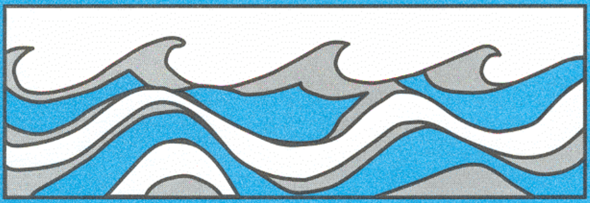
University of Washington
Department of Civil and Environmental Engineering

EVAULATION OF MOSES LAKE DILUTION

E.B. Welch
K.L. Carlson
R.E. Nece
M.V. Brenner



Water Resources Series
Technical Report No. 77
March 1982

Seattle, Washington
98195

Department of Civil Engineering
University of Washington
Seattle, Washington 98195

EVAULATION OF MOSES LAKE DILUTION

E.B. Welch
K.L. Carlson
R.E. Nece
M.V. Brenner

Water Resources Series
Technical Report No. 77

March 1982

EVALUATION OF MOSES LAKE DILUTION

E.B. Welch, K.L. Carlson ,R.E. Nece and M.V. Brenner

Environmental Engineering and Science Program
Department of Civil Engineering
University of Washington
Seattle, WA 98195

Water Resources Series
Technical Report No. 77

Prepared for

Moses Lake Irrigation and Rehabilitation District
Moses Lake, Washington

March, 1982

EVALUATION OF MOSES LAKE DILUTION

E.B. Welch, K.L. Carlson ,R.E. Nece and M.V. Brenner

Environmental Engineering and Science Program
Department of Civil Engineering
University of Washington
Seattle, WA 98195

Water Resources Series
Technical Report No. 77

Prepared for

Moses Lake Irrigation and Rehabilitation District
Moses Lake, Washington

March, 1982

NOTICE

Effective July 1982, and No. 77, the Water Resources Report series supersedes the Charles W. Harris Hydraulics Laboratory Technical Report series. The last publication in the Harris Hydraulics Laboratory series was Technical Report Number 76, June 1982. Requests for reports in either series should be addressed to:

Environmental Engineering and Science Program
Department of Civil Engineering, FX-10
University of Washington
Seattle, WA 98195

TABLE OF CONTENTS

ACKNOWLEDGMENTS

Warm appreciation is extended to the students who contributed to the understanding of the dilution process in Moses Lake through theses and the hard-earned collection (logistical problems are significant) of data presented here, namely in chronological order: Ronald M. Bush, James A. Buckley, Myron B. Saikewicz, James R. Reed, Clayton R. Patmont, Barbara M. Carey, and Mark D. Tomasek. R.J. Buchanan helped develop the predilution data base and valuable advice has been given by B.W. Mar and D.E. Spyridakis. Funding has been provided through research grants from the U.S. Environmenal Protection Agency (1968-1969 and 1977-1980), the Office of Water Resources Technology (1969-1977 and 1975-1976) and the National Science Foundation (1980-1982) as well as contracts with the Moses Lake Irrigation and Rehabilitation District (1972-1973 and this one) and Brown and Caldwell Engineers (1977-1978). Without the cooperation of J.V. Cole and F. Jensen of the U.S. Bureau of Reclamation, the institutional planning by S.A. Edmondson and Brown and Caldwell Engineers, the basic idea by R.O. Sylvester, and ultimately the 20-year determination of C.J. Connelly of the Moses Lake Irrigation and Rehabilitation District, Moses Lake would still be the most hypereutrophic lake in the State of Washington.

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

EVALUATION OF MOSES LAKE DILUTION

E.B. Welch, K.L. Carlson, R. E. Nece and M.V. Brenner

INTRODUCTION

Dilution of Moses Lake to control eutrophication was begun in the spring of 1977 and periodic releases of low nutrient Columbia River water have continued since that time. Dilution water inputs resulted in about a ten-fold increase in water movement through Parker Horn and the lower lake during the spring-summer periods. Lake quality in terms of the amount of algae, especially the nuisance-forming blue green species, the quantity of macronutrients, nitrogen and phosphorus, as well as lake clarity has improved on the order of 40-60 percent (Welch and Patmont, 1980; Welch and Tomasek, 1980). Although there was some question about possible detrimental effects on fish production by "washing out" fish food (zooplankton) such effects did not occur and dilution may have benefited fish consumption of such food items by increasing water clarity (Carey, 1981).

These improvements have resulted from dilution water inputs that entered one arm of the lake (Parker Horn) through Crab Creek via existing facilities (Rockey Coulee Wasteway, Fig. 1). Phase II of the restoration project is scheduled to begin in 1982 when the dilution water - lake water mixture in Parker Horn will be pumped into Pelican Horn, which has been previously untreated. Phase III of the project will involve the construction of facilities to deliver dilution water to the uplake end of the main arm. The realization that dilution water entering Parker Horn through Crab Creek reaches well into the main arm (Patmont, 1980) has resulted in questioning the cost-effectiveness of Phase III and lead to this evaluation. The objectives in 1981 were to: 1) compare lake quality in the upper main arm with that of the lower main arm and Parker Horn, 2) estimate the effectiveness of dilution

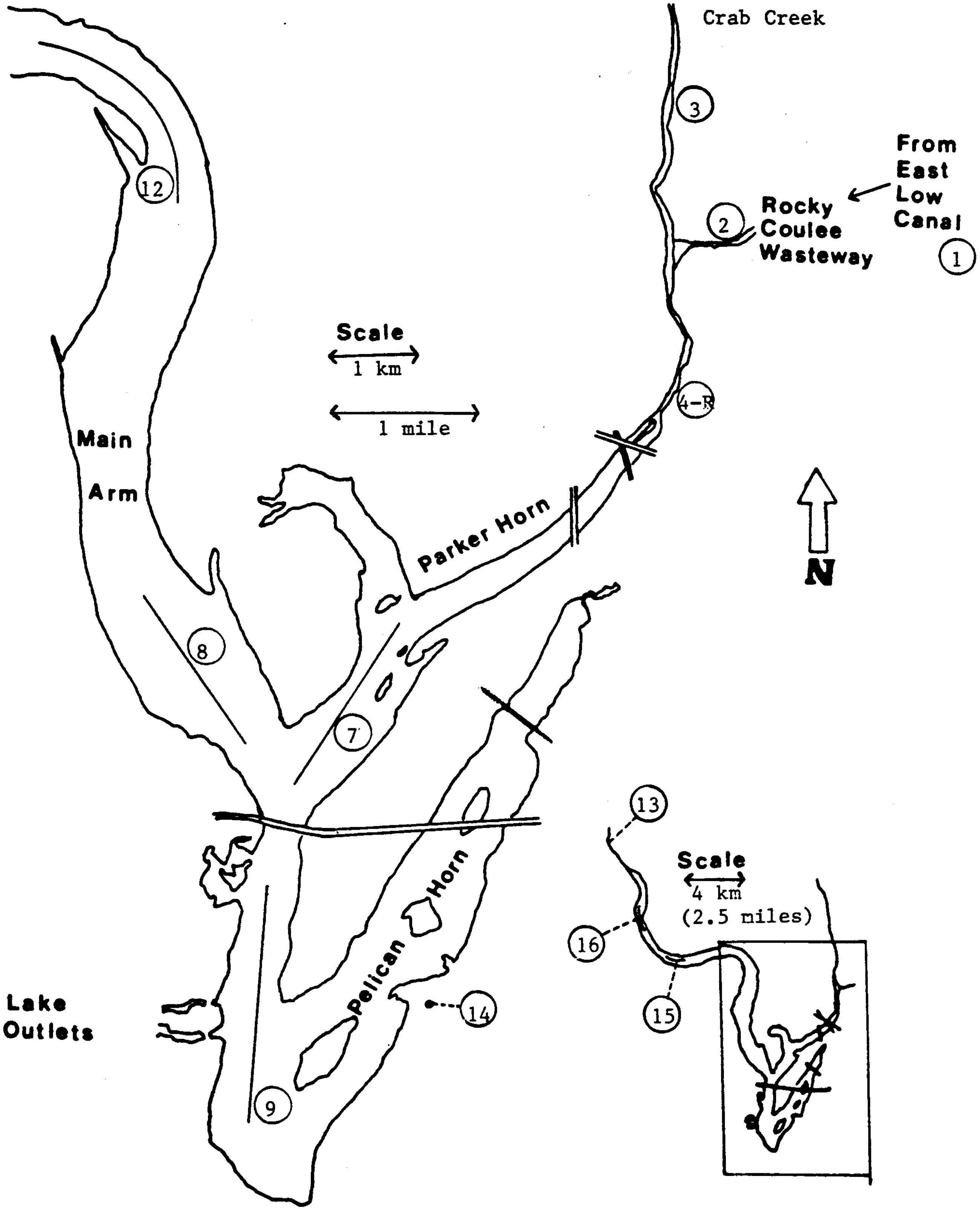


Figure 1. Location of sampling stations (transects at 0.5 m depth) in Moses Lake.

water movement from Parker Horn into the main arm, and 3) estimate potential effects on algal abundance in the main arm from different flows of dilution water through Parker Horn.

A comparison of lake quality before dilution (1969-70) and with lake quality at post dilution years 1977-81, in Parker Horn and the lower lake was done using mean spring summer values. Quality of the upper main arm was compared with that in the other parts of the lake in 1981-82 also utilizing mean spring-summer values for constitutents. Water movement was evaluated by determining what concentrations of dilution water could be obtained in the main arm of Moses Lake under essentially steady state concentrations of the dilution water in lower Parker Horn. The approximate predictive method used was based on field measurements conducted during 1981, using specific conductance as the "tracer." Some approximate calculations were performed to see if the crude model of "dispersive" transport could be quantitatively explained, at least in part, on relatively simple physical bases. A predictive method for algal mass was developed from a simple one-factor regression equation using nitrogen as the limiting nutrient. From estimates of water movement and algal biomass predictions from limiting nutrient concentration, the degree of lake improvement from dilution water inputs through Crab Creek and the upper main arm could be compared.

SAMPLING PROCEDURES AND ANALYSIS

Samples were collected from February through October 1981 at seven lake stations and five stream (inflow) stations (Figure 1 and Table 1). In-lake samples were collected from transects by pumping water from a depth of 0.4 m while traveling through the approximate mid-line of each sub basin (Figure 1). Discrete samples were collected from the midpoint of each transect at the surface, 2m, and 6 m as well as 1 m above the bottom where sufficient depth existed.

Temperature and pH profiles were determined at the midpoints of all transects at the time of collection using a YSI temperature meter and an Orion Research Specific Ion meter, respectively. Secchi disk depth was measured at the same point. Dissolved oxygen concentrations were determined using the azide modification of the Winkler titration for bottom-water samples (APHA, 1975). Specific conductance was determined with a resistance meter and alkalinity by potentiometric titration in the laboratory (APHA, 1975).

TABLE 1. Location and Type of Sample Collection from February through October 1981.

