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Influence of light on algal growth in the lower Willamette River

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During the summer of 1974 chemical conditions in the lower reaches of the Willamette River, Oregon were similar to those in other rivers currently experiencing nuisance algal growth problems. Temperature and chemical nutrients are not limiting. Relatively high populations of phytoplankton and productivity values for upstream periphyton beds and surface waters suggest moderately eutrophic conditions. However, with increased depth in the lower river, and a constant euphotic zone, the amount of photosynthetically available light is reduced. With sufficient depth and complete mixing the critical depth is exceeded. Primary productivity rates are subsequently limited by low light availability in the lower river.

INFLUENCE OF LIGHT ON ALGAL GROWTH
IN THE LOWER WILLAMETTE RIVER

by

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INTRODUCTION

History of the Willamette Basin. Although trading houses had been constructed a few years earlier, the first permanently manned trading post was not established in the Willamette Valley until 1813 at a site near the present town of Newberg. Actual settlement of the lower valley did not begin until 1829 at sites near Champoeg and Willamette Falls. It is true that some of the first settlers were living in the valley with their families before this time, but if they were farming the fact was not mentioned in the early accounts (Clark, 1927). Corvallis and Marysville, the first settlements in the upper basin, were established in 1846. At about the same time Eugene Skinner was founding Eugene City at the base of Skinners Butte, on the present site of Eugene. In 1850 the first steamboat was built in Milwaukie, the Lot Whitcomb. Steamboats began running from Portland to Eugene in 1856-57, and were instrumental in promoting a busy commerce between the new settlements along the river. Thus from the earliest times most of population of Oregon has been related to the Willamette River and has resided in the Willamette Valley. Presently within the basin are the State's three largest cities, Portland, Salem, and Eugene, and approximately 1.4 million people, representing 70 percent of the State's population (1970 census).

In the early 1920's, water quality tests conducted by the Oregon State Board of Health in the Portland Harbor area of the lower Willamette River indicated extensive pollution, a fact which should have been obvious since, at that time, all industries and municipalities on the river were dumping untreated wastes directly into the stream. Further tests conducted in 1926-27 by the City of Portland indicated continued heavy pollution in the lower reaches. Aroused public concern and a continued desire for action led to the creation of the Oregon State Sanitary Authority in 1938. The Sanitary Authority initiated the beginning of a pollution abatement program in 1939 by notifying all municipalities and industries on the Willamette River that primary treatment of wastes followed by chlorination of effluent would now be required under the law. It would not be until 1957 that these original directives would be complied with. At that time it was evident that the degree of treatment was still insufficient, and in early 1958 the cities of Eugene, Salem, and Newberg were instructed to install secondary treatment facilities, the City of Portland to accelerate its treatment facility program, and the pulp and paper operations to reduce further their pollutional loads. However, as late at 1963, all significant indices of water quality indicated that the pollutional load in the Willamette River was similar to that of 1926, when the public first became concerned. In 1964, after all municipalities downstream from Salem had instituted secondary treatment, the river began to show improved conditions. Secondary treatment of wastes was established as the minimal treatment for any sewage wastes discharged to the Willamette. Progress in river improvement was slow and expensive, but through continued effort water quality standards were met over the entire river in 1969. The State's water pollution control policy has since shifted in emphasis from pollution abatement to pollution prevention and water quality enhancement.

The population in the Willamette Basin is expected to double by the year 2000. Future population growth will require a continuing effort to maintain water quality. This thesis presents the results of a study of algal conditions in the Willamette River during the summer of 1974. The purpose was to describe the nature and effects of observed algal populations, the chemical and physical environment influencing algal growth, and to assess the possible implications these findings might have on future river water quality. Historically, dissolved-oxygen (DO) depletion has been the critical water-quality problem in the Willamette River. The introduction of secondary treatment has reduced significantly water quality problems associated with the depletion of DO. The research described in this thesis was intended to help determine if a new and different water quality problem, such as excess algal growth, could be anticipated, and therefore be avoided.

Description of Study Area. The Willamette River basin, a watershed of nearly 30,000 km^2, is located in northwestern Oregon between the Cascade and Coast Ranges (Fig. 1). The basin is roughly rectangular, with a north-south dimension of about 240 km and an east-west width of 120 km. The Middle Fork of the Willamette originates near the summit of the Cascade Range in the southeastern quadrat of the valley at an elevation of over 1800 meters. It flows northwesterly and is joined south of Eugene by the Coast Fork to form the main stem of the river at an elevation of 135 meters. After flowing northward approximately 300 km through the fertile Willamette Valley floor, and dropping about 121 m, it empties into the Columbia River 159 km from the Pacific Ocean.

The river is composed of three distinctive morphological reaches, each with its own hydraulic regime and, therefore, pattern of biological activity.

The Upstream Reach, beginning just above Eugene to near Newberg, is shallow, with the bed largely composed of cobbles and gravel which provide ample opportunity for attachment of periphytic biological growths. During the summer period, the mean velocity of this reach is about 10 times that observed in the Newberg Pool and nearly 20 times greater than that in the Tidal Reach (Table 1). Morphologically, this section of the river is an eroding reach.

From just above Newberg to Willamette Falls is a deep, slow moving reach known as the Newberg Pool. Hydraulically, the "Pool" can be characterized as a large stilling basin behind a weir (Willamette Falls). Travel times in this 41 km reach are relatively long during low-flow conditions. Morphologically, the Pool is a depositional reach.

The lower 43 km of the river is a deep, slow moving reach affected by tides (non-saline water), and during spring and early summer (April to July) by backwater from the Columbia River (Velz, 1961). The Tidal Reach is dredged to maintain a 12 m deep navigational channel up to river km 35.

During low flows net downstream movement is relatively slow, but tidal reversals can cause large changes in velocity. Low flow hydraulics are most complex in the lower 16 km where, depending on hourly changes in tidal and river stage conditions, Willamette River water may move downstream or Columbia River water upstream. Owing to morphological characteristics and the hydraulic conditions, the subreach below river km 16 is a depositional area of the Willamette River system.

TABLE I

SELECTED PHYSICAL CHARACTERISTICS OF THE MAIN STEM WILLAMETTE RIVER, OREGON

Reach	Length (km)	Approximate Bed Slope (m/km)	Bed Material	Representative Midchannel Water Depth (m)	Approximate Traveltime	
					Rate (km/hr)	Total in Reach (hr)
1	42.6	<.02	Intermixed clay, sand and gravel.	12.2	0.35	120
2	41.0	.023	Intermixed clay, sand, and gravel with some cobbles.	7.6	0.40	100
3	217	.053	Mostly cobbles and gravel.	2.1	2.6	82

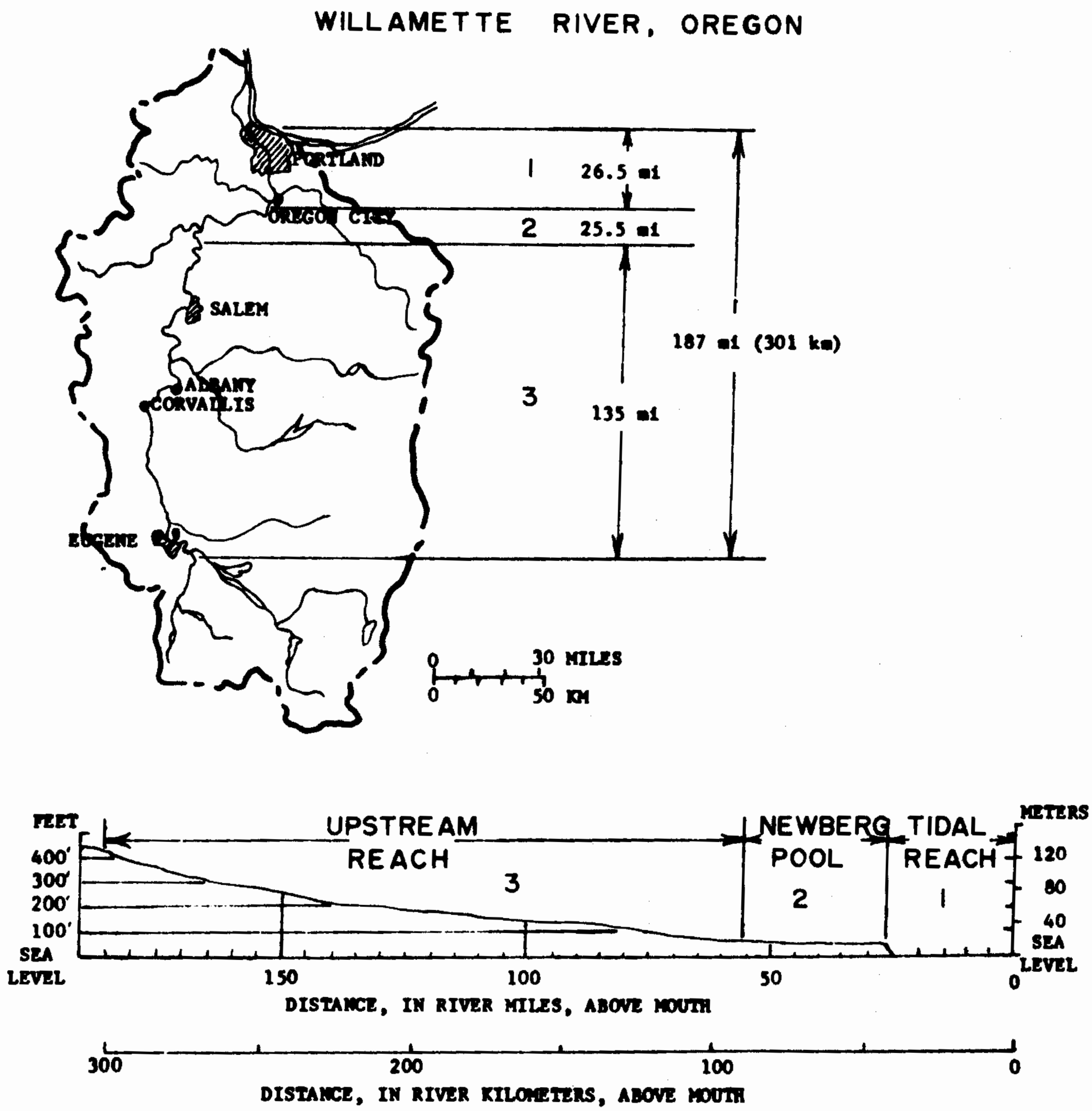

Figure 1. Willamette River, Oregon

MATERIALS AND METHODS

Water samples were taken bi-weekly from specified sites at regular intervals across the river. Each water sample consisted of several subsamples vertically integrated to the approximate depth of the euphotic zone by using a USDH-59 Depth Integrating Suspended Sediment Sampler. Each field sample was immediately proportioned and prepared for analysis. Aliquots for determination of population densities of suspended algae were prepared according to the Membrane Filter Concentration Technique (APHA and others, 1971; Slack and others, 1973); a sample size of 100 ml was usually suitable. The prepared slides were counted on a Zeiss Standard microscope with phase contrast objectives. Primary taxonomic references were Hustedt (1930), and Patrick and Reimer (1966). Aliquots for dissolved nutrients were field filtered using a Millipore TM filter of 0.45 μM pore size. Samples for nitrate, ammonia and silica analysis were transferred to 1 quart polyethylene bottles and kept on ice for return to the laboratory. Orthophosphorus was extracted with isobutanol immediately following filtration (Shapiro, 1973a).

