Yellowstone

TDS

52 - 80

X ca. 70

now about 30% repeat spawning

5-6 hrs. overexploit

each cutt 5-6 X

- Regier et al 1979 pred-prey relationship,
* factors re. large, piscivorous fishes

- Wenatchee
20 lb./acre s.c. or weeks
2-5 lb/yr pred. (weeks higher production rates + contrib. invert.)

? = ? - 2-5 lb/yr

POSTAGE AND FEES PAID
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YELLOWSTONE NATIONAL PARK, WY
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PRIORITY MAIL

- Yellowstone L. Limnology

- Impacts Man - Yellowstone

Bob,

Enclosed are the papers we discussed over the phone. Additionally, Joe included 2 papers (Knight 1975 and Marrett and Knight 1973) which give additional, and more current data concerning the limnology of YSL. As I mentioned, I would scrutinize the "Trout density and limnology" section of Benson's paper with great care. When we compared areas using adjustments for differences in fishing pressure, our conclusions were quite different from his. If you ever want to go into that in detail let me know. Also if we can be of further help, don't hesitate to call. See you in June.

Sincerely,
Bob Gresswell

LIMNOLOGY OF THE WEST THUMB OF YELLOWSTONE LAKE, YELLOWSTONE NATIONAL PARK

by

Paul A. Garrett

and

Jonathan C. Knight

1973

Montana State University

Bozeman, Montana 59715

A Final Report for Contract 2-101-0387

INTRODUCTION

The purpose of this study was to determine existing and potential effects of the operation of the sewage treatment facility at Grant Village on the high quality water resource in Yellowstone Lake. This secondary treatment plant, built in 1962, has a high rate trickling filter and design capacity of 250,000 gpd. The plant operates 60 to 90 days a year at a flow of about 180,000 gpd (EPA Baseline Water Quality Report, 1971). Effluent has been discharged directly into the West Thumb area of the lake via a submerged pipe at a point about 30 meters offshore and 3 meters below the water surface. This pipe apparently is stopped up and most of the flow was observed to be entering the lake at the shore-line about 2 meters from a manhole access to the discharge pipe.

To determine the extent of effects of the sewage effluent on the lake, a limnological investigation of biological, chemical, and physical characteristics of the West Thumb was carried out from June 1972 to June 1973. Also, laboratory assays were performed on lake water to determine the potential for algal growth present in West Thumb waters with various nutrient additions.

METHODS

The scope of the investigations was necessarily limited to the West Thumb area of the lake, and the most extensive studies were made in the immediate area of the sewage outfall. Biological, chemical, and physical data were collected at a number of sampling stations, including one immediately offshore from the sewage outfall (Fig. 1) from July 2 to October 4, 1972, and on June 13, 1973. Sampling was done on a weekly basis as much as possible.

Physical-Chemical

Vertical profiles of temperature and conductivity were taken in situ at every numbered station with a Beckman RB3-3341 Solu Bridge, which has an internal conductivity correction to 25°C, and a Hydro-Products temperature probe. The depth of the euphotic zone was estimated with a Beckman EV-6 Envirometer and photocell. Secchi disc readings were taken using a white, 25 cm disc.

Surface water samples were collected for analysis at each numbered sampling station including the area 10-15 meters offshore of the effluent, Station S. In addition, samples were collected at Stations I and IV at 5 meter intervals to a depth of 30 meters, and at 10 meter intervals below that to a maximum sampling depth of 70 meters, using a 3-liter poly-vinyl chloride Van Dorn type water sampling bottle.

Immediately upon collection of water samples, a 300 ml BOD bottle was filled and fixed for Winkler dissolved oxygen determination as described in Standard Methods (APHA, 1971). One thousand milliliters of water was filtered through a Gelman type A glass fiber filter and 300 ml saved in acid-washed glass reagent bottles for chemical analysis. The filter was dissolved with 10 ml of 90% acetone in a darkened centrifuge tube for chlorophyll "a" determinations. A 250 ml glass reagent bottle was filled with unfiltered water for alkalinity and chloride determinations.

