme for the complete oxidation of organic nitrogen compounds.

A-B-A products are added as a liquid or powder at the rate of one gallon per acre of lake surface. The recommended mode of application is through a 1 in. hose directly into the sediment or sludge. The company recommends three weekly treatments followed by monthly treatments for the duration of the lake restoration program. Water Quality Science, Inc. also warns that a severe, presumably temporary, drop in oxygen can occur and that this side effect should be treated by additional aeration.

RESTRICTIONS ON APPLICATION

No restrictions have been placed on the use of A-B-A products as a result of public health, environmental, or other concerns.

APPENDIX D. CASE STUDIES

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LAKE

Lake Effie
Polk County, Florida

SIZE

Surface Area (ha):	40.0
Mean Depth (m):	< 1.0

TREATMENT OBJECTIVES

Pilot study to assess the capability of introduced micro-organisms to decompose organic sediments.

TREATMENT TECHNIQUES

Biochemical, facultative, using introduced bacteria and enzymes.

RELEVANT LITERATURE

None available.

PARTIES CONTACTED

Jeff Spence, Polk County Department of Environmental Services
Gib Bourke, Organic Research
Barbara Novotny, Organic Research
Robert Staetler, Florida Department of Environmental Regulation

PROJECT CHRONOLOGY

Current status: Installation begins in winter 1988, 1989

PROJECT COST

Not available. Organic Research (Appendix C) is underwriting the project as a demonstration of their technology.

PROJECT SUMMARY

Lake Effie is hypereutrophic with observed concentrations of total phosphorus (TP), total nitrogen (TN), and chlorophyll a of 1.5 mg/l, 10.5 mg/l, and 532 ug/l, respectively. Organic sediments in excess of 3 m and a maximum water depth of 1 m are present. The primary source of nutrient loading, effluent from a 1 million gallon per day (MGD) treatment plant, was diverted from the lake 1 year ago.

Organic Research is conducting a pilot restoration study to assess the effectiveness of their proprietary microbial product in decomposing a portion of the organic sediment layer. The study will be conducted in 4 test chambers placed in the lake. The chambers are constructed of stainless steel pipes 2 m in diameter and long enough to be placed upright and extend from above the water line through a significant portion of the organic sediment layer. Organisms will be introduced, without aeration, to 3 of the 4 chambers, with the remaining chamber to be used as a control. Water and sediment quality and sediment depth will be monitored for the duration of the study.

LAKE

Little Muskego Lake
Muskego, Wisconsin

SIZE

Surface Area (ha): 210.0
Mean Depth (m): n/a

TREATMENT OBJECTIVES

Improve water quality through destratification and oxygenation of lower waters.

TREATMENT TECHNIQUES

Mechanically-induced aeration and circulation.

RELEVANT LITERATURE

Holmstrom, et al., 1988.

PARTIES CONTACTED

Mark Wolf, President, Little Muskego Lake Association
Robert Laing, President, Clean-Flo, Inc.
Steve Field, USGS

PROJECT CHRONOLOGY

Jan 1986: Baseline sediment bathymetry survey conducted.
Apr 1987: Aeration begins for summer season.
Apr 1988 : Aeration for second summer season begins.
Current Status: Year 3 of 5 year program has been completed.

PROJECT COST

$150,000 for purchase and installation of aeration equipment. Maintenance and electricity costs average $12,000 to $15,000 annually.

PROJECT SUMMARY

Little Muskego Lake is eutrophic with summer phytoplankton blooms resulting in recreational impairment. Nutrient loading from runoff and nutrient release from sediments have been identified as sources of eutrophication.

The Little Muskego Lake Association contracted Clean-Flo Laboratories, Inc. to install and maintain 72 aerators in the lake with the intention of improving water quality by disrupting summer stratification and supplying oxygen to the lower water column and organic sediments. It was the specific intention of the project to increase lake depth by decomposing organic sediments.

The Wisconsin Department of Natural Resources (DNR) has authority over lake restoration projects in that state and issued a permit for restoration of the lake through the use of mechanical aerators with the stipulation that water quality and sediment depth are monitored using reliable, repeatable techniques.

With the assistance of the USGS, which includes Little Muskego Lake in its water quality monitoring network, monthly samples are collected, with semi-weekly sampling during summer months. Water quality data from the first two seasons of aeration are available (Holmstrom, et al., 1988). The water quality response to aeration in the first (1987) summer season was obscured by heavy rainfall, resulting in high levels of nutrient loading to the system. Data from the second (1988) summer season indicate decreases in nutrient concentrations. It is believed that these decreases are due primarily to drought conditions during that summer, resulting in diminished nutrient loading from the watershed (Stephen Field, personal communication). Dissolved oxygen concentrations are reported to have increased, but consistent summer oxygenation to the lake bottom has not been observed (Mark Wolf, personal communication).

To map sediment depths, a sampling pattern was established with 18 cross-sections forming a grid with 400 ft. between nodes. To date, bathymetry comparing pre-treatment conditions to post-treatment conditions has not been performed. This project is unique in its rigorous approach to sediment mapping. The final results will provide some of the most reliable documentation of the sediment oxidation capacity of mechanical aeration.

LAKE

Long Lake (South Basin)
New Brighton, Minnesota

SIZE

Surface Area (ha): 48.0 (South Basin)
Mean Depth (m): 3.0

TREATMENT OBJECTIVES

To reduce phosphorus loading from organic sediments.

TREATMENT TECHNIQUES

Chemical, calcium nitrate injections into sediments.

RELEVANT LITERATURE

Willenbring, et al., 1984.
Verner, 1983.

PARTIES CONTACTED

Loren Larsen, E.A. Hickok and Associates
Terry Nunan, Ramsey County, MN

PROJECT CHRONOLOGY

Application of calcium nitrate occurred in 1984, with post-treatment water quality monitoring continuing to present.

PROJECT COST

$350,000

PROJECT SUMMARY

Summer stratification in Long Lake prompted anaerobic conditions in the organic sediments, resulting in phosphorus release into the water column. A proprietary sediment injection technique, RIPLOX (Appendix C), was used to inject calcium nitrate to a depth of approximately 13 cm into the sediments. The objective was to provide ample nitrate to the sediments to induce denitrification to oxidize the top centimeters of sediment. The oxidation process converts available iron from a ferrous state to ferric hydroxide, which readily combines with phosphate to form immobile phosphorus compounds (Willenbring, et al., 1984).

While the specific intention of this project was not to increase lake depth through sediment oxidation, and in fact, oxidation was only an intermediate step in the restoration process, a decomposition of organic sediment to the depth of injection was observed. The reaction products of the oxidation process remained as an unconsolidated, light floc, easily displaced by water currents (Willenbring, et al., 1984).

Ultimately, the project was considered unsuccessful, as post-treatment monitoring indicated elevated phosphorus concentrations in the hypolimnion. The treatment process itself, however was found to be quite effective: the injection apparatus was mechanically reliable (Terry Nunan, personal communication) and oxidation occurred as anticipated. Persistent external nutrient loading is believed to have been the primary factor associated with the return of phosphorus release.

LAKE

Lake Brooker
Tampa, Florida

SIZE

Surface Area (ha):	10.5
Mean Depth (m):	4.0

TREATMENT OBJECTIVES

Lake aeration to improve water quality and to study the response of microbial populations and sediments to aeration.

TREATMENT TECHNIQUES

Mechanically-induced aeration and circulation

RELEVANT LITERATURE

Crisman, et al., 1984
Cowell, et al., 1984
Cowell, et al., 1987

PARTIES CONTACTED

Thomas Crisman, University of Florida
Robert Laing, President, Clean-Flo, Inc.

PROJECT CHRONOLOGY

Aug 1980:	Pre-aeration data collection begins.
Jun 1981:	Clean-Flo aeration system activated.
Jun 1983:	Aeration-period data collection concluded.

PROJECT COST

Not available.

PROJECT SUMMARY

Mechanical aerators were installed on Lake Brooker and operated continuously over a two-year period. The University of Florida monitored water-column bacteria, sediment ATP (an indicator of microbial activity), and sediment composition and thickness.

Crisman et al., (1984) concluded that mechanical aeration did not appear to have an impact on either water column or sediment microbial communities. Aeration did not result in an increase in abundance of aerobic bacteria or a decrease in the abundance of anaerobic bacteria. "Sediment microbial biomass, as estimated from sediment ATP concentrations, did not change significantly as a result of aeration. Sediment thickness remained unchanged, and in the deeper areas ... there was a tendency for the thickness of the surficial flocculent zone to increase" (Crisman, et al., 1984).

Cowell, et al. (1984, 1987) monitored physical-chemical and biological water quality parameters in Lake Brooker and concluded that while many of the undesirable features of eutrophication were eliminated, trophic state was not improved. Moreover, to sustain the beneficial effects of mechanical aeration, multiple years of treatment may be necessary.

APPENDIX E. DATA BASE

Information collected for this study has been organized in an IBM-PC compatible data base using a dBASE III environment. The data base includes information provided in the appendices to this report and covers four subject areas: annotated bibliography, individuals interviewed for this study, commercial suppliers of in situ lake restoration technology, and selected lake restoration case studies.

The data base is menu driven and users can examine the output listings on the computer screen or on hard-copy printouts. Searches can be made for key words in any of the subject areas (annotated bibliography, case studies, etc.).

APPENDIX F. DATA SUMMARIES

Experimental data collected by Hanson (1981) and Szewczyk (1984) are included in this appendix. Section F.1 summarizes Hanson's (1981) results and Section F.2 summarizes Szewczyk's (1984) results.

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Table 2

Chemical Characterization of the Original Sediment Samples

	Lakes			
Parameter	LE	HH	LLK	LLM
COD mg/g	314	469	593	588
TS %	5.10	3.49	3.17	2.40
VS %	40.06	56.05	65.29	63.34
TKN-N %	2.1	3.1	3.0	2.9
	2.3[1]	3.3[1]	3.0[1]	3.3[1]
PO_4-P mg/g	1252	1020	648	589
			635[2]	394[2]
BOD-5 mg/g	5.6	7.6	2.5	3.3
Lignin %	8.90	11.67	11.00	4.68
Fe %	1.29	0.67	0.68	0.52
Mg Hardness %	1.76	0.23	0.73	0.37
Ca Hardness %	2.36	0.80	1.78	1.35
pH	7.8	7.3	8.3	8.4
Alkalinity mg/l as $CaCO_3$	893	231	799	536
O_2 Uptake mg/g VSS/day	1.73	0.95	0.34	0.22

[1] Performed by Soil and Plant Analysis Lab, Madison, Wisconsin

[2] Performed by Soil Department Lab, University of Wisconsin-Madison

Table 8

Final Sediment Comparisons

Treatment	Lake	COD[1] mg/g	TS %	VS[1] %	Settling Rate[2] in/hr@ % TSS	Vol. %
Original Sediment						
	LE	314	5.10	40.06		-
	HH	469	2.49	56.05		-
	LLK	593	3.17	65.29		-
	LLM	588	2.40	63.34		-
Air						
	LE	354	4.51	38.76	.054@2.32	-11
	HH	457	2.58	55.28	.049@1.27	-4
	LLK	601	2.51	64.48	.054@1.25	7
	LLM	601	2.15	65.95	.037@1.10	2
CF-1						
	LE	343	4.90	38.90	.042@2.45	-22
	HH	436	2.42	56.50	.058@1.12	4
	LLK	606	2.41	66.30	.057@1.14	27
	LLM	578	2.25	66.70	.061@1.07	12
CF-2						
	LE	344	4.96	38.60	.026@2.43	-5
	HH	447	2.56	55.87	.034@1.29	3
	LLK	603	2.50	65.06	.062@1.24	19
	LLM	566	2.13	65.75	.056@0.96	19
CF-3						
	LE	356	4.15	39.35	.039@2.13	-13
	HH	433	2.56	57.43	.033@1.30	-2
	LLK	579	2.36	66.48	.051@1.11	17
	LLM	566	2.27	66.81	.032@1.15	7
CF-4						
	LE	355	3.92	38.02	.035@2.02	-13
	HH	442	2.27	54.62	.024@1.18	-7
	LLK	611	2.07	63.04	.027@1.04	18
	LLM	585	1.84	65.96	.034@0.83	20
CF-Control						
	LLM	576	2.23	67.60	.062@1.07	15
	LLM	586	2.10	67.91	.070@0.99	21
	LLM	531	2.10	67.76	.067@1.02	20
	LLM	592	2.25	67.04	.062@1.04	22

[1] The standard deviation of these parameters is listed in Appendix 5.

[2] Settling rate of original sediments appears as a curve on Figures 18-21.

