LAKE RESTORATION BY NUTRIENT INACTIVATION

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ABSTRACT

Nutrient inactivation by use of chemical precipitants such as aluminum, iron, or calcium has been successfully practiced in the wastewater field for over 40 years. In comparison, the treatment of standing bodies of water is a relatively new procedure beginning in the Netherlands in 1962 when ferric chloride was applied to the Dordrecht reservoirs. Aluminum sulfate was used to inactivate phosphorus at Lake Langsjon, Sweden in 1968. Since 1970 most of the larger treatments have occurred in the United States, primarily in Wisconsin, Washington, and Ohio. Techniques, methodology, equipment, and costs of several lake treatments are discussed. Advantages, disadvantages, and limitations of this method of lake restoration also are discussed.

INTRODUCTION

Chemical coagulation and precipitation of undesirable suspended matter, dissolved substances, and bacteria from drinking water have been standard practice since the turn of the century. Aluminum and ferric salts as well as lime have been the most widely used precipitants. By the early thirties the concept and initial technology for use of the same compounds in improving sewage effluent had been developed (Sawyer, 1944; Rohlich, 1969). However, it was not until much later that nutrient removal from effluents became a widespread practice. Ockershausen (1975) observed that in 1972 the number of sewage treatment plants in the United States utilizing precipitants was fewer that 10 while by 1974 this number had risen to nearly 300.

The success in the water and wastewater fields in upgrading water quality has without question helped stimulate the development of in-lake nutrient inactivation methodology. One of the earliest experiments at inactivation was made in the Netherlands in 1962 when 2 mg/liter ferric chloride was applied to the Dordrecht reservoirs (Dunst, et al. 1974). The first apparent lake-wide use of aluminum sulfate for nutrient inactivation occurred in Sweden at Langsjon in 1968 (Jernelov, 1971; Peterson, et al. 1974). Two years later Horseshoe Lake, Wis. also was treated successfully with aluminum sulfate. In quick succession, Grangehergsviken, Sweden, Cline's Pond, Ore., and Fish Rearing Pond, Minn. were treated with aluminum compounds. During 1972–73 a series of Wisconsin lakes including Powderhorn, Long, Snake, and Pickerel were treated with aluminum sulfate or sodium aluminate (Dunst, et al. 1974). Two Ohio lakes, Dollar and Twin, received aluminum sulfate treatments in 1974 and 1975, respectively (Cooke and Kennedy, 1977a). Treatments mentioned to this point had been confined to lakes less than 40 ha in area.

Two larger lakes in Washington have received aluminum sulfate treatment, Liberty Lake (277 ha) in 1974 (Funk, et al. 1975), and Medical (63 ha) in 1977 (Soltero, et al. 1978). Hyrum reservoir (190 ha) in Utah is scheduled for a 1978 summer treatment (Medine, personal comm.)

Most of the lakes treated have shown reduced phosphorus content and less nuisance algal growth as well as higher hypolimnetic dissolved oxygen. Two exceptions have been Powderhorn and Pickerel Lakes where nuisances were not reduced. Cooke and Kennedy (1977a) have also reported less success in Dollar and Twin Lakes for reasons that will be discussed later.

It becomes evident from the literature to date that for several reasons phosphorus is the major nutrient targeted for inactivation. It has been shown to be a critical nutrient for nuisance algal and plant growth and is generally the most limiting nutrient in bodies of water because of its scarcity in relation to other major nutrients (Hutchinson, 1957; Vallentyne, 1968; Edmondson, 1972; Likens, 1972; and Miller, et al. 1974).

Phosphorus binds readily with most common inactivant cations such as calcium (II), iron (III), and aluminum (III), forming relatively insoluble compounds. Calcium(II) is of limited use in lake environments because it is ineffective below pH 9. Anoxic conditions in the hypolimnion of eutrophic lakes would reduce iron (III) to the soluble (II) state. Its addition might then aggravate rather than alleviate the problem. Zirconium and lanthanum rare earths have been shown to be very effective in phosphorus removal; however, more research into health aspects and direct toxicity are required before they are introduced into lakes on a large scale (Powers, et al. 1978).

Aluminum compounds have become the most widely accepted and utilized lake nutrient inactivants. As previously mentioned, this is largely because of these compounds' long association with water repair, effectiveness under eutrophic conditions, and relative innocuousness to most life forms. Aluminum also is the most prevalent metal in the earth's crust.

TREATMENT RATIONALE AND METHODOLOGY

The lakes described in the introductory section represent a good cross section of lake geomorphology, nutrient sources, water and climatic conditions, and usage. However, some have been documented more fully than others, and so we have chosen from those to review in this paper. Excellent summaries of many of the earlier treatments can be found in publications by the U.S. Environmental Protection Agency (1973); Peterson, et al. (1973, 1974); and Dunst, et al. (1974).

Horseshoe Lake

Background setting

This 8.9 ha lake represents the first reported full scale in-lake inactivation experiment in the United States. The lake setting is in glacial drift with silt loams and silt clay loamy soils developed on the deposits. Yearly precipitation averages 76 cm. A watershed of approximately 700 ha funnels water to Horseshoe Lake where retention time is estimated to be between 0.3 and 0.7 years. It is a dimictic hardwater lake with well established stratification. Physicochemical characteristics are summarized in Table 1.

Residents had noted extensive blue-green algal blooms beginning about 1962. Nuisance algal growth had been controlled to some extent by copper sulfate treatment since 1965. However, three winter fish kills had been cataloged during the same period of time.

Table 1. – Range of physicochemical data for Horseshoe Lake (Wis. Dep. Nat. Resour. 1966–67; Peterson, et al. 1973)

Parameter	Epilimnion	Hypolimnion
Temp. in°F	32–78	32–48
D.O. in mg/l	<0.5–14.3	0.0–4.3
pH	7.2–8.9	6.8–8.3
Total alkalinity (mg $CaCO_3$/l)	218–252	220–278
Total hardness (mg $CaCO_3$/l)	254–300	276–306
Nitrite-N in mg/l	0.004–0.089	0.002–0.213
Nitrate-N in mg/l	0.10–0.90	0.10–0.76
Ammonia-N in mg/l	0.06–1.96	0.16–6.33
Organic-N in mg/l	0.76–2.19	0.75–1.68
Diss. P in mg/l	0.01–0.48	0.26–1.52
Total P in mg/l	0.05–0.50	0.31–1.54

Pretreatment Procedures

Considerable pretreatment research and laboratory effort preceded treatment to determine levels of aluminum sulfate needed to effectively remove the maximum amounts of phosphorus without serious ecological consequences. Jar tests indicated that addition of 200 mg/l (18 mg Al/l) would remove 88 percent of the dissolved and 30 percent of the total phosphorus. A more intensive lake water testing program had been initiated 6 months prior to treatment to establish background limnological data. Fish toxicity tests were run on rainbow trout fingerlings at aluminum levels that bracketed treatment amounts. Only at aluminum levels 50 percent higher than treatment did mortality occur and these deaths were attributed largely to high solids content.

