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EVALUATION OF MOSES LAKE DILUTION: PHASE II

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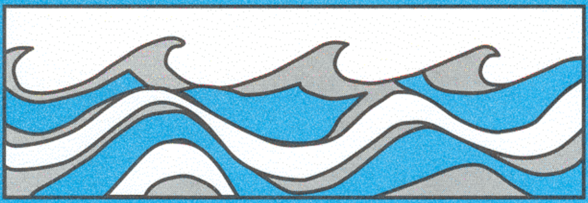

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July 1983

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Dilution: Phase II

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Environmental Engineering and Science
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Final report to Brown and Caldwell
Engineers on behalf of the Moses Lake
Irrigation and Rehabilitation District

University of Washington

Abstract

The second phase of a three-phased restoration plan to restore water quality in hypereutrophic Moses Lake, in eastern Washington, was implemented during the summer of 1982. Phase I involved the addition of high quality, low nutrient dilution water to Moses Lake at Parker Horn, while Phase II planned to transport diluted lakewater from Parker Horn to Pelican Horn, a fairly isolated region of the lake, by means of a pump-fed underground pipeline. However, the first full summer of pump delivery to Pelican Horn (1982) occurred largely in the absence of simultaneous dilution of Parker Horn and instead under typical high-nutrient inflow to the lake. Recent water conditions in Pelican Horn have been of generally very poor quality. Because secondarily treated sewage effluent enters Pelican Horn, nutrient loadings are very high, particularly in P, and algae are severely N-limited. Pumped water delivery at $1.4\ m^3.sec^{-1}$ (50 cfs) not only resulted in significantly accelerated exchange rates in two of the three basins comprising Pelican Horn, but also provided a large input of soluble N to a system containing N-starved algae. Despite the large input of N, algal biomass in the uppermost basin decreased 85 percent, while exchange rate increased from approximately $1\%\cdot day^{-1}$ to $19\%\cdot day^{-1}$, thereby indicating a washout effect. A moderate decrease in algal biomass was observed in the middle basin where sewage effluent is discharged and exchange rate increased from approximately 2%$\cdot$day^{-1} to 14% day^{-1}. A significant increase in algal biomass was observed in the lowermost basin of Pelican Horn where exchange rates remained quite low and substantial pump-induced input of nutrients were received from the middle basin was evidenced. The observed nutrient-algal responses in each of the three basins were predictable based on continuous culture concepts where inflow nutrient concentration controls algal growth rate and flushing controls cell loss or output.

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INTRODUCTION

General

A considerable technical effort has been directed in recent years toward the restoration of lakes and other natural water bodies subject to nutrient enrichment, or eutrophication, and concomitant blooms of nuisance algae. Dilution and/or flushing of such waters by influent additions has been one of several techniques proposed to reduce enrichment and its effects, most specifically in situations where nutrient sources are diverse or where diversion of nutrients is otherwise infeasible. The primary processes by which dilution/flushing manifest water quality improvements are three-fold: 1) algal cell washout through accelerated water exchange rates; 2) reduced concentrations of nutrients and other algal growth factors; and 3) decreased water column stability and stratification.

Manipulation of influent waters to dilute or flush an enriched aquatic system, with the intent of reducing algal biomass, has a theoretical basis in the dynamics of continuous culture systems. Such cultures consist essentially of laboratory vessels of constant volume in which are housed microorganisms (i.e. algae, bacteria) whose biomass is controlled by regulated additions of fresh medium (Novick and Szilard, 1950). In such cultures, as in most natural aquatic systems, concentration of that nutrient most limited in supply relative to the physiologic needs of the alga often becomes the critical determinant of algal biomass. By reducing the inflow nutrient concentration, potential biomass in the vessel (or eutrophic lake) can likewise be reduced. If, alternatively, the rate of inflow and, therefore, rate of water exchange in the vessel (or lake) is increased to a point approaching or exceeding the intrinsic growth rate of the algae, a significant reduction in potential biomass results from a "washing-out" effect.

With the concepts of continuous cultures in mind, it becomes important when considering the use of the dilution/flushing method to establish a distinction between the effects of dilution on the one hand and flushing on the other. Dilution emphasizes suppression of algae within the system by a reduction in nutrients and other algal growth factors that limit further growth and biomass accumulation. Flushing emphasizes removal of algae from the system and causes reduction in biomass in excess of intrinsic growth, irrespective of nutrient concentration and the influence of nutrients on growth and biomass formation. In other words, reduction in algal biomass is achievable by a sufficient increase in water flow through a lake without a decrease in influent nutrient concentrations.

Both mechanisms have been utilized to achieve water quality improvements in Moses Lake, Washington, which has had a recent limnological history of hypereutrophy and nuisance blooms of blue-green algae. Since 1977, the Moses Lake Restoration Project, jointly funded by the U.S. Environmental Protection Agency (EPA), the State of Washington Department of Ecology (DOE), and the Moses Lake Irrigation and Rehabilitation District, has used dilution water additions as the primary means of enhancing water quality in the lake. The original three-phased restoration plan called for the addition of low nutrient Columbia River water via existing irrigation canals into the lake at Parker Horn (since 1977), at Pelican Horn (commenced in 1982), and at the lake's northernmost end (Figure 1). Phase three will probably not be realized. Additions of dilution water to Pelican Horn (Phase two) are not direct but via a pump and pipeline system from Parker Horn, which receives its dilution water directly through Crab Creek. Thus, when pumps are operational, Pelican Horn receives a continuous 1.4 m^3 sec^{-1} (50 cfs) of entrained Parker Horn water.

Recent water conditions in Pelican Horn have been of generally very poor quality. Because secondarily treated sewage effluent enters Pelican Horn (Figure 2), nutrient loadings to this area of the lake are exceedingly high. In addition, the basins of Pelican Horn are quite shallow and normally experience limited circulation and/or exchange of water, which greatly reduces dilution potential and further exacerbates water quality problems. Since the proportion of nitrogen to phosphorus in the effluent is much less than that physiologically required by the phytoplankton, a severe nitrogen limitation has been noted in Pelican Horn compared to algae in other parts of the lake (Welch et al., 1969; Bush, 1971; Welch, 1980a).

These conditions prompted the plan to improve water quality in Pelican Horn by a pump-induced dilution/flushing program. While the original intent was to operate pumps while Parker Horn was being diluted with low-nutrient water from East Low Canal, the first full summer of water delivery to Pelican Horn (1982) occurred largely in the absence of simultaneous dilution of Parker Horn and instead while

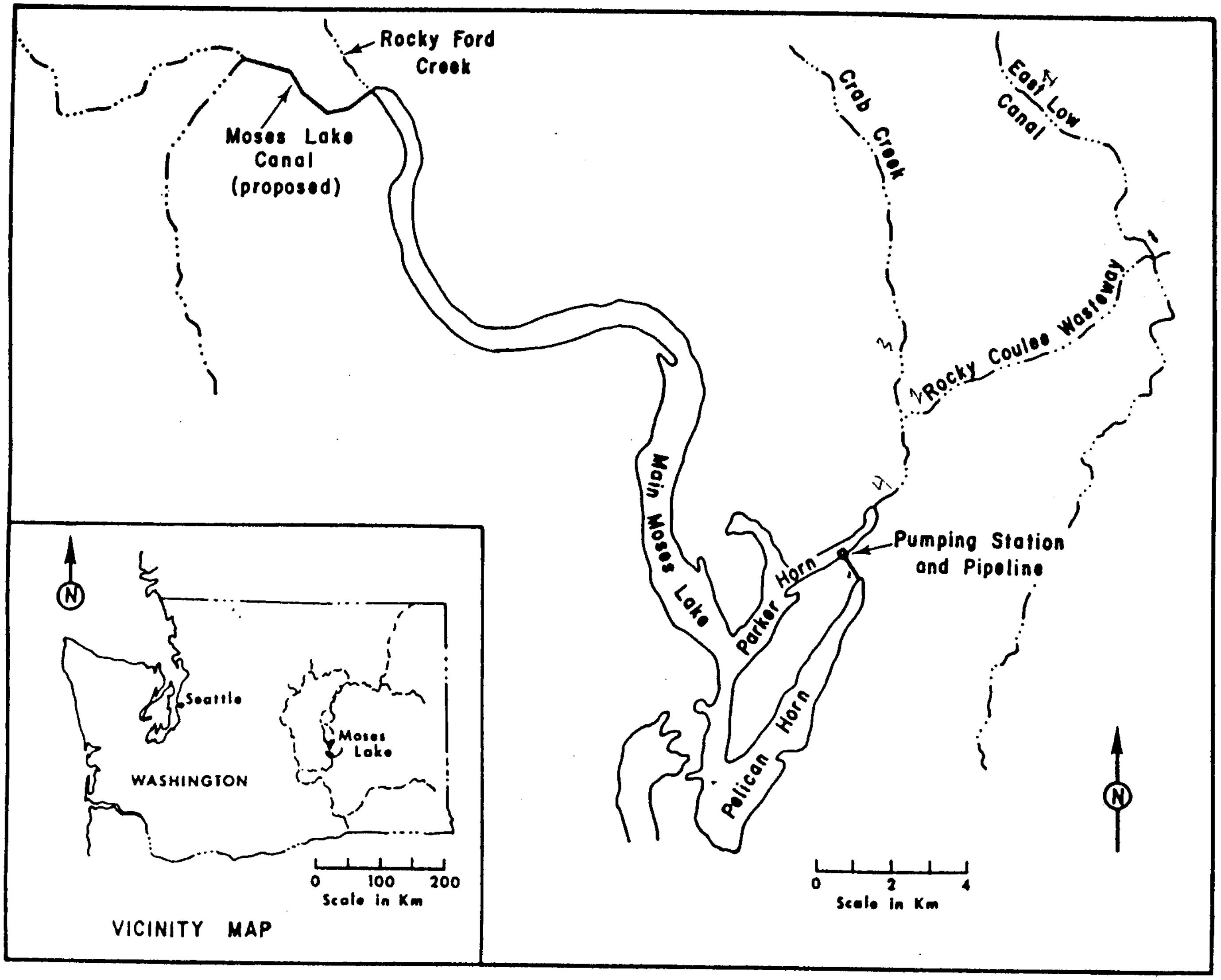

Figure 1. Moses Lake vicinity and project locations

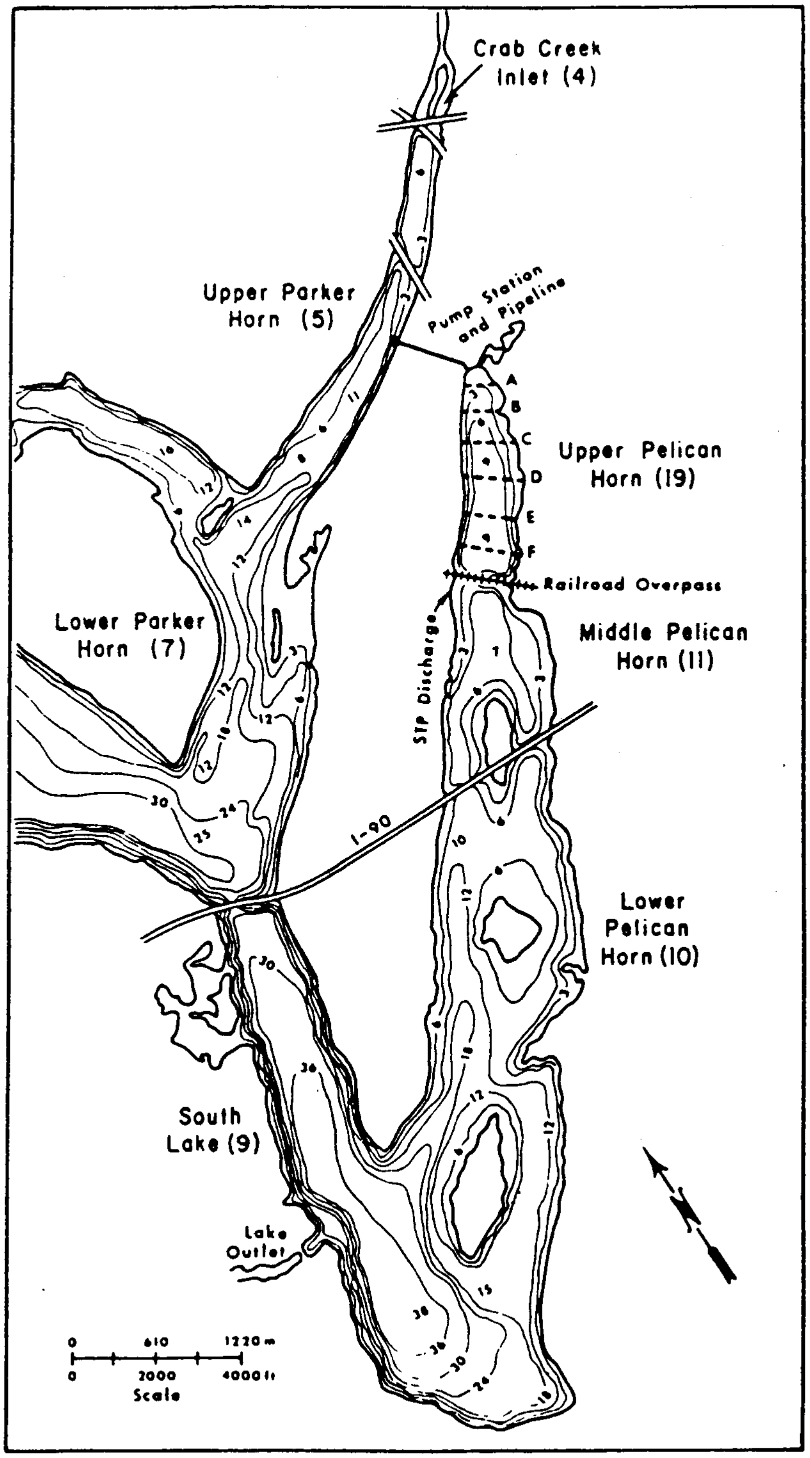

Figure 2. Pelican Horn vicinity map indicating basins, pumping facilities, and morphometry. Depth contours in feet (based on Sylvester and Oglesby, 1964).

high-nutrient Crab Creek waters dominated the inflow (Figure 1). Because of unavoidable delays in pump start-up, overlap with Parker Horn dilution occurred for only two of approximately ten weeks of operation. Continued operation of pumps after cessation of dilution water input was encouraged by those involved in the project in part to assess the effects of flushing in Pelican Horn as a mechanism independent of dilution.

On the basis of continuous culture concepts, it was postulated that two principal mechanisms should determine algal biomass levels during pumping operations in Pelican Horn: 1) a potential decrease in algal biomass due to washout when the basin flushing rate (inflow rate divided by basin volume) exceeds algal growth rate; and/or 2) a potential increase due to elevated inflow concentrations of the limiting nutrient (nitrogen). Furthermore, it was surmised that the extent to which the influence of one or the other of these mechanisms would influence the actual observed phytoplankton levels would differ between the basins comprising Pelican Horn (Figure 2). For example, Upper Pelican Horn, which is characterized by a relatively small intrinsic volume would experience a rather rapid flushing rate during pumping operations, subjecting phytoplankton there to potential washout despite high inflow nutrient levels. On the other hand, Lower Pelican Horn, with its relatively large volume, would remain at a very low flushing rate and thus would likely experience large algal biomass accumultion as a result of pump-induced high nutrient inputs. Finally, responses in Middle Pelican Horn would be expected to fall somewhere between those of the other two basins, although the discharge of sewage effluent to that basin adds a measure of complexity to predictions.

Using continuous culture principles as a conceptual framework, an assessment of pump-induced effects on nutrients, phytoplankton, and related lake quality parameters in Pelican Horn was undertaken during the inaugural 1982 pumping phase of the Moses Lake restoration project. This report includes the observed data, an interpretation of their meaning and recommendations for future management and study.

Objectives

The objectives of the study described herein were as follows:

1. Determine the water quality response in Pelican Horn from delivering 1.4 m^3 sec^{-1} of Parker Horn water. Compare results with other parts of the lake and other years through an analysis of the following:
   a. flushing rates and water movement,
   b. macronutrient concentrations and loading,
   c. phytoplankton composition and biomass, and
   d. water transparency.
2. Determine the response in the lower lake (South Lake) of moving these quantities of water through Pelican Horn using analysis of these same constituents.
3. Compare observed vs. predicted water quality responses in Pelican Horn using conventional continuity and nutrient loading equations.
4. Relate these responses to continuous culture concepts and

determine the relative importance of flushing (washout) vs. dilution (change in nutrient income).

5. Based on the findings, determine the adequacy of pumping for effecting water quality improvements and, if appropriate, suggest modifications in future operation and study.

Case Studies

Despite being straightforward theoretically, dilution/flushing has been used sparingly in lake restoration projects world-wide (Welch, 1979). While clearly the demand for supplemental inflow waters of either sufficient quality or quantity has made dilution and/or flushing prohibitive for many lake improvement projects, others in a position to receive such waters have found it an effective and economical approach.

In most instances where the idea of water replenishment has been attempted or proposed, the mechanism of dilution rather than flushing has usually been implicated as responsible for algal reduction. In Moses Lake, additions of high quality, low nutrient water to the lake's main inflow (Crab Creek) during spring and summer has resulted in significant improvements over pre-dilution levels in trophic state indicators, such as total phosphorus, chlorophyll a, and water transparency (Welch and Patmont, 1980; Welch et al., 1982). While the quantities of water needed to reduce inflow concentrations of nitrogen and phosphorus to the lake are often large (10-30 m^3 sec^{-1}), such additions have produced little increase in April - September whole lake flushing rates, which are on the order of 2.2 to

3.3 $year^{-1}$ (Welch and Patmont, 1980). Exceptions often arise in Parker Horn, a relatively shallow and narrow arm of the lake, which directly receives dilution inputs from Crab Creek (Figure 2). Here, during periods of dilution, exchange rates frequently reach 0.07 to 0.13 day^{-1}, compared to the normal 0.01 day^{-1}, with rates approaching 0.30 day^{-1} for short periods (Welch, 1979). Such rates were thought to result in significant algal biomass reduction in Parker Horn from cell washout to the lower lake.

The dilution of Green Lake, Seattle, Washington, beginning in 1962, involved long-term water additions at relatively low rates (Oglesby, 1969). The lake's flushing rate was increased from an estimated 0.83 to 2.6 $year^{-1}$ as a result of adding low-nutrient water from the Seattle domestic supply. However, the striking improvements in lake quality resulting from these additions, such as a 90 percent decrease in chlorophyll a and a four-fold increase in water transparency, resulted largely from reduced nutrient inflow, with washout having little or no effect.

An interesting contrast to Green Lake exists in the experiences of Switzerland's Rotsee, site of perhaps the earliest known lake flushing project (Stadelmann, 1980). Following construction of a canal connecting the lake and the Ruess River in 1922, inputs of diverted river water increased lake exchange rates from 0.33 to 2.5 $year^{-1}$ (approximately 0.01 day^{-1}), rates essentially identical to those obtained by dilution of Green Lake. Whereas in both Green Lake and Moses Lake dilution of inflow nutrients led to substantial improvements in lake quality, conditions in Rotsee actually worsened, due to high nutrient concentrations in the river water used to flush the lake. Considerable improvements were eventually realized, however, when Ruess River nutrient concentrations were reduced substantially by wastewater treatment during the 1970's. Still, the Rotsee experiment demonstrated that flushing rates of around 0.01 day^{-1} were insufficient to reduce algal biomass by cell washout alone.

Lake improvement projects are not the only situations in which the effects of flushing on phytoplankton has been explored. Biomass has been maintained at low levels in both lakes and estuaries by relatively high natural flushing rates. Dickman (1969) observed a four-fold increase in primary productivity and a three-fold increase in biomass within protected enclosures compared with open waters of Marion Lake, British Columbia, during rain-induced spates which increased lake flushing to 0.43 day^{-1}. Also noted was a successional shift in phytoplankton to a community dominated by small, predominantly flagellated species having high reproductive rates. It was therefore concluded that flushing, while causing a decline in biomass and productivity per unit volume, was also a dominant selective pressure for highly productive species. Findenegg (1965) made similar observations in the Lunzer See, Austria, when epilimnetic replacement on the order of 0.33 to 0.50 day^{-1} resulted in a 50 percent reduction in areal algal productivity within four days. However, as in Marion Lake, flushing in the Lunzer See resulted in increased productivity per unit biomass.

The relationship of flushing rates in lakes to their trophic status has been considered in detail by Dillon (1975). By comparing two Ontario lakes, Dillon established that widely dissimilar flushing rates (0.24 vs. 16 year^{-1}) were the key factor explaining an essentially identical trophic status despite a 20 times difference in respective phosphorus loadings. An increased rate of flushing was further found to decrease that fraction of the phosphorus input not lost to the outflow, referred to as the "phosphorus retention coefficient." Both findings indicated that inflow concentration of phosphorus is a more important determinant of trophic status than the annual phosphorus loading and enabled Dillon to suggest important improvements of Vollenweider's original total phosphorus loading - mean depth model (Vollenweider, 1968).

Persson (1981), observing the growth and temporal variation of the blue-green alga Oscillatoria in a Finnish hypereutrophic estuary, found that washout reduced biomass when specific algal growth rate was smaller than the flushing rate of the bay. At flushing rates of 0.081 and 0.094 day^{-1}, mean biomass was less than 50 percent that at 0.047 day^{-1}, while at 0.207 day^{-1}, mean biomass was approximately 30 percent of the 0.047 day^{-1} level.

Finally, Karp (1975) in a limnological investigation of Banks Lake, Washington, a pumped storage reservoir, noted that changes in flushing rates due to variations in pumping rates and lake elevation exerted a major influence on phytoplankton biomass and production. Based on variations in chlorophyll a levels, washout was considered a major factor when flushing rates of around 0.17 day^{-1} or greater were achieved and the nutrient supply rate was not limiting. Under low nutrient conditions, however, which were frequently observed in this oligotrophic reservoir, the mechanism of observed reductions was complicated by simultaneous changes in nutrient supply rate.

DESCRIPTION OF THE STUDY AREA

Moses Lake is a relatively large, shallow, polymictic lake that lies within the semi-arid region of the Columbia River Plateau in Central Washington, 290 km east of Seattle (Figure 1). The City of Moses Lake, population 11,300, occupies the lands surrounding Parker and Pelican Horns, and serves as a major commercial center in an agriculturally dominated region.

The lake lies within an ancient river bed formed largely by catastrophic floods and glacier recession in the Grand Coulee region during the Pleistocene Epoch 10 to 25 thousand years ago (McKee, 1972). Eventual natural damming by drifting sand dunes resulted in the formation of a lake with a characteristic dendritic shape.

The semi-arid climate of the region is characterized by extremes of temperature, commonly exceeding 38° C in summer and -18° C in winter. The lake normally experiences several weeks of ice cover during the winter months. Prevailing winds are southwesterly and are often strong, occasionally severe, during spring and fall. Total precipitation is only about 20 cm annually in the area, most of which occurs from November through March. Pan evaporation is characteristically high, particularly during the warm summer months, with a mean annual Class A pan of 150 cm.

Moses Lake's original socio-economic value was almost exclusively as a source of irrigation water for local agriculture; however, residential encroachment onto farmlands has reduced this demand somewhat. More recently, the lake has gained popularity as a major recreational area in the state. Shoreline land use includes 73 ha of parks and campgrounds open to the public. Fishing, boating, swimming, and water skiing are all popular recreational activities on the lake. Moses Lake experiences extensive angler use during most of the year and is currently considered one of the finest warm-water fisheries in the state (Brown and Caldwell, 1980).

Physical Features

Because of its dendritic shape, Moses Lake is morphologically composed of several distinct sub-basins. A plan view of the lake and the locations of the respective sub-basins are shown in Figures 2 and 3. Morphometric basin characteristics are listed in Table 1. The total surface area of the lake is 2,790 ha (at 319 m MSL), with a total volume of 156×10^6 m^3, a mean depth ($\bar{z}$) of 5.6 m, and a maximum recorded depth (Z_m) of 11.8 m. During non-dilution periods, mean flushing rate (ρ), computed as the mean annual inflow discharge divided by total lake volume, is on the order of 2.5 $year^{-1}$.

The two main surface water inflows are Crab Creek, entering Parker Horn, and Rocky Ford Creek, entering at the northernmost point of the main lake (Figure 1). Crab Creek has a catchment area above Moses Lake of approximately 5,180 km^2 with a mean annual discharge of 3.1 m^3 sec^{-1} (USGS, 1980). Sources of Crab Creek water include groundwater seepage, irrigation return flow, and runoff from precipitation. Rocky Ford Creek flows approximately 12 km to the lake from its source at Rocky Ford Springs and forms a catchment of only 62 km^2. Because it is spring-fed, Rocky Ford Creek maintains a rather

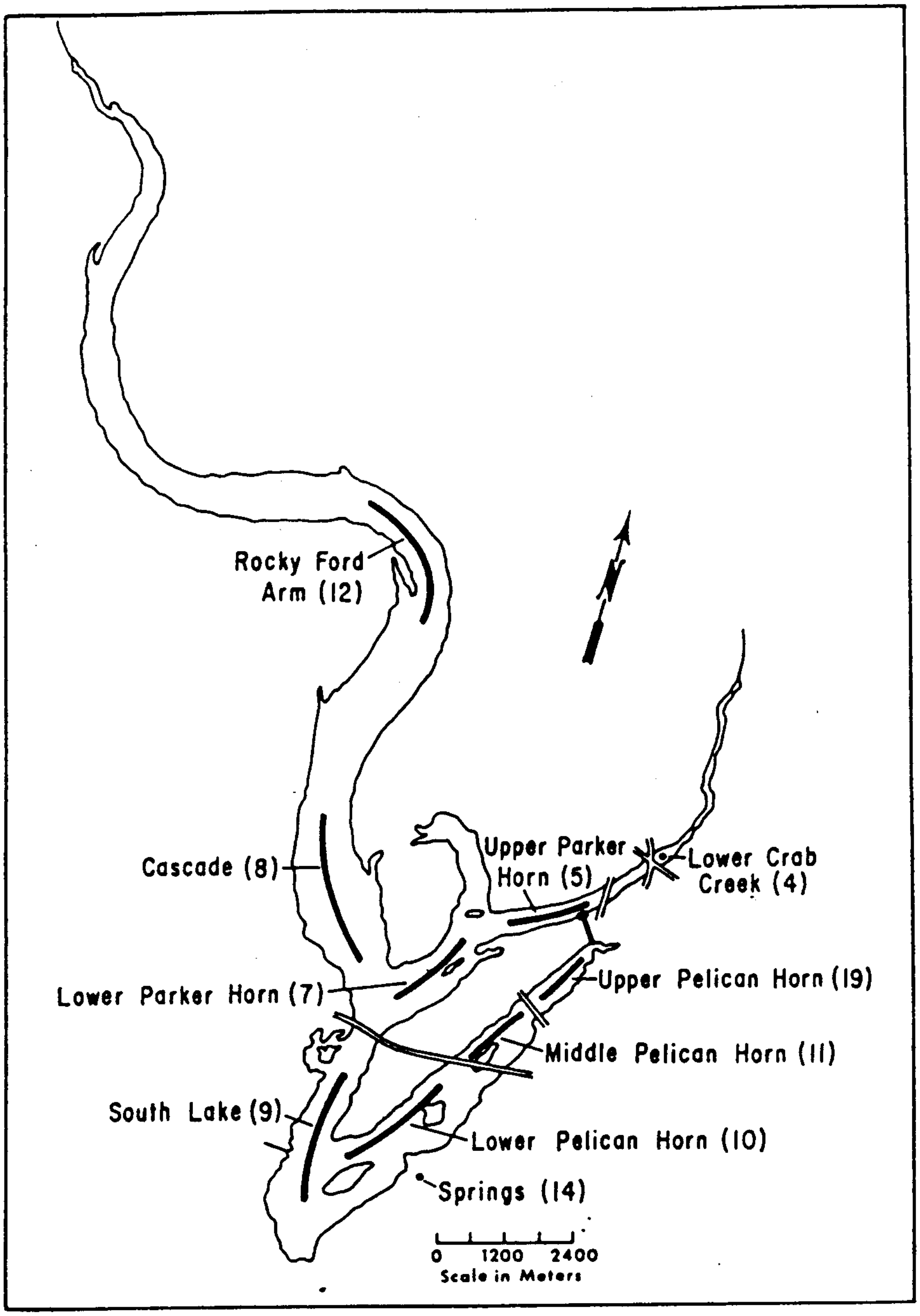

Figure 3. Moses Lake basins and sampling transect locations.

Table 1. Basin characteristics of Moses Lake.[1]

Basin	Depth (m)	Area (ha)	Volume (x 10^6 m^3)	% Lake Volume	Representative Station Sample Location
1. Upper Parker Horn	Z_m=4.0; $\bar{Z}$=1.8	79.3	1.44	0.9	5-T
2. Lewis Horn	Z_m=5.5; $\bar{Z}$=3.5	90.0	3.19	2.0	6-T[2]
3. Lower Parker Horn	$\bar{Z}$=4.9	221.3	10.88	7.0	7
a. strata 1	0-1.0		2.39	1.5	7-T, 7-S
b. strata 2	1.0-3.5		4.46	2.9	7-2
c. strata 3	3.5-9.5		4.02	2.6	7-B
4. Cascade	Z_m=11.5; $\bar{Z}$=8.4	385.8	32.32	20.8	8-C, 8-T
5. South Lake	$\bar{Z}$=7.2	441.4	31.85	20.5	9
a. strata 1	0-1.0		4.75	3.1	9-T, 9-S
b. strata 2	1.0-3.5		10.54	6.8	9-2
c. strata 3	3.5-8.5		13.16	8.5	9-6
d. strata 4	8.5-11.5		3.40	2.1	9-B
6. Lower Pelican Horn	$\bar{Z}$=3.5 m	236.7	8.37	5.4	10
a. strata 1	0-1.0		2.76	1.8	10-T, 10-S
b. strata 2	1.0-3.5		4.86	3.1	10-2
c. strata 3	3.5-7.0		0.75	0.5	10-B
7. Middle Pelican Horn	Z_m=2.2; $\bar{Z}$=1.3	81.6	1.07	0.7	11-T
8. Upper Pelican Horn	Z_m=2.2; $\bar{Z}$=1.4	49.2	0.69	0.4	19
9. Rocky Ford Arm	Z_m=9.5; $\bar{Z}$=5.5	1204.6	65.85	42.3	12-C, 12-T
Moses Lake - Total	$\bar{Z}$ = 5.6	2789.9	155.66	100.0	

[1] Based on lake level of 319 m MSL.

[2] Not sampled during this study.

consistent year-round discharge with an annual mean of 2.1 m^3 sec^{-1} (USGS, 1980).

Since the start of annual spring-summer dilution water additions in 1977, East Low Canal water (via Rocky Coulee Wasteway) has contributed the largest inflow volumes to Moses Lake on an annual basis (Brenner, 1983). Rocky Coulee Wasteway connects East Low Canal with Crab Creek at a point 2.4 km upstream of the outlet to Moses Lake. Although the capacity of the wasteway is approximately 130 m^3 sec^{-1}, flows during dilution are generally less than 30 m^3 sec^{-1} (U.S. Bureau of Reclamation records).

Groundwater seepage is thought to be a major source of inflow to Moses Lake. Although amounts cannot be directly measured, water budget calculations have estimated groundwater contribution at 20 to 33 percent of the total annual inflow (Patmont, 1980; Brenner, 1983). Furthermore, regional groundwater modeling studies have suggested that Moses Lake, along with adjacent Potholes Reservoir, is a major discharge area for much of the groundwater in the Quincy Basin lying to the north, east, and west of the lake (Tanaka et al., 1974).

Outflow sources from Moses Lake include controlled spillage to Potholes Reservoir over a dam and outlet works in South Lake (Figure 2), irrigation pumping, and evaporation. No apparent surface outlet existed until 1904 when severe flooding scoured a channel which lowered the lake level two to three meters (Graham, 1964). After an unsuccessful attempt in 1909, the dam and outlet works were eventually completed in 1929, which still serves to control spillage to Potholes Reservoir and maintain Moses Lake surface level at approximately 319 m MSL during summer and 318 m MSL during winter.

A limited amount of irrigation water (exact quantities unmonitored) is pumped from Moses Lake. Even these amounts are gradually declining, however, as agricultural lands around the lake are being converted to residential area (Brown and Caldwell, 1980).