Table 8--Continued

Treatment	Lake	COD mg/g	TS %	VS %	Settline Rate in/hr@ % TSS	Vol. %
Air-NO_3	LE	280	5.44	39.55	.052@2.61	-19
	HH	320	3.23	50.42	.065@1.55	-8
	LLK	375	3.50	58.03	.058@1.65	7
	LLM	393	3.07	56.83	.049@1.44	8
NO_3	LE	280	5.62	38.97	.053@3.00	1
	HH	302	3.55	48.82	.072@1.88	-16
	LLK	404	3.95	56.31	.058@2.09	7
	LLM	402	3.30	54.36	.094@1.68	17
Air-H_2O_2	LE	89	7.53	18.11	.031@3.76	-89
	HH	124	3.55	24.40	.015@1.27	-81
	LLK	176	5.07	30.02	.042@2.00	-76
	LLM	182	3.71	26.06	.013@1.14	-72
Air-O_3	LE	245	6.51	30.00	.031@3.19	-32
	HH	325	3.94	49.83	.032@1.83	-49
	LLK	437	3.49	56.61	.063@1.54	-29
	LLM	501	2.75	61.86	.055@1.24	-27
O_3	LE	282	5.00	33.34	.030@3.44	-37
	HH	351	3.50	51.04	.035@1.64	-33
	LLK	485	2.47	60.92	.056@1.53	-29
	LLM	511	2.62	63.11	.079@1.12	-27
N_2 Gas	LE	363	4.82	38.17	.042@2.33	-5
	HH	451	2.56	55.06	.036@1.31	5
	LLK	585	2.65	64.45	.039@1.40	14
	LLM	643	2.23	62.68	.065@0.91	22
No Treatment	LE	357	5.04	38.02	.047@2.16	0
	HH	447	2.68	55.32	.072@1.16	0
	LLK	632	2.67	63.90	.067@1.15	0
	LLM	578	2.36	64.75	.136@0.85	0

Table 9

Final Water Column Comparisons

Treatment	Lake	COD mg/l	TDS mg/l	VDS %	TKN-N mg/l	PO_4-P	BOD_5 mg/l	pH	SO_4 mg/l	Organic Acids
Original										
	LE	27	240	46.61	2.11	0.14		7.2	13.3	
	HH	38	0	-	2.06	0		6.2	10.3	
	LLK	29	240	52.54	2.52	0.03		7.8	20.9	
	LLM	43	190	49.46	2.68	0.03		6.5	27.0	
Air										
	LE	117	466	68.67	4.67	0.20		8.0		
	HH	22	182	48.35	3.02	0.10		7.4		*
	LLK	65	312	57.05	3.37	0.03		7.0		*
	LLM	68	324	41.98	5.50	0.03		7.9		
CF-1										
	LE	55	1290	87.00	81.20	0.24		7.0		
	HH	28	1386	96.00	176.90	0.18		6.6		
	LLK	70	1618	86.40	86.40	0.11		6.9		
	LLM	42	1480	87.00	123.20	0.22		6.9		
CF-2										
	LE	47	244	78.00	1.30	0.35		7.5		
	HH	28	110	78.00	0.30	0.07		7.7		
	LLK	32	258	74.00	1.10	0.27		7.2		
	LLM	40	320	70.00	1.40	0.07		7.7		
CF-3										
	LE	51	2040	56.00	0.50	1.36		6.5		
	HH	36	350	58.00	72.60	0.14		6.6		
	LLK	98	1202	61.00	61.30	0.10		6.5		
	LLM	70	748	66.00	50.60	0.11		6.8		

Table 9--Continued

Treatment	Lake	COD mg/l	TDS mg/l	VDS %	TKN-N mg/l	PO_4-P	BOD_5 mg/l	pH	SO_4 mg/l	Organic Acids
CF-4										
	LE	93	316	76.00	3.0	0.31		7.9		
	HH	20	360	52.00	6.5	0.09		6.5		
	LLK	112	500	64.00	2.7	0.14		7.4		
	LLM	81	360	65.00	2.8	0.10		7.2		
CF-Control										
1	LLM	52	1120	56.00	109.0	0.02		6.5		
2	LLM	48	1002	75.00	65.8	0.02		7.1		
3	LLM	56	1098	79.00	94.5	0.01		7.1		
4	LLM	52	948	76.00	91.7	0.01		7.3		
Air-NO_3	LE	32	11448	26.00	0.6	0.11		7.5		
	HH	26	10800	23.00	4.8	0.04		7.1		
	LLK	17	11340	26.00	0.2	0.04		7.4		
	LLM	56	11200	24.00	0.4	0.03		7.4		
NO_3										
	LE	32	7840	18.00	5.30	0.12		7.3		
	HH	13	7962	22.00	5.30	0.02		7.2		
	LLK	40	11894	25.00	3.30	0.02		7.0		
	LLM	38	8442	24.00	6.60	0.02		7.5		
Air-H_2O_2										
	LE	1045	3960	52.32	333.31	9.00		5.0	475.5	
	HH	653	2236	68.07	310.98	12.50		3.3	270.3	
	LLK	650	2592	59.95	340.24	6.10		4.6	253.6	
	LLM	1526	2556	64.08	234.39	2.90		3.0	277.9	

Table 9--Continued

Treatment	Lake	COD mg/l	TDS mg/l	VDS %	TKN-N mg/l	PO_4-P mg/l	BOD_5 mg/l	pH	SO_4 mg/l	Organic Acids
Air-O_3	LE	1185	2706	47.89	166.81	4.60	270	6.8	206.4	
	HH	1061	2292	76.53	144.41	6.30	405	2.9	163.9	*
	LLK	1278	2372	60.37	113.92	3.30	278	4.0	141.0	*
	LLM	720	1412	53.54	89.71	2.80	199	3.9	139.5	
O_3	LE	1502	3230	52.57	190.93	5.10	375	5.9	262.7	
	HH	1270	2528	84.73	177.69	2.30	593	3.0	173.0	*
	LLK	1889	3400	78.00	175.07	6.50	615	3.5	150.1	*
	LLM	1014	1836	79.19	98.13	5.40	210	4.2	145.6	
N_2	LE	161	292	44.52	8.00	1.53		7.8		
	HH	180	200	46.32	1.55	0.03		7.9		
	LLK	121	290	42.76	1.82	0.00		7.1		
	LLM	309	406	51.72	4.02	0.00		8.0		
No Treatment	LE	34	250	61.42	2.30	0.00		7.5	25.5	
	HH	23	0	-	2.03	0.00		6.1	31.6	*
	LLK	66	286	34.27	2.34	0.13		6.8	25.5	*
	LLM	16	306	30.72	5.71	0.00		8.2	28.5	