Concentrations of Na, K, Mg, and Ca were determined by atomic absorption-emmission spectroscopy using a Beckman DU flame spectrophotometer and Beckman atomic absorption unit. Alkalinity and chloride were determined titrimetrically as described in Standard Methods (APHA, 1971). Sulfate was determined turbidimetrically as described in Standard Methods (APHA, 1971). pH was measured in the field using an Orion expanded scale pH meter. Free carbon dioxide was estimated by calculation involving pH, total alkalinity and temperature, using the equations of Rainwater and Thatcher (1960).

Concentrations of N and P species were determined colorimetrically with a Bausch and Lomb Spectronic 20 spectrophotometer using the following tests: NH_3-N, phenolhypochlorite method of Solorzano (1969); NO_3-N, reduction method of Mullin and Riley (in Barnes, 1962); NO_2-N, Hach Chemical Co. reagents and procedures; O-PO_4, combined reagent method in Parsons and Strickland (1972).

Movement of the sewage effluent in the immediate outfall area was visually observed by adding 30-50 ml of Rhodamine-B fluorescent dye to the effluent at the shoreline manhole. Three trials were run under varying wind conditions, and movement of the dye was plotted as to direction and distance covered per unit time, giving an estimate of the rate of sewage dispersal. Sewage dispersal and dilution was also estimated by determinations of nitrate and phosphate in a grid pattern around the sewage outfall. The grid was laid out with floats and anchors extending 100 meters east and west of the point source sewage effluent and 35 meters offshore. Surface water samples were collected at points on the grid, and phosphate and nitrate concentrations determined in the field using Hach Chemical Co. reagents and a portable Delta Scientific Corp. spectrophotometer.

Surface planktonic algal standing crop estimations were made by measuring extracted chlorophyll "a" as described by Parsons and Strickland (1972) using a Beckman DU spectrophotometer at all numbered stations and immediately off the effluent (Station S). In addition, chlorophyll "a" determinations were made at depths of 5, 10, 15, and 20 meters at Stations I and IV to define distribution of phytoplankton in the euphotic zone.

Diatometers, as described in Standard Methods (APHA, 1971), were set out at Stations W, S, and B at depths of 2, 4, and 6 meters (Fig. 1). Locations were selected for similarity of bottom type. Daily accrual of benthic algal chlorophyll "a" on glass slides was estimated at 2, 3, and 4 week intervals by the trichromatic chlorophyll "a" method of Parsons and Strickland (1971) with a Beckman DU spectrophotometer.

