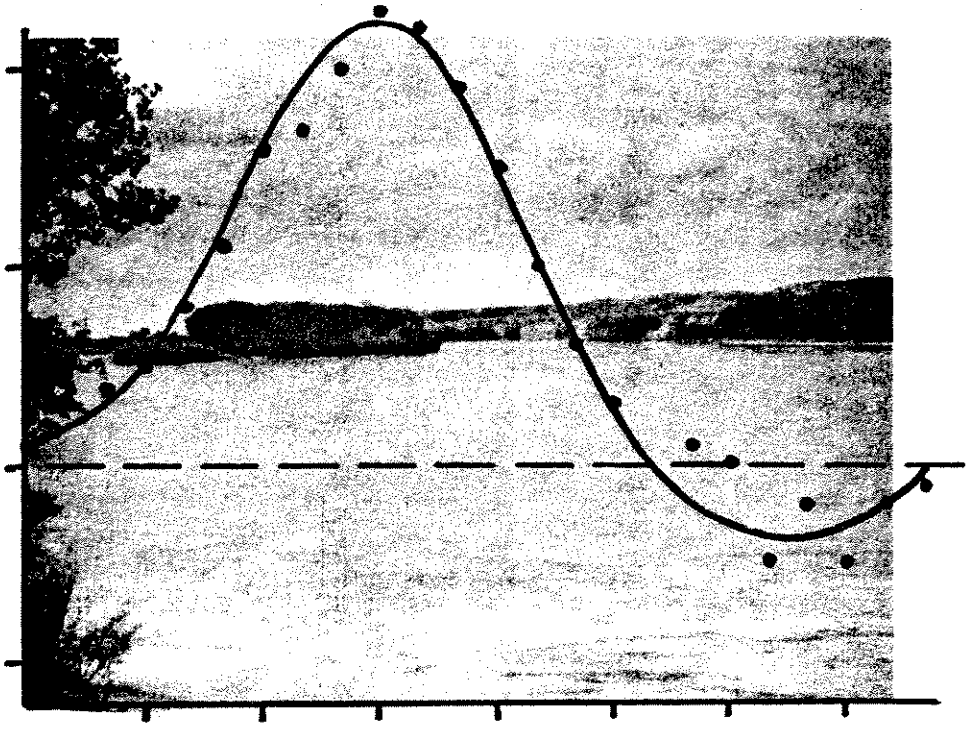
EFFECTS OF DECREASED WATER QUANTITY AND INCREASED NUTRIENT ADDITIONS ON ALGAL BIOMASS ACCUMULATION, AND SUBSEQUENTLY, THE DISSOLVED OXYGEN BALANCE OF THE YELLOWSTONE RIVER



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EFFECTS OF DECREASED WATER QUANTITY AND INCREASED NUTRIENT ADDITIONS ON ALGAL BIOMASS ACCUMULATION, AND SUBSEQUENTLY, THE DISSOLVED OXYGEN BALANCE OF THE YELLOWSTONE RIVER

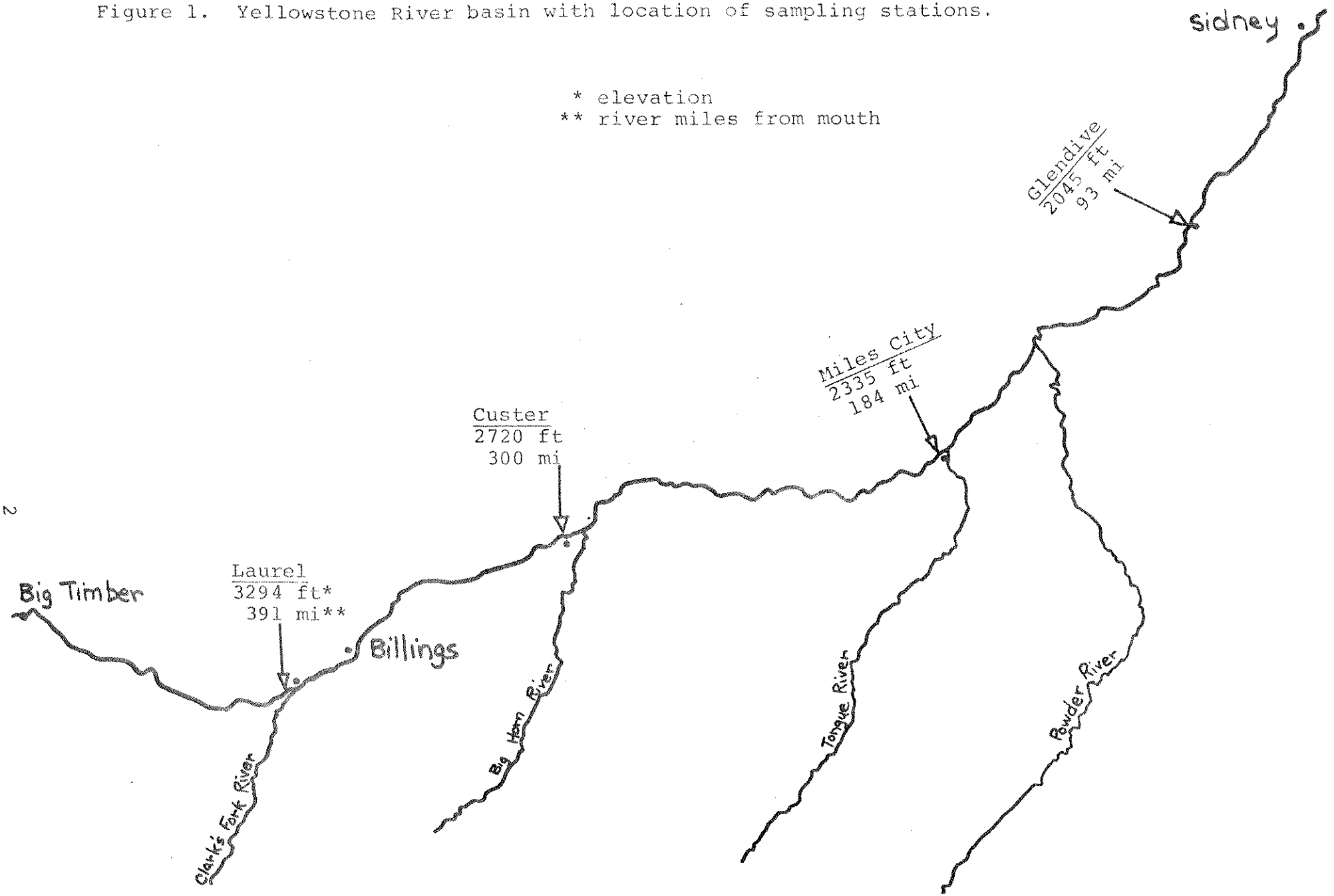
INTRODUCTION

The Yellowstone River is facing environmental degradation from two distinct, but interrelated factors, decreasing water quantity and increasing pollution loading (decreasing water quality). Massive water withdrawals from the river are expected for coal-related development; i.e., steam-fired generating plants, gasification plants, and coal-washing sites, as well as for the ever-expanding agricultural and human population needs. All of these water consumers are also generators of waste. The physicochemical composition of these wastes is complex and variable. Chemical parameters common to all, however, are plant-stimulating nutrients, particularly nitrogen and phosphorous compounds.

