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## The Dilution/Flushing Technique in Lake Restoration

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# THE DILUTION/FLUSHING TECHNIQUE IN LAKE RESTORATION

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ABSTRACT

Dilution/flushing has been documented as an effective restoration technique for Moses and Green Lakes in Washington State. The dilution water added in both lakes was low in nitrogen and phosphorus content relative to the lake or normal input water. Consequently, lake nutrient content dropped predictably. Dilution or flushing rates were about ten times normal during the spring-summer periods in Moses Lake and three times normal on an annual basis in Green Lake. Improvement in quality (nutrients, algae, and transparency) was on the order of 50 percent in Moses Lake and even greater in Green Lake.

The facilities for supplying dilution water were largely in place for the cited lakes; thus, costs for water transport were minimal. Available facilities, and therefore costs, for water transport would usually vary greatly, however. Achieving maximum benefit from the technique may be more limited by availability of low nutrient water rather than facilities costs. Quality improvement may occur from physical effects of washout and instability if only high nutrient water is available.

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## INTRODUCTION

The technique of dilution/flushing can achieve lake quality improvement by one of at least two processes. On the one hand, the concentration of limiting nutrient can be reduced, and on the other hand, the water exchange rate in the lake can be increased. Both changes can result in reductions in the biomass of plankton algae because loss rates exceed algal growth rate. The effect of dilution is to primarily reduce the growth rate and of flushing to increase the loss rate, but when increased inputs of low nutrient water occur, both effects can result. Other effects of adding dilution water are also possible, such as increased vertical mixing and a decrease in the concentration of algal excretory products, which can influence the kinds and abundance of algae.

The technique is most appropriate where large quantities of low nutrient water are available for transport to the lake needing restoration. The lower the concentration of limiting nutrient in the dilution water relative to that in the lake, the greater will be the treatment effectiveness. In some instances, improvements may be achieved by adding water of even moderate to high nutrient content; however, results would be less certain than with low nutrient water.

Dilution has produced striking improvements in the quality of Green Lake in Seattle (Oglesby, 1969) and in Moses Lake in eastern Washington (Welch and Patmont, 1979; Welch, 1979; and Welch and Patmont, in press). The technique has been used intentionally in at least one other situation; Lake Bled in Yugoslavia was flushed with water from River Radovna (Sketelj and Rejic, 1966). It has been proposed or considered for four other lakes: three in Washington State and Clear Lake in California (Goldman, 1968). Relatively high natural rates of dilution/flushing maintaining low phytoplankton concentrations is a commonly observed phenomenon (Dillon, 1975; Dickman, 1969; and Welch, 1969).

The theoretical basis for the dilution/flushing technique will be discussed followed by a summary of results from Moses Lake and Green Lake. Finally, some suggestions for application of the technique in general will be given.

## THEORY AND PREDICTIONS

The mechanisms involved in dilution/flushing techniques for the control of algal biomass in lakes are in many ways analogous to those in continuous culture systems. By adding low-nutrient dilution water to a culture system, the inflow concentration of limiting water is reduced, the maximum biomass concentration possible in the reactor vessel is likewise reduced and, at the same time, nutrients and algal biomass are more rapidly washed from the reactor vessel since the water exchange rate is increased. Concentration of limiting nutrient is the critical parameter that determines algal biomass in lakes as well as continuous culture systems. Therefore, the controlling factor can be analogous in the two environments.

There is a significant difference between the effect of "dilution" and "flushing." Flushing emphasizes what goes out of the lake and can be described as loss of biomass without consideration of the concentration of nutrients and their subsequent effect on growth. Dilution, on the other hand, emphasizes what is left in the lake and implies a reduction in nutrient concentrations to limit further growth as well as a washout of biomass.

There is an additional factor that greatly influences the lake concentration and that is sedimentation, which is not considered in continuous cultures. At very high rates of water exchange, the sedimentation loss can decrease and result in higher lake concentrations than at moderate exchange rates where sedimentation loss is greater.