Analysis carried out on filtered samples by standard methods described by the American Public Health Association (1971) included dissolved nitrate by the Brucine method and ammonia by Nesslerization following distillation. Analysis were run within 24 hours of sample collection. Dissolved silica was determined by the reactive silicate method (Golterman and Clymo, 1969).

Primary productivity was measured on several occasions at river km 11.3 and 20.6 by the light and dark bottle DO method and once by the

Carbon-14 method (Slack and others, 1973). Temperature and DO were routinely determined with a YSI Model 54 Oxygen Meter.

Light penetration was measured at one meter intervals using a Whitney Model LMD-8A underwater light meter without color filters.

RESULTS

Temperature. Water temperature in the Willamette River reached a maximum during the annual July-August low flow period. The water temperatures in the Newberg Pool and the Tidal Reach are controlled primarily by ambient air temperatures. Records compiled by the Willamette Basin Task Force (1969) indicate the average temperature during July varies from about 20°C at river km 80 to about 22°C at river km 11.

Figure 2 shows the minimum and maximum daily temperature for the Willamette at river km 11 for the period May-September 1974. The temperatures are about 10°C in mid-May and increase to only 13°C by mid-June. From this date the water temperatures increase steadily to a maximum of about 24°C in early August. The temperatures stayed about 20°C through the remainder of August and early September and then decreased steadily through the remainder of September.

Nutrients. The concentrations of dissolved algal nutrients by station and over time are shown in Figures 3 and 4.

The lowest observed concentration of orthophosphorus (as PO_4-P) was 35 parts per billion (ppb) on 25 June 1974 at river km 35. The highest was 90 ppb on 2 July 1974 at river km 21. Most concentrations were between 50 and 80 ppb, a surprisingly small range considering the number of potential phosphorus sources and large variations in river flow. Not only were the concentrations relatively stable, but they were at all times well above the concentrations of phosphorus observed in some highly productive natural waters (Schindler, 1971).