In any relatively undeveloped river system, any increase in these nutrients will very likely result in corresponding increases in algal biomass. In aquatic ecosystems this increase in plant growth yields increases in photosynthesis and plant respiration, which in turn develop direct and measurable changes in the dissolved oxygen saturation levels of the water body. These saturation changes are most evident in the summer and are manifested in diel fluctuations - high dissolved oxygen values during the hours of daylight and low values during darkness. These dissolved oxygen fluctuations have variable, but real, effects on aquatic populations. Any reduction in dissolved oxygen can reduce the efficiency of oxygen uptake by aquatic animals and hence their ability to meet the demands of their environment; this in turn may be harmful by affecting fish production and the potential yield of a fishery. It has been demonstrated that deleterious effects on fish seem to depend more on extremes than on averages. For example, the growth of fish is slowed markedly if the oxygen concentration falls to 3 mg/l for part of the day, even if it rises as high as 18 mg/l at other times (EPA 1973). In even more extreme cases, where algal biomass accumulation is even higher, the nighttime dissolved oxygen may be reduced to near 0 mg/l, resulting, of course, in the asphyxiation of aquatic populations.

With the potential for harmful dissolved oxygen fluctuations in mind, field investigations were made into the periphyton accumulation and diel dissolved oxygen fluctuations at four stations on the Yellowstone River - Laurel, Custer, Miles City and Glendive, during the late summer of 1976 (Figure 1). Laboratory assays were also conducted with water from each station to measure the algal growth responses at

Figure 1. Yellowstone River basin with location of sampling stations.



various simulated water withdrawal levels (with their resulting concentrated nutrient levels). We hoped not only to establish the present, baseline level of diel dissolved oxygen levels for the low flow, summer period, but also to predict the effects that decreased river volumes might ultimately have on the dissolved oxygen balance of the river.

It was intended that the results of this study would lend support to the summer portion of the Montana Department of Fish and Game's tentative determination of flows necessary to maintain a viable aquatic population in the river. (This flow reservation request is pending before the Montana Board of Natural Resources and Conservation.)

FIELD STUDY

Methods

Two sets of continuous diel dissolved oxygen measurements were made at the four stations, using UNI-LOC Model 870 dissolved oxygen analyzers, teamed with UNI-LOC Model 270 recorders (Uniloc Inc., Irvine, CA). The meters were calibrated to the nearest 0.2 mg/l and checked at least twice during each 24-hour period by utilizing the azide modification of the Winkler Method (APHA 1971). Diel temperature measurements were concurrently recorded with Taylor 7-day thermographs (Taylor Instrument Co., Rochester, NY). Two stations were measured on a given day, since two pairs of oxygen and temperature recorders were available. These data were collected on August 2-4 and again on August 16-18, 1976. On August 3-4, at all stations, glass microscope slides were suspended on floating periphyton collection trays similar to those described by Patrick (1954). After 14 days (August 17-18), the slides were field-preserved and returned to the laboratory where total algal biomass (as dry weight and ash-dry weight) and chlorophyll-a determinations were conducted (APHA 1971).

Results

The first set of diel measurements was taken during river flows that were much higher than normally occur during August. In fact, the river's discharge was as much as four times the Montana Department of Fish and Game's August flow reservation request. These high flows were aggravated by heavy thunderstorms which occurred for 2 days before, and continued throughout the field collection period. Particularly heavy rains occurred in the Livingston to Billings area. The second set of field measurements was made during somewhat lower flows (although the river's discharge, on the average, was still nearly twice the reservation request) and during warmer and less cloudy days. These flow data are presented in Table 1.

Table 1. Approximate* flow rates during the two sets of diel temperature and dissolved oxygen determinations. Also listed are the August Montana Department of Fish and Game flow reservation requests for each river segment (Custer is within segment #1, Miles City #2, and Glendive #3). All values are in cubic feet per second.

Station	August 2-4	August 16-18	Reservation Request
Laurel	14,000	6,500	-
Custer	16,500	7,000	3,800
Miles City	16,000	10,000	5,400
Glendive	11,500	9,000	6,000

*The flows for Custer are from the USGS station at Billings and the Glendive flows are from the Sidney station. The approximate Laurel flow is the difference between the Billings station and the Clarks Fork of the Yellowstone River station near its mouth at Silesia, Montana.

Table 2 demonstrates the ranges of percent saturation, temperature and dissolved oxygen that occurred during the two diel measurement periods. Figure 2 expands these data into hourly changes as percent saturation of dissolved oxygen. It can be seen that more extreme saturation fluctuations occurred at all four stations during the second set of diel measurements.

The results of the periphyton analyses from the artificial substrates are presented in Table 3. A considerable amount of silt was deposited on all of the glass slides except on those from the Miles City station - this is reflected by the low volatile solids:dry weight ratios at the three other stations. Besides having the highest percentage of volatile solids, the Miles City station also had the highest chlorophyll-a concentration. Weber (1973) designed an Autotrophic Index, using the dry weight and chlorophyll-a of periphyton grown on glass slides to describe the trophic condition of waters. He also stated, however, that waters containing a large amount of detritus (or silt?) will also show large values for this index. The principal argument inherent in his index is that "chlorophyll-a constitutes approximately 1-2 percent of the dry weight of organic matter in all algae." Therefore, rather than computing an Autotrophic Index, a "theoretical dry weight of algae" is presented here by estimating that the dry organic weight of an "average" algae cell is approximately 1.5 percent chlorophyll-a (66.7 x chlorophyll-a concentration). Using this computation, it can be seen in Table 3 that the Miles City station also had the greatest periphyton accumulation as theoretical dry weight of algae.

Figure 2. Diel dissolved oxygen fluctuations as percent saturation. The beginning time for each set of measurements varied from 0800 to 1800 hours; however, for comparative purposes each individual graph was adjusted to start at 0900 hours.