Station No.	Location	Sample Type	Frequency
1	East Low Canal	surface	biweekly[a]
2	Rocky Coulee Wasteway	surface	biweekly
3	Crab Creek above RCW	surface	biweekly
4	Crab Creek below RCW	surface	biweekly
7	M.L. Lower Parker Horn	D + T[b]	biweekly
8	M.L. lower Main Lake	D + T	biweekly
9	M.L. lower lake	D + T	biweekly
11	M.L. Pelican Horn-mid	T	monthly
12	M.L. upper main lake	D + T	biweekly
13	Rocky Ford Creek	surface	biweekly
14	Spring off Pelican Horn	groundwater	three times
15	M.L. upper main arm	D + T	biweekly
16	M.L. upper main arm	D + T	biweekly

[a] During dilution periods only.

[b] D -- discrete; T -- transect (see text).

Samples for chlorophyll a and soluble nutrients were filtered (0.45 m pore size) soon after collection, and along with those for total nutrient determinations, iced for return to the laboratory in Seattle where they were frozen for subsequent analysis. Soluble reactive phosphorus (SRP) as well as total P following persulfate digestion were determined by the acid molybdate heteropoly blue method (Strickland and Parsons, 1972). Nitrate was determined by the cadmium column reduction method and total N by uv oxidation and measurement of nitrate, both on an autoanalyzer (Strickland and Parsons, 1972). Chl *a* was determined on 90% acetone extracts with a fluorometer (Strickland and Parsons, 1972).

Nitrogen fixation rates were determined *in situ* on September 18, 1981 by the acetyline reduction technique (Stewart, et al. 1971). The experiment was performed at station 7 during a rather dense bloom of *Aphanizomenon*, a nitrogen fixer, and was repeated three times during the day. Water samples were collected in 125 ml glass stoppered bottles from depths of 0.5 and 2 m and incubated for three hours at those same depths.

Phytoplankton counts were performed on transect samples preserved with acid-lugols and stored in the dark (Vollenweider, 1969). Samples were concentrated 25 X by centrifugation and subsequent settling. Populations were estimated by counts using a Palmer-Maloney cell with an Olympus compound microscope at 200 X. Filaments were counted using the method of Olson (1972) and results were expressed as $mm^3\ l^{-1}$. Either 2.6 mm^3 of concentrated sample or 200 cells were counted, whichever occurred first. Cell sizes were determined by measurement with a calibrated occular micrometer.

RESULTS

Dilution Water Input

Low nutrient Columbia River dilution water was diverted into Moses Lake via East Low Canal for a 49-day period in 1981 extending from March 27, to May

15. Timing, discharge, and resultant water exchange rates for Parker Horn and Moses Lake as a whole are given in Table 2.

The quantity of dilution water added and the length of the diution period were both greater in 1981 than in 1980 but less than that for other dilution years (1977, 78, 79). For 1981, 0.46 lake volumes of dilution water were delivered, compared with 1.2 lakes volumes in 1977, 0.74 in 1978, 1.66 in 1979, and 0.23 in 1980. Dilution water added in 1980-81 averaged 71% less than in 1977-79.

In order to evaluate the overall effect of dilution during the critical spring-summer period of algal succession and growth in Moses Lake, average ratios of water exchange (day^{-1}), including dilution water plus existing Crab Creek flow, were calculated for April through September. During this period the exchange rate for Parker Horn is normally about 0.01 day^{-1}. Thus, the rate in Parker Horn in 1981 was, as it has been in most other dilution years, about ten times greater than normal.

The quality of East Low Canal water for dilution is shown in Table 3. Average inflow (Crab Creek) concentrations are characteristically high in phosphorus and nitrogen, whereas East Low Canal water, while somewhat lower in phosphorus, is substantially lower in total and soluble nitrogen. As indicated in Table 2, quantities of East Low Canal water released during the 1981 dilution period, as in other dilution years, were generally high relative to simultaneous Crab Creek flow. This resulted in significant reductions in nutrient concentrations, particularly nitrogen, in Crab Creek inflow to Parker Horn during dilution along with greater exchange rates than would otherwise occur.

Table 2. Dilution water inflow rates to Parker Horn, Moses Lake via Crab Creek showing hypothetical water exchange rates for Parker Horn (8 percent volume) and the whole lake (100 percent volume) during April (or start of dilution) through September of the three years.

Year	Dilution Periods	Mean Flows in M^3 Sec^{-1} Dil. Water	Crab Creek	April-September Exchange Rate in $Days^{-1}$ Parker Horn	Whole Lake
1977	3/20-5/07	33.6	0.4		
	5/22-6/04	10.5	1.3	0.10	0.008
	8/14-9/18	17.3	2.5		
	(96 Days)				
1978	4/20-6/18	21.7	1.7	0.07	0.006
	(60 Days)				
1979	4/03-6/04	25.1			
	7/11-8/28	16.3	1.5	0.13	0.010
	9/20-10/18	23.2			
	(138 Days)				
1980	2/18-3/01	6.1	19.4		
	5/13-6/10	11.4	1.7	0.09	0.007
	(41 Days)				
1981	3/27-4/15	8.5	0.4		
	4/16-4/21	19.1	0.3	0.12	0.010
	4/22-4/30	26.6	0.4		
	5/01-5/27	21.1	0.6		
	(49 Days)				

Table 3. Nutrient concentrations (µg l^{-1}) in inflow water to Parker Horn (Station 7) during April to September, 1981.

	Total P	SRP	Total N	NO_3-N
East Low Canal (Dilution) Water	19	3	106	5
Crab Creek (without dilution)	60	7	1443	1160
Inflow During Dilution (March 27 to May 15, 1981)	54	4	215	76

Lake Quality - 1981 versus Previous Years

Data obtained during 1981 indicated that improvements in lake water quality have continued to occur compared to pre-dilution levels of 1969-70. Table 4 presents data from Station 7 (Parker Horn) and Station 9 (lower lake) and compares 1981 with past dilution (1977-80) and pre-dilution (1969-70) years. Results of constituent concentrations from those stations have been shown to be representative of most of the lake (Welch and Patmont, 1980). May-September mean values at both stations for phosphorus, nitrogen, chlorophyll a, and Secchi (depth) visibility showed substantial improvement in 1981 over those during the 1969-70 pre-dilution period, but in general varied only slightly from other dilution years. The exception was 1980, following the ashfall from the Mount St. Helen's eruption.

Table 4. May-September mean transect values for phosphorus, nitrogen, chlorophyll a ($\mu g\ l^{-1}$) and Secchi visibility (m) at two stations in Moses Lake.

	Total P	SRP	Total N	NO_3+NO_2-N	Chl a	Secchi
Station 7						
1969-70[a]	158	28	(1,500)[b]	71	71	0.6
1977	81	30	540	69	35	1.3
1978	61	13	440	48	16	1.2
1979	67	9	532	52	29	1.5
1980	79	9	772	285	19	1.0
1981	70	5	537	71	25	1.2
Station 9						
1969-70[a]	156	48	(1,400)[b]	23	42	1.0
1977	92	56	620	48	27	1.8
1978	86	24	520	19	15	1.7
1979	83	27	600	19	23	1.7
1980	90	23	602	148	12	1.2
1981	79	21	541	34	21	1.3

[a] Predilution years.

[b] Estimated from sum of Kjeldahl, nitrate, nitrite and ammonia data (U.S. Bureau of Reclamation records).

Total phosphorus and soluble reactive phosphorus (SRP) concentrations during 1981 were, respectively, 55 percent and 82 percent lower than corresponding 1969-70 values at Station 7, and 50 percent and 56 percent lower at Station 9. Mean 1981 values for SRP at the respective stations were the lowest yet recorded for all years investigated. Total P at Station 9 in 1981 was the lowest recorded.

The values for soluble nitrogen (NO_3+NO_2) are noteworthy. Mean values obtained during 1981 for NO_3+NO_2-N were equal to and 48% greater at Stations 7 and 9, respectively, than corresponding 1969-70 predilution values.

Values in other dilution years also were greater than predilution levels. To some extent variations in NO_3+NO_2-N concentrations in Moses Lake between dilution years may be related to quantity and timing of dilution inflow periods and groundwater seepage relative to the whole lake water budget (Patmont, 1980). The excessively high values observed in 1980 may be further related to ashfall, (Welch and Tomasek, 1980). Ash in the water column may have acted to inhibit light penetration and hence, limit algal growth and uptake of soluble nitrogen. Reduced levels of NO_3+NO_2 in the lake are usually due to algal uptake and the values observed are simply a residual from the very high inflow concentration.

Mean chlorophyll a and Secchi visibility values during 1981 showed improvements of 65% and 50%, respectively, at Station 7 and 50% and 30%, respectively, at Station 9 over 1969-70 predilution levels. Despite an apparent increase from chlorophyll a values observed in 1980 (again, the likely cause being light limitation from volcanic ash), the 1981 values demonstrate a substantial reduction in algal biomass from pre-dilution levels and improvements over values from dilution years 1977 and 1979.

The blue-green component of the algal biomass, which often forms dense surface scums during summer months, constitutes the greatest concern toward which improvements in Moses Lake quality have historically been directed. These include primarily the genera Aphanizomenon, Microcystis and Anabaena. Mean values for percent blue-green algae by cell volume for the period June to August at both Stations 7 and 9 are given in Table 5 for several of the years previously investigated. While data are not available at Station 9 for the pre-dilution period (1970), inspection of data from Station 7 indicates a significant reduction in the blue-green component during 1981, which was similar to that observed in other dilution years.

The cause(s) for the observed effect of dilution water on decreasing both algal biomass and the blue-green fraction is not completely understood. It has been hypothesized that, along with the reduction in nutrients (especially N), dilution water acts to: (1) promote mixing, resulting in decreased water column stability which favors blue-greens; (2) increase cell washout potential; (3) reduce the free CO_2 concentration in favor of greens and diatoms; and (4) dilute toxic excretory products of blue-greens, alleviating possible inhibition of other algal groups (Patmont, 1980; Welch and Patmont, 1980; Welch and Tomasek, 1980).

Quality in the Upper Main Arm - 1981

Time-weighted mean transect values for phosphorus, nitrogen, chlorophyll a, and Secchi transparency for stations sampled during 1981 are presented in Table 6. Values in the main arm for total nitrogen and total phosphorus are shown in relation to distance in an uplake direction from Station 7 through Station 16 (Figure 2). Values for chlorophyll a and Secchi visibility are shown for the same sequence in Figure 3.

