SJC_213

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Dilution as an algal bloom control

EUGENE B. WELCH, JAMES A. BUCKLEY, AND RONALD M. BUSH

ACCELERATED ENRICHMENT OF LAKES and the associated consequences of a eutrophic state constitute an important and increasing problem in water quality management. Blooms of nuisance-causing algae, mostly members of the blue-greens, are the principal consequence of eutrophication that impair recreational and aesthetic enjoyment of waters. Although blooms of nuisance algae have been closely associated with increased enrichment in many situations,[1, 2] the phenomenon is poorly understood in a quantitative sense. For example, what combination of such important factors as increased nutrient income and decreased water exchange is required to produce algal nuisances and degrade water quality? To effect adequate control of eutrophication and nuisance algal blooms in a variety of physical situations, the role of such factors must be better defined.

Methods of eutrophication control that have met with some success are nutrient diversion, dredging of enriched sediments, tertiary treatment, and "flushing" or addition of low-nutrient dilution water. Control of other important factors such as light, temperature, and herbivorous grazing is theoretically possible but impractical at this time. Although treatment with algicides is practiced, it is not considered an ecologically sound long-term solution.

Addition of low-nutrient dilution water can principally affect the formation of nuisance algal blooms by decreasing water retention time, washing out algal cells, and reducing the nutrient concentrations to presumably growth-limiting levels. A decrease in water retention time may also prevent algae-caused changes in the nutrient regime that may be necessary for the dominance of blue-green algae.[3]

Decreasing the algal biomass by adding dilution water results from the fact that algal biomass is a function of both growth rate and cell washout rate. The biomass will decrease as cell washout rate or dilution rate approaches the growth or doubling rate of the algal cells. There are many lakes that naturally maintain low algal biomass as a result of high dilution rates. In Marion Lake, near Vancouver, B.C., Canada, the high rate of water renewal gives the smaller, faster-reproducing algae a selective advantage over the larger forms with relatively slow growth rates.[4] A study of four lakes in Scotland revealed that a high rate of water replacement resulted in a reduction of biomass through algal cell washout.[5]

Artificial dilution of several eutrophic lakes has been tried or recommended. A program of nuisance algal control through addition of low-nutrient dilution water was implemented in 1962 for Green Lake, Seattle, Wash., a lake that had previously supported heavy blooms of blue-green algae from March through November.[6, 7] Results of follow-up studies revealed a reduction of lake water nitrogen and phosphorus content caused by dilution, a reduction of summer algal biomass including the elimination of *Aphanizomenon*, and increased water transparency. The last two results are probably caused, at least in part, by cell washout.[8] In Yugoslavia, dilution water is being diverted from River Radovna into Lake Bled, a recreationally important eutrophic lake in the subalpine region.[9] In California, recommendations have been made to divert water from Eel River into Clear Lake. The lake is extremely productive and it is felt that, in addition to nutrient dilution, some flushing

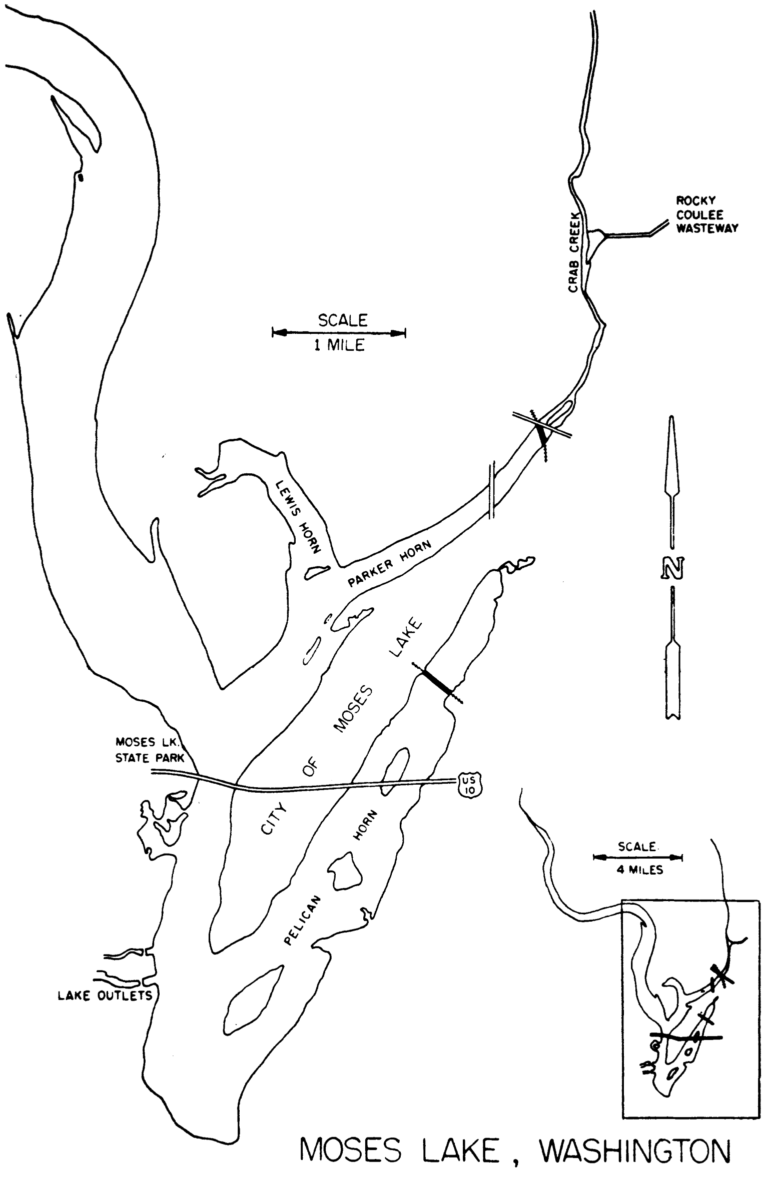


FIGURE 1.—Map of Moses Lake, Washington. (Miles × 1.6 = km.)

out of the sediment-bound nutrients may also be achieved.[10]

Another important factor to consider in water renewal is the chemical content of the old and new water. The conditioning or aging of the water is probably the result of secretion or excretion of dissolved organic matter into the system by phytoplankton or of cell decomposition. The aging effect of water may, in part, be explained by a continuing supply of dissolved organics in older water which provide a renewing source of inorganic nutrients for algal growth that is not available in new water.[11]

A program of dilution water addition was recommended for Moses Lake, a hypereutrophic 6,800-acre (2,750-ha) lake in eastern Washington (Figure 1). This potential solution to a nuisance algal problem is especially attractive because low-nutrient Columbia River water is available nearby. At the present time this water can be introduced only at the north end of Parker Horn where Crab Creek is connected to East Low Canal by Rocky Coulee Wasteway. Water reaches East Low Canal, the main irrigation canal of the Columbia basin project, from Banks Lake, a storage reservoir for Columbia River irrigation water.

During the summer of 1967, 472 acre-ft (580,000 cu m) of Columbia River water was experimentally introduced into Parker Horn (equal to 6 percent of the total volume of Parker Horn) over a period of 24 hr. This action resulted in a temporary increase in water transparency and provided data for more detailed recommendations as to the best use of the flushing water.[12, 13] Further experimentation was considered necessary to permit estimation of the degree to which dilution water addition would control nuisance algal blooms in a shallow [mean depth 18.5 ft (5.6 m)], very rich lake such as Moses Lake. As a result of the Green Lake work,[6] it was known that addition of dilution water reduces nutrient concentration, productivity, algal biomass, and the prevalence of nuisance blue-green species, and increases water transparency. However, in addition to estimating the degree of effect of dilution water on nuisance algae, the investigators were interested in determining the mechanism of effect.

To elucidate the relative importance of the separate effects of dilution water on nuisance algae and increase the usefulness of that control measure, *in situ* experiments in plastic bags were conducted during 1970 in Parker Horn of Moses Lake (Figure 1). Parker Horn is a shallow [mean depth 12.6 ft (3.8 m)] 758-acre (307-ha) section of Moses Lake that is bordered by the city on its eastern side and residential districts and open fields on its western shore. Like most of the lake it supports a heavy growth of blue-green algae from late spring to fall, thus providing typical levels of nuisance algae with which to test the effect of dilution.

The objectives of these experiments were to:

1. Determine the effect of diluting lake water with the low-nutrient Columbia River water on growth rate and maximum biomass of nuisance blue-green;
2. Determine the nutrient that was caused to be limiting by the dilution, by adding back nitrogen and phosphorus in separate dilution experiments;
3. Determine if nutrient manipulation or dilution altered species composition during the 2- to 3-wk study periods; and
4. Estimate the effects of different rates of dilution on cell washout and growth rate of nuisance algae in Parker Horn.