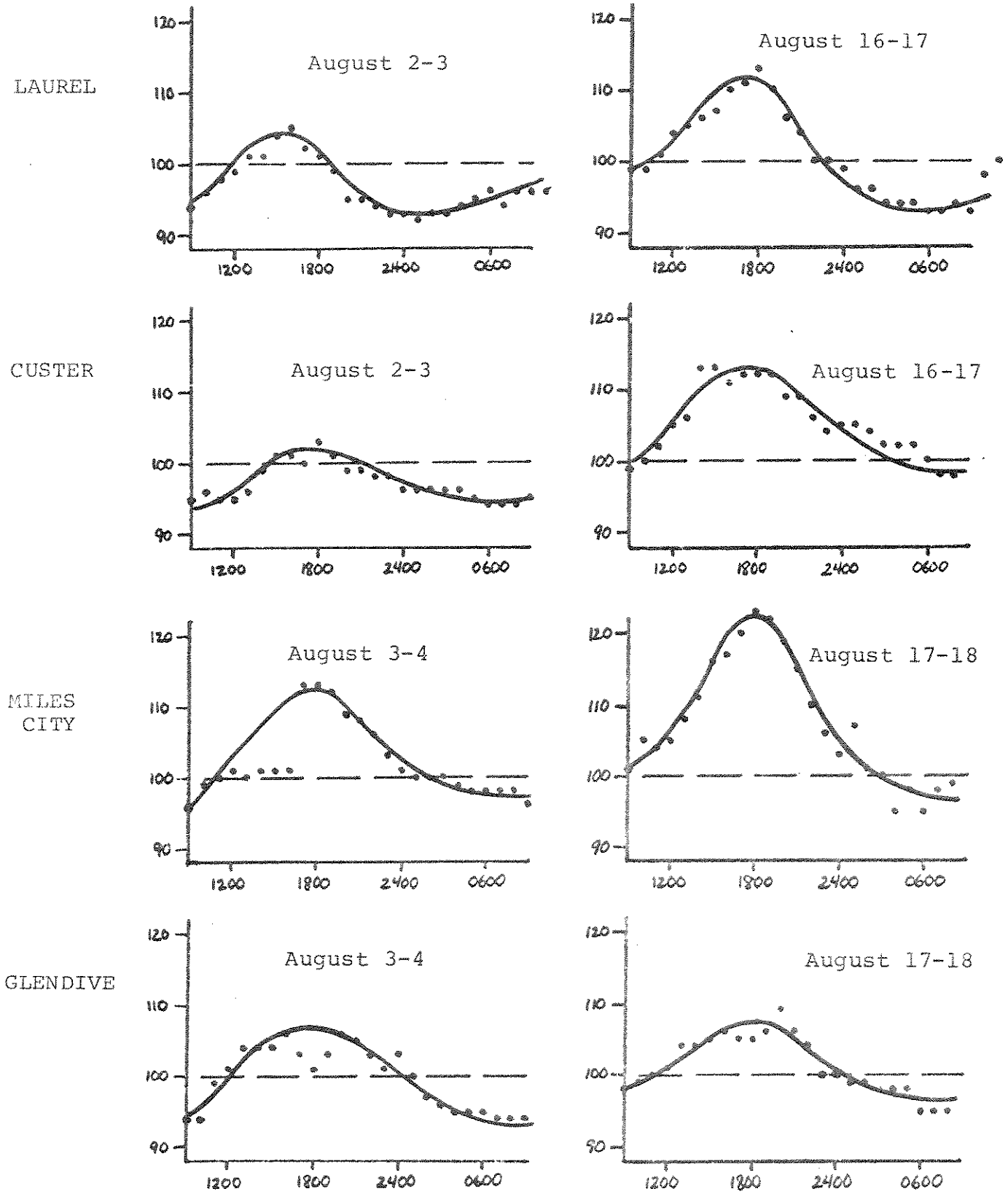


Table 2. Ranges of values for percent saturation (as dissolved oxygen), temperature and dissolved oxygen for two sets of diel measurements on 8/2-8/4 and 8/16-8/18/76

Station	Percent Saturation	Temperature (°C)	Dissolved Oxygen (mg/l)
		8/2-8/4	
Laurel	92-105	16.5-20.0	7.8-8.5
Custer	94-103	20.0-21.5	7.6-8.2
Miles City	96-113	22.5-25.5	7.7-8.8
Glendive	94-106	23.0-25.5	7.6-8.4
		8/16-8/18	
Laurel	93-113	16.0-21.0	7.9-8.9
Custer	98-113	20.0-23.0	8.0-8.9
Miles City	95-123	21.0-24.0	7.9-9.7
Glendive	95-109	22.0-25.0	7.8-8.5

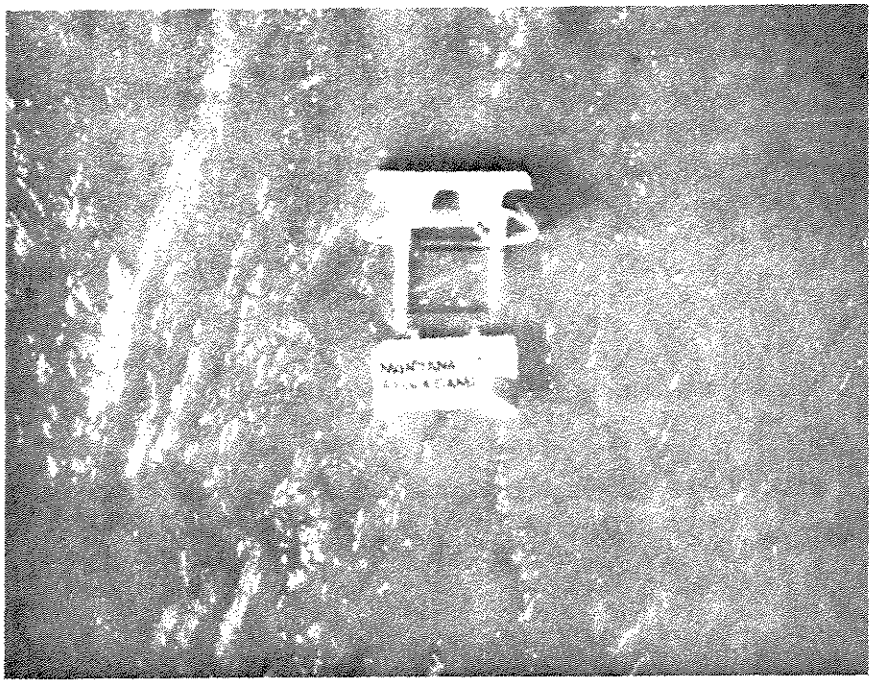
Table 3. Periphyton analyses from microscope slides which had been placed at four stations on the Yellowstone River. All values are in mg/M^2 surface area of artificial substrate. All slides were in the river for exactly 14 days.

Station	Dry Wt.	Ash-Dry Wt.	Volatile Solids	Chloro-phyll-a	Theoretical Dry Wt. Algae*
Laurel	27,553	24,693	2860	12.5	837
Custer	13,660	11,953	1707	6.6	442
Miles City	2,140	1,300	840	18.7	1253
Glendive	2,316	2,020	297	1.0	67

*Assuming that chlorophyll-a comprises 1.5 percent of the total weight of algae. The difference between this value and the total volatile solids figure is an estimation of the contribution of inorganic volatile solids; i.e., silt, to the volatile solids value.

Water samples for chlorophyll-a analyses were collected on 8 and 9 September, 1976. The results of these plankton analyses for the four stations are presented in Table 4. Miles City had the greatest chlorophyll-a (and theoretical dry weight of algae) concentration, followed by Glendive.

Yellowstone River at Custer



A floating periphyton collection tray with artificial substrates (microscope slides) suspended in the center.

Table 4. Plankton analyses of water samples collected on September 8 and 9, 1976 at four Yellowstone River stations. Data are reported as mg/M^3.

Station	Chlorophyll-a	Theoretical Dry Wt. Algae*
Laurel	2.8	188
Custer	7.6	509
Miles City	14.4	965
Glendive	11.2	750

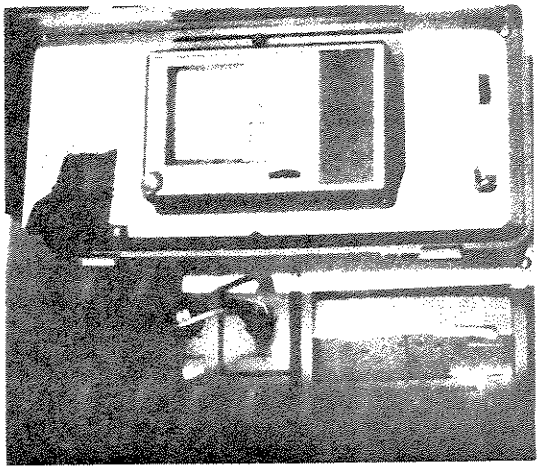
*Assuming that chlorophyll-a comprises 1.5 percent of the total weight of algae.