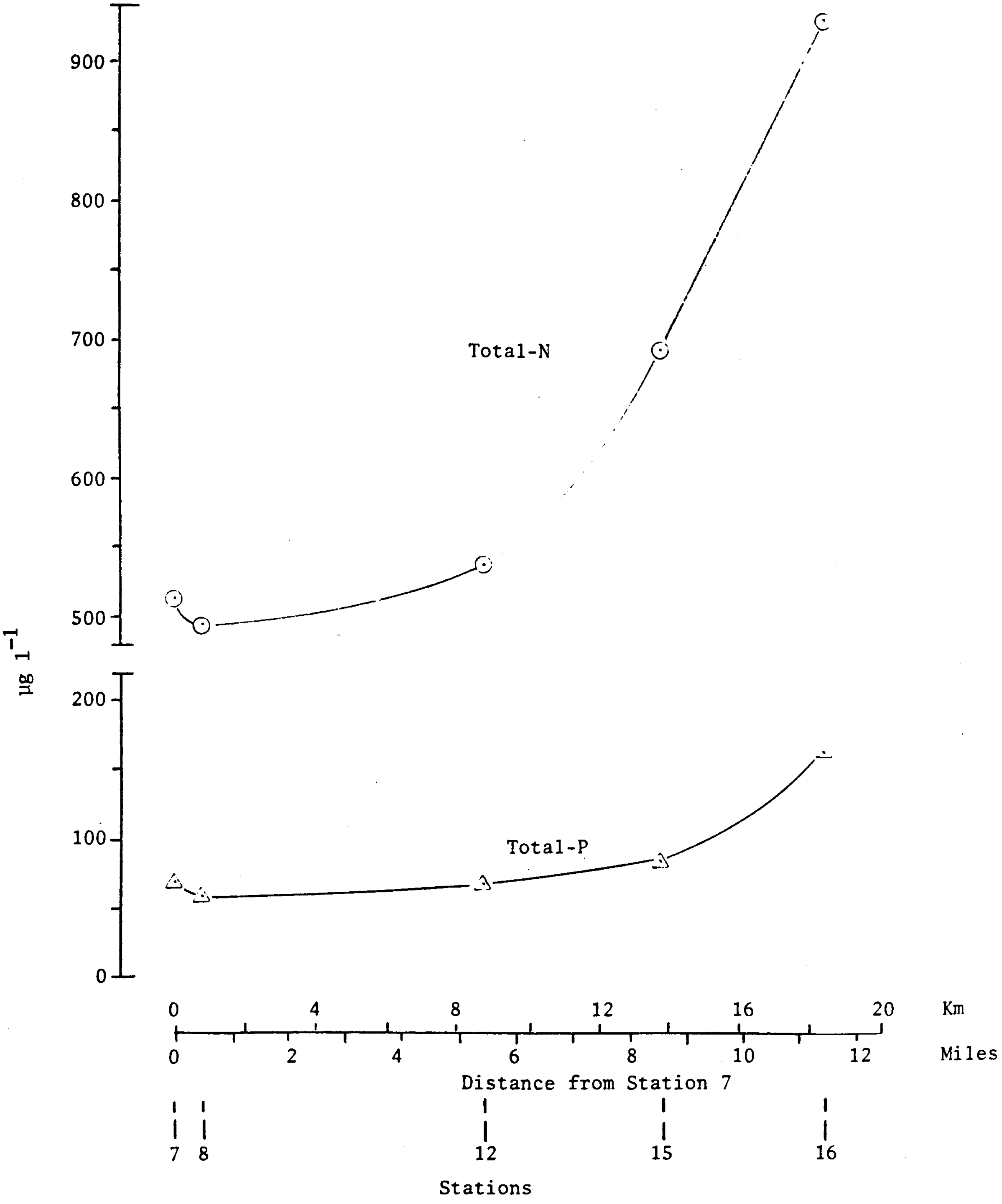


Figure 2. Mean total nitrogen (0 - 0) and total phosphorus (Δ - Δ) versus distance from Parker Horn through the main arm of Moses Lake, May - September, 1981.

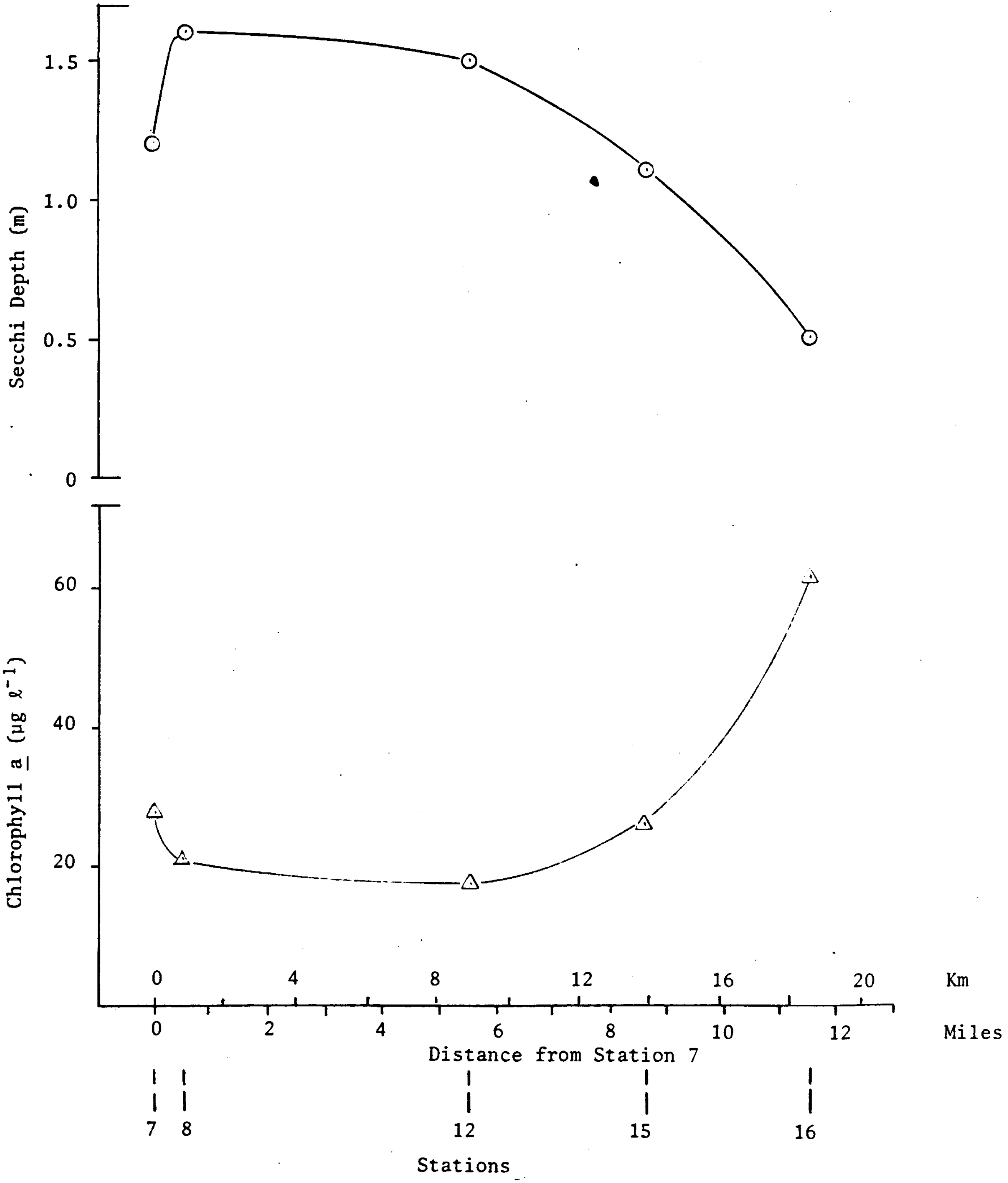


Figure 3. Mean Secchi transparency (0 - 0) and chlorophyll a (Δ - Δ) concentrations versus distance from Parker Horn through the main arm of Moses Lake, May - September, 1981.

Table 5. Percent blue-green algae by cell volume for the period June-August at Stations 7 and 9, Moses Lake.

	Station 7	Station 9
1970	96.6	---
1977	---	54.7
1978	59.9	56.2
1979	57.4	60.1
1980	---	---
1981	47.7	71.2

1) From data given in Buckley (1971) and the following estimated conversions:

<u>Aphanizomenon</u>: 37,000 mm^3/colony

<u>Anabaena</u>: 26,000 mm^3/colony

<u>Microcytis</u>: 44,000 mm^3/colony

Improvements in measured water quality characteristics were normally expected to be greatest at Station 7, simply because dilution water is introduced there and results in exchange rates considerably greater than attained in the lake as a whole (Table 2). However, as the 1981 data indicate, improvements at Stations 8 and 12, most notably in chlorophyll a and Secchi visibility, exceeded those at Station 7. This can be attributed, at least in part, to greater depth (about 5 m) and prevailing wind influence at Stations 8 and 12. The result is that algal cells are distributed over a greater depth and thus are exposed to reduced light available for growth. Stations 15 and 16, like Station 7, are shallower (2 - 3 m) than 8 and 12, and are generally less affected by prevailing winds. As a consequence, algal biomass would tend not to be as limited by light available in the water column. The fact that Station 7 values were lower than those at 15 and 16, considering the general morphometric similarities, undoubtedly resulted from the effects of dilution water input to Parker Horn. As was evidenced by specific conductance data from the various main lake stations, the change in mean concentration of total phosphorus, total nitrogen, chlorophyll a, and Secchi depth with distance up the arm (Figures 2 and 3) indicates that potential improvements due to dilution water penetration probably occurred as far as Station 12, but no further.

Table 6. May to September 1981, time-weighted transect mean values for total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate plus nitrite-nitrogen, chlorophyll a ($\mu g\ l^{-1}$), and Secchi transparency (m) for Moses Lake stations.

Station	Total P	SRP	Total N	NO_3+NO_2-N	Chl. a	Secchi depth
7	67	5	516	71	26	1.2
8	58	7	494	79	19	1.6
9	80	21	510	34	19	1.4
12	65	7	538	118	24	1.5
15	82	12	691	166	30	1.1
16	161	18	928	170	99	0.5

Dilution Caused Control of Algae

Although the mechanisms are not entirely clear, reduction in algal biomass, the blue-green component, and general improvement in Moses Lake quality resulting from dilution water additions has been thoroughly demonstrated and the possible causes examined (Patmont, 1980; Welch and Patmont, 1980; Welch and Tomasek, 1980). Nitrogen, more than any other factor, appears to control algal growth and account for the effects of dilution water addition. Data obtained during the 1981 study period indicate that the state of water quality was similar to that observed in other dilution years except for 1980, the ashfall year.