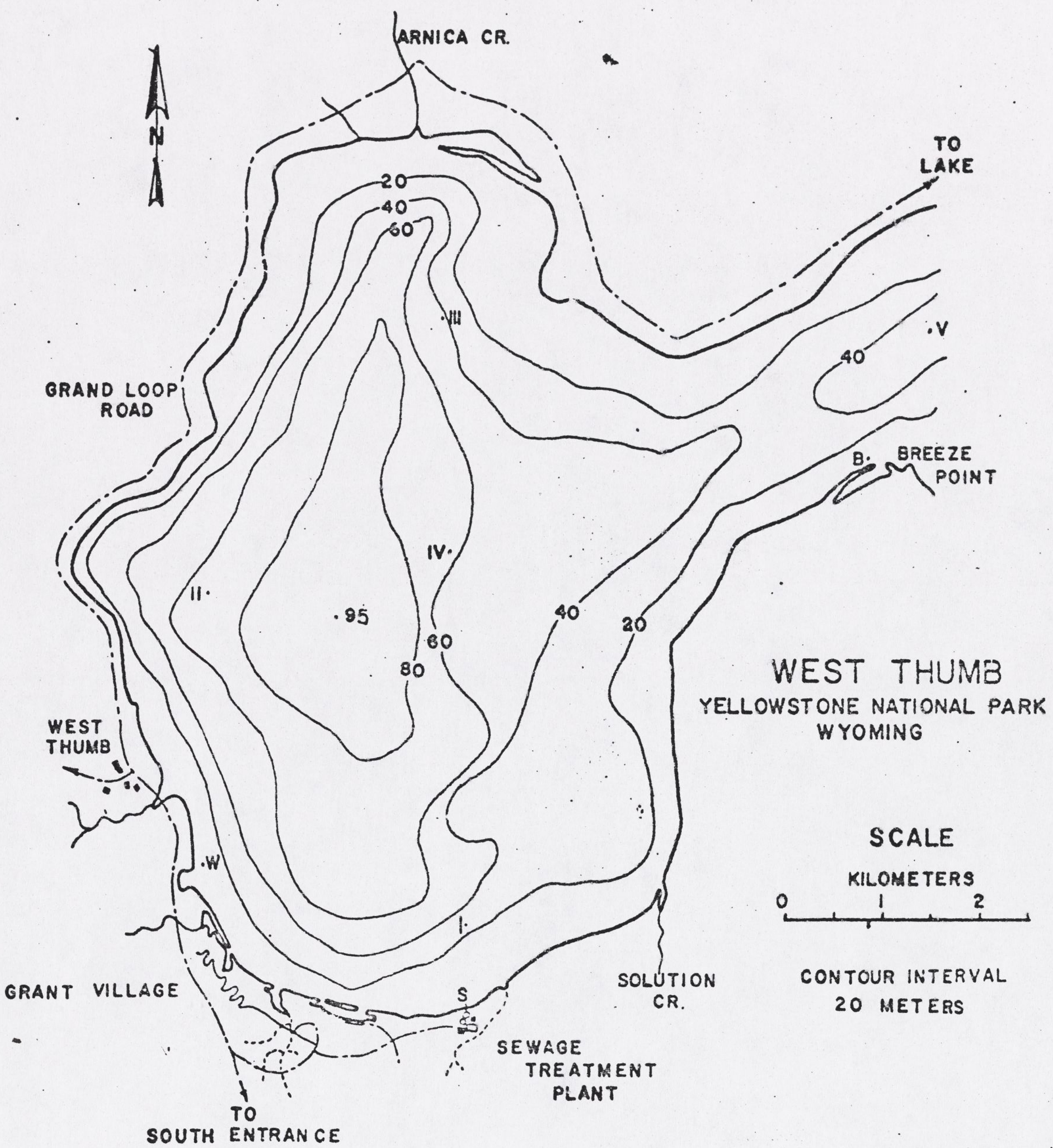
Zooplankton samples were collected at Stations I, II, IV, and V. Oblique tows from a depth of 20 meters to the surface were made using a Clark-Bumpus plankton sampler with a number 20 net. At Station S, near the sewage outfall, a horizontal tow at a depth of one meter was made. Zooplankters were counted and identified in the laboratory using a circular counting chamber, Sedgewick-Rafter cell, and dissecting and compound microscopes. Successive one or two ml aliquots were taken from each sample until 200-300 organisms had been counted.

Benthos samples were collected on 8 July and 8 August, 1972, with an Ekman dredge. Stations S and W (Fig. 1) were sampled in a grid pattern at depths of 1 to 7 meters. Samples were preserved in the field in quart French square jars with 10% formalin and separated in the laboratory by hand. Samples were washed on a number 30 seive before counting. Macroinvertebrates were either counted or their relative abundance estimated. Macrophytes were ranked by taxa according to visual prominence. Standing crop of biomass was determined by drying the entire sample at 105°C for 24 hours and weighing on an analytical balance.