Nitrate and ammonia concentrations (Fig. 3) were considerably

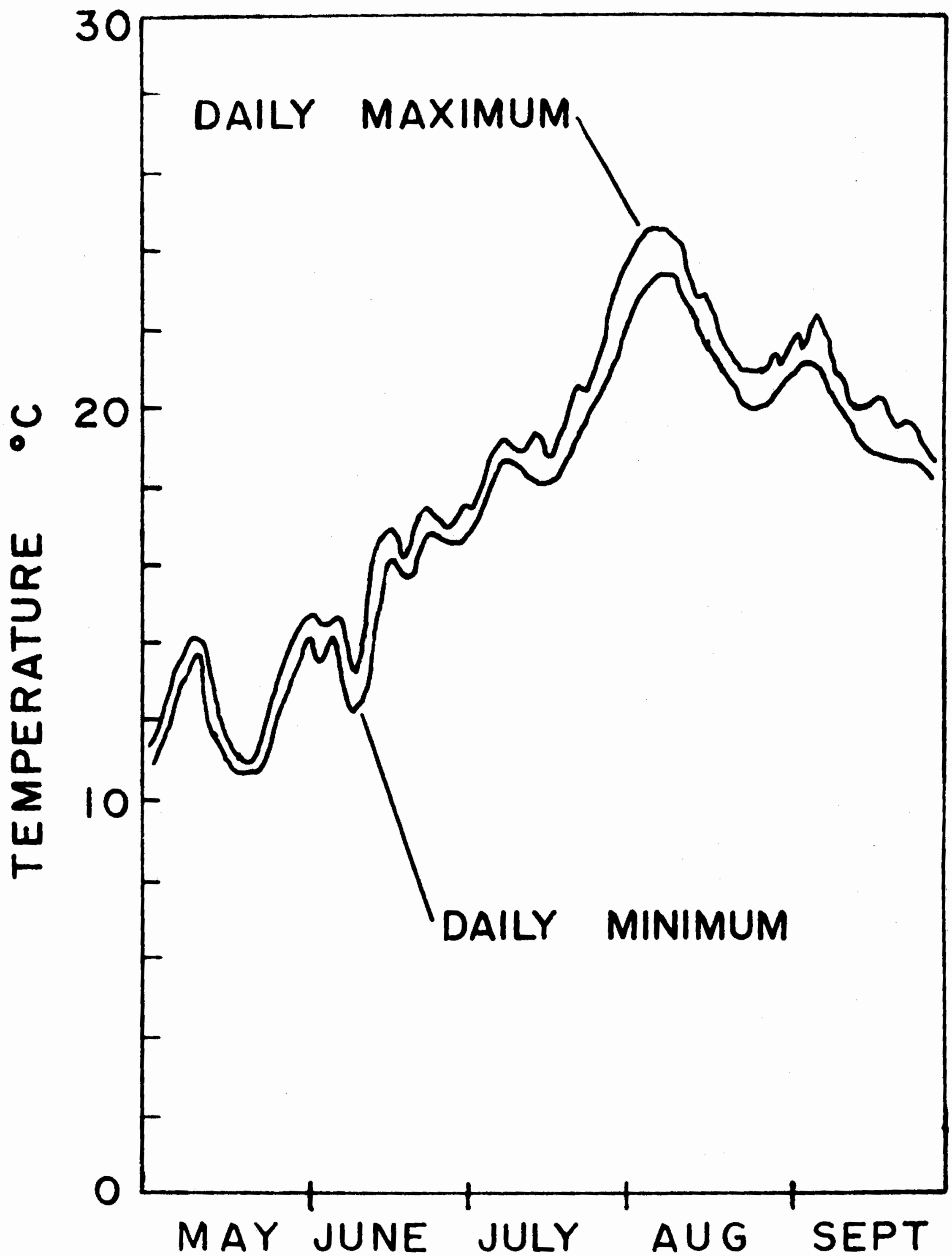

Figure 2. Water Temperature of the Willamette River, 1974

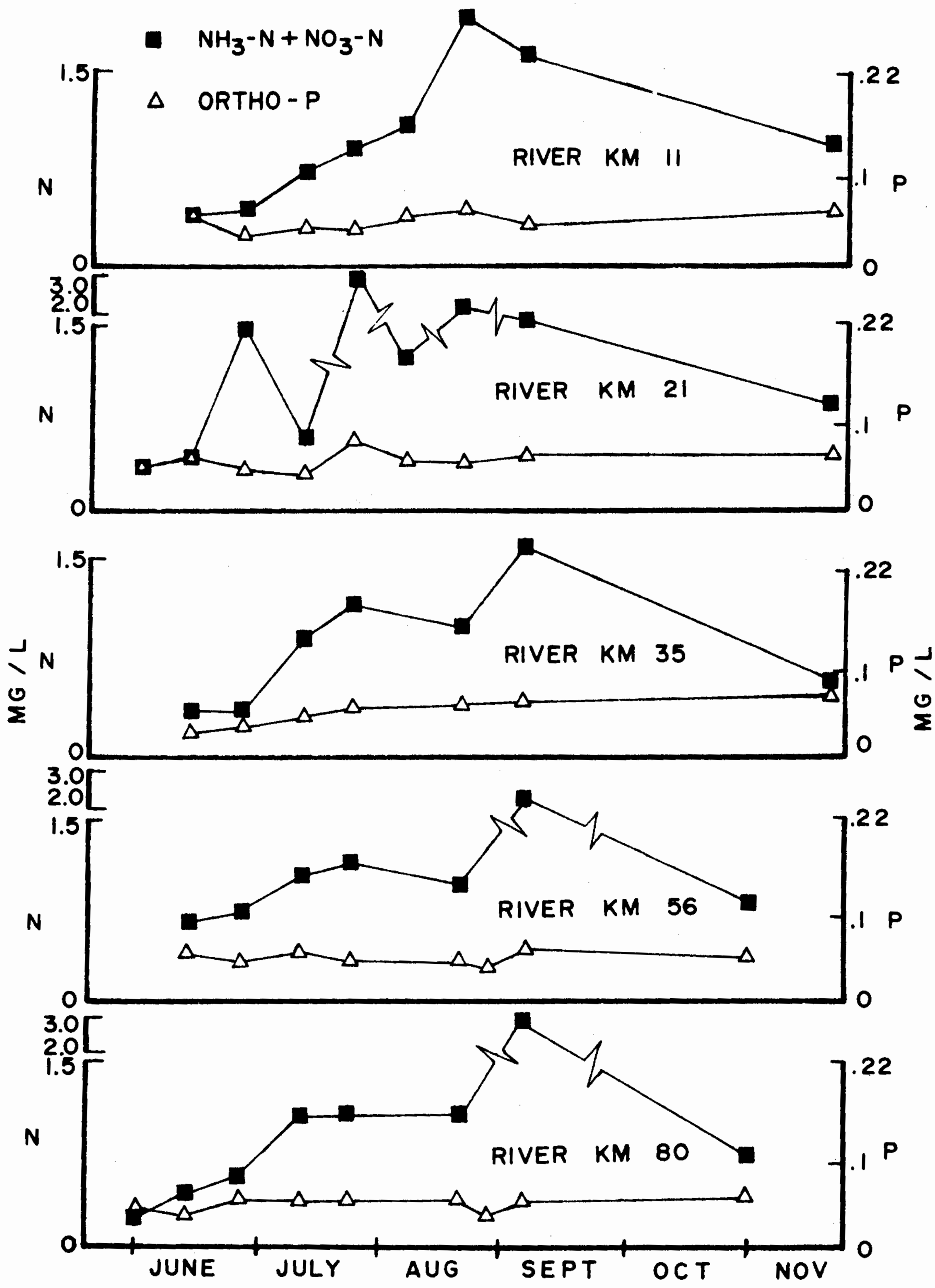

Figure 3. Nitrogen and Phosphorus in the Willamette River, 1974

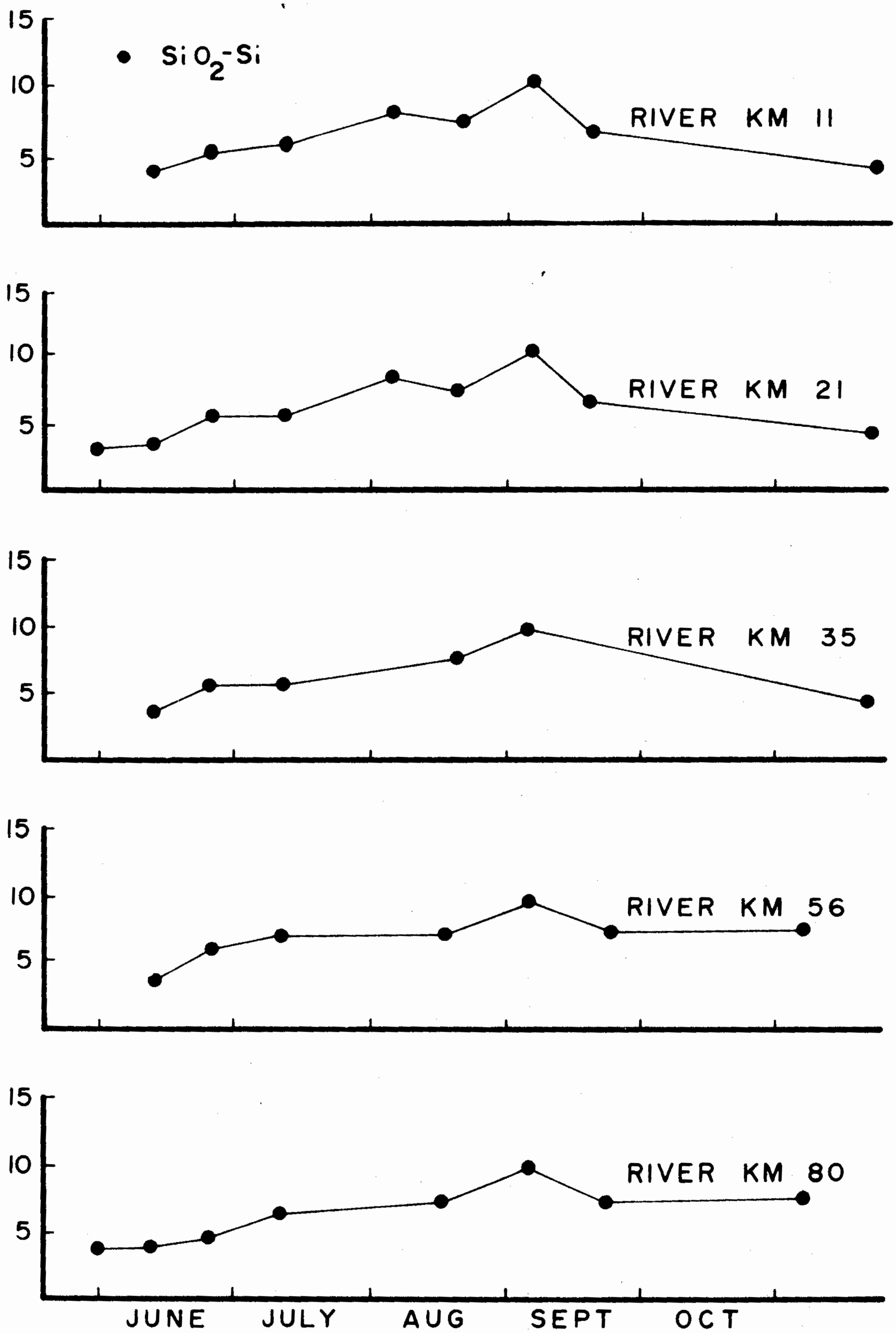

Figure 4. Silica in the Willamette River, 1974

more variable than phosphorus concentrations but were always quite high relative to algal requirements. The scales in Figure 3 are adjusted so that nitrogen and phosphorus concentrations appear equal when the two are present in a molar ratio of 16N:1P (approximate ratio in algal cells).

The concentrations of dissolved reactive silica (Fig. 4) are, at all times, above those required for diatom growth (Kilham, 1971). The plots show little evidence of a decrease in silica concentrations from upstream to downstream locations. Additional samples collected between river km 295 and river km 80 showed similar results, implying little downstream depletion of dissolved silica in spite of the presence of suspended diatoms throughout the river and extensive beds of periphytic diatoms above river km 84. The probably sources of silica are ground water and surface rock weathering which are diluted by precipitation so that observed concentrations decrease with flow.

Plankton populations. Overall, nearly 50 different taxa of suspended algae were identified and enumerated in the samples collected from the Newberg Pool and Tidal Reach. The more common genera were *Melosira*, *Stephanodiscus*, *Cymbella*, *Achnanthes*, *Nitzschia*, and *Fragilaria*. A variety of algae other than diatoms also appeared but because of fixation technique were difficult to positively identify. They were less abundant than the commoner diatoms in all the counts.

Population densities of suspended diatoms were generally rather high, with some individual species present in abundances of 10^2 to 10^3 cells/ml. Populations were remarkably stable over the course of the summer. The same species tended to persist through the spring, summer, and fall, with no major changes in the total abundance of cells with either location or time.

The species presented in Figures 5 through 9 provide a summary of the phytoplankton populations present in the deep, slow-velocity reaches characteristic of the lower Willamette River.

Stephanodiscus Hantzschii (Fig. 5) and *Achnanthes minutissima* (Fig. 6) were the most abundant organisms at all 5 stations during the sampling period. Both species are widely distributed in rivers throughout the United States (Williams, 1972). *Stephanodiscus Hantzschii* is considered indicative of eutrophic conditions (Hustedt, 1930; Huber-Pestalozzi, 1942) while *Achnanthes minutissima* is characterized as being tolerant of a wide range of conditions (Patrick and Reimer, 1966).

Melosira distans (Fig. 7) was very prominent at river kms 11 and 21 in late summer, but was less abundant during the earlier summer and throughout the sampling period at the 3 upstream stations. This species is especially abundant in Southeastern rivers (Weber, 1971) so the increasing abundance in the lower Willamette during June through mid-August may be related to increasing water temperatures.

Throughout the sampling period *Cymbella ventricosa* (Fig. 8) was present in abundances of 10 to 10^2 cells/ml at river kms 11 and 21 and in abundances exceeding that at the 3 upstream stations. This species is normally benthic or periphytic in character rather than planktonic (Huber-Pestalozzi, 1942). The higher numbers at the 3 upstream sites are consistent with the fact that extensive beds of periphyton exist in the Willamette above river km 84 (the Upstream Reach).

In contrast, *Asterionella formosa* (Fig. 9) is a classic planktonic diatom (Huber-Pestalozzi, 1942; Patrick and Peimer, 1966) and consistent