Since this study is concerned predominantly with Pelican Horn it is important to consider this area of the lake in detail. Pelican Horn is the southernmost extension of Moses Lake, oriented toward the northeast from the lake's main axis (Figure 1). In total, Pelican Horn has a surface area of approximately 368 ha, a volume of 10.1 x 10^6 m^3, a mean depth ($\bar{z}$) of 2.7 m, and a maximum depth (Z_m) of 7.3 m.

Three distinct sub-basins comprise Pelican Horn and these are further referred to in this study as: 1) Upper Pelican Horn, consisting of the region from the horn's apex to the railway overpass; 2) Middle Pelican Horn, from the railway overpass to the Interstate-90 freeway overpass; and 3) Lower Pelican Horn, from the I-90 overpass to the lower main lake, or South Lake (Figure 2). Both the railroad and I-90 overpasses are constructed principally atop earthfill with relatively short bridge sections providing only 4 m width and 13.5 m width, respectively, of water passage between the sub-basins. As such, these constrictions significantly impair water exchange and contribute to often substantial inter-basin variations in water quality characteristics. Pelican Horn morphometry is shown in Figure 2 and basin statistics are listed in Table 1.

Groundwater seepage and sewage treatment plant discharge constitute the two principal sources of inflow to Pelican Horn under normal (non-pumping) circumstances. Evidence suggests that a sizeable fraction of the total groundwater flow to Moses Lake discharges into Pelican Horn. Groundwater discharge into Upper and Middle Pelican basins has been estimated by sodium mass balance as 0.26 m^3 sec^{-1} based on 1969 - 70 and 1978 - 79 data (see Results). This quantity represents about eight percent of the annual total lake groundwater input in an area representing only about one percent of the total lake area and volume. In addition, U.S. Bureau of Reclamation piezometric contour data indicates that subsurface flow resulting from irrigation recharge of aquifers to the northeast of the lake is directed primarily to Pelican Horn (K. Behrens, USBR, pers. comm.). Groundwater flow is not constant during the year, but arrives at the lake principally during the fall, coincident with lowered lake level and cessation of seasonal irrigation.

The City of Moses Lake operates a secondary trickling-filter wastewater treatment plant that discharges approximately 1.39 x 10^6 m^3 of treated effluent per year into Pelican Horn with a mean discharge of approximately 3,800 m^3 day^{-1}. Although the plant is located alongside Upper Pelican Horn, it discharges into Middle Pelican Horn just south of the west end of the railway overpass (Figure 2). The motive behind siting the outfall in the Middle basin was to enhance effluent dispersal (J. Peck, Moses Lake STP, pers. comm.). Eventual complete diversion of the effluent away from the lake is tentatively planned by the year 1985.

SAMPLING PROCEDURES AND ANALYSIS

Design

The sampling design employed in this study was essentially a continuation of that proposed by Welch et al. (1969) and used in all subsequent pre- and post-dilution study years (1969 - 70, 1977 to present) (Bush, 1971; Patmont, 1980; Welch et al., 1982; Brenner, 1983). The motive behind this design was that, since Moses Lake is quite large and readily divisible into distinct morphological sections, a sampling scheme able to elucidate biological and chemical variation between basins was preferred. The establishment of eight different sampling regions in the lake resulted. Furthermore, pronounced patchiness in the distribution of phytoplankton and other constituents made sampling along transects desirable, since this would tend to "average out" horizontal variability. Finally, the use of discrete sampling was proposed to obtain measures of inflow and outflow parameters and vertical water column profiles at transect midpoints. The justification for this study design was that it allowed for horizontal and vertical characterization of a relatively large, irregularly-shaped lake, while also keeping the resultant number of samples for analysis within logistical constraints.

Field Sampling and Laboratory Analysis

Samples were collected approximately biweekly from March through October 1982 at eight lake stations and five inflow stations (Figure 3 and Table 2). In addition, a natural spring approximately 120 m

Table 2. Location and type of sample collection from March through October 1982.

Station No.	Location	Sample Type[a]	Frequency
1	East Low Canal	surface	biweekly[b]
2	Rocky Coulee Wasteway	surface	biweekly
3	Crab Creek above RCW	surface	biweekly
4	Crab Creek below RCW	surface	biweekly
5	M.L. Upper Parker Horn	T	biweekly
7	M.L. Lower Parker Horn	M+T	biweekly
8	M.L. Cascade Basin	M+T	biweekly
9	M.L. South Lake	M+T	biweekly
10	M.L. Lower Pelican Horn	M+T	biweekly
11	M.L. Middle Pelican Horn	T	biweekly
12	M.L. Rocky Form Arm	M+T	biweekly
13	Rocky Ford Creek	surface	biweekly
14	Spring off Pelican Horn	groundwater	monthly
19	M.L. Upper Pelican Horn	T	biweekly

[a] M -- midpoint discrete; T -- transect composite (see text).

[b] During dilution periods only.

from the east shore of Lower Pelican Horn was sampled monthly to characterize groundwater. A complete listing of water quality constituents analyzed during the study is presented in Table 3.

Composite lake samples were collected from transects by pumping water from a Pitot-like tube attached to the boat transom at a depth of 0.4 m while traveling through the approximate mid-line of each basin area. Discrete samples were collected at Stations 7, 9, and 10 with a 6-liter Van Dorn grab bottle from the midpoint of each transect at depths just below the surface, 2m, and 6m, as well as one meter above the bottom where sufficient depth existed. Composite vertical samples were taken at the transect midpoints of Stations 8 and 12 using a flexible PVC tube lowered to the bottom. Vertical water sampling was not performed at Stations 5, 11, and 19 due to the shallow nature of these basins (mean depth: 1.8m, 1.3m and 1.4m, respectively).

Water Analysis

Temperature was determined in one meter increments at each transect midpoint for each sampling date using a YSI temperature probe. pH was determined with an Orion Research pH meter at depths just below the surface, 2m, and 6 m, as well as one meter above bottom where sufficient depth existed. Secchi disk depth was also measured at transect midpoints on each sampling date. Dissolved oxygen concentrations were determined for bottom water samples using the azide modifications of the Winkler titration (APHA, 1975). Specific conductance was determined with a Barnstead conductivity

Table 3. Analyzed water quality constituents, Moses Lake sampling of March through October 1982.

Parameter (units)	Analytical Precision
Temperature (C)	0.1 °C
pH (units)	0.1 unit
Secchi depth (m)	0.1 m
Dissolved oxygen (mg l^{-1})	0.1 mg l^{-1}
Specific conductance (μmhos cm^{-1})	1 μmho cm^{-1}
Soluble reactive phosphorus (μg P l^{-1})	5 μg P l^{-1}
Nitrate-nitrite nitrogen (μg N l^{-1})	10 μg N l^{-1}
Ammonia nitrogen (μg N l^{-1})	10 μg N l^{-1}
Total phosphorus (μg P l^{-1})	5 μg P l^{-1}
Total nitrogen (μg N l^{-1})	10 μg N l^{-1}
Alkalinity (meq l^{-1})	0.1 meq l^{-1}
Chlorophyll _a_ (μg l^{-1})	5 μg l^{-1}
Cell volume (mm^3 l^{-1})	1 mm^3 l^{-1}
Cell carbon (μg C l^{-1})	10 μg C l^{-1}

bridge and alkalinity by potentiometric titration with 0.02 N H_2SO_4 to endpoint pH 4.8 in the laboratory (APHA, 1975).

Samples for soluble nutrients were obtained by filtering lake water through 0.45 micron glass-fiber filters 2 to 6 hours after collection, pouring the filtrate into acid-rinsed polyethylene bottles, and preserved by freezing for subsequent analysis. Filters used for soluble nutrients were soaked in distilled water prior to use. Soluble reactive phosphorus (SRP) was determined by the acid molybdate heteropoly blue method (Strickland and Parsons, 1972). Soluble nitrogen as nitrate plus nitrite was determined by cadmium reduction and soluble nitrogen as ammonia by the phenate method, both on a Technicon II autoanalyzer (EPA, 1979).

Unfiltered water samples for total phosphorus and total nitrogen analyses were placed in individual acid-rinsed poly bottles and preserved with 1 N H_2SO_4 (4 drops per 60 ml sample) and by freezing, respectively, for subsequent laboratory analysis. Total phosphorus was analyzed by the acid molybdate heteropoly blue method after persulfate digestion (Strickland and Parsons, 1972). Total nitrogen was determined by UV light oxidation followed by autoanalysis of nitrate (Strickland and Parsons, 1972).

Phytoplankton

Samples for phytoplankton pigment chlorophyll a (chl a) were obtained by filtering 100 ml of lake water onto 0.45 micron glass-fiber filters 2 to 6 hours after collection. Six drops of one percent magnesium carbonate suspension were added during the filtering process. Exposed filters were then folded, placed in labeled envelopes and stored frozen in opaque jars containing desiccant. Chl _a_ was analyzed using the fluorometric technique on 90 percent acetone extracts before and after addition of three drops of 1N HCl to correct for pheaophyton (Strickland and Parson, 1972).

Phytoplankton counts were obtained from transect samples from Stations 5, 7, 9, 10, 11, and 19. Samples were preserved with Lugol's acid-iodine solution and stored in the dark (APHA, 1975). Populations were estimated by cell counts using a Palmer-Maloney cell with an Olympus compound microscope at 20 power. Counts were based on 100 Whipple grids, or a total of 300 discrete algal cells over the Palmer-Maloney field, whichever came first. Identifications of algae were made to the genus level and were based on the taxonomic keys of Palmer (1977) and Prescott (1979). Filamentous algal forms were enumerated using the method of Olson (1972). Phytoplankton biovolumes were calculated by multiplying the number of cells of a given genus by the mean individual cell volume for that taxon. Mean individual cell volumes were determined on the basis of stage micrometer measurements and appropriate geometric configurations of at least ten discrete cells per taxon. The phytoplankton volume to carbon relationships of Strathmann (1977) were used to compute cell carbon content based on cell volumes.

Water Movement

In addition to the samples described above, _in situ_ measurements of specific conductance were performed at inflow locations and at the middle and endpoints of each transect to trace movement of East Low Canal (dilution) water in the lake. The large difference in concentrations of dissolved solids between water from East Low Canal and that in the lake make specific conductance measurements a very adequate "tracer" of dilution water in the lake.

Following start-up of pumping into Pelican Horn, mixing, movement, and circulation of water within Upper Pelican Horn resulting from the discharge were investigated. To assess completeness of mixing from a chemical standpoint, samples were collected from five additional lateral transects in Upper Pelican Horn (Figure 2) on each of the five sampling dates that followed pump startup, and were subsequently analyzed for specific conductance and chl _a_. The trajectories of small drogues released in the approximate centerline of the discharge plume were used to re-evaluate circulations approximately seven weeks after pump start-up. Drogues consisted of two perpendicular plexiglass vanes, each of approximately 900 cm^2 surface area, attached by monofilament line to an 8 cm diameter styrofoam sphere. Vanes were set to a depth of 0.5 m which was roughly equal to one-half the plume depth at the discharge pipe.

RESULTS

Sources and Movements of Water in Pelican Horn

Dilution Input and Pump Delivery

Pumped delivery of entrained Upper Parker Horn waters to Upper Pelican Horn during 1982 occurred at the pump design rate of 1.42 m^3 sec^{-1} over an operation period of 1720 hours (71.7 days) between July 1 and September 30 (Table 4). Despite plans to operate pumps concurrently with dilution water additions from East Low Canal to Parker Horn, early delays and interruptions in pump start-up resulted in an abbreviated period of overlapping operation. Of the 8.79×10^6 m^3 total pump water delivery to Pelican Horn only 1.76×10^6 m^3, or 20 percent, occurred during dilution.

The addition of East Low Canal dilution water to Parker Horn in 1982 occurred during a period of 124 days from March 28 to August 2. The quantity introduced was relatively large compared with previous dilution years (1977-81). For 1982, 1.18 entire lake volumes of dilution water were delivered, compared with 1.20 lake volumes in 1977, 0.74 in 1978, 1.66 in 1979, 0.23 in 1980, and 0.46 in 1981.

Water Movement

The most obvious physical effects imparted by additions of pumped and/or dilution waters to the basins of Pelican and Parker Horn, respectively, were significant increases in average water exhanges rates (Table 4). Such rates are particularly critical during the spring-summer period of algal succession and growth

Table 4. Dilution water and normal inflows to Moses lake during 1982 and resultant flushing rates.

	Inflow Discharge ($m^3 \times 10^6$)				Average Water Flushing Rates (day^{-1})			
Period	East Low Canal Addition[1]	Crab Creek + RCW[2]	STP[3]	Pelican Horn Pumps[4]	Lower Parker Horn (7)	Upper Pelican Horn (19)[5]	Middle Pelican Horn (11)[6]	Lower Pelican Horn (10)[6]
3/28-4/4 (7 days)	5.14	1.37	0.03	0	0.09	0.01	0.02	< 0.01
4/4-5/16 (41 days)	50.16	7.18	0.15	0	0.13	0.01	0.02	< 0.01
5/16-7/11 (53.5 days)	104.73	11.55	0.20	0.08	0.20	0.02	0.03	< 0.01
7/11-7/25 (14 days)	17.13	3.85	0.06	0.71	0.14	0.09	0.07	0.01
7/25-8/2 (8 days)	5.87	2.24	0.03	0.98	0.09	0.19	0.14	0.02
8/3-9/30 (59 days)	0	16.01	0.24	7.02	0.02	0.19	0.14	0.02
7/1-9/30 (92 days)	42.58	26.29	0.37	8.79	0.07	0.15	0.11	0.01

[1] Discharges into Crab Creek (4)

[2] Discharges into Upper Parker Horn (5)
RCW = Rocky Coulee Wasteway baseflow = 83600 m^3 day^{-1}

[3] Discharges into Middle Pelican Horn (11)

[4] Discharges into Upper Pelican Horn (19)

[5] Includes groundwater discharge = 9500 m^3 day^{-1}

[6] Includes groundwater discharge = 22460 m^3 day^{-1}

in the lake because they can be the mechanism responsible for potential cell washout. Pumping into Pelican Horn resulted in rates approaching 0.19 and 0.14 day^{-1} in Upper and Middle Pelican Horn, respectively, as a result of the relatively small intrinsic basin volumes (see Table 1). The larger volume of Lower Pelican Horn accounted for maintenance of a significantly lesser rate of 0.02 day^{-1}.

Since there are no natural surface inflows of any significance to Pelican Horn, exchange rates in Pelican Horn during non-pumping periods are not directly measureable, but are estimated to be quite low (0.01 day^{-1}). Natural water exchange must result primarily from groundwater seepage and wind-driven currents emanating along the fetch of Pelican Horn. This exchange is made all the more difficult in Upper and Middle Pelican Horns by the restrictions to throughflow imposed by the railway and I-90 overpasses, as previously mentioned.

Groundwater discharge into Upper and Middle Pelican Horn basins was estimated using a mass balance of sodium (Na$^+$) based on values from 1969-70 and 1978-79 measurements. The mass balance equation used was of the form:

$$Q_{STP}\,C_{STP} + Q_{GW}\,C_{GW} = (Q_{STP} + Q_{GW} + Q_{EVAP})\,C_{PEL} \qquad (1)$$

which, when rearranged to solve for groundwater discharge (Q_{GW}), yields:

$$Q_{GW} = \frac{Q_{STP}\,(C_{PEL} - C_{STP}) - Q_{EVAP}\,C_{PEL}}{C_{GW} - C_{PEL}} \qquad (2)$$

where: Q_{STP} = mean sewage plant discharge = 4.6×10^{-2} m^3 sec^{-1},
C_{STP} = mean sewage plant Na^+ concentrations = 81.8 mg ρ^{-1}
C_{PEL} = mean Na^+ concentration for Upper and Middle Pelican
Horn basins = 41.4 mg l^{-1}
Q_{EVAP} = mean summer evaporation = 5.0×10^{-2} m^3 sec^{-1}
and C_{GW} = mean groundwater Na^+ concentration (station 14)
= 2.6 mg $l-^{1}$

Precipitation and water exchange through the I-90 overpass were assumed negligible.

The solution based on the above mean values gives an estimated groundwater discharge of 2.6×10^{-1} m^3 sec^{-1} for Upper and Middle Pelican basins combined. If this discharge is assumed homogeneous throughout the basins, component discharges would be roughly 1.0×10^{-1} m^3 sec^{-1} and 1.5×10^{-1} m^3 sec^{-1} for Upper and Middle Pelican basins, respectively, based on difference in areas. These estimates are included in the flushing rates of Table 4 as indicated.

With the commencement of pumping into Pelican Horn in July and a brief ensuing period of simultaneous dilution inflow to Parker Horn, East Low Canal dilution water, which has a relatively low specific conductance (148 ± 7.5 μmhos.cm^{-1}) compared with normal non-dilution inflow and typical lake concentrations (350-575 μmhos.cm^{-1}), was used to trace the movement of pumped inflow and flushing efficiency in the basins of Pelican Horn. Conductance is a measure of ionic concentration in solution and is due primarily to the cations Na^+, Ca^{2+}, and Mg^{2+} and the anions HCO_3^-, SO_4^{2-}, and Cl^-. For purposes as a tracer of water movement, it is assumed that specific conductance, and thus the principle representative ions in solution, is conservative.

The fraction of East Low Canal water achieved in the basins of Pelican Horn with time are listed in Table 5 and compared aside South Lake, Rocky Ford, and Parker Horn basins. The values achieved on each sampling site were determined by:

$$R = (C_i - C_m)/(C_i - C_d) \tag{3}$$

where R = relative concentration (fraction) of dilution water in the lake at time t,

C_i = lake water conductivity at initial time 0,

C_m = lake water conductivity at time t,

and C_d = conductivity of dilution water.

Calculated R values reveal that fractions of dilution water in Upper Pelican Horn rose from 0.02 to 0.56 between June 22 and July 20, based on a pumped inflow of 5.66×10^5 m^3 or 0.84 times the volume of Upper Pelican Horn. The maximum measured dilution water fraction (R = 0.71) in Upper Pelican Horn occurred on August 3, the day after dilution additions to Parker Horn were halted. At that point, the dilution fraction in Upper Pelican Horn was essentially equivalent to that of Parker Horn inflow and indicated that equilibrium between Parker Horn and Upper Pelican Horn was approached. Smoothed specific conductance curves (Figure 4) in fact indicate that

Table 5. Percent East Low Canal water (R) achieved in various lake basins, 1982[1].

Date[2]	Upper Pelican(19)	Middle Pelican(11)	Lower Pelican(10)	South Lake(9)	Rocky Ford(12)	Lower Parker(7)	Upper Parker(5)
3/18	-	0	0	0	0	0	0
——> 4/1	-	0	0	0	0	0.46	-
4/13	-	0	0	0	0	0.38	-
4/27	-	-	-	-	-	0.55	-
5/11	-	0.02	0.13	0.19	0.16	0.76	0.89
5/25	0	0.04	0.20	0.31	0.21	0.74	0.81
6/11	0.01	0.10	0.31	0.46	0.32	0.74	0.81
6/22	0.02	0.12	0.36	0.47	0.34	0.68	0.77
---> 7/7	0.09	0.08	0.51	0.60	0.45	0.73	0.75
7/20	0.56	0.14	0.51	0.51	0.54	0.70	0.69
——> 8/3	0.71	0.37	0.57	0.63	0.63	0.70	0.66
8/17	0.51	0.41	0.61	0.61	0.64	0.62	0.54
8/31	0.43	0.35	0.55	0.59	0.60	0.53	0.48
9/14	0.16	0.31	0.49	0.48	-	0.44	0.18
9/21	0	0.18	0.41	0.47	-	-	0
---> 10/5	0	0	0.33	0.37	0.41	0.26	0
10/19	0	0	0.33	0.34	0.35	0.22	0

[1] Crab Creek inflow to Parker Horn had average R = 0.85.

[2] ——> indicates approximate start and end of dilution addition to Parker Horn.

---> indicates approximate start and end of pumping into Pelican Horn.

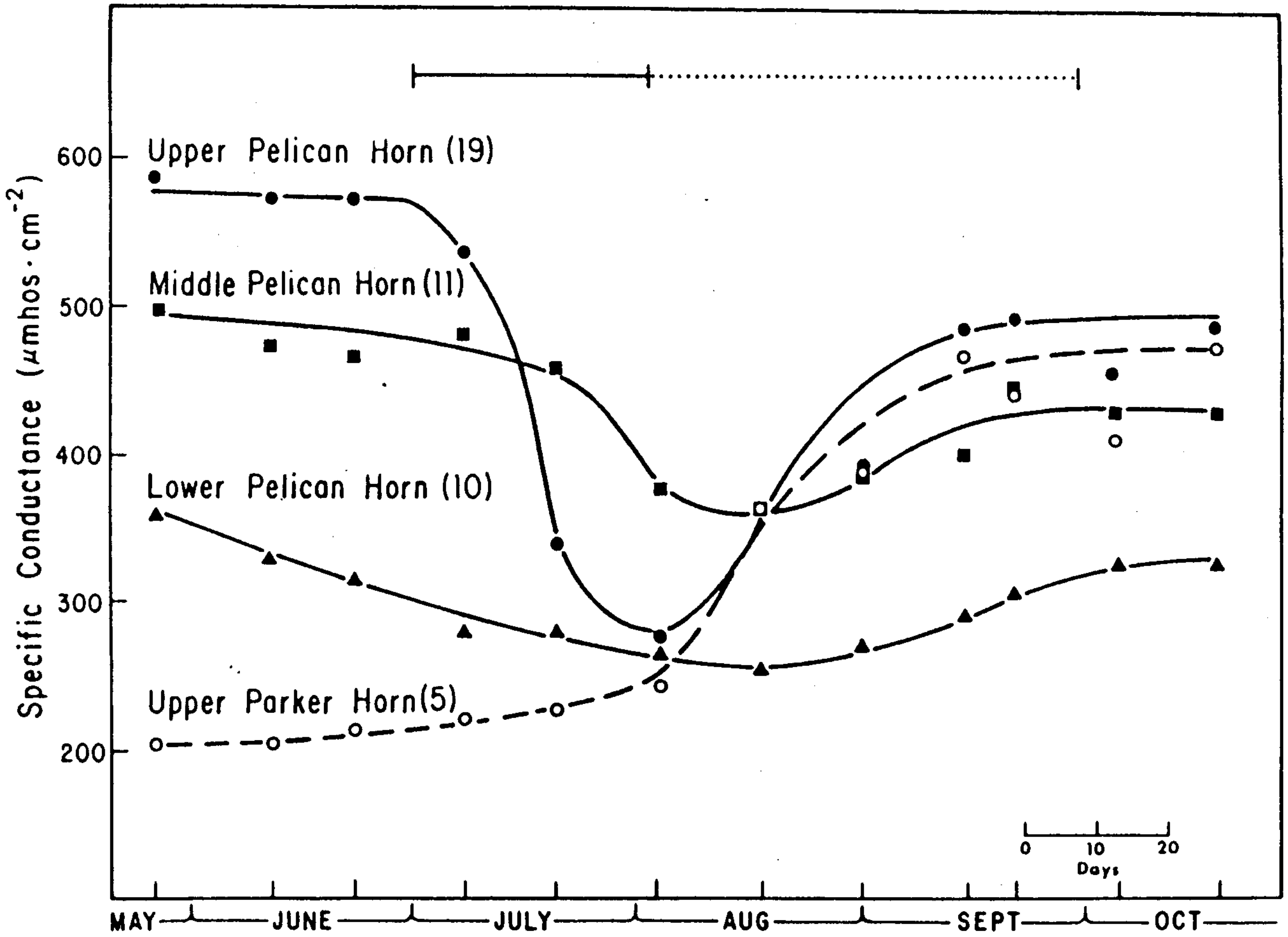

Figure 4. Smoothed specific conductance curves for Pelican Horn and Upper Pelican Horn, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

equilibrium was likely achieved just after the sampling of August 3, or 370 hours of pump operation.

Dilution water fraction (R) in Middle Pelican Horn also increased substantially as a result of pumping. R values rose from 0.08 on July 7 to a maximum of 0.41 on August 17. From examination of smoothed specific conductance curves (Figure 4) it appears that Middle Pelican Horn achieved equilibrium with Upper Pelican inflow on August 17, 706 pump-hours and 3.61 x 10^6 m^3 water delivery after pump start-up. Because over two weeks had elapsed since cessation of dilution, equilibrium with dilution water from pumped inflow did not occur in Middle Pelican Horn. It is therefore likely that a much greater fraction of dilution water would be attained if longer periods of simultaneous pumping and dilution transpire in the future.

Dilution water fraction (R) in Lower Pelican Horn reached a maximum of 0.71 on August 17. By comparison, 0.56 and 0.41 values are reported for 1977 and 1978 dilution years, respectively (Lindell, 1977; Patmont, 1980). The difference between the 1978 values and those from 1977 and 1982 may be a result of a significant difference in total dilution water inputs to Parker Horn (0.74 lake volumes in 1978 versus 1.20 in 1977 and 1.18 in 1982). Some contribution of dilution water to Lower Pelican likely resulted from the pumping activity. However, no dramatic increase in the dilution fraction was observed in the Upper and Middle basins in 1977/78 as in 1982. Undoubtedly, the relatively large basin volume of Lower Pelican Horn and an effective wind-induced mixis with South Lake waters are more dominant factors in the hydrodynamic behavior of this basin.

Based on the results summarized in Table 5, as well as the previous data of Patmont (1980) and Lindell (1977), the time to equilibrium of Moses Lake basins with respect to inflow is dependent on the respective basin volumes. Thus, the larger the basin volume, the slower the response to changing conditions and the greater the time required to reach steady-state. While this is borne out on the basis of conductivity measurements and the physical mass balance of water in respective basins, it would also have important implications on the basin chemical and biological characteristics.

Further interesting results are suggested by the derived R values. As expected the percent dilution water values (R) achieved in Parker Horn and South Lake basins were high, owing largely to the fact that natural flow normally traverses these basins as dilution water travels from the Crab Creek inlet in Upper Parker Horn to the lake's outlets at South Lake. However, a significant fraction was observed in Rocky Ford Arm uplake from the outlets (R = 0.64). This is in agreement with, if not somewhat higher than, values from previous years (Patmont, 1980; Welch et al. 1982). The transport of dilution water by currents generated by strong up-arm winds, which prevail at Moses Lake during the summer, is indicated to be largely responsible for the observed phenomenon.

Wind is also the likely mechanism for apparent water mixing between South Lake and Lower Pelican Horn, as can be seen from the R values achieved in the study (Table 5) and by Patmont (1980). Because of the relatively shallow and exposed nature of Pelican Horn, as indeed with Moses Lake in general, it has been assumed here that wind-driven circulation, near the lake surface, transports water effectively along fetch lengths. Using NOAA wind data for April-October 1982 taken from nearby Grant County Airport (located approximately 10 km north of Pelican Horn) daily wind travel in km was calculated and is presented in Figure 5. Only those winds within a 30 degree envelope from the axis of Pelican Horn were assumed to contribute to fetch length currents along the axis. The data indicate both strong summertime wind velocities and a prevailing up-arm (southwesterly) vector.

A simple estimation of wind-driven water displacement up Pelican Horn can be estimated using the results of Wu (1973) and Baines and Knapp (1965) and the average daily up-arm wind travel based on Figure 5 of 84 km for the study period. If it is assumed, for the sake of simplicity, that the data accurately represent conditions 10 meters over the water surface, then water velocity at the surface can be approximated as being 0.03 times the 10-meter speed. Therefore, average travel of a water parcel at the surface would be roughly 2.5 km in one day. The velocity profiles of Baines and Knapp (1965) further show that waters at a depth approximately 0.03 times the total depth are displaced half the distance of surface waters, in this case roughly 1.3 km. Therefore in an average day, wind transport accounts for up-arm displacement of approximately 3 percent of down-arm waters over a distance of 1.3 km (approximate Pelican Horn axial distance equals 6 km). These findings are roughly equivalent to those of Welch et al. (1982) based on wind-water interactions in the upper main lake during 1981.

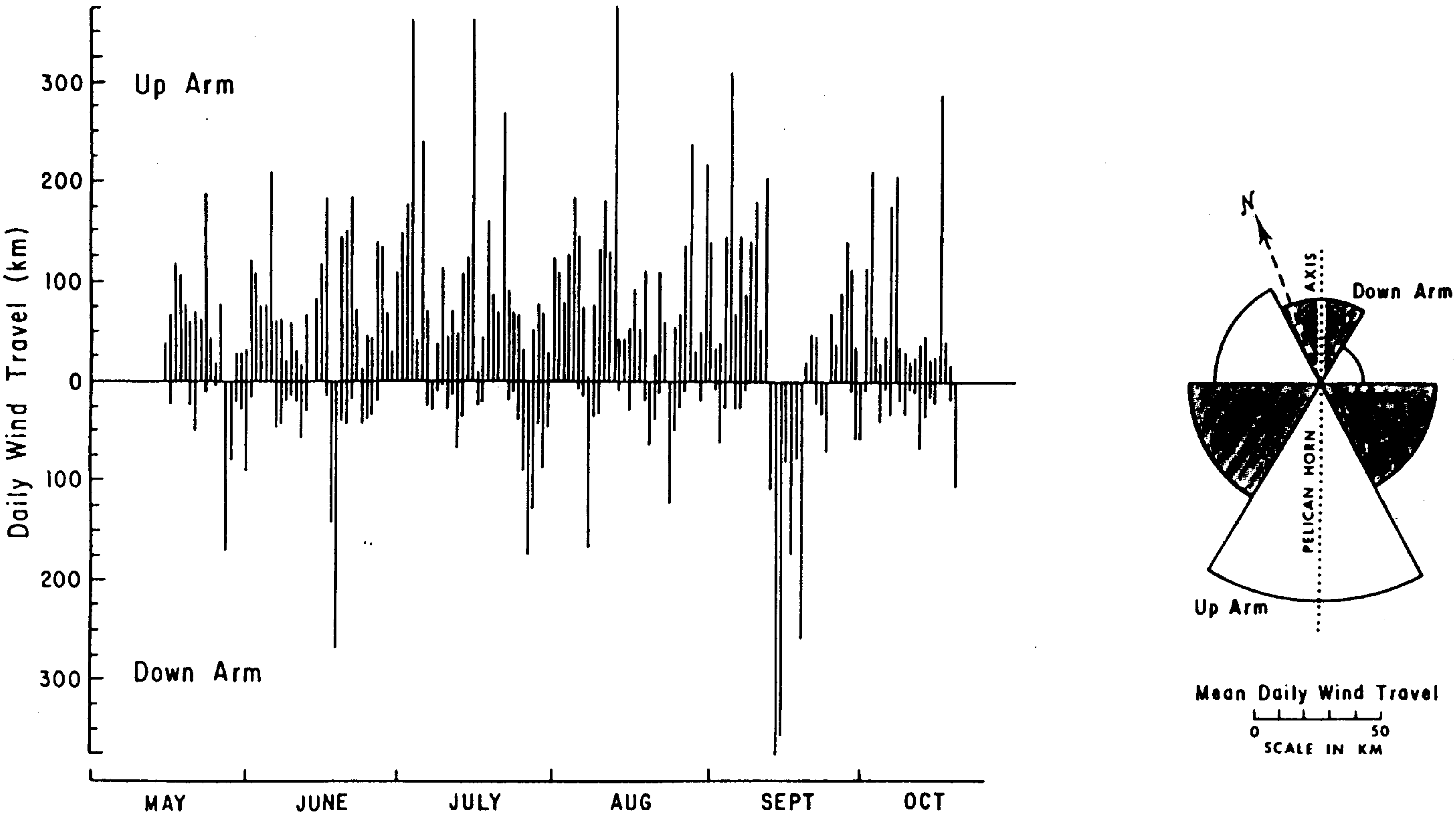

Figure 5. Daily wind travel and mean daily directional magnitudes along the axis of Pelican Horn, April to October, 1982.

While wind can be an effective force of water movement between the basins of Lower Pelican Horn and South Lake, Upper and Middle Pelican Horns are effectively isolated, as previously discussed, due to the inherent minimal through-flow of the railway and I-90 causeways. For example, the fraction of dilution water achieved (R) in Upper and Middle Pelican Horn prior to pumping was approximately 0.02 and 0.12 respectively, which agrees very closely with the findings of Patmont (1980) and Lindell (1977). While these values are exceedingly small relative to the other lake basins, and probably less than the error associated with summertime specific conductance measurements, a small "leakage" of dilution water into Upper and Middle Pelican Horn from South Lake may very well occur, and is likely caused by the large net up-arm wind movement (Figure 5).