Short Term

The transient reduction in lake concentration of a nutrient by adding dilution water in rather large quantities can be reasonably predicted in the short term by a simple continuity equation:

$$C_t = C_i + (C_o - C_i)e^{i\rho t}$$

where $C_t$ is the concentration of time t, $C_i$ is the concentration in the inflow water, $C_o$ is the initial lake concentration, and $\rho$ is the water exchange or flushing rate. This equation assumes that the lake is well mixed, that no other sources of nutrients exist, and that the limiting nutrient "percent lake water" can be treated as conservative. Since this equation does not include a sedimentation term, it is really only useful in the short-term as a tracer for nutrient behavior and with rather large water exchange rates, that is, several percent per day or more. It allows one to estimate the potential for reducing lake concentrations with a given source of water and the time necessary for that reduction.

Long Term

To predict long-term changes in the concentration of limiting nutrient from adding rather small quantities of low-nutrient dilution water, a term for sedimentation should be included. That requirement is best approximated by Vollenweider's (1969, 1976) equation for steady-state phosphorus content ($\bar{P}$):

$$\bar{P} = \frac{L}{\bar{Z}(\rho + \sigma)}$$

where L is the areal loading rate for P, $\bar{Z}$ is mean depth and ρ and σ are rate coefficients for flushing and sedimentation, respectively.

Uttormark and Hutchins (1978) have evaluated the use of that and similar equations for estimating the long-term effect of dilution water addition. They noted that adding more water with lower nutrient content also increases nutrient loading, while the resulting increased flushing rate can also decrease the loss through sedimentation. The processes could be counteracting in some instances, since "a reduction in the influent concentration tends to reduce in-lake concentration, but a reduction in phosphorus retention tends to increase in-lake concentrations." Figure 1 (from Uttormark and Hutchins, 1978) illustrates this phenomenon for a dilution water concentration that is 40 percent of the normal inflow concentration. An increase in combined flushing rate ($\rho_2$) obtained by adding low-nutrient water could theoretically increase the lake nutrient concentration if the original rate ($\rho_1$) was low enough--0.1 $yr^{-1}$ or so. If the flushing rate is large initially ($\geq$ 1.0 $yr^{-1}$), a reduction in lake concentration will result, but large quantities of water will be necessary.

## CASE STUDIES OF DILUTION/FLUSHING

Two lakes where dilution is in use can be used as guides to apply the technique, and both are in the State of Washington. Moses Lake lies in Eastern Washington, has an area of 2,753 ha and a mean depth of 5.6 m. Dilution water from the Columbia River has been added to it during the spring-summer periods of 1977-80 and that practice will continue. Green Lake has an area of 104 ha and a mean depth of 3.8 m. It has received dilution water from the city domestic supply beginning in 1965 and continuing to the present. The suitability of dilution water for the restoration of these lakes is apparent from the large differences between lake and inflow nutrient concentrations as a result of adding dilution water. The ratios of lake:inflow concentrations range from 5 to 10.

### Moses Lake

Dilution water from the Columbia River has been added to Parker Horn in Moses Lake through the U.S. Bureau of Reclamation's East Low Canal and Rocky Coulee Wasteway (Figure 2). Plans by Brown and Caldwell Engineers call for the addition of dilution water to Pelican Horn as well as to the upper main arm (see inset Figure 2) in two remaining project phases. Although a variety of input patterns was desired for experimental purposes during the spring-summer periods, those desires have been only partly attained. Three periods of dilution were provided in 1977 and 1979, but only one in 1978. The total number of days of dilution ranged from 60 to 138, and the average exchange rates during April-September for Parker Horn, where the water enters (Figure 2), ranged from 0.07 to 0.13 $day^{-1}$. The normal summer exchange for that arm is 0.01 $day^{-1}$. For the whole lake, the Parker Horn inflow (excluding groundwater and flow from Rocky Ford Creek into the main arm) represented an exchange rate of only 0.06 to 1.0 percent per day.