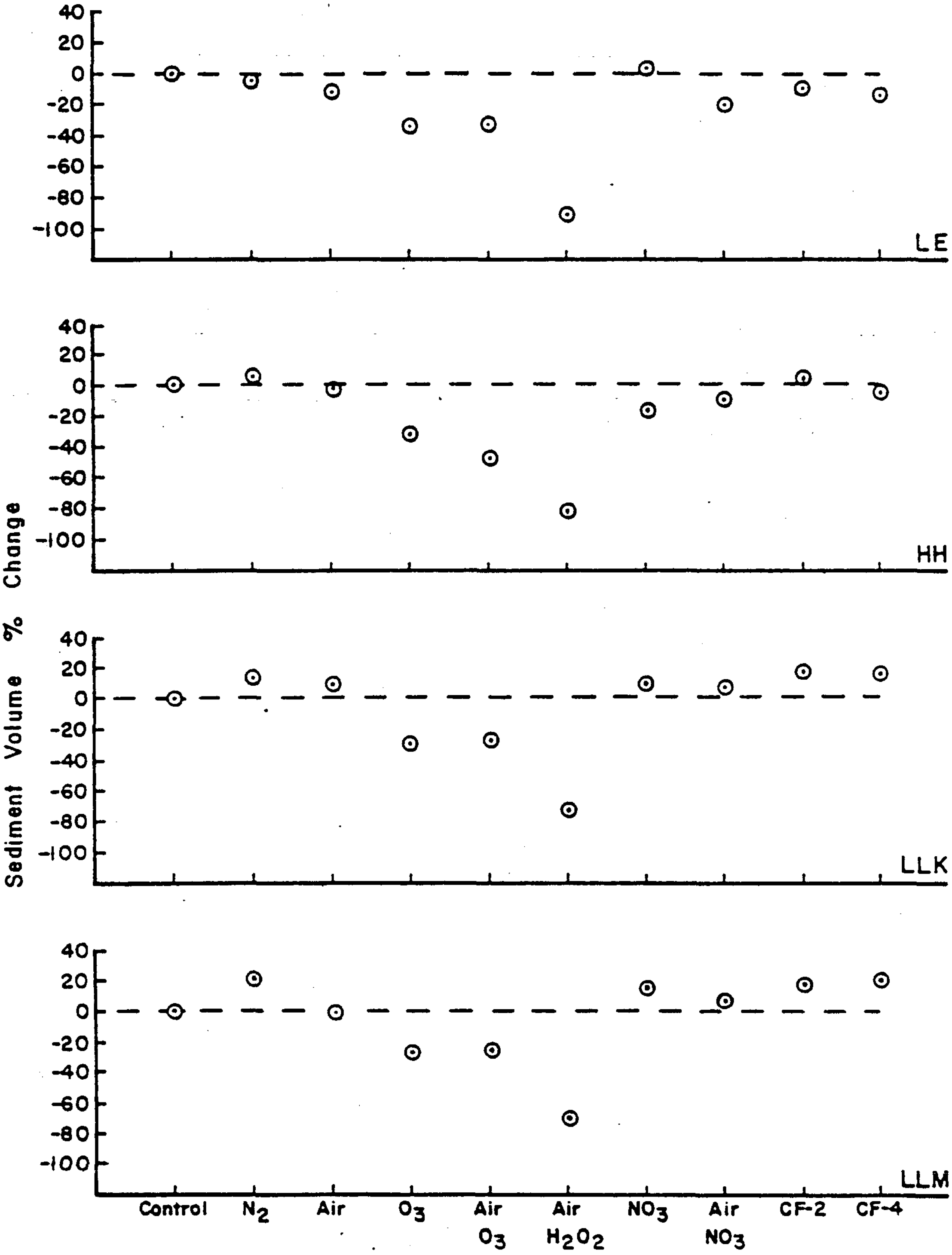

Figure 10. Comparison of Final Sediment Volumes with Initial Volume

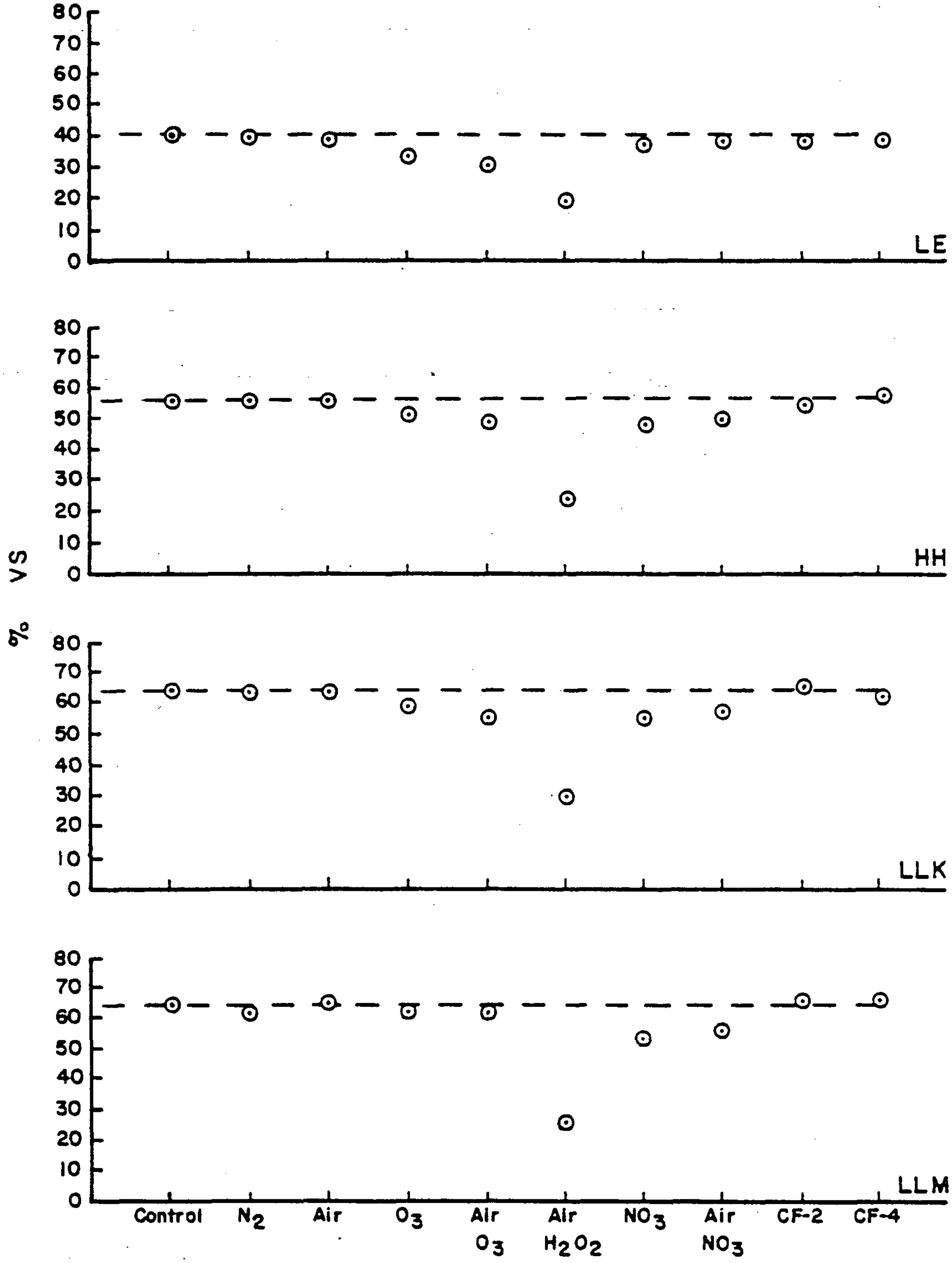

Figure 11. Comparison of Final Sediment % VS with Original Sediment % VS

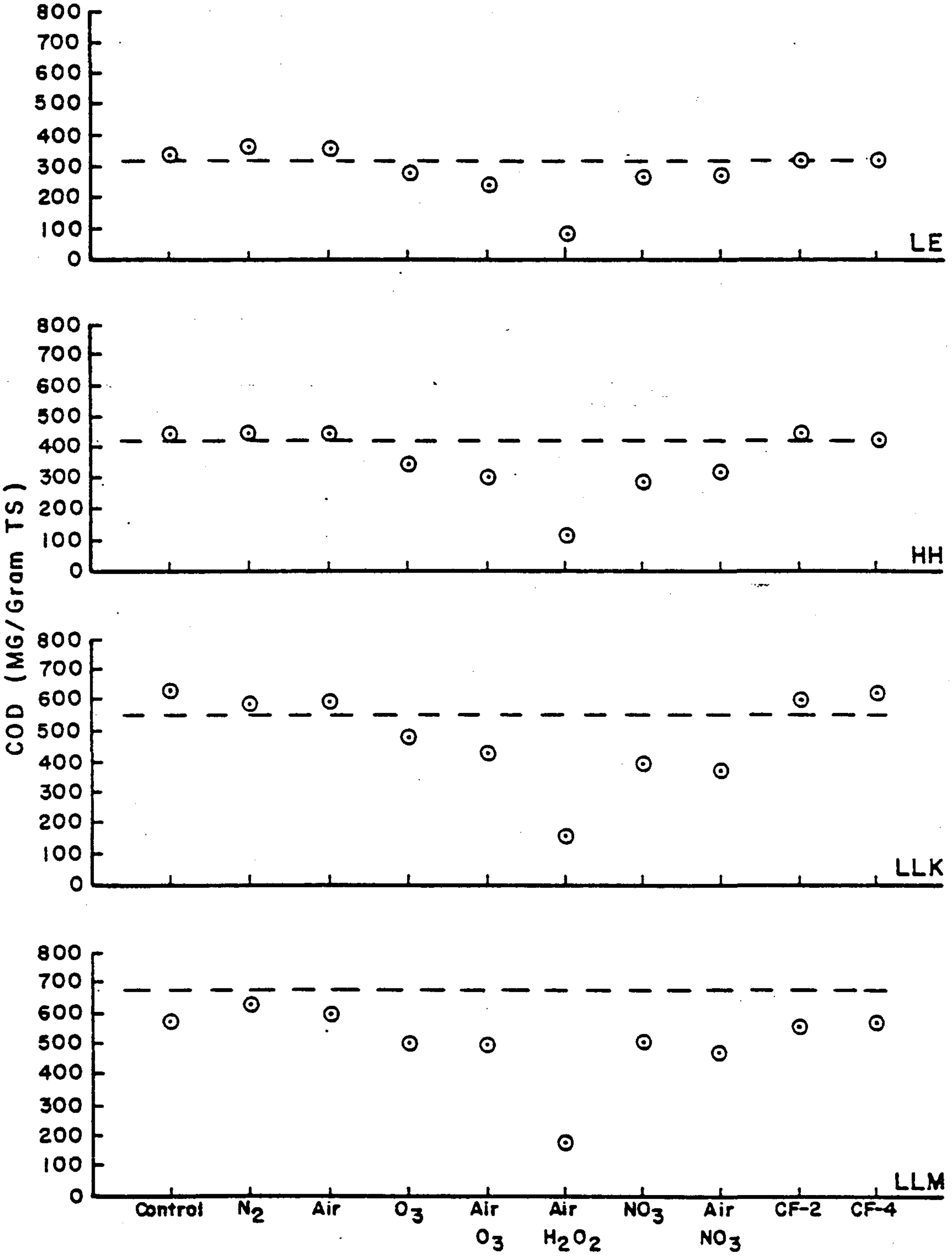

Figure 12. Comparison of Final Sediment COD with Original Sediment COD

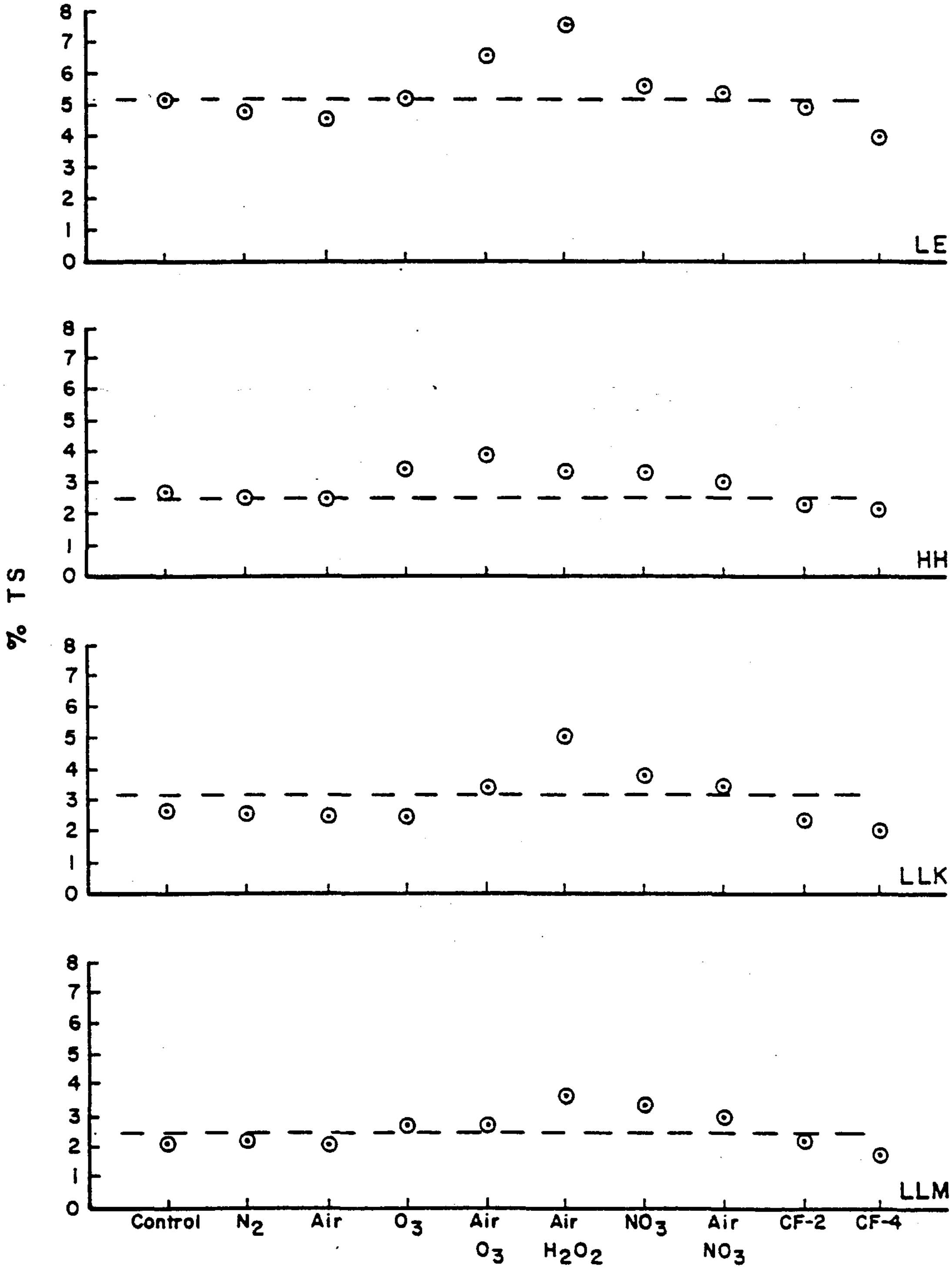

Figure 13. Comparison of Final Sediment % TS with Original Sediment % TS

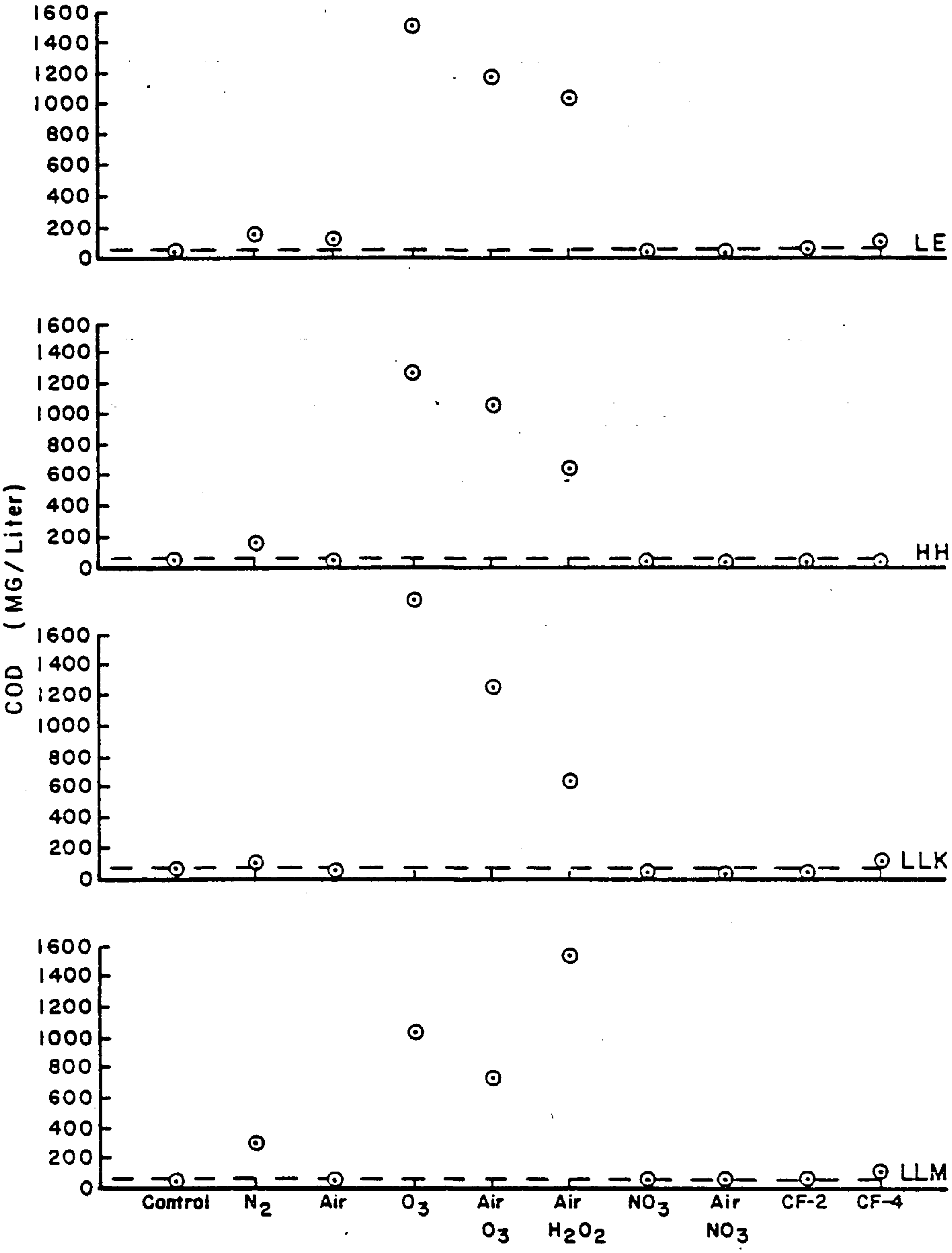

Figure 14. Comparison of Final Water COD with Original Water COD

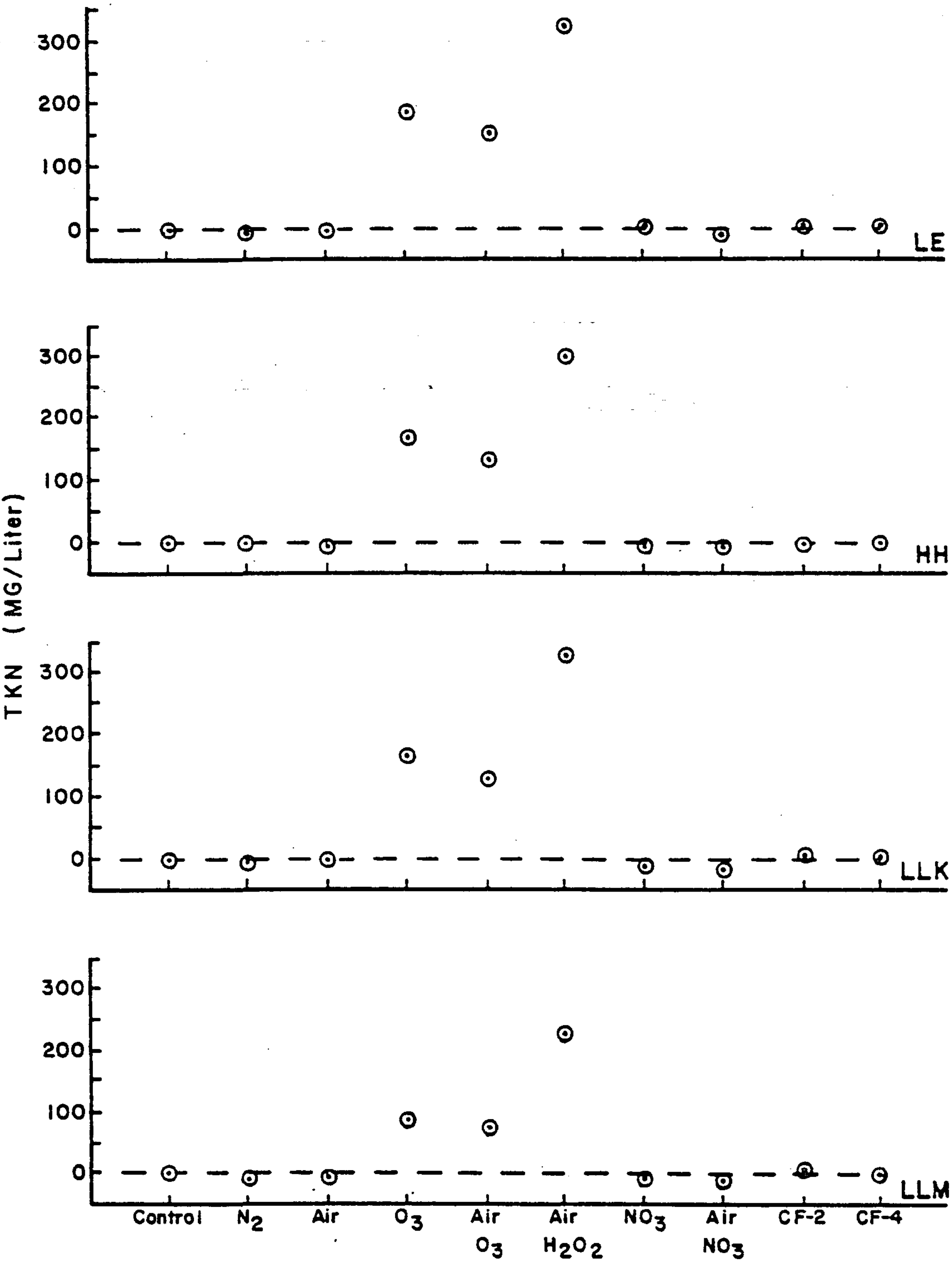

Figure 15. Comparison of Final Water TKN with Original Water TKN

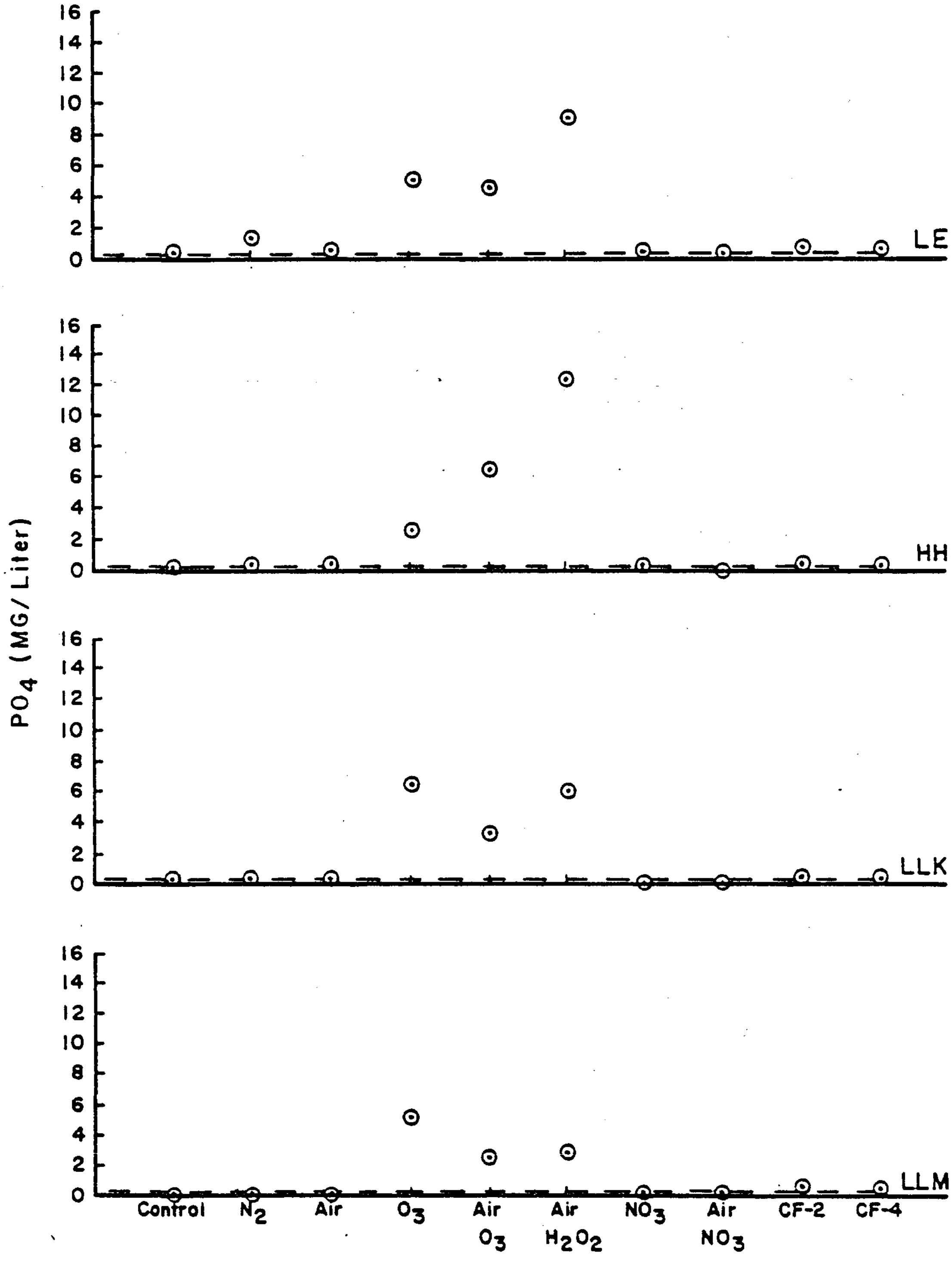

Figure 16. Comparison of Final Water PO_4 with Original Water PO_4

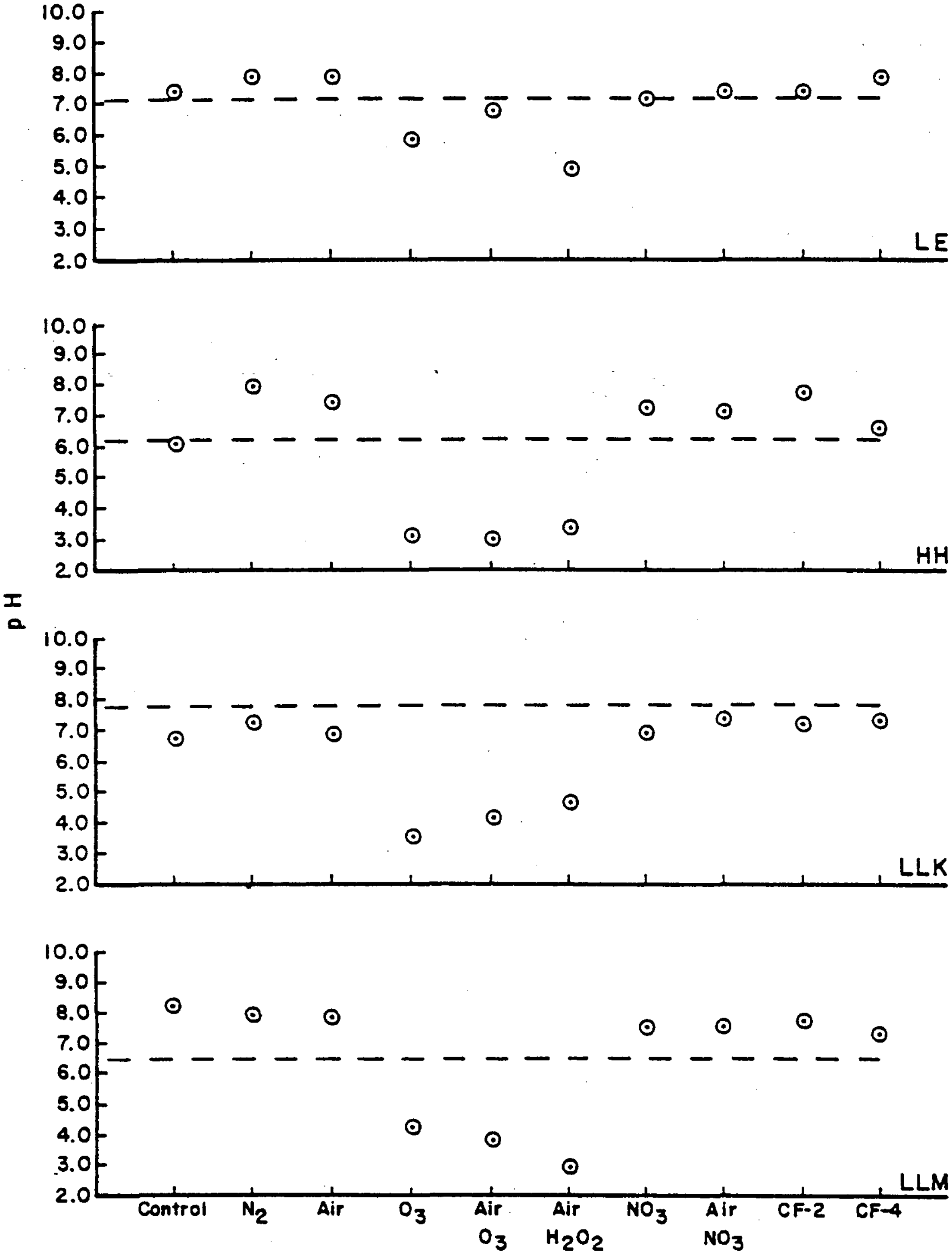

Figure 17. Comparison of Final Water pH with Original Water pH

APPENDIX F.2. EXPERIMENTAL DATA COLLECTED BY SZEWCZYK (1984).

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TABLE 3. Experimental Treatments

JAR NUMBER (*)	SEDIMENT TREATMENT
A1a, A1b, B1a, B1b	H2O2 + Lime
A2a, A2b, B2a, B2b	H2O2 + Lime + Aeration
A3a, B3a	H2O2 + Lime + Seed + NO3
A4a, B4a	H2O2 + Lime + Seed
A5a, A5b, B5a, B5b	57 g Ca(NO3)2 * 4H2O
A6a, A6b, B6a, B6b	113 g Ca(NO3)2 * 4H2O
A7a, A7b, B7a, B7b	170 g Ca(NO3)2 * 4H2O
A8a, A8b, B8a, B8b	NH4+ Control
A9a, A9b, B9a, B9b	Aeration Control
A10a, A10b, B10a, B10a	No Treatment Control

(*) : A - Lily Lake, Marathon Co.
B - Little Elkhart Lake
a,b - duplicate treatment (different jars)

TABLE 4. Chemical Characterization of the Original Sediment Samples.