METHODS AND MATERIALS

Experimental design. To test the effect of low-nutrient dilution water on the growth rate and total yield of natural phytoplankton populations, an *in situ* experiment was conducted in July 1970. The study was conducted by suspending in Moses Lake various dilutions of lake water enclosed in water columns (bags) made of polyethylene plastic. The water columns were supported by wooden frames anchored 40 m off shore in Parker Horn, Moses Lake.

The experiment involved the incubation of 100-l water columns containing the following percentages of lake water: two columns of 0 percent lake water, two of 25 percent, three of 50 percent, three of 75 percent, and two of 100 percent. Low-nutrient Columbia River water collected from the East Low Irrigation Canal at a point approximately 5 miles (8 km) northeast of Moses Lake was used for dilution. The lake water was obtained from Parker Horn in Moses Lake. In order for each experimental chamber to begin with the same biomass, a volume of lake water equal to the volume of Columbia River dilution water in each bag was filtered through a 110-micron mesh plankton net. The filtrate was discarded, and the algae were then

TABLE I.—Nitrogen Addition Schedule, Mean of Initial NO_3-N Concentration in Duplicate Cultures

Percentage Lake Water	NO_3-N before N Addition (mg/l)	Stock Solution Added (ml)	NO_3-N after N Addition (mg/l)	Expected NO_3-N Concentration (mg/l)	Stock Solution Added Daily (ml)
Control:					
25	0.003	—	—	0.250	—
50	0.002	—	—	0.500	—
75	0.004	—	—	0.750	—
N added:					
25	0.004	53.6	0.751	1.00	5.4
50	0.003	35.7	0.502	1.00	3.6
75	0.004	17.9	0.232	1.00	1.8

added to the 100-l solution. The assumption was that the amount of algae in the Columbia River water is negligible, and to bring each experimental cell up to the same starting concentration, it was necessary to add back algae from a volume of lake water equal to the volume of dilution water used.

An attempt was made to prevent the cultures from eventually becoming individual lakes after the initial addition of dilution water by daily exchanging the appropriate proportions of dilution water and lake water with the cultures at a rate that was determined to be less than the algal growth rate. In this way it would be possible to prevent cell washout and thereby relate changes in algal concentration and community composition to environmental manipulations, that is, to vary the concentrations of dilution water.

Biomass data from preliminary dilution experiments conducted in 1969 and 1970 provided growth rate coefficients that were used in determining how much water should be exchanged daily to stay below the growth rate of the cultures and therefore prevent cell washout. The lowest value calculated was 0.17 doublings/day. From this figure it was decided that replacement of 0.1 or 10 percent of the water in the cultures each day would keep cell removal below the growth rate of the algal community. The procedure of adding algae filtered from a volume of lake water equal to the volume of dilution water replaced was also used in the daily exchanges.

The water removed in the daily exchange was sampled for the analysis of phytoplankton, chlorophyll *a*, nitrate, orthophosphate, total phosphate, total alkalinity, conductivity, and pH. The water temperature in each experimental cell was also measured.

In order to determine whether or not the effect of dilution water on algal growth was caused by the reduction in concentration of either of the macronutrients, nitrogen or phosphorus, *in situ* dilution experiments with nutrient additions were conducted in August and September 1970.

The nitrate addition experiment employed experimental design and apparatus similar to those of the July dilution experiment. Twelve experimental cells were set up, with four each of 25 percent, 50 percent and 75 percent lake water. Two cells of each dilution were enriched with inorganic nitrogen ($NaNO_3$). The nitrogen additions were intended to bring the enriched experimental cells up to a uniform concentration of 1.00 mg N/l. The nitrate concentration of the lake water was lower than expected, and thus the desired concentrations from nitrogen addition were not achieved. Table I shows the initial nitrate concentration in the test cells and the amount of nitrogen added.

In the phosphate addition experiment, 9.5-l clear plastic containers (water jugs) were used instead of plastic bags. A test of the light-transmitting properties of the containers revealed a 5 percent reduction in intensity of transmitted light and no selective absorbance of any wavelength from 350 to 700 mμ.

For the phosphate addition experiment, 12 experimental cells were set up, with four each of 25 percent, 50 percent, and 75 percent lake water. Two cells of each dilution were enriched with inorganic phosphorus (Na_2HPO_4) to give cultures of approximately the same phosphate concentration. Table II shows the orthophosphate concentrations before and after the additions of Na_2HPO_4.

In the nutrient enrichment studies the procedure of adding algae filtered from a volume of lake water equal to the volume of dilution water was used, as was the procedure of 10 percent daily exchange. Also in these experiments, 10 percent of the initial addition of stock solution was added with the daily renewal throughout the study. The same sampling procedures used in the July dilution experiment were used in the nutrient addition experiments.

Biological and chemical analyses. Phytoplankton samples from the dilution experiment were preserved in Lugols solution after collection, while samples from the nutrient addition experiments were counted live. Two aliquots were taken from each phytoplankton sample and placed in 1-ml Sedgwick-Rafter cells. In each cell a strip of known volume was scanned at 100× and 210× using a standard light microscope. Phytoplankton were identified by genus and counted, and the mean generic count of the two aliquots was calculated.

Chlorophyll *a* samples were obtained by filtration through a Reeve-Angel No. 934AH glass fiber filter at 2.5 in. (6.3 cm) of mercury. The chlorophyll *a* was extracted from the filters by grinding the cells in 90 percent aqueous acetone. The extract was analyzed by the fluorometric method of Strickland and Parsons.[14]

Orthophosphate samples were filtered through Schleicher and Schuell No. 27 glass fiber filters. The filtrate was fixed with chloroform and frozen in 250-ml polyethylene bottles. Total phosphate samples were similarly fixed and stored, but without filtration. Both ortho and total phosphate were determined by using the phosphomolybdate complex method of Strickland and Parsons.[14] Nitrate samples were frozen in polyethylene bottles. Determinations were made by the cadmium-copper column method of Strickland and Parsons.

Total alkalinity was determined by using the procedures of the American Public Health Association [15] and titrating to an equivalence point of pH 4.8. Conductivity measurements were determined with a portable conductivity meter.

Results

A statistically significant decrease in biomass of blue-green algae occurred with an increase in the percentage of dilution water at all dilution levels (Figure 2). The dominating blue-greens were *Aphanizomenon* (*A. flos-aquae*) and *Anabaena* (*A. circinalis*). The net increases or decrease of blue-green algal cells is shown in Figure 3. At 0 percent and 25 percent lake water, the blue-green algae either decreased in number or were just able to maintain their initial concentration.

TABLE II.—Schedule of Phosphate (PO_4-P) Addition with Actual and Expected Concentrations, Mean of Duplicate Cultures

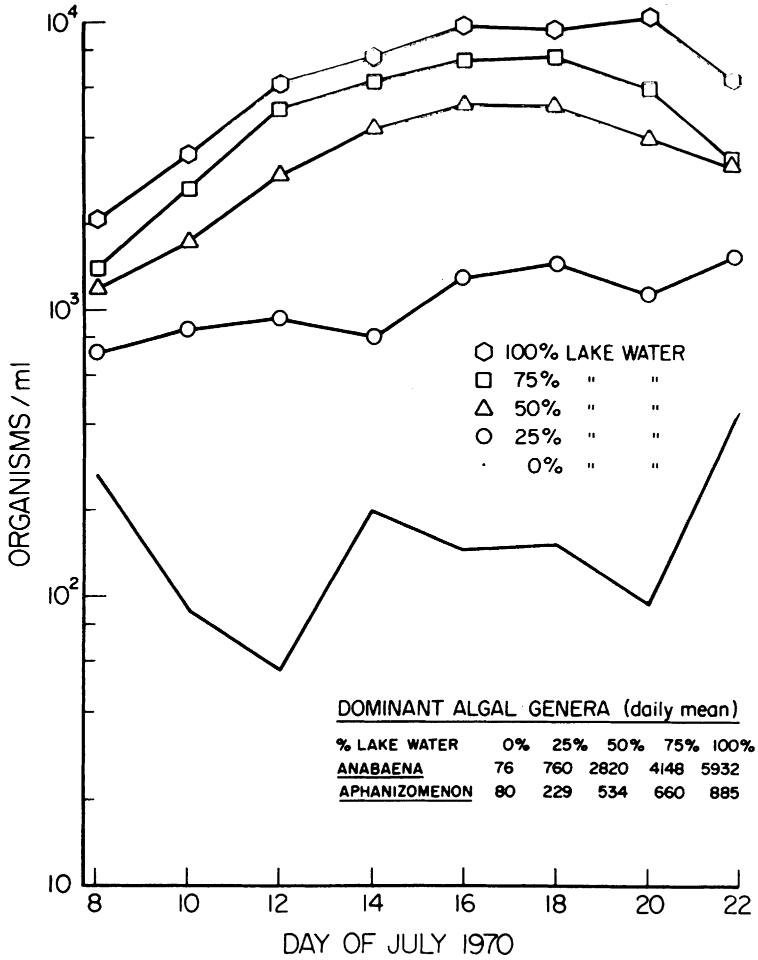
Percentage Lake Water	P before P Addition (mg/l)	Stock Solution Added (ml)	P after P Addition (mg/l)	Expected P Concentration (mg/l)	Stock Solution Added Daily (ml)
Control:					
25	0.022	—	—	0.019	—
50	0.035	—	—	0.024	—
75	0.037	—	—	0.028	—
P added:					
25	0.022	33.0	0.035	0.032	3.3
50	0.029	22.0	0.038	0.032	2.2
75	0.034	11.0	0.039	0.032	1.1

A decrease in green algal biomass was not shown with an increase in the percentage of dilution water (Figure 4). The green algae were dominated by species of *Scenedesmus* and *Ankistrodesmus*.