The treatment was planned to inactivate phosphorus shortly after spring runoff and actually took place in May 1970.

Treatment Devices and Methods

The lake was divided into nine plots of about 1.01 ha each as shown in Figure 1.

Previous tests with fluorescein dye and granular alum had shown that the best application method would be a slurry injected by manifold in the propellor wash about 0.3 m below the water surface.

A unit distribution system consisted of slurry tanks, a freshwater supply for filling the tanks, a mixer and application pump, and a distribution manifold for each vessel. The three units involved were a 4.9 m aluminum workboat, a 3 by 6 m barge, and an amphibious truck (DUKW-353). Carrying capacity varied with each system. Two individuals on the small boat could dispense 317 kg/hour, three people on the barge could apply 1,135 kg/hour, and three individuals on the DUKW could spread 1,360 kg/hour.

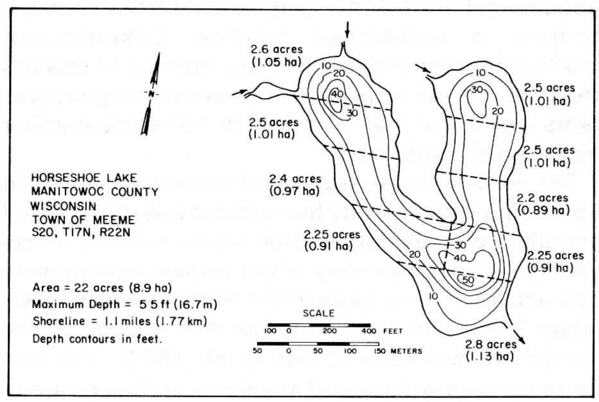

Figure 1.- Depth contours and treatment sections of Horseshoe Lake (redrawn from Peterson, et al. 1973).

Twin and Dollar Lakes

Background

Twin Lakes are small (27–35 ha) dimictic lakes located in semiforested, urban Ohio near Kent. They are of glacial origin, the basins being formed in partially sealed kettle (Kent Till) depressions. The shorelines have been subject to septic tank drainage that ultimately closed both lakes to contact recreation in 1970. In 1972, sewage was diverted but extensive blue-green algae blooms and macrophyte growth continued. Dollar Lake is a small alkaline bog lake (2.2 ha) in the same drainage. This latter lake was utilized for development of techniques and pilot treatment in preparation for treatment of West Twin Lake. Table 2 gives general limnological characteristics.

The aluminum sulfate treatment at West Twin Lake described by Cooke and Kennedy (1977a) was directed primarily at covering the bottom sediments with a layer of aluminum hydroxide to absorb phosphorus molecules released from the sediment. They assumed that the anaerobic sediments were the chief source of internal phosphorus loading. It also had been observed in the preliminary studies that surface application resulted in large floc particles, which Cooke and Kennedy believed descended too slowly for phosphorus removal in the hypolimnion. A final stated reason was that a hypolimnetic treatment would avoid any localized toxicity problem in the epilimnion.

Table 2. – Limnological features of Twin Lakes and Dollar Lake (Cooke and Kennedy, 1977)

	West Twin	East Twin	Dollar Lake
Area (ha.)	34.02	26.88	2.22
Volume ($x10^5M^3$	14.99	13.50	0.864
Mean depth (M)	4.34	5.03	3.89
Maximum depth (M)	11.50	12.00	7.50
Mean water residence (yrs.; N=5)	1.28	0.57	
Mean areal load (gms. P/M^2/yr.; N=5)	0.311	0.649	
Classification	Eutrophic	Eutrophic	Eutrophic

The treatments were carried out in July of 1974 at Dollar Lake and in July 1975 at West Twin. East Twin was not treated but was held as a control lake. Depth contours are shown in Figure 2.

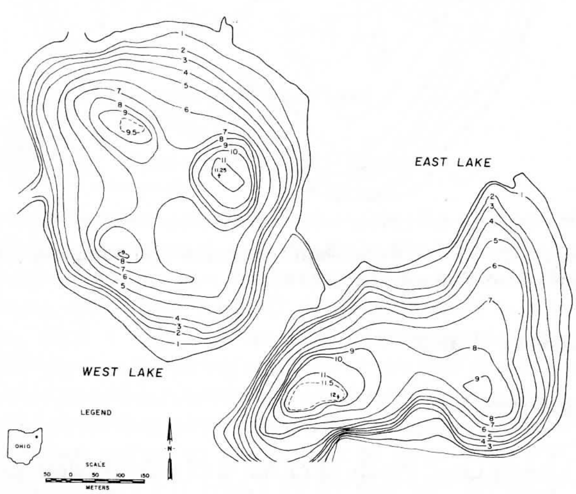

Figure 2.- Depth contours of Twin Lakes (redrawn from Cooke and Kennedy, 1977).

Treatment Devices and Methods

Dosage rates were based upon alkalinity and aluminum sulfate added to the point where the pH began to fall and dissolved aluminum began to increase.

Extensive testing by in situ columns, as well as the pilot lake treatment of Dollar Lake, was made before treatment of West Twin Lake.

Barges were constructed by welding five 208-liter drums together to form pontoons. Each barge had five pontoons floating it. The pontoons were tied together and to a steel support frame by a 0.6 cm diameter steel cable. The Dollar Lake barge had a 1.04 m^3 holding tank. Two barges were constructed for the West Twin Lake treatment and each had two holding tanks. In both treatments a shore based holding tank (portable swimming pool) was utilized to receive truck shipments of 15.1 m^3 of liquid aluminum sulfate. A shore to barge pipeline was laid out utilizing 6 cm inner diameter PVC pipe supported by anchored barrel floats to a mid-lake supply station. Gravity aided by a pump served the barges. Pumping was actuated by radio.