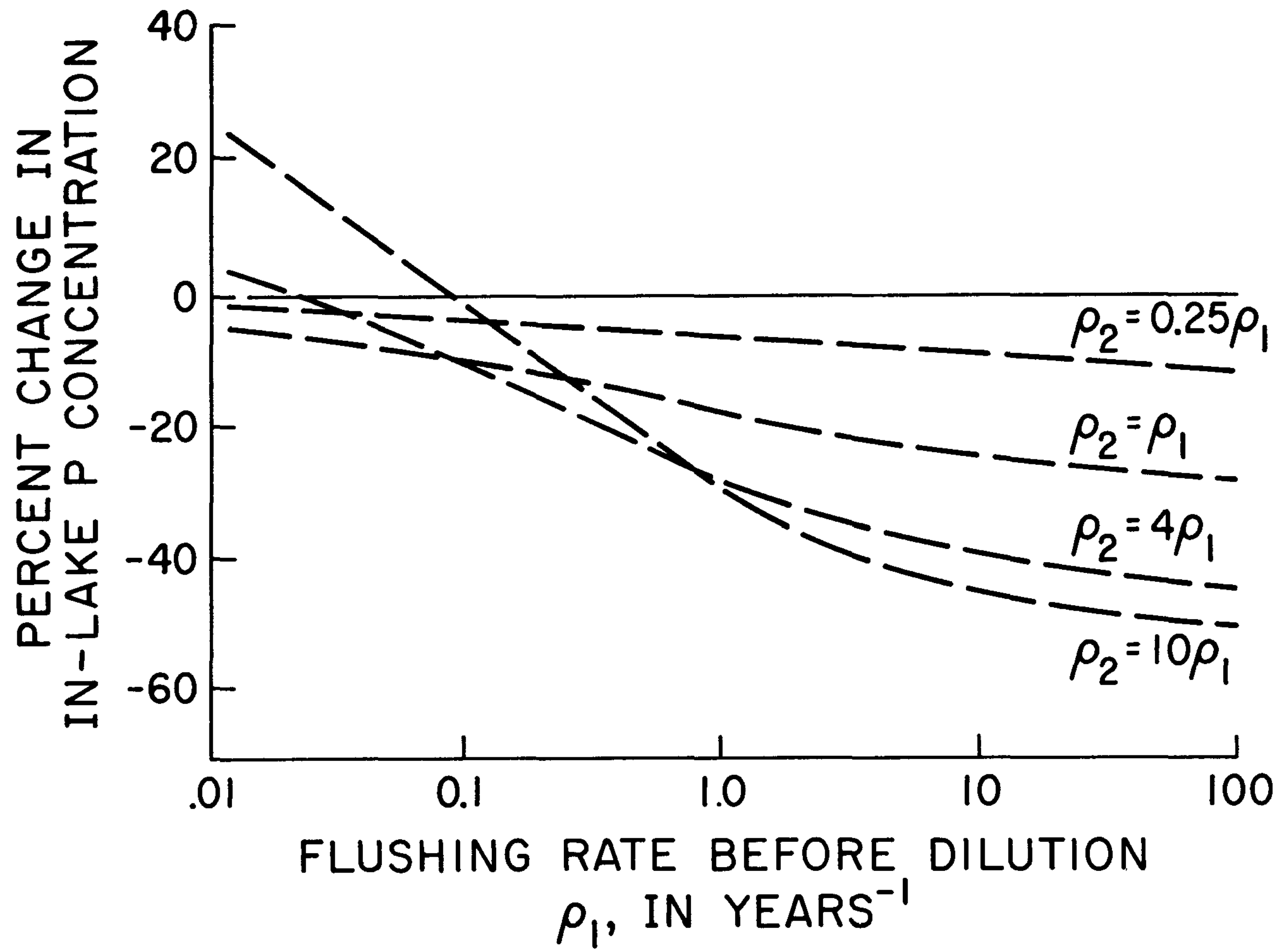


Figure 1. Theoretical effect of dilution when P concentration in dilution water is 40% of normal inflow concentration. Combined flushing rate is indicated by $\rho_2$ (after Uttormark and Hutchins, 1978).

