Feasibility of Inactivating Phosphorus
with Aluminum Salts in Ball Pond, CT

By Wendell A. Norvell

BALL POND
NEW FAIRFIELD, CONN.

TRACED FROM AERIAL SURVEY MAP
89 ACRES PLANIMETER MEASUREMENT

CONTOUR INTERVAL
3 FEET

SCALE 1" = 600'

Bathymetric map of Ball Pond. Connecticut State Board of Fisheries and Game, 1959.

THE CONNECTICUT AGRICULTURAL EXPERIMENT STATION NEW HAVEN

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The value of many lakes in Connecticut as aesthetic, recreational, and water-supply resources could be increased by reducing the availability of phosphorus (P) to algae (Norvell and Frink 1975; Norvell, Frink and Hill 1979). This bulletin evaluates the feasibility of reducing the availability of P in Ball Pond by adding soluble salts of aluminum (Al) to remove P from the water and retard release of P from lake-bottom sediments.

The treatment of lakes with Al to inactivate P is a method of lake restoration of relatively recent origin (Dunst et al. 1974; Jernĕlov 1971). This approach utilizes the well-known ability of Al to bind phosphate ions through precipitation and adsorption reactions which produce insoluble hydroxides of Al containing variable amounts of tightly bound P. Several of these treatments to inactivate P have been effective and all have provided valuable insight into the processes removing P from lakes, the equipment required for treatment, and the types of lakes that might benefit from treatment (Cooke and Kennedy 1981; Dunst et al. 1974; Peterson et al. 1973).

Ball Pond, located in New Fairfield, CT, was selected as a candidate for in-lake treatment with Al to inactivate P after considering the criteria listed below. These criteria for selection were modified and extended slightly from those suggested by Peterson et al. (1973):

- The lake should be mesotrophic or eutrophic so that any improvement in lake condition is easily detectable and of significance to lake users.

- The retention time of water in the lake should be long enough to permit improvements to be observable and persistent. In general, this implies that the ratio of watershed to lake area should be relatively small.

- Phosphorus should be the limiting nutrient for planktonic algae or should effectively become the limiting nutrient after treatment.

- A substantial percentage of P in the lake should be in forms susceptible to inactivation at the time of treatment.

- Inputs of P from the watershed should not be so large as to negate the effects of treatment. Phosphorus present in the lake or supplied to the lake from internal sources, e.g. sediments, should represent a substantial portion of the annual supply.

- Lake depth should be great enough to permit effective settling and prevent resuspension of precipitated P from the bottom.

- The surface area should be small enough to permit treatment at acceptable cost, however, if possible, large enough to allow generalization of results to other lakes.

- The lake should have sufficient value for recreation or other uses to justify the expense of treatment.

- Background data should be available or should be obtained on physical, chemical, and biological characteristics of the lake and its watershed.

The characteristics of Ball Pond and its watershed meet many of the above criteria (Table 1, cover). Ball Pond is a small and moderately deep lake with a small ratio of watershed to lake area and a long water retention time of about five years. Considerable data on the lake and its watershed have been collected sporadically since at least 1939. The lake is a recreational and aesthetic asset to nearby residents. It is stocked with trout by the Department of Environmental Protection and public access is provided at the State launching area at the southern end. The lake is eutrophic, well supplied with plant nutrients, and deficient in oxygen in the hypolimnion where hydrogen sulfide (H_2S) is present. The ratio of total N to total P is usually greater than 20, which is high enough so that P is expected to be the major nutrient limiting the populations of planktonic algae. These characteristics of Ball Pond and its watershed suggest that effective reduction of P concentrations would significantly restrict the growth of algae, reduce the degree of eutrophy, and increase the value of the lake as a recreational and fishery resource. Any benefits from inactivating P could persist for several years because of the long water retention time.

Table 1. Characteristics of Ball Pond.

Characteristic	Value		Reference
Physical			
Surface area	36.4	ha	1,2
Volume	2.5×10^6	m3	2
Maximum depth	15.9	m	2
Mean depth	6.9	m	2
Watershed/lake area ratio	2.6		1,5
Estimated water load	1.4	m/yr	5
Estimated retention time	5.0	yr	5
Land use			
Residential	39	%	5
Agricultural	15	%	5
Wooded	9	%	5
Lake surface	38	%	5
Chemical			
Total P, spring	35-40	ppb	3,5,6,7
Total N, spring	660-960	ppb	3,6,7
Alkalinity, spring	0.98	meq/1	7
N/P ratio, spring	16-35		3,6,7
Hypolimnetic H_2S	strong odor by midsummer		6
Hypolimnetic O_2	depleted by midsummer		1,2,6,7
Biological			
Secchi depth, spring	1.3-2.0	m	3,7
Secchi depth, summer	2.0-3.8	m	3,7
Chlorophyll-a, summer			
Epilimnion	3	ppb	7
Metalimnion	25	ppb	7
Major planktonic algae	Oscillatoria rubescens		3,7
Major rooted weeds	Potamogeton amplifolius		7
	Ceratophyllum, sps		7
	Elodea, sps		7
Weed beds, areal extent	intermediate		7
Weed beds, density	moderate		7