The treatment area was defined by buoys anchored around the depth contour of the top of the hypolimnion. This area was subdivided into 10 x 50 m sections and the volume under each was calculated so that each would receive dosage in relation to its alkalinity. The liquid aluminum sulfate was pumped out of the barge holding tanks, mixed with water in the line, and moved down to a 7 m long PVC manifold, 6 cm inner diameter and perforated with 0.6 cm holes. Surface markers 7 m apart assured proper distribution. At Dollar Lake 9.3 metric tons of aluminum sulfate were applied, 10 percent on the surface to give a dose of 20.9 mg Al/*l* to the hypolimnion. At West Twin Lake about 91 metric tons were applied in 3 days for a dose of 27.6 mg Al/*l* to the hypolimnion. One day was required for the Dollar treatment, 3 days for the West Twin Lake application.

Medical Lake

Medical Lake, Wash. is a 63 ha lake, a result of the Great Spokane floods some 18 to 20,000 years ago (U.S. Geol. Survey, 1973). Massive walls (km^3) of water moved through the Spokane Valley westward and southward gouging out several hundred lake basins of which 20 to 30 small (0.1 to 869 ha) lakes remain today. Medical Lake is an extremely alkaline seep lake and received sewage for a considerable number of years. Sewage diversion has not restored the lake. Both surface and hypolimnetic liquid aluminum sulfate treatments were made in late summer of 1977 and will be reported later in this conference (Gasperino and Soltero, 1978).

Cline's Pond

Background

Cline's Pond (0.4 ha) near Corvallis, Ore., is a manmade, highly eutrophic farm pond with a mean depth of 2.4 m. Source waters are mainly infiltration with some slope wash from cultivated fields (Sanville, et al. 1976; Powers, et al. 1978). It has a unique history in restoration research in that it received aeration treatment in 1969, a sodium aluminate treatment in 1971, and a zirconium treatment in 1974. In addi-

Table 3. – Summary of Cline's Pond limnological data (mg/*l* except where noted; Sanville, et al. 1976)

		1970 Apr. 15 – Sept. 15			1971 Apr. 15 – Sept. 15		
	Depth*	Avg.	Min.	Max.	Avg.	Min.	Max.
P-total	S	.29	.13	.60	.06	.01	.11
	B	.35	.18	.48	.09	.02	.33
P-ortho	S	.03	< .01	.09	.01	< .01	.02
	B	.09	< .01	.28	.01	< .01	.02
N-ammonia	S	.22	< .01	.84	.03	< .01	.13
	B	.56	< .01	1.40	.03	< .01	.15
N-nitrate	SB	< .01	< .01	.04	< .01	< .01	.09
N-nitrite	SB	.003	< .002	.009	< .002	< .002	.007
N-total Kjeldahl	SB	2.6	.9	7.0	1.1	.5	2.5
Fe-soluble	SB	.92	.20	1.70	.06	.02	.63
Fe-total	SB	1.84	.50	3.70	.78	.30	3.50
Alkalinity (mg $CaCO_3$ /*l*)	SB	46	31	61	32	22	47
D.O.	S	8.4	2.0	16.5	10	7.0	13.4
	B	.8	.2	1.7	3.2	.0	9.7
pH	S	8.8	6.7	10.9	7.4	6.5	9.5
	B	7.2	6.4	8.9	7.0	6.5	7.5
Secchi disk (cm)		90	12	180	117	50	200
Temperature (°C)	S	21.7	17.0	28.5	18.6	11.0	25.8
	M	18.7	15.5	21.1	18.0	11.0	24.8
	B	15.4	11.7	19.8	15.8	10.0	21.5
Chlorophyll *a* (mg/m³)	SB	187	8.0	1682	54	2.0	179

*S = surface, M = middle, B = bottom

tion, between the latter two treatments the pond was drained and the surface sediments removed. The inactivation experiments will be discussed in chronological order.

Aluminate Treatment Method

The pond was treated in April 1971 with 227 kg of sodium aluminate by manifold injection behind an outboard powered boat. The aluminate was neutralized with hydrochloric acid prior to treatment to alleviate rapid pH shifts in the unbuffered waters. Selected physicochemical conditions are shown in Table 3. Five individuals completed the treatment in 1 day.

Zirconium Tetrachloride Treatment Method

The pond was divided into two approximately equal areas and volumes in February 1974 with a suspended, nylon reinforced, vinyl curtain. A portion of the curtain was sealed to the bottom with sand bags. This created an experimental side and a control side for treatment purposes. Pond depth contours and sampling stations are shown in Figure 3.

Limnological and water quality parameters including plankton and macrobenthos were monitored weekly prior to and after pond division. Treatment of the experimental side occurred on March 26–27, 1974 with the addition of 63 kg of anhydrous zirconium tetrachloride mixed with water and transported to the pond as a concentrated solution. Laboratory jar tests were made 2 days before treatment and the necessary quantity to be added for inactivation and precipitation calculated in relation to total phosphorus concentration. The amount of zirconium added gave a concentration of 5 mg/*l* in the pond waters. Distribution was made through a manifold system from an outboard boat. A second system applied sodium hydroxide to counteract lowering of pH. Kamloops rainbow trout had been stocked (250 in each side) 1 week prior to the zirconium treatment to test for immediate adverse effects upon higher food chain organisms and to reflect possible zirconium uptake over a longer time period.

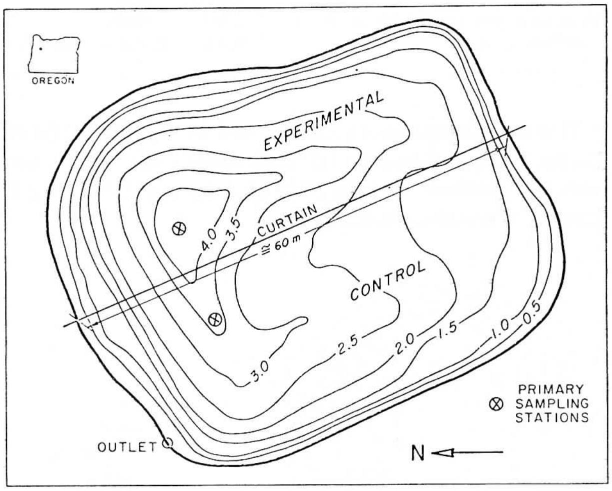

Figure 3.- Cline's Pond depth contours and sampling stations (from Powers, et al. 1978).