Laboratory algal assays were carried out on lake water collected near the sewage outfall. Procedures given in the Provisional Algal Assay Procedure Bottle Test (Joint Industry/Government Task Force on Eutrophication, 1969) were followed. Subsamples were taken and spiked with varying amounts of phosphorous and/or nitrogen to determine the limiting nutrient in West Thumb water. Each treatment was run in triplicate. Subsamples were inoculated with an initial concentration of 1×10^3 cells per ml of <u>Selenastrum capricornutum</u> and incubated at 24 ± 0.05°C under an illumination of approximately 300 foot candles. Growth rate and standing crop determinations were made from count data obtained on a Model B Coulter Counter with a 100 mu aperature.

✓

FIGURE 1


ARNICA CR.
N
TO LAKE
20
40
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III
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GRAND LOOP ROAD
B.
BREEZE POINT
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WEST THUMB
W
I
S
GRANT VILLAGE
SOLUTION CR.
SEWAGE TREATMENT PLANT
TO SOUTH ENTRANCE
WEST THUMB
YELLOWSTONE NATIONAL PARK
WYOMING
SCALE
KILOMETERS
0
1
2
CONTOUR INTERVAL
20 METERS

RESULTS AND DISCUSSION

Temperature and Conductivity

Temperature and conductivity profiles are summarized in Table 1. The period of thermal stratification lasted a maximum of forty days, from about 20 July to 30 August. During this period, the maximum depth of the metalimnion (defined as the region of maximum temperature change with increase in depth) was between 15 and 20 meters, at Station IV on 25 August. On this date, the metalimnion was at a depth of 10 to 12 meters at Station II, indicating an upward tilting of the thermocline from east to west. The maximum surface temperature observed was 16.9^{o}C on 25 August. Temperatures in deeper water strata during stratifications remained near 6^{o}C. The strong, prevailing westerly winds of this region were sufficient to break up stratification by 7 September and full circulation was occurring on 24 September, with all water strata near 6^{o}C.

Weekly temperature and conductivity profiles at all stations show an irregular pattern of temperature and conductivity isoclines, probably due to the movement of internal seiches (Hutchinson, 1957). To minimize the distortion of the data caused by seiche movements, and to determine a general current pattern in West Thumb, average temperature and conductivity isoclines during summer stratification have been plotted in Fig. 2. The plots represent line transects in east-west (Stations II, IV, V) and north-south (Stations I, IV, III) orientations. Analysis of these plots indicates a general current pattern in agreement with theoretical considerations of Hutchinson (1957) and that postulated for the West Thumb area by Benson(1961). Warm, less dense, surface water tends to pile up in the central and east sections of West Thumb, with cold, denser water from deep strata being pushed up along the north, west, and southern shorelines. Circulation of deep strata appears to be in a clockwise direction, with a west-to-east, wind-driven, surface current which moves a large volume of water out of the neck of West Thumb. The downward inclination of isoclines from Station V to IV indicates a movement of hypolimnetic water into West Thumb from the main body of the lake.