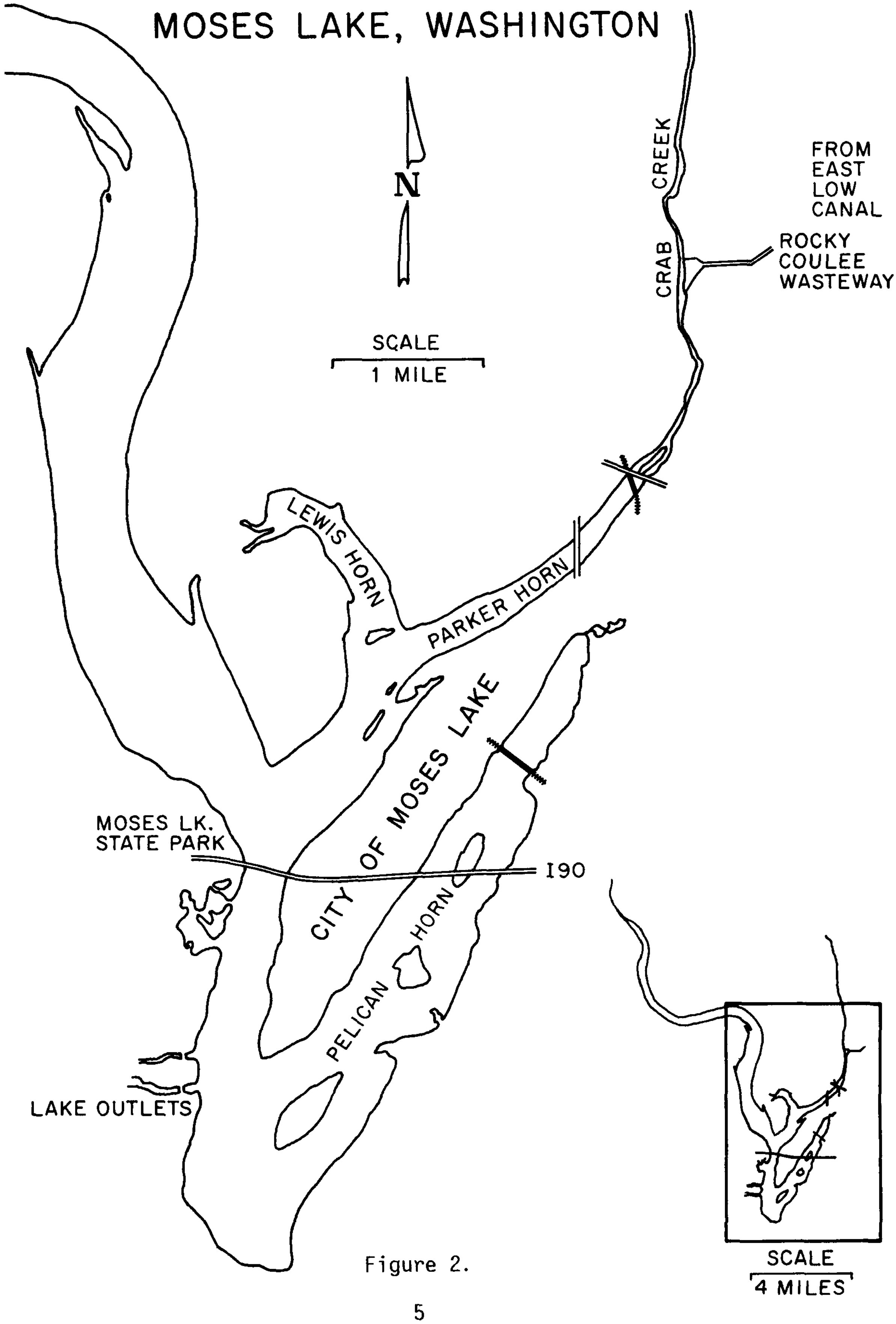
MOSES LAKE, WASHINGTON
N
SCALE
1 MILE
CRAB CREEK
FROM EAST LOW CANAL
ROCKY COULEE WASTEWAY
LEWIS HORN
PARKER HORN
CITY OF MOSES LAKE
MOSES LK. STATE PARK
I90
PELICAN HORN
LAKE OUTLETS
SCALE
4 MILES

Figure 2.

The suitability of Columbia River water for dilution can be seen in Table 1. Because the P and N concentrations in Crab Creek are so high, relatively large quantities of Columbia River water (25 μg $l^{-1}$) are needed to significantly lower the composite inflow concentration which is necessary to lower the lake concentration. This results in larger exchange rates than would otherwise be necessary without the Crab Creek inflow. Unfortunately, however, the diversion of Crab Creek is economically infeasible.