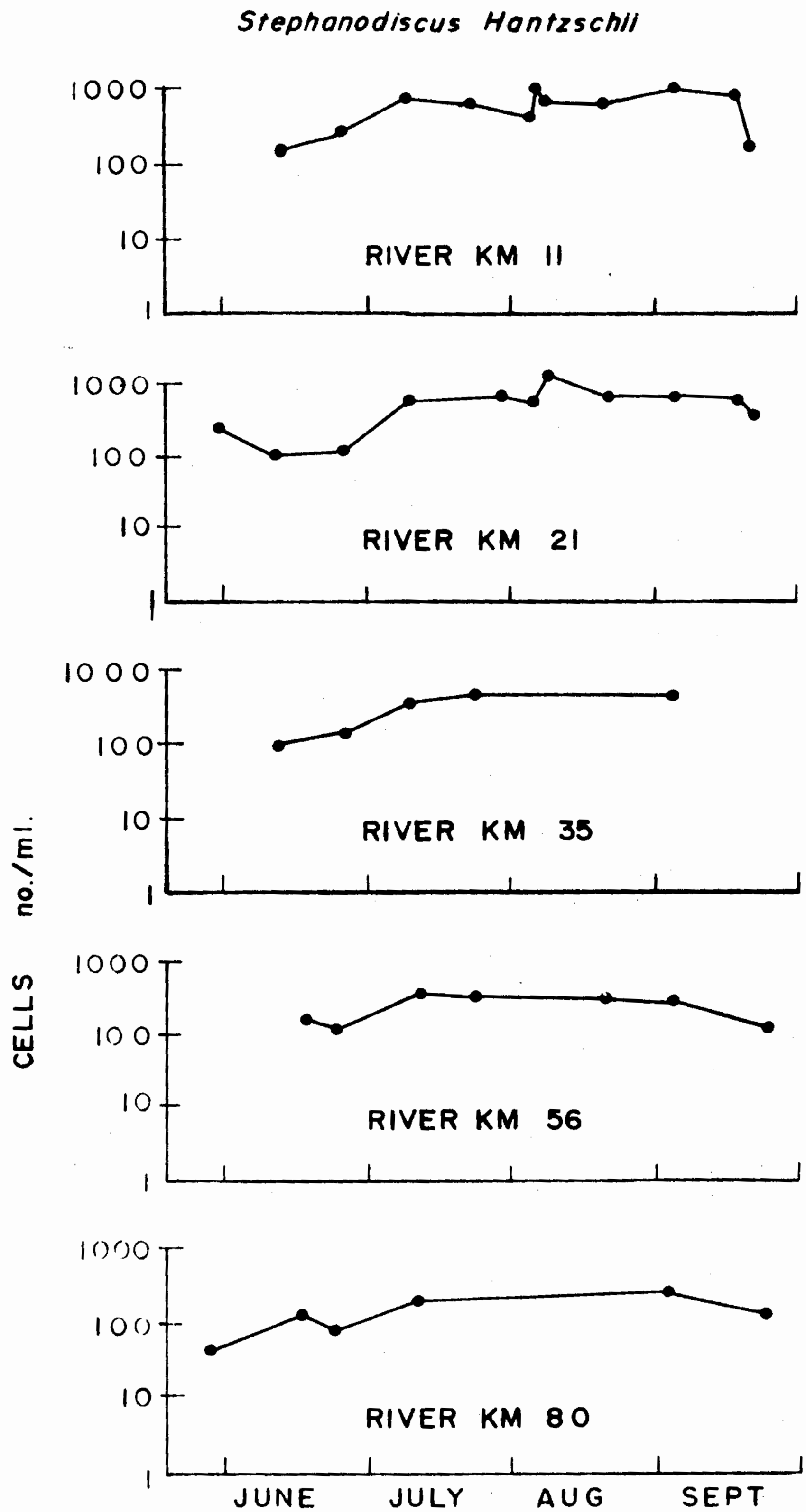

Figure 5. Population Density of Stephanodiscus Hantzschii in the Willamette River, 1974

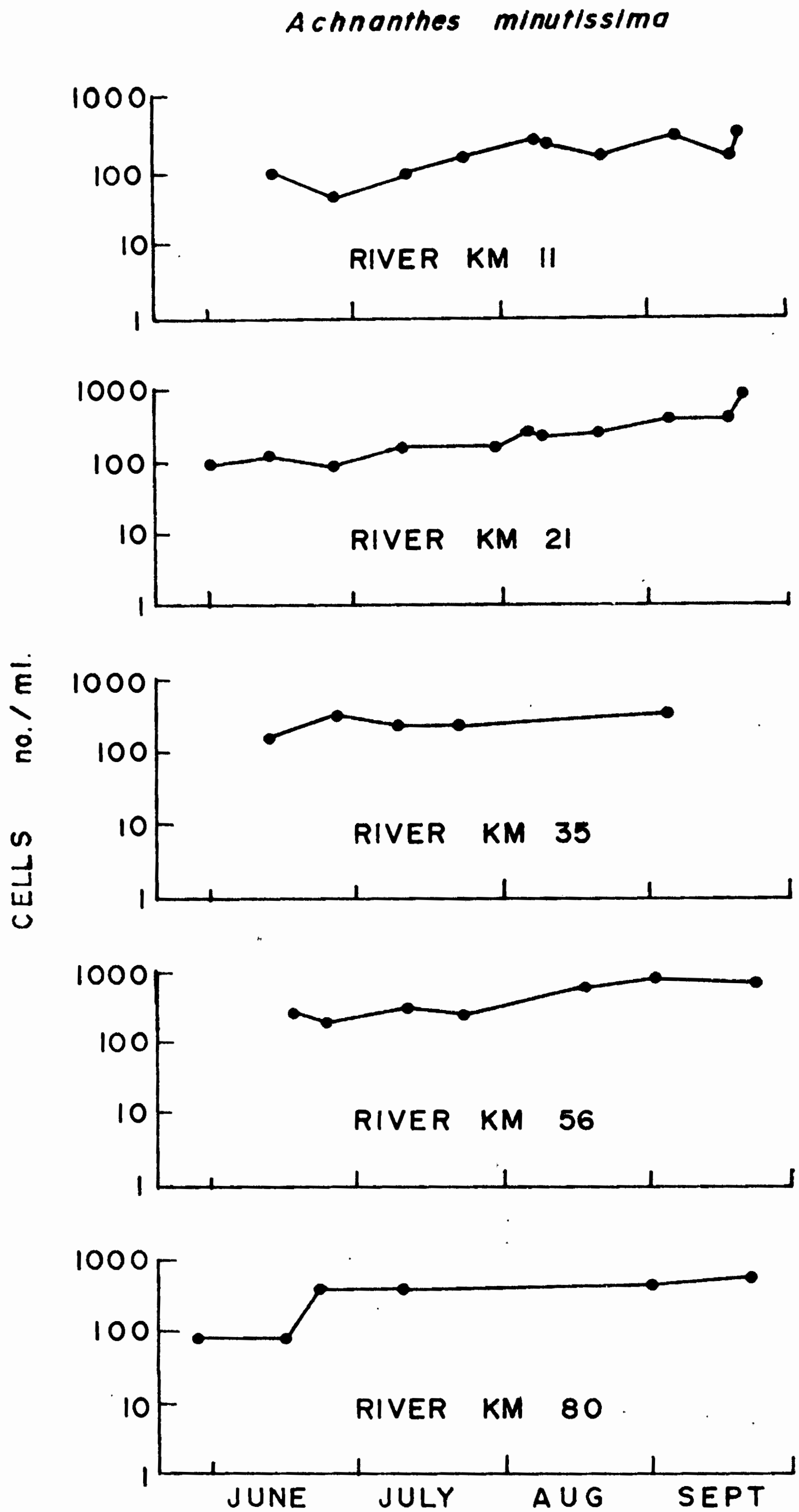

Figure 6. Population Density of Achnanthes minutissima in the Willamette River, 1974