The effects of dilution water inputs on phosphorus compared to nitrogen can be examined by inspecting the time series data distributions of those

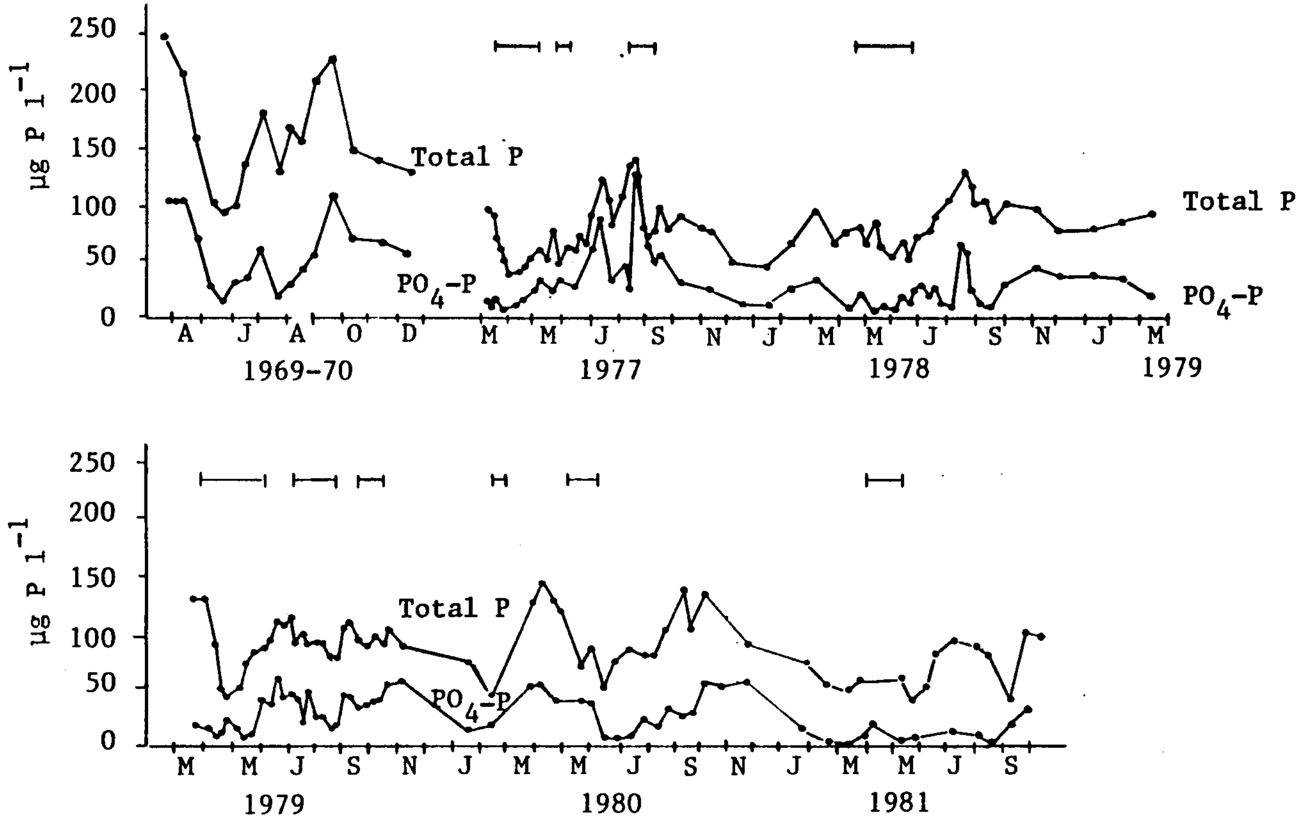


Figure 4. Mean lake total phosphorus and soluble reactive phosphorus (µg P l^{-1}) for years 1969-70 (predilution) and 1977-1981 for Moses Lake. Dilution periods are indicated by overbars.

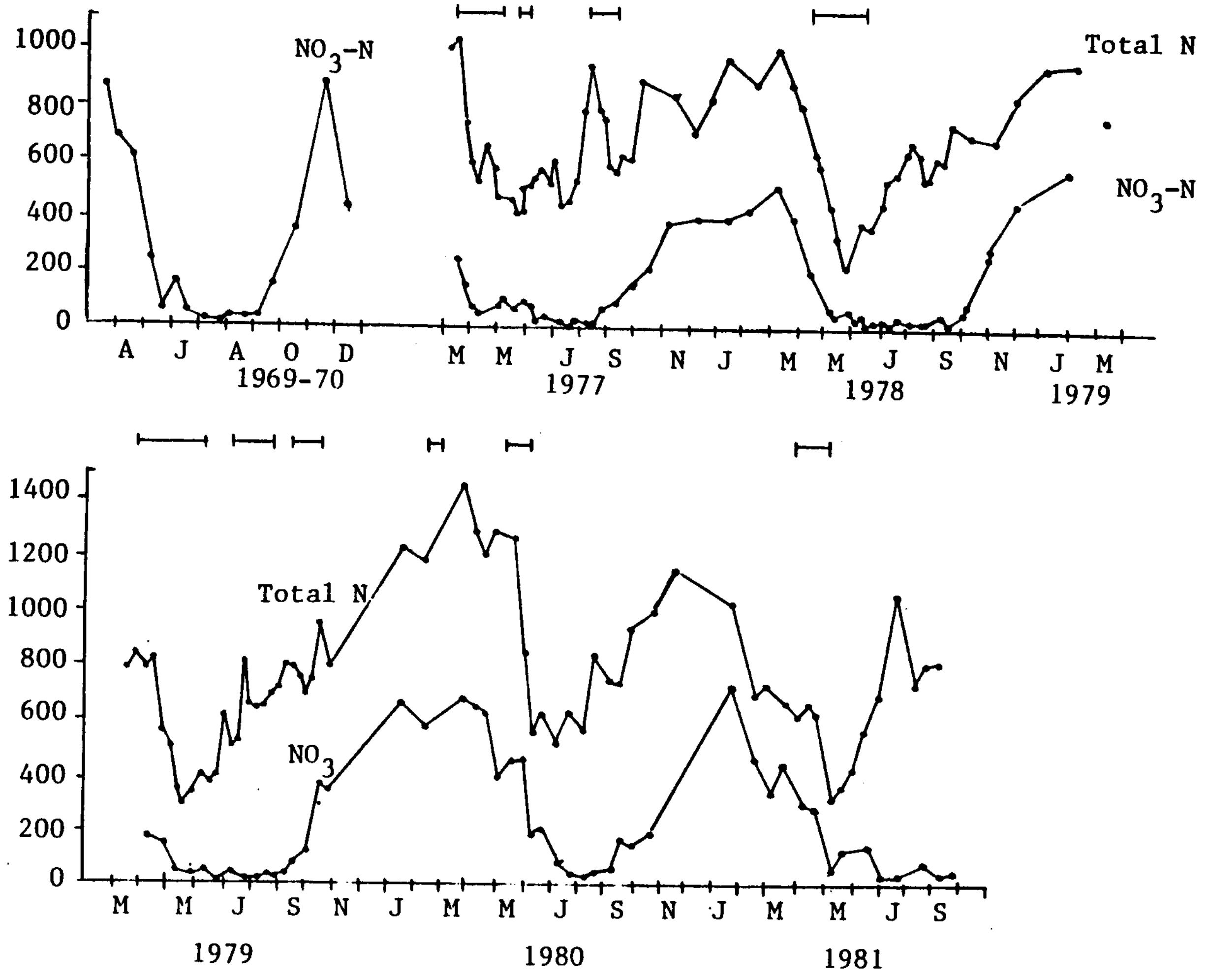


Figure 5. Mean lake total nitrogen and $NO_3 + NO_2$ ($\mu g\ N\ l^{-1}$) for years 1969-70 (predilution) and 1977-1981 for Moses Lake. Dilution periods indicated by overbars.

nutrients. Nutrient concentrations relative to various dilution periods and the predilution years 1969-70 are shown in Figures 4 and 5. Values were derived for each sampling date from a combined volume-weighted mean for Stations 7, 8, 9, 10, and 12.

When one examines data for all years, it appears that soluble inorganic N (NO_3+NO_2), rather than SRP, most frequently limited growth in Moses Lake. Nitrate remained at lower concentrations than SRP, relative to the needs of algae (ratio of 10:1) and such low values persisted for longer periods. Values for 1981 indicated an appreciable reduction in both total and soluble nitrogen components during the 27 March to 15 May dilution period. Similar reductions in total phosphorus and SRP were not as evident. This has been the pattern during all years - that nitrogen responded much more predictably (like a conservative substance) to dilution than did phosphorus (Welch, 1979).

Following cessation of dilution water delivery (15 May 1981), NO_3+NO_2 remained relatively low while total nitrogen increased steadily to a large July-August maximum coincident with a similar maximum of algal biomass. Since lake inflows at this time were minimal and the phytoplankton were dominated by heterocyst-bearing Aphanizomenon flos-aquae, the observed total nitrogen peak was likely due in large part to the accumulated products of nitrogen fixation. It is typical of Moses Lake and other highly productive lakes, that N rather than P is the growth-rate limiting nutrient and that nitrogen-fixing blue-green species dominate during the summer months when the potential for significant nitrogen loss is high due to oxygen depletion and resulting denitrification (Welch, 1980).

In order to document the occurrence and magnitude of nitrogen fixation in Moses Lake, an experiment was conducted in Parker Horn on 18 September 1981 using the acetyline reduction technique (Table 7). Results indicated that fixation rates were similar to those in other eutrophic lakes (Stewart, et al., 1971). The effects of time of day and depth of sample were also consistent with results from other studies (Rusness and Burris, 1970). Since these rates are only for a single day and at one location in the lake, they cannot be extrapolated over the entire summer to give a value for nitrogen loading from fixation. However, they do indicate fixation was taking place and at an expected rate. Rough conversions of algal N content from chl a, in order to approximate algal growth or turnover rates, indicates that growth due to N fixation was proceeding at less than 10 percent per day.

Table 7. Nitrogen fixation rates based on an in-site experiment at Station 7, Moses Lake, 18 September 1981.

Time	Depth	Fixation Rates		Chl a	Aphanizomenon Cell Volume
(PDT)	(m)	(nmole C_2H_2 $l^{-1}hr^{-1}$)	(ng $N_2 l^{-1}hr^{-1}$)	(μg l^{-1})	(mm^3 l^{-1})
0900	0.5	89 ± 16	728	45.9	5.8
	2	70 ± 11	653	44.0	9.7
1230	0.5	120 ± 6	1120	52.7	7.5
	0.5[a]	129 ± 21	1204	52.7	7.5
	2.0	52 ± 7	485	36.3	7.5
1600	0.5	120 ± 23	1120	45.4	6.7
	2.0	18 ± 2	168	50.2	4.6

[a] Fe added to test for possible limitation.

The fact that certain blue-green algal species can fix atmospheric nitrogen means that under conditions where depletion of soluble nitrogen would normally limit algal productivity, N-fixing species can prosper and dominate the phytoplankton. Under such circumstances, the available soluble phosphorus can continue to be utilized for growth even after NO_3 has been exhausted.

Phosphorus, rather than N, could then be considered the long-term limiter of algae.

Dilution water input during 1981 did not appear to significantly alter in-lake phosphorus concentrations, since inflow values for both total and soluble fractions remained high (Table 3). In addition, Moses lake has frequently experienced conditions favorable for internal phosphorus loading (Patmont, 1980). Such conditions, coupled with the anomolous response observed in phosphorus values during dilution, supports the conclusion that reductions in algal biomass in Moses Lake are probably not caused by phosphorus limitations as hypothesized at the beginning of the dilution project.