Pump Induced Mixing and Water Exchange

In order to establish a case for reduction in algae or other water quality parameters by increased water exchange rates, it is crucial to determine efficiency or "completeness" of water exchange between inflow and receiving waters. The definition of water exchange rate (inflow discharge divided by receiving basin volume) essentially describes the replacement rate of an "average" water particle. In the real world, the presence of turbulence, eddies, and heterogenous physical boundaries can mean a large range of replacement rates for such particles so that, as an example, a particle may exit quickly if it follows the approximate mid-line of the discharge plume or be continually delayed by recirculating gyres. Such hydrodynamic features may often lead to heterogenous or "patchy" spatial distributions of various water quality parameters throughout a particular water body.

The use of horizontal transects to sample respective Moses Lake basins was implemented to reduce this potential spatial variability as discussed previously. Figure 6 shows that 1982 longitudinal transect measurements of specific conductance in Upper Pelican Horn closely resembled that predicted by the mass balance equation:

$$C_t = C_i + (C_o - C_i)\ e^{-\rho t} \tag{4}$$

where C_t = concentration at time t,
C_i = weighted inflow concentration, period t-1 to t,
C_o = lake concentration at time t-1
and ρ = water exchange rate, period t-1 to t.

Predicted and observed values should agree when the constituent (in this case conductance) responds as a conservative substance and when the lake (or basin) behaves as a perfectly mixed system relative to inflow (in this case represented by pump delivery from Parker Horn). Based on the results shown in Figure 6, these assumptions appear valid in the case of Upper Pelican Horn when characterized by transect sampling.

Similar assumptions do not appear as valid for Middle and Lower Pelican Horn (Figure 6). In the case of Middle Pelican, predictions based on pump-induced inflow concentrations from Upper Pelican clearly do not account for observed condition, suggesting incomplete basin mixing and/or an influence from the sewage treatment plant effluent. Predictions for Lower Pelican Horn, based on pump-induced

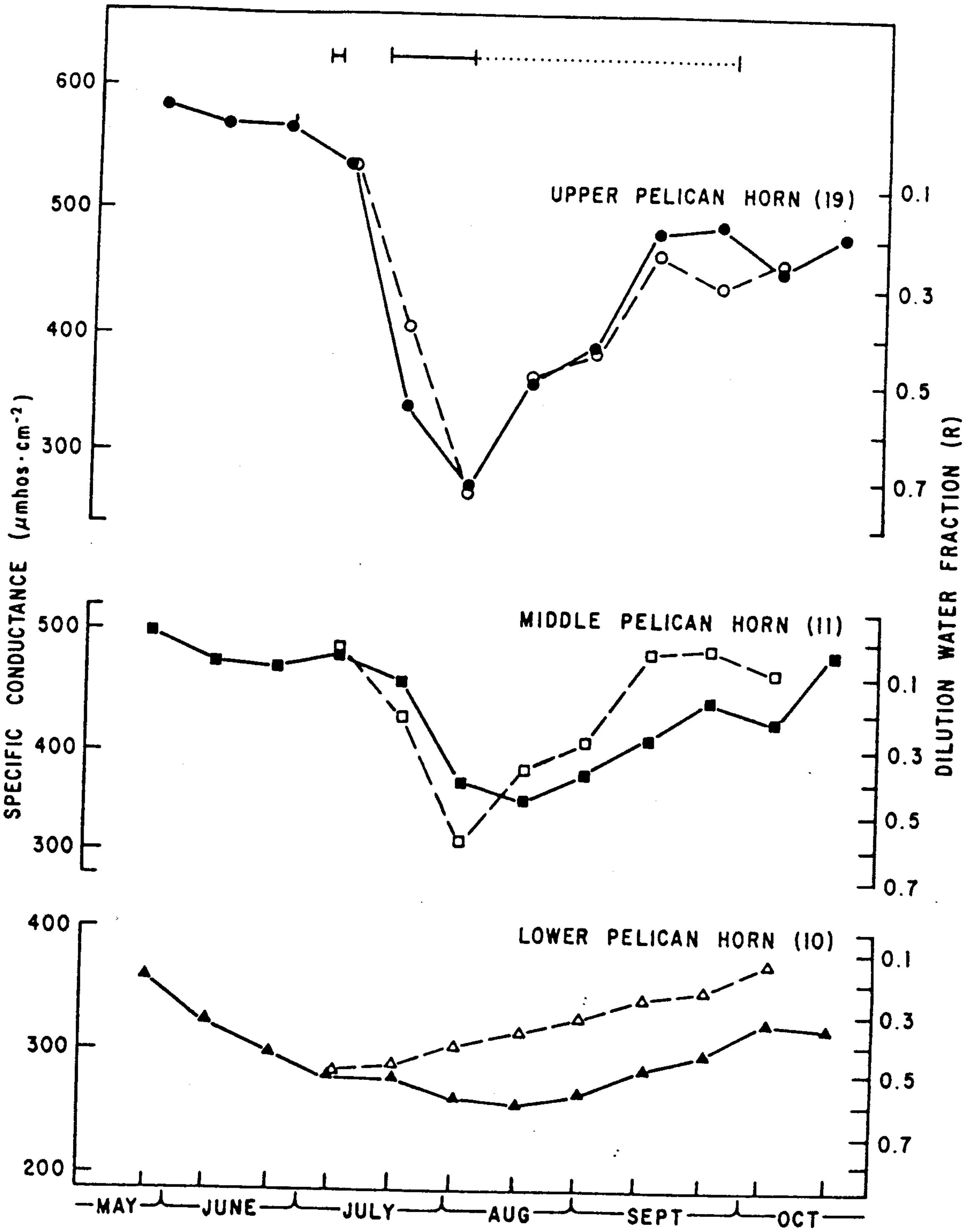

Figure 6. Observed (solid) versus predicted (dashed) specific conductance and dilution water fraction in the basins of Pelican Horn, May to October, 1982.

inflow from Middle Pelican, also deviate from observed values, suggesting incomplete basin mixing and/or a strong inflow influence from adjacent South Lake as has been previously suggested.

Table 6 presents the results of five additional lateral transects sampled in Upper Pelican basin in 1982. Based on both relatively conservative specific conductance and non-conservative chl a measurements, the data indicate that the waters in the basin were reasonably well-mixed with distance from the outfall. Furthermore, a general increase in mixing effectiveness was indicated during latter sampling dates by a general decrease in transect variability.

The character of the discharge plume was clearly visible in low altitude aerial photographs taken over Upper Pelican near the end of July. At the time the pictures were taken, dilution water additions to Parker Horn were still underway, so that a noticeable difference between influent and ambient waters was evident. The plume itself demonstrated a tendency to flow along the west shoreline despite an outfall trajectory which is oriented more toward the middle of the basin. This shoreward pattern was verified on September 21 by droques released at the discharge and tracked over a drift distance of approximately 200 m. Circulating eddies were evident at a point approximately 100 m downstream of the discharge. The formation of eddies appears to have been caused by a separation of discharged waters as they encountered the trailer park point. This resulted in back-circulation of a portion of the plume and active entrainment of sediment laden water from the northeast corner of the basin. It seems reasonable to conclude that the formation of a relatively large

Table 6. Specific conductance (μmhos.cm^{-1}) and chlorophyll <u>a</u> (μg l^{-1}) values from transects sampled in Upper Pelican Horn during July-August 1982.

Transect[1]	July 1[2]	July 20	August 3	August 17	August 31
<u>Specific Conductance</u>					
A	557	-	-	-	-
B	589	333	261	380	397
C	581	384	288	363	397
D	587	370	283	351	401
E	595	372	273	337	394
F	599	382	303	342	389
LT	610	339	275	361	393
Mean (±SD)	588 (±17)	363 (±21)	281 (±14)	356 (±15)	395 (±4)
<u>Chlorophyll a</u>					
A	42.2	-	-	-	-
B	46.3	46.1	12.2	16.5	26.4
C	31.3	66.2	27.1	21.4	30.5
D	24.9	47.1	26.0	20.0	29.6
E	18.5	38.5	32.9	19.0	36.8
F	29.0	44.5	29.3	20.9	37.9
LT	26.7	55.6	20.0	17.8	21.1
Mean (±SD)	31.3 (±9.8)	49.7 (±9.8)	24.6 (±7.4)	19.3 (±1.9)	30.4 (±6.3)

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[1] Transects A through F represent lateral transects (Figure 2). Transect LT represents main longitudinal transect (Figure 3).

[2] July 1 values are prior to pump start-up; subsequent dates are after pump start-up.

eddy in the near vicinity of the discharge may eventually act to "push" the plume away from expected orientation and alongside the west shore as observed.

Although the exchange rate in Upper Pelican Horn was increased from a value estimated at approximately 0.01 day^{-1} under normal circumstances to 0.19 day^{-1} during continuous pumping (equivalent to a residence time of 5.3 days), the time required for initially discharged waters to reach Middle Pelican Horn through Upper Pelican was probably much less. This raised the question of how fast pump discharge waters could be expected to enter downstream basins and begin to cause water quality changes. The results of Albertson et al. (1950) were used to calculate a simple approximation of theoretical maximum time-averaged velocity of water on the plume centerline, and hence, minimum travel time required for initial discharged waters to reach Middle Pelican Horn. Because of the shallow nature of Upper Pelican basin (mean depth, 1.4 m) relative to the discharge width (0.9 m), the discharge was assumed to behave as a two-dimensional momentum jet. The empirically derived equation presented by Albertson et al., (1950) for maximum time-averaged velocity, U_m, is:

$$\frac{U_m}{U_o} = 2.3 \left(\frac{B_o}{x}\right)^{0.5} \qquad (5)$$

where U_o = discharge exist velocity = 2.2 m sec^{-1},

B_o = discharge width = 0.9 m,

and x = distance from discharge.

Taking the midpoint in the basin length (x = 760 m) as the location of mean centerline velocity, U_m, for the entire basin length (x = 1520 m), U_m equals approximately 0.17 m sec^{-1}. The approximate travel time, t, for centerline waters to traverse the entire Upper basin length (x = 1520 m) is then given by:

$$t = x/U_m, \tag{6}$$

which results in a time of approximately 2.5 hours. While clearly this represents a grossly simplified approximation, based on an equation which assumes idealized conditions, it does indicate that initial invasion of pumped discharge into Middle Pelican Horn via Upper Pelican Horn, may have been on a scale of hours while the exchange rate was on a scale of days.

Estimates of minimal travel times of pump-induced waters through Middle Pelican to Lower Pelican and through Lower Pelican to South Lake were derived in similar fashion. Assuming a discharge at both the railway and I-90 throughflows of 1.4 $m^3 \cdot sec^{-1}$ (equal to pump discharge), cross-sectional areas of 2.4 and 27.0 m^2, respectively, and discharge widths, B_o, of 4.0 and 13.5 m, respectively, the discharge exit velocities, U_o, were calculated to be 0.6 and 0.05 m sec^{-1}, respectively. With basin lengths in Middle and Lower Pelican Horn of 1520 and 3040 m, respectively, minimum travel times for waters through the basins were calculated to be roughly 4 hr and 4 days, respectively.

Again, because ideal conditions are assumed, these values represent only order-of-magnitude estimates. On this basis, it was estimated that minimum travel time of pump-induced flows through

Upper and Middle Pelican Horn basins was on the order of hours and in Lower Pelican Horn on the order of days. The implications in terms of water quality effects are that the initiation of pump operation or changes in influent character may begin to cause water quality changes within the basins of Pelican Horn on these time scales. This becomes important when trying to relate pump activity with water quality observations in downstream basins.

Chemical-Biological Responses in Pelican Horn

Data obtained during 1982 indicated that improvements in lake water quality in all areas of the lake, compared to pre-dilution levels of 1969-70, continued to occur. A comparison of May-September transect means by lake basin for the various study years is presented in Table 7. Included as indicators of trophic conditions are measurements of Secchi depth, chl *a*, total and soluble nutrients (nitrogen and phosphorus), and phytoplankton volume.

Along with the general improvement observed over pre-dilution levels, the data for 1982 reveal some important and interesting variations from other dilution years (1977-1981). Owing to the relatively large quantity of dilution water added to Parker Horn during 1982, several basins, notably Upper Parker, Lower Parker, Rocky Ford Arm, and Cascade showed their greatest annual improvement to date. Yet, this trend failed to hold throughout Pelican Horn, and perhaps South Lake as well, where algal biomass (as indicated by chl *a* and Secchi depth) was relatively high compared with other post-dilution years. While it is generally true that dilution waters

Table 7. May-September transect means for each station, 1969-70, 1977-82.

	Upper Pelican(19)	Middle Pelican(11)	Lower Pelican(10)	South Lake(9)	Cascade(8)	Rocky Ford(12)	Lower Parker(7)	Upper Parker(5)
Specific Conductance (µmhos.cm^{-1})								
1969-70	603	536	411	407	405	-	411	434
1977	-	-	-	-	-	-	-	-
1978	-	445	322	320	321	331	297	319
1979	-	414	274	274	269	278	257	265
1980	-	443	353	348	363	349	348	379
1981	-	447	341	326	310	325	305	-
1982	459	439	334	285	263	297	246	263
Secchi Depth (m)								
1969-70	0.4	0.4	0.9	1.0	1.0	-	0.6	0.5
1977	-	-	1.3	1.8	1.7	-	1.3	0.9
1978	-	0.4	1.1	1.7	1.8	1.4	1.2	0.8
1979	-	0.5	1.2	1.7	2.1	1.8	1.5	1.3
1980	-	0.3	0.7	1.3	1.6	1.6	1.0	0.6
1981	-	-	-	1.4	1.6	1.5	1.2	-
1982	0.4	0.4	0.9	1.7	2.6	1.7	1.7	1.2
Chlorophyll _a_ (µg l^{-1})								
1969-70	50	48	54	42	34	-	71	101
1977	-	-	30	26	24	-	33	46
1978	-	39	17	15	9	15	16	17
1979	-	39	27	23	18	19	29	23
1980	-	41	18	11	9	21	18	27
1981	-	46	20	19	19	24	26	-
1982	40	41	40	19	9	16	15	23

Table 7 - Continued

	Upper Pelican(19)	Middle Pelican(11)	Lower Pelican(10)	South Lake(9)	Cascade(8)	Rocky Ford(12)	Lower Parker(7)	Upper Parker(5)
NO_3+NO_2-N (µg l^{-1})								
1969-70	11	10	38	25	87	-	69	181
1977	-	-	41	50	75	-	73	185
1978	-	26	10	16	51	68	43	213
1979	-	43	12	19	28	40	52	211
1980	-	50	92	148	169	173	285	425
1981	-	31	-	34	79	118	71	-
1982	219	39	46	20	32	69	90	179
Phytoplankton Volume (mm^3 l^{-1})								
1969-70	-	-	-	-	-	-	25.4[2]	-
1977	-	-	-	7.7	-	-	-	-
1978	-	-	-	7.2	-	-	8.2	-
1979	-	-	-	23.4	-	-	20.2	-
1980	-	-	-	5.2	-	-	10.2	-
1981	-	-	-	5.2	-	6.6	6.9	-
1982	37.1	26.8	18.6	8.4	-	-	8.4	7.4

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

[2] June-September.

Table 7 - Continued

	Upper Pelican$^{(19)}$	Middle Pelican$^{(11)}$	Lower Pelican$^{(10)}$	South Lake$^{(9)}$	Cascade$^{(8)}$	Rocky Ford$^{(12)}$	Lower Parker$^{(7)}$	Upper Parker$^{(5)}$
Total P ($\mu g\ l^{-1}$)								
1969-70	559	920	186	156	133	-	152	189
1977	-	-	93	90	67	-	78	96
1978	-	715	99	86	67	68	58	85
1979	-	533	111	83	66	82	67	82
1980	-	668	125	87	70	84	83	113
1981	-	718	121	80	58	65	67	-
1982	244	617	138	79	55	55	54	45
SRP ($\mu g\ l^{-1}$)								
1969-70	269	643	52	48	39	-	28	30
1977	-	-	60	55	37	-	26	20
1978	-	420	22	24	14	11	9	9
1979	-	462	27	27	16	18	9	13
1980	-	367	27	23	18	12	9	7
1981	-	-	-	21	7	7	5	-
1982	25	364	35	29	10	10	5	5
Total N ($\mu g\ l^{-1}$)								
1969-70	-	-	-	(1400)[1]	-	-	(1500)[1]	-
1977	-	-	605	614	605	-	531	650
1978	-	854	558	523	437	498	438	656
1979	-	884	698	556	496	587	518	697
1980	-	1027	692	634	669	812	725	961
1981	-	812	500	510	494	538	516	-
1982	1215	1090	520	647	429	560	438	386

do not effectively penetrate Middle and Upper Pelican Horns under normal (non-pumping) circumstances, Lower Pelican and South Lake usually achieved a relatively high dilution water component during 1982 (as documented in Table 5). The fact that Lower Pelican and South Lake did not show water quality improvements to the extent of the basins, suggests an effect on Pelican Horn quality by pumping activities during 1982.

Quality of Influent Water

The quality of waters influent to Pelican Horn are summarized in Table 8 on the basis of the primary sources sampled during the 1982 study. These sources include: (1) influent from the Pelican Horn pumping operation as characterized by samples from Upper Parker Horn (Station 5), (2) sewage treatment plant discharge based on effluent samples taken by plant personnel, and (3) groundwater seepage characterized by samples from springs near Lower Pelican Horn (Station 14).

Pumped inflow to Upper Pelican Horn varied in quality depending on simultaneous dilution water addition to Parker Horn. As summarized in Table 8, constituents were generally lower in concentration in the pumped inflow during dilution, than after dilution ceased. However, because only 20 percent of pumping occurred during dilution water additions, the mean concentrations of constituents for the entire pumping period were higher and therefore closer to the concentrations observed in the pumped inflow after dilution water input ended.

Table 8. Mean inflow and basin concentrations of pH, alkalinity (meq l^{-1}), specific conductance (μmhos cm^{-1}), and nutrients (μg l^{-1}) in Pelican Horn, March to October, 1982.

Source/Period	pH	Alk	Cond	Total P	SRP	Total N	NO_3+NO_2-N	NH_3-N
Pump Inflow								
During dilution (July 15-Aug 3)	8.3	1.7	231	34	5	-	125	-
After dilution (Aug 3-Sept 30)	8.3	3.2	386	55	8	-	791	-
Entire period (July 15-Sept 30)	8.3	2.9	355	51	7	-	657	-
Sewage Plant Discharge	7.7	4.4	1230	6515	2431	-	4890	1161
Groundwater	7.6	4.5	646	48	19	8205	7052	-
Ambient Basin Values Prior to Pumping (up to July 15)								
Upper Pelican	8.3	4.2	572	468	38	1398	65	23
Middle Pelican	9.1	3.7	483	808	400	890	51	15
Lower Pelican	8.5	2.6	330	83	17	492	12	< 10

When comparing constituent concentrations in the pumped inflow to those observed in the ambient receiving waters of the Pelican Horn basins prior to pump start-up, it is apparent that large differences initially existed. Both soluble and total phosphorus concentrations in Pelican Horn waters were quite high relative to the pumped inflow, especially in Upper and Middle basins, which are significantly affected by sewage treatment plant effluent. On the other hand, soluble nitrogen concentrations were significantly higher in the pumped inflow than in Pelican Horn receiving waters, which had very low concentrations of soluble N despite probable high groundwater contribution. However, a high percentage of groundwater inflow nitrogen to Pelican Horn may be denitrified (Welch, 1980a). Because soluble P was so high in the basins, soluble N was the limiting nutrient to algal growth and thus subject to rapid uptake.

Alkalinity was also somewhat lower in pumped inflow which, together with an essentially unchanged pH, indicated lower free CO_2 concentrations compared with ambient receiving waters.

Resultant Loadings from Pumped Inflow

Loadings into Pelican Horn of total phosphorus, soluble reactive phosphorus (SRP), and soluble nitrogen (NO_3+NO_2-N) from pump, groundwater, and sewage treatment plant inflows, which occurred during the pumping period July 1 to September 30, 1982 are summarized in Table 9. Lower Pelican Horn was not described separately since inflows and outflows into that basin are non-point and therefore not measureable. Nutrient loadings were calculated simply as the sum of loadings between sampling dates, where the concentration of inflow (ML^{-3}) on each sampling date was multiplied by the source discharge (L^3T^{-1}) during the intervening period.

Examination of Table 9 reveals that nutrient loadings from pump, treatment plant, and groundwater discharges were generally quite high. In the past, under pre-pumping circumstances, sewage treatment plant outflow has contributed most of the nutrient load to Pelican Horn (Patmont, 1980). This seems self-evident since nutrient concentrations in sewage plant effluent, particularly phosphorus, are characteristically very high (Table 8).

The relatively large loading of nitrogen estimated from groundwater contribution raises the question of why N:P ratios in Pelican Horn have been so low and nitrogen so severely limiting to algal growth. Since Pelican Horn and groundwater have approximately equal phosphorus concentrations but quite different nitrogen concentrations (greater than ten-fold, Table 8), it is possible that wind-induced dispersion from the rest of the lake may account for the discrepancy in N:P ratios. In short, groundwater and dispersive inflows may be similar in magnitude. Another explanation, however, is denitrification. Welch (1980a) has speculated that groundwater seepage in Pelican Horn may undergo as much as a 75 percent denitrification. This is consistent with the findings of a detailed groundwater analysis of Lake Mendota, Wisconsin, where similar discrepancies in nitrogen levels were observed (Brock, et al., 1982). Groundwater soluble nitrogen contributions listed in Table 9 (as $NO_3 + NO_2 - N$) are thus reported as 75 percent denitrified.

Table 9. Water, phosphorus, and nitrogen loadings to Pelican Horn during 1982 pumping phase (July 1 to September 30).

Source	Water (10^5 m^3)	Total P (kg)		SRP (kg)		NO_3+NO_2-N (kg)	
		import	export	import	export	import	export
Upper Pelican							
Pump Inflow	87.69	439	-	66	-	5648	-
Groundwater Inflow	9.12	48	-	23	-	1609	-
Basin Outflow	96.81	-	1119	-	120	-	3043
Net Change	0	-	642	-	31	4214	-
Middle Pelican							
Upper Pelican Inflow	96.81	1119	-	120	-	3043	-
STP Inflow	3.77	3000	-	1075	-	1893	-
Groundwater Inflow	13.27	70	-	36	-	2340	-
Basin Outflow	113.85	0	6686	-	2911	-	308
Net Change	0	-	2497	-	1680	6968	-
Total Inflow Loadings							
Pump Inflow	87.69	439	-	66	-	5648	-
STP Inflow	3.77	3000	-	1075	-	1893	-
Groundwater Inflow	22.39	118	-	59	-	3949	-
TOTAL	113.85	3557		1200		11490	

Obviously the introduction of pumped inflow to Pelican Horn during 1982 further increased respective loadings to the basins, often to a large extent. Examination of the values given in Table 9 indicates that pumping accounted for 77 percent of total water loading, 12 percent of total P loading, five percent of SRP, and 50 percent of soluble N during the overall pumping period, July 1 to September 30. However, pumping also concurrently increased basin outflow such that nutrient retention was greatly affected. Estimates of retention in both Upper and Middle Pelican basins, based on differences between inflow concentration (taken as the concentration in the "upstream" basin) and outflow concentration (that in the receiving basin itself) demonstrated a net import, or increase, in soluble N but a large net reduction in total P and SRP. In other words, both total and soluble P were effectively reduced or flushed from the basins while nitrogen was largely retained.

The cause of nitrogen retention can be explained in part by considering the nutrient regime in Pelican Horn water prior to pump start-up (Table 8). Nitrogen clearly appeared to be the limiting nutrient relative to algal physiological demand (based on a N:P ratio of roughly 7:1 by weight) and would therefore be subject to active utilization by algae when made available. On the other hand, phosphorus concentrations were excessive relative to available nitrogen, so that the large pool remaining after algal uptake was subject to accelerated removal by increased water flushing rates.

Differences between import and export of nutrients were evident throughout the entire pumping period in Pelican Horn, indicating that steady-state conditions with respect to nutrients were not achieved. It should be noted, however, that these calculated loadings assume that steady-state conditions existed with respect to inflow and outflow discharges. While it was verified by flow measurements through the railway bridge that outflow discharge from Upper Pelican to Middle Pelican during the study was essentially equal to pump inflow discharge (1.42 $m^3.sec^{-1}$), outflow from Middle Pelican Horn was not measureable, since cross-sectional area of throughflow under the I-90 overpass was large and thus water velocities were below detection. It could therefore only be assumed that steady state discharge occurred in Middle Pelican Horn during most of the pumping period.

Nutrient Responses in Receiving Waters

Time series distributions of soluble reactive phosphorus (SRP) and soluble nitrogen (NO_3+NO_2-N and NH_4-N) during the 1982 study period are presented in Figures 7, 8, and 9 for Upper, Middle, and Lower Pelican Horn basins, respectively. These graphs effectively illustrate that the large variation in nutrient concentration in pumped inflow versus ambient Pelican Horn waters translated into dramatic changes in nutrient content following pump start-up. Upper Pelican basin in particular showed a distinct shift from a P-rich/N-limited to a N-rich/P-limited system (Figure 7).

Figure 10 shows the temporal distribution of N:P ratios in each of the three Pelican Horn basins, as well as Upper Parker Horn, which serves as the source of pump influent. Further indicated on

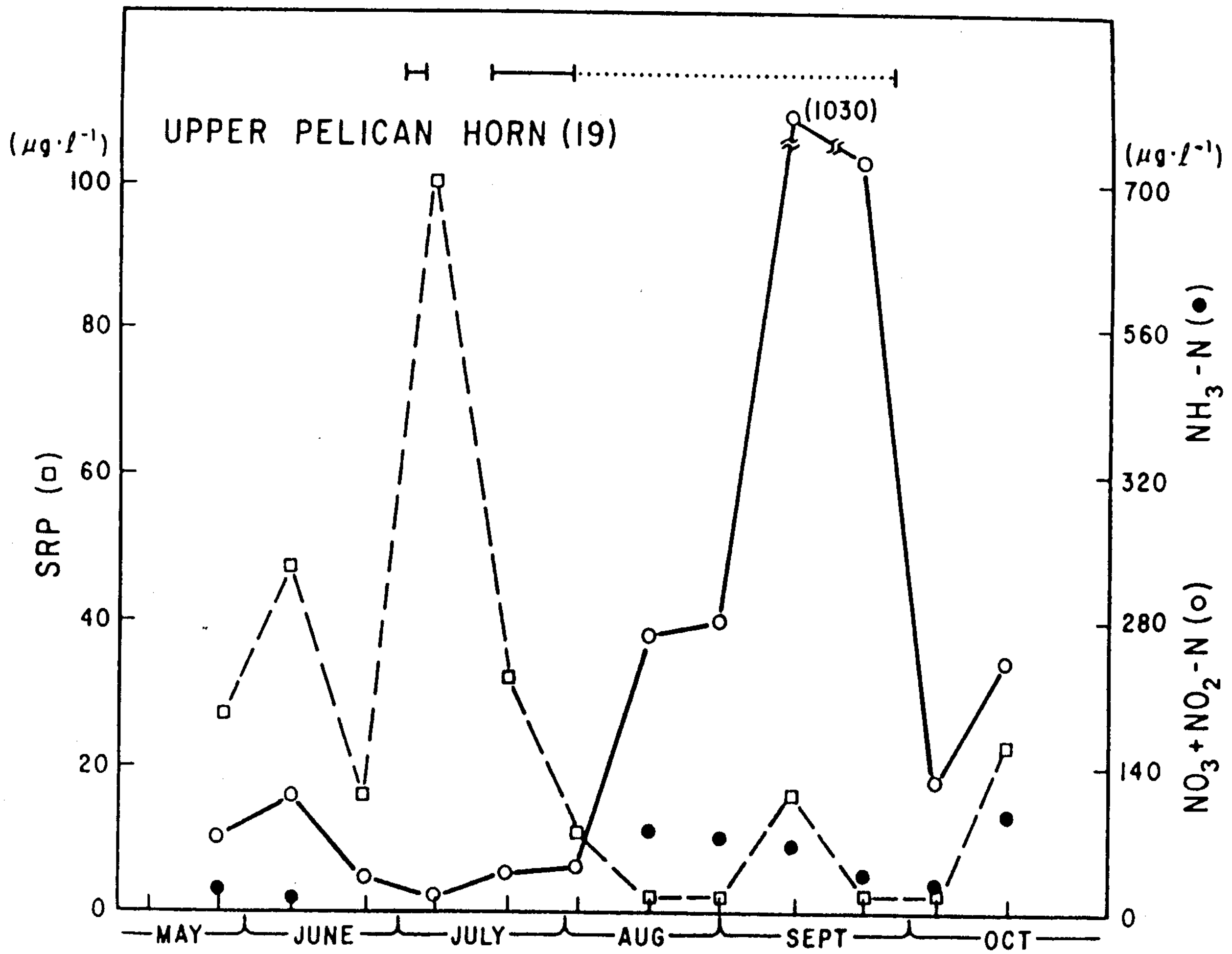

Figure 7. Time series data distribution of SRP, NO_3+NO_2, and NH_4 in Upper Pelican Horn, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

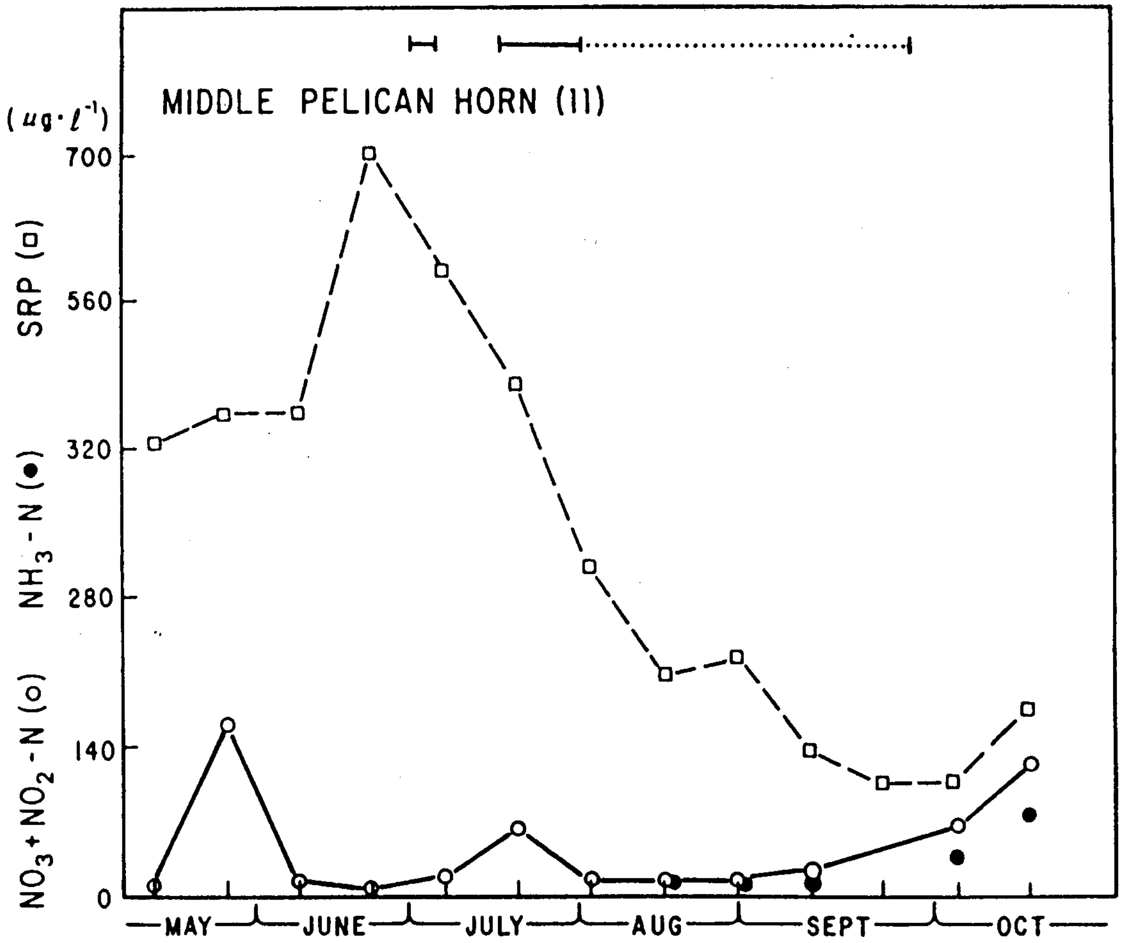

Figure 8. Time series data distribution of SRP, NO_3+NO_2, and NH_4 in Middle Pelican Horn, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

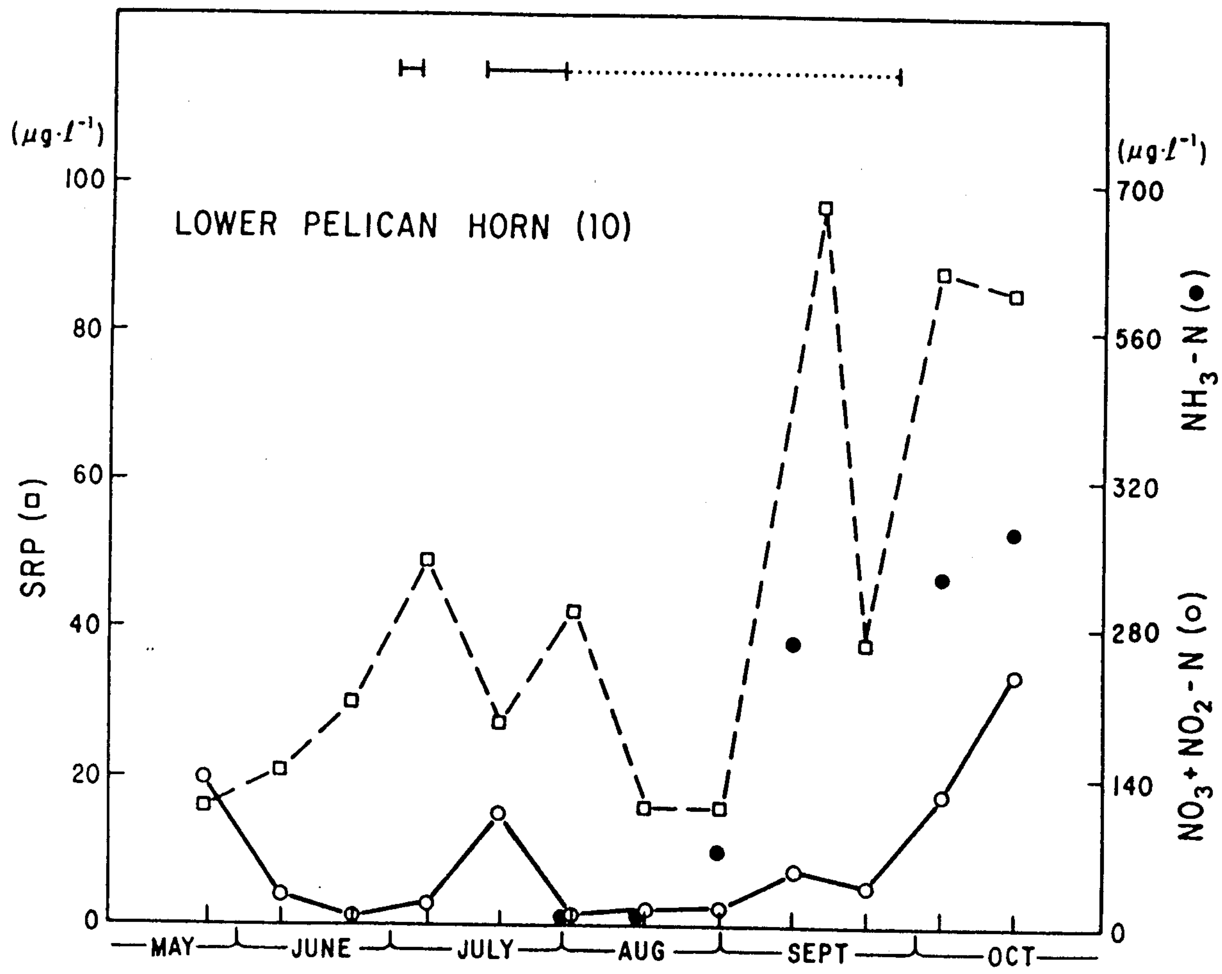

Figure 9. Time series data distribution of SRP, NO_3+NO_2, and NH_4 in Lower Pelican Horn, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

Figure 10 is a line representing the approximate ideal ratio of algal nutrient requirement (7:1 by weight) and thus an approximate "boundary" between nitrogen and phosphorus limitation (Wetzel, 1975; Welch, 1980b).