TABLE 1. INFLOW CONCENTRATIONS TO PARKER HORN DURING MAY-SEPTEMBER, 1977 AND 1978 (μg $l^{-1}$)

| | Total P | Total N | $PO_4$-P | $NO_3$-N |
|---|---|---|---|---|
| Inflow Without Dilution | 148 | 1,331 | 90 | 1,096 |
| East Low Canal Dilution Water | 25 | 308 | 8 | 19 |

As a short term phenomenon, the addition of dilution water to Moses Lake, Washington predictably and rapidly replaced lake water as judged by specific conductance measurements (Figure 3). Values for percent lake water were calculated assuming that 100 percent was represented by the conductance of Crab Creek and 0 percent by the conductance of Columbia River water. Percent lake water reached values of 20 in Parker Horn (where the water enters), much less than in other parts of the lake. This was expected because the average dilution rate during the April to June dilution period described here was 15% $day^{-1}$ for Parker Horn, which is a small (8 percent) portion of the lake volume. The dilution rate decreased, of course, as more lake volume was included. As the dilution water input declined in June, the percent lake water quickly rose to between 50 and 60 percent. Part of that increase was no doubt caused by wind pushing lake water into Parker Horn.

Because Moses Lake is rather dissected and most of the lake's volume (63%) appeared out of a direct path of the inflow, dilution water was expected to have little effect other than in Parker Horn and the lower lake, which together represent 29 percent of lake volume. However, the lake water residual decreased similarly in the whole lake as well as the lower lake. Lake water residuals reached levels between 50 and 60 percent in late May and early June and then began the more gradual return to normal as dilution input declined. In fact, there was little difference between actual and predicted removal of lake water in the whole and lower lake (Figure 3).

Improvement of lake quality in 1977-79, compared to 1969-70, was near or in excess of 50 percent for P and N as well as chlorophyll *a* for not only Parker Horn, but also most of the lake (Table 2). Visibility was also substantially improved. Of course, improvement was better in Parker Horn where the fraction of dilution water was greater, but most of the lake responded almost as well. As noted earlier, the dilution water was distributed throughout the lake, largely due to the wind and probably the large