	LAKES	
Parameter	LLM (A)	LE (B)
COD, mg/g	829 (588)	639 (314)
TS, %	2.64 (2.4)	6.45 (5.1)
VS, %	70.6 (63.34)	33.89 (40.06)
TKN-N, %	(2.9)	(2.1)
PO4-P, mg/g	(589)	(1252)
BOD-5, mg/g	(3.3)	(5.6)
Lignin, %	14.94 (4.68)	12.98 (8.9)
Cellulose, %	26.2	12.6
Fe, %	(0.52)	(1.29)
Mg Hardness, %	(0.37)	(1.76)
Ca Hardness, %	(1.35)	(2.36)
pH	(8.4)	(7.8)
Alkalinity, mg/l as CaCO3	(536)	(893)
O2 Uptake, mg/g VSS/day	(0.22)	(1.73)

( ) - data from Hanson (1981)

% - percent composition on a dry weight basis

TABLE 7. Final Sediment Comparisons

Treatment Jar No. (*)	COD mg/g	VS %	TS %	Volume % change'	Lignin %	Cellulose %
A-Original	829	70.6	2.64	--	30.55	26.15
A1a	505	34.5	4.03	- 65	11.47	7.76
A1b	631	42.8	3.78	- 52	12.34	10.79
A2a	454	32.6	5.37	- 72	11.88	4.37
A2b	460	32.9	5.89	- 69	7.43	5.30
A3a	346	41.7	5.67	- 56	7.02	4.65
A4a	473	31.5	3.76	- 60	9.49	4.06
A5a	414	49.7	3.04	+ 33	23.02	3.28
A5b	595	45.6	3.35	+ 38	22.01	4.02
A6a	486	49.2	4.00	+ 43	14.52	4.93
A6b	486	48.5	4.10	+ 36	12.51	3.89
A7a	397	50.4	4.88	+ 39	6.99	5.11
A7b	382	43.9	5.08	+ 37	6.51	5.44
A8a	596	64.4	3.62	+ 35	15.34	5.73
A8b	670	66.3	4.21	+ 58	12.86	6.23
A9a	788	58.0	2.85	+ 40	29.05	4.20
A9b	629	40.6	3.50	+ 37	29.50	3.52
A10a	803	54.2	2.62	+ 46	29.86	4.25
A10b	884	59.4	2.42	+ 41	30.11	3.86
B-Original	639	33.9	6.41	--	16.55	12.60
B1a	239	19.8	10.19	- 69	6.67	3.81
B1b	213	20.7	8.54	- 71	5.82	4.26
B2a	163	16.2	13.62	- 69	5.95	3.14
B2b	204	18.4	12.93	- 75	6.34	3.30
B3a	153	20.5	15.83	- 69	4.97	2.68
B4a	156	16.3	11.80	- 79	6.41	3.93
B5a	530	37.5	6.13	+ 28	9.99	6.74
B5b	402	36.4	6.97	+ 27	9.87	7.33
B6a	382	38.4	7.31	+ 25	6.39	6.39
B6b	369	43.8	7.25	+ 23	4.37	3.75
B7a	360	39.9	8.47	+ 21	4.52	4.47
B7b	344	39.4	8.55	+ 30	4.80	4.12
B8a	505	47.8	6.58	+ 27	13.25	5.16
B8b	393	46.7	6.88	+ 30	12.79	5.11
B9a	432	27.6	7.61	+ 18	9.79	4.34
B9b	256	21.4	10.60	+ 35	9.50	3.86
B10a	582	34.1	5.25	+ 32	16.50	4.82
B10b	521	33.9	5.49	+ 32	16.53	4.20
PEAE	29	0.7	0.37	--	0.68	0.69
D.F.	16	11	11	--	32	28

(*) - see Table 3 for treatment descriptions
' - (-) % reduction from original sample volume
' - (+) % increase from original sample volume
PEAE = Pooled Estimate of [illegible] te Error
D.F. = Degrees of Freedom

TABLE 8. Continued

Treatment Jar No. (*)	Total-PO4 mg/l	Ortho-PO4 mg/l	TKN mg/l	NO2/NO3 mg/l	NH3 mg/l
A1a	0.98	0.77	1329	0	483
A1b	0.64	0.28	1445	14	336
A2a	2.80	1.50	1420	8	638
A2b	7.03	3.70	1565	0	725
A3a	8.45	4.50	2001	10175	392
A4a	4.28	2.30	1376	17	560
A5a	0.11	0.02	45	28	0
A5b	0.11	0.00	72	--	0
A6a	0.16	0.15	32	19	0
A6b	0.16	0.19	55	26	6
A7a	0.35	0.29	28	26	35
A7b	0.38	0.43	36	15	48
A8a	0.51	0.41	10987	0	10786
A8b	0.56	0.58	9744	0	9173
A9a	0.31	0.02	7	0	0
A9b	0.23	0.04	2	0	0
A10a	0.19	0.00	11	4	3
A10b	0.08	0.00	13	2	5
B1a	1.37	1.10	1033	8	412
B1b	1.15	1.00	1033	17	454
B2a	1.31	0.75	876	25	596
B2b	1.10	0.57	1064	0	627
B3a	0.85	1.19	1767	703	804
B4a	1.17	1.10	948	36	524
B5a	0.13	0.15	20	15	0
B5b	0.08	0.08	73	38	15
B6a	0.15	0.14	22	5	16
B6b	0.19	0.01	28	13	13
B7a	0.19	0.19	9	0	10
B7b	0.25	0.29	3	0	5
B8a	0.65	0.65	10206	35	10018
B8b	0.78	0.78	10451	64	10668
B9a	0.35	0.30	0	0	0
B9b	0.31	0.31	0	0	0
B10a	0.23	0.25	6	0	0
B10b	0.42	0.41	12	8	0
PERE, %	17	26	36	30	27
D.F.	15	42	8	12	12

(*) - see Table 3 for treatment discription.
PERE, % - Pooled Estimate of Relative Error, % basis
D.F. - Degrees of Freedom

TABLE 8. Final Water Column Comparisons

Treatment Jar No. (*)	D.O. mg/l	TDS mg/l	VDS mg/l	pH	COD mg/l	TOC mg/l
A1a	0.5	6128	4160	8.2	4268	1830
A1b	0.5	6604	3840	8.4	4663	2000
A2a	8.0	4328	1500	8.9	3636	1410
A2b	5.7	4932	4046	8.3	3952	1500
A3a	8.6	25916	22468	7.0	5138	2130
A4a	0.6	5464	3736	7.6	3676	1500
A5a	5.7	8920	3968	7.4	8	30
A5b	6.0	7864	3224	7.4	8	29
A6a	4.5	13308	3632	7.2	8	31
A6b	5.5	15372	4808	7.2	8	36
A7a	4.5	21032	5760	7.1	15	39
A7b	4.9	21592	3652	7.0	23	39
A8a	4.7	13328	12268	7.3	218	32
A8b	5.2	11176	10196	7.2	162	22
A9a	7.3	464	348	7.5	23	42
A9b	7.8	452	312	7.5	68	46
A10a	3.7	452	136	7.5	0	52
A10b	3.8	180	76	7.5	0	60
B1a	0.6	5096	1608	8.4	3241	1485
B1b	0.8	4980	1788	8.4	3083	1340
B2a	6.9	2936	2060	9.0	1700	820
B2b	7.0	3812	1320	9.0	2529	1170
B3a	0.8	21820	14996	7.4	2846	1190
B4a	0.8	4588	2100	7.9	2925	1300
B5a	5.9	7212	2156	7.6	0	30
B5b	6.2	8016	2888	7.6	0	34
B6a	6.0	13416	4524	7.5	0	29
B6b	6.1	12784	3144	7.4	0	34
B7a	5.8	20764	4240	7.1	0	31
B7b	5.9	20908	4632	6.8	0	30
B8a	4.0	12760	11804	7.3	177	48
B8b	3.5	15976	13904	7.4	218	46
B9a	7.3	724	580	7.2	68	52
B9b	6.9	448	320	7.2	68	56
B10a	5.3	284	146	7.0	23	42
B10b	3.9	352	52	6.4	0	42
PERE, %	--	13	15	--	5	10
D.F.	--	17	16	--	7	22

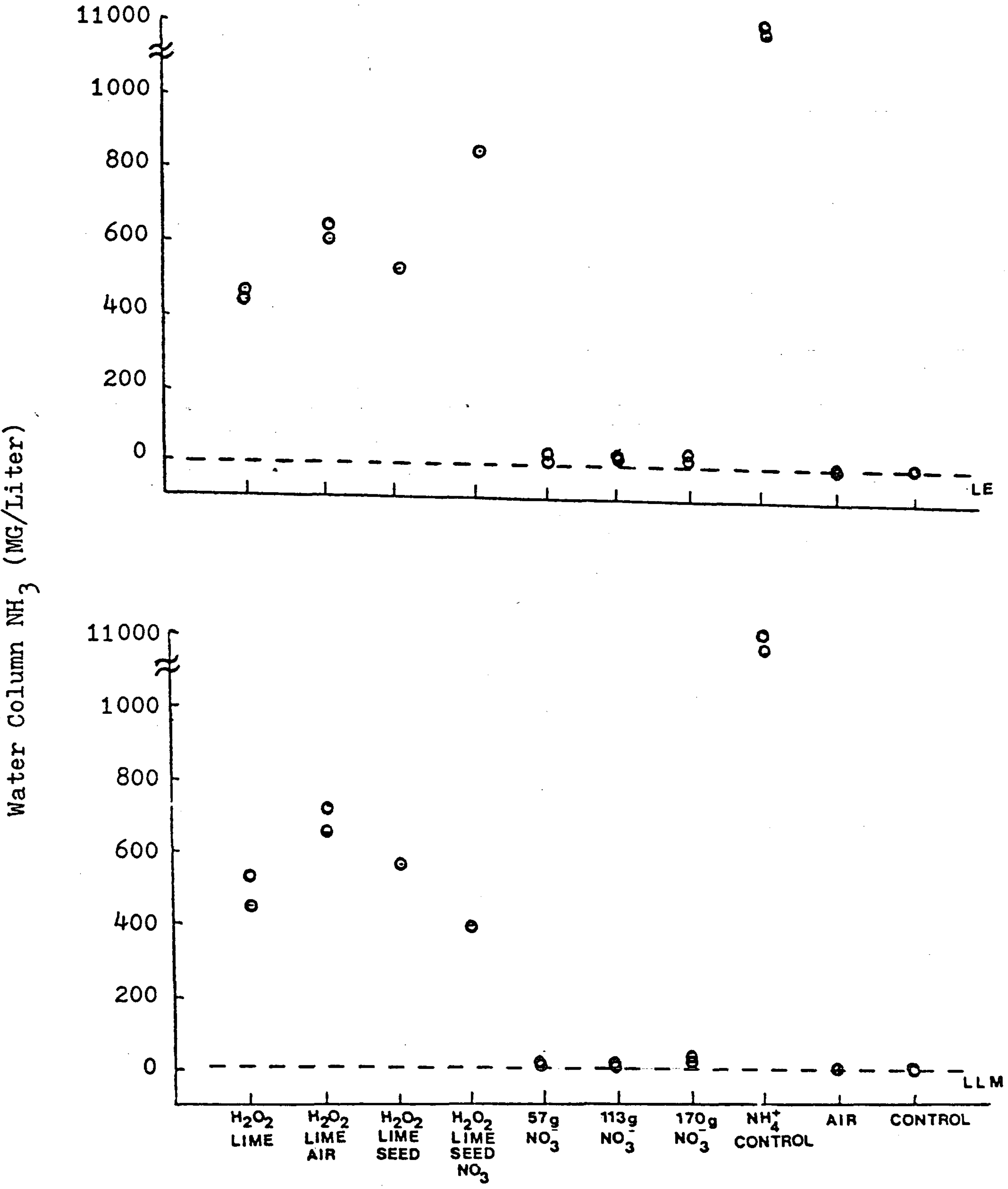

Figure 13. Comparison of Final Water NH_3 with Original Water NH_3.

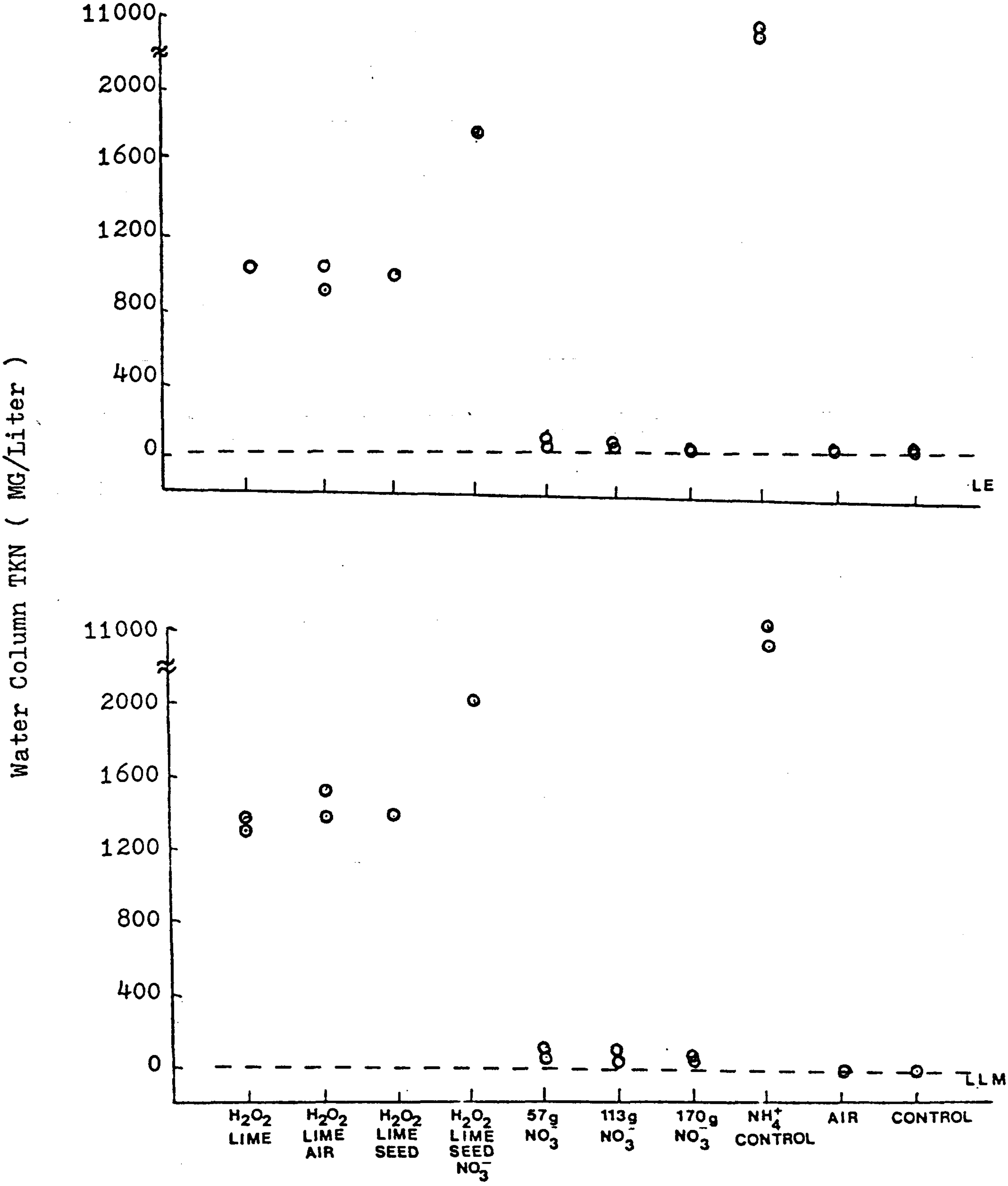

Figure 14. Comparison of Final Water TKN with Original Water TKN.