On the basis of both Figures 7 and 10, it can be seen that the N-rich/P-limited influent from Parker Horn contributed high nitrogen input to Upper Pelican Horn while accelerating reduction of phosphorus. The result was a shift from an initially N-limited system to one that was P-limited. It is important to note that soluble N concentrations in the pumped inflow were significantly less during the period prior to cessation of dilution additions to Parker Horn (Table 8). Although these concentrations were still higher than those in ambient Upper Pelican waters prior to pumping, the large increase in nitrogen input to Upper Pelican did not occur until simultaneous dilution water input to Parker Horn had ceased.

In Middle Pelican Horn, accelerated input of Upper Pelican waters, as a result of pumping, caused a continual decline in SRP (Figure 8). A concomitant increase in soluble nitrogen was not observed despite the fact that waters entering from Upper Pelican were N-rich. The reasons for this apparent anomaly were likely related to rapid algal uptake of nitrogen, since nitrogen appeared to remain limiting in Middle Pelican throughout the study period (Figure 10).

Data distributions for Lower Pelican Horn similarly reveal that soluble N remained quite low and potentially limiting throughout the entire study period (Figure 9 and 10). However, noticeable increases

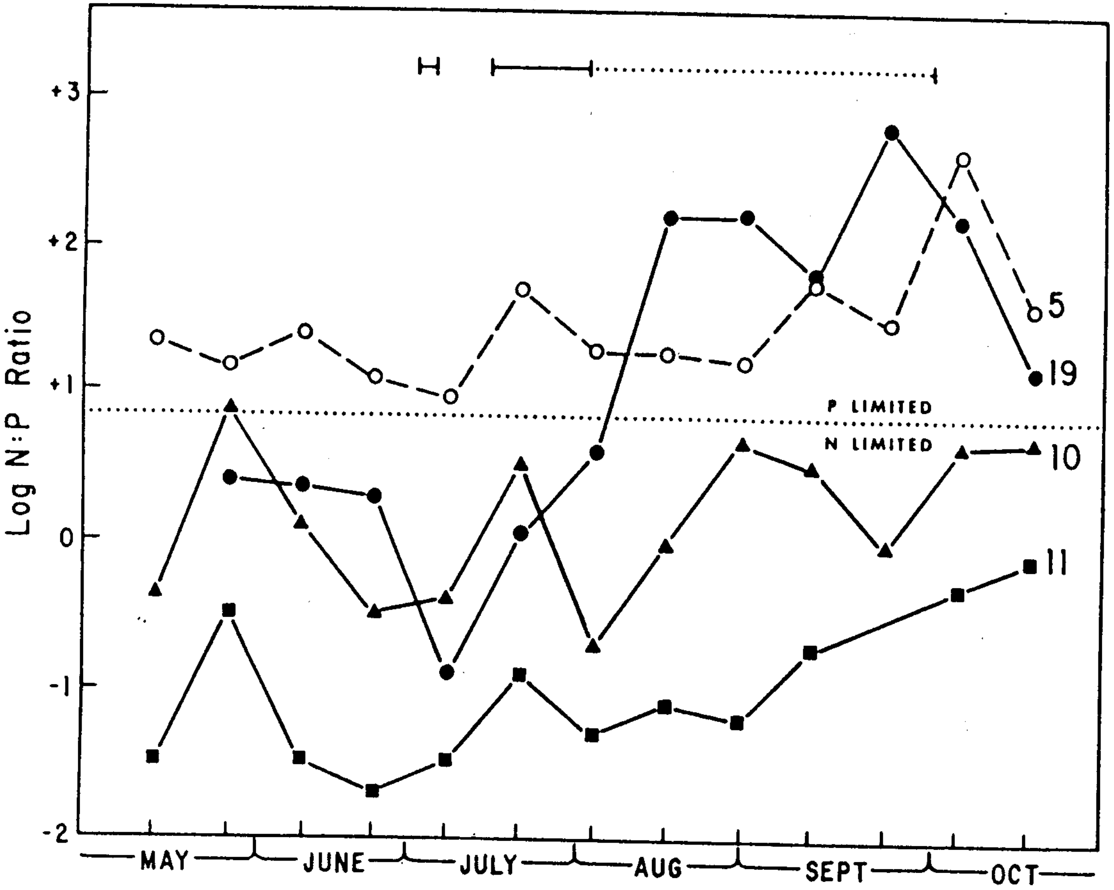

Figure 10. Soluble N:P ratios in waters of Upper (19), Middle (11), and Lower (10) Pelican Horn and Upper Parker Horn (5), May to October, 1983. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

in each of the soluble N and P forms occurred at and after mid-September. Despite elevated levels, nitrogen continued to be limiting based on N:P ratios.

Time-based data distributions of total inorganic carbon (C_T) and free carbon dioxide (H_2CO_3*) for the three Pelican Horn basins during the study period are shown in Figure 11. Concentrations were calculated from transect alkalinities and pH, and corrected for temperature and ionic activity based on the equations of Stumm and Morgan (1981). Results indicate that pumped inflow caused a depression of total inorganic carbon in Upper Pelican Horn during initial pumping while simultaneous dilution of low alkalinity waters occurred in Parker Horn. Little, if any, effect on inorganic carbon levels from pumping was evident in Middle and Lower Pelican Horns since concentrations remained relatively stable.

Free carbon dioxide levels remained quite low during most of the study, probably a result of demands from high primary productivity. A certain amount of increase was evident late in the study period, particularly in mid-September, when high winds occurred during sampling, likely accelerating gaseous CO_2 exchange and reducing algal activity.

No strong correlation between free CO_2 and time of pumping is evidenced by the data. While the levels suggest that carbon was likely not a factor in limiting algal biomass in the long term, depressed free CO_2 levels may have affected algal community succession and perhaps short-term growth rates. The role of carbon in algal succession will be discussed later.

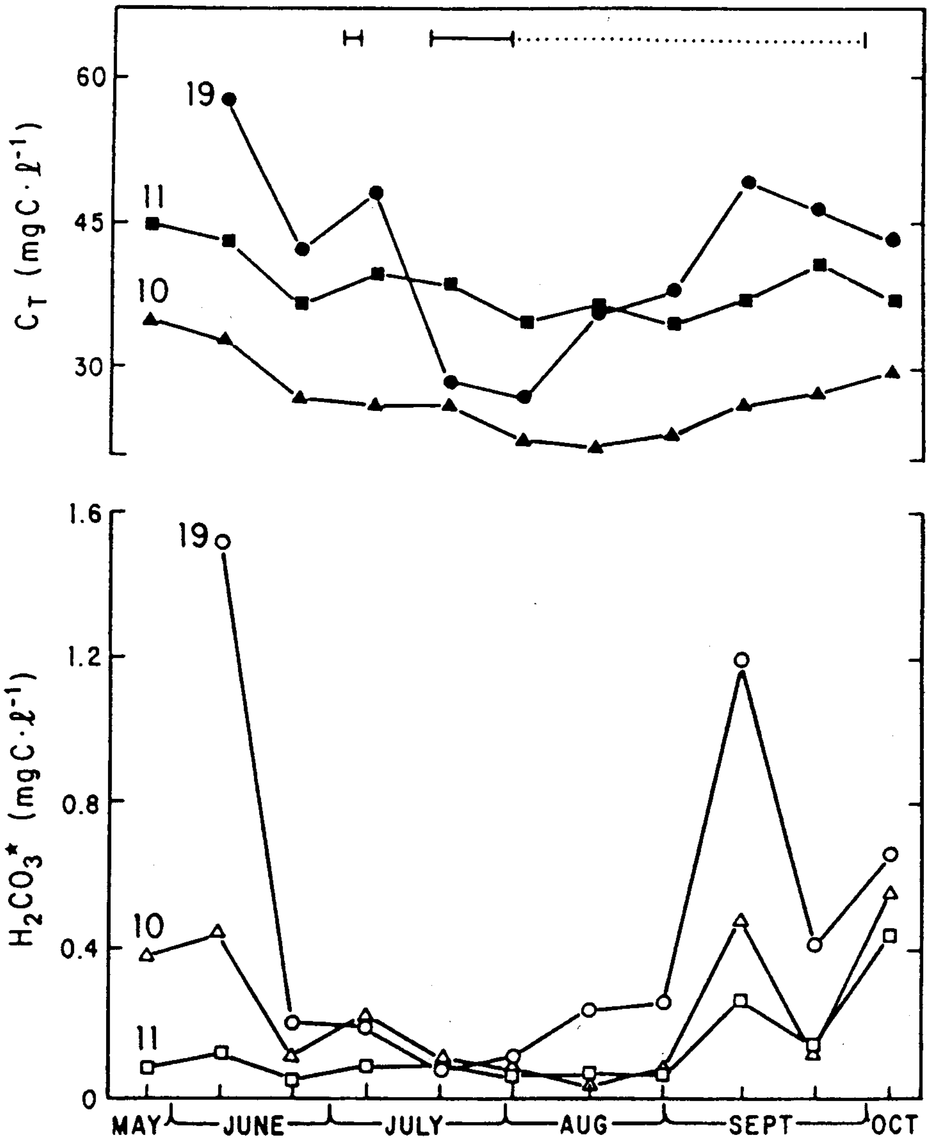

Figure 11. Total inorganic carbon (C_T) and free carbon dioxide ($H_2CO_3^*$) concentrations in Upper (19), Middle (11), and Lower (10) Pelican Horn basins, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

Algal Responses in Receiving Waters

Chlorophyll a

Time series data distributions of transect chl a concentrations during the 1982 study period are presented in Figure 12 for Pelican Horn, South Lake, and the remaining lake volume (constituting 71 percent of the entire lake volume).

The data indicate a precipitous decline from intially high values in chl a after pump start-up in Upper Pelican Horn. For example, chl a values dropped from a maximum of 72 µg l^{-1} on July 7 to 20 µg.l^{-1} on August 3, a decline of approximately 72 percent.

Chl a levels in Middle Pelican Horn remained relatively unchanged except for a large increase during later September - early October when blooms dominated by the blue-green alga *Aphanizomenon* occurred. Meanwhile, in Lower Pelican Horn chl a concentration steadily increased from relatively low levels through June and early July to a large peak of 213 µg l^{-1} on September 21, which ranks as the highest value yet recorded in Moses Lake during a dilution year. Again, chl a here was represented by a nearly monospecific bloom of *Aphanizomenon.*

This same bloom was also evident in adjacent South Lake basin where chl a was measured at 67 µg l^{-1}. During all other sampling observations, however, South Lake values correlated closely with those observed in the rest of the lake (71 percent remaining volume), where chl a was generally less than 20 µg l^{-1} during dilution and between 20 and 40 µg l^{-1} for the remaining summer growth period after cessation of dilution.

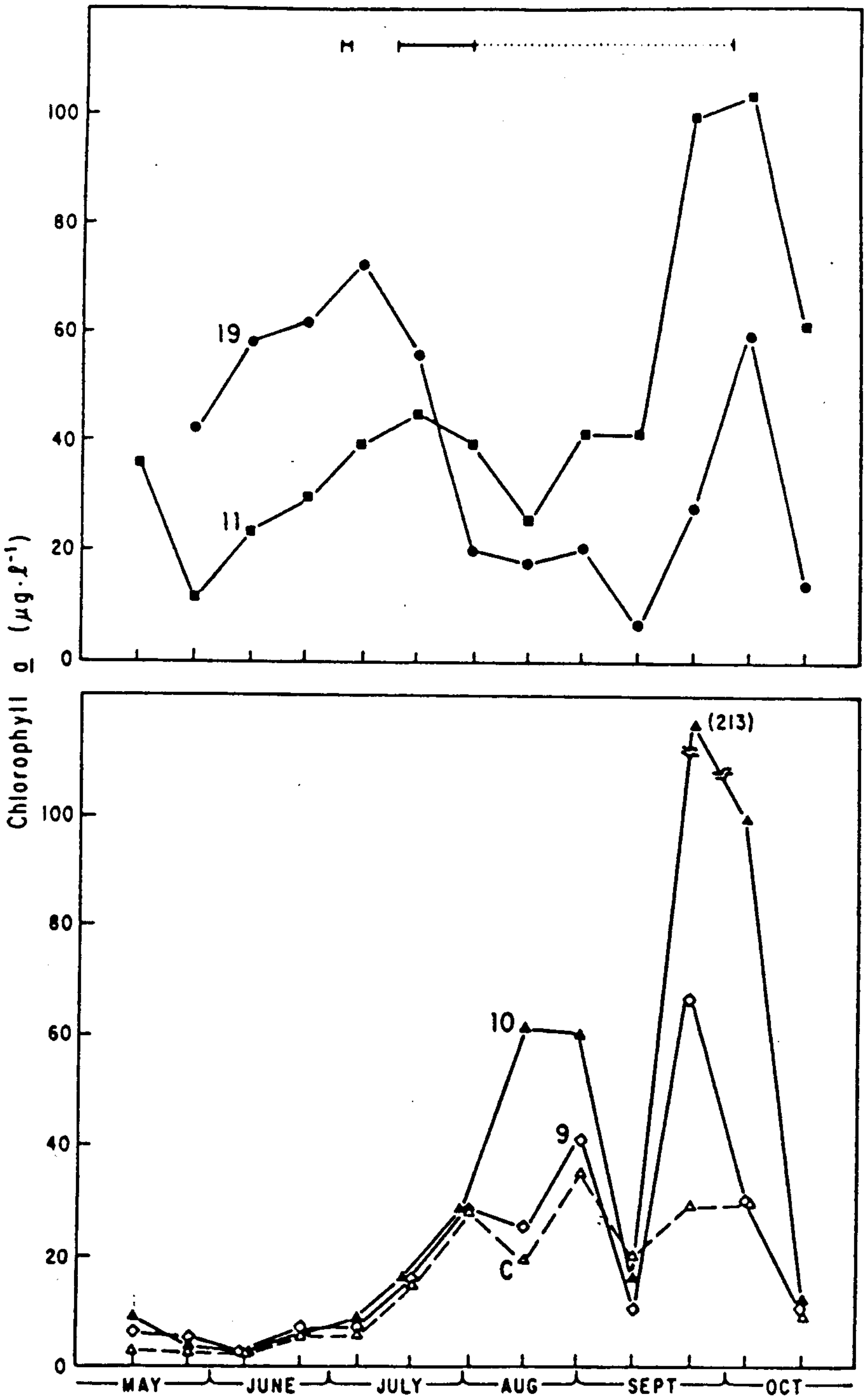

Figure 12. Chlorophyll a concentrations in Upper (19), Middle (11), and Lower (10) Pelican Horn, South Lake (9), and a composite mean of remaining lake basins (c), May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

Upon initial inspection, the timing of pump operations appears to have had a marked influence on chl a, and hence phytoplankton content, in Pelican Horn. First, it is apparent that chl a was trending upwards in Upper Pelican Horn just prior to pump start-up, only to decline dramatically thereafter and remain at relatively low levels until pumping ceased at the end of September. Secondly, both Middle and Lower Pelican Horn, and to a certain extent South Lake, experienced large increases during the latter stages of pump operation. From a standpoint of nuisance algal blooms, conditions clearly worsened in these particular basins. Although the reasons for this phenomenon could be complex and not strictly a result of pump influence, it is apparent that observed increases were far in excess of those observed in the remaining 71 percent of the lake. Finally, it is important to note the apparent effect of ongoing dilution in suppressing chl a early in the study period in all areas except Upper and Middle Pelican Horn. This again emphasizes the probable lack of dilution water penetration into Pelican Horn in the absence of pumping, which was previously discussed based on specific conductance measurements (Table 5).

Phytoplankton Biomass and Composition

The 70 plankton samples collected from Pelican Horn, Parker Horn, and South Lake between May 25 and October 19, 1982 yielded a total of 39 genera, in six classes, of indigenous phytoplankton. A complete list is given in Table 10, along with their occurrence in those basins sampled. Of the 39 total genera identified, 24 were observed in Lower Parker Horn, 27 each in Upper Parker and South Lake, 28 in Lower Pelican Horn, 31 in Middle Pelican, and 35 in Upper Pelican.

The list comprises an algal association typical of highly productive, fresh water, temperate lakes (Taylor et al., 1979). Moreover, many, if not most of the genera present in Upper and Middle Pelican Horns are known to occur in such abundance only in highly enriched lakes or wastewater treatment ponds (Palmer, 1977). The Pelican Horn algal assemblage thus reflects the high ambient nutrient conditions caused by effluent discharge into the Middle basin from the sewage treatment plant.

Phytoplankton volumes estimated from sample cell counts are presented in Figure 13 for the Pelican Horn basins, and Figure 14 for South Lake and Parker Horn basins. Total volumes (represented by the topmost line in each graph) are shown relative to the component volume of blue-green genera (Family Cyanophyceae), greens (F. Chlorophyceae), diatoms (F. Bacillariophyceae), and "others" (all remaining genera).

The derived volume estimates indicate generally higher values in the Pelican Horn basins (Figure 13) than neighboring Parker Horn and South Lake basins (Figure 14). While values in Pelican Horn were often on the order of 30 $mm^3\ l^{-1}$ or greater, those occurring simultaneously in Parker Horn were generally less than 10 $mm^3\ l^{-1}$. As indicated with chl a, the effects of dilution water additions to Parker Horn and high nutrient levels in Pelican Horn are mostly accountable for the contrasting values. Mean May-September

Table 10. Taxonomic list of phytoplankton genera identified from samples taken at selected Moses Lake stations May-October, 1982.

	Stations Present[1]					
	5	7	9	10	11	19
CHLOROPHYCEAE (greens)						
Ankistrodesmus	x	x	x	x	x	x
Bohlinia					x	x
Characium	x					
Chlamydomonas	x	x	x	x	x	x
Chlorosarcinia						x
Chodatella					x	
Cosmarium		x		x	x	x
Franceia	x	x	x	x	x	x
Gloeocystis	x	x	x	x	x	x
Golenkinia				x	x	x
Oocystis	x	x	x	x	x	x
Pediastrum	x	x	x	x	x	x
Scenedesmus	x		x	x	x	x
Selenastrum				x	x	x
Sphaerocystis	x	x	x	x	x	x
Staurastrum	x	x	x			x
Tetraedron	x				x	x
Tetrastrum			x	x	x	x
Ulothrix			x	x		x
BACILLARIOPHYCEAE (diatoms)						
Achnanthes	x			x		x
Asterionella		x	x		x	
Cyclotella	x	x	x	x	x	x
Cymbella						x
Fragilaria	x	x	x	x	x	x
Gomphonema	x					
Melosira	x	x	x	x	x	x
Navicula	x	x	x	x	x	x
Stephanodiscus	x	x	x	x	x	x
Synedra	x	x	x	x	x	x
CHRYSOPHYCEAE (golden-browns)						
Dinobryon						x
Mallomonas	x	x	x	x	x	x

Table 10 - Continued

			Stations Present[1]			
	5	7	9	10	11	19
DINOPHYCEAE (dinoflagellates)						
Ceratium	x	x	x	x	x	x
CRYPTOPHYCEAE (cryptomonads)						
Chroomonas	x	x	x	x	x	x
Cryptomonas	x	x	x	x	x	x
CYANOPHYCEAE (blue-greens)						
Anabaena	x	x	x	x	x	x
Aphanizomenon	x	x	x	x	x	x
Gleocapsa			x		x	x
Merismopedia	x	x	x	x	x	x
Microcystis	x	x	x	x	x	x
TOTAL GENERA 39	27	24	27	28	31	35

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[1] 5-Upper Parker Horn, 7-Lower Parker Horn, 9-South Lake, 10-Lower Pelican Horn, 11-Middle Pelican Horn, 19-Upper Pelican Horn

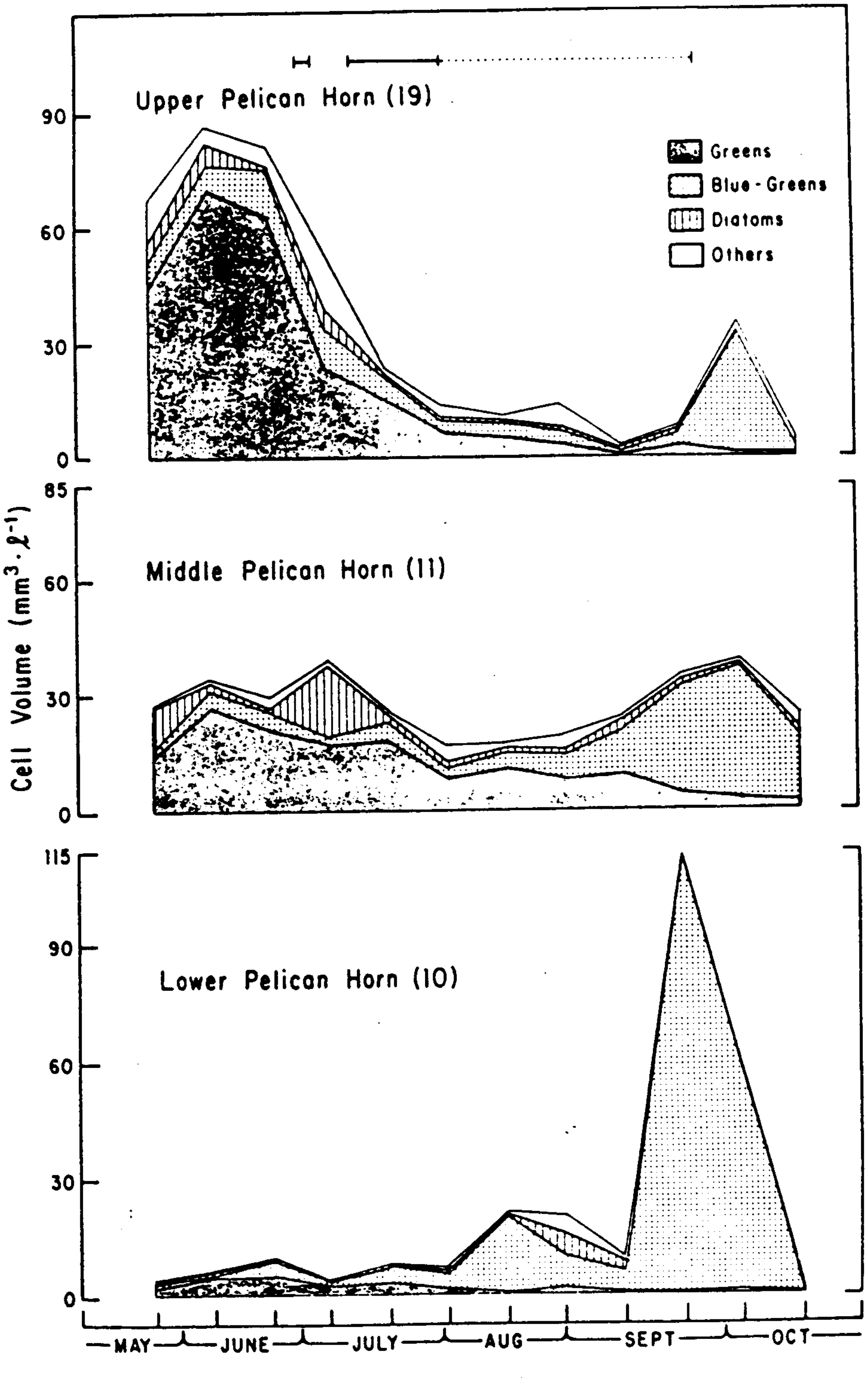

Figure 13. Phytoplankton volume estimates for Pelican Horn basins, May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

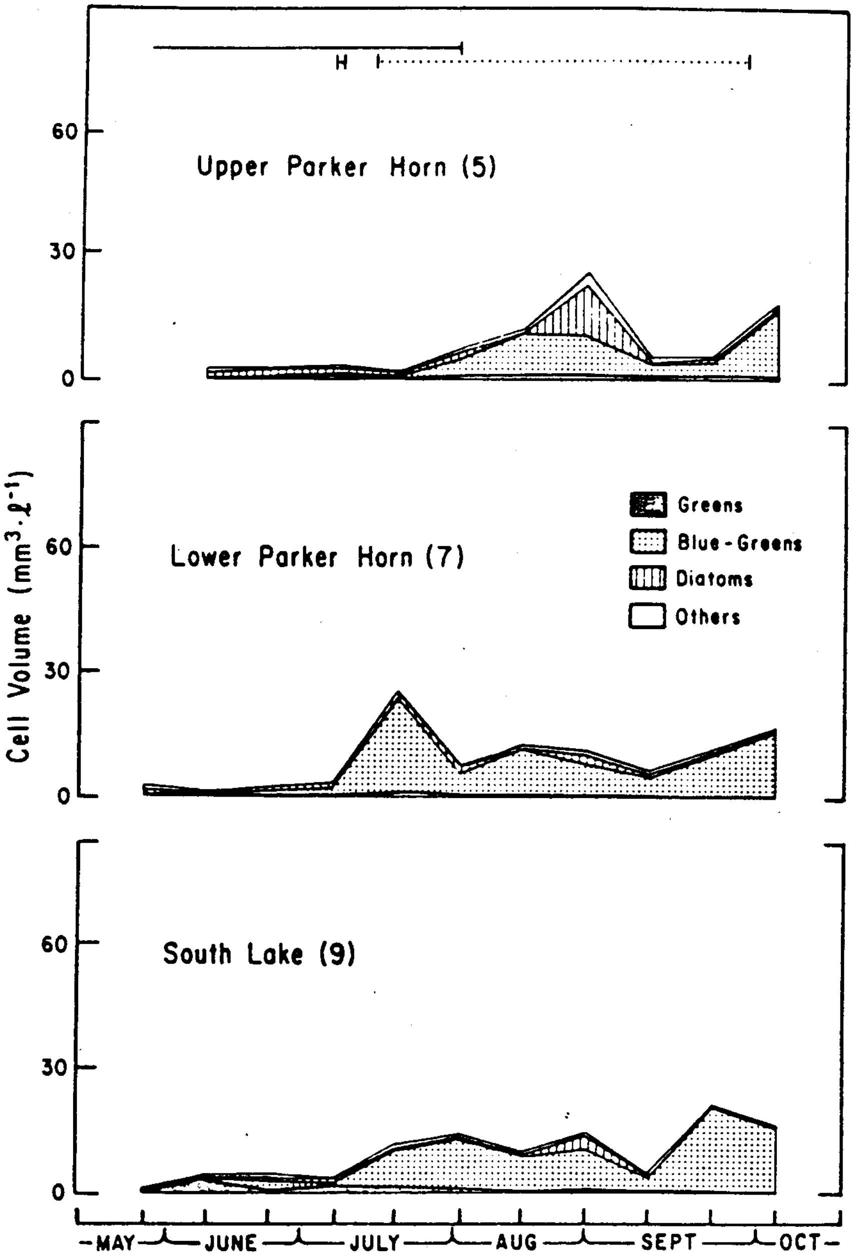

Figure 14. Phytoplankton volume estimates for Parker Horn and South Lake basins, May to October, 1982. Overbars indicate periods of dilution water additions to Parker Horn (solid) and pumping to Pelican Horn (dotted).

phytoplankton volumes for Lower Parker Horn and South Lake were similar to those obtained in other dilution years and considerably less than those observed in pre-dilution years (see Table 7).

Phytoplankton volumes responded similarly to chl a in Upper Pelican Horn, where quite large pre-pumping values declined dramatically after initial pumping operation (Figure 13). For example, values dropped from 81 $mm^3\ l^{-1}$ on June 22, nine days prior to initial pumping, to 22 $mm^3\ l^{-1}$ on July 20, a decline of 72 percent, after 111 hours of pump operation.

Green algae were clearly dominant in Upper Pelican Horn prior to pumping, constituting up to 90 percent of the total plankton volume. However, the large decrease observed after initial pumping was primarily the result of a change in the green algal component of the community, particularly the genera *Oocystis*, *Gloeocystis*, and *Sphaerocystis*. Although other component groups (i.e. blue-greens, diatoms, others) were initially of relatively small volumes and remained so, their proportionate decrease was less. For example, between the sampling of June 11 and August 17, volume of greens fell approximately 92 percent, while blue-greens, diatoms, and others declined by approximately 33, 80, and 70 percent, respectively.