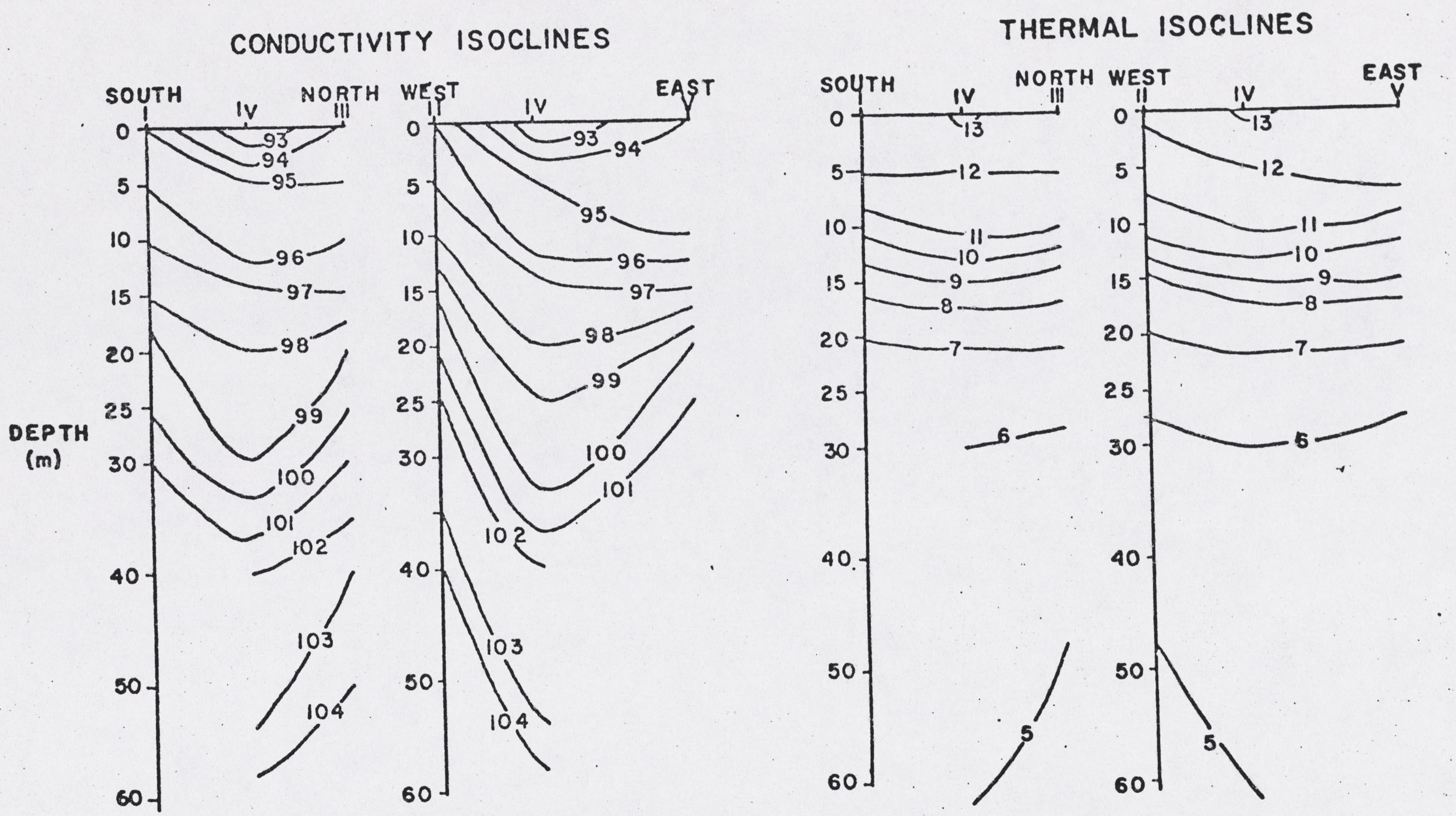
Light

The depth of the euphotic zone (defined as the depth at which 1% of the incident surface light is still present) remained near 20 meters throughout the summer, including the period during which the *Anabaena* pulse occurred.

TABLE 1. Temperature (°C) and conductivity (corrected to 25°C) values for selected dates at Stations I, II, and IV.