1. Connecticut State Board of Fisheries and Game (1942).
2. Connecticut State Board of Fisheries and Game (1959).
3. Connecticut Department of Environmental Protection (1979).
4. Norvell and Frink (1975).
5. Norvell, Frink, and Hill (1979).
6. Norvell, unpublished.
7. Norvell (1980).

The objectives of this investigation were to confirm the suitability of Ball Pond for treatments to inactivate P and to answer specific questions concerning the forms and amounts of P susceptible to inactivation, the proportion of P from external vs. internal sources, the choice of Al salts and their rate of application, the volume of the lake needing treatment, and whether or not such treatment could be made without damage to the fish population.

METHODS

Ball Pond was visited on April 11, July 1, July 24, August 26, October 15, and November 13, 1980 to collect water samples and measure dissolved oxygen, temperature, and sulfide throughout the water column. Water samples were collected with a 2 liter PVC Kemmerer sampler and stored in ice during transport to the laboratory.

Field analyses for dissolved O_2 and temperature were made with a YSI model 54RC oxygen-temperature meter and 30 meter probe. Field analyses for sulfide were made immediately after sample collection using a Bausch & Lomb Mini 20 spectrophotometer and sulfide reagent kit with a standard curve verified in the laboratory.

Alkalinity was measured by titration using methyl purple as the end-point indicator. About one-half of the sample was filtered through a well-rinsed 0.45 μm millipore filter. Soluble reactive P in the filtered portion was measured before freezing both the filtered and unfiltered sample. Later, water samples were thawed and analyzed for soluble P, total P, NH_4-N, and Kjeldahl-N using methods described by Norvell and Frink (1975). Nitrate-N was measured by a cadmium reduction method (U.S. Environmental Protection Agency 1974), and SO_4-S was measured turbidimetrically as $BaSO_4$ (American Public Health Association 1975). Aluminum was measured by atomic adsorption spectrophotometry following extraction by 8-hydroxyquinoline into methyl-isobutylketone (Amer. Publ. Health Assoc. 1975) and pH was determined potentiometrically.

The relationship between area and depth in Ball Pond was determined by measuring the area between contours on the bathymetric map shown on the cover. This information was used to prepare a graph of the percentage of surface area below any depth (Fig. 1). This curve, in turn, was used to prepare the accompanying graph of the percentage of lake volume beneath any depth. These relationships and the area and volume data provided in Table 1 were combined with concentration data from lake samples to calculate the mass of each chemical constituent of interest within any depth interval of the lake. Mass balance calculations for P on different sampling dates were used to estimate internal release of

P and the fraction of total P present as soluble reactive P, primarily inorganic orthophosphate.

On July 24, 1980 a bulk sample of hypolimnetic water from the 12 meter depth was collected under oxygen-free conditions by displacing N_2 from a glass carboy. The sample was packed in ice, kept in the dark, and prevented from contacting oxygen during transport to a laboratory cold room. One liter portions were treated under a N_2 gas atmosphere with soluble Al in the form of diluted liquid alum following the general approach outlined by Cooke and Kennedy (1981). After mixing slowly for 5 minutes, each sample was allowed to stand for 15 minutes. The pH was then measured and the sample was filtered through a 0.45 μm pore size filter. One portion of the filtrate was titrated for alkalinity and another acidified for later analysis for soluble Al, SO_4-S, soluble P, and soluble reactive P.
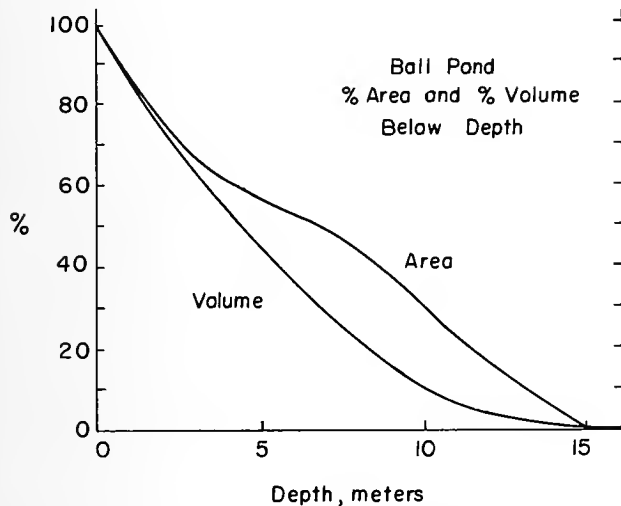

Fig. 1 Percentage of surface area and volume of Ball Pond below any depth.