LABORATORY STUDIES (Algal Assays)

Methods

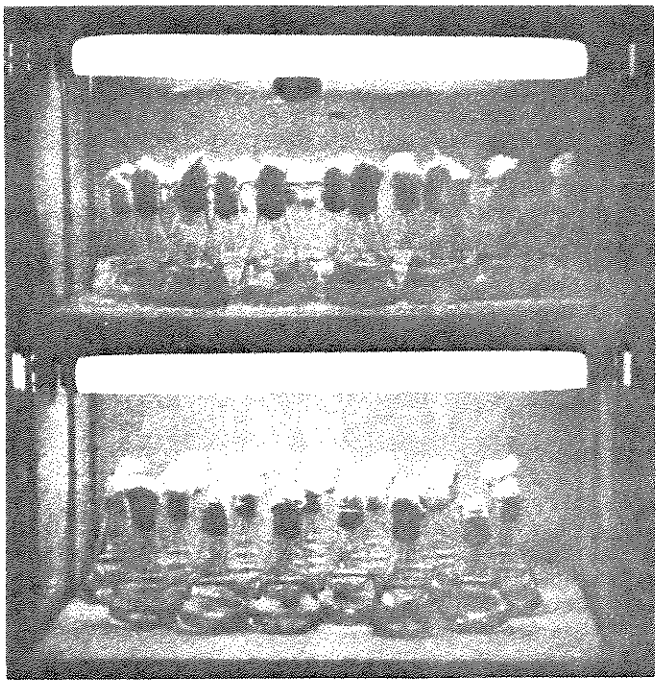
Algal assays were conducted to demonstrate the effects that increasing nutrient levels might have on the algal production of the Yellowstone River. Two sets of assays were conducted beginning on 10 August and again on 18 September, 1976. River water from all four stations was returned to the laboratory and filtered through 0.45 micron Millipore filter paper. A small portion of each sample was left unfiltered to be used as algal "seed." To simulate water withdrawals (loss of dilution), certain percentages of water from all stations was then evaporated. In the first assay 20, 50 and 80 percent of the water was evaporated at 100°C; 15 percent of this evaporated volume was then added back as irrigation water - this water had been collected from an irrigation return flow to the Yellowstone River near Pompeys Pillar, Montana. The irrigation water had also been filtered through Millipore filters to remove any suspended solids. In the second assay 20, 40, and 60 percent of the water was evaporated, but this time at 25-35°C under 625 mm of vacuum. No irrigation water was added to the second set of assays. The resulting algal assay setup for each test is described in Figure 3.

To begin the assays, triplicate 160 ml portions of each evaporated solution (plus controls) from each station were added to 250 ml erlynmeyer flasks. Two mls of algal "seed" were added to each flask. In each test a total of 48 flasks - 4 stations x 4 concentrations (3 evaporated + 1 control) x 3 replicates of each concentration - were stoppered with cotton and incubated at 20± 1°C in an AMBI-HI-LOW chamber (Lab-Line Instruments, Melrose Park, IL). Two sets of two 20-watt fluorescent lamps were placed above the flasks. To approximate summer conditions, the lamps were cycled on and off for 14 hours and 10 hours, respectively. During the assays, the flasks were swirled daily to provide adequate CO_2 exchange.



UNI-LOC Model 870 dissolved oxygen analyzer and model 270 recorder

Taylor 7-day thermograph (Munitions case containing UNI-LOC equipment in background).



160 ml portions of evaporated river water incubating under 40-watt light banks in AMBI-HI-LOW chamber

Figure 3. Comparison of river water concentrations used in the algal assays, expressed as percent water evaporated (see text for further explanation).

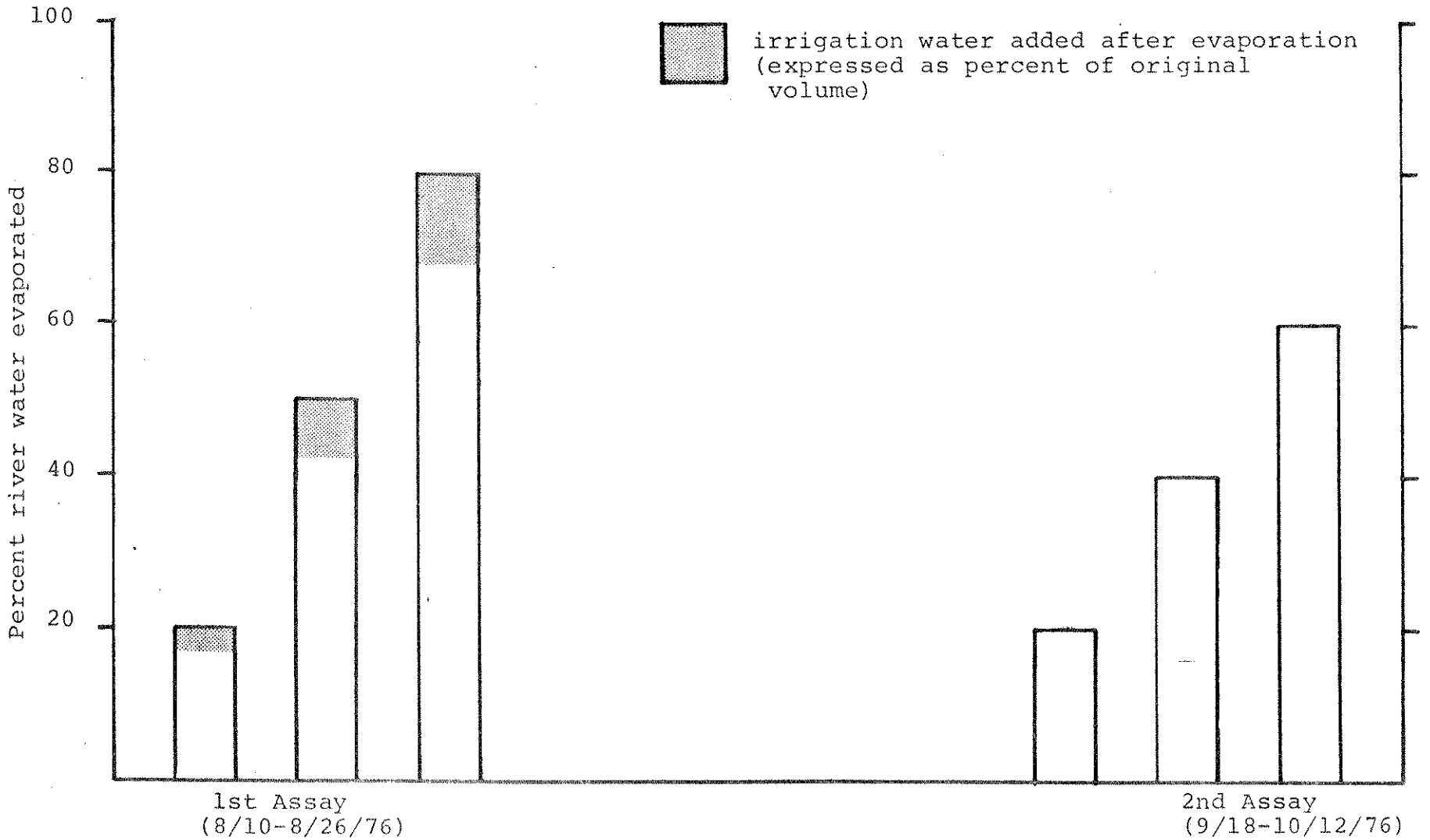


Table 5. Chemical analyses of algal assay test solutions at the start of the second assay, 18 September 1976. (Key to assay concentrations - L = Laurel, C = Custer, M = Miles City, G = Glendive, 0-60 = percentage evaporation).