Liberty Lake

Background

Liberty Lake, Wash. (277 ha) is of glacial origin set in a basin enclosed on three sides by small mountain ranges that rise about 500 to 900 m above the surface level of the lake. The watershed (3,446 ha) is relatively undisturbed and the major tributary is very low in major nutrients. Mean residence time of lake water is 3 years. In quiescent summers the lake becomes weakly stratified. Relatively shallow soils (Spokane series) exist around much of the lake and are underlain by bedrock. Residential areas occupy 83 percent of the shoreline. Resorts, a public park, and a marsh at the southern end occupy the remainder. Waste disposal has been mostly by septic tank or less efficient means; an antiquated sewage collection and treatment system built in 1910 has served about 40 percent of the residences. A new collection and treatment system is scheduled for completion in 1979. Depth contours are shown in Figure 4.

Residents have complained since 1969 about blue-green algal blooms in the lake and large deposits of algal and macrophyte debris along the shoreline. Background data gathered since 1971 (Funk, et al. 1975; Gibbons, 1976) indicated that the major nutrients were at limiting levels throughout much of the year, especially in early spring and summer. Algal growth in the lake at these times was not prolific. It was noted that 50 percent or more of the large macrophyte populations (especially in the southern end of the lake) senesce and decline during late August-September (Funk, et al. 1975; Gibbons, 1976; Morency, 1978). This event signals the beginnning of large *Gloeotrichia, Anabaena, Coelosphaerium*, and *Aphanizomenon* blooms. For these reasons aluminum sulfate treatment was planned to intercept the weed release of phosphorus.

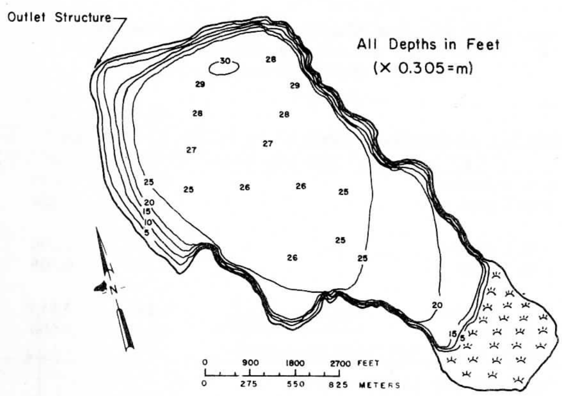

Figure 4.-Depth contours of Liberty Lake.

Treatment Procedures and Devices

Numerous jar tests and in situ tests (the latter with 208 liter vinyl liners) were made in the lake prior to treatment application. It was decided to treat the lake volume with less than 10 mg/*l* aluminum sulfate (less than 1 mg/*l* Al) to avoid overwhelming the alkalinity and buffering capacity of the lake (Table 4).

After considerable literature review and experimentation (including observations of dry applications of aluminum sulfate to the surface of large clear PVC water columns 5 m long x 20 cm diameter tubes), an apparatus was devised to partially dissolve the alum granules before dispensing them to the lake (Figure 5). In addition, the device was mounted to dispense the slurry to the water in front of the barge to take advantage of the roiling effect of the pontoons and then the mixing action of the propellers. Four systems were built for placement on three rented barges and the department barge. The water pump was placed aft on each barge where the helmsman could operate it and the outboard motor as well. Two crewmen mixed the alum.

Table 4. – Selected Liberty Lake constituents and physical characteristics, 1974–75

Parameter	Description		
Stream inflow & residence time	Total annual $6.3 \times 10^6 m^3$		Mean lake residence time 3 years
Estimated phosphorus in inflowing waters	Total annual ~263 kg		Mean concentration .03 mg/l
Estimated nitrogen in inflowing waters	Total annual 2763 kg		Mean concentration .27 mg/l
Mean concentration dissolved reactive phosphorus in lake water (.45 um filtered)	Mid to late summer .001 to .004 mg/l		Fall .02 to .04 mg/l
Concentration of total phosphorus in lake water at time of treatment	Before alum treatment .026 mg/l		After alum treatment .001 to .015 mg/l
General lake characteristics	Total alkalinity 14 – 26 mg/l	pH 6.6 – 9.3	Hardness as $CaCO_3$ 15 to 37
Physical characteristics	Shoreline configuration 1.27	Development of volume 1.27	Mean slope 1.9%
	Volume $20.23 \times 10^6 m^3$	Surface area 277 ha	Mean depth 7.0 m

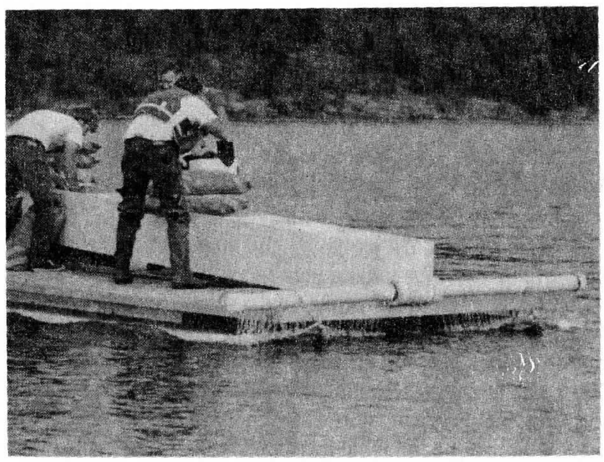

Figure 5.- Barge distribution system for aluminum sulfate treatment at Liberty Lake.

The lake was divided into quadrants and further divided into sections by shoreline markers and a buoy flag system so the helmsman could see his exact location (Figure 6). The volume under each section had been calculated as well as the number of sacks required for treatment. The lake was treated by quadrant (one per day) to allow for possible biological migration. About 12,000 kg alum could be distributed in 6 to 8 hours. Over 95 metric tons of alum (dry weight) was distributed over a 4-day period. The major limitation to treatment was the inability of the chemical supply house to deliver the aluminum sulfate on time.

A laboratory boat and divers were present to test and observe lake conditions. Physicochemical and biological samples were taken throughout the treatment and for 6 months following treatment; intermittent samples were taken thereafter. In June 1977, regular sampling was resumed to establish background data for additional restoration efforts and the effect of sewering.