RESULTS AND DISCUSSION

Chemical Composition and Trophic Condition

The results of field and laboratory analyses of water samples from Ball Pond are presented in Tables 2 and 3. The data confirm that Ball Pond is indeed eutrophic. Concentrations of P and N were moderately high. The spring concentration of P was 37 ppb in 1980 which compares closely to concentrations of 35 ppb and 39 ppb that were found during spring overturn in 1977 and 1978 respectively. These concentrations are roughly two and one-half times the levels found in the 1939 Survey (Connecticut State Board of Fisheries and Game 1942), and are

in the range of 20-50 ppb typical of eutrophic lakes. Spring N was also elevated at 0.89 ppm, and more than 20% of this N was present as readily available NO_3^-. Phosphorus limitation of algae is strongly suggested by the spring N/P ratio of 24 and by the fact that free NO_3^- was present despite the on-going bloom of O. rubescens.

Another index of eutrophy is provided by hypolimnetic oxygen (Table 3) which was consumed rapidly during the spring and early summer. Between April 11, 1980 and July 1, 1980 virtually all O_2 in the hypolimnion was consumed, yielding a minimum rate of oxygen depletion of approximately 54 mg/cm²/day. This rate of hypolimnetic oxygen depletion is in the middle of the 45-75 mg/cm²/day range typical of eutrophic lakes (Norvell and Frink 1975), and is roughly three times the rate found in 1939 (Connecticut State Board of Fisheries and Game 1942). In contrast to present conditions, oxygen was present in the upper hypolimnion even in August 1939.

Chlorophyll-a concentrations (Norvell 1980) and algal numbers (Connecticut Department of Environmental Protection 1979) were high during 1979 and 1980. The dominant algae in the lake during winter, spring, and most of the summer appears to be O. rubescens. Algae counts taken from February through October 1979 indicated that this algae began "blooming" throughout the lake following fall overturn. As thermal stratification began in the spring, the algae concentrated in the thermocline and remained there in declining numbers throughout the summer (Connecticut Department of Environmental Protection 1979). In addition to planktonic algae, Ball Pond contains dense growths of Spatterdock (Nuphar sps.), Bigleaf Pondweed (Potomogeton sps.), Coontail (Ceratophyllum sps.), and filamentous algae (Spirogyra sps., Cladophora sps) in water less than two meters deep, particularly in the extensive shallow areas at the southern end (Norvell 1980).

During 1980, hydrogen sulfide was found throughout most of the hypolimnion, with concentrations approaching 2 ppm in the deeper waters. This too is an index of eutrophy, and also of major change since 1939 when Deevey noted that iron dominated the redox system rather than hydrogen sulfide (Connecticut State Board of Fisheries and Game 1942). At present, reducing conditions in the hypolimnion are much more severe with $SO_4^=$ undergoing reduction and H_2S accumulating throughout the summer (Table 2, Fig. 2). The anoxic, sulfide-rich waters of the hypolimnion are not a suitable habitat for trout or most other organisms.

These results confirm the eutrophy of Ball Pond and document the degradation in water quality that has occurred during the last 40 years.

Table 2. Chemical composition of water samples collected from Ball Pond during 1980.