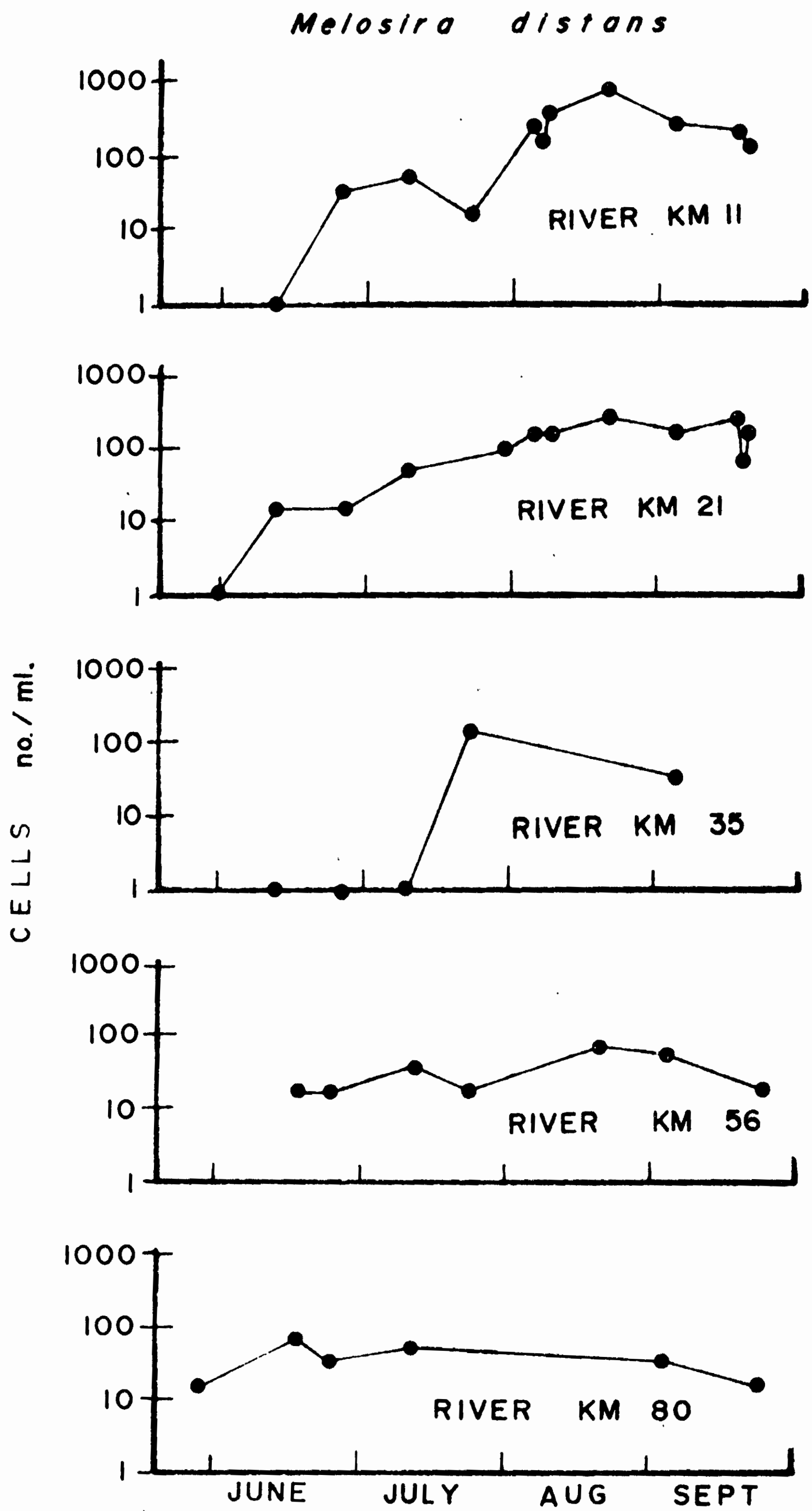

Figure 7. Population Density of Melosira distans in the Willamette River, 1974

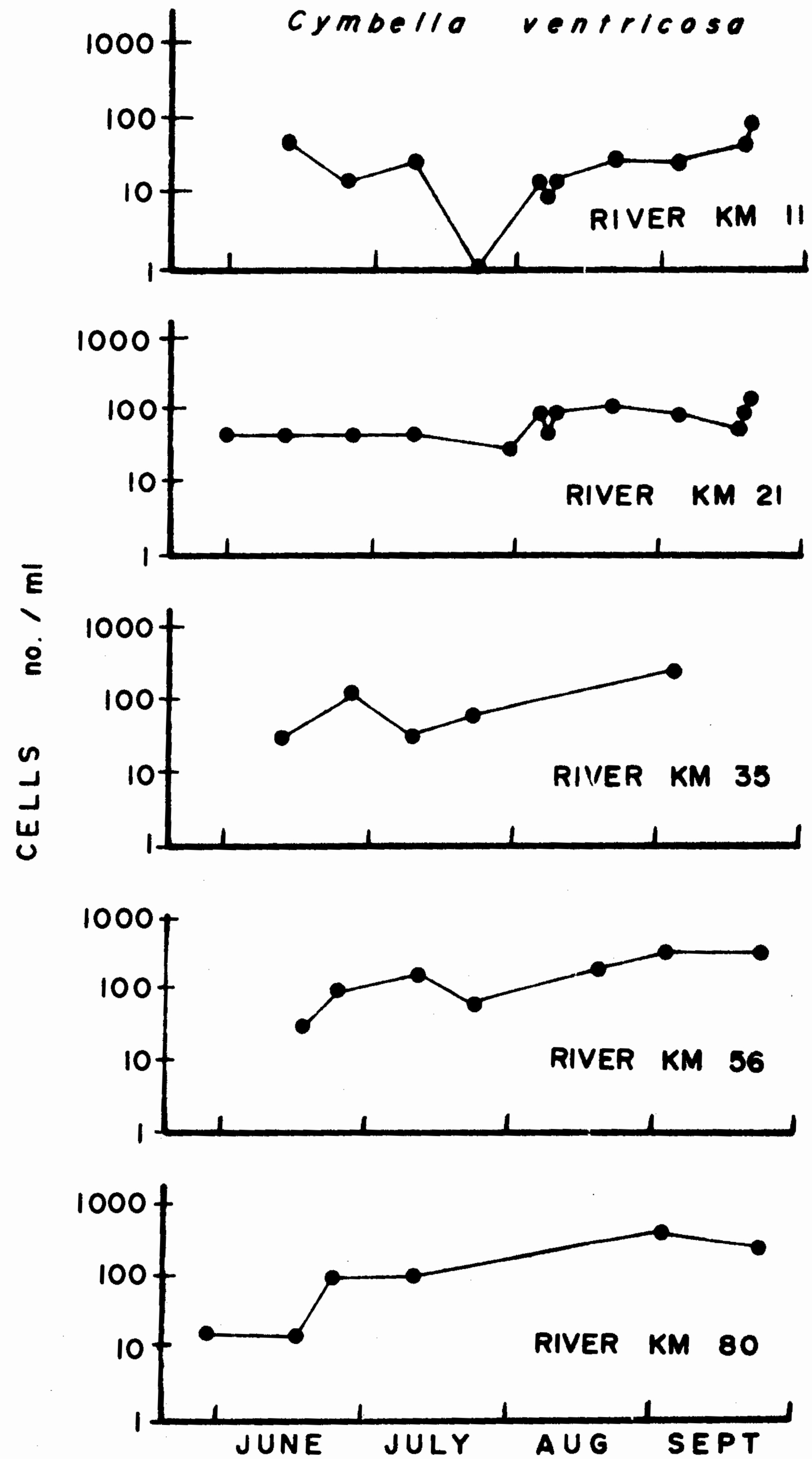

Figure 8. Population Density of Cymbella ventricosa in the Willamette River, 1974

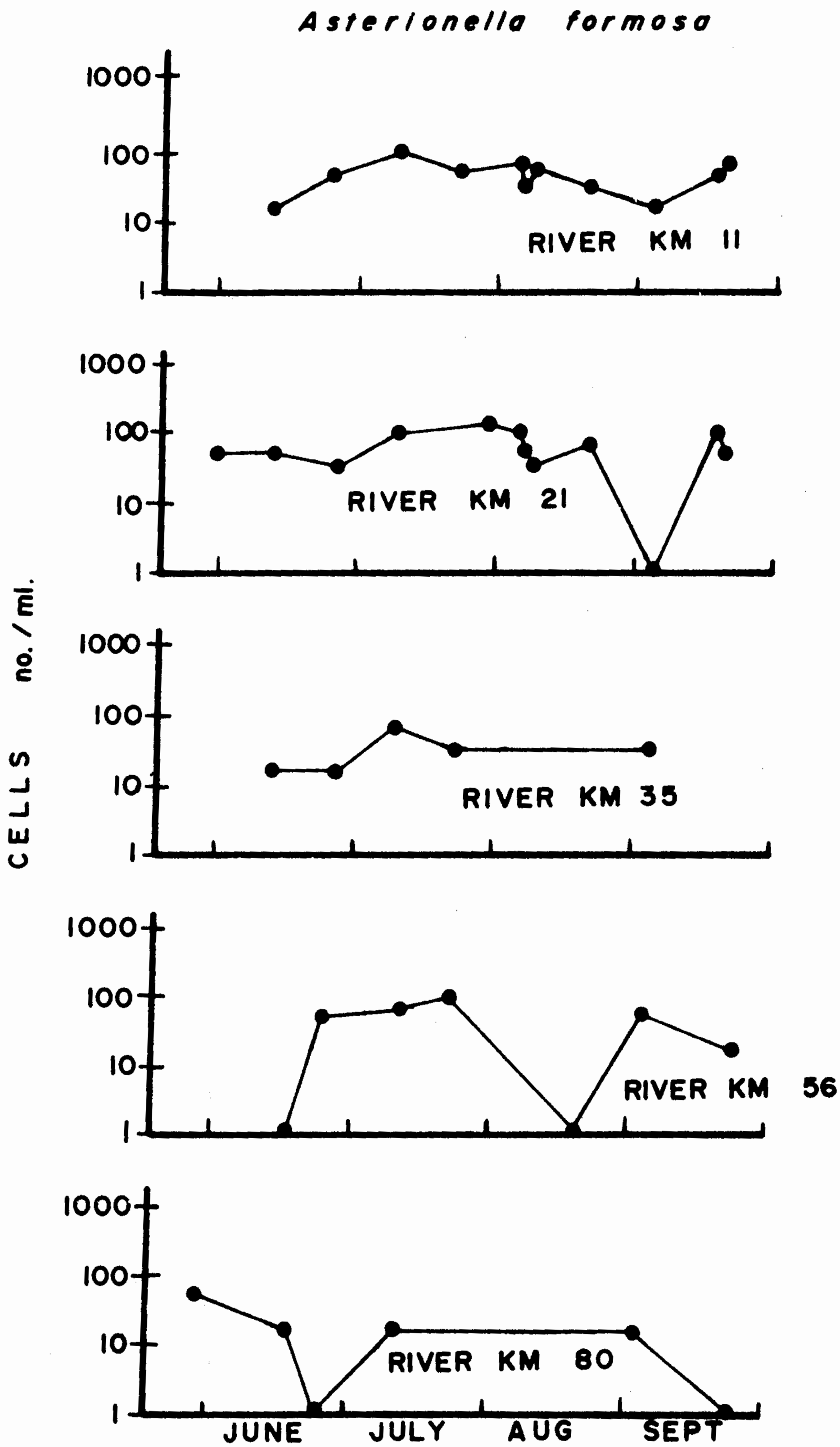

Figure 9. Population Density of Asterionella formosa in the Willamette River, 1974

with its character, is more persistent and abundant at river kms 11 and 21 than further upstream. This species is described as a widely distributed diatom (Weber, 1971), which is especially common in moderately eutrophic waters (Hustedt, 1930; Huber-Pestalozzi, 1942).

A lumping of all enumerated forms of green algae (see appendix), including the occasional observations of Scenedesmus and Pediastrum, creates a category that is more abundant and persistent at river km 11. The occurance becomes more sporadic and abundances generally lower at each successive upstream station. When Anabaena, the only blue-green genus identified, is similarly examined a trend not unlike that of the green algae in exhibited.

Collectively, the common species of diatoms observed can be described as cosmopolitan and eutrophic. No species appeared which is thought to represent pathological conditions, although some of the common species are known to be tolerant of organic enrichment (Palmer, 1969). At no time did any species appear which might be regarded as causing nuisance conditions. Although short filaments of Anabaena were observed in some samples, no "blooms" of any Cyanophyta appeared during the study. This is in marked contrast to reported blooms of Anabaena in upstream storage reservoirs (Douglas Larson, personal communication, 1974) and a high abundance of blue-green algae in certain slow moving tributaries (Carter, 1975). The principal diatom species are described as widely distributed and abundant or present in greatest abundance in highly eutrophic waters (Hustedt, 1930). Thus, it appears that the species composition of the suspended algae suggests moderately eutrophic or nutrient enriched conditions, but do not indicate gross pollution.

Only a few of the species observed in the lower reaches of the river can be regarded as truly planktonic forms. Faculative planktonic forms, including Achnanthes minutissima, Melosira varians, and Synedra ulna, were also common and have frequently been observed as members of the plankton of rivers (Williams, 1964; Williams, 1972). These may, however, have been derived from the same upstream periphyton communities as other commonly observed species (Rhoicosphenia curvata, Cymbella ventricosa, and numerous other species of Cymbella and Nitzschia). It thus appears that the dominant diatom populations result from growth of suspended planktonic forms in the river, as well as exported cells from the upstream periphytic communities.

Primary Productivity. Vertical distributions of the gross productivities are presented in Figure 10. For each plot the area enclosed by the smooth curve has been integrated to obtain a total gross productivity for the entire water column. Productivity varied in magnitude from 1.6 to 4.4 g $O_2/m^2/d$. The September 19 tests were conducted by carbon-14 uptake and the data converted to equivalent units of oxygen. All other results were determined by direct measurement of oxygen production.

The measured levels of productivity are low (Table II) but, nevertheless, further indicate that some of the suspended algae in the lower Willamette are metabolically active and not dead cells washed downstream from the extensive periphytic beds upstream.