Physical displacement of algal cells by washout likely further contributed to biomass reduction in Parker Horn (Station 7). Dilution input acted to significantly increase water exchange rates as previously discussed (Table 2). Considering the slow rates of N fixation, the increased exchange rates may not allow enough time for blue greens to utilize available P through that process once NO_3 is exhausted. For the lake as a whole, however, the observed levels of dilution water input in 1981 were probably insufficient to cause algal reduction by washout, but may still have been high enough to interfere with P utilization and growth if N fixation were the only N source.

If N fixation is unlikely to supply enough N for growth to be limited by P then algal abundance should be largely dependent on available N. The largest fraction of available N is in the form of NO_3 and normally enters the lake in excess of 1000 $\mu g\ l^{-1}$ (Table 3). The addition of dilution water markedly reduces NO_3 in the lake inflow because East Low Canal water contains very low levels - 5 $\mu g\ l^{-1}$ in 1981 (Table 3). Although NO_3 is available for uptake and has been the growth rate limiting nutrient (depletes before P during growth), the dependence of algae on NO_3 in the lake water can only be shown by an inverse relationship. Figure 5 shows that NO_3 remains in low concentration during the summer growth period and represents the residual after algal uptake.

The persistence of low concentrations of the limiting nutrient (NO_3) in Moses Lake is analogous to conditions in a continious culture system. In such a system the limiting nutrient concentration in the mixed culture medium and outflow remains very low, while the algal biomass depends on the concentration in the inflow stream prior to algal utilization. With exchange rates through Parker Horn being rather rapid (10 percent per day) it is reasonable to consider the system to behave like that of a continuous culture. With that assumption, the flow weighted mean NO_3-N content in the inflow during May through August was related to average chl a in the lake from the time when the water temperature reached 20 until the end of September. This time period provided a good indication of the magnitude of the summer algal bloom(s). This was done for Station 7 only as well as a composite (volume weighted mean) of Stations 7, 8 and 9, which represented about one half the lake volume. These results are shown in Figure 6.

A good relationship exists between inflow NO_3 and lake chl a for the dilution years 1977, 1978 and 1979. The improvement in lake quality (algal abundance) in excess of 50 percent following dilution compared to predilution years (1969, 1970) is evident from the relationship. Furthermore, the year with the lowest algal abundance, 1978, was apparently a result of more dilution water being added later in the spring which provided the lower inflow NO_3 concentration. The lower slope for Stations 7, 8 and 9 chl a reflects the nutrient uptake and sedimentation occurring as inflow water moves throughout the lake.

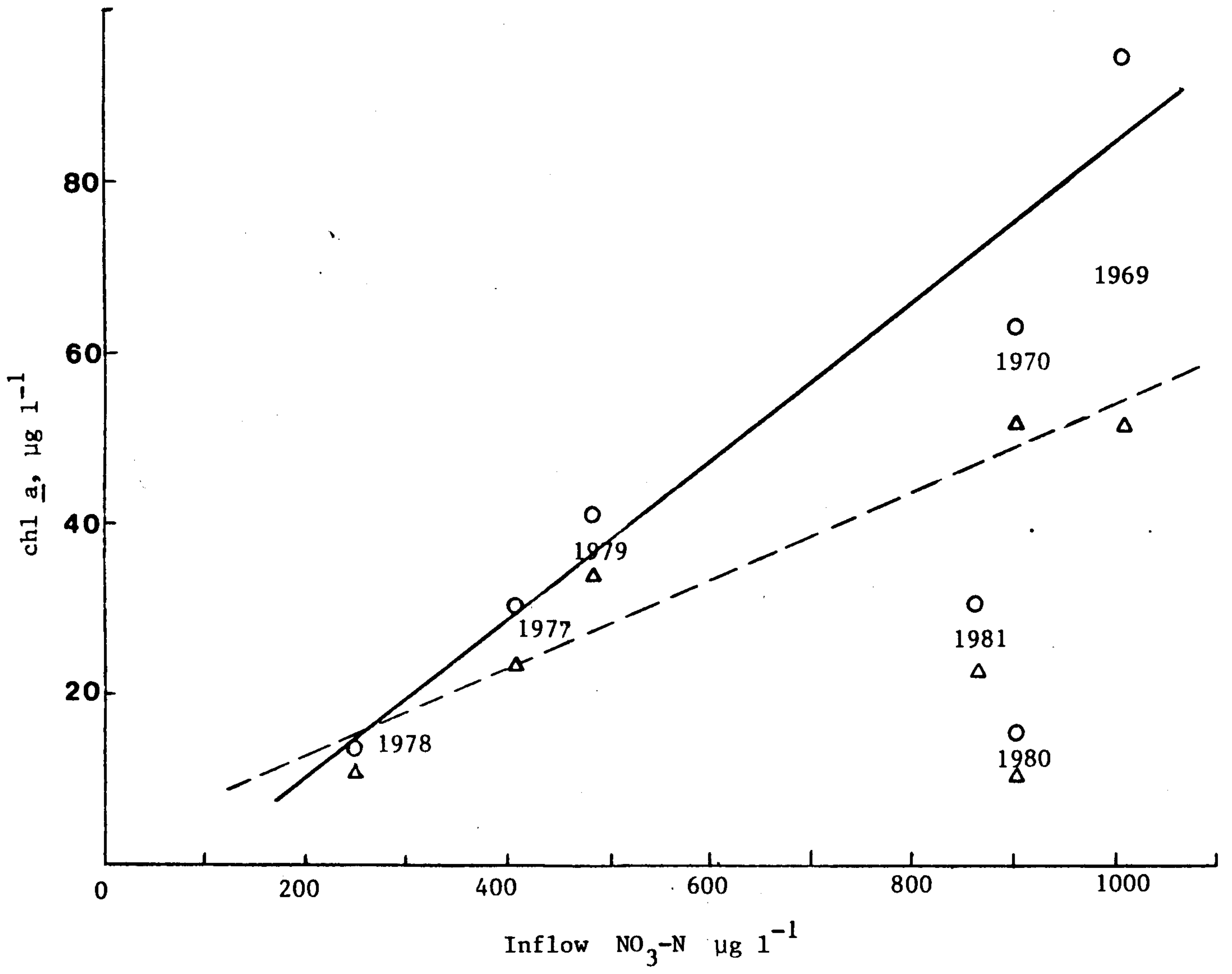


Figure 6. Relationship between mean flow weighted concentration of NO_3-N in the Crab Creek inflow to Moses Lake during May through August and mean chlorophyll a at Station 7 (0 ——— 0) and at Stations 7, 8 and 9 (Δ – – – – Δ, volume weighted) during the period from a temperature maximum of 20° through September. Correlation coefficients for both regressions are 0.97 and the equations for Stations 7 and 7,8,9, respectively, are chl a = 0.092 NO_3 - 7.37 and chl a = 0.052 NO_3 + 3.27).

The data from 1980 and 1981 do not fit the relationship, which is probably due to the effect of the Mt. St. Helen's ashfall. Although not thoroughly evaluated at this time, the cause(s) for decreased algal productivity may be a combination of increasd turbidity (reduced light available) from the ash, which continues to be stirred into the lake water during windy conditions, as well as the possibility of increased limitation from phosphorus. The mean NO_3-N:PO_4-P ratio in Crab Creek during spring and summer changed from 19 in 1977-78 to 165 in 1981. The total N:Total P ratio also increased from 9 to 24. While it is not clear from Figures 4 and 5 that lake PO_4-P was any more abundant than NO_3 in the summer during 1980-81 than in earlier years, mean April-September ratios of NO_3-N:PO_4-P did actually increase from 3 to 23 (Sta. 7, Table 4), which indicates a change from N to P limitation of growth rate during most of the growth period after the ashfall and helps explain why chl a levels in 1980-81 are low relative to the NO_3 available.

Dilution of the Main Arm

An empirical approach to estimate the extent of dilution water movement into the man arm (Stations 8, 12, 15, 16) utilized specific conductance data at Stations 4-R, 7, 8, 12, 15, 16 during the dilution period in March-May, 1981 (Fig. 1). Use of these particular stations is described below.

Station 4-R. Water at this station was used to characterize the dilution water. When dilution water from the East Low Canal is being added to the lake via Rocky coulee Wasteway and Crab Creek, water at Station 4-R is considerd to characterize the dilution water. A sample taken elsewhere in the lake while dilution was going on and which had the same specific conductance as measured at 4-R would be considered entirely dilution water - i.e., un-mixed with any original lake water.

Station 7. Water characteristics at Station 7 were assumed to represent conditions in lower Parker Horn caused by the mixture of dilution and lake waters as the dilution water moves from upper parker Horn to the lake outlet.

Station 8. For calculation purposes, conditions at the center of the Station 8 transet were considered to apply at a station 1.0 mile (1.6 km) removed from the "interface" between the main arm and lower Parker Horn.

Station 12. Again, for calculation purposes, the conditions at the center of the Station 12 transect were considerd to lie 5.5 miles (8.8 km) "up-lake" from the main arm-lower Parker Horn junction. These distances are approximate, lacking specific detail on sampling stations, but are accurate enough for present purposes.

Stations 15 and 16. These main arm stations were not used in the final analysis. Variations in specific conductance with time were small, and appeared to be independent of variations at Stations 8 and 12.

Three samplng modes were used during the field study. One was to obtain a composite water sample drawn from the entire depth of the water column at a mid-transect station. Use of data from this sampling mode was the first choice in the analysis and was followed wherever such data were available. The next choice was to use results from discrete samples taken at the top of the water column, at 2 meters depth, and at the bottom. If only data from a horizontal transect were available, these were used.

Only one period of dilution water input occurred in 1981. Initially it was hoped that two periods of two radically different dilution water flows would be available for evaluation (e.g., 1000 cfs and 250 cfs). However, dilution water entered at an intermediate rate and only for one period. Data used in the estimates of water movement are listed in Table 8, where the sampling modes are indicated. For use in this approximate analysis, a specific conductance (μ) of 170 micromhos cm^{-1} was selected to represent dilution water and 420 to characterize pre-dilution lake water. (It should be noted that so far as specific conductance data were concerned, there was relatively little difference between results from different sampling modes at a station on a particular date).

Table 8. Conductivity Data Used in Analysis (Specific Conductance, μ, in micromhos cm^{-1}).

Station	3/10	3/28	3/29	4/7	4/25	5/9	5/23	6/5
4-R	551_b	177		176_b	162_b	168_b	432_b	431
7	430^b		404^c	287^b	227^b	227^b	286^b	
8	431^a	411^c	412^c	392^a	331^a	298^a	289^a	321_a
12	409^a	401^c	394^a	400^a	364^a	368^a	353^a	357^a
15	382^a	377^c	376^a	374^b	386^b	394^b	369^b	
16		331^c	330^c	358^c	336^c	388^c	381^c	

Sampling Mode:

[a] Composite sample over water column.
[b] Average of T, 2, B.
[c] Horizontal transect.

Figure 7 shows plots of vs distance x measured from the main arm-lower Parker Horn junction, uplake along the main arm, for the three dates, 4/7, 4/25, and 5/9. Dilution started on 3/27. Gradients of with distance along the arm are apparent, but the data at stations 15 and 16 indicate why these stations were not used in the analysis. On 4-7, little response to dilution was observed at Station 8. Consequently, calculations are limited to the 4/25 and 5/9 field data.