Date	Depth	Alkalinity	Soluble Reactive P	Soluble P	Total P	NH_4-N	NO_3-N	Organic N	Total N	SO_4-S	H_2S-S
	m	meq/l	--------------ppb---------------			---------------------------ppm---------------------------					
4-11	0 - 10	0.98	-	14	37	0.05	0.19	0.65	0.89	-	-
7-1	0 - 3.5	1.12	6	15	36	0.09	0.01	0.57	0.67	3.2	0.00
	5	1.10	6	12	84	0.08	0.00	0.95	1.03	3.2	0.00
	7	1.12	2	11	25	0.06	0.03	0.26	0.35	3.2	0.00
	9	1.22	18	28	40	0.86	0.00	0.44	1.30	2.6	0.48
	11	1.36	120	120	150	1.37	0.00	0.47	1.85	1.9	1.14
	13	1.38	170	180	210	1.65	0.00	0.45	2.10	1.9	1.16
	14	1.38	220	210	250	1.86	0.00	0.68	2.54	1.6	1.16
7-24	0 - 3.5	1.08	3	7	23	0.03	0.00	0.51	0.54	3.2	0.00
	5	1.04	2	8	40	0.01	0.00	0.62	0.63	2.9	0.00
	7	1.08	2	15	42	0.21	0.01	0.46	0.68	2.6	0.00
	9	1.30	28	34	66	0.90	0.00	0.47	1.37	2.2	0.38
	11	1.40	160	160	200	1.69	0.01	0.71	2.41	1.3	1.40
	13	1.43	230	240	250	2.09	0.00	0.75	2.76	1.0	1.65
	14	1.82	250	250	340	2.20	0.00	0.65	2.85	0.6	1.90
8-26	0 - 4	0.93	1	6	17	0.12	0.00	0.45	0.57	3.0	0.00
	5	1.08	1	4	20	0.04	0.00	0.51	0.55	3.2	0.00
	7	1.08	1	6	38	0.05	0.00	0.62	0.67	2.6	0.00
	9	1.36	11	14	63	1.10	0.00	0.95	2.05	1.1	0.39
	11	1.50	190	200	230	2.32	0.00	0.94	3.26	0.7	1.40
	13	1.48	260	270	280	2.88	0.00	0.48	3.36	0.8	1.80
	14	1.48	280	290	310	2.79	0.00	0.77	3.56	0.6	1.80
10-15	0 - 6	0.88	0	13	15	0.05	0.00	0.34	0.39	3.0	0.00
	7	1.16	1	4	16	0.03	0.00	0.50	0.53	2.9	0.00
	8	1.20	1	4	36	0.31	0.00	0.63	0.94	2.6	0.35
	9	1.58	8	14	70	1.08	0.01	0.86	1.94	3.2	0.68
	11	1.68	172	162	207	2.18	0.00	0.77	2.95	1.0	1.70
	13	1.94	310	306	354	2.96	0.00	1.31	4.27	0.3	1.90
	14	1.91	268	270	294	3.09	0.01	0.73	3.81	0.6	1.90
11-13	0 - 14	1.22	1	4	46	0.39	0.02	0.59	1.00	2.6	0.00

Table 3. Temperature and dissolved oxygen data for Ball Pond during 1980.

Depth, m	Temperature, °C						Dissolved O_2, ppm					
	4-11	7-1	7-24	8-26	10-15	11-13	4-11	7-1	7-24	8-26	10-15	11-13
0	10.3	22.0	26.8	24.5	14.0	6.2	12.0	8.8	9.3	8.3	10.2	10.4
1	--	--	--	23.7	--	--	--	--	--	8.8	--	--
2	--	21.8	26.6	23.3	13.2	6.1	--	9.0	9.1	9.0	9.2	9.6
3	--	21.8	26.0	22.7	--	6.1	--	9.2	9.0	9.4	--	9.5
4	7.8	16.0	19.2	22.1	13.2	6.0	11.8	11.2	9.4	9.0	8.5	9.4
5	--	13.0	15.0	18.4	13.2	6.0	--	1.4	7.6	8.6	8.7	9.4
6	--	10.0	11.2	13.8	13.2	6.0	--	0.6	2.0	4.2	9.1	9.3
7	--	9.0	9.7	10.2	13.2	6.0	--	0.3	0.5	0.5	9.0	9.3
8	7.0	--	8.7	8.9	10.0	6.0	11.6	--	0.3	0.3	0.6	9.2
9	--	8.0	8.1	8.1	8.4	6.0	--	0.2	0.3	0.2	0.4	9.2
10	--	--	7.7	--	7.8	6.0	--	--	0.2	--	0.4	9.1
11	--	7.3	7.1	7.2	7.2	6.0	--	0.2	0.2	0.2	0.3	9.1
12	5.8	--	7.0	--	7.1	6.0	10.5	--	0.2	--	0.3	9.1
13	--	7.0	7.0	7.1	7.0	6.0	--	0.2	0.2	0.2	0.3	9.2
14	5.8	7.0	6.9	7.0	7.0	6.0	10.2	0.2	0.2	0.2	0.3	9.1
15	--	6.9	6.9	6.9	--	--	--	0.2	0.2	0.2	--	--

Form, Distribution, and Internal Loading of P

The success of P inactivation in lakes depends in part on the forms and distribution of P in the water column. Table 2 shows the marked increase in P concentrations in the hypolimnion that occurred primarily during the early part of the summer. Decomposition of settling organic debris and release of sediment P under anoxic conditions both appear to have contributed to the elevated concentrations of P in the hypolimnion. As a result of these processes, the mass of P in the lake is increased and redistributed into deeper waters during the summer. Redistribution is clearly illustrated by Fig. 3 which shows a pronounced peak in the mass of P in the middle of the hypolimnion at 11 meters. In contrast to the results for April 11, 1980, the great majority of P was present in the hypolimnion on August 26, 1980. In addition the total mass of P in the lake was higher by almost 35%.