Assay (Concentration)	Specific Conductivity		Total Dissolved Solids	Na		Total Hardness (Ca+Mg)		Total Alkalinity[4]		pH	Total Phosphorus		NO_2/NO_3	Orthophosphate[5]	
	Actual	Percent of Theoretical[1,2]	[3]	Actual	Percent of Theoretical	Actual	Percent of Theoretical	Actual	Percent of Theoretical		Actual	Percent of Theoretical		Actual	Percent of Theoretical
L0	278		203	17		97		103		8.0	.006		<.01	.001	
L20	335	96	245	21	100	125	103	124	96	8.3	.023	306	<.01	.009	750
L40	417	90	304	27	96	157	97	162	94	8.7	.011	110	.01	.002	125
L60	529	76	386	41	96	179	74	188	73	8.5	.012	80	.03	.009	360
C0	475		374	34		158		132		8.2	.006		.03	.005	
C20	565	95	412	43	100	207	105	162	98	8.2	.012	160	.04	.006	100
C40	657	83	480	53	93	220	84	163	74	8.4	.008	80	.07	.005	63
C60	877	74	640	76	89	290	73	203	62	8.4	.014	93	<.01	.008	64
M0	558		407	46		184		136		8.3	.006		<.01	.002	
M20	669	96	488	60	103	227	99	161	95	8.4	.020	266	<.01	.004	160
M40	781	84	570	71	92	248	81	160	70	8.5	.004	40	<.01	.002	61
M60	1032	74	753	95	83	298	65	179	53	8.4	.004	27	<.01	.002	40
G0	598		437	52		172		140		8.4	-	-	<.01	.002	
G20	697	93	509	63	97	227	106	160	91	8.3	.006	-	<.01	.002	80
G40	832	83	607	76	87	262	91	165	71	8.3	.006	-	.01	.002	61
G60	1095	73	799	108	83	314	73	181	52	8.3	.024	-	.01	.002	40

1. Percent of theoretical = $\left(\frac{\text{actual}}{\text{theoretical}}\right) \times 100$

   $\text{theoretical} = \frac{\text{actual control concentration}}{\text{percent water remaining after evaporation}}$

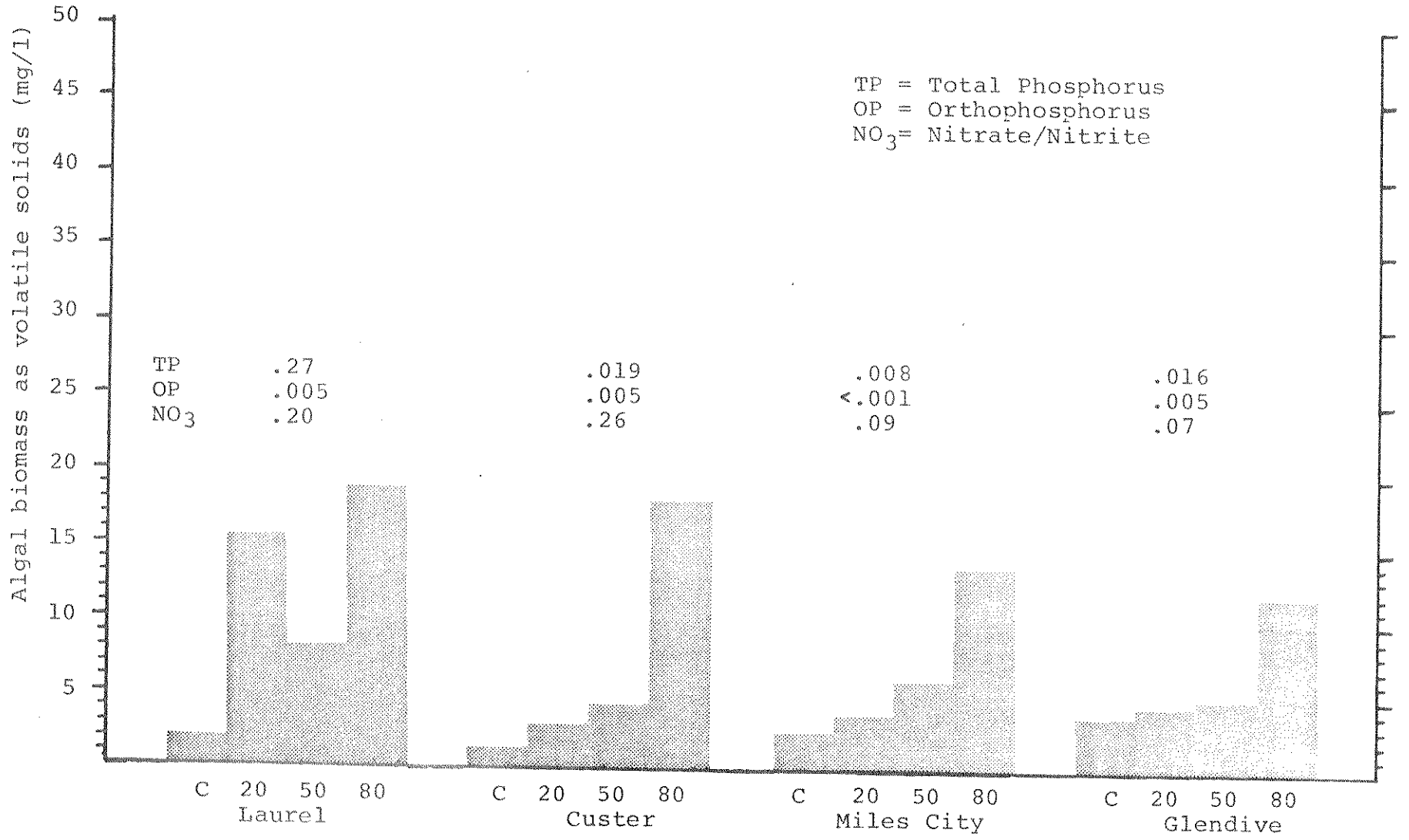
2. (Values <100 percent interpreted as loss due to precipitation, >100 percent interpreted as gain due to contamination)

3. Calculated using .73 x actual spec. cond. (from past Yellowstone calculations).

4. As $CaCO_3$

5. As Phosphorus

Figure 4. Result of the first algal assay, presented as total volatile solids. Nutrient concentrations (mg/l) of the controls (0 percent evaporation) are presented above each station. No analyses were conducted on any of the 20-80 percent evaporated solutions.



algal biomass. The results of the first assay are illustrated in Figure 4. It can be noted that the total biomass (as total volatile solids) appeared to increase in nearly a "stair step" manner as the percent evaporation increased. However, since the amount of insoluble, inorganic precipitate in the assay flasks appeared, visually, at least, to be present in greater amounts than the algal biomass, these results may have more closely reflected the amount of precipitate that was volatilized, rather than the organic volatiles (actual algal biomass). Also, by using total volatile solids, rather than dry weight, as the final measure of total algal biomass, the contribution of the siliceous portions of diatoms would not be accurately measured.

In the second algal assay, nutrient and other basic water analyses were conducted on all of the control and evaporated test solutions. These results are presented in Table 5. With regard to the basic chemical parameters (sodium, hardness, alkalinity and dissolved solids) it can be noted in this table that the percentage formation of insoluble precipitates increased as the percentage of evaporation increased. However, the nutrients, particularly phosphorus, did not follow any such pattern. The nutrient concentrations in this assay were extremely low, even when compared to normal values for the Yellowstone River during August. Consequently, any sources of nutrient contamination, i.e., on glassware, filter papers, or sample storage bottles, would have made significant contributions to the total values which were eventually present in the assay flasks. The results of the second assay, as phosphorus versus total algal biomass concentrations (as dry weight) are presented in Figure 5. It is interesting to note in this illustration that the fluctuations in final algal biomass closely correlate to the corresponding values for total phosphorus in each test concentration at each station. The one glaring exception to this pattern is in the Glendive 60 percent evaporated test series. However, other factors limiting to algal growth such as high total dissolved solids, and/or a low total alkalinity to total hardness ratio, may have been responsible for growth inhibition.