STATION	DEPTH (m)	20 July 72 T	3 Aug 72 T	3 Aug 72 C	25 Aug 72 T	25 Aug 72 C	24 Sept 72 T	24 Sept 72 C
I	0	10	15.3	99	14.8	97	6.5	97
	5	10	14.9	99	14.5	98	6.6	98
	10	9.8	12.0	102	14.5	97	6.6	101
	15	9.5	8.0	105	8.9	105	6.5	101
	20	6.5	6.5	106	7.1	104	6.5	101
	25	6.8	6.0	106	6.6	106	5.8	101
	30	---	5.9	---	6.5	107	5.8	101
II	0	9.8	13.0	97	16.8	95	6.0	---
	5	9.8	12.3	100	14.7	95	6.5	---
	10	9.1	11.5	100	14.2	96	6.5	---
	15	8.7	8.7	100	9.0	100	6.3	---
	20	7.5	7.2	100	8.0	101	6.2	---
	30	6.8	5.4	102	5.4	102	6.2	---
	40	6.1	4.9	103	4.9	104	5.8	---
	50	5.7	4.5	104	---	---	5.3	---
IV	0	10.8	13.0	98	14.7	93	6.9	101
	5	10.8	12.0	98	14.3	96	6.9	101
	10	10.7	10.0	98	14.0	96	6.5	101
	15	9.9	7.2	100	13.5	99	6.3	101
	20	8.1	6.7	102	6.8	102	6.2	101
	30	6.8	5.4	103	5.7	103	6.2	101
	40	6.4	4.7	104	5.2	104	5.8	101
	50	4.9	4.7	105	4.8	105	5.3	101

FIGURE 2


CONDUCTIVITY ISOCLINES
THERMAL ISOCLINES
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NORTH
WEST
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II
III
IV
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DEPTH (m)
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The average secchi disc depth was 8 meters, which agrees with values obtained by Benson (1961).

General Chemistry

Table 2 shows the ranges and means of concentrations of chemical constituents in lake and effluent water samples taken during the period of thermal stratification. Values for the epilimnion (0 to 20 m) and hypolimnion (20 m to maximum sampling depth) are averaged over both depth and time.

Both lake water and sewage effluent showed chemical characteristics of waters originating in rhyolite drainages (Roeder, 1966; Martin, 1967). The water is basically a sodium bicarbonate type with low concentrations of divalent cations (Ca, Mg). The sewage effluent is not significantly enriched with divalent cations, thus alteration of the ratio of monovalent:divalent cations would not have occurred. Table 2 also indicates that the effluent has no detectable effect on chemical characteristics of water in the immediate vicinity of the effluent. In spite of the pronounced differences between chemistry of lake water from Station I and the effluent, the ratio of chemical concentrations of similar species in water near the effluent to those in lake water approaches one (Table 3). It is apparent that the dilution rate of the effluent is very high.

Fig. 3 shows profiles for dissolved oxygen during the period of thermal stratification. The minimum relative saturation value (as defined by Hutchinson, 1957) of 85% was obtained on 17 August at 50 m. On 25 August, at maximum stratification, the relative saturation at 50 m was 90%. The generalized oxygen curve is orthograde in nature, and typical of unproductive, temperate lakes (Hutchinson, 1957).

Nitrogen and Phosphorus

Results of chemical analysis of nutrients (nitrogen and phosphorus) are shown in Table 4. Ortho-phosphorus (PO_4-P) increased slightly in the epilimnion during the sampling period, while nitrate (NO_3-N) concentrations rapidly approached 0.000 mg/l subsequent to spring overturn. Ammonia nitrogen (NH_3-N) increased in epilimnetic waters from July to August. The ratio of PO_4-P : (NH_3 + NO_3)-N in surface waters is considerably in excess of the critical 1:16 requirement discussed by Parsons and Strickland (1960), indicating that phosphorous is present in excess of that required for the utilization of the nitrogen resource by the natural plankton population.

TABLE 2. Means and ranges of chemical data (mg/l) obtained during summer stratification.