Of particular note in Table 2 is the preponderance of soluble reactive P (largely or entirely orthophosphate) and the relatively small fraction of organic and particulate P in the hypolimnion during summer. A high proportion of soluble inorganic P is desirable for the objective of lake treatment because this form of P is readily precipitated by multivalent metals such as Al^{3+} and is strongly adsorbed by many metal oxides and hydroxides, including $Al(OH)_3$. The amounts of total and soluble reactive P in the lake are compared in Table 4 for six dates.
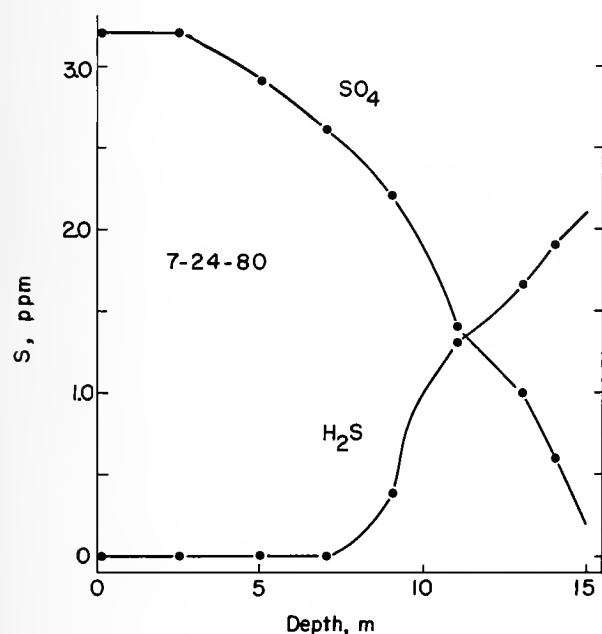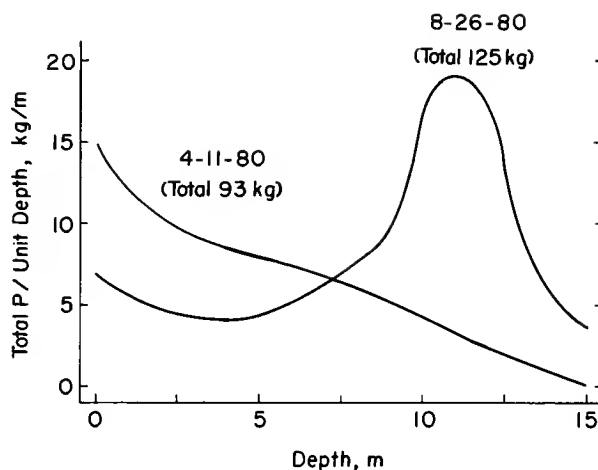

Fig. 3   Distribution of total P in Ball Pond on two dates. The mass of P contained in each one meter depth interval is shown as a function of depth.

Fig. 2   Concentrations of sulfate and sulfide as a function of depth in Ball Pond.

By late August, two-thirds of the total amount of P present at spring overturn was present in the hypolimnion as easily precipitated soluble reactive P. Nearly all of this was present below 10 meters, a region containing less than 11% of the volume of the lake. Relatively high concentrations of soluble reactive P in the hypolimnion persisted throughout the fall until autumnal circulation, when soluble reactive P virtually disappeared as oxygen mixed through the lake and the fall bloom of O. rubescens began again. During the late summer and fall it is obvious that the form of P most susceptible to inactivation is concentrated in a region where desirable fish species would not be present.

Results in Table 4 indicate that internal release of P contributes significantly to the summer increase in concentrations of P. Between April 11, 1980 and July 1, 1980, total P increased by 52 kg or 56%. Work by Norvell, Frink, and Hill (1979) suggests that for Ball Pond and its watershed, the gross annual addition of P to Ball Pond would be about 73 kg with about 18 kg lost through the outflow. Thus, the net potential input is only 55 kg/year or about 4.6 kg/month. Even if none of this P were lost by sedimentation or uptake by plants, external loading could account for only 12 kg of the 52 kg increase measured between April 11, 1980 and July 1, 1980. The data suggest strongly that internal release of P constitutes a major input to the lake during the early summer. This contribution occurs during the same period as the onset of anoxia and severe reducing conditions. Release of P from the sediments certainly appears to be the most plausible source.