The vertical distributions show that gross productivity decreases rapidly with depth, a result consistent with the low light transmission of the water. The clarity of the water varied over the summer, but the

TABLE II

EXAMPLES OF ESTIMATED GROSS PRIMARY PRODUCTION IN STREAMS AND RIVERS BY DIURNAL CHANGES IN OXYGEN OR pH. (AFTER WETZEL, 1975)

River and Location	Rates of production ($g\ O_2\ m^{-2}\ d^{-1}$)
Silver Springs, Florida, USA	18
Nine streams of North Carolina, USA	0.3-9
River Ivel, England	3.2-17.6
Sacramento River, California, USA	0.3-45
River Lark, England	<6-14
Madison River, Montana, USA	0.4-3.4 (as $g\ C\ m^{-2}\ d^{-1}$)
Middle Oconee River, Georgia, USA	0.07-0.28
Blue River, Oklahoma, USA	1.4-48
Willamette River, Oregon, USA	1.6-4.4

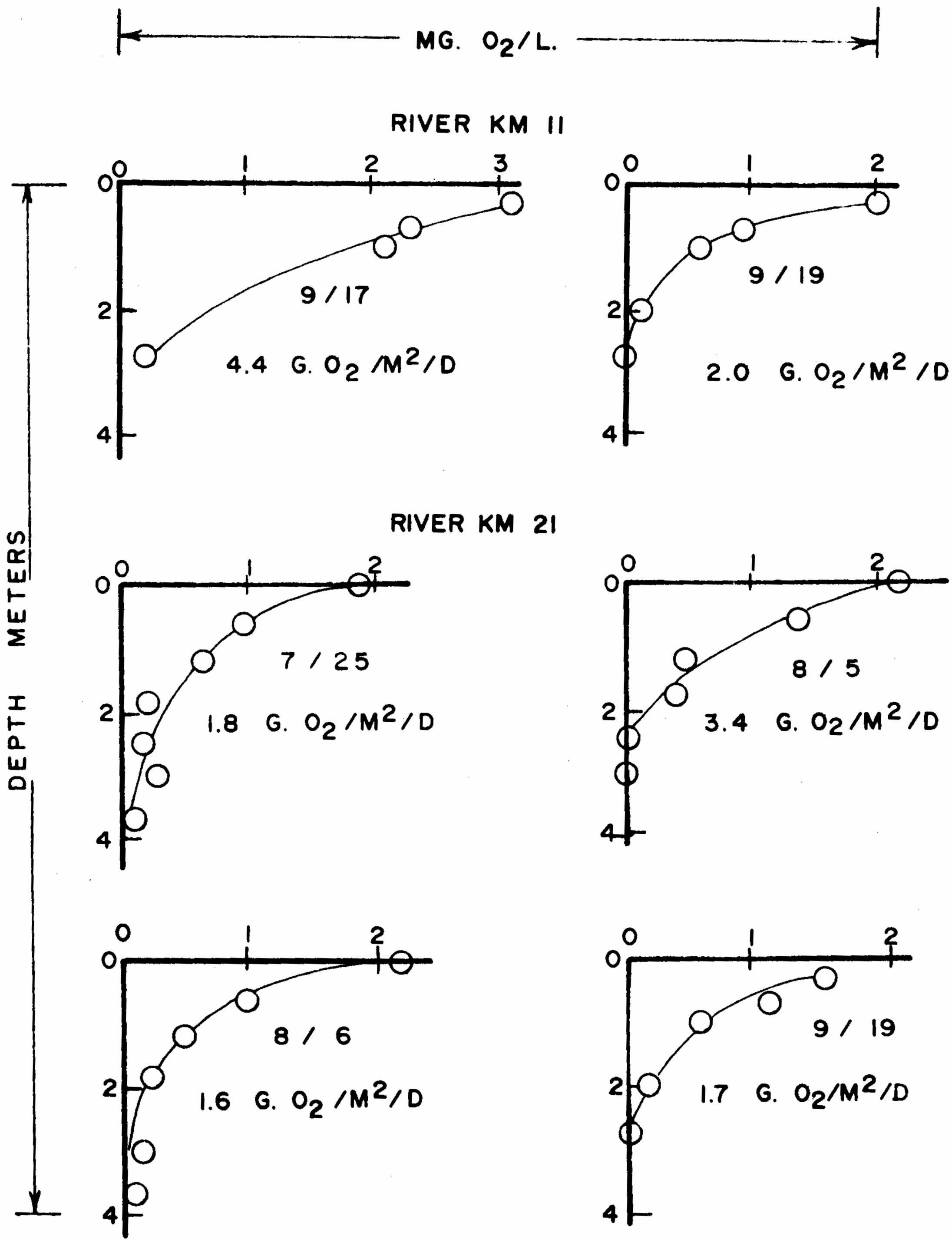

Figure 10. Vertical Distribution of Primary Productivity, 1974

depth of the euphotic zone at the lower 2 stations was usually within the range of 2.5 to 3.5 m. In contrast, the depth of the total water column is 12.8 m at river km 11 and 11.4 m at river km 21.

Net productivities were determined from the gross productivities by subtracting community respiration as calculated through use of a dissolved oxygen model (Hines and others, 1976). In using this method net production could be estimated for the entire water column as well as the euphotic zone. At river km 11, the resultant net productivities are 1.3 and 3.7 g $O_2/m^2/d$ for the euphotic zone, and -1.7 and 0.7 g $O_2/m^2/d$ for the entire water column. At river km 21, the net productivities values are 1.3, 1.4, 1.5, and 3.1 g $O_2/m^2/d$ for the entire water column. These estimated values indicate that algal productivity approximately balanced total community respiration at river km 21 on three of the four test days and exceeded it on the fourth. In contrast, at river km 11, estimated net productivity apparently added oxygen to the total water column on September 17, whereas respiration exceeded gross production by a considerable margin on the 19th. Except for the indicated input of oxygen of September 17 at river km 11, the net productivities are in general accord with the DO regime of the lower river as measured in the field.

Estimates of primary production in 1973 by graphical analysis of diel oxygen curves yielded results similar to those obtained by the light- and dark-bottle methods used in 1974 (Rickert and others, 1976). Observations suggested that in the upstream reach the entire water column was within the euphotic zone (thus encouraging predominantly periphytic growth) and primary productivity occurred at moderately high rates.

Nutrient concentrations bore little relationship to primary productivity or phytoplankton populations.

Light. The euphotic zone of a body of water may be defined as the thickness of the surface layer which receives sufficient light for algal photosynthesis to equal or exceed algal respiration. This thickness is approximately equal to the depth to which 1 percent of the surface light penetrates. Extinction coefficients of between 1.4 m^{-1} to 2.0 m^{-1} were calculated from relative light measurements taken to 3 m depth. This observed range implies a euphotic zone of from 2.3 to 3.3 meters along the course of the Willamette River. Coefficients calculated for 1 m depth were higher, presumably owing to selective wavelength absorption.

The observed high light extinction appeared to be only slightly related to the presence of suspended diatom cells. Talling (1960) reported that a growth of *Asterionella* in Lake Windermere produced an increase in the extinction coefficient of 0.02 to 0.05 $m^{-1}/10^9$ cells/ m^3. With total diatom populations observed in the Willamette on the order of 3 x 10^9 cells/ m^3, at most about 10 percent of the observed extinction coefficient can be ascribed to self-shading by suspended algae.

The considerable amount of other suspended particulate materials, both organic and inorganic, present in the water was more important and was primarily responsible for the relatively high turbidity.

DISCUSSION

<u>Temperature</u>. Water temperatures in the Willamette River reflect the moderate air temperatures of the basin and usually peak in August at about 25°C (Fig. 2). The recorded temperatures are lower than those observed in many lakes and rivers which experience nuisance algal growths. Cairns (1956) showed that diatoms are favored when incubated on slides in the laboratory through the range 20-30°C. When the incubation temperatures were slowly raised higher, the algal flora changed to green algae as dominants from 30-35°C and to blue-green algae above 35°C. Hutchinson (1967) concluded that blue-green algae may dominate in mid to late summer because they out-compete other forms by growing faster at low inorganic nutrient content and at high temperatures. However, in the Willamette River basin, short duration blooms of <u>Anabaena</u> occur in certain headwater reservoirs at water temperatures below 18°C. Nonetheless, the moderate summer temperatures experienced in the lower reaches of the Willamette could well be one factor which contributes to dominance by diatoms.

Retention time has also been considered as a possible influence on the development of planktonic algal populations in the lower Willamette (Rickert and others, 1976). Residence time in the lower reaches of the Willamette does not exceed 10 days because of flow augmentation from upstream flood storage reservoirs during the summer. As a consequence, the tidal stretch of the river shows little tendency to develop thermal stratification, which may well influence the development of planktonic algae.

Nutrients. The Willamette River may have a potential for future algal growth problems because, whereas the carbon loadings, measured as biochemical oxygen demand (BOD), are decreasing, the inorganic nitrogen and orthophosphorus loadings are increasing (Rickert and others, 1975).

Compared to concentrations of nitrogen and phosphorus observed in other waters, amounts in the lower Willamette can be considered moderate. The concentrations observed exceeded those reported by Sawyer (1954) and Schindler (1971) as sufficient to cause nuisance algal blooms in lakes. Lower concentrations have been observed in certain rivers and estuaries which have nuisance algal problems (Shane and others, 1971; Jaworski and others, 1971; Clark and others, 1973). However, the values observed in the Willamette are much less than those sometimes observed in seriously polluted waters.

Comparison of N:P ratios in Willamette River water (Fig. 3) to reported ratios in algal tissue indicate that not only are both nutrients present in sufficient concentrations to support higher levels of primary production than observed, but that nitrogen is relatively more abundant than phosphorus. Thus, if algal production were greatly increased and nutrient concentrations remained constant, it appears that phosphorus would become the limiting major nutrient. This possibility was remote during 1974, as observed concentrations of phosphorus were far from the point where they might limit productivity (Schindler, 1971).

Bioassays run in the Tidal Reach provided evidence that trace elements (B, Mn, Zn, Co, Cu, Mo, Fe) do not limit algal growth nor prevent development of nuisance algal growth (Rickert and other, 1976).