Although not as dramatic, a similar, but lesser change in volumes occurred in Middle Pelican Horn, as evidenced by the decline from 39 $mm^3\ l^{-1}$ on July 7 to values less than 20 $mm^3\ l^{-1}$ on subsequent sampling dates in August (Figure 13). By comparison, the only previous analysis of phytoplankton volumes in Middle Pelican Horn during 1979, revealed a less significant trend with higher values ranging from 40 to 52 $mm^3\ l^{-1}$ (M. Tomasek, pers. comm.). A gradual increase was subsequently observed during the latter stage of 1982 pumping activity, with cell volume reaching 39 $mm^3\ l^{-1}$ in early October. This gradually increasing trend, which commenced around mid-August, appears to have coincided with the pump-induced high soluble nitrogen inflow from Upper Pelican Horn which followed cessation of dilution water input (Figure 7).

As in Upper Pelican Horn, the generic composition of the phytoplankton in Middle Pelican was initially dominated by greens, primarily *Oocystis*, *Sphaerocystis*, *Gloeocystis*, and *Scenedesmus*. Although the decline was not as precipitous, the green component in Middle Pelican similarly declined during the study, gradually being replaced in dominance by blue-greens, primarily *Aphanizomenon*, which formed extensive surface blooms.

The dynamics of algal biovolume in Lower Pelican Horn was nearly opposite that observed in Upper Pelican (Figure 13). Values were initially very low until nearly mid-August when an extensive biomass of *Aphanizomenon* began to dominate. Very high maximum volumes of 114 and 56 $mm^3\ l^{-1}$ were reached on September 21 and October 5, respectively, coincident with the termination of pumping operations. As suggested with respect to similar observed increases in chl *a* values, causes for these increases were probably pumping-related. Moreover, the observed increase of nutrients in Lower Pelican (Figure 9), coupled with the obvious lack of similar blooms in Parker Horn (Figure 14), implicates the transport of sewage effluent from Middle Pelican by pumping as the cause. A dramatic decrease in phytoplankton was observed in nearly all basins sampled on September 14. This matches and verifies a similar response in chl a values (Figure 13). The causes are attributable, in large part, to high winds and lowered water temperatures (see Figure 5). Subsequent sample collection on September 21 and October 5 marked a return to relatively warm, quiescent conditions conducive to blue-green algal growth.

The relatively small biovolumes observed during most of the study period in Parker Horn, as well as South Lake, were likely the result of dilution water additions. Increases in biovolume became apparent in these basins in July, again with the appearance and dominance of *Aphanizomenon*, but cell volume only occasionally exceeded 10 $mm^3 l^{-1}$.

The contrast in algal community composition between Parker Horn and Pelican Horn is of interest. As pointed out earlier, an increase in the number of genera present was generally noted with distance toward Upper Pelican Horn. In addition, the presence and initial dominance of green algal genera was quite dramatic in Upper and Middle Pelican basins, while at the same time being virtually absent from Parker Horn. The potential mechanisms and relative importance of this phenomenon will be discussed further.

Transparency

The transparency of surface waters, as measured by Secchi disk depth (m), is depicted in Figure 15 for the three Pelican Horn sub-basins, and the remaining 71 percent of the lake volume. The data indicate that Secchi values generally varied inversely with chl *a* concentrations (Figure 15). However, those Secchi depths measured at both Upper and Middle Pelican basins were significantly less than elsewhere in the lake, even at equivalent or lesser chl *a* concentrations. This suggests that attenuation of light in the waters of these basins may have been further increased by a relatively large turbidity component not accounted for by chl *a* content and, hence, algal biomass. Two principle observations during the study suggested a probable cause. First, the relatively shallow mean water depths in Upper and Middle Pelican basins (1.4 and 1.3 m, respectively), provide effective water-sediment interaction, particularly during a vertical mixing. This is likely accelerated by wind action or the benthic feeding activity of carp, (*Cyprinus carpio*), which are numerous in the lake. The result is continual resuspension of flocculent sediments, giving Pelican Horn a characteristic "dirty" appearance, even when algal biomass (as indicated by chl *a* and cell volumes) was quite low. Second, it was common to find often large amounts of unidentifiable detritus in phytoplankton samples from Upper and Middle Pelican Horn, and while such would not be reflected in chl *a* or biovolume measures, it would obviously contribute to light attenuation.

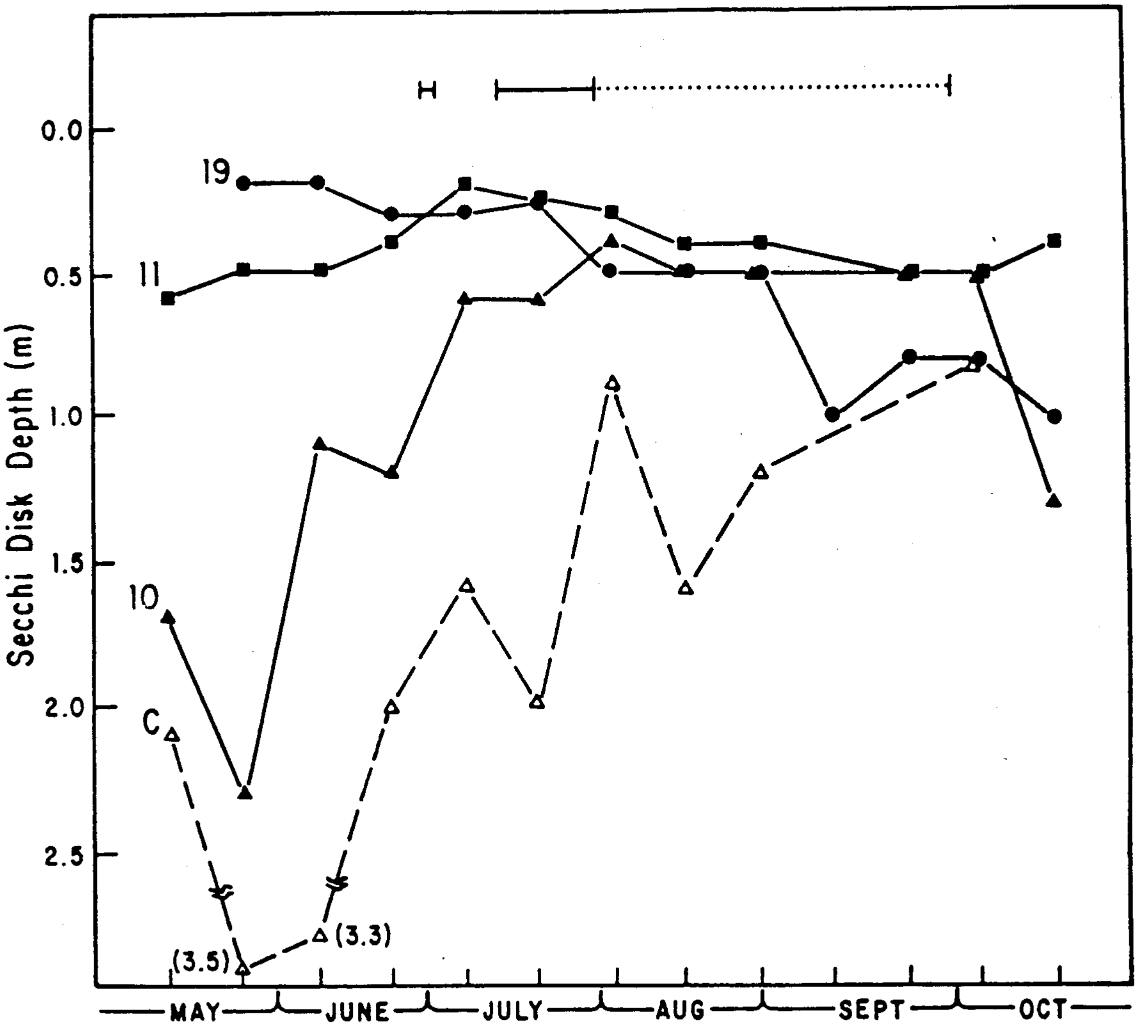

Figure 15. Secchi disk depths in Upper (19), Middle (11), and Lower (10) Pelican Horn, and a composite mean of remaining lake basins (c), May to October, 1982. Overbar indicates pumping period during (solid) and after (dotted) dilution water additions.

While it remains a common practice in limnological water quality investigations to use Secchi depth as a correlate of algal biomass, it seems obvious when considering Pelican Horn that such use would yield a gross overestimation of actual biomass at certain times. Despite decreases in both chl _a_ and phytoplankton cell volume in Upper and Middle basins, Secchi depth remained low during the study. In this case, water column transparency was affected strongly by a sediment-detrital component over and above the observed algal dynamics.

DISCUSSION

From known relationships in continuous culture systems, algal biomass levels observed in Pelican Horn during pumping operations were expected to be a function of inflow nutrient concentration and/or water exchange rate. The effect of these two mechanisms on the observed biomass levels was expected to differ between the three basins comprising Pelican Horn. For example, Upper Pelican Horn, because of its small volume, would have a rather rapid pump-induced exchange rate, subjecting algae there to potential washout despite high inflow nutrient concentration. By contrast, Lower Pelican Horn, with a relatively large basin volume, would sustain a very low exchange rate during pumping, which could result in algal biomass accumulation if pumping increased nutrient inputs. Finally, responses in Middle Pelican Horn were expected to fall somewhere between, because the basin volume and, hence, pump-induced exchange rate are intermediate compared to the other two basins. The discharge of sewage effluent into Middle Pelican Horn was expected to complicate these rather simplified interpretations.

Before proceeding to a detailed discussion of water quality responses in each basin, the importance of mixing and water movement should be re-emphasized. The ideal continuous culture vessel is one in which complete mixing of vessel volume with inflow is achieved. It has been shown here that, despite some evidence of horizontal variability, the assumption of complete mixing was valid for Upper Pelican Horn based on the use of integrated transect sampling for algal biomass and a comparison of predicted versus observed specific conductance values. However, this same assumption did not appear valid in Middle and Lower Pelican Horn, where sewage treatment plant effluent and uplake wind-driven entrainment of adjacent South Lake waters complicated the interpretation of pumped inflow effects. During the subsequent discussion, therefore, the reality of incomplete mixing should be kept in mind when results are interpreted using continuous culture relationships.

Nutrient - Phytoplankton Responses

Upper Pelican Horn

As expected, algal biomass in Upper Pelican Horn declined sharply following initiation of pumping, in spite of the fact that pumped influent soluble nitrogen concentrations were maintained at high levels. Because this significant decrease in biomass occurred while the basin was apparently still N-limited, it seems clear that washout was the mechanism responsible, since the exchange rate of the basin was so dramatically accelerated by pump operation. However, simultaneous influent phosphorous concentrations were relatively low, so that an equally rapid depletion of P occurred in the waters of Upper Pelican Horn, eventually producing a switch from apparent N to P limitation relative to algal demand. Therefore, this decline in P cannot be discounted as a potential contributor to the observed algal biomass reduction.

In fact, the loading data presented in Table 9 revealed that Upper Pelican Horn experienced a net loss of both total and soluble P throughout most of the pumping period. Only after phosphorous

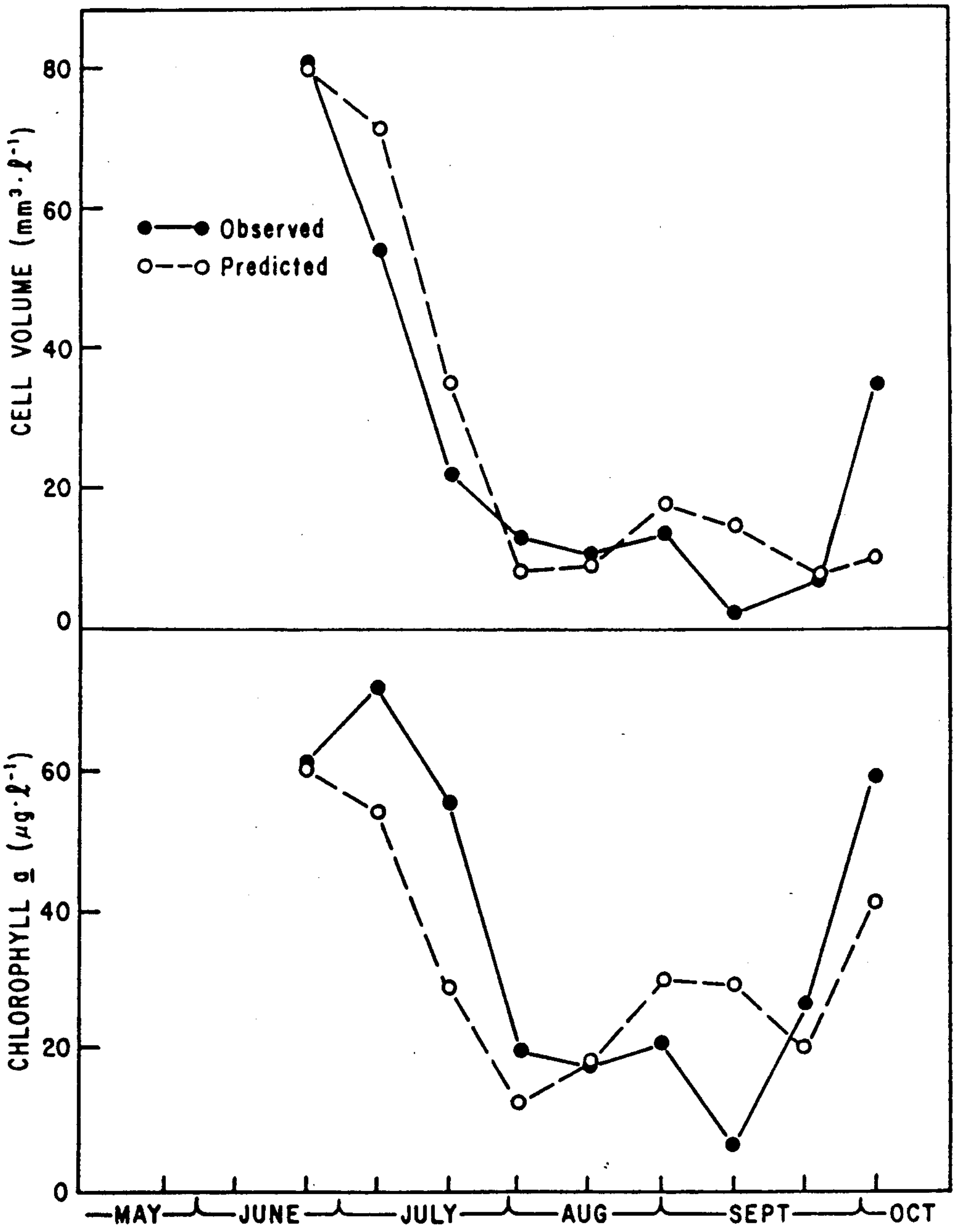

Figure 16. Observed versus predicted algal biomass (as cell volume and chl a) in Upper Pelican Horn during pumping operation period, 1982.

apparently became limiting during mid-August was soluble P present in the outflow in smaller quantities than the inflow. This can be explained on the basis of replacement of the originally high P waters of Upper Pelican with influent at much lesser P levels during pump operation. Once waters in the basin were essentially replaced by low P pump inflow and the shift to P limitation occurred, basin soluble P was further reduced below the inflow level by algal uptake.

Both the relatively high P levels and the severe N limitation observed in the basin prior to pumping operations, raises the question of where Upper Pelican derived its large phosphorous concentrations in the first place, particularly since no apparent external surface inputs exist for that basin. Groundwater seepage, as previously mentioned, is a significant contributor to hydraulic loading, but is nonetheless characteristically low in P (Table 8). Influence from sewage treatment plant effluent, discharged into Middle Pelican Horn, is probably experienced in Upper Pelican, because the outfall is located close to the throughflow separating the basins (Figure 2). During non-pumping periods, movement of water from Middle to Upper Pelican, most likely wind-driven, has often been observed and probably transports nutrient-laden waters into Upper Pelican. Furthermore, the fact that, prior to pumping, Upper Pelican Horn phytoplankton and nutrient concentrations were essentially identical in composition and character to Middle Pelican Horn, which were also characteristic of sewage effluent receiving waters (Palmer, 1977), attests to sewage effluent influences in the upper basin. Other significant contributions of phosphorous to Upper Pelican Horn are likely derived from sediment resuspension, enhanced by strong winds, together with the basin's low volume:sediment area ratio, and biologically-mediated nutrient recycling from sediments, particularly by macrophytes and carp (*Cyprinus carpio*), which are numerous in the basin.

The argument that the rapid reduction in P during pumping in Upper Pelican Horn contributed to the algal decline can in part be dismissed on the basis of nutrient limitation and the observed N:P ratios (Figure 10). Because it was seen that N:P ratios remained low in Upper Pelican Horn and, thus, N-limited during the phase of rapid algal decline, it follows that observed biomass levels were not determined by P concentrations during the initial phase of pumping. At that time P was not yet limiting but rather still excessive relative to available N.

Evidence for a washout effect on phytoplankton in Upper Pelican Horn rather than an effect from P reduction also was derived from a comparison of observed algal biomass (based on chl *a* and cell volumes) with values predicted by the mass balance equation as previously described. Because the equation assumes that the modeled substance behaves conservatively, zero growth is implied, and resultant calculations, when compared directly with observed values, are therefore useful in detecting washout, increases in biomass, and inhibition or death. Plots of observed versus predicted values of chl *a* and cell volume for Upper Pelican Horn are presented in Figure 16.

Calculations derived for Upper Pelican Horn reveal that a predicted sharp decline in algal biomass closely follows what was actually observed. During the decline phase (approximately July 7 to August 3), predicted cell volume values were greater and predicted chl _a_ values were less, than those values actually observed. While the error associated with prediction based on such a simple model may account for these observations, it also suggests the possibility of phytoplankton loss greater than that due to washout (based on cell volume), as well as improved cell nutrition (based on chl _a_).

This apparent dichotomy can be explained in part on the basis of algal succession. For example, it was shown that certain taxa (i.e., mostly greens) were significantly reduced during pumping, and to a degree beyond that of other algal groups (Figure 13). Because these taxa constituted much of the prior community biovolume, a particular inhibition during pump operation would have resulted in a biomass reduction beyond that predicted on a conservative basis. At the same time, the remaining, less-affected taxa (i.e., blue-greens) stood to profit from more favorable nutrient and/or light conditions as competition from the dense green algal crop decreased. The improved ambient conditions would therefore be expressed in a higher chl _a_ concentration per unit biomass.

Comparison of observed to predicted values of algal biomass in Upper Pelican Horn also shows that cell volume during the stationary phase (approximately August 3 to September 21) was similar to cell volume in pump inflow. While this comparison suggests that phytoplankton from Upper Parker Horn inflow constituted that observed in Upper Pelican Horn during this period, analysis of phytoplankton samples from both basins indicated that the dominant genera were different. Thus, it must be assumed that the algae present in Upper Pelican Horn during this phase were mostly indigenous.

The relatively substantial increases in both cell volume and chl a which were observed in Upper Pelican Horn after pumping was halted further attest to algal suppression induced by pump operation. The fact that observed values significantly exceeded those predicted for both volume and chl a indicates that there was relatively rapid, well-nourished cell growth during this period. By the end of the study period (mid-October) algal levels in Upper Pelican Horn, as in the lake generally, had again declined to low levels, associated with decreased water temperatures.

Middle Pelican Horn

The interpretation of effects of pump-induced dilution/flushing in Middle Pelican Horn were complicated to an extent by the sewage treatment plant discharge. Nonetheless, washout effects were apparent. An initial decline followed by a substantial increase in both cell volume and chl a occurred during the pumping period, which was apparently a function of soluble N input from Upper Pelican Horn coupled with the significantly increased exchange rate.

Nutrient loading to Middle Pelican Horn was very high during the study period, consisting of P contributed largely from sewage plant discharge, and N washed in from Upper Pelican Horn (Table 9). Despite the large increase in N loading to Middle Pelican Horn from pumping activities, the phytoplankton within the basin remained severely N-starved (Figure 11). This resulted in a large retention of N (nearly 96 percent) concurrent with a large net loss of P from the basin. In other words, soluble P input to the basin, primarily from sewage treatment discharge, was far in excess of algal demands, such that a the large unused fraction was carried from the basin. Soluble N, meanwhile, as the limiting nutrient relative to algal needs, was almost completely removed from basin waters by algal uptake.

The striking sensitivity of phytoplankton in Middle Pelican Horn to inflow nitrogen was effectively demonstrated during the pump operation. Comparison of observed versus predicted cell volumes and chl _a_ for Middle Pelican Horn indicates a close correlation during initial pumping operation, but a rather sharp deviation subsequent to the August 3 sampling (Figure 17). The deviation coincides with the timing of cessation of dilution water additions to Parker Horn, which resulted in a return to elevated soluble N levels in inflow to Parker Horn and consequently increased N levels in pump influent to Upper Pelican Horn. This suggests that under the initial conditions of a relatively low inflow of soluble N from Upper Pelican Horn, biomass in Middle Pelican Horn appears to have responded to a wash-in of algae from Upper Pelican and a washout of algae from its own basin. However, with the subsequent large inflows of soluble N into severely N - limited Middle Pelican Horn from Upper Pelican Horn after August 3, phytoplankton biomass responded with substantial increases. This relationship is illustrated effectively in Figure 18, where soluble N in Upper Pelican Horn, as representative of inflow, is plotted against phytoplankton cell volume in Middle Pelican Horn. Note also that despite increases in both chl _a_ and cell volume in Middle

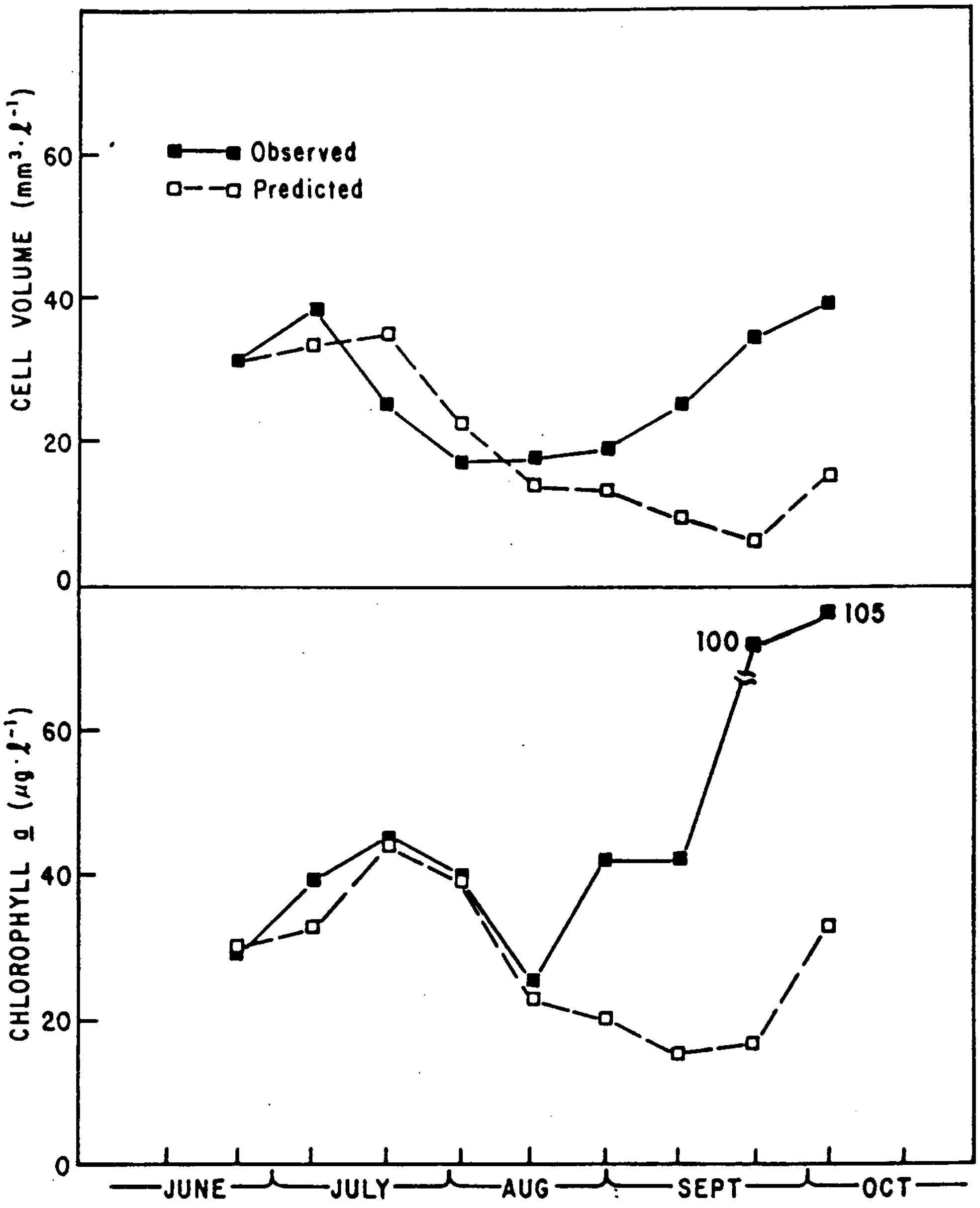

Figure 17. Observed versus predicted algal biomass (as cell volume and chl a) in Middle Pelican Horn during pumping operation period, 1982.

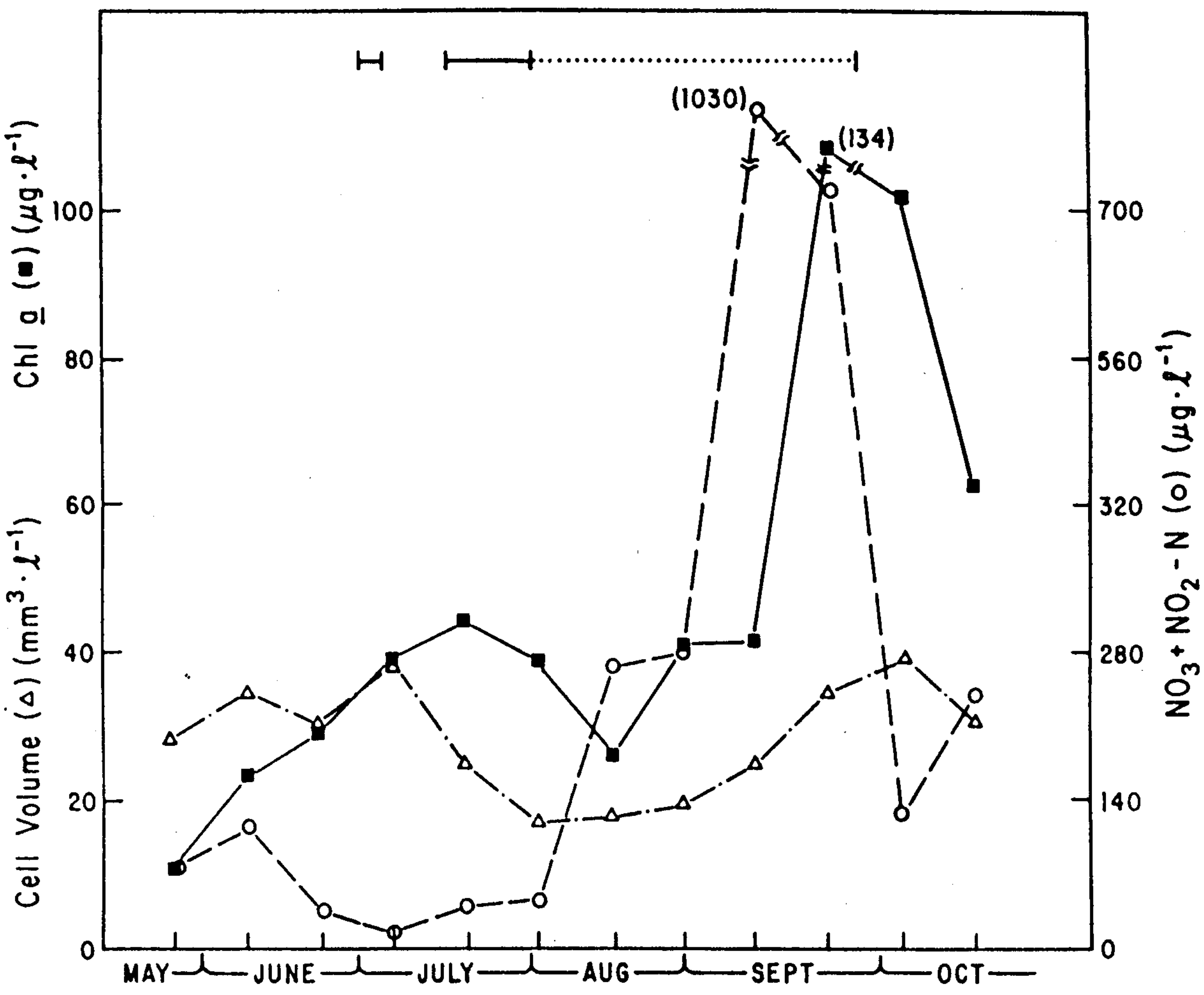

Figure 18. Soluble nitrogen (NO_3+NO_2) concentrations in Upper Pelican Horn (circles) and phytoplankton cell volume and chl a levels in Middle Pelican Horn (triangles and squares, respectively), May to October, 1982. Overbars indicate pumping period during (solid) and after (dotted) dilution water additions.

Pelican Horn with elevated inflow of soluble N from Upper Pelican Horn, the chl a values responded to a much greater extent. This indicates that, due to severe N limitation, phytoplankton in Middle Pelican Horn experienced greatly increased cell nutrition and, in turn, produced levels of chl a over and above that explained through increased biomass alone.

The responses observed in Middle Pelican Horn thus suggest that continuous culture relationships hold. Biomass levels were determined by inflow concentrations of the limiting nutrient. When concentrations of N remained low, phytoplankton levels were explained by wash-in and washout of algal cells. When concentrations of N dramatically increased, so did phytoplankton levels, suggesting that improved cell nutrition caused increased algal growth rates. As such, the pump-induced basin exchange rate of approximately 0.14 day^{-1} was exceeded by rates of algal productivity, resulting in biomass accrual.

Lower Pelican Horn

Because exchange rates in Lower Pelican Horn remained quite low during the study (0.01 day^{-1}), there was initial concern that potential washout effects on algae in this basin would be insignificant and that wash-in of nutrients and algae from Middle Pelican Horn could produce significant biomass increases. From the data, a case for such a phenomenon seems evident. Soluble P concentrations in the water of Lower Pelican Horn remained rather high during the study, likely a result of large inputs from Middle Pelican Horn (Figure 8). Little input of soluble N to Lower Pelican was expected, however, based on the fact that soluble N was so effectively consumed in Middle Pelican Horn.

Despite the low soluble N inputs from Middle to Lower Pelican Horn, the concentrations of nitrate plus nitrite and particularly ammonia were observed to increase substantially during September and early October (Figure 9). These increases were probably due in large measure to pump-induced wash-in of particulate N forms from Middle Pelican Horn. Decomposition and remineralization of that N could explain both the elevated levels of ammonia measured in Lower Pelican Horn and the presence of relatively large quantities of unidentifiable detrital material in analyzed phytoplankton samples. Because soluble N levels were similarly elevated in adjacent South Lake basin, an extension of the effects of input from Middle Pelican Horn is suggested there also. However, an alternative explanation is possible. Because South Lake is the deepest area in the lake (Figure 2), summer anoxia normally occurs, and did so during July-August 1982. As expected the resultant reduced state produced very high hypolimnetic ammonia levels. Eventual water column destratification and turnover, estimated to have occurred around the time of the September 14 sampling, likely contributed to elevated surface levels of soluble N in South Lake, and perhaps to an extent in Lower Pelican Horn as well. Nevertheless, because the observed soluble N levels in both basins (particularly ammonia), maintained elevated, even gradually increasing levels, a reasonably long-term continual source is suggested. Ammonia derived from short-term hypolimnetic turnover events would have been rather quickly taken up by algae or oxidized to nitrite and then nitrate. Therefore, the observed NH_3 levels appear to have been due largely to pump-induced input from Middle Pelican Horn.

A comparison of observed versus predicted values for chl a and cell volume in Lower Pelican Horn reveals that pump-induced input of algae alone from Middle Pelican Horn cannot explain observed biomass levels (Figure 19). Assuming, as discussed above, a significant pump-induced input of suspended particulate material from Middle Pelican Horn, it is believed that this material was either non-algal in origin or consisted of non-viable, decaying cells. Whichever was the case, the relatively high algal levels in Lower Pelican Horn were considered to be due to growth from abnormally high nutrient influxes and not cell wash-in.

The significant decrease observed in the algal levels in Lower Pelican during the sampling of September 14 occurred during several days of seasonally inclement weather. Strong winds (see Figure 5), overcast skies, and relatively low air and water temperatures (Appendix I) which occurred during this period, probably caused severe inhibition of algal activity as indicated by very low biomass levels. A subsequent return to more favorable climatic conditions (i.e., higher temperatures, greater incident light, water column stability), together with the nutrient-enriched conditions, resulted in a rapid and dramatic increase in phytoplankton biomass thereafter.