Table 4. Distribution of total and soluble reactive P in Ball Pond on six dates in 1980.

Region	Depth Interval		Date					
			4-11*	7-1	7-24	8-26	10-15	11-13
			---------------------kg------------------------					
Entire Lake	(0-15 m)	Total P	93	145	139	125	121	116
		Solb. Reac. P	<13	53	65	64	64	3
Hypolimnion	(7-15 m)	Total P	28	64	88	90	94	33
		Solb. Reac. P	<4	44	61	62	62	1
Lower Hypolimnion	(10-15 m)	Total P	10	46	59	63	67	12
		Solb. Reac. P	<1	39	49	57	57	<1

* Soluble reactive p was not measured on 4-11-80. Values shown are for soluble P which includes both organic and inorganic P. The mass of soluble reactive P was probably 1/4 to 1/3 of these values.

Table 5. Effect of alum additions on composition of hypolimnetic water from 12 m depth in Ball Pond.

Chemicals Added			Composition of Sample						
Liquid Alum	Aluminum		pH	Alka- linity	Al	SO_4-S	Soluble Reactive P	Soluble P	Total P
mg/l	mg/l	meq/l		meq/l	ppb	ppm	-------------ppb--------------		
0	0	0	7.11	1.34	0	1.0	208	216	249
30.7	1.3	0.14	6.80	1.16	12	2.6	6	9	-
61.4	2.6	0.29	6.68	1.00	5	-	3	6	-
123.0	5.2	0.58	6.50	0.67	12	10.2	2	6	-
184.0	7.8	0.87	6.20	0.46	20	15.0	2	9	-
245.0	10.4	1.16	5.70	0.28	52	18.9	3	6	-
307.0	13.0	1.44	5.23	0.08	610	22.7	3	9	-
368.0	15.6	1.73	4.65	0.00	>2500	26.9	3	3	-

During July through October, losses of P from the lake exceeded gains and the total mass of P present fell from 145 kg on July 1 to 125 kg on August 26, and to 121 kg on October 15, 1980. However, these losses occurred in the epilimnion and metalimnion only. As mentioned above, the mass of P found in the hypolimnion actually increased during this same period.

Area, Volume, and Time of Treatment

Treatment of Ball Pond with Al would have two specific objectives: removal of P from the lake, and reduction in internal release of P following treatment. Efficient removal of P could be most easily achieved when a major fraction was present in an easily precipitated form, when it was concentrated in a relatively small volume, and when the precipitated P could be deposited in deeper waters and removed from biological cycles. These conditions exist in the hypolimnion of Ball Pond during late July and August and persist through most of the fall. Fig. 3 and Table 4 show that both total P and soluble P were concentrated in the anoxic hypolimnion below 7 meters, especially in the deepest waters. The area and volume below 7 meters are 180,000 m² (44.5 acres, 50% of lake surface area) and 723,000 m³ (191,000,000 gal., 29% of lake volume). Treatment of the hypolimnion would also achieve the second objective by covering the sediments of the anoxic zone with a layer of flocculated Al(OH)$_3$ to absorb any P released by the sediment before it could mix with the lake. Further, restricting the treatment to the anoxic hypolimnion would have the important benefits of reducing any chance of deleterious effects on fish populations and reducing costs by decreasing the portion of the lake to be treated.

Because soluble reactive P concentrated rapidly in the hypolimnion and persisted there throughout the summer, the timing of treatment does not appear critical. Successful treatment of the hypolimnion appears possible from late July through October. Treatment during September or October would avoid disruption of recreational uses during mid-summer.

Source of Al and Rate of Addition

Many salts of Al could serve as sources of soluble Al, e.g. alum, Al$_2$(SO$_4$)$_3$, sodium aluminate Na$_2$Al$_2$O$_4$, and aluminum chloride AlCl$_3$. Among the available sources, liquid alum appears to be the best choice for treatment of Ball Pond because of its lower cost, ease of application, and ready commercial availability (Cooke and Kennedy 1981; Loureiro Engineering Associates 1980).

The amount of alum to be added to the hypolimnion should be sufficient, at the very least, to precipitate, absorb, or entrap the great majority of P in a good settleable floc of Al hydroxide. When feasible, higher rates of addition are desirable to cover the bottom sediments with a thicker layer of Al hydroxide to retard future releases of P. For this purpose, Cook and Kennedy (1981) suggest applying Al at the highest rate that will not depress pH to the point that residual dissolved Al could become toxic to fish. This limit is necessitated by the acidity released during hydrolysis of Al which lowers pH and retards further precipitation of Al hydroxide. A minimum pH of 6 and a maximum residual dissolved Al concentration of 50 µg/l appear to provide an adequate margin of safety, even for trout.