DISCUSSION

The diel dissolved oxygen measurements demonstrated that during August 1976, greater fluctuations occurred during lower flows. For example, at Custer this fluctuation was 9 percent of saturation during flows of 16,500 cfs and 15 percent during flows of 7,000 cfs. On 28-29 August 1967, abbreviated diel dissolved oxygen measurements were taken below Billings, near Custer (MDFG 1967). The saturation of dissolved oxygen was found to fluctuate 70 percent. The river flow at this time was approximately 4,000 cfs. These data are presented in Figure 6. This graph illustrates that river discharge conditions were more conducive for an extreme fluctuation during August 1967 than during August 1976; not only was the river flow on the date of the diel measurement in 1967 much lower than it was on either

The total algal biomass, after a given time period, was used to evaluate the growth of the algal populations. The first assay was concluded after 16 days. The algal mass in each flask was thoroughly mixed and total dry weight, ash-dry weight and total volatile solids of the suspensions were determined (APHA 1971). It was necessary to determine all of these parameters, since an insoluble precipitate had formed during evaporation of the river water at 100°C. After evaporation, this precipitate was physically resuspended to ensure that all chemical parameters would be present in the assay solutions (even if some were present in suspended rather than dissolved form). In preparation for the second assay, which was concluded after 24 days, river water was evaporated under a partial vacuum. It was hoped that by utilizing this technique, which lowered the boiling point of the water to just above room temperature, the formation of insoluble precipitates would be eliminated. However, even at these lower temperatures, some precipitation did occur. For this second assay, it was desired to measure the final algal biomass as total dry weight rather than as total volatile solids, since (1) there is a possibility that some inorganics may volatilize at 550°C, (2) the majority of the accumulated periphyton appeared to be diatoms, and the siliceous portions of these cells would not be volatilized, and (3) there is room for error with any additional analytical weighing. With these sources of error in mind, the evaporated solutions were filtered through 0.45 micron Millipore filters to remove all of the inorganic precipitates before preparation of the 160 ml solutions. It was realized, of course, that the accuracy gained by the less involved dry weight determination for the final, total weight of algae might have been negated by the possible loss of some precipitated nutrients during the second micro-filtration.

Results

In the first algal assay, nutrient analyses for total phosphorus, orthophosphorus, and nitrate/nitrite were conducted on the control (0 percent evaporation) waters from all four stations and on the filtered irrigation water. No analyses were performed on any of the evaporated solutions. At the time, it was assumed that the nutrient values would increase in proportion to the amount of water evaporated; the influence of irrigation water (15 percent of the evaporated volume) was then calculated into the remaining, then concentrated, water to give the final "calculated" nutrient values. As was found in the second assay, where analyses for nutrients were conducted, by station, for all of the evaporated concentrations, it is not possible to assume that the nutrient values will follow any such proportional concentration pattern. The results of the first assay, then, are presented here only to show the erroneous results that could be obtained by assuming that (1) nutrients are concentrated in proportion to the amount of water evaporated, and (2) total volatile solids are an accurate measure of total

Figure 5. Result of the second algal assay presented as dry weight. Total phosphorus and orthophosphate concentrations are plotted above each evaporated test solution. Note the correlation between total phosphorus and algal biomass (except in Glendive 60 percent).

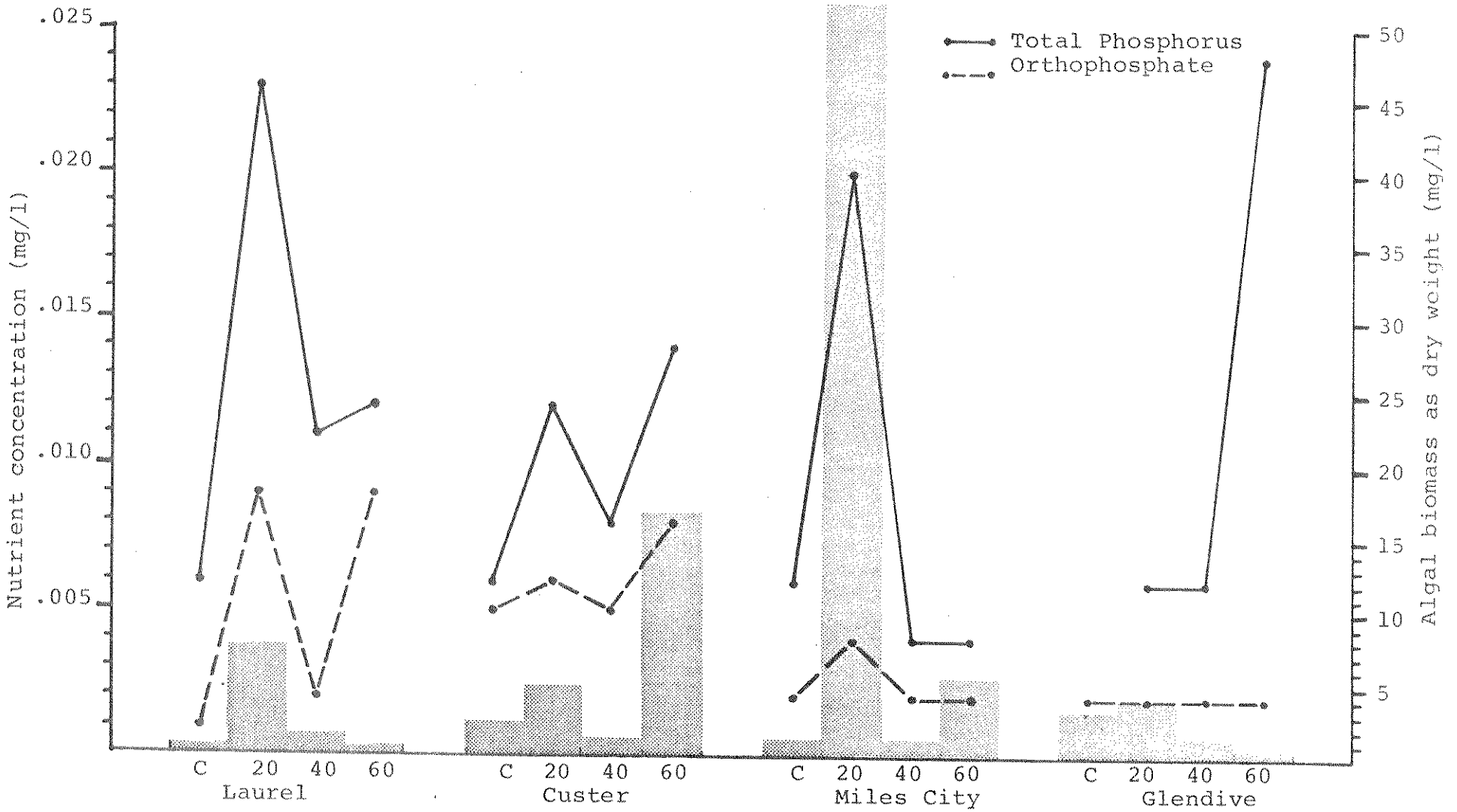
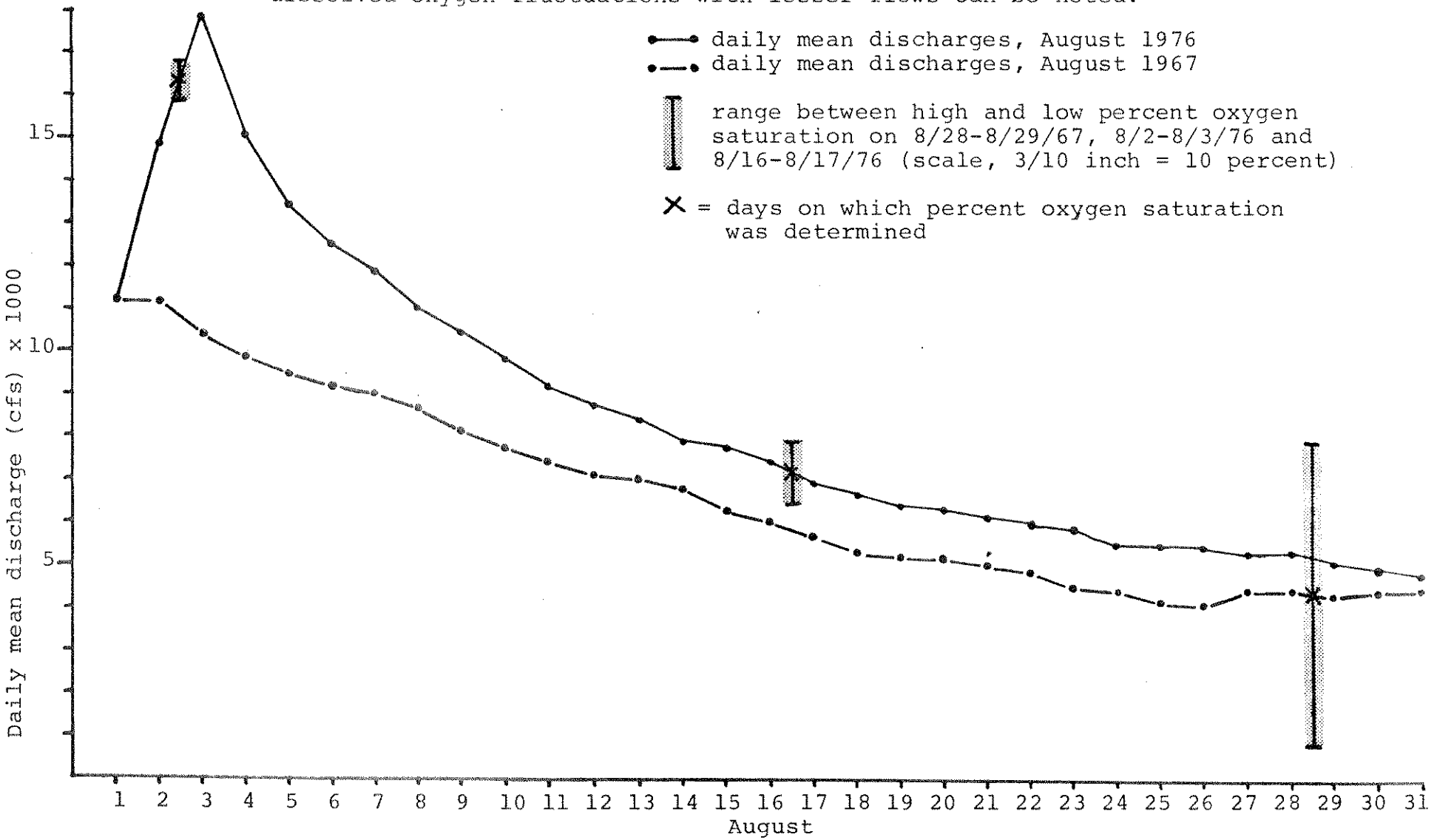