Hypotheses to interrelate broad types of algal populations with observed levels of major nutrients have recently been proposed (Hutchinson, 1967; Bush and others, 1972; and Shapiro, 1973). In general, these hypotheses suggest that (1) diatoms predominate in low to moderately enriched waters when concentrations of the major nutrients remain high and at about the initially observed ratios; (2) green algae dominate in moderately to greatly enriched waters, again when nutrient concentrations remain high and in proportion; and (3) blue-green algae dominate in enriched waters, especially during periods when prior productivity has depleted the concentration of one or more major nutrient, and in particular when the concentration of CO_2 is low because of high pH. Under the condition of low nutrient concentrations, and especially at high temperatures, the blue-greens apparently have a competitive advantage resulting from their nutrient uptake kinetics and the ability of certain species to fix atmospheric nitrogen.

In the lower Willamette, nitrogen and phosphorus are present in sufficient concentrations to support considerably more algal growth, which could conceivably lead to higher pH and the appearance of blue-green algae as the dominant phytoplankters. However, pH remains relatively low (below 8) and diatoms remain the dominant algal forms. Evidently, factors other than nutrient availability restrict algal growth.

Light. The euphotic zone in the Upstream Reach is about 3.5 m thick, but the average depth of the river is less than 2 m. The entire water column in this reach is included in the euphotic zone and it is therefore not surprising that the river bed supports a considerable growth of attached algae.

Downstream, throughout the Newberg Pool and Tidal Reach, the average depth of the river increases considerably but the euphotic zone thickness remains relatively constant. Accordingly, there is a decrease in the average amount of light available throughout the water column to promote algal growth. The water in these deeper reaches is usually mixed to depth, so only part of the total population of suspended algae is capable of photosynthesis at any moment, whereas all the algae are respiring.

Talling (1971) has described the significance of light as a controlling factor in the ecology of freshwater phytoplankton. He points out that a high ratio of mixed depth to euphotic depth will act to "dilute" light income per unit area over a deeper population, until respiration losses exceed gross photosynthesis. The depth at which respiration over the entire mixed layer exceeds the gross production possible is called the "critical depth" (Sverdrup, 1953). Talling (1971) cites three general cases in which critical depth is likely to be exceeded: (1) deep lakes during isothermal mixing, (2) very densely populated "hypereutrophic" waters with self-shading reducing the eutrophic zone and (3) slowly flowing river water of high extinction not due to algae. On the basis of the productivity data this last case appears to apply at river km 11 in the Willamette. This finding is especially significant to the DO regime of the lower river because, owing to low-flow velocities, the reach below river km 16 is a depositional zone of the Willamette. Thus, not only is there the possibility of a critical depth respiration excess from living algae, but there is the distinct possibility that algal cells settle to the bottom in this zone and thereafter die and decay.

The results of the light-dark bottle productivity experiments lend further support to the possibility of light limitation in the lower Willamette River. As shown in Figure 10, gross productivity falls off rapidly with depth and is nil below about 2 m.

The combined evidence suggests that low light availability limits the rate of primary productivity in the Tidal Reach and the Newberg Pool. It is quite likely that there is insufficient light throughout the water column for neutrally buoyant suspended algae to grow rapidly in these reaches.

Interrelationships. The factors of temperature, background water chemistry and light availability are related in a number of ways. Foremost among these are water detention time, algal residence time, primary productivity and the observed nature of the phytoplankton. Many arguments have been presented supporting water retention time as the key to river management (Uhlmann, 1968; Welch, 1968). Residence time appears to control the other factors in a manner that prevents, in free flowing rivers, the onset of conditions conducive to nuisance algal growth.

As retention time increases in reservoirs or slow moving streams and rivers, the water column may become thermally stratified. As temperature and photosynthetically available light increase under these conditions, biological activity reduces one or more major nutrient to low concentrations. Under these conditions blue-green algae apparently often gain a competitive advantage.

In rivers which flow at moderate summertime velocities these advantages tend to be negated by turbulence and constant nutrient influx. In addition, flowing water carries suspended sediment so that rivers are usually more turbid and permit less light penetration. This appears to be the case in the lower Willamette River.

Summary. During the summer of 1974 conditions in the lower reaches of the Willamette River were similar to those in other rivers currently experiencing nuisance algal growth problems. Temperature is evidently not a limiting factor to algal growth, nor are supplies of chemical nutrients. Quantities of nutrients are sufficient to support considerably more algal activity than was observed. The relatively high but stable planktonic populations indicated moderately eutrophic conditions. Productivity values for upstream periphyton beds and surface waters also suggest eutrophic conditions. However, productivity values decreased with increased depths in the lower river. With increased depth, and a constant euphotic zone, the amount of photosynthetically available light is reduced. With sufficient depth and complete mixing (i.e., no stratification) the critical depth is exceeded, resulting in the physical condition of low light limiting primary productivity rates in the lower river.

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APPENDIX I

ALGAL COUNTS AT RIVER km 11 DURING 1974

(cells/ml)

	6-12	6-25	7-09	7-22	8-07	8-20	9-04	9-18
DIATOMS								
Melosira distans	0	35	50	15	315	735	255	200
M. granulata	0	0	0	35	15	70	70	345
M. italica	0	50	90	70	35	15	155	90
M. varians	0	0	0	0	0	0	0	0
M. spp.	0	0	0	0	0	0	0	0
Achnanthes minutissima	90	50	90	175	130	175	315	315
A. lanceolata	0	0	0	0	0	0	0	0
A. lewisiana	0	0	0	0	0	0	0	0
A. spp.	0	0	0	70	0	35	50	15
Stephanodiscus hantzschii	155	285	805	660	805	660	805	805
S. astraea	70	200	315	380	35	175	110	455
S. spp.	0	70	50	70	90	70	50	70
Cymbella ventricosa	50	15	35	0	0	35	35	50
C. sinuata	15	15	0	0	0	0	35	0
C. tumida	0	0	0	0	0	0	0	0
C. spp.	70	35	50	70	35	70	35	70
Nitzschia spp.	735	285	315	175	200	315	415	380
Navicula spp.	50	70	50	110	15	50	90	0
Synedra ulna	15	15	0	15	0	50	35	35
S. Cunningtonii	15	90	0	0	15	0	0	15
S. mazamaensis	0	0	0	0	0	0	0	0
S. spp.	0	0	0	0	0	0	0	0
Cocconeis spp.	0	0	35	0	0	15	15	35
Cyclotella stelligera	0	0	15	50	15	35	50	70
C. Meneghiniana	0	0	50	0	35	70	110	15
C. spp.	0	0	0	15	0	35	35	0
Rhoicosphenia curvata	0	0	0	0	0	0	15	0

(cells/ml)

	6-12	6-25	7-09	7-22	8-07	8-20	9-04	9-18
Diatoma heimale	0	0	0	0	0	0	0	0
D. vulgare	0	0	0	0	0	0	0	0
D. spp.	0	0	0	0	0	0	0	0
Asterionella formosa	15	50	110	50	50	35	15	50
Hannaea arcus	0	0	0	0	0	0	0	0
Gomphoneis/Gomphonema	50	0	50	30	0	0	15	50
Fragilaria crotonensis	70	15	50	0	15	0	0	15
F. spp.	35	0	0	15	0	0	0	0
Miscellaneous Diatom Spp.	175	35	70	90	15	15	35	35
GREENS								
Scenedesmus	0	0	0	15	0	0	0	0
Pediastrum	0	0	0	0	0	0	0	0
Single cell	0	0	0	0	0	90	15	0
Colonial	15	15	35	50	50	15	130	15
Filamentous	0	0	0	0	0	15	0	0
BLUE GREENS								
Anabaena spp.	15	0	50	35	35	50	0	15
TOTALS								
Diatoms	1605	1315	2215	2065	1820	2650	2945	3110
Greens	15	15	35	65	50	120	145	15
Blue Greens	15	0	50	35	35	50	0	15
Total	1636	1330	2300	2165	1905	2820	2890	3140

APPENDIX II

ALGAL COUNTS AT RIVER km 21 DURING 1974

(cells/ml)

	5-16	5-31	6-12	6-25	7-09	7-29	8-09	8-20	9-04	9-18
DIATOMS										
Melosira distans	0	0	15	15	50	90	175	285	175	70
M. granulata	15	0	0	35	15	110	70	35	35	110
M. italica	15	0	15	0	50	50	70	90	110	130
M. varians	15	35	0	0	0	0	0	0	0	0
M. spp.	0	0	0	0	0	0	0	0	0	0
Achnanthes minutissima	15	90	130	110	175	155	255	285	415	455
A. lanceolata	0	0	0	0	0	0	0	0	0	0
A. lewisiana	0	0	0	0	0	0	0	0	0	0
A. spp.	15	0	15	50	0	15	0	35	15	0
Stephanodiscus hantzschii	155	225	90	130	660	660	1710	660	600	500
S. astraea	90	50	110	15	415	455	90	175	90	130
S. spp.	50	15	0	70	255	225	110	110	90	175
Cymbella ventricosa	0	50	50	50	50	35	70	130	90	110
C. sinuata	0	0	0	0	0	15	0	0	0	0
C. tumida	0	0	0	0	15	0	0	0	0	0
C. spp.	35	90	200	110	15	90	15	110	90	50
Nitzschia spp.	550	455	345	415	380	315	380	455	345	805
Navicula spp.	15	0	155	155	50	50	50	110	110	35
Synedra ulna	0	0	15	0	15	15	15	35	15	15
S. Cunningtonii	50	70	50	70	0	35	0	0	0	0
S. mazamaenis	0	0	0	35	0	0	0	0	0	0
S. spp.	0	0	0	0	0	0	0	15	0	15
Cocconeis spp.	0	0	15	0	0	0	0	110	35	70
Cyclotella stelligera	0	0	15	70	15	35	70	15	15	0
C. Meneghiniana	15	0	0	0	50	50	50	90	70	35
C. spp.	0	0	0	0	35	0	0	15	15	0