The relations among P concentrations, pH, alkalinity, residual dissolved Al, and additions of alum are described below for hypolimnetic water taken from the 12 m depth in Ball Pond. Commercially available liquid alum was used as the source of Al. Experiments were conducted under an oxygen-free atmosphere and at a temperature of about 5 C to approximate conditions in the hypolimnion. Differing amounts of diluted liquid alum were added to portions of the water sample to give 0 to 15.6 mg/l of added Al. The flocculated Al (OH)$_3$, containing precipitated and absorbed P, was separated from soluble constituents by filtration.

Alum additions were very effective in removing P as shown in Table 5 and Fig. 4. Even the lowest rate of addition, 1.3 mg/l of Al, removed 96% of soluble P. Total P concentrations were reduced at least 83% simply by losses of soluble P. Actual removal of total P would have been even somewhat greater because of entrapment and settling of particulate matter. This small additional benefit could not be measured because of the experimental method used, but any losses of particulate matter would increase the overall effectiveness of treatment even further. The results suggest that almost any reasonable dose of alum would remove P effectively if well-mixed into the hypolimnion of Ball Pond.

Additions of alum caused the pH to fall from 7.11 to 4.65 following a "buffer" curve typical of the weak acid HCO$_3^-$ with a pK = 6.8 (Fig. 5). Alkalinity declined linearly with added alum until the pH decreased to close to 6. Below this pH, the hydrolysis of Al was less complete, alkalinity declined more slowly, and more Al remained soluble. An addition of 210 mg/l of liquid alum or 8.9 mg/l of Al was sufficient to depress the pH to 6. This addition of alum neutralized about 75% of the initial alkalinity of 1.34 meq/l. Residual dissolved Al
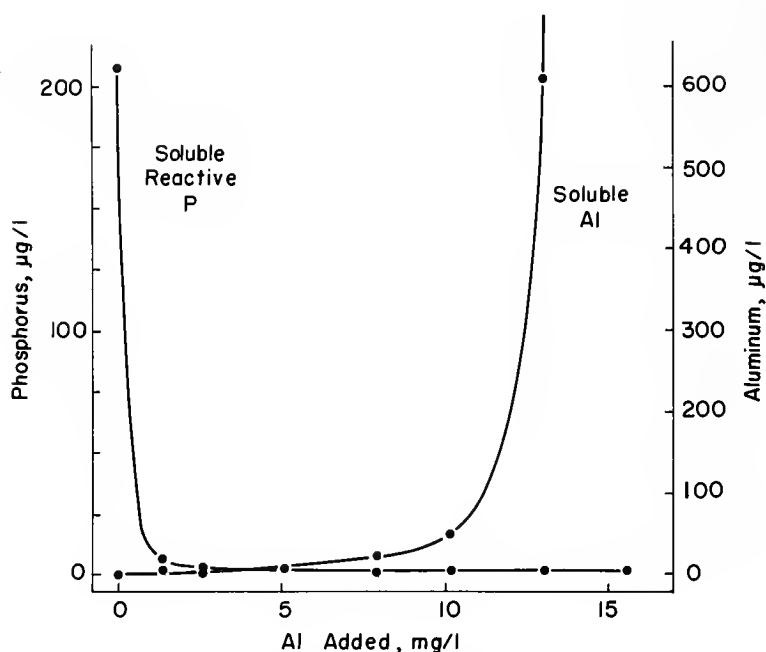
Fig. 4 Concentrations of soluble reactive P and residual dissolved Al as
functions of Al added to hypolimnetic water from 12 m depth in Ball Pond.

increased as the pH fell, especially below pH 5.5. Fig. 4 suggests that up to 10 mg/l of Al could have been added before residual dissolved Al rose above the 50 μg/l limit suggested by Cooke and Kennedy (1981). This rate of alum addition was equivalent to 83% of the initial alkalinity. Thus, for control of both pH and dissolved Al, the maximum advisable rate for addition of alum would be equivalent to 75 to 83% of the initial alkalinity. Higher rates could be achieved with mixtures of acid-forming and alkali-forming salts, such as alum and sodium aluminate (Dominie 1980), but that does not appear necessary for treatment of Ball Pond.

A volume-weighted calculation of alkalinity indicates that about 940,000 equivalents were contained in the hypolimnion below a depth of 7 meters during the late summer. At an 80% neutralization rate, this alkalinity is equivalent to an addition of Al of about 6,800 kg or roughly 9.4 mg/l of Al in the treated volume. However, considering that the above rate is maximal and that hydrolysis of Al will occur largely in the zone of application, a more conservative rate of 5 mg/l or 3,700 kg of Al allows a greater margin of safety and should still be adequate for treatment.