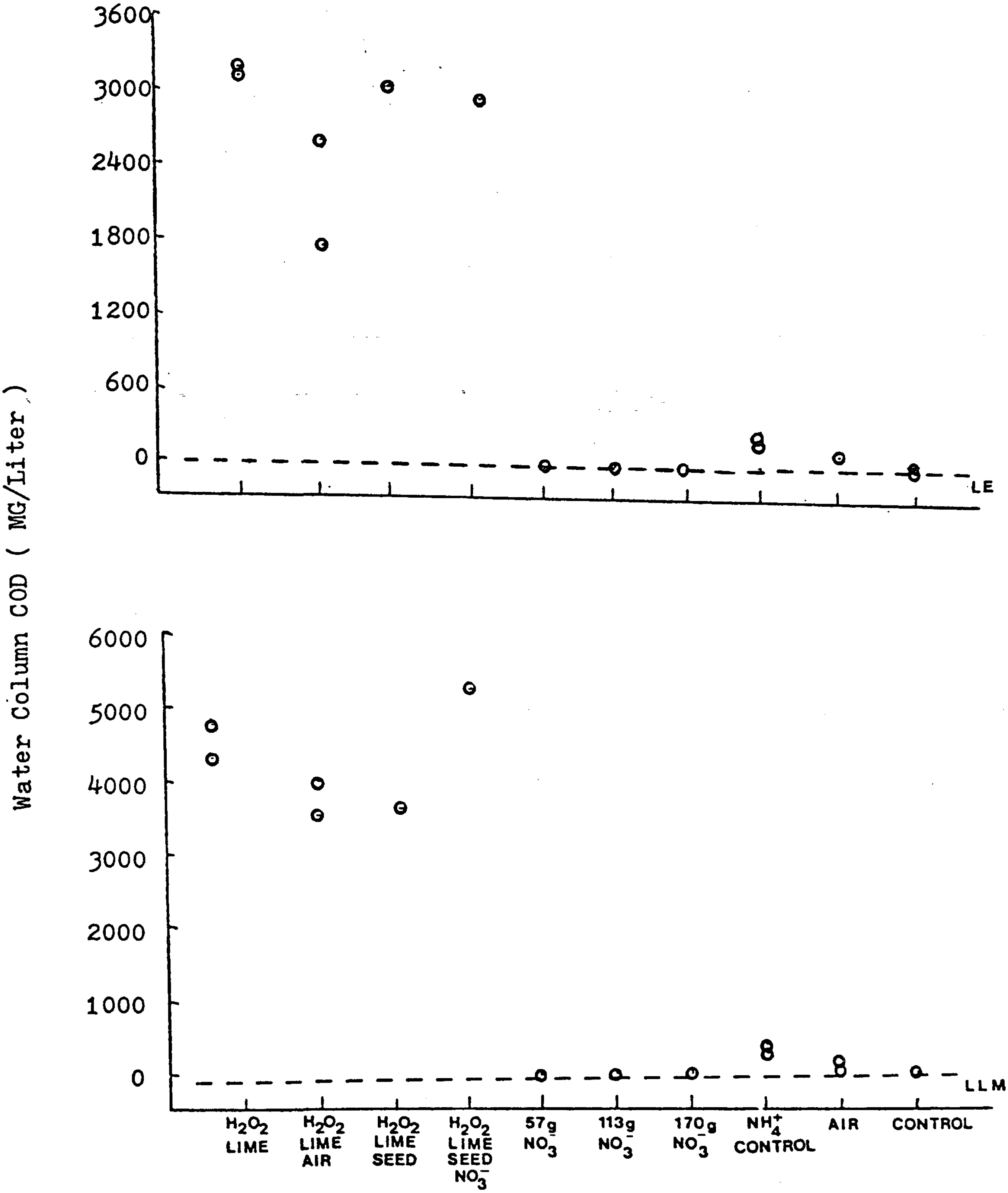

Figure 15. Comparison of Final Water COD with Original Water COD.

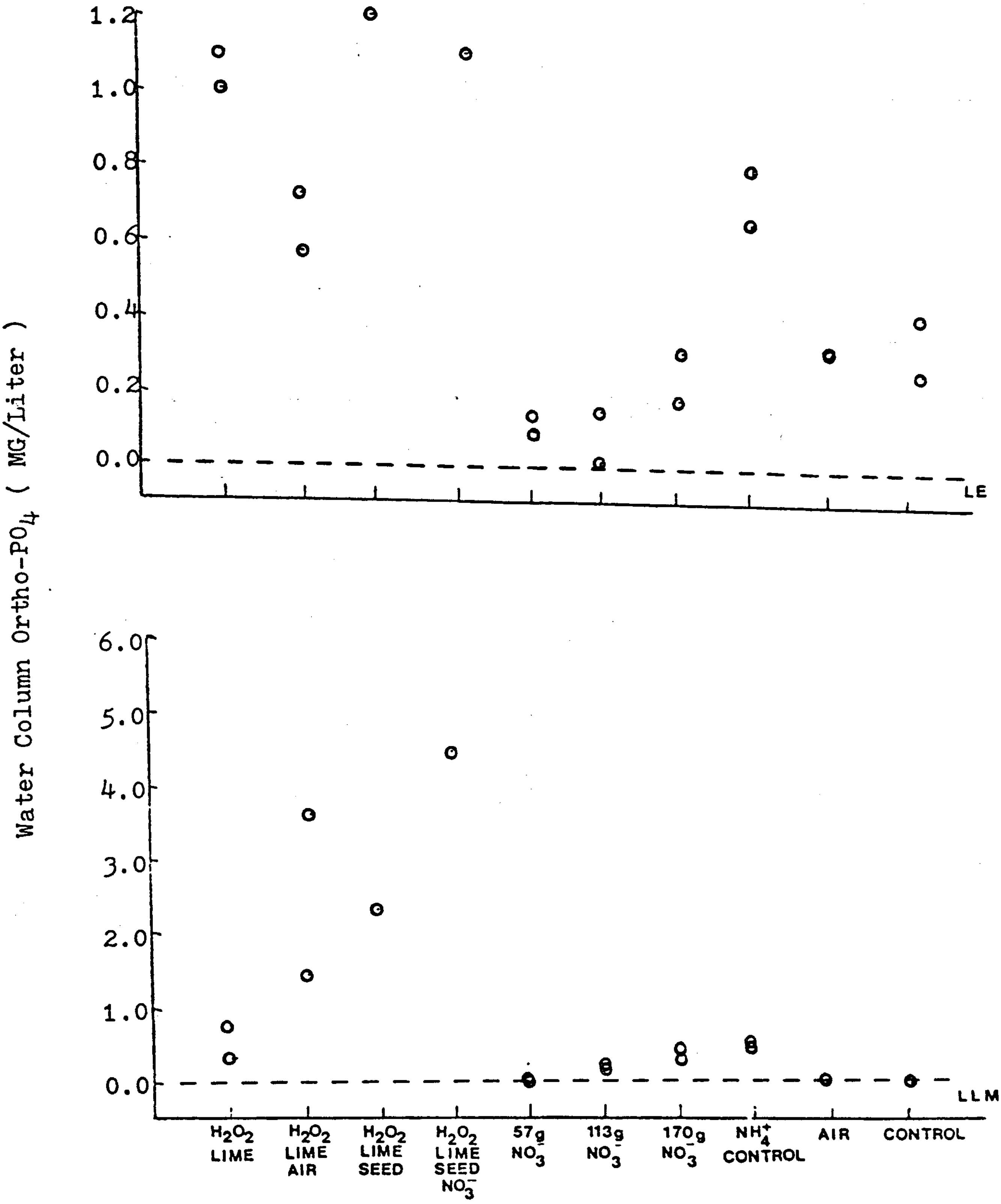

Figure 16. Comparison of Final Water Ortho-PO_4 with Original Water PO_4.

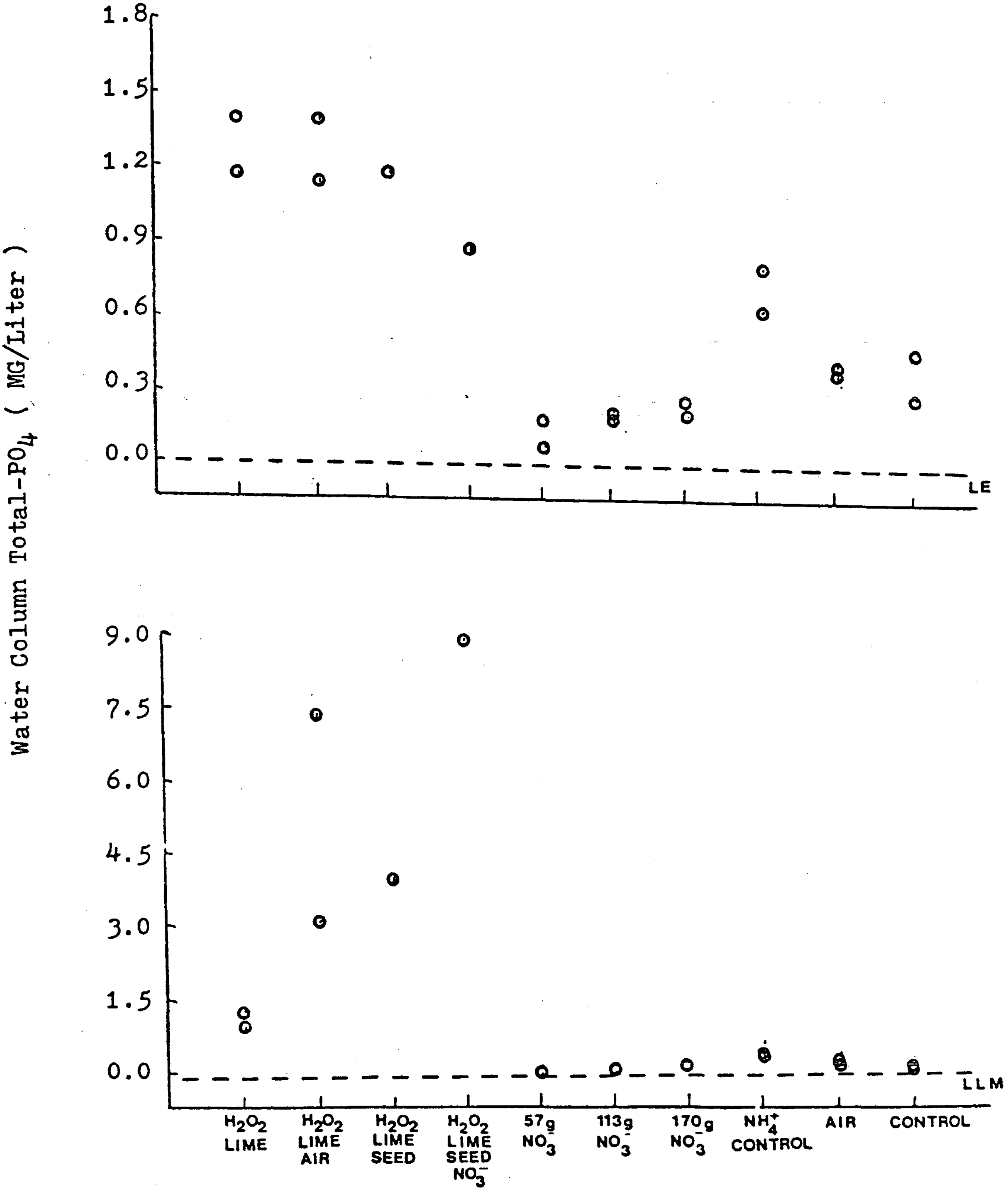

Figure 17. Comparison of Final Water Total-PO_4 with Original Water PO_4.