The growth of the diatoms was directly related to increased percentage of dilution water (Figure 5). Higher biomasses of diatoms were attained in the cultures with less lake water. The dominant diatom genera represented were *Fragilaria* and *Nitzschia*.

A decrease in biomass as measured by chlorophyll *a* was also shown in similar *in situ* dilution experiments in which there was no daily renewal of dilution and lake water. However, chlorophyll *a* concentrations in the dilution experiment with daily renewal showed very little change from initial concentrations for about 12 days, after which they began to increase.

The initial and final nutrient concentrations in this experiment are shown in Table III. The extremely low nitrate concentrations both at the beginning and end of the experiment resulted in lower than optimum N:P ratios of about 1:3. However, in-



% LAKE WATER	0%	25%	50%	75%	100%
ANABAENA	76	760	2820	4148	5932
APHANIZOMENON	80	229	534	660	885

FIGURE 2.—Variation in blue-green algal concentrations in experiments with daily water exchange.

organic levels of both nitrogen and phosphorus were low and suggest a dependence of the algae on recycled organic supplies.

Effect of dilution with added nitrogen. Addition of nitrate-nitrogen to dilution experiments in amounts to equal a maximum lake concentration of 1.0 mg/l resulted in an increase in abundance of blue-green algae (*Anabaena*, *Aphanizomenon*, and *Microcystis*) over that in the control cultures (Figure 6). This increase at all levels of dilution is statistically significant at the 95 percent level. The increase in blue-green biomass over the control was nearly as great in the 25 perecent and 75 percent lake water cultures with nitrate added as at the 30 percent level, as shown in Figure 6. This increase in biomass in response to nitrate addition was more apparent from an analysis of chlorophyll content (Figure 7). Again, at all dilution levels, the increase in biomass with added nitrate was significant at the 95 percent level. This is understandable because river dilution water is low in nitrate-N relative to phosphate-P [0.009 and 0.016 mg/l, respectively, (Table IV)]. With nitrate addition, initial nitrate-N was increased to levels from 0.232 mg/l to 0.751 mg/l in the three dilutions compared to levels from 0.002 to 0.004 mg/l in the control cultures.

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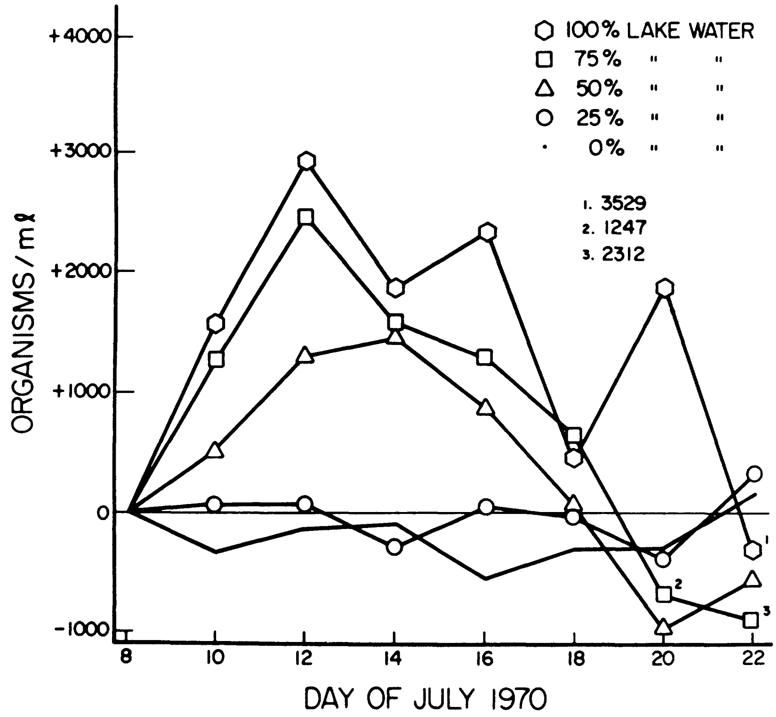

FIGURE 3.—Net change in blue-green algal colonies in experiment with daily water exchange.

The increase in blue-green algae was also greater with nitrate added as more river dilution water was added, that is, as the percent of lake water was reduced. This trend corresponds to the actual amount of nitrate added to attain an equal concentration of 1.0 mg/l in the test bags; the initial nitrate concentrations were 0.751, 0.502, and 0.232 mg/l at the 25, 50, and 75 percent dilution levels, respectively (Table I). Although the unexpected low lake concentration (0.002 mg/l) accounted for the failure of the initial test concentrations to approach the goal of 1.0 mg/l, the importance of reduction in nitrate concentration by dilution as an important inhibitor to algal growth is even clearer. This is true because algal biomass attained was pro-

TABLE III.—Initial and Final Nutrient Concentrations (Mean of Duplicates) in Experiments at Five Levels of Columbia River Water/Lake Water Dilutions

Lake Water (%)	Orthophosphate (mg PO_4-P/l)			Total Phosphate (mg PO_4-P/l)			Nitrate (mg NO_3-N/l)		
	July 8	July 24	July 29	July 8	July 24	July 29	July 8	July 24	July 29
0	0.019	0.006	—	0.039	0.070	—	0.002	0.001	—
25	0.003	0.008	—	0.062	0.098	—	0.001	0.001	—
50	0.003	0.008	—	0.093	0.133	—	0.001	0.001	—
75	0.003	0.007	—	0.119	0.156	—	0.001	0.002	—
100	0.004	—	—	0.172	0.179	—	0.003	0.002	—
Ambient	0.002	0.005	0.011	0.053	0.049	0.239	0.002	0.003	0.001
Dilution	0.017	—	—	0.024	—	—	0.003	—	—

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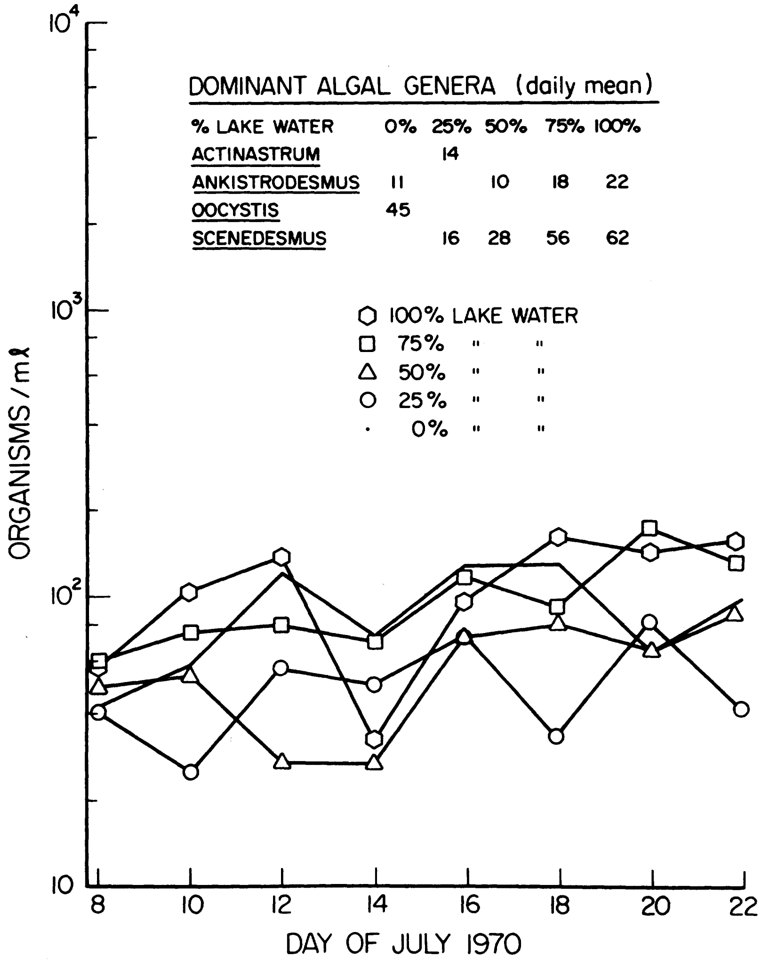

DOMINANT ALGAL GENERA (daily mean)

% LAKE WATER	0%	25%	50%	75%	100%
ACTINASTRUM		14			
ANKISTRODESMUS	11		10	18	22
OOCYSTIS	45				
SCENEDESMUS		16	28	56	62

FIGURE 4.—Variation in green algal concentration in experiment with daily water exchange.

portional to initial nitrate content in spite of this increase occurring with reduced fractions of lake water.