Straight line time vs conductivity plots for the stations are shown in Figure 8, where the data points are those listed in Table 8. The curves have been replotted in Figure 8 in an effort to represent more realistically the variations in with time, between the sampling dates and the stations utilized.

The dilution inflows were:

	Flow	
Dates	cfs	m^3 sec^{-1}
3/27 to 4/15	300	8.6
4/16 to 4/21	675	19.3
4/22 to 4/30	940	26.9
5/1 to 5/15	745	21.3

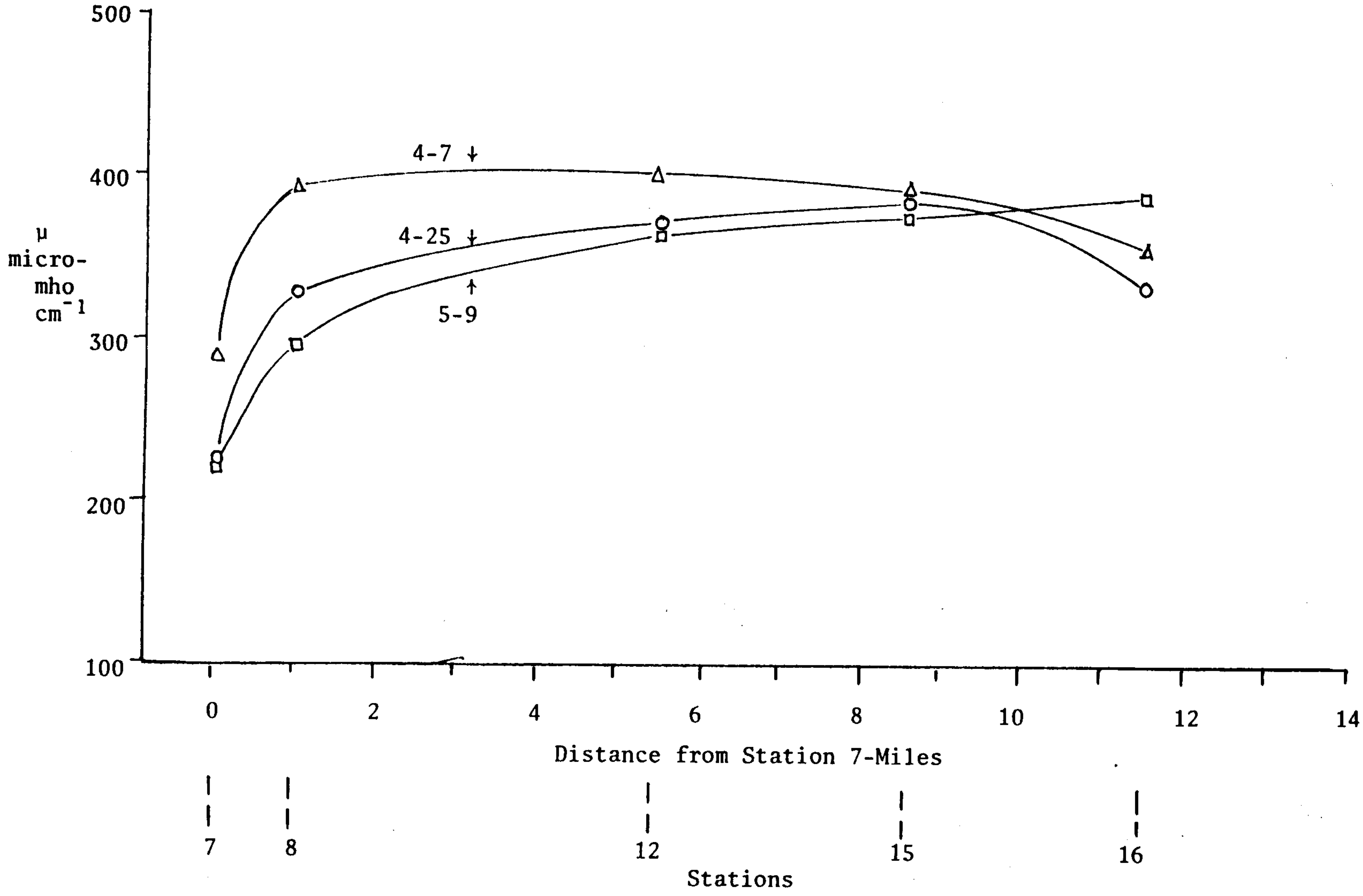


Figure 7. Specific conductance (μ) versus distance from Parker Horn through the main arm of Moses Lake on three occasions in 1981.

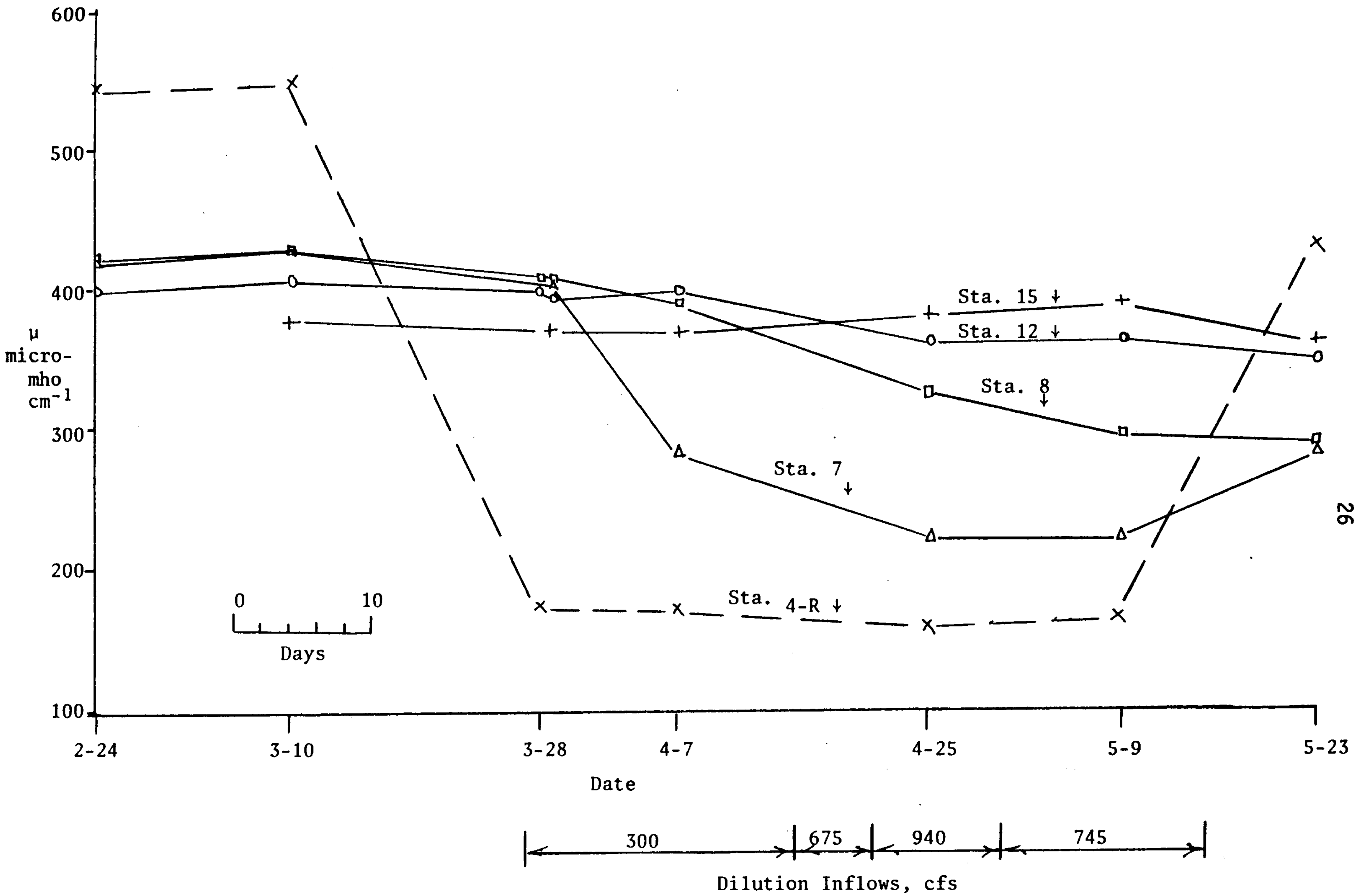


Figure 8. Specific conductance (μ) versus time at five stations in Moses Lake during 1981.

The mean dilution inflow over the 50-day period was then 594 cfs ($17\ m^3\ sec^{-1}$). The smoothed curves of Figure 8 indicate that a near-equilibrium condition between dilution water and lake water was reached at Station 7 on 4/18, 22 days after the start of the dilution period. At this time 77 percent of the water in lower Parker Horn was dilution water; 23 percent was "lake water". This determination was made using $\mu = 227$ from the smoothed curve for Station 7 in Figure 8. On 4/7, 11 days after the start of the dilution, $\mu = 287$ at station 7 and the fraction of lake water still present was 47 percent. These values are in moderately good agreement with physical hydraulic model results presented by Nece et al. (1976), and with field observations reported by Lindell (1977).

The above results were determined as follows:

Let c = relative concentration (fraction) of dilution water at conductivity μ_d

μ_i = initial lake water conductivity

μ = conductivity of the mix

$$(1-c)\mu_i + c\ \mu_d = (1)\mu$$

$$c = (\mu_i - \mu)/(\mu_i - \mu_d)$$

From Figure 8, on 4/18, $c = (420 - 227)/(420 - 170) = 0.77$.

All calculations are based on values taken from the smoothed curves of Figure 9. From that figure it can be noted that the concentration of dilution water at Station 7 remained essentially constant after 4/18, even though dilution flows did vary with time as noted above.