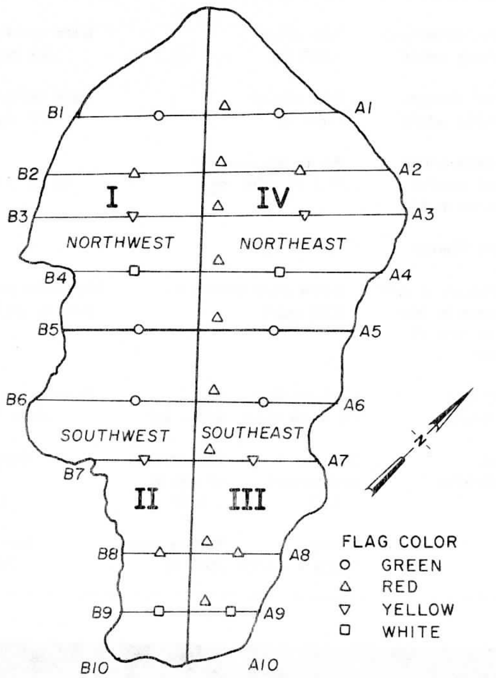

Figure 6.- Delineation of treatment for Liberty Lake (Funk, et al. 1975).

RESULTS AND DISCUSSION

In general, the majority of the in-lake inactivation projects have been very successful within their stated objectives. In view of time and space constraints only those salient features emphasized by the original investigators are listed or discussed in this section. The results of the Horseshoe Lake treatment as described by Peterson, et al. (1973) include:

1. A decrease in total phosphorus in the lake following the summer after treatment. No large increases in hypolimnetic total phosphorus for the next 2 years during stratification. Total phosphorus (pre- and posttreatment) is shown in Figure 7.

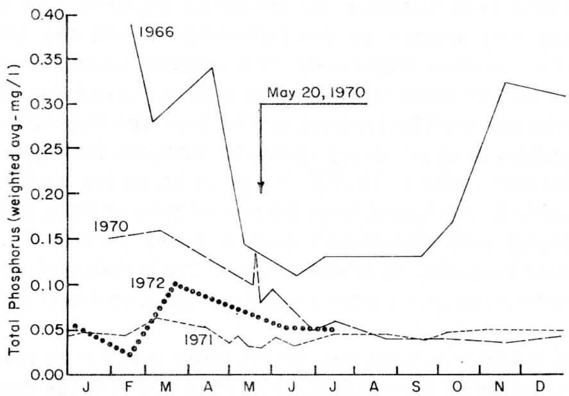

Figure 7.- Weighted average total phosphorus, Horseshoe Lake (redrawn from Peterson, et al. 1973).

2. Improvement in dissolved oxygen was reflected in considerably higher levels during wintertime for 2 years.

3. Absence of the usual nuisance algal blooms was noted and was accompanied by an increase in transparency and a short-term decrease in color.

4. Aluminum concentration in surface waters returned to pretreatment levels within 6 days and no adverse ecological effects were recorded.

West Twin and Dollar Lakes

Concentration of total phosphorus in Dollar and West Twin Lake hypolimnetic waters was much less than before treatment. Seepage monitoring devices also showed considerably less phosphorus release from treated anaerobic sediments at Dollar Lake (Table 5). Cooke and Kennedy (1977b) describe the hypolimnion as being clear and lighted and the bottom sediments covered with a white floc layer 1 to 2 cm in thickness. It was also reported that the longevity of the floc layer was about 1 year. Alkalinity and pH were initially lower than pretreatment levels but then recovered within a few weeks.

Table 5. - Total phosphorus concentration in waters from treated and untreated anaerobic Dollar Lake sediments (Cooke and Kennedy, 1977)

Depth of half-barrels (seepage waters)	1974 mg/l	1976 mg/l
6 M Untreated	0.701	1.021
6 M Treated	0.130	0.224
4 M Untreated	0.315	1.200
4 M Treated	0.198	0.705
4 M Untreated	0.392	3.519
4 M Treated	0.033	0.600

The reduction in the phosphorus content of the two treated lakes is shown in Figures 8, 9, and 10. However, the investigators noted that epilimnetic filtrable phosphorus fractions did not significantly decline after treatment. Neither treated lake showed immediate decreases in algal cell volume or chlorophyll nor did Secchi disk measurements increase. The rate of carbon assimilation even in the treatment lake indicated a phosphorus utilization three times greater than the internal loading, based on budget analysis. These events led Cooke and Kennedy to believe that the summer internal loading is epilimnetic in origin and comes from phosphorus held by littoral muds during

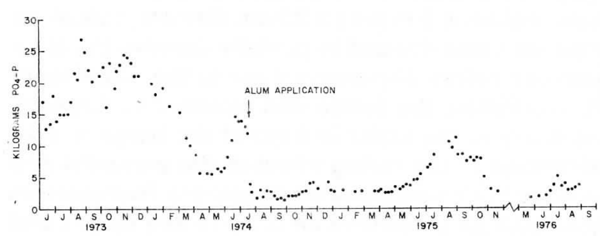

Figure 8.- Total phosphorus content of Dollar Lake before and after treatment (redrawn from Cooke and Kennedy, 1977).

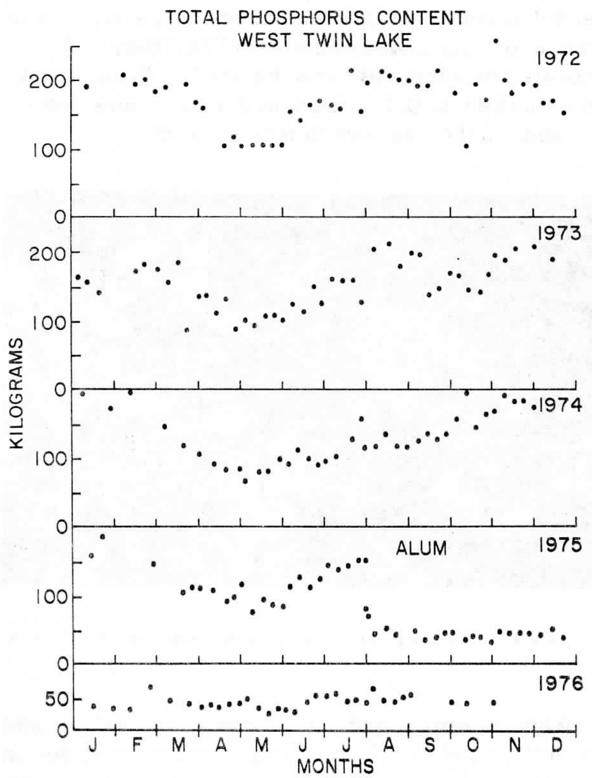

Figure 9.- Total phosphorus content of West Twin before and after treatment (from Cooke and Kennedy, 1977).