In summary, pump-induced input of soluble and particulate forms from Middle Pelican Horn appeared responsible for elevated nutrient concentrations in Lower Pelican Horn, although there remains the

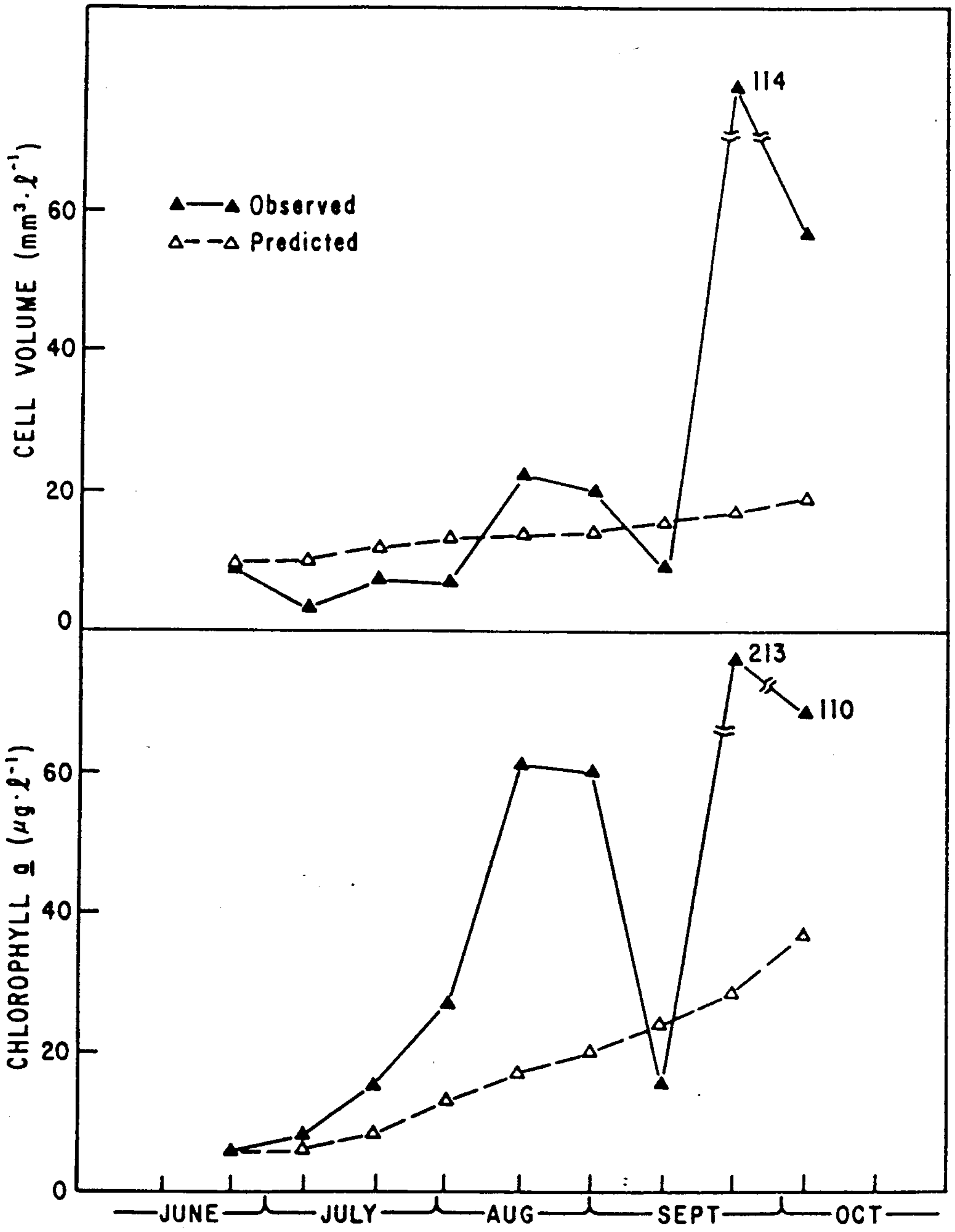

Figure 19. Observed versus predicted algal biomass (as cell volume and chl a) in Lower Pelican Horn during pumping operation period, 1982.

possible influence of South Lake hypolimnetic contributions. Since the minimum travel time for pump induced flows to traverse the basin of Lower Pelican Horn from Middle Pelican Horn was estimated to be on a scale of several days, it is appropriate that a lag time of three to four weeks was indicated between initial pump start-up and the large increase in nutrient levels observed in Lower Pelican Horn (Figure 9).

Nuisance levels of algal biomass were observed in Lower Pelican Horn and, to an extent, South Lake. The clearly worsened conditions which occurred during pump operation, and were not as extensive in previous dilution years either there or in other areas of the lake not affected by pumping, further implicates the accelerated input of nutrient-rich Middle Pelican Horn waters.

Prediction of Algal Productivity and Biomass

The difference between algal growth rate and water exchange rate ultimately determines whether washout is the principal mechanism of algal biomass control in a dilution/flushing experiment. Clearly, as the maximum growth rate of indigenous algal populations is approached and exceeded by accelerated water exchange rates, a cell washout occurs.

Despite this seemingly straightforward relationship, the determination of algal growth rates, particularly *in situ*, is difficult. *In situ* productivity is affected by numerous simultaneous controlling factors, such as nutrient availability, temperature, light, zooplankton grazing pressure, sinking, and antibiosis, among others. It is therefore intuitive that the rate at which a population increases will fluctuate downward from a theoretical maximum depending on the combined effects of these limiting factors. In addition, variations in intrinsic growth kinetics exist among different phytoplankton species. Therefore, not all species will be washed out at the same rate from a system where the exchange rate is fixed. This may help to explain the successional changes observed during the pumping period when, for example, green algae declined in more rapid fashion than other algal taxa.

One of the commonly used formulations for correcting phytoplankton growth rates for limiting nutrients and suboptimal light is the Monod version of Michaelis-Menten growth kinetics (Sykes, 1973). The proposed relationship is of the form:

$$\mu = \mu \frac{S}{K_S+S} \qquad (7)$$

where μ = specific growth rate,
μ = maximum specific growth rate
S = ambient limiting nutrient concentration,
and K_S = a half-saturation constant.

This is the form widely adopted and used in many models which simulate algal population dynamics (see Zison et al, 1978). The described relationship is illustrated in Figure 20 and indicates that, as the limiting nutrient concentration is increased, growth rate of an alga increases toward an asymtotic maximum. If the

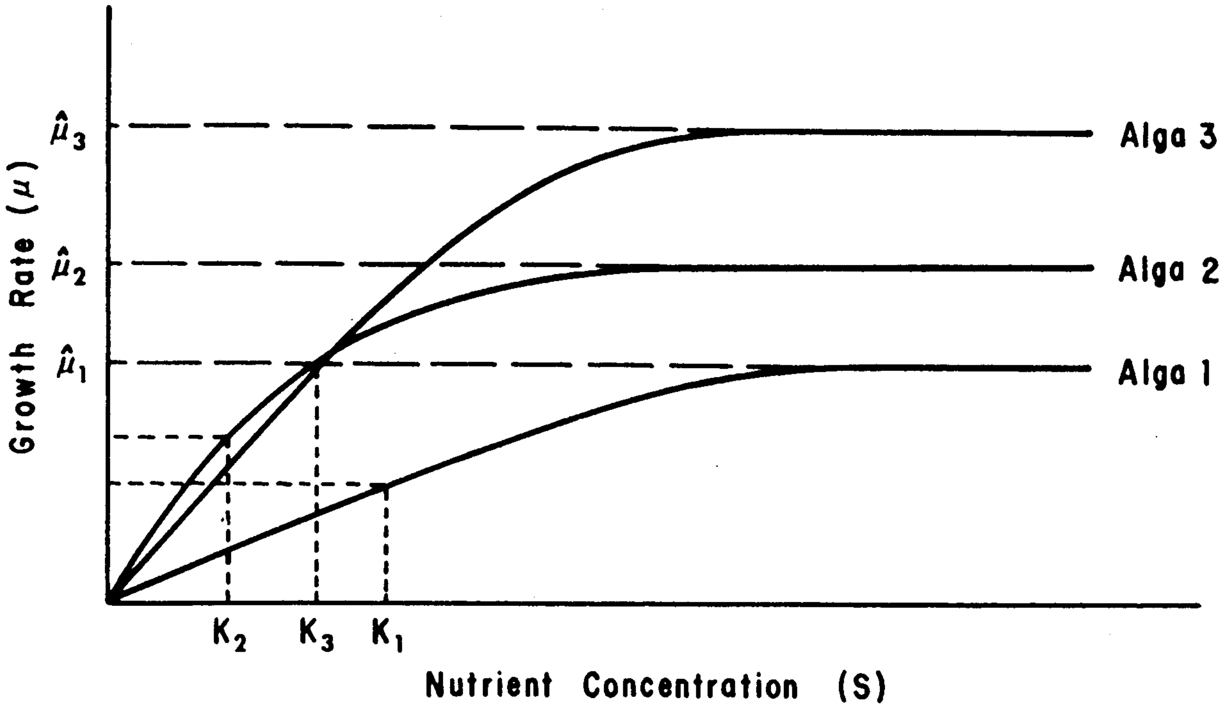

Figure 20. Hypothetical relationship between algal growth rate and nutrient substrate concentration based on Michaelis-Menten kinetics.

relationship is substituted into the first order growth equation $dX/dt = \mu X$, where X indicates biomass or population size, then:

$$\frac{dX}{dt} = \mu X \left(\frac{S}{K_S+S}\right) \tag{8}$$

This equation then describes biomass changes in response to a limiting nutrient. If, as in Pelican Horn, the population changes are explained on the basis of a continuous culture system, the exchange rate, ρ (inflow rate divided by basin volume), should be included as a biomass loss-rate term, such that:

$$\frac{dX}{dt} = \mu X \left(\frac{S}{K_S+S}\right) - \rho X \tag{9}$$

A more complete equation to describe algal biomass change or production in nature includes two additional loss terms, those accounting for grazing and sinking. However, data are not available for these factors in Pelican Horn and cannot therefore objectively be considered here. The possible effect of such factors, however, is discussed later.

By including loss due to exchange rate, it follows that as that rate becomes greater than algal growth rate, biomass loss will exceed gain, thereby reducing the existing population. Similarly, if the exchange rate is less than the algal growth rate, biomass gain will exceed loss, increasing the existing population by the difference between the rates. If a steady-state in biomass level is achieved, that being where loss due to water exchange exactly counters the gain from natural growth, the time derivative in the above equation is zero, and:

$$\mu X \left(\frac{S}{K_S+S}\right) = \rho X \tag{10}$$

In a continuous culture experiment where a steady-state biomass is maintained, the following relationships can be illustrated when considering the two variables, S and ρ:

1. Water exchange rate controls or determines output or production of alga cells from the chemostat vessel, since it determines the delivery or rate of nutrient supply. For example, if exchange rate increases and inflow nutrient concentration remains constant, the nutrient supply rate increases in proportion to the exchange rate. As nutrient is converted efficiently to cell mass, the increased quantity of cells is washed out, raising output of cells from the vessel.
2. Growth rate is controlled by <u>in situ</u> nutrient concentration, <u>not</u> the exchange rate. However, at steady state, growth rate equals the water exchange rate. That nutrient which is depleted in the basin relative to inflow concentration is that nutrient which is limiting to algal growth.
3. Biomass level is largely determined by the difference between inflow and outflow nutrient concentrations. For example, if exchange is constant and inflow nutrient concentration is increased, the additional nutrient input results in biomass increase, since the loss rate due to water exchange is constant.

In summary, an increase in inflow nutrient concentration increases growth rate and biomass, whereas an increase in flushing only increases cell production or output.

A response similar to that in a continuous culture vessel can be illustrated for Upper and Middle Pelican Horn basins by comparing smoothed curves of data for algal biomass (based on cell volume) and limiting nutrient concentrations in both the inflow and basin waters (Figures 21 and 22). In the Upper Pelican Horn example, both phosphorus and nitrogen are shown since a shift from N to P limitation occurred during pumping operations (Figure 21). Only nitrogen is plotted in Figure 22, since algae in Middle Pelican Horn were N-limited throughout the study period.

The curves suggest that with pump start-up both basins initially tended toward steady-state biomass levels where growth rate (μ) would have equaled exchange rate (ρ). In trending toward steady-state, the initial biomass concentrations decreased due to washout (where $\rho > \mu$). This decline occurred because inflow limiting nutrient concentrations were insufficient to maintain biomass at original levels according to Equation 9 and Michaelis-Menton kinetics, as depicted in Figure 20.

An approximate steady-state condition with respect to algal biomass was indicated in Upper Pelican Horn by August 3. During this phase, it was assumed that the growth rate of the algae remaining in the basin (minus loss rates due to grazing, sinking, etc.) was approximately equal to the exchange rate. Furthermore, with this assumption, and a derivative of biomass change with time of

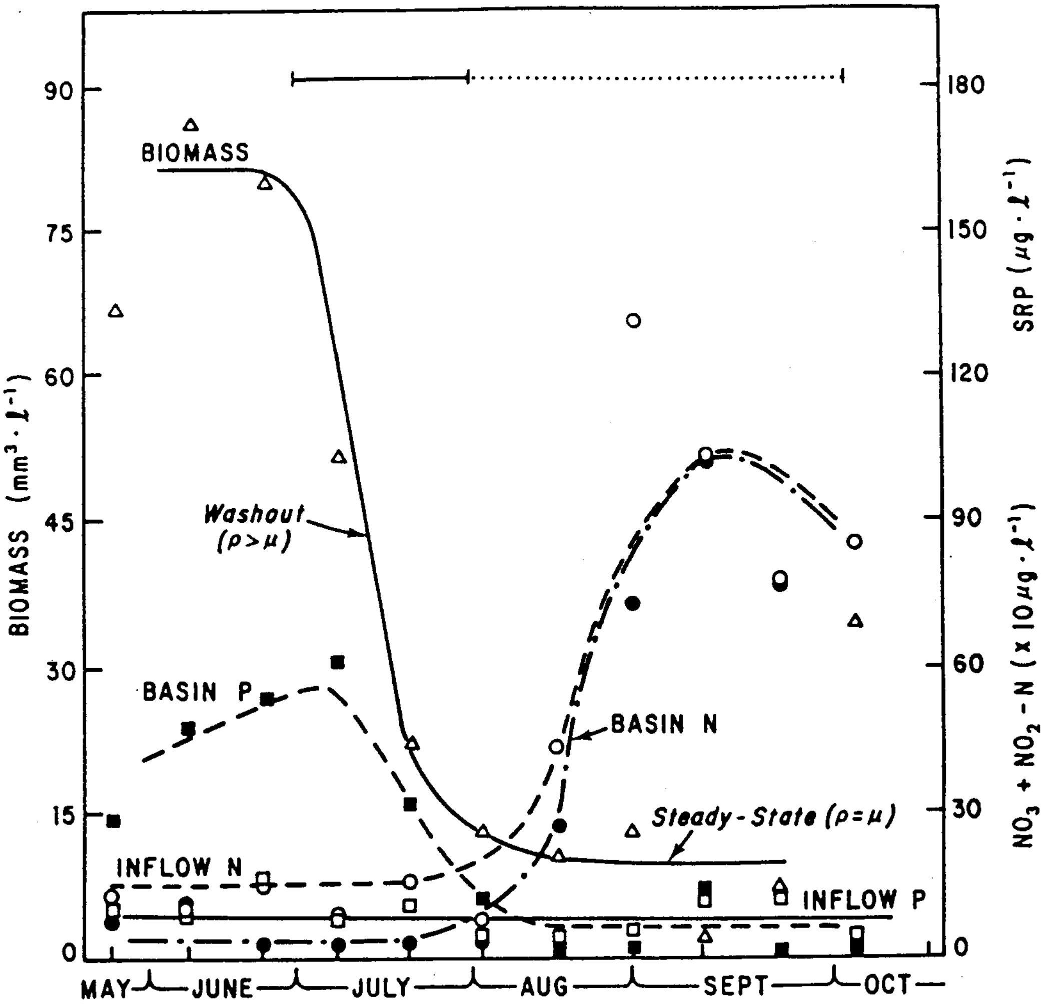

Figure 21. Smoothed curves of biomass and limiting nutrient concentrations in Upper Pelican Horn, May to October, 1982.

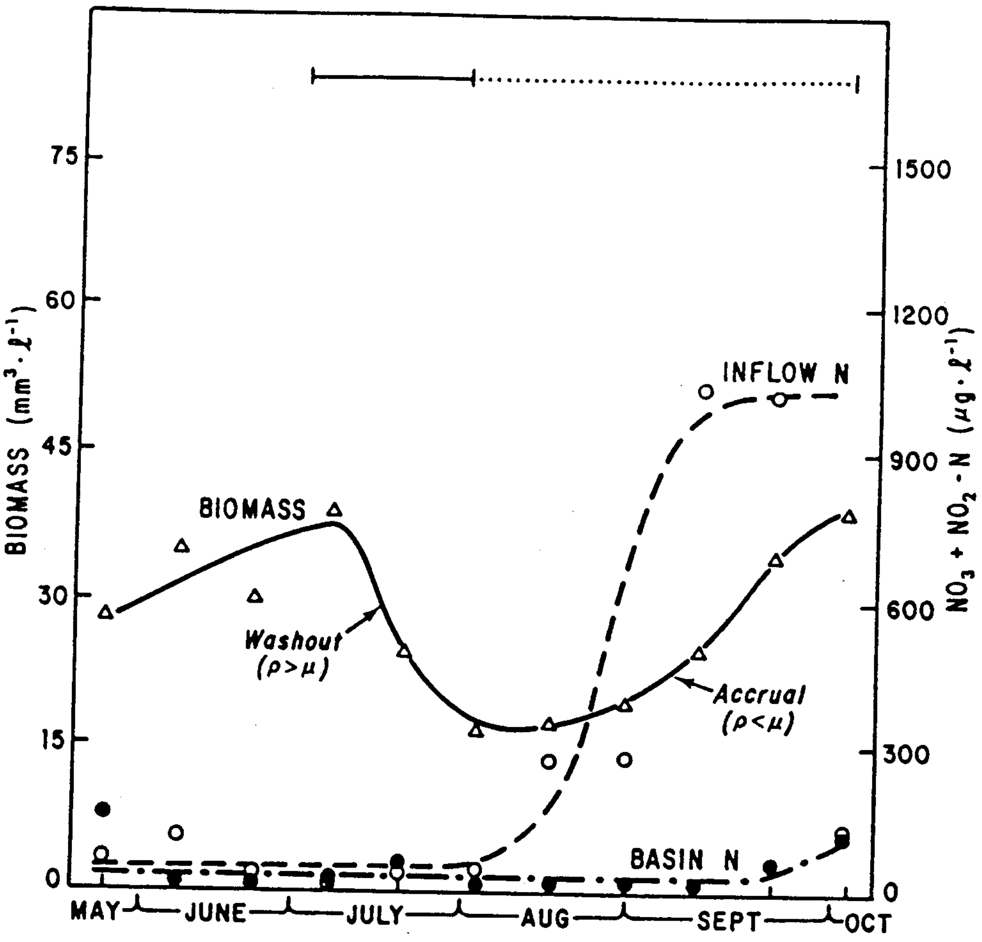

Figure 22. Smoothed curves of biomass and limiting nutrient concentrations in Middle Pelican Horn, May to October, 1982.

essentially zero, Equation 10 was used to estimate the maximum population growth rate (μ). Based on a constant exchange rate of 0.19 day^{-1}, a mean limiting nutrient concentration during the steady-state phase of 8 μg P l^{-1}, and an assumed half-saturation constant for P-limited growth of 5 μg P l^{-1} (Zison, et al, 1978), a maximum population growth rate of 0.3 day^{-1} was calculated. In addition to allowing accurate numerical predictions from the above equations, the maximum population growth rate is useful in indicating the flushing rate needed to obtain washout of algal biomass when excess (non-limiting) nutrient levels exist.

In the example of Middle Pelican Horn, steady-state conditions with respect to biomass were not clearly indicated by the data. In contrast to Upper Pelican Horn, the inflow concentration of limiting nutrient to Middle Pelican Horn increased significantly, allowing the algal population growth rate to also increase such that loss due to washout was overcome and actual biomass accrual resulted. It can be further speculated that if a steady-state in biomass had been achieved in Middle Pelican Horn, Equation 10 would dictate that, at a similar _in situ_ limiting nutrient concentration, the steady-state biomass level in Middle Pelican would be greater than that in Upper Pelican Horn (approximately 10 mm^3 l^{-1} cell volume), since the exchange rate of the former is less.

A model to predict steady-state algal biomass levels has, in fact, been developed by Uttormark and Hutchins (1978). This biomass model extends the simple input/output nutrient models of Vollenweider (1976) and Dillon and Rigler (1974) by adding an additional step which describes incorporation of nutrient into biomass based on Michaelis-Menten growth kinetics. Since at steady-state, the balance in biomass requires that growth rate equal flushing rate (plus other losses), as previously described, and the mass balance in nutrient is as follows:

$$X = Y\,(S_i - S_o) \tag{11}$$

where X = concentration of in-lake biomass (ML^{-3})

Y = yield coefficient = biomass produced per nutrient incorporated (dimensionless),

S_i = inflow nutrient concentration (ML^{-3}),

and S_o = outflow nutrient concentration (ML^{-3}),

steady-state biomass can be calculated by simultaneous solution of these mass balances with Michaelis-Menten growth as described in Equation 7. The model is also corrected for nutrient "sedimentation", or internal basin loss, based on the concepts of Dillon and Rigler (1974), such that nutrient income is partitioned into (1) that fraction which is incorporated into biomass, and (2) that fraction which is retained and remains unused.

The calculation of the maximum population growth rate of 0.3 day^{-1}, based on data from Upper Pelican Horn, and acquisition of data to describe nutrient income to the basins of Pelican Horn prior to and during the pumping operation, permitted revisions of original predictions by Welch (1980a) of biomass levels in Pelican Horn during pump operation using the Uttormark and Hutchins (1979) model. The results are presented in Table 11.

The two scenarios considered include Pelican Horn with (Case I) and without (Case II) removal of sewage treatment plant effluent. In the former case, the extent of biomass reduction upon diversion of sewage effluent (scheduled to occur by 1985) was predicted. In the latter case (II), predicted steady-state biomass levels under conditions of continued effluent discharge was assessed. Since steady-state was essentially achieved in Upper Pelican Horn and approached in Middle Pelican Horn, the results of the model could be verified with the actual data. Because the model yields a prediction of biomass concentration in terms of the limiting nutrient (as in Equation 11), conversions were made to report biomass in more meaningful units of chl a ($\mu g\ l^{-1}$) and cell volume ($mm^3\ l^{-1}$). These conversions are described in the footnotes to Table 11.

Under conditions of severe N-limitation in Pelican Horn, as currently exist with discharge of sewage effluent, the chl a predicted by the model is actually about six times greater than would normally occur in Pelican Horn. This result is due to the extremely low chl a:volume ratio found in the algae in Pelican Horn compared to other areas of the lake. For example, based on 1982 data, the typical chl a:volume ratio in N-limited Pelican Horn algae was approximately 0.7 versus approximately 4 in P-limited Parker Horn algae. Therefore, these factors were applied to the respective P-or N-limited scenarios for Pelican Horn, depending on presence or absence of sewage effluent. Where effluent remains and N continues to limit, chl a will not reach the levels predicted, but proportionate levels of cell volume as indicated will be attained. The

Table 11. Steady-state biomass levels expected for Pelican Horn with and without removal of sewage treatment plant effluent.

Case I. Sewage effluent removed and algae are P-limited[a]

Source	Flushing Rate (% day^{-1})	Biomass Predictions[b]	
		Algal Biovolume (mm^3 l^{-1})	Chl a (µg l^{-1})
Welch (1980a)[c]			
- no pumping	1.3	11	43
- pumping with D.W.	9.7	7	26
This study			
1) Upper Pelican			
- no pumping	1.3	10	39
- pumping with D.W.	19.0	W[d]	W[d]
- pumping without D.W.	19.0	3[1]	10
2) Middle Pelican			
- no pumping	1.3	10	39
- pumping with D.W.	14.0	3	10
- pumping without D.W.	14.0	4	16
3) Lower Pelican			
- no pumping	0.3	5	20
- pumping with D.W.	1.7	4	17
- pumping without D.W.	1.7	6	25

Case II. Sewage effluent remains and algae are N-limited[e]

Source	Flushing Rate (% day^{-1})	Biomass Predictions[f]	
		Algal Biovolume (mm^3 l^{-1})	Chl a (µg l^{-1})
Welch (1980a)[c]			
- no pumping	1.6	77	325
- pumping with D.W.	10.0	28	117
This study			
1) Upper Pelican			
- no pumping	1.6	71	300
- pumping with D.W.	19.0	8	35
- pumping without D.W.	19.0	18	75

Table 11 - Continued

		Biomass Predictions[b]	
Source	Flushing Rate (% day^{-1})	Algal Biovolume (mm^3 l^{-1})	Chl a (μg l^{-1})
2) Middle Pelican			
- no pumping	1.6	71	300
- pumping with D.W.	14.0	15	64
- pumping without D.W.	14.0	29	122
3) Lower Pelican			
- no pumping	0.3	8	35
- pumping with D.W.	1.8	7	31
- pumping without D.W.	1.8	24	99

[a] When the P-rich sewage effluent is removed, algal growth is limited by the low concentration of available P, and therefore predicted as a function of P.

[b] Algal biomass predicted from model of Uttormark and Hutchins (1978) assuming algae are P-limited and that actual biomass will be in between high values using Total P and low values using SRP. Maximum growth rate $\hat{u}$ = 0.3/day; K_s = 5 μg P/l. Biomass is predicted in units μg P/l and converted to chl a by dividing by 1. Biovolume is derived by a Chl a: volume ratio of 4 for P-limited algae in Moses Lake during 1982.

[c] Prediction by Welch (1980a) based on the same model are for Upper and Middle Pelican Horn basins combined.

[d] W indicates that the model predicts algal washout from the basin.

[e] Because sewage effluent is rich in P, algae grow rapidly until available N approaches depletion and limits continued algal growth. Therefore algal biomass is predicted as a function of N.

[f] Algal biomass predicted from the model of Uttormark and Hutchins (1978) assuming algae are N-limited and that actual biomass will be in between high values using Total N and low values using NO_3+NO_2-N. Maximum growth rate $\hat{u}$ = 0.3/day; K_s = 35 μg N/l. Biomass is predicted in units μgN/l and converted to chl a by dividing by 7. Chl a is overestimated by a factor of 6 to correct for the low chl a:volume ratio of 0.7 for N- limited algae in Pelican Horn during 1982.

difficulty in biomass prediction is choosing the fraction of nutrient available. For purposes here, available nutrient was considered as the mean between biomass predicted with total and soluble nutrient concentrations, with probably errors on the high side.

Table 11 also lists the expected biomass resulting from pumping into Pelican Horn after diversion of sewage (Case I). In this scenario, P would be limiting because of the relatively high influent N:P ratio from Parker Horn waters (see Figure 10). The results of no pumping represent groundwater only and are based on discharge estimated from a sodium balance previously described and mean P concentrations from groundwater samples (Station 14).

With or without pumping, the model predicts a significant reduction in cell volume in Pelican Horn following sewage diversion. In all instances, pumping concurrent with dilution water additions is predicted to result in the most significant biomass reductions. In fact, the model predicts cell washout in the basin of Upper Pelican Horn, where flushing rate would exceed population growth under the expected nutrient conditions during pumping with dilution. In reality, some biomass would be present because of areas of incomplete basin mixing and incoming cell volume from pump influent. Pumping without dilution water additions would result in lesser, but still large reductions in algal biomass in Upper and Middle Pelican Horn. Note that the model also predicts a slight increase in steady-state biomass levels in Lower Pelican Horn during pumping without dilution water additions as opposed to no pumping at all due to accelerated nutrient input.

Under conditions where sewage effluent remains in Pelican Horn and algae are severely N-limited (Case II as currently exists), predicted steady-state cell volume under all conditions is much greater than that predicted with sewage diversion. This outcome is somewhat obvious owing to the large contribution made to the nutrient budget of Pelican Horn by sewage effluent (see Table 9). During pumping operations, only slightly greater steady-state chl a values are indicated if considering that the values are six-fold overestimates. However, as discussed in the following section chl a : volume ratios increased in Pelican Horn with 1982 pumping operations, especially when pump influent was without dilution water additions. Therefore, predicted chl a values during pumping are probably overestimated by considerably less than the six-fold factor and chl a would undoubtedly remain much higher with or without pumping than will be the case after sewage effluent is diverted.

As in Case I, the high water exchange rates of Upper and Middle Pelican Horn induced from pump operation, result in the prediction of significant reductions in steady-state algal biomass over levels with no pumping. Further significant biomass reductions in these basins are predicted under conditions of pumping with dilution water. In Lower Pelican Horn, however, where flushing rate remains quite low and nutrient delivery is accelerated during pumping, a significantly higher steady-state biomass level is predicted without concurrent dilution water additions. This predicted response, and the nuisance levels actually observed during this study, suggests that for best results pumps should be operated only during periods of simultaneous dilution water additions to Parker Horn, particularly while sewage effluent is still being discharged into Middle Pelican Basin.

The similarity of the response in Lower Pelican to that predicted by the Uttormark and Hutchins (1978) model or continuous culture relationships is complicated by the uncertain origin of the relatively high nutrient levels observed. As discussed previously, it appears likely that a large increase in nutrients was derived by input from Middle Pelican basin with pumping, mostly regenerated from suspended particulate materials and sewage effluent. However, the substantial intermixing possible between Lower Pelican Horn and South Lake, raises the likelihood of contribution from overturn of nutrient-rich hypolimnetic waters. In the final analysis, biomass response in Lower Pelican, largely because of a characteristically long detention time, may prove to be more typical of growth in a closed container (that is, a batch culture) where steady-state may not be reached. This occurs because nutrient levels decrease as biomass increases, having been converted into algal cells. With insufficient incoming nutrient levels to replace what has been depleted, growth eventually stops.

Chlorophyll:Biomass

A significant feature of the phytoplankton response in Pelican Horn during 1982 pumping operations was the disproportionate effect on chl *a* values relative to cell volume. Data showed that chl *a* values, specifically in Upper and Middle Pelican basins, generally increased relative to cell volume, often in dramatic fashion (for example, see Figure 18).

Phytopigment content per unit cell volume is due primarily to (1) physiological factors, mainly the result of light or nutrient stress, and (2) species-specific differences (Tolstoy, 1979; Yentsch, 1980). Of these, the effect of nutrient deficiency has been investigated most frequently. Most workers have utilized controlled laboratory cultures to demonstrate conclusively that chl *a* content per unit cell (as volume, dry weight, or carbon) decreases with increasing nitrogen and phosphorus deficiency (Steele and Baird, 1962; Healey, 1978; Ahlgren, 1978; Healey and Hendzel, 1979; Tolstoy, 1979). However, few such indicators for nutrient stress have been applied to natural populations. Steele and Baird (1961) and Tett et al. (1975) found that chl *a*: cell carbon ratios indeed decreased when natural algal populations became nutrient deficient. It was argued that the observed changes could be conclusively assigned to nutrient stress in the natural mixed aggregations since species dominance and relative biomass remained fairly constant.

Under conditions of nutrient deficiency, phytoplankton respond by shifting organic matter synthesis away from proteinaceous compounds and towards stored carbohydrates (Droop, 1974; Sakshaug, 1980). The resultant decrease in the ratio of protein to carbohydrate also results in a general decrease in the ratios of cellular nitrogen:carbon, phosphorus:carbon, ATP:carbon, and chl *a*:carbon, among others. In addition, it is important to reiterate that nutrient deficiency also results in a proportionate reduction in specific growth rate.

Because changes in phytoplankton composition as well as nutrient income were clearly evident during the course of this study, one or both of these factors must be responsible for increasing chl a:C ratios in Upper and Middle Pelican basins (Figure 23). Water column light levels were probably not a factor since Secchi disk depths were relatively constant in Pelican Horn throughout the study (Figure 15). A successional effect could have caused part of the change in chl a:C because of the large decline in both the relative biomass and absolute numbers of green algae compared to other algal taxa in Upper and Middle Pelican basins taxa (Figure 13). The relative contribution of this factor compared to that based solely on the observed nutrient enrichment is not clear. In other studies, it has been inferred that taxon-specific differences in cellular chl a content were relatively low, due to similar environmental conditions, compared to the effects imposed by nutrient stress (Parsons, 1961; Tolstoy, 1979). In Pelican Horn, the effects of nutrient stress followed by pump-induced enrichment is probably the dominant effect also.