Also, Figure 9 indicates that there was relatively little indication of dilution water at Station 8 until equilibrium conditions were approached at Station 7. The next objective was to determine how well the further movement of dilution water into the main arm of Moses Lake could be represented by a

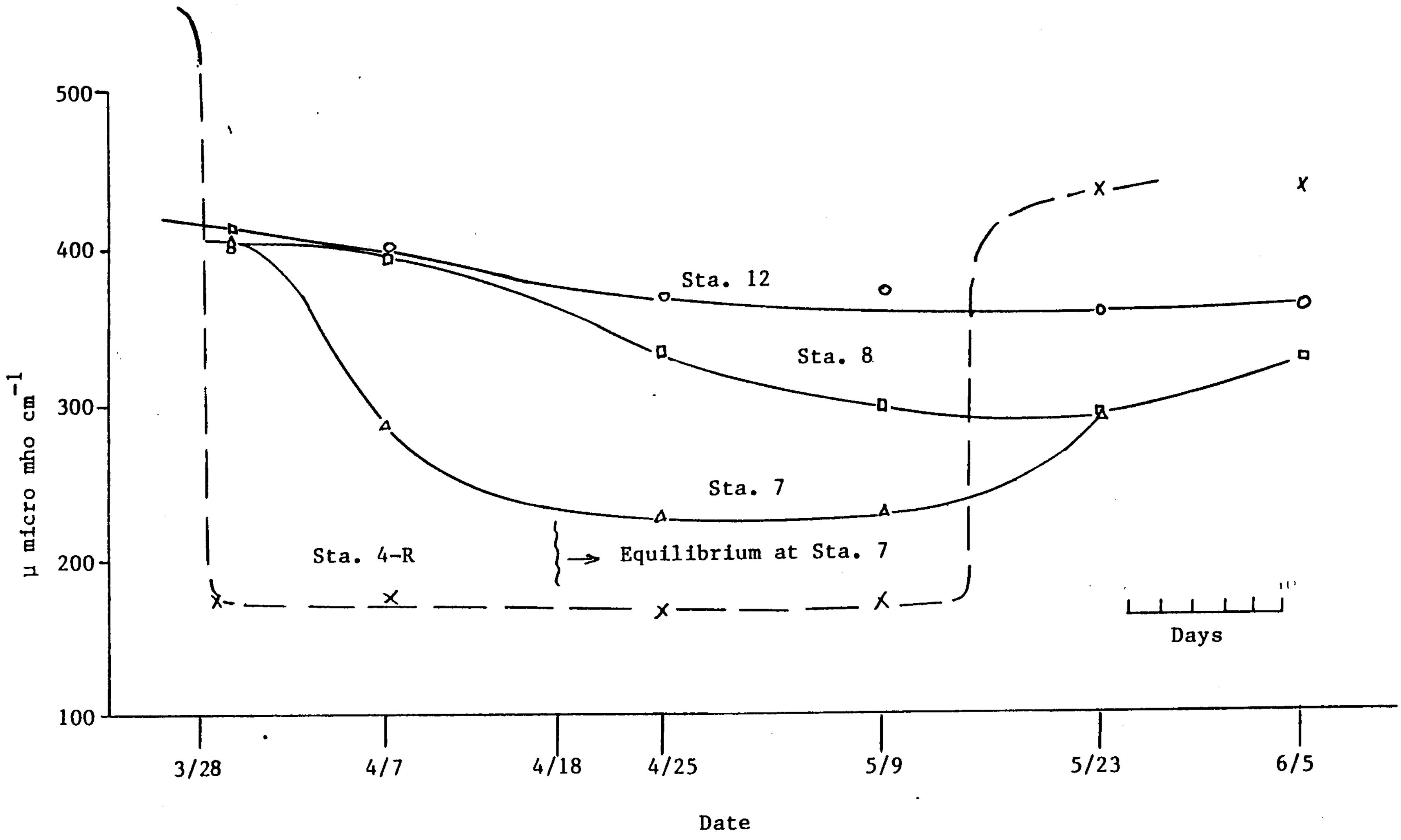


Figure 9. Smoothed data for specific conductance (μ) versus time at four stations in Moses Lake during 1981.

simple diffusion model in which the tracer (dilution water) diffuses into the main arm when the dilution water concentration at the lower Parker Horn - main arm junction (represented by Station 7) is held constant. The appropriate solution for such a case, where the tracer diffuses into a channel of constant cross-section area and where advective currents are not present is given by Fisher et al. (1979):

$$C_o = 1 - \mathrm{erf}\ x\ \sqrt{4Dt}$$

where: C_o = constant reference tracer concentration at the source.
c = $c(s,t)$ = concentration of tracer, variable with time at a station.
x = distance from the boundary where $c = C_o$ = constant.
t = time.
D = one-dimensional dispersion coefficient.

For the present calculations, times t were 7 days and 21 days, using an equilibrium starting date of 4/18 and the field data of 4/25 and 5/9, respectively. The distances x were 1.0 and 5.5 miles from Station 7 to Stations 8 and 12, respectively. The calculated diffusion coefficient D for each of the four cases was then expressed in $\mathrm{mi}^2\ \mathrm{day}^{-1}$ ($\mathrm{km}^2\ \mathrm{day}^{-1}$). Results are listed in Table 9. The reference conductivity at Station 7 was taken as constant, $\mu = 227$; initial values at Stations 8 and 12, estimated from Figure 9, were $\mu = 362$ and $\mu = 370$, respectively. The c/C_o ratio at Station 8, for example, was calculated as follows: 362-331/362-277 = 0.23.

Large variations in the quasi-diffusion coefficient D are noted. The calculated values are sensitive to the approximate x-distances, especially the small 1-mile value used between Stations 7 and 8, and also to μ values approximated from the plots of Figure 9. The D coefficient, absorbs and hides all the physics of the actual transport mechanisms by which dilution water moves into the arm. The four values, however, are nearly the same order of magnitude. A representative value selected for further calculations to empirically describe the process is 0.20 $\mathrm{mi}^2\ \mathrm{day}^{-1}$ (0.5 $\mathrm{km}^2\ \mathrm{day}^{-1}$). This choice is based on the results using the largest x, t values for which field data were available.

Table 9. Calculated Effective Diffusion Coefficients, Main Arm, Moses Lake. (x 1.6 = km; x 2.56 = $\mathrm{km}^2\ \mathrm{day}^{-1}$).

Date	Station	x-mile		c/C_o	D - $\mathrm{mi}^2\ \mathrm{day}^{-1}$
4/18	7	0	227	1.00	
	8	1.0	362	--	
	12	5.5	370	--	
4/25	7	0	227	1.00	
(t=7)	8	1.0	331	0.23	0.050
	12	5.5	364	0.04	0.52
5/9	7	0	227	1.00	
(t=21)	8	1.0	298	0.47	0.046
	12	5.5	358	0.08	0.23

Sample predictive calculations using D = 0.20 $\mathrm{mi}^2\ \mathrm{day}^{-1}$ (0.5 $\mathrm{km}^2\ \mathrm{day}^{-1}$) are shown in Table 9 for one case which incorporates the following assumptions:

1. An equilibrium condition at Station 7, with 77 percent of the water being dilution water. This matches the 1981 conditions, and could be reached within 20 days after the start of the dilution if the dilution inflows were equal to or greater than 600 cfs (17 $\mathrm{m}^3\ \mathrm{sec}^{-1}$).
2. Dilution water is added at the same rate for an additional 100 days at the same rate after the establishment of equilibrium conditions at Station 7, maintaining this equilibrium there.
3. Wind patterns and Rocky Ford inflows are the same as those experienced during the 1981 observations.
4. The equation is valid for Station 15 (x = 8.5 miles, 13.6 km).

Table 10. Predicted Levels of Dilution Water in Main Arm Stations. (x 1.6 = km; x 2.56 = km^2 day^{-1})

For: Dilution Q = 600 cfs

Dilution Period = 120 days, continuous (times in table are measured from day 120, when dilution water level at Station 7 has reached equilibrium at 0.77)

$D = 0.20\ \text{mi}^2\ \text{day}^{-1}$

Station	x miles	t days	C_o	Relative Concentration of Dilution Water
12	5.5	16	.03	.02
		25	.08	.06
		49	.21	.16
		100	.38	.29
15	8.5	16	µ 0	0
		25	.01	.01
		49	.05	.04
		100	.17	.13

These assumptions should produce the most optimistic predicted levels of dilution water in the upper arm under lake dilution programs which might be feasible.

As noted, the crude diffusion model masks the true physics of the process. One consideration is the fact that the dilution water movement into the main arm is opposed to the direction of the net flow, fed by Rocky Ford Creek, through the arm. However, the average discharge of Rocky Ford Creek is 78 cfs (2.2 m^3 sec^{-1}) and is even less during March-May (U.S.G.S., 1979) and the cross-sectional area of the main arm between stations 8 and 12 varies within approximate limits of 25,000-50,000 ft^2 (2,322-4,645 m^2). Therefore, average through-flow velocities are of the order of 0.001-0.003 fps (0.03-0.09 cm sec^{-1}), values which are small compared to wind driven surface currents discussed later.

While numerical models for wind driven circulation in shallow lakes have been developed, the sparse data and also the objectives of this study do not make their use attractive. However, a working hypothesis is that wind driven currents are the primary mechanism for the uplake movement of dilution water. If winds over the main arm are predominantly to the north, it can be assumed that the wind driven circulation, near the lake surface, will transport water from lower Parker Horn into the main arm. Turbulence generated within the wave field in the shallow lake, and diurnal cooling, tend to minimize stratification. The 1981 densities do not show obvious density gradients which could account for the observed movement of dilution water.

Accordingly, a simple crude evaluation of possible wind driven circulation was performed using NOAA* wind records for Moses Lake. These wind data were obtained at the Grant County Airport, located just east of the lake opposite Station 12. These data, for lack of further detail, were considered accurate enough for present purposes to describe the winds 10 meters over the main arm. Hourly observations of wind speed (knots) and direction were available for 17 out of 24 hours each date. Each hourly reading was assumed to represent average conditions for one hour.

Winds were assumed to act along the lake if their direction were 30 from the lake axis. Between stations 7 and 8 the uplake direction of the lake axis is 330 , and between Stations 8 and 12 the average direction has a compass bearing of 360 . Therefore, uplake winds were considered to lie within the envelope of wind directions, lying between 120 and 210 (customary notation for wind); down-lake winds were considered as lying between 300 and 30 . Winds from all other directions were assumed not to contribute to any axis-direction drift currents. The knot-hours of wind within each envelope were found for each of the 21 days between 4/18 and 5/9. The average daily wind movement, for the 17 hours of record, was 38 knot-hours, in the uplake direction. Assuming further that the 17-hour records could be prorated over the entire day, the average daily uplake wind travel was

24/17 x 38 = 54 nautical miles = 62 statute miles (99 km)

Using the results of Wu (1973) and Baines and Knapp (1965), the velocity of water at the surface can be approximated as being 0.03 times the 10-meter wind speed. Therefore, the displacement of a water particle at the surface would be 1.86 statute miles (3 km) in one day. For approximation, let this displacement be 2 miles (3.2 km). Further, using the velocity profiles presented by Baines and Knapp (1965) a daily displacement of one mile, where the local velocity is 0.5 times that at the surface, occurs at a depth approximately 0.03 times the local water depth. Therefore, due to wind transport using the approximate values above, in one day and at a distance of one mile from the start of calculations, 3 percent of the water at the "downstream" station is displaced. Using $c/C_o = 0.003 = 1 - \mathrm{erf}\ x \quad 4Dt$ $= 1 - \mathrm{erf}\ 1/2 \quad D$, produces a value of D = 0.11 $\mathrm{mi}^2\ \mathrm{day}^{-1}$ (0.28 $\mathrm{km}^2\ \mathrm{day}^{-1}$). This result, reached by crude methods, is of the right order of magnitude when compared with the field observations. The simplistic wind-driven current approach then does predict the rates of water movement, which substantiate the importance of this transport mechanism.

* National Oceanographic and Atmospheric Administration.