As shown in Figure 6 for the 50 percent lake water dilution level, and equally for the 25 and 75 percent levels, green or diatom algae were not favored by nitrate addition. The dominant green alga *Oocystis* was greater in mean concentration in the control (43 organisms/ml) than with nitrate added (36 organisms/ml). The dominant diatom *Melosira,* although greater with nitrate added at the 50 percent dilution level, actually averaged 94 and 74 organisms/ml in the control and nitrate-added cultures, respectively, considering all dilution levels.

Nitrate addition raised the N:P ratios to values from 140 to 330 at the three dilution levels compared to ratios of 0.2 to 1.5 in controls, which might be considered to exert selective advantage from one group of algae to another. Furthermore, free CO_2 decreased from about 0.15 mg/l as $CaCO_3$ to less than 0.01 mg/l in the bags with nitrate added. Concentrations remained at or above 0.05 mg/l in the controls. This too could have exerted a selective force and encouraged change in dominant genera during the 2-wk experiment.

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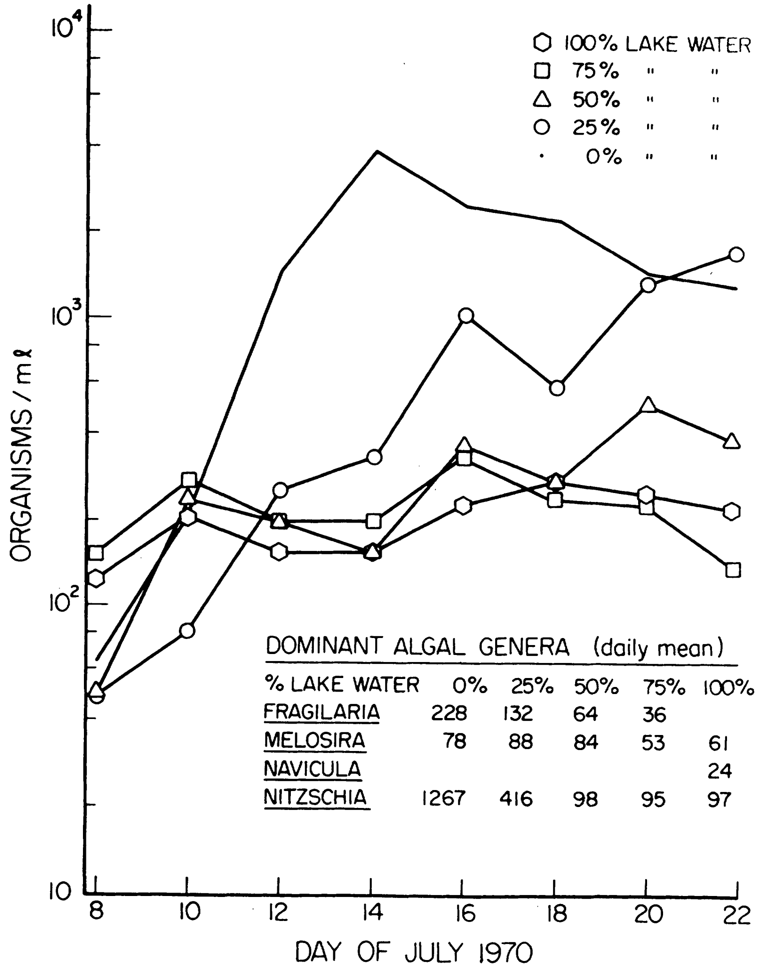


DOMINANT ALGAL GENERA (daily mean)

% LAKE WATER	0%	25%	50%	75%	100%
FRAGILARIA	228	132	64	36	
MELOSIRA	78	88	84	53	61
NAVICULA					24
NITZSCHIA	1267	416	98	95	97

FIGURE 5.—Variation in diatom algal concentration in experiment with daily water exchange.

Effect of dilution water with added phosphate. The growth pattern shown by blue-green algae (principally *Aphanizomenon* and *Microcystis*) at the three dilutions (25, 50, and 75 percent) of lake water were similar. Maximum abundance ranged from 200 to 300 organisms/ml with increase in dilution causing a slight decrease in mean abundance throughout the experiment. However, an increase in blue-green algae abundance in response to added phosphate did not occur (Figure 8). Phosphate was added to equalize the three levels of Columbia River water/lake water dilutions at the mean inorganic phosphate content in Parker Horn during 1970 (0.032 mg/l P). The mean content in Columbia River water was 0.015 mg/l.

Green algae dominated by *Oocystis* and *Scenedesmus* also decreased slightly in abundance with increased dilution water and in general were more abundant than blue-greens. Phosphate addition did not stimulate green algae.

Diatoms, principally *Fragilaria, Nitzschia,* and *Cyclotella,* dominated the algal community in September. These organisms increased in abundance in response to increased percentage of Columbia River water in contrast to blue-green and green

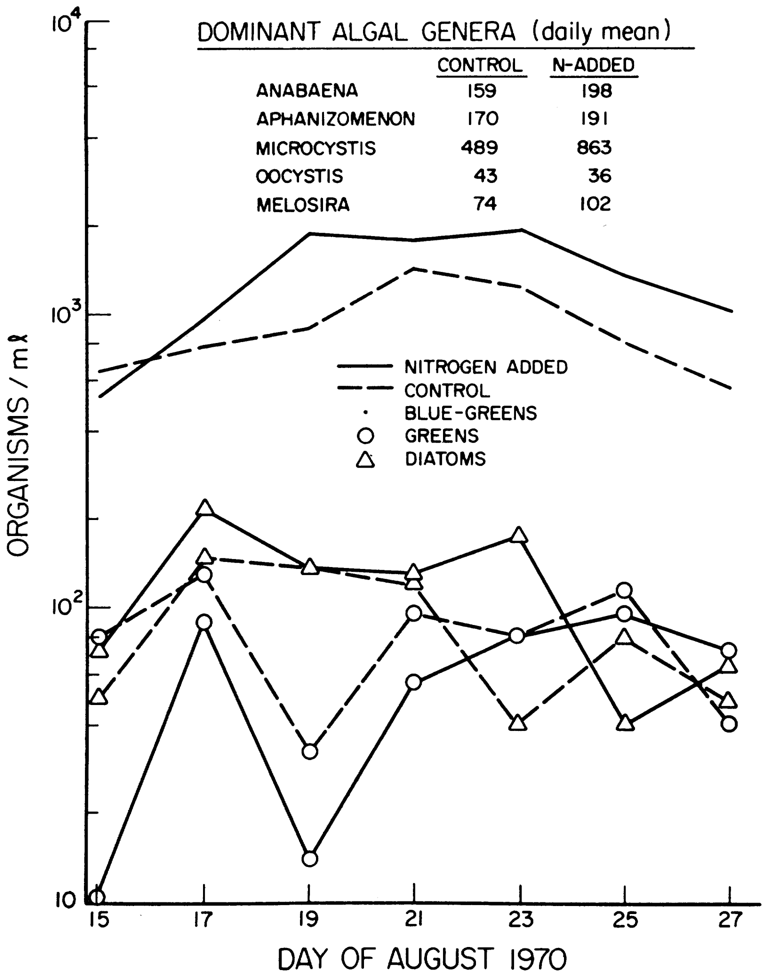


FIGURE 6.—Algal concentration (colonies) and genera dominating (mean of duplicates) in 50 percent lake water—Columbia River water dilution with and without nitrate added to equal 1.0 mg/l maximum lake water concentration.

algae in either this or the nitrate-addition experiment. Phosphate addition was associated with an increased diatom growth only at the 25 percent lake water (75 percent Columbia River water) dilution level. Although statistically significant, the increase was only slight.

As was the case in previous experiments, there was no tendency for the community to change dominance—the three algal groups increased and decreased in nearly parallel fashion (Figure 8). However, at the highest level of Columbia River water, diatoms were continuing to increase at the end of the 2-wk experiment and had exceeded 10,000 organisms/ml.