	(cells/ml)									
	5-16	5-31	6-12	6-26	7-09	7-29	8-07	8-20	9-04	9-18
Rhoicosphenia curvata	0	0	0	15	15	35	15	90	35	50
Diatoma heimale	0	15	0	0	0	0	0	0	0	0
D. vulgare	0	0	0	0	0	0	0	0	0	0
D. spp.	0	0	0	0	0	0	0	15	0	0
Asterionella formosa	15	50	50	35	110	130	15	70	0	110
Hannaea arcus	0	0	0	0	0	0	0	0	0	0
Gomphoneis/Gomphonema	15	0	35	15	0	35	15	0	30	0
Fragilaria crotonensis	50	15	70	0	90	90	15	70	0	35
F. spp.	15	0	15	15	35	0	35	0	35	0
Miscellaneous Diatom Spp.	130	255	175	35	35	130	50	0	0	0
GREENS										
Scenedesmus	0	0	0	0	0	15	0	0	0	0
Pediastrum	0	0	0	0	15	0	0	0	0	0
Single cell	0	0	15	15	0	0	35	15	15	50
Colonial	15	0	0	15	0	50	50	35	35	0
Filamentous	0	0	0	15	0	0	0	15	0	0
BLUE GREENS										
Anabaena spp.	0	0	0	0	15	0	50	35	0	0
TOTALS										
Diatoms	1260	1415	1565	1445	2510	2820	3275	2990	2415	2900
Greens	15	0	15	45	15	65	85	65	50	50
Blue Greens	0	0	0	0	15	0	50	15	0	0
Total	1275	1415	1580	1490	2540	2885	3410	3070	2465	2950

APPENDIX III

ALGAL COUNTS AT RIVER km 35 DURING 1974

	(cells/ml)				
	6-12	6-26	7-09	7-22	9-04
DIATOMS					
Melosira distans	0	0	0	130	35
M. granulata	0	35	15	15	35
M. italica	0	15	35	50	50
M. varians	15	0	0	0	0
M. spp.	0	0	0	0	0
Achnanthes minutissima	175	285	255	225	315
A. lanceolata	0	0	0	0	0
A. lewisiana	0	0	0	0	0
A. spp.	35	70	15	50	15
Stephanodiscus hantzschii	110	155	380	550	500
S. astraea	35	35	155	175	35
S. spp.	0	50	110	110	50
Cymbella ventricosa	35	130	35	70	255
C. sinuata	0	0	35	50	0
C. tumida	0	0	35	0	0
C. spp.	90	90	110	110	175
Nitzschia spp.	600	550	500	500	660
Navicula spp.	90	130	155	130	130
Synedra ulna	15	0	0	15	15
S. Cunningtonii	50	35	50	15	15
S. mazamaensis	0	0	0	0	0
S. spp.	0	0	0	0	0
Cocconeis spp.	15	15	0	0	15
Cyclotella stelligera	0	0	15	50	35
C. Meneghiniana	0	0	35	15	50
C. spp.	0	0	0	0	0

(cells/ml)

	6-12	6-26	7-09	7-22	9-04
Rhoicosphenia curvata	0	15	0	90	35
Diatoma heimale	15	0	0	0	0
D. vulgare	0	0	0	0	0
D. spp.	0	0	0	0	0
Asterionella formosa	15	15	70	35	35
Hannaea arcus	0	0	0	0	0
Gomphoneis/Gomphonema	35	0	35	85	70
Fragilaria crotonensis	35	30	15	35	35
F. spp.	0	15	15	35	15
Miscellaneous Diatom Spp.	155	70	90	90	50
GREENS					
Scenedesmus	0	0	0	35	0
Pediastrum	0	0	0	0	0
Single cell	0	15	0	15	0
Colonial	15	0	0	35	35
Filamentous	0	0	0	0	15
BLUE GREENS					
Anabaena spp.	0	0	0	0	0
TOTALS					
Diatoms	1520	1735	2160	2630	2625
Greens	15	15	0	85	50
Blue Greens	0	0	0	0	0
Total	1535	1950	2160	2715	2675

APPENDIX IV

ALGAL COUNTS AT RIVER km 56 DURING 1974

	6-17	6-24	7-11	7-23	8-19	9-03	9-23
	(cells/ml)						
<u>DIATOMS</u>							
Melosira distans	15	15	35	15	70	50	15
M. granulata	0	0	0	50	15	15	0
M. italica	35	0	50	35	15	35	0
M. varians	0	0	15	0	0	0	0
M. spp.	0	0	0	0	0	0	0
Achnanthes minutissima	255	200	315	385	600	805	805
A. lanceolata	0	0	0	0	0	0	0
A. lewisiana	0	0	0	0	0	0	0
A. spp.	35	35	35	35	50	50	0
Stephanodiscus hantzschii	175	130	380	380	315	345	130
S. astraea	35	35	130	200	175	70	15
S. spp.	15	130	50	110	90	50	15
Cymbella ventricosa	15	90	155	70	225	285	345
C. sinuata	0	0	0	35	0	0	70
C. tumida	0	0	0	0	0	15	0
C. spp.	130	225	130	110	130	90	15
Nitzschia spp.	500	735	660	805	895	500	735
Navicula spp.	155	225	0	130	0	70	130
Synedra ulna	15	0	70	35	0	15	70
S. Cunningtonii	35	70	0	15	0	0	0
S. mazamaensis	0	0	0	15	0	0	0
S. spp.	0	0	0	0	0	0	0
Cocconeis spp.	0	0	35	15	35	130	130

	(cells/ml)						
	6-17	6-24	7-11	7-23	8-19	9-03	9-23
Cyclotella stelligera	0	130	0	15	15	0	0
C. Meneghiniana	0	0	15	15	90	0	0
C. spp.	15	0	50	0	0	0	0
Rhoicosphenia curvata	15	0	15	0	70	15	35
Diatoma heimale	0	15	0	0	0	0	0
D. vulgare	0	0	0	0	0	0	0
D. spp.	0	0	0	0	15	0	0
Asterionella formosa	0	50	70	90	15	50	15
Hannaea arcus	0	0	0	0	0	0	0
Gomphoneis/Gomphonema	105	35	15	50	0	85	35
Fragilaria crotonensis	50	35	35	35	0	15	35
F. spp.	0	15	0	0	0	50	15
Miscellaneous Diatom Spp.	90	255	15	50	35	35	35
GREENS							
Scenedesmus	0	0	0	0	0	0	0
Pediastrum	0	0	0	0	0	0	0
Single cell	0	0	15	0	35	0	15
Colonial	15	0	0	35	50	35	0
Filamentous	0	0	0	0	15	15	0
BLUE GREENS							
Anabaena spp.	0	0	0	0	50	15	0
TOTALS							
Diatoms	1690	2420	2275	2595	2840	2775	2645
Greens	15	0	15	35	100	50	15
Blue Greens	0	0	0	0	50	15	0
Total	1705	2420	2290	2630	2990	2840	2660

APPENDIX V

ALGAL COUNTS AT RIVER km 80 DURING 1974

(cells/ml)

	4-17	4-30	5-14	5-28	6-17	6-24	7-11	8-02	9-03	9-23
<u>DIATOMS</u>										
Melosira distans	35	0	0	15	70	35	50	15	35	15
M. granulata	0	0	0	0	0	15	0	0	0	0
M. italica	35	110	0	0	50	0	35	0	15	35
M. varians	0	15	0	35	0	0	15	0	0	0
M. spp.	0	0	0	0	0	0	0	0	0	0
Achnanthes minutissima	550	50	70	90	110	380	415	600	550	660
A. lanceolata	0	0	0	0	0	0	0	50	0	0
A. lewisiana	0	0	0	0	0	0	0	0	0	0
A. spp.	70	90	0	35	35	35	50	0	0	90
Stephanodiscus hantzschii	550	90	130	50	175	90	225	600	315	175
S. astraea	110	50	50	0	15	50	35	35	50	35
S. spp.	50	0	0	15	70	35	15	315	15	35
Cymbella ventricosa	70	15	0	15	15	110	90	110	415	255
C. sinuata	0	0	0	0	0	0	0	35	50	0
C. tumida	0	0	0	0	0	0	0	15	15	0
C. spp.	70	15	50	200	255	200	70	110	130	285
Nitzschia spp.	805	225	550	805	500	735	1150	1010	660	735
Navicula spp.	35	15	50	90	70	130	90	315	90	15
Synedra ulna	50			15		15	35	0	15	50
S. Cunningtonii	110	50	50	15	15	15	0	0	15	0
S. mazamaensis	0	0	0	0	0	0	15	0	15	0
S. spp.	0	35	0	0	0	0	0	0	0	0
Cocconeis spp.	0	0	0	0	15	15	0	90	155	225
Cyclotella stelligera	0	0	0	0	0	0	0	0	0	0
C. Meneghiniana	15	15	15	0	0	0	0	70	35	0
C. spp.	0	0	0	0	0	0	0	0	0	0

Rhoicosphenia curvata	0	0	0	0	0	35	15	35	70	90
Diatoma heimale	0	15	0	15	0	0	0	0	0	0
D. vulgare	0	0	0	0	0	0	0	0	0	0
D. spp.	0	0	0	0	0	0	0	0	0	0
Asterionella formosa	70	15	0	50	15	0	15	0	15	0
Hannaea arcus	35	35	50	15	15	15	0	0	15	15
Gomphoneis/Gomphonema	50	15	50	70	50	110	50	35	155	35
Fragilaria crotonensis	0	0	70	15	0	15	35	35	0	15
F. spp.	0	35	35	35	0	15	35	0	0	0
Miscellaneous Diatom Spp.	90	130	455	175	285	225	70	90	0	35
GREENS										
Scenedesmus	0	0	0	0	0	0	0	15	0	0
Pediastrum	0	0	0	0	0	0	0	0	0	0
Single cell	0	0	0	0	0	0	0	0	0	0
Colonial	35	0	0	0	0	0	0	155	0	15
Filamentous	0	0	0	0	0	0	0	0	15	0
BLUE GREENS										
Anabaena spp.	0	0	15	0	0	0	0	0	15	0
TOTALS										
Diatoms	2800	1020	1625	1755	1760	2297	2510	3565	2830	2800
Greens	35	0	0	0	0	0	0	170	15	15
Blue Greens	0	0	15	0	0	0	0	0	15	0
Total	2835	1020	1640	1755	1760	2275	2510	3735	2860	2815