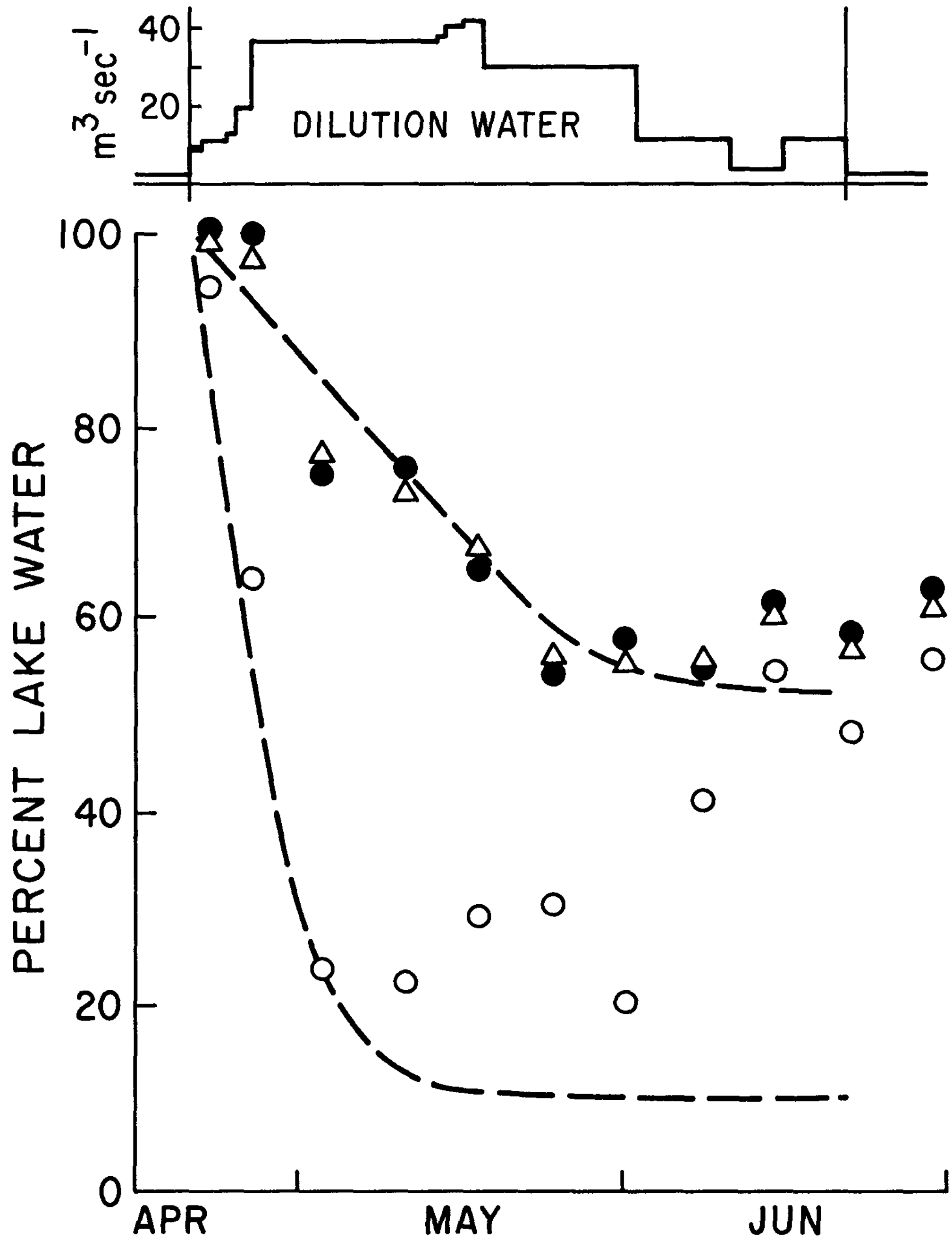


Figure 3. Residual percent lake water in Parker Horn (Station 7, open circles), the lower lake (Station 9, closed circles), and the whole lake (triangles) compared to that predicted (based on an average inflow) for the whole lake and Parker Horn in response to dilution water addition in 1978. Parker Horn, the lower lake, and the whole lake represent 8, 21, and 100 percent of the lake volume. Dotted lines represent predicted values.

TABLE 2. AVERAGE APRIL-SEPTEMBER DILUTION RATES AND MAY-SEPTEMBER CHLOROPHYLL a, TOTAL PHOSPHORUS, AND SECCHI VISIBILITY FOR TWO PORTIONS OF MOSES LAKE DURING THE SPRING-SUMMER PERIODS OF 1977-79 COMPARED TO THE CONTROL YEARS 1969-70. PERCENT IMPROVEMENT IN (0-100%)

| Years | Dilution Rate, % $Day^{-1}$ | Total P, $\mu g\ l^{-1}$ | Chl a, $\mu g\ l^{-1}$ | Secchi, m |
|---|---|---|---|---|
| | | PARKER HORN | | |
| | | 8 Percent of Lake Volume | | |
| 1969-70 | No Dilution | 158 | 71 | 0.6 |
| 1977-79 | 10.0 | 71 (54%) | 26 (63%) | 1.3 (54%) |
| | | 58 Percent of Lake Volume | | |
| 1969-70 | No Dilution | 158 | 71 | 0.6 |
| 1977-79 | 10.0 | 71 (54%) | 26 (63%) | 1.3 (54%) |

volumes introduced (Welch and Patmont, in press). Part of the improvement in areas away from Parker Horn is considered to be due to the natural depletion of usable fractions of nutrients with time.

Presentation of means for the May-September period obscures the high quality conditions, such as visibility reaching a maximum of 3 m in June in most of the lake as well as poor quality such as maximum chlorophyll a reaching peaks near 50 $\mu g\ l^{-1}$ in late July-August after water input had been curtailed for 2-4 weeks. Unless water was continually added, blooms would return as the fraction of dilution water left in the lake declined. This "boom and bust" situation promoted by large inputs followed by no input at all has prompted the proposing of continual input at low rates throughout the summer, employing similar total amounts of water. The large quantities added over a short period of time, that exchanged water in Parker Horn at the rate of about 20 percent per day and in most of the lake at 2-3 percent per day, are probably unnecessary considering the general response of the phytoplankton, particularly the blue-greens, to dilution water addition.

The exact cause(s) for the improvement of Moses Lake quality from the addition of Columbia River water is not entirely clear. Several possibilities exist, and these have been discussed elsewhere (Welch and Patmont, in press; and Welch, in press). Of the nutrients and particulate fractions that could account for the decreased biomass, total N appears most important. Soluble N, rather than P, has always been the nutrient that most frequently limits growth rate in Moses Lake. Although soluble N was not appreciably reduced by dilution, total N was and appeared to set the limit on average chlorophyll a and probably biomass as well. One lake N was decreased below about 600 $\mu g\ l^{-1}$, chlorophyll a likewise decreased (Welch, in press).