DISCUSSION

Several objectives were achieved in this investigation. Quality status of the upper main arm had not been previously determined with respect to the need for delivering dilution water directly to that portion of the lake. Dilution water entering through Crab Creek had been shown previously to reach part way through the main arm (Station 12; Patmont, 1980; Welch and Patmont, 1980). However, it was not known if that transport would likely occur independently of the rate of dilution water inflow; that is, would most of the main arm be diluted as effectively with a relatively low, constant input (5.7 $m^3 s^{-1}$, 200 cfs) through Crab Creek as has occurred in past years when flows were 20 $m^3 s^{-1}$ (735 cfs) or more. Also, the specific cause(s) for improvement in Moses lake quality (less algae, greater transparency) had not been adequately determined for predictive purposes. Such a cause-effect relationship was needed to develop scenarios of dilution water input patterns to satisfactorily manage the lake. To a surprising degree these objectives were achieved.

Quality was observed to deteriorate considerably progressing uplake from Station 12. Chl a, transparency and nutrient content in the uppermost main arm in 1981 were similar to the condition in the lower lake during predilution years (1969-70). It was apparent from the quality status that significant amounts of dilution water did not extend much beyond Station 12, although quality status at that midway point was substantially improved by virtue of dilution water entering through Crab Creek.

The mechanism of dilution water transport through the main arm from the Crab Creek input in 1981 was investigated by assuming a steady state condition, using specific conductance as a conservative tracer and employing a diffusion model. Calculated diffusion coefficients were considered, similar enough to use a mean value (0.5 km^{-2} day^{-1}, 0.2 mi^2 day^{-1}) for purposes of prediction. Using that coefficient, a flow of 17 m^3 s^{-1} (600 cfs), which produced 77% dilution water at Station 7, should result in about 30% dilution water at Station 12, given 100 days to equilibrate, but less than one-half that amount at Station 15, three-fourths the distance up the main arm.

Although this experiment could not be performed at two different inflows, as desired, comparison with wind-caused diffusion estimates strongly suggests that the transport through the main arm will occur regardless of dilution inflow rate, because it is largely wind driven. Thus, similar rates of dilution water movement can be expected to occur through the main arm at low constant inflow rates as well as at intermittent high rates. The ultimate level of dilution water reaching midway through the main arm is dependent primarily on the fracton of dilution water attained at Station 7, which of course is a function of inflow rate. While the wind-driven diffusion process is effective at transporting dilution water, causing substantial quality improvement midway through the main arm, its effect diminishes considerably beyond that point. Table 11 shows five different scenarios of dilution water input during May-August and the approximate percentages of dilution water expected at Stations 7 and 12.

Inflow NO_3 concentration was found to be the best determinant of algal abundance and hence transparency, in the lake. The results of this approach are especially attractive because they are consistent with theory. The results are similar to those in a continuous culture system where the concentration of algae in the receiving system is directly proportional to the concentration of limiting nutrient in the inflow to the system. This occurs because there is nearly a complete uptake by the algae resulting in very low concentrations of the limiting nutrient. Very low concentrations of NO_3 normally occur in Moses Lake during the growing season, identifying it as the growth rate limiting nutrient. Fixation of atmospheric N, when NO_3 becomes low, exists, but is apprently not sufficiently fast to cause PO_4 to be depleted and be the limiting nutrient.

Table 11. Selected scenarios for the pattern of dilution water (D.W.) input through Crab Creek, % D.W. reaching Station 7/12, inflow NO_3-N during May-August and predicted summer chl a (Fig. 6) in $\mu g\, l^{-1}$.

	D.W. inflow	D.W. inflow	D.W. %	NO_3-N	Chl a	Chl a
Scenario	$m^3 s^{-1}$*-mo.	$m^3 \times 10^6$	Sta.7/12	C.C.	Sta. 7	Sta.7,8,9
1	5.7, 5-8	59	65/25	442	33	26
2	8.6, 5-8	89	74/28	334	23	21
3	11.4, 5 3.8, 6-8	59	61/23	489	38	29
4	17.1, 5, 1.9, 6-8	59	50/19	631	51	36
5	22.8, 5, 0, 6-8	59	22/8	975	82	54
1977-79	Dilution			385	29	
1969-70	Predilution			965	79	52

* 1 $m^3 s^{-1}$ = 35 cfs

The Mt. St. Helens ashlayer on the lake bottom has effectively reduced the internal recycling of P from the sediment (Welch, et al. 1982). This may be contributing to the increased NO_3:PO_4 ratio in the lake which may have caused P rather than N to be the principal limiting nutrient in 1980 and 1981. The continual blowing of ash into the lake and stirring ash from the shallows into the water column has no doubt reduced available light for algal growth compared to pre-ash years. These two factors may be contributing to the relative independence of algal abundance on inflow NO_3 concentration in the two recent years (Fig. 6). The lesser than normal amount of dilution water added in 1980 and 1981 (71% less than in 1977-79) failed to substantially reduce NO_3 in the inflow and should have resulted in predilution algal abundance if apparent and related factors had not occurred.

Assuming that the lake returns to NO_3 limitation in the near future (N:P ratios were lower in 1981 than in 1980), expected amounts of algae (chl a) were calculated using the regressions in Figure 6 and flow weighted inflow NO_3 values that should result from the dilution scenarious indicated in Table 11. Comparison of the four different patterns of dilution water inflow, in which the same water quantity is added (59×10^6 m^3), shows the advantage of the lowest, but constant, flow. Regardless of how great the flow is for the first month (May), allowing Crab Creek irrigation return flow to make up a larger portion of the flow for the next three months (June-August) progressively increases the NO_3 concentration. Of course, a higher constant flow (8.6 m^3 s^{-1}, 300 cfs), amounting to more water totally (89×10^6 m_3) will naturally produce lower NO_3 and expected algal amounts (23 μg l^{-1} chl a) much less than what has occurred in post dilution years (29 μg l^{-1}). Considering the potential uncertainty in the predictions, 33 μg l^{-1} expected in Parker Horn, from 5.7 m^3 s^{-1} (200 cfs) continuous inflow, would produce a quality status in the lake at least as good as what has existed over the past five years (50% less algae), notwithstanding the St. Helens ashlayer (algae abundance has been less than predicted since the ashfall). The status would still be considered eutrophic, but much improved from the previous hypereutrophic state, and probably in keeping with the desires of many to maintain a highly productive fishery.

Quality at other stations in the lake can also be expected to be in line with what has occurred during pre-ash, postdilution years. Algal abundance throughout most of the lake (volume weighted mean for Sta. 7,8,9) tends to be less than that at Station 7 (Table 11), largely due to nutrient loss through algae uptake and sedimentation. Quality at Station 12 should be similar to the mean of 7,8, and 9, which has been the case previously. Chl _a_ was actually less at Station 12 in 1981, but that may have been due to greater ash-caused turbidity there.

SUMMARY

1. The upper portion of the main arm of the lake was observed to receive only a small amount of dilution water from inputs through Crab Creek and to exhibit poor quality conditions similar to those that occurred in the lower lake prior to dilution.
2. Transport of dilution water through the main arm can be hypothesized to occur in large part by wind-caused diffusion. Using an estimated diffusion coefficient, and with several assumptions, at least one-third of the dilution water entering through Crab Creek can be expected to reach midway through the main arm under any flow regime. The actual fraction would depend upon that fraction achieved in Parker Horn, which would depend upon inflow rate of dilution water to Crab Creek. Dilution water reaching as far as three-fourths the way through the main arm and beyond would diminish markedly producing only minor to no improvements in quality.
3. Algal abundance, as chl _a_, was found to be directly dependent upon inflow concentrations of NO_3, the nutrient limiting growth in the lake, for all preashfall years. Phosphorus and light limitation since the ashfall may have resulted in less algae in the lake than what would have been

expected from inflowing NO_3, which was relatively high in 1980 and 1981 as a result of much less dilution water added than in 1977-1979.

4. A constant flow through the May-August period, even though at a low rate, can be expected to provide better lake quality than the same water quantity added mostly as initially high flows. A constant inflow of 5.7 m^3 s^{-1} (200 cfs) through Crab Creek can be expected to provide a quality throughout most of the lake at least as good as what has occurred during the past five dilution years. Lake quality will progressively return to the condition in predilution years as the tendency becomes greater to distribute a given volume of water with initially high flows in May, leaving relatively undiluted irrigation return flow water to enter the lake during June through August.

LITERATURE CITED

APHA. 1975. Standard Methods for the Examination of Water and Wastewater, 14th edition. American Public Health Association, Washington, D.C.

Baines, W.D. and D.J. Knapp. 1965. Wind driven water currents. J. Hydraul. Div., Am. Soc. Civil Eng. 91:205-221.

Buckley, J.A. 1971. Effects of low nutrient dilution water and mixing on the growth of nuisance algae. M.S. Thesis, Univ. of Washington, Seattle. 116 p.

Carey, B.M. 1981. The effects of restoration by dilution on zooplankton in Moses lake, Washington. M.S. thesis, Univ. of Washington, Seattle.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. Mixing in Inland and Coastal Waters. Academic Press, New York, 483 pp.

Lindell, T. 1977. Physical aspects on the dilution of Moses lake, 1977. Dept. Civi Eng., Univ. of Washington, Seattle (unpublished).

Nece, R.E. J.R. Reed and E.B. Welch. 1976. Dilution for eutrophication control in Moses lake: hydraulic model study. Harris Hydraulics Laboratory Rept. No. 49, Dept. Civil Eng., Univ. of Washington, Seattle 57 pp.

Olson, F.C.W. 1972. Quantitative estimates of filamentous algae. Trans. Amer. Micro. Soc. 69:272-279.

Patmont, C.R. 1980. Phytoplankton and nutrient responses to dilution in Moses Lake. M.S. Thesis, Univ. of Washington, Seattle. 100 pp.

Rushess, D. and R.H. Burns. 1970. Acetyline reduction in Wisconsin lakes. Limnol. Oceanogr. 15:808-813.

Stewart, W.D.P., T. Magne, G.P. Fitzgerald and R.H. Burris. 1971. Nitrogenase activity in Wisconsin lakes of differing degrees of eutrophication. New Phytol. 70:497-509.

Strickland, J.D. and T.R. Parson. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can. No. 67.

U.S.G.S. 1979. Water Resources Data for Washington, Volume 1. United States Dept. of interior. U.S. Geologial Survey.

Welch, E.B. 1979. Lake restoration by dilution. _in_ Lake Restoration, EPA 440/5-79-001, pp. 133-139.

Welch, E.B. 1980. Ecological Effects of Waste Water. Cambridge University Press, 337 pp.

Welch, E.B. and M.D. Tomasek. 1980. The continuing dilution of Moses Lake, Washington. in Proceedings Internat. Conf. Restoration Lakes and Inland Waters, EPA 440/5-81-010, pp. 238-244.

Welch, E.B. and C.R. Patmont. 1980. Lake restoration by dilution; Moses Lake, Washington. Water Research 14:1317-1325.

Wu, J. 1973. Prediction of near-surface drift currents from wind velocity. J. Hydraul. Div., Am. Soc. Civil Eng. 99:1291-1302.