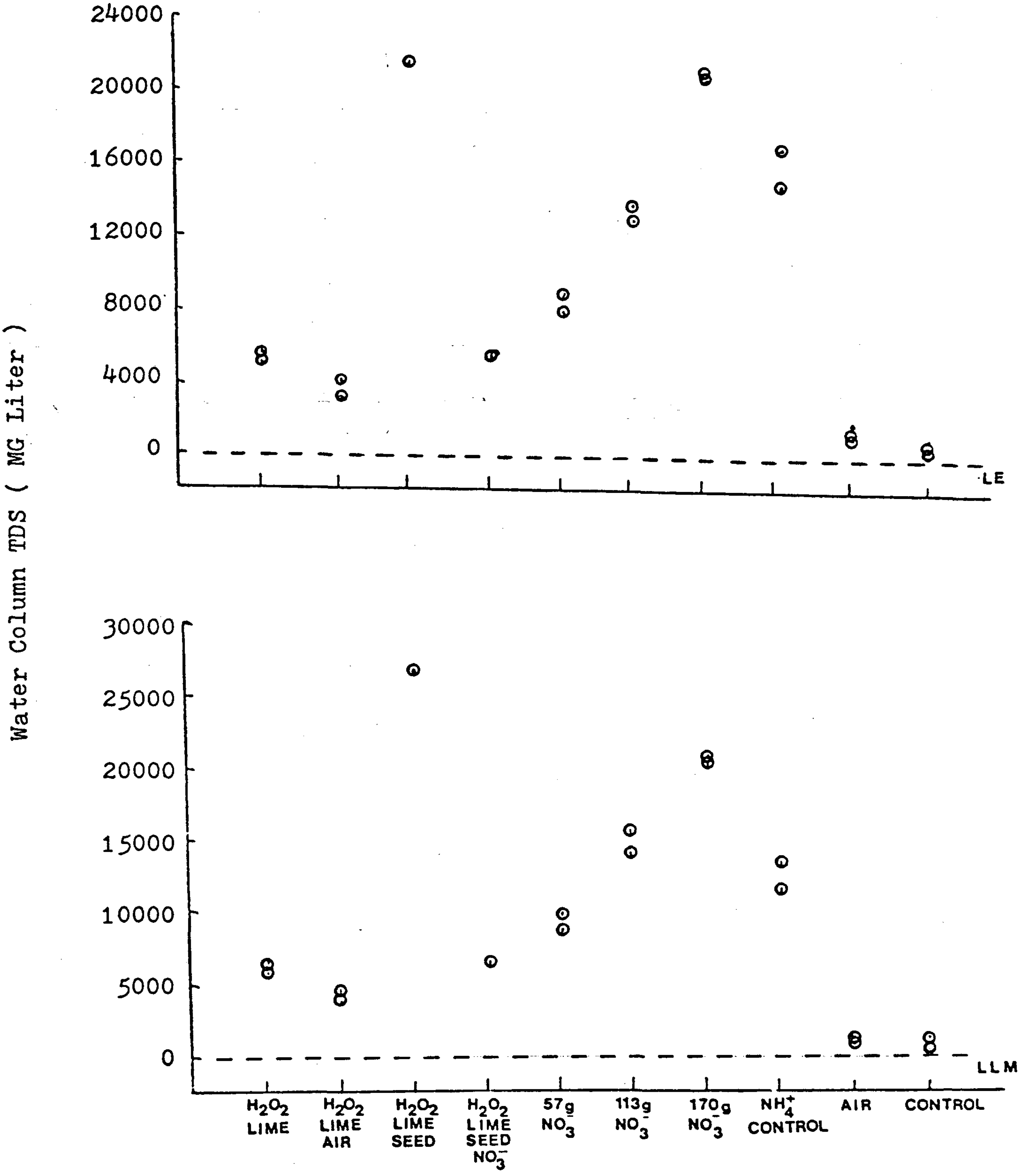

Figure 18. Comparison of Final Water TDS with Original Water TDS.

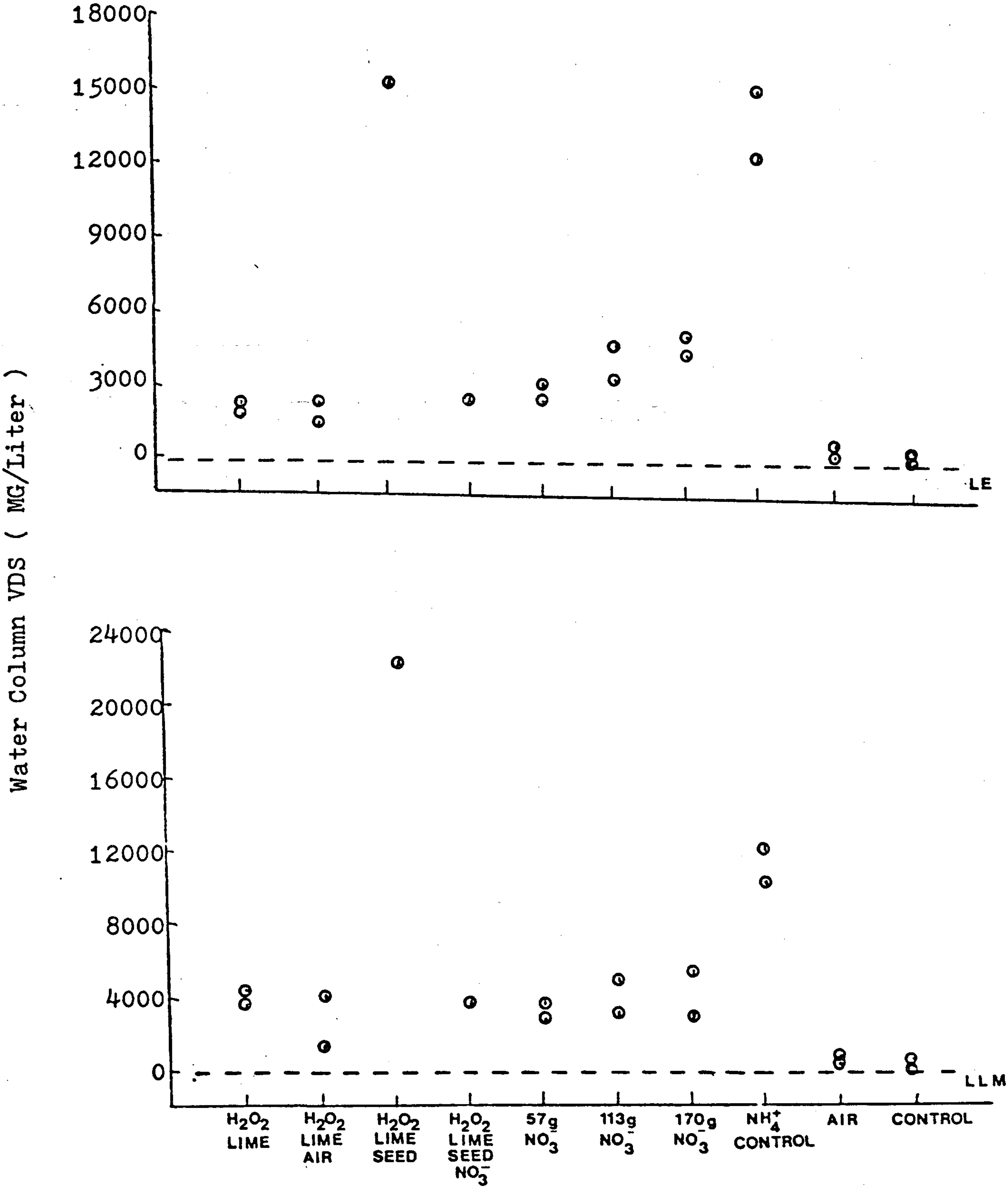

Figure 19. Comparison of Final Water VDS with Original Water VDS.

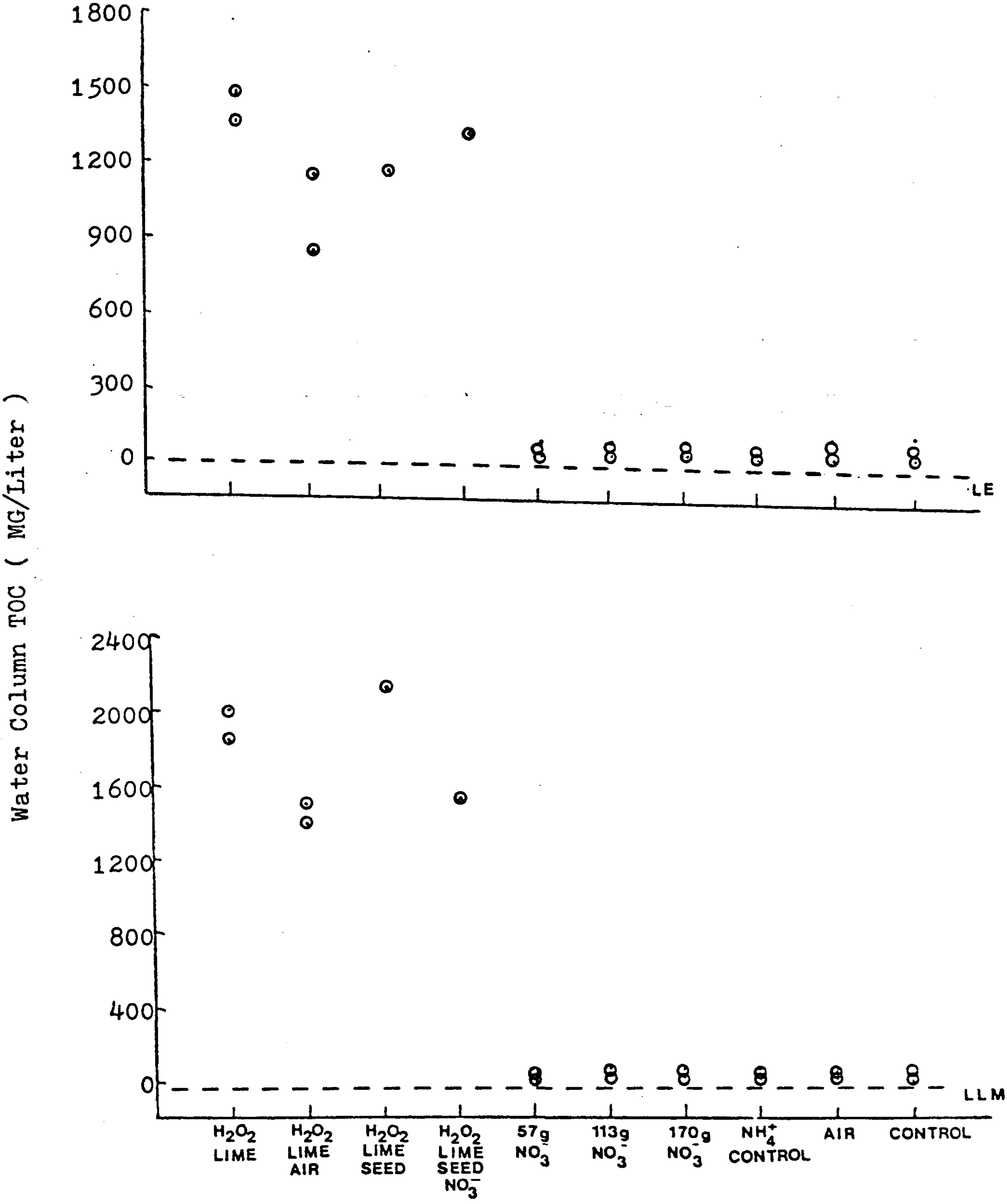

Figure 20. Comparison of Final Water TOC with Original Water TOC.

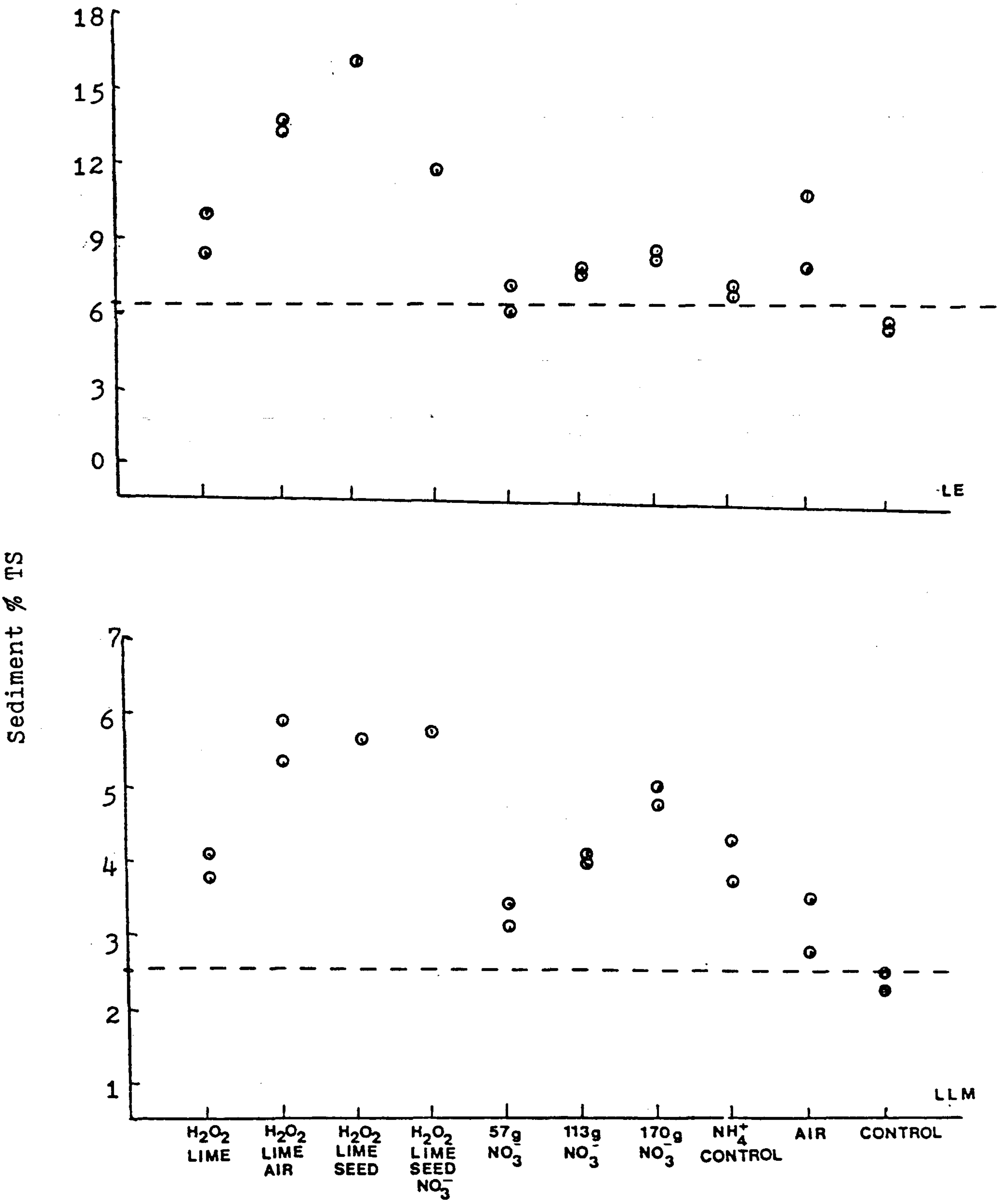

Figure 21. Comparison of Final Sediment % TS with Original Sediment % TS.