Chlorophyll concentration at the three levels of dilution, with and without phosphate added, indicates only slight differences among the treatments (Figure 9). Maximum chlorophyll content ranged from 75 to 100 μg/l at the various treatments, not very different from that in the nitrate-addition experiment (35 to 120 μg/l). In agreement with results from colony counts of diatoms, only at the highest proportion of Columbia River water was mean chlorophyll content greater in response to phos-

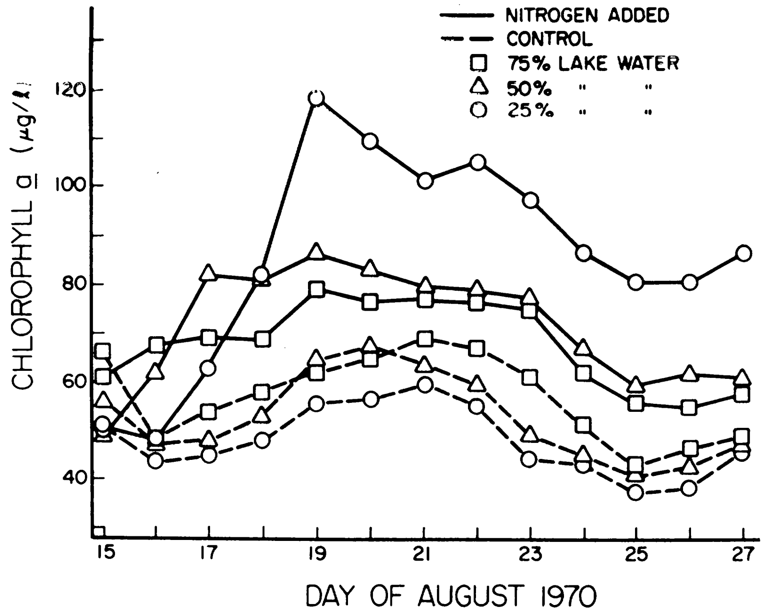


FIGURE 7.—Chlorophyll *a* concentration with and without nitrate added at various dilutions.

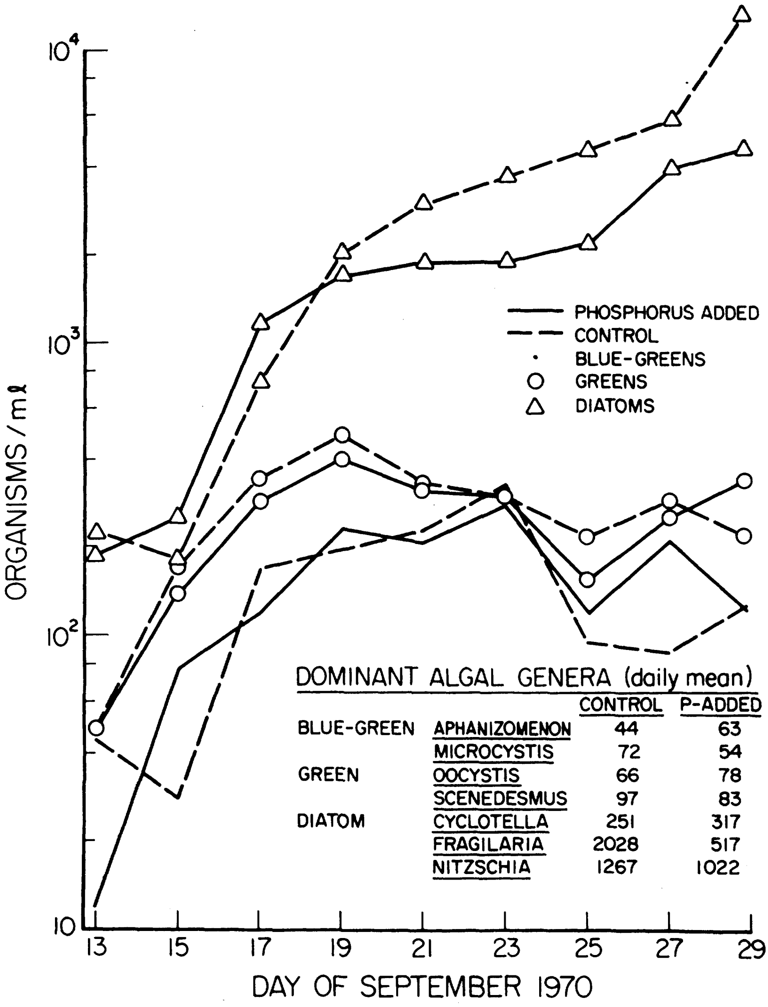
phate addition than in the control without phosphate.

That this increase in diatom abundance and chlorophyll concentration at the highest proportion of Columbia River water (75 percent) with phosphate added was not caused by the phosphate *per se* is suggested by the similar initial concentrations of phosphate at all levels (0.035 to 0.039 mg P/l) (Table IV). Although inorganic phosphate was considerably reduced at the end of the experiment, nitrate was nearly depleted (Table IV). As a result, N:P ratios declined in containers both with and without phosphate addition from between 6 and 11 to less than 1. In contrast to the nitrate addition experiment, CO_2 was not depleted more with phosphate added than in control without phosphate. In both situations, with and without phosphate, CO_2 decreased from initial concentrations of about 1.0 mg/l as $CaCO_3$ to about 0.1 mg/l.

TABLE IV.—Initial and Final Nutrient Concentrations (Mean of Duplicates) in Experiments with and without Nitrate Added at Three Levels af Columbia River Water/Lake Water Dilutions

Lake Water (%)	Orthophosphate (mg PO_4-P/l)		Total Phosphate (mg PO_4-P/l)		Nitrate (mg NO_3-N/l)	
	August 15	August 27	August 15	August 27	August 15	August 27
Controls:						
25	0.004	0.008	0.155	0.173	0.003	0.003
50	0.022	0.007	0.134	0.218	0.002	0.003
75	0.008	0.008	0.214	0.235	0.004	0.004
NO_3 added:						
25	0.005	0.006	0.080	0.232	0.751	0.005
50	0.004	0.007	0.132	0.310	0.502	0.004
75	0.008	0.011	0.147	0.149	0.232	0.002
Ambient Lake	0.009	0.010	0.123	0.222	0.002	0.004
Dilution water	0.016	—	0.232	—	0.009	—

SJC_213



DOMINANT ALGAL GENERA (daily mean)

		CONTROL	P-ADDED
BLUE-GREEN	APHANIZOMENON	44	63
	MICROCYSTIS	72	54
GREEN	OOCYSTIS	66	78
	SCENEDESMUS	97	83
DIATOM	CYCLOTELLA	251	317
	FRAGILARIA	2028	517
	NITZSCHIA	1267	1022

FIGURE 8.—Algal concentration (colonies) and genera dominating (mean of duplicates) in 50 percent dilution with and without phosphate-P added to equal 0.032 mg/l mean lake water concentration.

Thus, nitrogen seems to have been in shorter supply than carbon or phosphorus in this experiment as well as in the previous experiment with nitrate added. This is supported by the general lack of stimulation from phosphate addition, but very positive stimulation from nitrate addition. Because nitrate was relatively high initially in the September phosphate addition experiment (0.111 to 0.319 mg N/l) (Table V), it is not surprising that dilution with low-nitrate (0.015 mg N/l) dilution water had little effect on algal growth.

Expected effect of dilution in Parker Horn. If Parker Horn were diluted with Columbia River water at arbitrary rates of 1, 2, and 10 percent/day, the percent of lake water remaining would be expected to decrease according to the equation:

$$C = C_0 e^{-Kt}$$

where

C = concentration at time t,
C_0 = initial concentration, and
K = dilution rate constant.

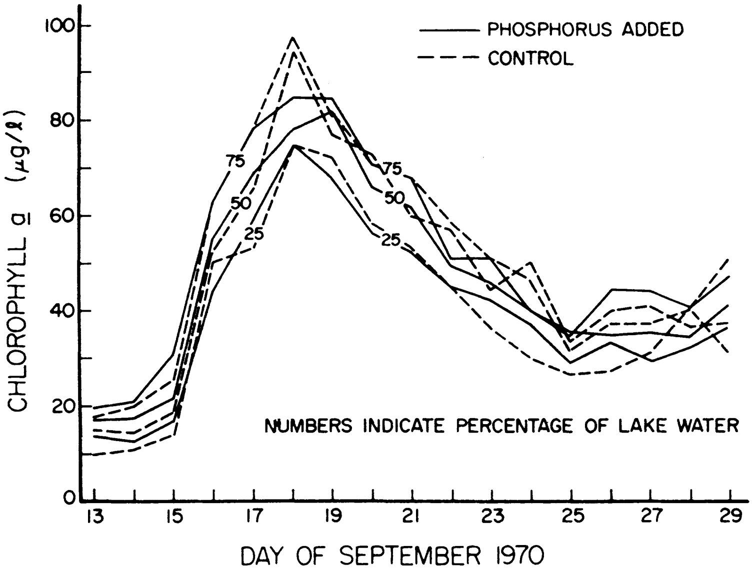


FIGURE 9.—Chlorophyll *a* concentration with and without phosphate-P added at various dilutions.