Other factors contributed to the biomass decrease as well. The physical loss of algal cells by washout no doubt affected biomass in Parker Horn where high rates of exchange (20-25% $day^{-1}$) existed. However, instability of the water column, as indicated by decreased vertical temperature gradient, probably contributed to the crash and/or prevention of blue-green blooms there as well as elsewhere in the lake (Welch, in press). Because the flotation capability of blue-greens provides them with advantages over greens and diatoms when mixing is poor, decreased stability may hinder the dominance of blue-greens.

There are yet other factors resulting from dilution that may have contributed to reduced biomass of algae and reduce contribution by blue-greens. Some of those considered are: iron limitation of the N fixation process in blue-greens, a reduction in free $CO_2$ favoring greens and diatoms, and the dilution of excretory productions of blue-greens decreasing their inhibition of diatoms and greens (Patmont, 1980; Welch and Patmont, in press; and Welch, in press).

Although the specific cause(s) for the improvement is unclear, attaining a lake water residual of 50 percent or less provided desirable results in Moses Lake. Dilution of lake water to fractions between 40 and 65% was attained during mid-summer in various areas of Moses Lake during 1978 (Figure 2), along with mean chlorophyll a values of about 14 μg $l^{-1}$, when the exchange rate in Parker Horn was 0.07 $day^{-1}$. Therefore, a conservative estimate of an adequate dilution rate for Parker Horn would be around 0.05 $day^{-1}$ or a flow of dilution water of about 6 $m^3$ $sec^{-1}$. That would represent a 3:1 dilution of Crab Creek, which flows at about 1.52 $m^3$ $day^{-1}$ in summer. Such a flow would represent about 87 x $10^6$ $m^3$ of dilution water for the entire summer. In 1978, about 112 x $10^6$ $m^3$ of dilution water entered the lake, but over a two-month period. Thus, slightly less total water volume spread evenly over the whole summer should provide for ≦ 50 percent lake water remaining by mid-summer throughout Parker Horn and the lower lake.

Although not specifically tested, it seems that a continuous low-rate input would be preferable to a high rate input for a relatively short period, followed by complete cessation of input. This "low-inflow" procedure will not reduce the lake water fraction as quickly as the large spring output "boom and bust" approach, but it may, nonetheless, more effectively restrict the large blooms of blue-greens during mid and late summer.

Green Lake

The dilution of Green Lake beginning in 1962 represents another case for the benefits of this technique of restoring lakes. Sylvester and Anderson (1964) proposed the manipulations, and Oglesby (1969) reported the water quality changes. The technique applied to Green Lake was one of long-term dilution at a relatively low rate. The average combined water exchange rate was increased from an estimated 0.83 $yr^{-1}$ to 2.3 $yr^{-1}$ as a result of adding low-nutrient water from the Seattle domestic supply. The addition of dilution water over 13 years of data during 1965-1978 produced a flushing rate for the dilution water only that ranged from 0.88 $yr^{-1}$ to 2.4 $yr^{-1}$.

A striking improvement in the chlorophyll a, P, and Secchi visibility depth resulted from the dilution. Only one pre-dilution measurement existed and post-dilution three years of monitoring was not begun until 1965 in spite of dilution starting in 1962. Based on these limited data, summer water clarity increased nearly four-fold and chlorophyll a decreased over 90%. Total P declined to about 20 µg $l^{-1}$ from a summer mean of 65 µg $l^{-1}$. A marked decrease in the fraction of blue-green algae was seen, particularly in the spring and early summer.

The percent decrease in P concentration is about what would be expected, using Vollenweider's equation for steady-state P and $\sigma = \sqrt{\rho}$ (Uttormark and Hutchins, 1978). The expected P concentration in Green Lake prior to dilution and based on external loading should have been about 80 µg $l^{-1}$, but in fact, the P content was about 65 µg $l^{-1}$. Following dilution, the steady-state concentration should have been about 35 µg $l^{-1}$, but it actually declined much lower, to about 20 µg $l^{-1}$ by 1967. The concentration decrease (45 µg $l^{-1}$) is the same, however, for actual and expected. The reductions in P and chlorophyll a in Green Lake occurred over several years, and were closely related. This is in contrast to the rapid, more short-term response in Moses Lake resulting in marked improvements in blue-green algae and chlorophyll a content that begin to wane when dilution is curtailed.