Figure 6. Average daily river discharges and three dissolved oxygen fluctuations measured at the Custer station during August 1967 and 1976. Greater dissolved oxygen fluctuations with lesser flows can be noted.

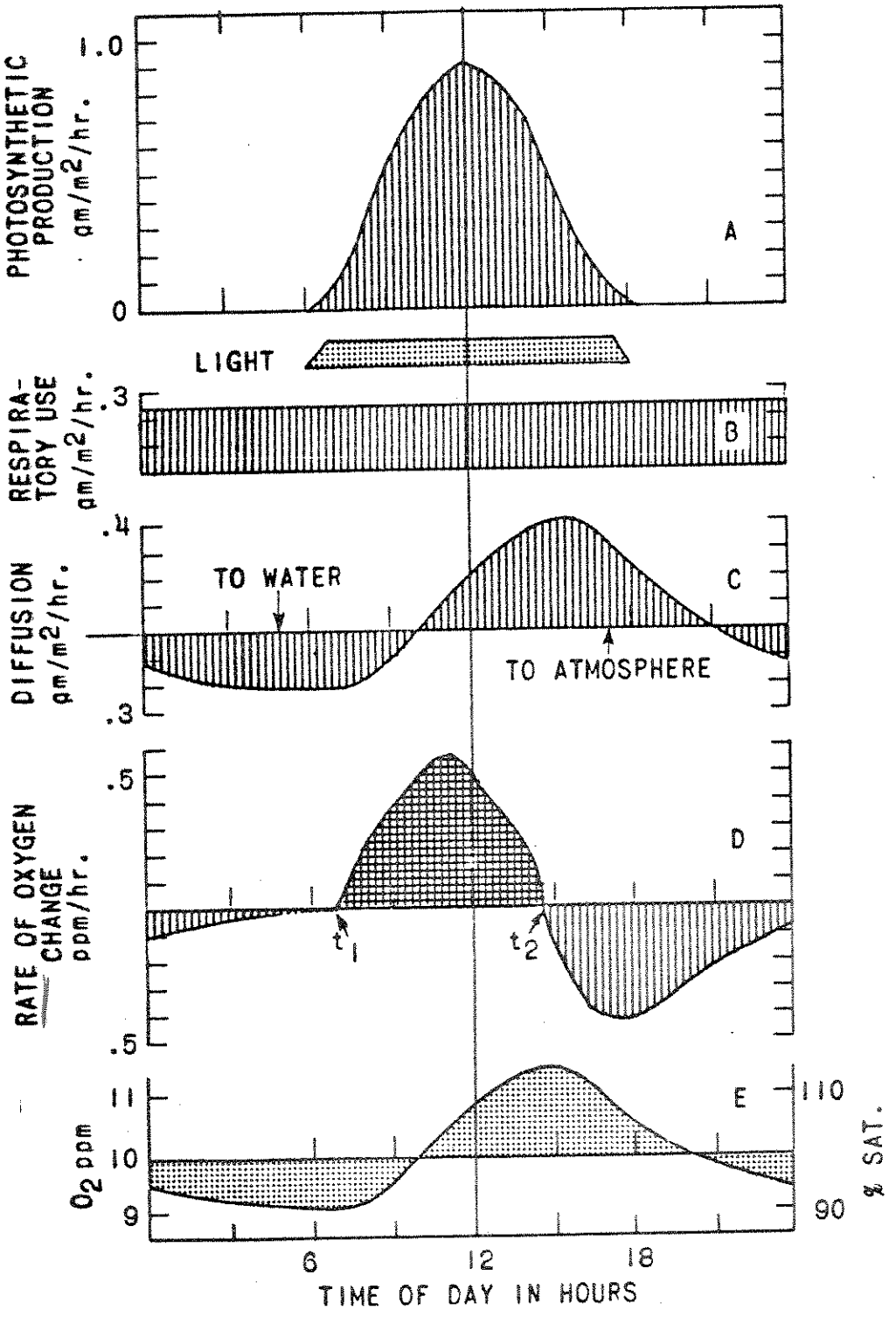


date in 1976, but also the total discharge for August 1967 was considerably lower than for the same month in 1976.