For the twin objectives of removing P from the water and covering sediments with a layer of Al hydroxide, the distribution of alum requires a compromise between equal treatment per unit area and equal treatment per unit volume. For example, areas of the lake 7 to 11 meters deep could be treated at the 7 meter depth at the rate of 18 g/m² of Al, while areas greater than 11 meters in depth would be treated at the 7 meter depth but at the rate of 24 g/m² of Al. Such a treatment adds the desired total of about 3,700 kg Al to the hypolimnion but adds 1/3 more per unit area to the deeper sections of the hypolimnion. Other compromises could easily be designed and the ultimate choice may be strongly influenced by equipment capabilities.

The only significant caveat with respect to applicatons of liquid alum arises from the SO_4 anion associated with the soluble Al. Table 3 and Fig. 2 show that Ball Pond suffers at present from accumulation of H_2S in much of the hypolimnion. Some hypolimnion H_2S undoubtedly comes from the reduction of SO_4 and major increases in concentrations of SO_4 might enhance H_2S accumulaton. Were this to occur, the higher H_2S concentrations could be deleterious to trout and might even enhance release of P from sediments. However, allowing for some loss of SO_4 through lake outflow, anticipating some reduction in hypolimnetic oxygen demand as a benefit of treatment, and by treating only the hypolimnion at the conservative rate of 5 mg/l, the potential hazard from added SO_4 appears small while the cost advantage of liquid alum is large (Loureiro Engineering Associates 1980).
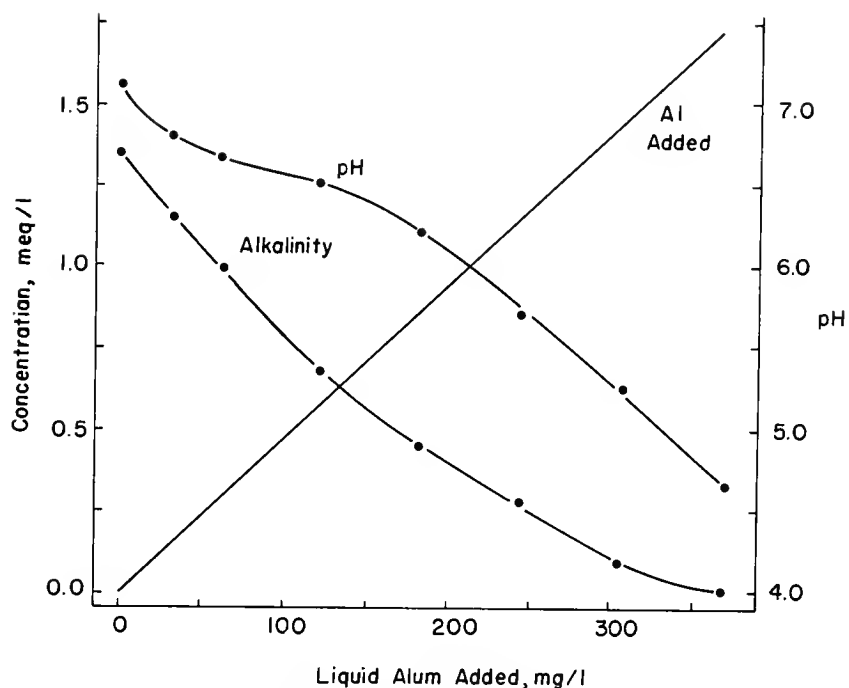
Fig. 5 Change in pH, alkalinity, and added Al as a function of additions of liquid
alum to hypolimnetic water from 12 m depth of Ball Pond.

CONCLUSIONS

Ball Pond is well-suited to treatment by aluminum salts for the inactivation of phosphorus. The majority of P in the lake becomes concentrated in the hypolimnion during summer stratification and a large proportion is present as easily precipitated inorganic phosphate. Laboratory studies suggest that treatment of the hypolimnion with liquid alum in late summer or early fall would remove about one-half of the total P in the lake, an amount somewhat greater than the estimated annual supply from external sources.

Treatment of waters below 7 meters at a rate of 5 mg/l of Al should be adequate to remove P and provide a thin layer of aluminum hydroxide to retard future releases of sediment P. Such a treatment would cover an area of 180,000 m^2, adding 3,700 kg of Al to 730,000 m^3 of hypolimnetic water. An application of about 85,000 kg of liquid alum would provide the desired addition of Al. Benefits from treatment should be relatively long lasting because of the large fraction of P removed and the five-year water retention time.

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