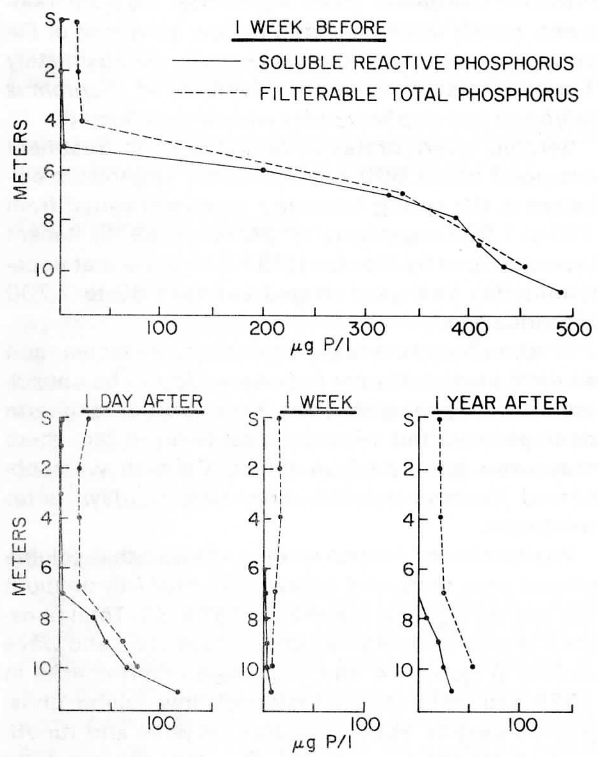

Figure 10.- Soluble reactive and filtrable total phosphorus of West Twin Lake before and after hypolimnetic aluminum sulfate treatment (redrawn from Cooke, et al. 1978).

the spring. They have suggested that sources of this phosphorus may be macrophytes and littoral fauna, as well as ground water. Ground water has been estimated at 30 to 50 percent of the inflow of West Twin (Cooke and Kennedy, 1977b). The investigators have made a strong recommendation that careful investigation of major internal sources of phosphorus be made prior to aluminum sulfate treatment of small lakes with large littoral areas.

Cline's Pond

The sodium aluminate treatment reduced total phosphorus, ammonia, total Kjeldahl, nitrogen, and iron during the summer and fall following treatment (1971). The algal standing crop was reduced and a shift from blue-green to green dominance was recorded. Dissolved oxygen, transparency, and pH indicated significant improvement with the change in numbers and kinds of algae as previously indicated in Table 3. No adverse impact on the pond's vertebrate and invertebrate populations was recorded.

Treatment with zirconium in 1974 of the experimental portion of Cline's Pond reduced total phosphorus. Phosphorus release from the bottom sediments and from the initially precipitated floc (during treatment) was inhibited. Selected data are shown in Table 6.

Table 6. – Limnological conditions 1 day before, 1 day after, and 1 week after zirconium inactivation (Powers, et al. 1978)

	March 25		March 28		April 3	
	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.
TP mg/l	0.121	0.131	0.071	0.134	0.058	0.104
TIN mg/l	0.96	1.14	0.95	0.92	0.87	0.87
Temp. °C	8.2–12.0	8.2–12.0	9.8–10.4	8.3–10.2	10.5	10.2–10.7
D.O. mg/l	4.7–15.8	4.5–14.5	7.3–10.5	3.1–9.8	9.1–5.0	8.5–8.9
Secchi disk m	0.7	0.7	0.7	0.8	0.9	1.0
pH	7.2–9.8	7.2–9.8	6.6–6.9	6.2–7.8	6.7–6.8	6.9
Turbidity NTU	20	24	24	23	16	23

Algal productivity and chlorophyll *a* were fivefold less in the treated side than in the control portion. Oxygen depletion to 1.0 mg/*l* in the experimental side was attributed to organic matter not previously removed prior to testing. Some leakage from the experimental to the control portion after the first year may have helped to reduce the control's productivity during the second year.

Figure 11 illustrates reduced total phosphorus and chlorophyll. Figure 12 demonstrates the difference in algal growth between the two portions of the pond.

Some fish appeared to be stressed during the first day of treatment; however, there were no deaths. No long-term toxic effects upon benthic macroinvertebrates were noted.

The investigators have recommended studies be undertaken to determine any health hazards.

Medical Lake

The Medical Lake experiment has been reported to be successful (Gasperino and Soltero, 1978), especially in reducing soluble reactive phosphorus by 90 percent, from 300 to 30 mg/*1*. Light penetration (1 percent of incident) has been increased from 3.7 to 6.1 m. Late summer and fall blue-green blooms have been replaced by green algae, predominately *Oocystis* sp. Keizur (1978) also reports development of healthy zooplankton populations. This treatment will be discussed elsewhere in this conference.

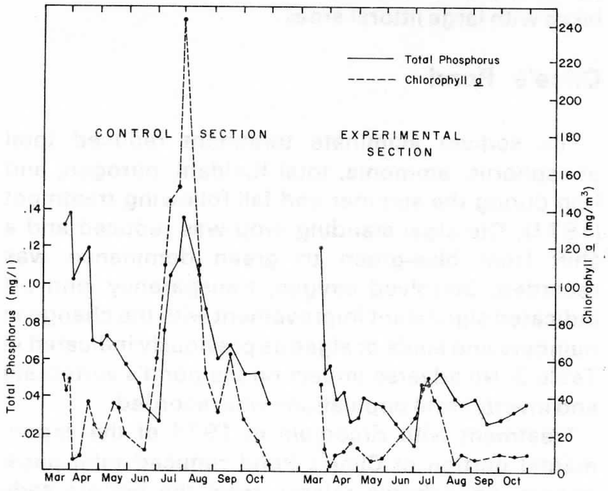

Figure 11.- Total phosphorus and chlorophyll *a* in control and experimental sections of Cline's Pond after zirconium treatment (redrawn from Powers, et al. 1975).