Odum (1956) described the oxygen fluctuation in a hypothetical stream as being regulated by three main daily processes. These are release of oxygen into the water during daylight through photosynthesis (A in Figure 7), absorption of oxygen by all organisms (B) and oxygen exchange between water and air (C). Interplay of these three processes determines the rate of oxygen change (D) and the resulting diel oxygen fluctuations that would appear in the stream (E). It is likely that during August 1976 the high river discharge (and therefore the total physical diffusion of oxygen to the water, C in Figure 7) at all of the stations was high enough to offset the respiratory use (B), giving a rather small nighttime oxygen depletion, compared to the relatively higher daytime supersaturation values. For example, at Miles City on 17-18 August the peak afternoon dissolved oxygen value was 23 percent above the saturation value calculated from the recorded water temperature and elevation (atmospheric pressure), while the predawn low was only 5 percent below this similarly calculated saturation value. If the river discharge for August 1976 had been as low as for August 1967, we would have expected more extreme diel dissolved oxygen fluctuations if for no other reason than the river would have had less nighttime physical diffusion potential.

Of the four study stations, Miles City had the greatest diel dissolved oxygen fluctuations on both dates during the 1976 study. It is important to note that this station also had the highest algal concentrations, both as periphyton accumulation on artificial substrates and as plankton. The other three stations were relatively similar in algal concentrations and subsequently, in the ranges of dissolved oxygen fluctuations. Laurel, for example, had the second highest concentration of periphyton, but the lowest phytoplankton concentration; conversely, Glendive had the lowest periphyton but the second highest plankton concentrations. Thus, considering the Miles City extremes, it is apparent that in the Yellowstone River, significant increases in algal biomass will lead to corresponding increases in dissolved oxygen fluctuations. This is certainly not an original finding, since other studies (Odum 1956, Hoskin 1959, Gunnerson and Baily 1963) have noted this relationship and have attempted to quantify by analyses of diel curves of dissolved oxygen the combined influences of algal photosynthesis and respiration on the oxygen balance of flowing waters. In this study it was intended to use algal assays to predict the effects that decreased river flows and/or increased nutrient levels might ultimately have on the Yellowstone River's dissolved oxygen balance.

Figure 7. Diurnal oxygen relations in a hypothetical stream section (modified from Odum 1956).



The results of the second algal assay draw attention to the trend that doubling of the total phosphorus concentrations could lead to a 5-10 fold increase in algal production (compare Laurel 20 percent and 40 percent evaporations and Custer 40 percent and 60 percent evaporations in Figure 5). It should be noted that the highest total phosphorus concentration in any of these assay replicates was 0.024 mg/l, which is quite low compared to past summer concentrations on the Yellowstone River (USGS 1965-1974). Nutrient data for this 10-year period are very limited, both in frequency of sample collections and in number of stations sampled. However, during the late summer of 1969, which was a low total-discharge year for the river (for example, the average flow at Billings on 28 August was 3599 cfs), the total phosphorus concentration at Laurel on the 1 day sampled was 0.19 mg/l, and at Custer it was 0.27 mg/l. Even though these values were obtained from a single late-summer sample at each station, they still serve to illustrate that the nutrient concentrations tested in the algal assays did not come close to examining "worst possible" conditions for algal growth on the Yellowstone River; they also reflect the trend of higher nutrient concentrations being present during lower annual discharge periods.

It can be stated then, that decreasing summer flows lead to greater dissolved oxygen fluctuations, since: (1) less physical reaeration potential is available for diffusion of oxygen into the water during darkness, and more importantly, (2) increasing nutrient levels (caused by loss of dilution) will lead to greater algal production. Data from the summers of 1967 and 1969 serve to illustrate the nutrient/dissolved oxygen conditions for the Billings-Custer area during flows of 3500-4000 cfs. In these years, nutrient levels and dissolved oxygen fluctuations were much higher than during the "wet" summer of 1976; it must also be remembered that these conditions were measured during the pre-1970 level of development period for the Yellowstone River basin. In the future, if average, late summer river flows at Custer are reduced to less than 4000 cfs because of increased demands for domestic, industrial and agricultural use, rather than as a normal dry year occurrence, the increase in algal production and the resulting dissolved oxygen fluctuations will rapidly increase to nuisance or harmful proportions, since: (1) any new water consumption for industrial use would not be returned to the river, thus eliminating this quantity for downstream dilution, (2) only a small percentage of any water for expanded agricultural operations would be returned, also reducing dilution, but even more significantly, this returned water would be laden with nutrients at concentrations much higher than were present when the water was removed, (3) any increase in consumption by human populations will lead to increases in total nutrient loads to the river, since no sewage treatment plants in the Yellowstone basin provide tertiary treatment for nutrient removal.

Although no pre-1970 data are available for the lower Yellowstone River as are available for the Billings-Custer

(middle river) area, with the 1976 field results in mind, it is very likely that even greater algae and dissolved oxygen problems existed near the Miles City station during the low-flow years of 1967 and 1969 than existed at Custer. A reduction of flow from 7000 to 4000 cfs (60 percent) for the Custer station was extremely significant, since it brought this section of the river to nearly harmful dissolved oxygen levels. If a similar percentage reduction is applied to the 1976 flow at Miles City, .60 x 10,000 cfs = 6000 cfs would have been the flow that would have been approaching critical levels for dissolved oxygen fluctuations in this section of the river. Also, since the recorded fluctuations in 1976 were more extreme at Miles City than at Custer, the potential for harmful dissolved oxygen levels would have been even higher here than in the middle portion of the river.

FLOW RECOMMENDATIONS

If domestic, industrial, or agricultural water consumption were to expand in the Yellowstone River basin, increases in nutrients would occur through lowered river flows (loss of dilution) and by the return to the river of nutrient "wastes." Algal assays have demonstrated that increases in nutrients (particularly phosphorus) could lead to exponential increases in algal biomass. Diel measurements demonstrated that increases in dissolved oxygen fluctuations can be expected with increases in this algal accumulation. The flow at which near critical dissolved oxygen fluctuations occurred at Custer was approximately 4000 cfs (measured) and at Miles City near 6000 cfs (calculated). Using the 1976 data for diel dissolved oxygen measurements and algal accumulation, it appears that the lower river has a greater potential for reaching harmful dissolved oxygen fluctuations with less reduction over the 1976 flows than does the middle river. Based on the above information, the following tentative recommendations are made for average, late summer flows (1 August through 15 September) necessary to protect the aquatic ecosystem of the Yellowstone River from harmful dissolved oxygen fluctuations:

Segment 1 - The Yellowstone River from the confluence of the Clarks Fork River to the confluence of the Bighorn River - 4500 cfs

Segment 2 - The Yellowstone River from the confluence of the Bighorn River to the North Dakota state boundary - 7000 cfs

FURTHER STUDY RECOMMENDATIONS

To further substantiate or slightly adjust the above flow recommendations, the present study should be expanded to include:

(1) More data on correlations between river flows and the resulting nutrient concentrations,

(2) Further algal assay data, using wider ranges of natural nutrient levels, and with better techniques to concentrate nutrients and other basic water quality constituents during evaporation of the test solutions,

(3) More diel dissolved oxygen measurements, covering wider ranges of summer river flows and consequently, wider ranges of algal concentrations, and

(4) More field collections of periphyton and plankton concentrations, again taken over more extreme ranges of nutrient concentrations, and also over wider ranges of river flows and temperature regimes.

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