Previous Moses Lake results (Patmont, 1980), and those from other workers (Nicholls and Dillon, 1978; McCarthy, 1980), suggest that chl a: C ratios in algal cells are particularly sensitive to nitrogen limitation. This has profound repercussions for Pelican Horn since algal populations here were known to be highly N-starved (Bush, 1971; Welch, 1980b) and were then exposed to high nitrate inflow during 1982 pumping operations. Because of the sewage

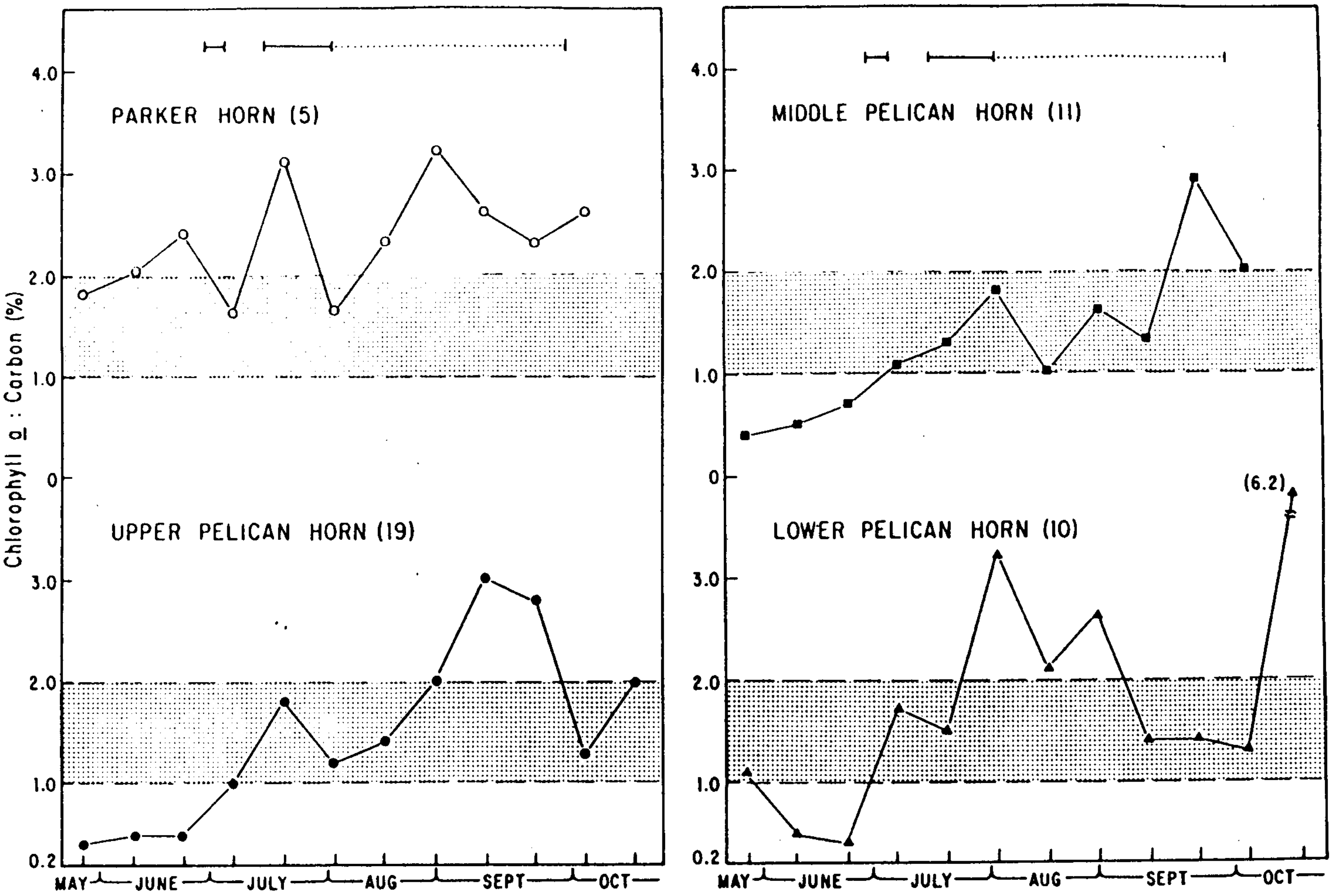

Figure 23. Chl a: cell carbon ratios for phytoplankton in Parker Horn and Pelican Horn, May to October, 1982. Shaded areas indicate Healey's (1978) zone of "moderate" nutrient deficiency.

effluent entering Middle Pelican Horn, nutrient input has been very high but dominated by phosphorus, such that the N:P ratio available to the phytoplankton remained quite low. N:P ratios less than 0.1 were frequently observed in previous years (Bush, 1971; Patmont, 1980) and during this study prior to pumping (Figure 10). The result has been that prior to pumping the actual biomass present in Pelican Horn was on the order of six times that indicated by chl a.

The trends in chl a:C depicted in Figure 23 reveal a general escalation during the 1982 pumping period in both Upper and Middle Pelican Horns, where nitrogen shortages relative to phosphorous have normally been greatest. For example, ratios of chl a:C in both basins increased from a minimum of around 0.3 percent prior to pumping in June to a maximum of around 3.0 percent during mid-September. Meanwhile, in neighboring Parker Horn, values oscillated rather randomly between about 1.6 and 3.2 percent.

Healey's (1978) work with laboratory chemostats resulted in estimates of chl a:dry weight ratio bounds for "moderate" and "severe" nutrient deficiency. Using a carbon:dry weight conversion factor of 0.2 (Ahlgren, 1978), the bounds convert on a chl a:C basis to approximately two percent and one percent, respectively, for moderate and severe deficiencies. These are indicated relative to the trends shown in Figure 23 and suggest that the nutrient and, hence, physiological status of the phytoplankton in Pelican Horn improved significantly in 1982 concurrent with pumping. Such a positive response indicates not only improved nutritional conditions with pumping but probably a significant increase in population growth rate as well. Thus, the large effect that pump-induced exchange rates had on reducing algal biomass levels in Upper and Middle Pelican Horn through washout is further emphasized, because population increases might have been expected from increased N had the exchange rates been negligible as in Lower Pelican Horn.

The realiability of chl _a_ values as a measure of algal biomass and as a trophic state indicator in highly enriched areas like Pelican Horn can be questioned. The relative concentrations of chl _a_ compared to cell volume or cell carbon in Pelican Horn have been characteristically low compared with other areas in Moses Lake (Patmont, 1980; Welch, 1980a; Figure 23 - Pelican Horn vs. Upper Parker Horn) and they were observed to increase substantially, relative to cell mass, during pumping. Although chl _a_ is an accepted trophic state indicator, the problems evident in the case of Pelican Horn are likely similar for water bodies with similar high nutrient input and low N:P ratios.

Phytoplankton Composition and Succession

The interpretation of results would be greatly simplified if the phytoplankton could be regarded as a single homogenous entity and the consideration of species-specific responses to physical and chemical factors could be disregarded. But, in fact, the principal fault in explaining algal responses in Pelican Horn by continuous culture relationships is that phytoplankton populations _in situ_ are composed of mixed assemblages, while that in the chemostat is monospecific. Still, by identifying the different taxa (to genera here) and their relative abundance, interpretation of the effects of water exchange or nutrient changes can be further clarified, particularly if a change or succession in dominant algal taxa occurred.

Such was the case during 1982 pumping activities in Pelican Horn. Both Upper and Middle Pelican basins, in particular, showed not only a change in dominant taxa during the study, but a wholesale shift from a green dominated community to one dominated by blue-greens. The fact that blue-greens have rarely approached or exceeded dominant greens before in Upper and Middle Pelican basins (Welch et al., 1969; Bush, 1971; M. D. Tomasek, pers. comm.), indicates that the summertime succession to blue-greens, which is typical of many eutrophic lakes, as well as in other parts of Moses Lake, has not been typical in Pelican Horn. On the other hand, the large fraction of greens in Upper and Middle Pelican basins, has been in stark contrast to the remainder of Moses Lake, where species of green algae have rarely reached dominant proportions (see also Patmont, 1980; Brenner, 1983). This was observed again during 1982 (Figures 14 and 15).

The reason why greens are dominant in Upper and Middle Pelican basins in the first place is likely due to the influence by the sewage treatment plant discharge. Released effluents have provided a continuous source of nutrient-rich inflow with a very low N:P ratio, which results from a relatively large phosphorus contribution. Many of the greens present may indeed require high phosphorous concentrations (Welch, 1980a) and low N:P ratios (Pearsall, 1932; Wetzel, 1975) relative to blue-greens. Whether, in the latter situations, low N:P ratios are simply an artifact of high phosphorus concentrations is not certain. However, phosphorus uptake kinetics might provide a clue. For example, Hutchinson (1967) and Shapiro (1973) have hypothesized that blue-greens outcompete greens (and other algal groups) at low nutrient concentrations. Bush et al. (1972) hypothesized this as an explanation for green dominance in Pelican Horn.

The implications of this finding can be demonstrated by the hypothetical nutrient uptake relationships in Figure 20. According to the above criteria, greens could be conceptualized as responding similarly to Alga 3 as shown, and blue-greens as Alga 2. The resulting inference is that greens grow faster and thus out compete blue-greens at high phosphorus concentrations, with the trend reversed at low concentrations. In the case of Pelican Horn, such a reversal in competitive advantage may have resulted from pumping activities and concomitant reductions in ambient phosphorous levels (see Figures 8 and 9). It therefore appears plausible that green algal growth rates may have been more effectively reduced, particularly in relation to blue-green growth rates, to a point where greens were more susceptible to pump-induced washout.

A real paradox in the assessment of algal succession in Pelican Horn arises when considering the potential influence of nitrogen. A great deal of research devoted to the dominance of blue-greens in eutrophic waters has focused not only on their superior kinetics at low nutrient concentrations, but the ability of certain species to fix atmospheric nitrogen in the virtual absence of soluble nitrogen in the water column. However, because nitrogen fixation is costly from the standpoint of bioenergetics, non-N-fixing algae presumably grow faster when soluble nitrogen is available than do blue greens when fixing N. Indeed, evidence for such interactions exist from both field and laboratory research. For example, both Droop (1974) and Ahlgren (1977) reported higher growth rates for several species of green algae compared with blue-greens at high nitrate supply in chemostats. Moss (1973b) demonstrated the same effect in limnocorrals, and Schindler et al. (1973) noted a succession to green algal dominance in an experimental lake fertilized with nitrate in relatively high proportions to phosphate.

If nitrogen were indeed a factor in the observed succession in Pelican Horn, one would expect that the high nitrate levels introduced by pumping activities would have favored greens and prevented replacement by nitrogen-fixing blue-green algae. Despite this, blue-greens did supplant greens in Upper and Middle Pelican Horn and were composed almost entirely of the nitrogen-fixing Aphanizomenon. This phenomenon was also observed by Buckley (1971) in bag experiments conducted at Moses Lake. Although expecting nitrogen additions to favor greens, Buckley (1971) observed an actual increase in the ratio of blue-greens to greens. Although the reason for this response remains unclear, it has been speculated that added nitrate may indirectly affect phytoplankton dynamics by altering inorganic carbon balance (Welch, 1980a). By this mechanism, the addition of nitrate acts to increase pH and, hence, decrease the concentration of free carbon dioxide according to dissolved carbonate equilibria.

The idea that free CO_2 is a key factor in algal succession has received considerable attention and debate. The theory advanced by King (1970) and demonstrated by Shapiro (1973) that low free CO_2 concentrations favor blue-greens has been challenged by Goldman (1973), who maintained that it is not free CO_2 concentration which is critical to growth rate, but rather the concentration of total inorganic carbon (C_T). Recently, Pearl and Ustach (1982), in a well-controlled experiment, demonstrated convincingly that low free CO_2 concentration resulted in blooms of the blue-greens Anabaena and Aphanizomenon without a noticeable change in C_T. On the other hand, DeNoyelles and O'Brien (1978), studying succession in limnocorrals, noted that several species of green algae, including Scenedesmus and Sphaerocystis, which were also prevalent in Pelican Horn, always dominated at high pH levels (10-11), and demonstrated rapid inorganic carbon uptake capability. The differing results from these studies suggest that both blue-greens and greens produce species having very low carbon half-saturation constants and that in some cases low carbon concentrations may not be a factor in succession.

Such a case may have existed in Pelican Horn during 1982 pumping operations. As was shown in Figure 11, free CO_2 concentrations were indeed very low throughout most of the study period, but were just as low after as before pumping commenced. While these low values may well have contributed to the algal types found in Pelican Horn, they probably did not contribute appreciably to the observed succession since free CO_2 concentrations remained relatively unchanged prior to and during pumping activities.

Before concluding consideration of carbon, it should be noted that many of the phytoplankton species tolerant of low CO_2 concentrations (which reportedly include species from the genera _Anabaena_, _Aphanizomenon_, _Scenedesmus_, and _Sphaerocystis_) have been shown to possess the capability of utilizing bicarbonate (HCO_3^-) when free CO_2 is depleted (Moss, 1973a; DeNoyelles and O'Brien, 1973; Paerl and Ustach, 1982). Therefore, it appears that, considering the phytoplankton genera present, carbon probably was not limiting the algal biomass in the long term in Pelican Horn, although a certain short-term growth rate limitation may have been imposed through the use of HCO_3^- in the absence of free CO_2. This point is mentioned to dismiss arguments that C may be the nutrient most limiting to biomass increase in Pelican Horn rather than N or P.

Other physical and chemical factors known to contribute to natural phytoplankton succession probably did not contribute significantly to the changes observed in Pelican Horn. Light, temperature, and water column stability were all either unchanged or clearly out of phase temporally with the observed successional changes. Theories based on excretion of allelopathic substances (Keating, 1978) or trace metal interferences (Murphy et al., 1976; Juttner, 1981) by blue-greens are discounted largely because the absolute abundance of blue-greens in Upper Parker Horn, which served as pump feed, was roughly the same or less than blue-green abundance in Pelican Horn prior to pump start-up.

Biological factors, primarily zooplankton grazing, which can be particularly selective against greens relative to blue-greens, may apply here, although lack of data makes this mechanism hard to assess.

Finally, it is possible that the observed algal succession can also be explained in part by the introduction of algal biomass characteristic of Upper Parker Horn to Upper Pelican Horn via the pump and pipeline. Examination of phytoplankton volumes in these basins (Figure 13 and 14), and comparison of observed algal biomass in Upper Pelican Horn with that predicted by a simple input/output model (Figure 16), reveals that total cell volume in Upper Pelican during pumping can be explained by algal input from Upper Parker Horn. Since the quantity of greens in Upper Parker Horn was very low, pump introduction to Upper Pelican Horn provided a means of "diluting out" the characteristically large fraction of greens in the latter basin. At the same time, blue-green volume could be maintained in Upper Pelican Horn by a continual "seeding" of blue-greens from the Parker Horn pump influent. However, because (1) greens in Upper Pelican Horn declined in a more dramatic fashion than would have occurred with mere dilution or water replacement by pump influent, and (2) blue-greens actively increased in volume over and above pump-induced input alone in Middle Pelican Horn (Figure 13), algal input from pump influent can only partially explain the successional phenomenon.

Water Clarity - Observations and Prospects

One of the more interesting results of the study was the relatively invariable and quite low Secchi disk transparency recorded in Pelican Horn thoughout the pumping period despite often dramatic decreases in cell volume and chl a values. While the quantitative relationship between water clarity, or transmissivity of light (as measured by Secchi disk depth), and chl a or algal biomass is somewhat variable among lakes, they are usually highly correlated, thus justifying the common use of Secchi disk depth as a trophic state indicator (Carlson, 1977).

However, by comparing measured Secchi disk depths with simultaneous cell volume or chl a values, it can be seen that water clarity in Pelican Horn, particularly within the upper and middle basins, changed little over the observed range of algal biomass levels and was considerably less than at similar biomass levels in other areas of the lake (Figure 24). In fact, at equal cell volume or chl a concentrations, associated Secchi depths in Pelican Horn were roughly half those measured in other Moses Lake basins (Parker Horn, South Lake, Cascade, Rocky Ford Arm).

The primary agent of the decreased clarity in Pelican Horn waters was undoubtedly suspended detrital materials and sediment. Owing to the very shallow morphometry and the general prevailing wind exposure characteristic of Pelican Horn, resuspension of bottom sediment likely occurs frequently, if not continuously.

Because poor water clarity is that quality of a water body most obvious to the public, it is important to emphasize that, although often dramatic decreases in chl a values were observed in Pelican Horn, these changes were not visually evident, except that the water remained "dirty" throughout. On this basis, if significant algal reductions accompany future introductions of high quality, low

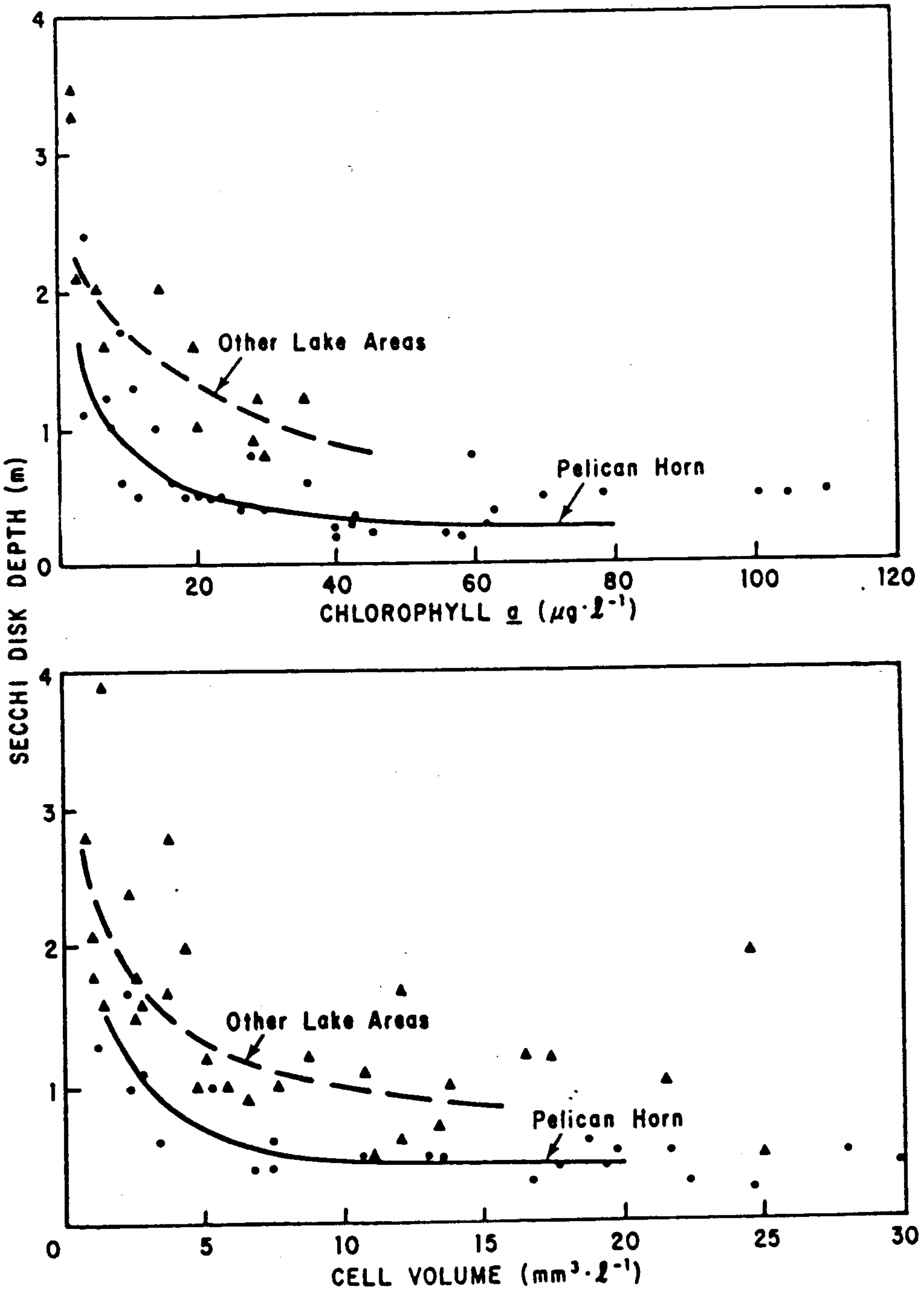

Figure 24. Secchi disk depth versus algal biomass (as chl a and cell volume) for Pelican Horn (circles) and other areas in Moses Lake (triangles) derived from 1982 data.

nutrient dilution water to Pelican Horn via pumping, equally significant water clarity improvements are unlikely. This is particularly true of the shallow Upper and Middle Pelican Horn basins.

The decreased water clarity in Pelican Horn raises the question of whether light might have limited algal productivity. Due to the very shallow Secchi depths observed, it was apparent that the photic zone depth was also quite shallow. In fact, based on Talling's (1971) relationship (photic depth equals two times Secchi disk depth), the photic zone in Pelican Horn extended to only about one meter during the spring-summer period. While such shallow photic depths usually occur in only the most productive waters (i.e. sewage lagoons), much of the light attenuation observed in Pelican Horn was not due to viable phytoplankton biomass.

Compared to the estimated photic depth, actual mean depths in Pelican Horn, particularly Upper and Middle Pelican basins (1.4 and 1.3 m, respectively), were not much greater. Therefore, a typical phytoplankton cell likely received adequate light exposure. If light was to be limiting, however, the fact that Secchi disk depths were fairly constant in Pelican Horn throughout the study suggests the effects on algae were rather constant and, thus, probably did not cause the observed changes in algal biomass.

Potential Role of Zooplankton, Macrophytes, and Fish

Although not investigated directly, the activities of certain aquatic organisms no doubt had a potentially important influence on the overall effects observed during the study period. Specifically, those organisms thought to have the greatest potential influence on events within Pelican Horn include zooplankton, macrophytes, and fish. Both the macrophyte Potamogeton pectinatus and the common carp Cyprinus carpio were extensively observed in Upper Pelican Horn. Several taxa of zooplankton were observed in samples analyzed for phytoplankton. From a qualitative standpoint, a discussion of observations provides some additional insight into the possible role of such organisms in the effects observed in Pelican Horn.

Zooplankton, as efficient grazers of phytoplankton, may have a profound influence on the size and structure of target algal populations. Evidence from many lake experiments has emphasized the role of herbivorous zooplankters in controlling algal blooms and selecting for, by preferential grazing activities, the dominance of blue-green forms such as Aphanizomenon (Shapiro, 1980). Gelatinous coatings and the relatively large size of trichome bundles in many blue-greens makes them difficult for zooplankton to consume, thus favoring survival of blue-greens over other algal forms under grazing pressure (Porter, 1977; Welch, 1980a). The fact that blue-greens, composed primarily of Aphanizomenon, replaced greens during pumping operations in Pelican Horn suggests the possibility that part of the cause may have been due to zooplankton grazing.

Continual observations of zooplankton appearing in Pelican Horn phytoplankton samples indicated a composition that included rotifers (Rotatoria), the common cladoceran genera Daphnia and Bosmina, and an occasional copepod (Eucopepoda). No appreciable change in abundance was apparent during the study period, however. On the basis of this observation, together with the previous consideration of nutrient-algal interactions, it seems likely that the dramatic reduction in green algae, which followed pump start-up in Upper Pelican Horn, was not caused in a major way by changes in zooplankton grazing activity. Clearly, quite substantial numbers of zooplankton would have been required to elicit such a reduction. On the other hand, zooplankton could have influenced the succession in Middle Pelican Horn, since the shift from greens to blue-greens in that basin was more gradual.

The extensive beds of Potamogeton pectinatus observed in the shallower areas (generally less than one meter depth) of Upper Pelican Horn (see Plate I), suggest a potential source of internal nutrient regeneration and, moreover, a potential for future expansion of plants during pump operations. The role of macrophytes in nutrient processing and recycling has been intensively studied and is somewhat controversial. Research has documented reductions in sediment and water column nutrients by active macrophyte uptake, as well as nutrient increases by active secretion or senescense (Wetzel, 1975; Carpenter, 1980; Carignan and Kalff, 1980, 1982). In a more pertinent case, Lehman and Sandgren (1978) reported an increase of soluble P following scenescence and decomposition of Potamogeton spp. in monomictic Egg Lake (Washington). In that study, as well as those by Carignan and Kalff (1980) and Landers (1982), simultaneous increases in phytoplankton chl a were observed and correlated to macrophyte-induced nutrient increases. Interestingly, Wetzel (1975) cited a detailed study of the influence of submersed macrophytes on phytoplankton, which showed that phytoplankton productivity decreased

60 percent in the presence of Potamogeton pectinatus. Both the effects of shading and excreted inhibitory organic compounds were implicated. Wetzel (1975) further suggested the possible impact on phytoplankton productivity by a reduction in free CO_2, which occurs in dense stands of actively photosynthesizing submersed macrophytes. This may have significant meaning in the basins of Upper and Middle Pelican Horn. Characteristic low free CO_2 concentration in these basins probably result in some short-term limitation of phytoplankton productivity.

A rather complete dissappearance of P. pectinatus was observed during mid-September in Pelican Horn. This was undoubtedly associated with annual fall die-back known to occur with this species (Wetzel, 1975) and not necessarily a cause of pump-induced water quality changes. It seems plausible that resulting senescense of macrophyte biomass could have contributed to the observed increase in nitrogen, phosphorus, and free CO_2 observed during the sampling of September 14 (see Figure 7 and 11). However, relatively strong winds which occurred on that date (Figure 5) were thought to be the primary contributor to the observed nutrient increases through resuspension of sediments, reduced primary productivity, and increased gaseous diffusion.

The common carp Cyprinus carpio was abundant in Pelican Horn throughout the study period and were observed frequently in the entire lake. Particularly noticeable was carp spawning activity which occurred in Upper Pelican Horn in late June - early July. Upper Pelican Horn has been previously identified as a major carp spawning area for Moses Lake (Nunnallee, 1968). Carp have been so numerous in Moses Lake over the years that some commercial harvests have occurred (Wydoski and Whitney, 1979) and plans for large-scale eradication were formulated (Sylvester and Oglesby, 1964).

The significance of carp in Pelican Horn is primarily two-fold. First, these fish are detrital feeders and are capable of recycling large quantities of phosphate and ammonia through excretion. Lamarra (1975) showed that a carp population in a Minnesota lake was capable of releasing to the water enough of these nutrients to exceed Vollenweider's (1968) safe loading limits and result in massive algal growths. Secondly, their benthic feeding orientation results in continued stirring of sediments, which could act to increase further turbidity and remineralization of particulate nutrient forms. Sylvester and Oglesby (1964) suggested that much of the turbidity in Moses Lake waters was caused by carp activities. On the basis of these observations, it seems quite plausible that the additional high turbidity and phosphorus concentrations typical of Pelican Horn, particularly in Upper Pelican basin, are carp-related. As noted previously, the poor water clarity in Pelican Horn (low Secchi transparency) is only partly correlated with algal biomass and, therefore, indicates a high non-algal turbidity component.

SUMMARY AND RECOMMENDATIONS

1) The nutrient-phytoplankton responses observed in Pelican Horn during 1982 pumping operations were generally predictable on the basis of continuous culture concepts. Biomass levels were determined

by inflow concentrations of limiting nutrient and intrinsic basin flushing rates. When limiting nutrient concentrations remained low, phytoplankton levels were explained by washout of algal cells. When limiting nutrient concentrations dramatically increased, so did phytoplankton levels, suggesting that improved nutrition caused increased algal growth rates.

2) Predicted steady-state phytoplankton levels, and the nuisance algal levels actually observed during this study, clearly advocates the operation of pumps only during periods of simultaneous dilution water additions to Parker Horn, particularly while sewage effluent is still being discharged into Pelican Horn. With or without pumping, the most significant reductions in phytoplankton cell volume are predicted for Pelican Horn following diversion of sewage effluent.

3) The use of chl *a* to indicate algal biomass changes in response to future pumping is not recommended, since the ratio of chl *a* to cell volume increased substantially in Pelican Horn during pumping. Although chl *a* is an accepted trophic state indicator, the problems with such use are evident in the case of Pelican Horn and likely for water bodies with similar high nutrient and low N:P ratios. Future biomass values should be determined by cell volume estimates, with chl *a* maintained as an indicator of phytoplankton nutritional status.

4) Water clarity in Pelican Horn (as measured by Secchi disk) changed little over the observed range of algal biomass levels and was considerably less than at similar biomass levels in other areas

of the lake. This suggests a relatively large turbidity component not accounted for by chl a content and, hence, algal biomass. If significant phytoplankton reductions accompany future introductions of high quality, low nutrient water to Pelican Horn via pumping, equally significant water clarity improvements are unlikely.

5) While the cause and effect relationships of algal changes and biotic factors, such as zooplankton, macrophytes, and fish, can only be speculated, it seems clear that a more thorough understanding of water quality dynamics both before and after pumping events requires that these factors be investigated in order to attribute the proper portion of the cause for algal control to dilution/flushing in Moses Lake. Regular zooplankton sampling and a more formalized reconnaissance of macrophyte abundance is needed, and these will be implemented. Experimental evaluation of the significance of carp in internal nutrient loading and sediment suspension should also be performed.

6) Statistical analysis and assessment of data is constrained under the current Moses Lake sampling format. It is recommended that two or three sampling trips per year be devoted to establishing some record of statistical variability with sampling locations by obtaining additional replicates. In this way, the scope of the sampling program could be maintained with only a relatively moderate annual increase in required sample analysis workload.