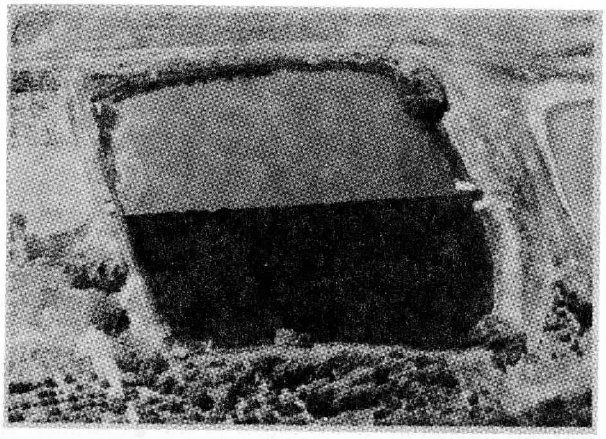

Figure 12.- Photograph of Cline's Pond showing contrast between zirconium treated side (dark) and control side (photo courtesy of W. D. Sanville).

Liberty Lake

At the time of treatment soluble phosphorus had increased from 0.004 to 0.04 mg/*1* concomitant with macrophyte decline. After application of the aluminum sulfate, soluble phosphorus was reduced to less than .005 while total phosphorus was reduced from 0.026 to less than 0.015 mg/*1*.

The most striking manifestation of the treatment was the rapid decline of the bloom and increased clarity of the water as each quadrant was treated. In some areas where previous visibility was less than 0.5 m, the bottom could now be seen (vertical extinction coefficients were reduced from greater than 2.0 to less than 0.6). Long forgotten boat tieups, anchors, and discarded paraphernalia became visible. The remaining aquatic weeds appeared as if they had been covered by a layer of snow (Figure 13). Even distribution of the floc 0.7 to 2 cm in thickness was verified by sediment cores collected by scuba divers.

Figure 13.- Floc settling upon aquatic macrophytes at Liberty Lake, Wash.

A short-term drop of 10 to 12 mg/*1* in alkalinity and a drop in pH of 0.7 to 1.1 units were measured in areas receiving treatment. Within 24 to 48 hours these measurements returned to pretreatment levels. Plankton tows made a week previous to the aluminum sulfate treatment contained no zooplankton. Tows made the day previous to treatment were filled with *Anabaena* and *Gloeotrichia* cells but no zooplankton. The lack of zooplankton was attributed to a rotenone treatment. Three weeks after the alum treatment, zooplankton collected by tow consisted of *Eucyclops prasinus* and *Cylops vernalis*. Approximately 1 month later considerable numbers of *Diaptomus reighardi* and *Daphnia pulex* were also collected.

Benthic invertebrates collected prior to treatment averaged about 600 organisms/m^2. Organisms collected in the spring following treatment varied from 110 to 1,675 organisms/m^2 (Morency, 1975). Recent investigations by Stanford (1977) indicate that populations this past year ranged between 80 to 2,700 individuals/m^2.

In sampling benthic populations, seasonal and sampling variability are important facts to be considered but it appears that very little short or long-term damage occurred with the treatment. In fact there may even be a positive effect. Crayfish were observed feeding in the floc several days after treatment.

Posttreatment measurements showed that soluble phosphorus remained below 0.01 mg/*1* throughout the fall, spring, and summer of 1974–75. Total phosphorus rose temporarily during heavy wind and wave activity (Figures 14 and 15). Intermittent checks in 1975 and 1976 showed relatively low soluble phosphorus despite above average snowfall and runoff. With disappearance of the floc layer in the later summer of 1976 a moderate *Anabaena flos aquae* bloom and *Coelosphaerium naegelianum* appeared that fall. Heavy *Gloeotrichia echinulata*, *Coelosphaer-*

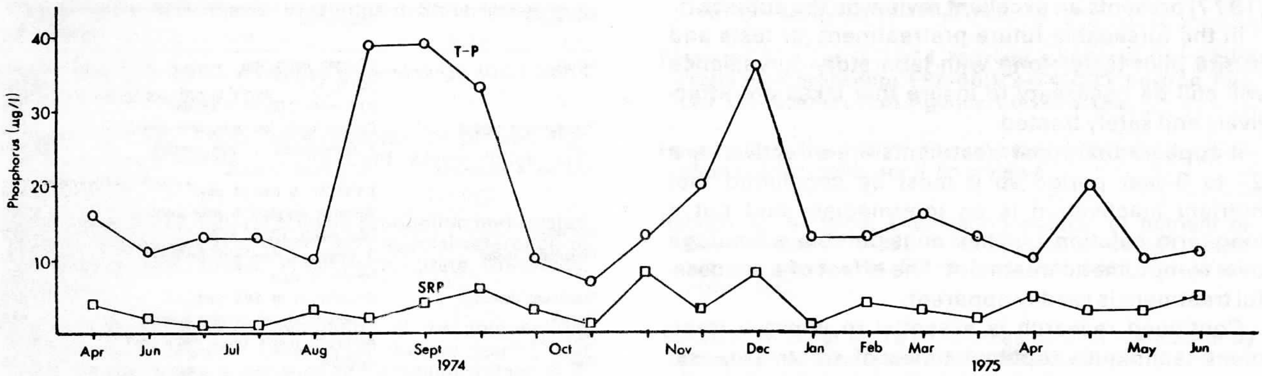

Figure 14.- Southeast Liberty Lake station soluble reactive and total phosphorus (*ug/1*).