Expected decreasing concentrations are shown by the solid lines in Figure 10.

From the experimental evidence of the effect of low-nitrate dilution water on the growth rate of nuisance blue-green algae, it is clear that to reduce algal biomass by decreasing growth rate would require a replacement of more than 50 percent of the lake water. By plotting associated growth rates $K_{(g)}$ as the three levels (75, 50, and 25 percent) of lake water are achieved at the three arbitrary dilution rates, the time necessary for dilution rate to equal algal growth rate and result in zero biomass increase can be estimated. For dilution rates of 0.01, 0.02, and 0.1/day the estimated time periods are about 200, 100, and 20 days (Figure 10). To cut the growth rate in half, from 2 to 1 doublings/day, would require about 15, 75, and 150 days for the three dilution rates, 10, 2, and 1 percent/day, respectively. The inflow rates to attain these dilution rates would be about 50, 100, and 500 cfs (85, 170, and

TABLE V.—Initial and Final Nutrient Concentrations (Means of Duplicates) in Experiments with and without Phosphates Added at Three Levels of Columbia River Water/Lake Water Dilutions

Lake Water (%)	Orthophosphate (mg PO_4-P/l)		Total Phosphate (mg PO_4-P/l)		Nitrate (mg NO_3-N/l)	
	September 13	September 29	September 13	September 29	September 13	September 29
Controls:						
25	0.022	0.007	0.241	0.124	0.112	0.002
50	0.035	0.011	0.266	0.323	0.227	0.002
75	0.037	0.007	3.212	0.458	0.319	0.001
PO_4 added:						
25	0.035	0.009	0.120	0.204	0.111	0.003
50	0.038	0.007	0.494	0.216	0.140	0.002
75	0.039	0.016	0.688	0.210	0.272	0.002
Ambient lake	0.044	0.032	0.247	0.179	0.437	0.669
Dilution water	0.018	—	0.152	—	0.015	—

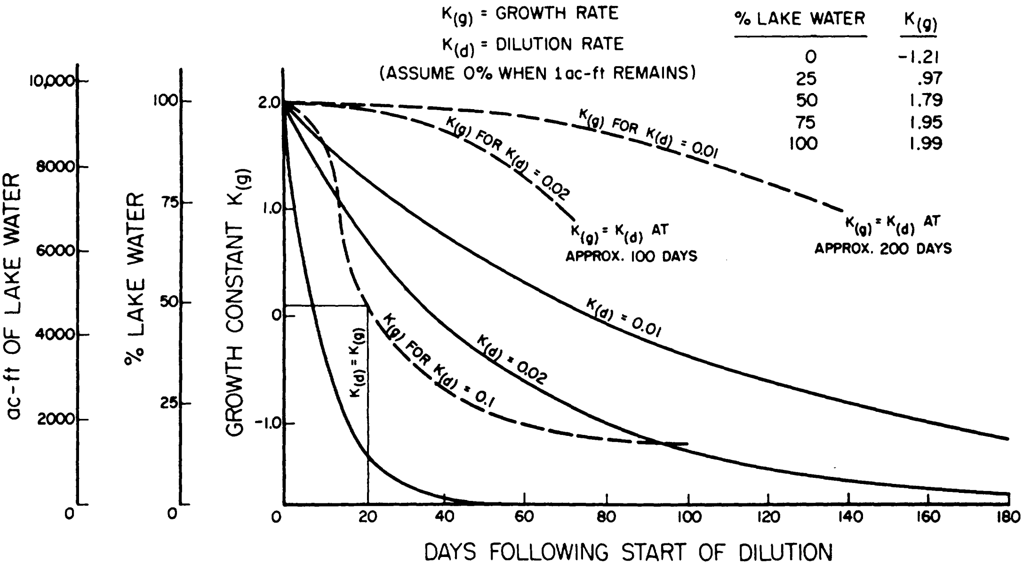


FIGURE 10.—Effect of dilution on growth rate of blue-green algae. Steady state is reached when growth rate reaches cell washout rate.

850 cu m/min), respectively. Only the lower end of this series would be compatible with the physical constraints of the inflow channel.

To decrease algal biomass by the strictly physical process of washing them out of Parker Horn faster than they could grow would require dilution rates in excess of 50 percent/day. The blue-green algae would continue to replace their biomass totally each day at a lesser dilution rate because the blue-greens grew at a maximum rate of 2 doublings/day in the experimental chambers. Of course at such rates of dilution, before cell washout caused a biomass reduction, growth rate would actually be declining because of nutrient reduction as a result of dilution with low-nutrient river water.

Expecting growth rate to be affected by dilution with low-nutrient river water, as suggested in Figure 10, precludes any interacting effect on nutrient concentration from sediment-water interchange and nutrient uptake and release from suspended particulate matter that would occur over a longer period than that of the 2-wk experiments. To obtain a better idea of what might happen to growth rate over an extended period requires some estimate of the dilution effect on nutrient concentration. An expected decrease in nutrient concentration can be expected to follow the curves of water replacement in Figure 10 according to the equation

$$C = C_i + (C_o - C_i)e^{-Kt}$$

where

C = concentration at time t,
C_o = initial concentration,
C_i = concentration in the inflow water,
and
K = dilution rate constant.

Beginning with the mean concentrations of nitrate-N and phosphate-P of 0.484 and 0.032 mg/l, respectively, the concentrations would be expected to reach 0.175 and 0.021 mg/l of nitrate and phosphate, respectively, after 100 days at 1 percent/day replacement.

Because several biological and chemical factors, particularly sediment interchange, could interact to produce considerable variation from these calculated rates of concentration decrease, results from an actual dilution in Green Lake were used to indicate the magnitude of interacting fac-

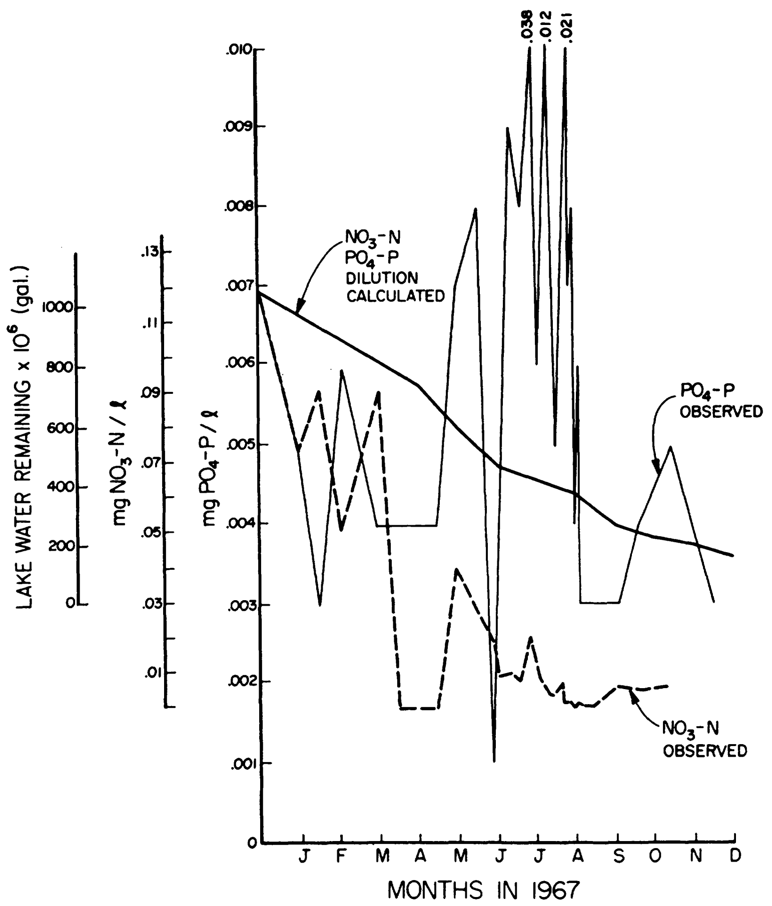


FIGURE 11.—Calculated dilution of lake water and macronutrients compared to observed changes in nutrient concentration for Green Lake study. (Gal × 3.785 = l.)

tors (Figure 11). The actual concentrations of nutrients do not decrease gradually throughout the year, as expected from the calculated values. Phosphate varied considerably but tended to remain higher than the calculated values while nitrate decreased to much below expected values. Similar variation between expected and observed values also occurred for two other years, 1965 and 1966; however, the mean annual concentration progressively decreased over this 3-yr period.[6, 8]

The physical characteristics of both lakes are similar, as shown in Table VI. Also, thermal stratification is periodically destroyed by wind-induced currents in both lakes. The combination of shallowness, transitory stratification, and wind reaeration of water precludes continuous periods of anaerobic conditions in both Green Lake

TABLE VI.—Comparison of Physical Characteristics in Green Lake and Parker Horn, Moses Lake

Characteristic	Green Lake*	Parker Horn
Volume (acre-ft)	3,340	9,520
Mean depth (ft)	12.5	12.6
Lake basin	Complete	Incomplete, connected to main body of lake

* Initial concentrations in Green Lake at the beginning of 1967 were 0.007 mg PO_4-P/l and 0.118 mg NO_3-N/l.