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APPENDIX I

MOSES LAKE COMPREHENSIVE DATA

1982

KEY:

Station Location:

1 - East Low Canal
2 - Rocky Coulee Wasteway
3 - Crab Creek above RCW
4 - Crab Creek Inlet
5 - Upper Parker Horn
7 - Lower Parker Horn
8 - Cascade
9 - South Lake
10 - Lower Pelican Horn
11 - Middle Pelican Horn
12 - Rocky Ford Arm
13 - Rocky Ford Creek
14 - Groundwater springs
19 - Upper Pelican Horn
STP - Sewage Treatment Plant effluent

Sample Type:

S - surface discrete
2 - 2m discrete
6 - 6m discrete
B - bottom discrete
C - vertical composite
T - horizontal (transect) composite

Parameters (units reported):

Temperature (°C)

pH (units)

Secchi (m)

SRP (μg P.l^{-1})

Total P (μg P.l^{-1})

NO_3-N (μg N.l^{-1})

Total N (μg N.l^{-1})

Chl *a* (μg.l^{-1})

Conductivity (μmhos.cm^{-1})

Alkalinity (mg.l^{-1} as $CaCO_3$)

Dissoved oxygen (mg.l^{-1})

NH_3-N (μg N.l^{-1})

MOSES LAKE DATA

Date 1/21/82

Air Temp.: 37°c Wind Speed: 0 Wind Direction: 0 Cloud Cover: 0.8

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2	7.2			108	116	3628			466	373.0		
3	0.0			42	61	1736			535	459.0		
4-R	2.5			62	118	3768			519	412.0		
5-T												
7-S	1.8	8.0		14	39	601			375	291.0		
7-2	1.9	8.0		16	52	619			372	286.0		
7-B	2.0	8.1		14	40	649			393	284.0		
7-T												
8-S	2.0	8.0		14	37	789			396	289.0		
8-B	2.5	8.0		18	26	781			412	304.0		
8-C												
8-T												
9-S	0.9	8.2		25	17	625			401	290.0		
9-2	1.9	8.2		16	36	598			393	287.0		
9-6	2.1	8.1		40	71	671			404	295.0		
9-B	2.1	8.1		99	52	582			414	295.0		
9-T												
10-S	0.5	8.3		31	40	364			392	286.0		
10-2												
10-B	2.5	8.3		75		353			405	290.0		
10-T												
11-S	0.2	8.0		1620	1232	1444			586	352.0		
11-B	4.0	8.0		1876	1676	1660						
11-T												
12-S	1.2	7.9		41	75	1356			399	283.0		
12-B	3.2	7.7		47	46	806			411	297.0		
12-C												
12-T												
13	6.0			203	193	1959			360	255.0		
14												
19												
STP												

Note: Ice Cover

MOSES LAKE DATA

Date 2/23/82

Air Temp.: Wind Speed: Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2				89	160	2780						
3				32	195	1310						
4-R				66	166	2738						
5-T												
7-S												
7-2												
7-B												
7-T												
8-S												
8-B												
8-C												
8-T												
9-S												
9-2												
9-6												
9-B												
9-T												
10-S												
10-2												
10-B												
10-T												
11-S												
11-B												
11-T												
12-S												
12-B												
12-C												
12-T												
13				166	336	1694						
14												
19												
STP												

MOSES LAKE DATA

Date 3/4/82

Air Temp.: 50°F Wind Speed: 0-2 mph Wind Direction: N Cloud Cover: 0.3

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2	8.9			79	113	2560			531	386		
3	4.2			102	373	609			266	168		
4-R	5.5			91	173	798			311	198		114
5-T												
7-S												
7-2												
7-B												
7-T												
8-S												
8-B												
8-C												
8-T												
9-S	5.0	8.7	0.9	7	119	200		50.7	425	289		
9-2	4.8	8.7		12	116	187		67.8	434	289		
9-6	4.5	8.7		6	49	206		68.7	434	288		
9-B	4.5	8.7		6	83	157		68.9	433	288	15.6	<10
9-T												
10-S	5.5	9.0	0.9	5	96	<10			419	269		
10-2	5.5	9.0		4	62	<10			426	276		
10-B	5.5	9.0		4	121	<10		67.5	423	275	18.1	
10-T				3	97	43		70.6	417	268		<10
11-S	6.7	9.7	0.4									
11-B	6.7	6.7										
11-T				280	630	105		120	512	310	20.4	<10
12-S												
12-B												
12-C												
12-T												
13	11.0			182	247	1485			374	235		
14				24	101	8140			618			
19												
STP												

MOSES LAKE DATA

Date 3/18/82

Air Temp.: 48°F Wind Speed: 5-15 Wind Direction: N Cloud Cover: 0.9

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2	8.2			117	134	3256	2780		528	366		
3	5.3			73	260	948	1520		230			
4-R	6.0			64	240	1649	2350		397	266		
5-T												
7-S	5.5	8.2	0.7	10	97	525		38.3	396			
7-2	5.5	8.2		7	110	523		35.1	403			
7-B	5.5	8.3		17	190	539		26.3	404		12.7	
7-T				9	97	550	1230	36.3	403	279		
8-S	5.5	8.3	0.8									
8-B	5.0	8.3										
8-C				5	73	501		31.7	403		12.3	
8-T				9	64	474	1200	31.5	409	281		
9-S	5.5	8.5	0.7	4	86	72	953	68.5	387			
9-2	5.5	8.5		3	77	53		81.2	407			
9-6	5.0	8.5		3	89	53		87.1	413			
9-B	5.0	8.5		3		55		65.5	411		14.5	
9-T				2	84	124	949	74.5	411			
10-S	5.5	8.5	4.0	4	98	53		75.5	406			
10-2	5.5	8.5		3	87	<50		70.3	406			
10-B	5.0	8.5		5	112	<50		82.3	406		1.54	
10-T				3	84	<50	725	90.1	403	267		
11-S	5.2	9.3	0.4									
11-B	5.2	9.3										
11-T				207	620	<50	1920	76.7	512		14.4	
12-S												
12-B												
12-C												
12-T												
13	9.1			147	201	1584	2050		380			
14				23	46	9486	9490		635			
19												
STP												

MOSES LAKE DATA

Date 4/1/82

Air Temp.: 55°F Wind Speed: 0-10 Wind Direction: Cloud Cover: 0.0

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	5.7			2	17	31	96		154	62.0		<10
2	9.0			18	60	140	285		174	73.0		
3	12.8			32	105	687	1228		412	174.0		
4-R	8.6			14	53	249	726		210	222.0		<10
5-T												
7-S	6.5	8.2	0.7	5	12	300		13.2	264			
7-2	6.0	8.2		4	43	458		10.7	262			
7-B	6.5	8.3		5	19	314		9.5	271		13.2	
7-T				7	38	300	544	10.0	292	124.0		<10
8-S	8.0	8.0	0.9									
8-B	6.2	8.2										
8-C				12	24	337		8.0	407			
8-T				8	25	393	612	8.1	417	180.0	10.2	
9-S	8.0	8.4	1.0	3	6	54		12.5	417			
9-2	6.8	8.5		4	47	65		16.5	419			
9-6	5.4	8.5		5	47	57		16.3	420			
9-B	4.8	8.5		8	45	32		12.2	410		11.0	
9-T				18	24	79	571	11.0	423	181.0		61
10-S	7.8	8.7	4.0	6	22	13		17.1	422			
10-2		8.6		7	14	18		21.6	425			
10-B	7.5	8.5		4	17	7		24.7	423		12.1	
10-T				5	30	9	560	23.3	422	179.0		<10
11-S	8.0	9.3	0.4									
11-B	7.9	9.3										
11-T				260	340	47	986	93.2	504		14.4	<10
12-S	8.4	8.2	0.6									
12-B	6.5	8.4										
12-C				5	24	255		14.2	398		10.0	
12-T				7	58	287	729	10.1	406	178.0		
13	11.3			146	61	1520	1586		389	161.0		
14				49	41	9669	7990		621			
19												
STP												

MOSES LAKE DATA

Date 4/13/82

Air Temp.: 50-60°F Wind Speed: 10-35 Wind Direction: Cloud Cover: 0.9

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	6.5			8	11	12	199		156	59.0		<10
2	7.5			13	28	78	437		171	67.0		
3	12.0			11	239	392	1273		439	197.0		
4-R	8.5			11	83	106	517		191	75.0		<10
5-T												
7-S	8.5	8.2	0.7	5	91	218		18.9	320	132.0		
7-2	8.5	8.2		4	96	350		18.2	318	140.0		
7-B	8.5	8.2		5	99	257		19.9	325	136.0	10.7	
7-T				8	84	212	660	21.1	314	130.0		<10
8-S			0.7									
8-B												
8-C												
8-T				5	37	296	759	20.4	374	162.0		
9-S	9.2		0.8	4	104	204		21.7	421	182.0		
9-2	9.2			5	189	114		21.0	422	179.0		
9-6	9.2			5	102	100		20.1	420	176.0		
9-B	9.2			6	100	102		18.0	422	180.0		
9-T												
10-S	9.5		0.7	11	130	69		33.3	427	186.0		
10-2	9.5			3	157	65	900	25.1	424	181.0		20
10-B	9.5			6	163	74		18.4	428	183.0	11.3	
10-T												
11-S												
11-B												
11-T												
12-S	9.7	8.1	0.4									
12-B	9.7	8.2										
12-C				7	159	309		16.3	389	179.0	10.2	
12-T				9	111	323	809	12.5	390			
13	11.5			131	347	1412	1874		398	163.0		51
14												
19												
STP												

MOSES LAKE DATA

Date 4/27/82

Air Temp.: Wind Speed: 2-5 Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	9.0			17	34	21	75		146	57		
2	10.0			16	49	53	96		161	63		
3	16.2			12	57	237	268		441	198		
4-R	12.0			15	50	52	83		182	75		
5-T												
7-S	12.0	8.6	1.2	6	55	88		12.1	270	111		
7-2	11.3	8.6		22	43	65		8.7	273	114		
7-B		8.4		8	48	51		9.7	309	129	10.9	
7-T												
8-S												
8-B												
8-C												
8-T												
9-S												
9-2												
9-6												
9-B												
9-T												
10-S												
10-2												
10-B												
10-T												
11-S												
11-B												
11-T												
12-S												
12-B												
12-C												
12-T												
13	15.8				279	426		384	156			
14												
19												
STP												

*Note: Boat breakdown prevented complete sampling

MOSES LAKE DATA

Date 5/11/82

Air Temp.: Wind Speed: 0-5 Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1				9	17	37	130		151	56		
2				9	21	49	100		162	61		
3				12	303	493	1160		424	188		
4-R				8	109	78			172	66		
5-T			1.5	5	37	112	210	2.1	183	78		
7-S	14.0	8.2	1.8	5	26	73	243	3.1	224	99		
7-2	13.9	8.2		7	21	62	375	3.3		98		
7-B	13.0	8.2		10	47	65		3.5	201	89	9.9	<10
7-T				5	33	65	300	5.5	215	92		
8-S	14.2	8.3	2.8									
8-B	13.3	8.2										
8-C				13	62	113	676	2.0	274	130	8.5	
8-T				10	29	115	400	2.2	295	122		
9-S	15.1	8.6	1.8	16	60	<10	387	9.2	371	151		
9-2	14.9	8.7		7	60	<10		1.8	372	150		
9-6	13.3	8.5		9	33	26		6.7	349	140		
9-B	11.5	8.3		28	53	240	870	1.4	358	143	7.5	
9-T				15	44	27	520	6.2	362	147		
10-S	15.1	8.5	1.7	34	63	<10	511	6.6	376	153		
10-2	15.0	8.6		14	60	<10		8.0	378	152		
10-B	13.6	8.7		29	66	13	698	9.0	378	154	9.5	
10-T				23	53	<10	710	8.8	377	154		
11-S	16.8	9.4	0.6									
11-B	15.9	9.4										
11-T				339	580	<10	760	35.5	502	194	11.5	
12-S	15.5	8.2	1.8									
12-B	13.0	8.1										
12-C				15	51	178	487	2.3	362	142	8.3	
12-T				10	32	197	490	2.7	368	148		
13				123	176	1232	1550		411	156		
14				36	69	4200			657	240		
15-S	15.0	2.0							456			
16-T		2.1		9	31	159	441	2.8	329			
19												
STP				1145	5130	1440	3370		1615	269		~13,000

MOSES LAKE DATA

Date 5/25/82

Air Temp.: 23°C Wind Speed: 0-15 Wind Direction: NW Cloud Cover: 0.5

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	14.2			4	14	<10	136		152	57		
2	15.0			5	21	35	207		161	64		
3	20.9			7	60	735	1169		442	220		
4-R	14.8			5	46	71	227		195	74		
5-T	14.8		1.7	2	22	29	215	6.4	204	84		
7-S	19.0	8.0	2.1	6	19	38	225	6.8	220	90		
7-2	17.5	8.1		2	20	17	246	7.5	225	93		
7-B	16.0	7.9		1	21	72	380	6.6	237	97	9.4	
7-T				3	12	37	237	4.1	221	92		
8-S	18.5	8.0	4.5									
8-B	16.0	7.9										
8-C				3	44	86	311	4.4	278	116	8.4	
8-T				0	25	37	300	2.0	248	102		
9-S	19.7	8.3	3.9	5	46	<10	390	6.6	336	142		
9-2	18.0	8.3		8	32	15	320	5.9	334	139		
9-6	16.0	7.9		20	63	61	378	6.6	299	123		
9-B	13.5	7.6		61	82	88	531	2.3	339	141	5.6	
9-T				5	28	35	542	4.7	331	137		
10-S	19.0	8.3	2.4	11	52	<10	470	4.2	358	149		
10-2	19.0	8.3		13	49	<10	485	4.0	360	149		
10-B	16.5	8.3		16	59	<10	398	4.3	358	148		
10-T				16	64	140	406	3.6	359	146		
11-S	21.2	9.1	0.5									
11-B	20.5	9.1										
11-T				455	655	160		11.5	497	199	12.9	
12-S	20.0	8.0	3.2									
12-B	15.0	7.5										
12-C				5	40	204	590	4.3	374	148	6.0	
12-T				14	18	240	466	2.6	357	133		
13	19.5			118	281	1035	1587		412	157		
14				6	58	5800	6940		671	241		
15-S	20.6		3.0									
19				27	570	70	1681	41.6	584	215		
STP												

MOSES LAKE DATA

Date 6/11/82

Air Temp.: 90°F Wind Speed: 0-5 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	16.0	7.4		3	14	11			159	58		<10
2	16.5	7.4		4	17	84	175		167	64		12
3	22.3	8.0		4	55	935	1390		430	205		46
4-R	18.5	7.8		5	25	116			196	76		<10
5-T	18.3	7.6	1.6	4	26	97	310	3.1	204	80		<10
7-S	19.9	8.2	2.8	3	27	44		4.6	220	90		
7-2	19.1	8.4		2	35	72		2.9	230	93		
7-B	16.3	8.3		4	33	27		4.7	246	101	10.2	
7-T		8.2		3	27	38	138	2.5	222	101		<10
8-S	20.0	8.2	4.0									
8-B	17.4	7.9										
8-C		7.8		7	41	27		5.2	276	112	7.7	
8-T		8.1		4	28	<10		2.1	269	112		
9-S	20.3	8.3	2.8	7	52	10		3.4	293	118		
9-2	19.5	8.2		4	47	<10		4.5	301	125		
9-6	17.2	8.2		18	62	<10		8.9	292	120		
9-B	14.1	7.7		60	103	27		2.5	307	124	4.3	
9-T		8.2		3	41	<10		3.1	293	119		40
10-S	20.9	8.4	1.1	23	100	<10		4.0	329	137		
10-2	18.9	8.3		23	91	<10		4.6	328	134		
10-B	18.0	7.9		15	79	12		9.7	300	123	9.1	
10-T		8.2		21	90	28		2.1	330	136		<10
11-S	21.0	8.9	0.5									
11-B	20.5	8.9							478	187		
11-T		8.9		457	670	15	968	23.3	474	188	12.7	<10
12-S	19.9	8.2	2.8									
12-B	16.3	8.3										
12-C		7.9		30	91	107		2.2	351	142	5.5	
12-T		8.0		9	35	80	457	1.6	329	134		47
13	20.7	7.7		141	213	1165	1525		383	154		120
15-S	22.2		2.1			90		5.2	432			
19 STP	22.0	7.9	0.2	47	494	113	1089	57.9	571	238		25

MOSES LAKE DATA

Date 6/22/82

Air Temp.: Wind Speed: 0-10 Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	18.4	7.5		0	6	<10	148		160	51.7		<10
2	18.5	7.6		0	10	122	350		172	56.4		
3	16.5	7.8		7	62	962	1710		454	208.3		
4-R	18.3	7.7		7	23	192	520		199	68.4		<10
5-T	19.1	8.0	1.5	9	18	114	410	3.8	214	73.9		
7-S	22.6	8.6	2.8	5	23	<10		6.0	247	91.4		
7-2	22.9	8.5		0	12	13		10.9	248	91.4		
7-B	18.6	8.1		11	42	65		3.8	227	81.1	8.3	
7-T		8.3		0	16	35	310	3.5	236	86.7		<10
8-S	23.0	8.7	3.5									
8-B	19.2	8.0										
8-C		8.3		0	31	100		5.7	267		6.0	
8-T		8.5		2	21	13	405	2.6	278	97.3		
9-S	23.0	8.8	1.7	1	42	<10		7.2	301	108.1		
9-2	23.0	8.8		0	58	<10		10.6	300	109.7		
9-6	18.5	8.1		56	104	16		5.3	300	105.9		
9-B	15.0	7.6		118	161	24		4.9	312	113.7	1.4	
9-T		8.7		2	35	<10	665	6.2	289	104.9		98
10-S	24.0	8.9	1.2	0	68	<10		7.4	309	112.9		
10-2	24.0	8.8		3	60	<10		7.9	290	112.1		
10-B	21.0	8.6		11	64	<10		5.7	294	109.7	8.7	<10
10-T		8.7		30	77	<10	480	5.9	318	114.5		
11-S	23.5	9.2	0.4									
11-B	24.0	9.2										
11-T		9.0		702	897	<10	876	29.2	468	165.4	8.3	20
12-S	24.0	8.8	1.2									
12-B	18.0	8.8										
12-C		8.3		2	82	30		7.1	394	116.1	4.8	
12-T		8.4		0	41	13	500	7.0	323	117.7		
13		7.7		80	192	1080	1750		410	139.1		
14		7.6		18	42	8206	9470		651	217.8		
15-S	23.7	8.5	0.7	5	49	<10		24.5	357	120.8		
19	24.0	8.6	0.3	16	296	32	1174	61.4	567	179.7		20
STP												

MOSES LAKE DATA

Date 7/7/82

Air Temp.: 75-85°F Wind Speed: 0-5 Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1	16.0	7.7		6	15	13			142	53.3		
2	14.5	7.8		72	103	1601			433	171.7		
3	15.5	7.8		3	34	779			466	208.3		
4-R	16.5	8.0		17	50	1108			432	180.5		
5-T		8.2	1.5	10	32	92		3.2	220	88.2		
7-S	21.0	8.5	1.5	8	54	<10		6.5	236	92.2		
7-2	20.5	8.5		12	76	35		4.6	241	92.2		
7-B	18.0	8.4		13	59	18		9.9	236	93.0	10.0	
7-T		8.4		6	38	20		7.7	225	89.8		
8-S	21.3	8.4	1.9									
8-B	19.4	8.3										
8-C		8.3		24	63	18		8.2	248	98.6	8.1	
8-T		8.4		19	57	<10		3.1	258	101.0		
9-S	21.0	8.6	1.1	25	100	<10		9.5	254	100.2		
9-2	20.3	8.6		34	106	16		10.7	261	102.6		
9-6	19.3	8.3		49	112	18		8.1	267	104.9		
9-B	15.9	7.6		140	190	29		3.9	278	108.1	1.3	
9-T		8.5		26	84	12		7.0	257	100.2		
10-S	21.0	8.4	0.6	48	129	<10		9.2	278	108.9		
10-2	20.5	8.4		53	136	36		11.4	281	109.7		
10-B	19.8	8.1		58	125	119		6.6	277	105.7	7.2	
10-T		8.4		49	122	18		8.2	281	109.7		
11-S	21.0	9.0	0.2									
11-B	20.2	9.0							479	172.5		
11-T		8.9		589	1181	18		39.7	480	174.9	10.7	
12-S	22.3	8.5	1.4									
12-B	19.0	8.0										
12-C		8.0		85	155	43		7.5	301	116.1	4.6	
12-T		8.5		17	73	26		5.9	296	111.3		
13		7.9		123	177	1216			381	139.1		
14		7.6		34	49	8799			630	215.4		
15-S				25		35		30.1	314			
19	24.0	8.7	0.3	101	367	13		71.7	539	205.9		
STP		7.8		4292	6261	4979			1072	195.0		

MOSES LAKE DATA

Date 7/20/82

Air Temp.: 90°F Wind Speed: 0-15 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1		7.9		3	13	16	167		177	52.5		
2		7.8		13	13	63	174		152	56.4		
3		8.3		6	30	684	950		366	182.9		
4-R		8.4		5	40	181	339		217	81.9		
5-T	18.8	8.2	1.5	3	26	137		6.5	234	83.5		
7-S	24.0	8.6	1.9	7	50	55		9.7	238	93.8		
7-2	23.0	8.5		5	45	40		14.2	239	93.0		
7-B	20.0	8.2		12	46	149		6.5	226	88.2	10.7	
7-T		8.2		3	124	421	822	52.7	232	88.2		
8-S	23.0	8.6	2.0									
8-B	19.5	8.0										
8-C		8.3		31	88	30		10.6	263	95.4	6.1	
8-T		8.6		19	58	15	343	7.3	258	99.4		
9-S	22.2	8.8	1.1	26	140	20		22.6	272	107.3		
9-2	20.9	8.7		37	97	23		19.8	272	107.3		
9-6	19.1	8.1		88	132	34		5.9	275	105.7		
9-B	16.1	7.5		269	349	53		10.1	299	111.3	0.0	
9-T		8.6		20	94	30		15.5	281	104.9		
10-S	23.7	8.8	0.6	40	148	27		12.8	284	106.5		
10-2	23.0	8.7		30	171	34		20.0	280	110.5		
10-B	20.0	8.4		58	152	147		15.4	280	108.9	5.5	
10-T		8.7		27	124	101	534	15.2	281	112.1		
11-S	23.7	9.1	0.25									
11-B	23.0	9.1										
11-T		9.0		482	721	60		44.6	459	170.9	10.7	
12-S	24.9	8.6	2.0									
12-B	20.0	7.7										
12-C		8.4		41	106	48		10.7	283	111.3	7.1	
12-T		8.7		21	53	26		12.0	272	108.1		
13		7.9		117	160	1189			390	141.5		
14												
19	24.5	8.9	0.25	32	236	36		55.6	339	125.6		
STP												

MOSES LAKE DATA

Date 8/3/82

Air Temp.: 70°F, cool Wind Speed: 5-15 Wind Direction: 0.5 Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2		7.8		50	126	1895	2010		450	182.9		
3		7.8		4	11	884	950		475	213.1		
4-R		7.9		11	34	1091	1200		441	191.6		
5-T	21.5	8.5	0.9	4	37	80	310	13.3	242	90.6		
7-S	22.2	8.4	1.0	5	72	42	520	22.2	244	93.8		
7-2	22.0	8.4		5	77	63	480	16.7	235	93.8		
7-B	20.9	8.2		11	42	116	315	17.6	243	93.0		
7-T		8.5		1	50	32	360	8.8	232	89.8		
8-S	22.5	8.3	1.4									
8-B	21.3	7.8										
8-C		8.2		29	86	22	480	10.0	254	98.6	2.6	
8-T		8.4		12	69	29	390	12.5	242	97.0		
9-S	22.7	8.8	1.0	12	91	<10	610	25.3	255	97.0		
9-2	22.5	8.8		13	80	<10	1420	67.6	246	97.0		
9-6	21.7	8.5		42	127	12	600	14.0	262	102.6		
9-B	17.2	7.5		498	666	12	2210	2.6	344	139.9	0.3	
9-T		8.7		11	82	<10	610	28.8	249	96.2		
10-S	23.0	8.9	0.4	25	55	<10	760	30.0	261	95.4		
10-2	23.0	8.8		25	140	<10	760	32.0	267	99.4		
10-B	22.4	8.7		15	169	26	610	23.5	254	100.2		
10-T		8.8		42	138	<10	580	27.2	265	99.4		
11-S	22.0	8.7	0.3									
11-B	21.9	9.2										
11-T		9.0		309	633	14	940	39.7	378	144.7		
12-S	23.2	8.3	0.7									
12-B	22.5	8.3										
12-C		8.6		3	90	<10	780	35.2	252	93.8		
12-T		8.8		11	80	15	700	39.2	248	96.2		
13		7.9		87	182	1266	1590		386	142.3		
14												
19	21.7	8.7	0.5	11	109	43	530	20.0	275	111.3		
STP		8.0		2625	4636	5280			777	212.3		

MOSES LAKE DATA

Date 8/17/82

Air Temp.: 85-90°F Wind Speed: 0-5 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2		7.9		55	71	2036			462	194.8		
3		7.8		2	12	864			493	218.6		
4-R		7.9		8	19	892			455	195.6		81
5-T	21.0	8.8	0.6	4	81	77		54.1	273	110.5		
7-S	24.0	8.8	1.7	5	44	19		4.6	254			
7-2	22.0	8.6		8	78	26		12.8	254			
7-B	21.0	8.7		19	89	23		11.2	259		8.5	<50
7-T		8.8		2		17		21.2	253	101.8		<50
8-S	21.5	9.0	1.7									
8-B	21.0	8.6										
8-C				26	84	17		23.2	255		7.2	
8-T		8.8		10	60	16		13.6	250	99.4		
9-S	23.2	9.1	1.2	17	58	14		12.8	250			
9-2	22.0	9.0		11	115	197		81.5	253			
9-6	21.0	8.6		57	106	14		24.0	264			
9-B	18.0	7.8		136	198	58			278	107.3	2.2	342
9-T		9.1		12	83	<10		23.3	255	99.4		<50
10-S	24.0	9.3	0.5	9	109	<10		106.7	253			
10-2	22.0	9.1		14	142	<10		102.5	260			
10-B	20.7	8.3		60	127	27		10.8	262		4.9	
10-T		9.2		16	112	14		61.4	254	97.8		<50
11-S	23.3	9.1	0.4									
11-B	21.5	8.9										
11-T		9.0		208	363	14		25.5	363	142.3	7.7	<50
12-S	22.5	9.2	1.5									
12-B	21.0	8.7										
12-C				6	99	32		25.4	257		6.8	
12-T		8.9		3	77	<10		20.9	247	95.4		
13		7.9		109	171	1252			385	143.1		
14												
19	22.2	8.5	0.5	2	92	265		17.8	361	149.5		78
STP												

MOSES LAKE DATA

Date 8/31/82

Air Temp.: Wind Speed: Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2		7.9		64	143	1910			476	197.2		
3		7.9		5	23	916	1110		508	221.0		
4-R		7.8		19	73	1264	1710		489	202.7		75
5-T	19.5	8.8	0.5	4	73	61	800	67.4	287	116.9		
7-S	22.3	9.1	0.5	4	80	51		34.7	270			
7-2	21.9	8.5		10	128	44		36.9	269			
7-B	21.0	8.5		14	101	56		23.8	272		7.0	
7-T		8.6		4	88	50	850	49.0	275	104.9		96
8-S	23.6	8.8	2.0									
8-B	21.1	7.8										
8-C				61	139	31		9.1	272		0.2	
8-T		8.6		11	131	26	740	26.4	265	97.8		
9-S	23.0	9.1	0.7	21	70	11		41.7	271			
9-2	22.1	9.0		19	160	<10		60.4	261			
9-6	21.7	8.8		29	121	14		19.8	264			
9-B	18.0	7.7		310	365	13		4.8	298	116.9	0.0	986
9-T		8.8		12	108	17	850	41.4	260	96.2		105
10-S	23.0	9.1	0.5	25	160	54		79.9	265			
10-2	22.0	9.0		24	173	14		83.4	268			
10-B	21.3	8.8		14	150	43		30.6	265		5.4	
10-T		8.8		16	158	14		60.1	270	101.0		69
11-S	21.9	9.0	0.4									
11-B	21.2	9.0							391			
11-T		8.9		222	445	14	870	42.4	386	151.8		>50
12-S	24.2	8.9	1.0									
12-B	22.0	8.7										
12-C				7	100	58		29.1	260			
12-T		8.8		3	79	35	720	37.0	258	96.2		
13		8.0		110	182	1276	1530		387	141.5		
14		7.6		2	20	7504			622	213.1		
19	21.0	8.5	0.5	2	100	279	863	21.1	393	161.4		72
STP												

MOSES LAKE DATA

Date 9/14/82

Air Temp.: Chilly Wind Speed: 15-35 Wind Direction: Cloud Cover:

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl *a*	Cond	Alk	DO	NH_3-N
1												
2	11.5	7.8		58	75	1518			476	194.8		
3	10.5	7.6		10	38	927			527	228.2		<10
4-R	10.8	7.7		13	35	1370			498	208.3		12
5-T	13.8	8.1	1.0	11	68	688		17.4	436	180.5		
7-S		8.3	1.0									
7-2		8.3										
7-B		8.3										
7-T		8.2		25	94	85		19.8	298	114.5		150
8-S		8.2										
8-B		8.2										
8-C												
8-T												
9-S	17.5	7.8	2.0						291	109.7		
9-2												
9-6												
9-B												
9-T	17.5	7.9		116	174	<10		10.1	287	107.3		385
10-S												
10-2												
10-B												
10-T		8.1		97	176	51		15.7	290	108.9		268
11-S		8.5		112	428	118		34.1	415	164.6		13
11-B												
11-T		8.5		135	337	26		42.1	399	155.8		13
12-S												
12-B												
12-C												
12-T												
13	12.8			114	188	1032						
14												
19	13.5	8.0	1.0	16	78	1030		7.3	485	203.5		60
STP		7.5		1660	3385	7860			1455	191.6		5560

*Note: Very Windy; abbreviated sampling

MOSES LAKE DATA

Date 9/21/82

Air Temp.: 80-85°F Wind Speed: 0-10 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2												
3												
4-R	13.2	7.9		8	28	1260			516	218.4		51
5-T	16.0	8.6	1.2	0	61	298		15.7	363	151.2		
7-S												
7-2												
7-B												
7-T								19.3				
8-S												
8-B												
8-C												
8-T								31.6				
9-S			1.0									
9-2												
9-6												
9-B		8.6										
9-T				113		24		66.9	290	113.6		
10-S												
10-2												
10-B												
10-T	19.8	8.7	0.5	38	402	32		213.0	305	116.0		
11-S												
11-B												
11-T	17.0	8.8	0.5	107	324			100.1	444	176.8		
12-S												
12-B												
12-C												
12-T												
13												
14												
19	17.4	8.4	0.8	0	36	718		27.5	492	196.8		33
STP												

MOSES LAKE DATA

Date 10/5/82

Air Temp.: 50-65°F Wind Speed: 0-10 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl *a*	Cond	Alk	DO	NH_3-N
1												
2	10.5			73	82	2804						
3	11.5			8	33	1111						
4-R	12.5			17	56	1282						
5-T	12.7	8.3	1.2	2	89	439		79.5	410	164.6		
7-S	14.8	8.3	1.2	12	72	197		44.2	339	132.0		
7-2	14.9	8.3		11	94	197		58.5	339	134.4		
7-B	14.9	8.3		11	69	177		21.0	338	132.0	9.1	
7-T		8.3		3	84	267		40.4	344	135.2		107
8-S	15.6	8.2	1.1									
8-B	15.2	8.2										
8-C		8.3		13	72	125		13.4	314	119.2	8.1	
8-T		8.2		24	73	92		14.3	308	119.2		
9-S	16.1	8.2	2.1	81	145	130		33.7	314	119.2		
9-2	15.8	8.2		84	142	56		25.7	314	120.8		
9-6	15.8	8.1		96	157	64		15.7	314	118.4		
9-B	15.7	8.1		88	145	62		11.9	314	117.6	6.9	377
9-T		8.2		77	139	62		29.7	315	118.4		333
10-S	15.8	8.4	0.5	81	344	54		188.5	334	113.6		
10-2	15.2	8.3		91	251	67		97.6	329	120.0		
10-B	14.9	8.2		87	184	61		26.6	323	122.4	7.2	
10-T		8.1		85	247	125		99.6	325	121.6		332
11-S	13.9	8.6	0.5									
11-B	13.4	8.4						54.0	451	172.0		
11-T		8.3		110	326	62		105.4	431	156.0	8.9	37
12-S	15.2	8.2	0.6									
12-B	15.0	8.2										
12-C		8.0		20	103	100		10.9	309	115.2	7.1	
12-T		8.1		13	55	100		34.0	305	112.0		
13	12.5			126	150	1586						
14		7.3		38	66	6476				650	222.4	
19	13.3	8.2	0.8	0	84	128		59.6	456	179.2		26
STP												

MOSES LAKE DATA

Date 10/19/82

Air Temp.: 0-8°c, cold Wind Speed: 0-5 Wind Direction: Cloud Cover: 0.1

Sta.	Temp.	pH	Secchi	SRP	Total P	NO_3-N	Total N	Chl a	Cond	Alk	DO	NH_3-N
1												
2		7.9							480	186.4		
3		8.1							518	231.2		
4-R		8.3							503	211.2		
5-T	8.5	8.1	2.0	18	77	714		13.7	443	182.4		
7-S	11.7	8.1	1.3	22	66	215		15.0	337	133.6		
7-2	12.1	8.1		19	72	213		12.4	339	133.6		
7-B	11.3	8.1		23	72	317		8.1	351	140.0	9.0	103
7-T		8.2		23	74	316		15.0	352	138.4		110
8-S	12.0	8.2	0.5									
8-B	12.0	8.2										
8-C		8.0		38	91	136		6.4	326	126.4	7.8	
8-T		8.0		34	88	135		8.1	326	128.0		
9-S	12.8	7.9	1.9	98	145	86		5.8	323	126.4		
9-2	12.8	7.9		96	140	83		6.7	323	126.4		
9-6	12.8	7.9		92	137	85		4.0	322	125.6		
9-B	12.8	7.9		97	140	106		4.8	322	125.6	7.0	420
9-T		8.0		86	130	126		8.1	323	126.4		333
10-S	11.2	7.9	1.3	87	151	101		12.5	324	127.2		
10-2	11.8	8.0		83	154	94		9.7	323	125.6		
10-B	10.8	7.9		81	142	93		11.2	323	125.6	8.0	
10-T		7.9		85	150	118		10.2	326	126.4		368
11-S	9.3	8.1	0.4									
11-B	9.8	8.1										
11-T		8.5		174	337	125		62.6	427	161.6	8.4	73
12-S	12.0	7.9	0.5									
12-B	12.0	8.0										
12-C		8.0		32	134	209		9.7	323	127.2	7.9	287
12-T		8.0		35	98	156		9.0	321	125.6		
13		7.7							385	145.6		
14		7.4		38	67	8950			639	224.0		13
19	9.3	8.3	1.0	23	97	243		13.9	484	192.0		94
STP												