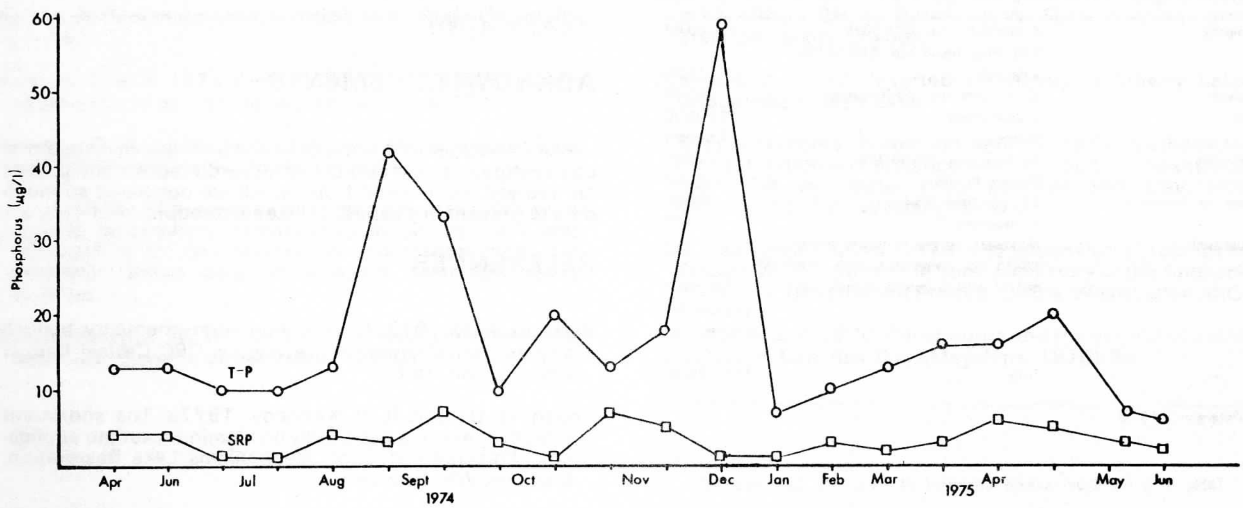

Figure 15.- Northwest Liberty Lake station soluble reactive and total phosphorus (*ug/l*).

ium, and *Anabaena* blooms equivalent to those of pretreatment levels occurred in the fall of 1977.

TREATMENT COSTS

No attempt has been made to update expenses to the 1978 level because local salaries, rentals, equipment costs, and price of chemicals vary greatly from location to location. Insight may be gained from the listing of people and equipment as to project needs; local chemical supply houses can provide latest chemical costs. The following tables give costs for most of the treatments previously described.

SUMMARY

The previously described lake treatments have succeeded in reducing phosphorus and in most instances many of the algal nuisances plaguing the particular lake under discussion. Usually there is an immediate response such as reduction of turbidity and clearing of the waters. This aspect has a certain aesthetic and public appeal. Treatment has been successful in forestalling or reducing algal blooms over a variety of conditions by removal of phosphorus from the water column at ice-out, neutralizing release of phosphorus from weed senescence and from lake sediments.

Treatment is relatively inexpensive in comparison to many algicides but rapidly escalates when larger lakes are treated. In most instances, symptomatic treatment with algicides has been worked out and is comparatively straightforward. On the other hand, considerable information about a lake needs to be gathered before inactivation can be carried out. Enough inactivant must be applied to insure precipitation of phosphorus but not so much that the alkalinity buffering action is overcome, pH falls, and the residual dissolved ion is above that amount, causing injury to valuable food chain organisms or fishes. The critical level for dissolved aluminum is greater than 0.05 mg/*1* according to some researchers (Everhart and Freeman, 1973). The authors believe, however, that overemphasis has been placed upon the toxicity aspect in view of the "matter of fact" treatment with certain algicides and fish toxicants that not only kill the target species but may eliminate or disrupt aquatic food chains for several months to years. In many instances aluminum toxicity bioassays have been carried out without apparent consideration of

the effect of the counterion, pH, or alkalinity. Burrows (1977) presents an excellent review on the subject.

In the forseeable future pretreatment jar tests and in situ pilot tests along with laboratory surveillance will still be necessary to insure that lakes are effectively and safely treated.

It appears that most treatments are effective for a 2- to 3-year period so it must be concluded that nutrient inactivation is an intermediate and not a long-term solution but has considerable advantage over symptomatic treatment. The effect of a successful treatment is readily apparent.

Continued research is essential to improve treatment techniques, optimal times of treatment, and overall effects upon food chain organisms.

Table 7. – Aluminum sulfate treatment of Horseshoe Lake (1970)*

Procedure	Description	Cost
Sampling	8 manhours/trip @$5.00/hr	$ 40.00
	270 miles round trip @$3.00/day	
	+6¢/mile	19.20
Analyses	12 samples/trip @$30/sample	360.00
Staff	1 professional	13,000.00
	Overhead	7,300.00
Chemicals	12 tons alum @$60/ton	720.00
	Delivery to site	180.00
Labor for treatment	12 man days @$40	480.00
	+ expenses	100.00
Equipment	Workboats, barges, outboard motors, 18–25 h.p., amphibious truck, DUKW–35 and associated pumps, mixers, etc.	Essentially all equipment was on loan.
	Total	$22,199.00

* Peterson, 1973

Table 8. – Aluminum sulfate treatment of West Twin Lake (1974)*

Procedure	Description	Cost
Sampling	Not listed	Not given
Construction	2,000 hours	Not shown
Application	590 hours	Not shown
Equipment	Barges, lines, storage, storage containers	$4,058.00
Supplies	Expendable	646.00
Rentals	Not listed	262.00
Chemicals	Aluminum sulfate (91 metric tons)	6,803.00
	Total	$11,779.0

*Cooke, et al. 1978

Table 9. – Sodium aluminate and zirconium treatment of Cline's Pond

Procedure	Description	Cost
	Sodium Aluminate Treatment (1971)*	
Sampling	Not listed	Not available
Staff	Five professionals/1 day	Not shown
Chemicals	Sodium aluminate (227 kg)	$102.00
	Hydrochloric acid	60.00
	Zirconium Treatment (1974)**	
Sampling	Not listed	Not available
Staff	Not listed	Not shown
Chemicals	Zirconium tetrachloride (63 kg)	Not shown

* Sanville, et al. 1976
** Powers, et al. 1978

Table 10. – Aluminum sulfate treatment of Liberty Lake (1974)*

Procedure	Description	Cost
Sampling	10 man hours/trip	
	10/hr x 31	$ 3,100
	212 miles/10¢/mi +$6/day	916
Pretreatment testing	Column tests, jar tests, lake tests	1,100
Staff	4 professionals, 7 man months	14,209
(analyses & treatment)	15 graduate students	
	$3.85/hr, 8 hour/4 days	1,848
	Research assistant 6 man months	5,000
Per diem	Four nights/17 at $14	952
Equipment rental	3 barges, 4 days with motors	700
	Forklift, 4 days	233
Treatment devices	Construction at $85 each	340
Pumps	4 centrifugal self priming pumps	546
Chemicals	Aluminum sulfate (95.3 metric ton)	13,781
Fuel	Gasoline	65
Miscellaneous	Flags, paint, line, pipe, hoses, screens, filters, shovels, life jackets, strainers, fluorescent dyes, analytical chemicals	884
Overhead (off campus)	6,000	
	Total	$49,692

* Funk, et al. 1975

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