Note: Acre-ft × 1,233 = cu m; ft × 0.305 = m.

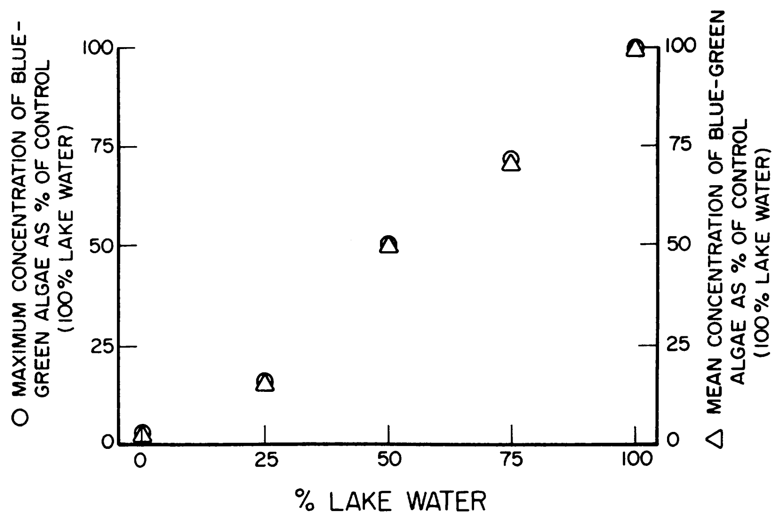


FIGURE 12.—Effect of dilution water on concentration of blue-green algae compared to 100 percent lake water control.

and Parker Horn of Moses Lake. As a comparison of other conditions related to dilution, the mean rate at which city water was added to Green Lake in 1967 was 0.54 percent/day. The mean contents of phosphate-P and nitrate-N in city dilution water in 1967 were 0.003 and 0.030, respectively.

DISCUSSION

The addition of low-nutrient dilution water to lake water significantly reduced the maximum biomass or yield of blue-green algae as determined by colony counts. As shown in Figure 12, the reduction in yield is proportional to the amount of dilution water added. The same trend for reduction in yield of blue-green algae proportional to the amount of dilution water is found in the control cultures for experiments with added nitrate and phosphate. This is understandable because if dilution is actually proportionately lowering the concentration of limiting nutrient, then growth will stop when the nutrient supply is exhausted.

When the growth constant *k* is plotted against percent lake water, the resulting curve shows that the growth rate of the blue-green algae is reduced very little until more than 50 percent dilution water is added to the cultures (Figure 13). These findings indicate that large amounts of dilution water were necessary to reduce the growth rate by nutrient dilution. This observation conforms to the typical relation of algal growth rate to limiting nutrient concentration. That is, growth rate is constant at high saturating nutrient concentration and then tends to decrease rapidly as the growth-limiting concentration is reached. Addition of dilution water appears to have less effect on the growth of greens than on the growth of blue-greens, while stimulating the growth of diatoms. In other words, adding dilution water decreases the abundance of blue-green algae without necessarily increasing or decreasing the abundance of greens and increasing the abundance of diatoms.

The reduction in growth rate of nuisance blue-green algae that would be expected from adding Columbia River water to Parker Horn would probably result from a reduction in nitrate concentration. This is supported by the positive stimulation from nitrate addition and lack of any real consistent increase from phosphate addition. Such a result might be expected from adding Columbia River water because it is rather low in nitrate-N (0.009 mg/l) and even higher in phosphate-P (0.015 mg/l),

SJC_213

resulting in an N:P ratio of less than one. In addition, nitrate tends to be very low in Moses Lake during the summer (0.002 to 0.004 mg/l). Addition of nitrate might be expected to increase growth under those conditions, but it is not so clear why addition of dilution water with a similar and even higher nitrate content would decrease growth rate. The answer may be that the dilution water is low in total nitrogen, which would reduce the total N supply on addition to lake water. This was true for total phosphorus in three of the four experiments and total P supply was reduced from 0.115 to 0.024 and 0.172 to 0.039 mg/l with increased percentage of river water in June and July dilution experiments, respectively. However, in the nitrate addition experiment in July, dilution water nitrate was greater than that in lake water, therefore raising the mixed concentrations over those in the lake. Although nitrogen reduction was apparently responsible for the effect of dilution water on growth rate of blue-green algae, the lack of total nitrogen data clouds the picture.

The effects of dilution water on growth rate in July tended to be negated by nitrate addition in the July experiment. Table VII shows the algebraic sum of net increase and decrease in blue-green algae abundance at the various treatments. Positive values describe a growing community, zero values a static community, and negative values a declining community. The figures were obtained by keeping a record of the number of blue-green colonies lost or gained at each daily exchange. By this procedure it was possible to correct for cell washout and arrive at values that reflect only the effect of dilution on algal growth or, in the case of nutrient addition, the effect of adding NO_3 or PO_4. The effect of nutrient dilution with daily renewal is a reduction in the net yield of blue-green algae that is proportional to the amount of dilution water added to the cultures. The nearly equal and greater increase with nitrate added compared to the control further suggests that the dilution effect resulted from nitrogen decrease. Phosphate showed no such pronounced or consistent stimulation.

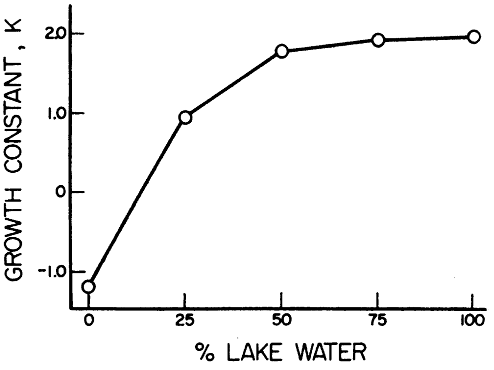


FIGURE 13.—Effect of dilution water on maximum growth rate of blue-green algae.

Comparison of the effect of nitrogen and phosphorus may be slightly biased by the changing composition of the algal community. While blue-green algae peaked in abundance both in the experimental bags and in the lake during July and August, diatoms and green algae dominated the community in June and September. Because temperature plays an important part in community composition in Moses Lake,[16] the described community shifts may be occurring according to temperature optima that may affect response to nutrient availability. That is, the response of blue-green algae to phosphate addition may have been greater if the experiment had been performed during July or August. However, the fact remains that N:P ratios during midsummer suggest that nitrogen is limiting and because dilution water is lower in

TABLE VII.—Net Yield of Blue-Green Algae in Three Experiments in Parker Horn

Lake Water (%)	Net Yield (colonies/ml)				
	Dilution	Nitrate Addition		Phosphate Addition	
		Control	N-added	Control	P-added
0	−1,590	—	—	—	—
25	− 313	+277	+743	−12	− 99
50	+2,596	+ 57	+896	−19	+ 14
75	+3,673	+ 40	+796	+41	+124
100	+7,366	—	—	—	—

TABLE VIII.—Daily Mean Ratio of Algal Concentrations in Control to Experimental Cultures with Added Nitrate

Lake Water (%)	Algae Concentrations (control/experimental)	
	Greens	Diatoms
25	1.9	1.3
50	1.4	0.7
75	0.9	0.7

nitrate than phosphate, the most likely cause for the growth-rate-inhibiting effect of dilution water is a reduction in nitrogen supply.

Green and diatom algae do not show a similar consistent increase in response to nitrogen addition. It was expected that greens and diatoms, being unable to fix nitrogen, would respond to nitrogen addition most vigorously, especially in view of the low ratio of N:P existing in the lake and cultures. However, this was not the case. One explanation is found in recent literature,[17] where evidence indicates that green algae are more intolerant of low CO_2 concentrations than are blue-green algae. This may be an explanation for the inability of green algae to exploit the added nitrogen because CO_2 decreased to low levels (less than 0.005 mg/l as $CaCO_3$) in these cultures.* Table VIII shows the ratio of algal cell counts in the control to nitrogen added cultures using the mean of daily phytoplankton counts. Green algal abundance was less than that in controls in two dilution levels out of three and the diatoms in one case out of three. The lowest yield of green algae relative to the controls occurred in the two dilutions (25 percent and 50 percent) with the lowest CO_2 concentrations. The low yield of diatoms also occurred in the dilution (25 percent) with the lowest CO_2 values.