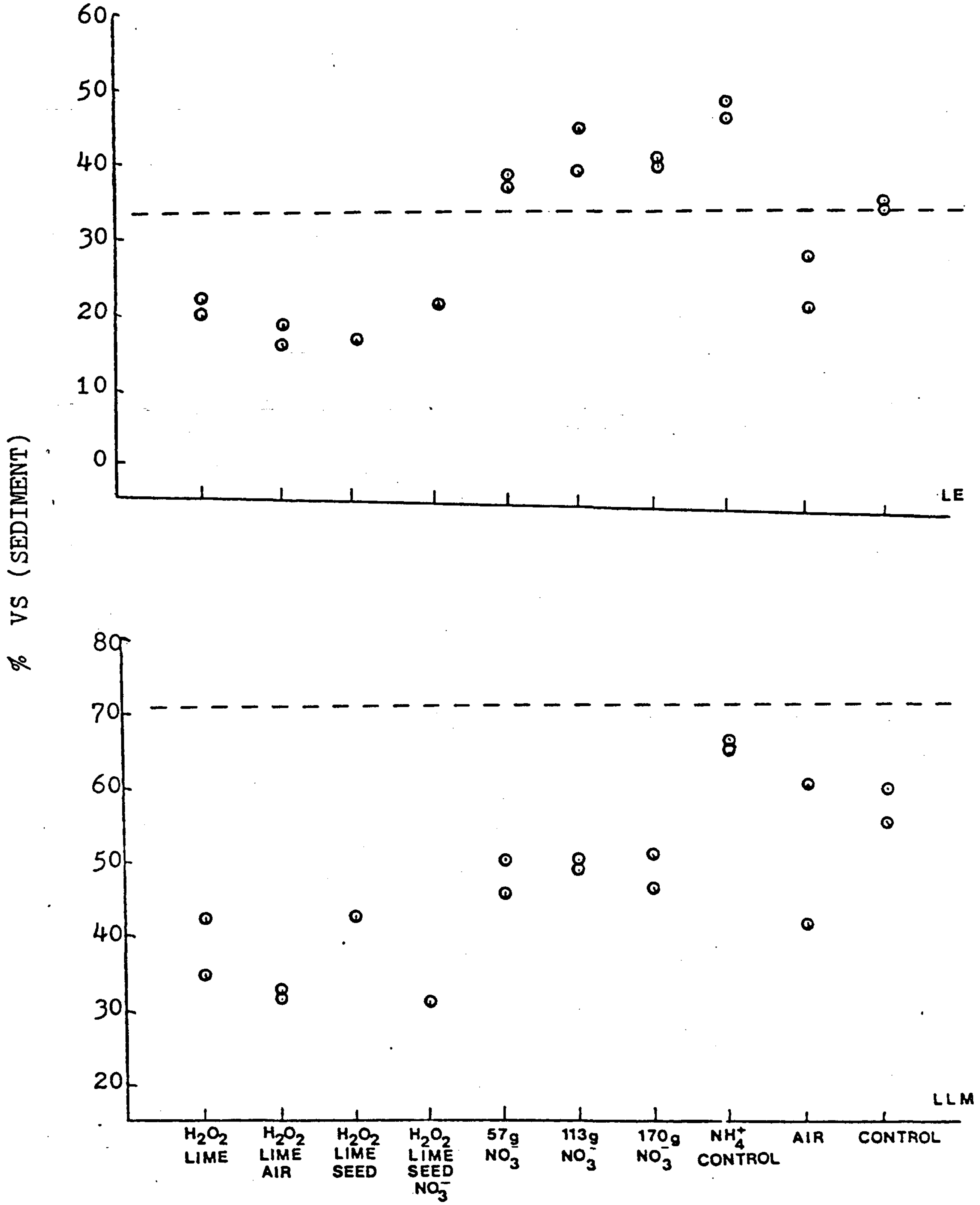

Figure 22. Comparison of Final Sediment % VS with Original Sediment % VS.

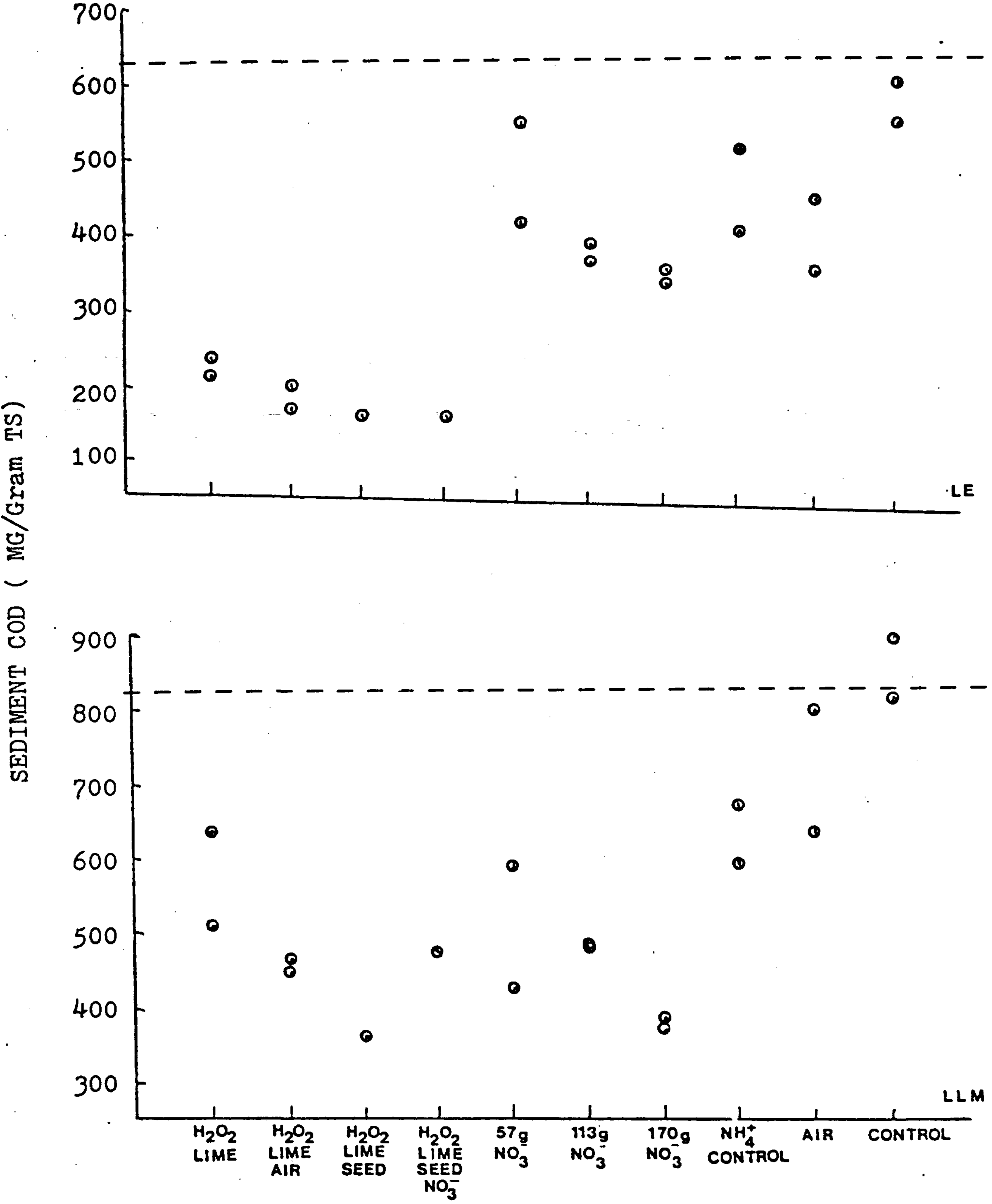

Figure 23. Comparison of Final Sediment COD with Original Sediment COD.

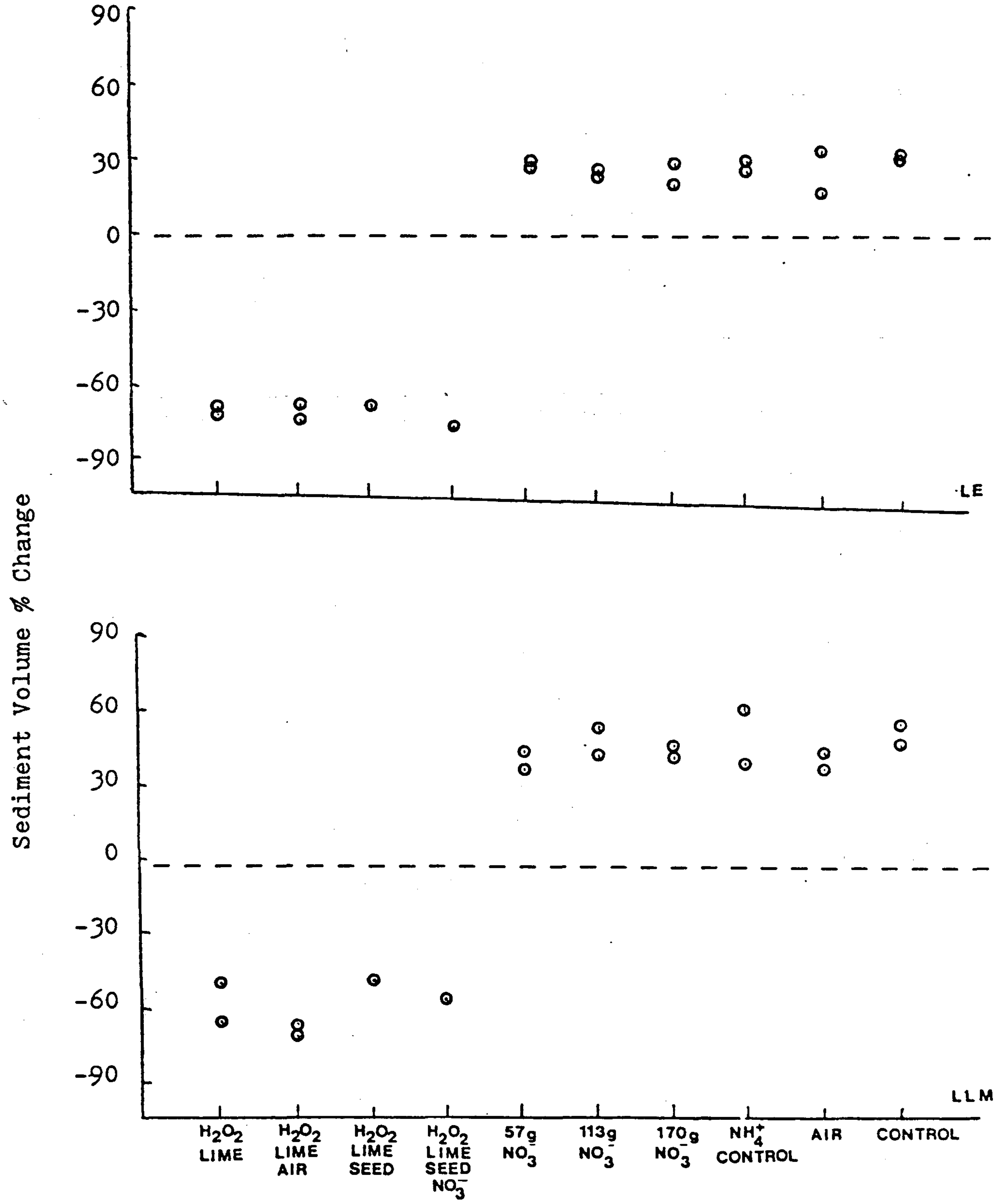

Figure 24. Comparison of Final Sediment Volumes with Original Volume.