The Moses Lake and Green Lake cases illustrate the difference between short-term and long-term dilution schemes. Both have attained greater than expected results in lake quality.

## GENERAL APPLICATION

Dilution is frequently used synonomously with flushing as a restoration technique. In fact, the effect of dilution includes both a reduction in the concentration of nutrients and a washout of algal cells, while flushing may only cause the latter. For dilution, or a reduction in nutrient concentration to occur, the inflow water must be lower in concentration than that of the lake. Effectiveness will, of course, increase as the difference between inflow and lake concentrations becomes greater. For washout of algal cells to be an effective control on algal blooms, the water exchange rate must be a sizable fraction of or preferably approach the algal growth rate.

The ideal dilution scheme would be one to attain a long-term reduction of the limiting nutrient content through low-rate input of low-nutrient water. Where there is an existing high nutrient input, it should be diverted if possible in order for the low dilution rate to be most effective. This scheme would provide for reduction in biomass primarily through nutrient limitation. If diversion is not possible, one is faced with high-rate inputs over the short-term in order to sufficiently reduce the inflow nutrient concentration. If only moderate to high-nutrient water is available, a short-term dilution may work well because the loss rate of cells is sufficiently great relative to the growth rate and washout becomes significant. Also, the blue-green blooms may be discouraged by decreased water column stability.

Costs will be highly variable depending upon the presence of facilities to deliver the water and the availability of water. If the lake is in an urban setting and domestic water is available, then improvement may be possible for less than $100,000 for construction and first year maintenance and operation. If near a free-flowing river and diversion of a portion of the flow through the lake during the summer is feasible, then the costs involve that of facilities, pumps and pipes, operations, and prevention of side effects (entraining fish).

The advantages for using dilution water are primarily: (1) relatively low cost if water is available; (2) immediate and proven effectiveness; and (3) may be successful even if only moderate-to-high-nutrient water is available through physical limitations to large algal concentrations. The principal limitation for use is, of course, that the availability of low nutrient dilution water, the effect of which has been demonstrated, is probably poor in most areas.

## SUMMARY

Two examples of the use of dilution water for lake restoration are in the State of Washington--Green Lake in Seattle and Moses Lake in the eastern part of the state. Green Lake received nutrients from urban runoff and subsurface inflow. Domestic water, low in P, was added by the City of Seattle beginning in 1962. The amount added raised the water exchange rate to an annual average of 2.4 $yr^{-1}$ from 0.83 $yr^{-1}$. After five years of treatment, the summer Secchi visibility had changed from 1 to 4 m, chlorophyll *a* from about 45 to 3 $\mu g\ l^{-1}$, and total P from about 54 to 20 $\mu g\ l^{-1}$. The treatment has continued to the present.

Moses Lake has received low-nutrient dilution water from the Columbia River via an irrigation canal during the spring-summer periods of 1977-79. The average total P concentration for the whole lake during spring-summer had been normally about 150 $\mu g\ l^{-1}$ and chlorophyll *a* 45 $\mu g\ l^{-1}$ before dilution. Although the dilution water addition quickly reduced the P to about 50 $\mu g\ l^{-1}$, a much greater improvement was seen in chlorophyll *a* to less than 10 $\mu g\ l^{-1}$. Average post-dilution spring-summer values for P and chlorophyll *a* were 86 and 21 $\mu g\ l^{-1}$. Secchi visibility improved from 0.9 to 1.5 m. Dilution addition reduced the biomass of algae as well as the blue-green fraction in Moses Lake by presumably a combination of reducing total N, decreasing the water column stability, limitation by iron, and reducing the free $CO_2$ content, which are discussed elsewhere (Patmont, 1980; Welch and Patmont, in press; Welch, in press).

Dilution/flushing can be considered as an effective technique for restoring lakes, especially if a supply of low nutrient water exists. The costs involved are the facilities to deliver the water and maintenance and operation. In the case of the two lakes mentioned here, the facilities were largely in existence. While the irrigation water had a cost, the Bureau of Reclamation was able to deliver the water to users via the lake. For Green Lake, a domestic supply was used, and with the facilities, the dilution water has been added since 1962 with little operation cost. Thus, the costs for this technique may not limit its use as much as the availability of low-nutrient water. Even if a supply of such water is not readily available, high nutrient water may provide improvements.

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