Concerning blue-green algae, the same paper[17] states that CO_2 concentrations of less than 2.5 μ moles/l (0.25 mg CO_2/l as $CaCO_3$) have been found to result in carbon-limited growth of mixed cultures of blue-green algae. Results from these experiments do not seem to support that hypothesis. Abundant growth of blue-green algae occurred at CO_2 concentrations well below 0.25 mg/l. However, results do support the contention that blue-green algae are more tolerant of low CO_2 than are green algae.

Community shifts were expected in the experiments during the 2- to 3-wk incubation periods, but they did not occur. In the nitrate-addition experiment, blue-green algae abundance increased and decreased in response to the various treatments nearly in parallel with greens and diatoms, although blue-greens dominated throughout. A succession from blue-greens to greens was expected when nitrate was added and shown to be limiting growth. Nitrogen fixers *Aphanizomenon* and *Anabaena*[18] might be expected to dominate when nitrate content is low,[8] but when nitrate is made plentiful the advantage should pass to the faster-growing greens and diatoms. This did not occur in these experiments. Blue-green algae responded positively to the addition, continuing to dominate, while nitrate addition generally had less or no effect on greens or diatoms.

Periods longer than 2 to 3 wk may be necessary for succession of the dominant groups to occur. However, other work has supported the hypothesis that blue-green algae can compete more successfully than the other groups when nutrient content is low and temperature high.[16] The concentration of nutrients in the bags and in the lake was consistently low in the July and August experiments when blue-greens dominated and high in the September experiments when diatoms dominated, in spite of attempts to alter the concentrations by nitrate and phosphate addition. To force succession it may be necessary to maintain higher or lower nutrient content than that existing in the lake at the time of the experiment.

As was stated earlier, it is clear that cell washout to control nuisance algal blooms in Parker Horn is probably not feasible because, unless water was exchanged at a

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* In September, when CO_2, concentrations were higher in both the lake and the cultures, green and diatom algae showed a more typical growth curve.

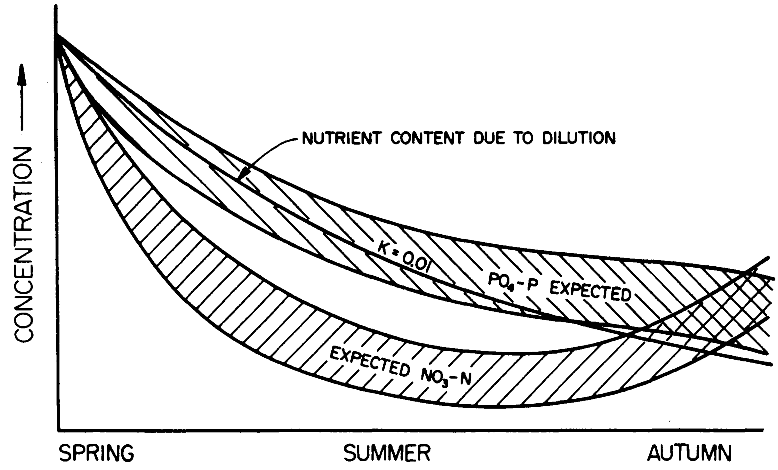

FIGURE 14.—Relative reduction in nutrient concentration at dilution rate of 1 percent/day and expected trend in nutrient concentration in Parker Horn, as projected from Green Lake study results.

rate greater than 50 percent/day, biomass would still maintain a steady state because the maximum growth rate was 2 doublings/day. However, addition of low-nutrient dilution water could still be expected to inhibit nuisance algal blooms because the nutrient concentrations would decrease. Growth rate would slow for this reason and biomass would decline long before simple washout would have an effect on biomass. At continuous addition of Columbia River water at a low rate, the concentration of limiting nutrient (probably nitrogen) will be decreased exponentially to a level at which growth rate will be reduced, neglecting nitrate regeneration from the sediments. As an approach to controlling nuisance algal blooms in Parker Horn, a dilution rate of at least 1 percent/day seems necessary throughout a period from March or April to August. At that rate, about 150 days would be required to reach a river/lake water mixture that would reduce the growth rate by one-half, from 2 to 1 doublings/day, and 200 days to reach a steady state at which growth rate equals dilution rate. Such a dilution rate over a 6-month period is twice the dilution rate and amounts to about three times the total supply of water added to Green Lake in 1967.

The two counteracting forces that would dampen the effect of nutrient reduction and biomass decrease are sediment regeneration of limiting nutrient and strong southwesterly winds that tend to blow the floating masses of blue-green algae toward the inlet where dilution water would enter. Both of these forces would contribute a reverse flow of nutrients, the extent of which is difficult to estimate. However, projecting the results of expected and observed nutrient reduction in Green Lake to Parker Horn provides some estimate of interacting effects on nutrient change. The effect of wind transportation of algae and their incorporated nutrients into Parker Horn is unknown and must be neglected for now. Other important physical characteristics of Parker Horn and Green Lake are similar, for example, destratification occurs periodically, allowing for upwelling of enriched bottom water, and mean depth is the same, allowing about equal opportunity for sediment-water interchange. Figure 14 is an estimate of how nitrate and phosphate might change in Parker Horn with continuous addition of dilution water at 1 percent/day. Nitrate might be expected to remain lower than calculated values during the growing period because greater demand for nitrogen than phosphorus was demonstrated in experiments. Phosphate may tend to remain higher relative to nitrate in Moses Lake than in Green Lake because wind-induced currents are probably stronger in Moses Lake and an inflow to Parker Horn contains high content of phosphate. Because nitrate reduction from adding the low-nitrate dilution water would probably be the principal deterrent to algal growth, the higher phosphate may not be important. However, other work on the lake has shown that phosphate control, even though concentrations are high, may lead to biomass reduction in spite of low nitrate levels which suggest that nitrogen is limiting.[16] Both nutrients would tend to increase in the fall because of reduced growth, greater wind-induced mixing, and the associated nutrient release from decomposing biomass and sediments. Increased nutrient content in the ambient lake water was observed in the September experiments. Even though the extent to which possible interacting factors dampen the dilution effect on nutrient content is unknown, the potential for a low rate of continuous dilution water addition to reduce nuisance algal biomass seems great enough to justify the cost of experimentation.

SUMMARY

1. The addition of low-nutrient Columbia River water to Moses Lake water reduced the subsequent maximum biomass of nuisance blue-green algae attained in the dilution water/lake water mixture in direct proportion to the amount of dilution water added. The effect of dilution water on maximum biomass was not simply a result of serial dilution of an initial biomass because techniques were employed to equalize initial biomass throughout each dilution series. Furthermore, the response was caused by growth because maximum biomass in excess of 100 μg/l chlorophyll occurred in the experimental bags as a result of growth rates as high as 2 doublings/day.

2. In contrast to biomass, the relationship between dilution water addition and maximum growth rate of blue-green algae is nonlinear. Growth rate remained high (2 doublings/day) and relatively constant at lake water concentrations down to about 50 percent, and then dropped rapidly to negative rates at 0 percent lake water.

3. Addition of nitrate along with low-nitrate dilution water to equalize the initial concentrations at 1.0 mg N/l (observed lake water maximum) significantly stimulated the growth rate and increased the maximum biomass of blue-green algae compared to control cultures without added nitrate but had little or no effect on subdominant green or diatom algae. Phosphate addition to equalize initial concentrations to 0.032 mg P/l (mean lake water concentration) had no appreciable effect on any group, although lake biomass was initially low and diatoms were dominant. Although blue-green algae were not dominant and temperature probably favored diatom growth in the phosphate addition experiment, the positive stimulation from nitrate addition, the much lower content of nitrate than phosphate in dilution water ($N:P < 1$), and the low lake water N:P ratio suggest that nitrogen reduction accounted for the inhibiting effect of dilution water on nuisance blue-green algae. Nutrient or dilution water/lake water manipulation had no apparent effect on algal group dominance, although diatom growth was favored by dilution water addition, the opposite effect from that on blue-greens.

4. Comparison of results of dilution water addition to Green Lake in Seattle with experimental and calculated potential effects of dilution water in Parker Horn of Moses Lake allowed estimates of dilution rates that might offer some control of blue-green algal blooms. Addition of low-nutrient river water at about 1 percent/day would be expected to result in a lake water/river water mixture that would reduce maximum growth rate by one-half in about 150 days and reach a steady-state biomass in about 200 days. Loss of biomass by washout rate would not have a significant effect on existing biomass unless water were replaced at a rate greater than

50 percent/day, which is impractical. Actual control would probably fall short of these goals by an unknown degree because of dampening effects from nutrient renewal from sediment-water interchange and wind-driven return of nutrient-laden algal biomass. Because Moses Lake's Parker Horn is physically similar to Green Lake, where one-half the dilution rate and one-third of the total volume of water suggested for Parker Horn were successful in significantly controlling nuisance algal blooms over a 3-yr period, the suggested control procedures should be at least partially successful.

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