	I 0-15 m	I 15-bottom	II surface	III surface	IV 0-15 m	IV 15-bottom	V surface	10-15 m off sewage	Sewage Effluent
O_2									
mean	9.07	8.70	8.64	8.12	8.61	8.75	8.63	8.42	5.53
max.	12.8	9.44	9.74	8.92	8.96	9.58	9.27	10.57	5.53
min.	7.91	8.36	7.93	7.67	7.65	8.00	7.65	7.93	5.53
pH									
mean	7.09	6.79	6.54	6.89	6.84	6.65	6.73	7.03	6.81
max.	7.59	7.30	7.80	8.2	7.45	7.55	7.4	7.21	7.05
min.	6.57	6.49	6.6	6.65	6.3	6.1	6.3	6.96	6.56
CO_2									
mean	4.7	10.1	17.3	7.5	8.13	13.2	10.6	5.5	45.8
max.	15.7	17.9	56.7	13.0	26.7	15.4	25.7	6.16	39.5
min.	1.7	2.8	0.9	0.4	2.0	1.7	2.3	3.6	33.0
Cond									
mean	98	105	99	95	95	102	95	92	600
max.	109	110	103	100	109	108	99	110	940
min.	75	67	91	91	71	90	92	74	490
Na									
mean	10.0	10.7	9.8	9.6	9.6	10.2	9.2	9.3	54.9
max.	11.0	12.9	10.1	9.9	11.7	11.6	9.2	10.7	80.5
min.	8.4	8.7	9.0	9.2	8.1	9.0	9.2	8.2	29.3
K									
mean	1.5	1.6	1.7	1.5	1.4	1.6	1.6	1.5	12.8
max.	2.4	4.2	2.2	2.0	2.2	2.2	1.8	1.8	24.2
min.	1.1	1.0	1.3	1.2	1.3	1.3	1.3	1.3	7.8

TABLE 2. (continued)

	I 0-15 m	I 15-bottom	II surface	III surface	IV 0-15 m	IV 15-bottom	V surface	10-15 m off sewage	Sewage Effluent
Ca									
mean	0.5	0.6	0.6	0.9	0.8	0.6	0.8	0.5	2.2
max.	1.0	1.0	1.1	1.1	1.1	1.2	1.0	0.6	4.7
min.	0.3	0.3	0.3	0.7	0.1	0.3	0.4	0.4	0.6
Mg									
mean	1.5	1.6	1.6	1.8	1.6	1.7	1.6	1.4	3.3
max.	2.0	2.1	2.0	1.8	2.3	2.8	1.9	2.3	4.0
min.	0.9	0.6	1.0	1.8	0.4	1.0	1.5	1.1	2.4
HCO_3									
mean	36.6	39.1	37.8	36.6	35.4	37.2	36.0	37.2	186.0
max.	39.7	40.9	44.5	39.1	42.7	44.5	37.2	36.6	233.1
min.	26.2	34.8	35.4	33.6	24.4	31.1	32.3	35.4	90.3
SO_4									
mean	5.8	5.8	6.0	5.7	5.5	5.5	8.1	5.3	33
max.	8.9	7.9	7.8	7.9	9.3	9.9	9.3	6.7	43.5
min.	2.7	2.3	4.0	3.4	3.1	2.3	6.5	2.5	180
Cl									
mean	5.7	5.6	5.3	5.2	5.3	5.5	5.3	5.4	55
max.	7.7	6.9	6.5	6.1	6.9	6.9	5.9	6.3	70.1
min.	4.2	4.4	3.7	4.2	3.8	3.9	4.4	4.9	19.9
OPO_4-P									
mean	0.015	0.020	0.014	0.010	0.018	0.022	0.015	0.017	6.4
max.	0.028	0.029	0.035	0.013	0.046	0.106	0.033	0.028	8.5
min.	0.006	0.007	0.003	0.004	0.006	0.008	0.009	0.012	0.47

TABLE 2. (continued)

	I 0-15 m	I 15-bottom	II surface	III surface	IV 0-15 m	IV 15-bottom	V surface	10-15 m off sewage	Sewage Effluent
NO_3-N									
mean	0.006	0.014	0.002	0.0	0.004	0.021	0.0	0.004	2.12
max.	0.029	0.034	0.018	0.0	0.022	0.047	0.001	0.017	2.9
min.	0.0	0.001	0.0	0.0	0.0	0.0	0.0	0.0	1.3
NH_4-N									
mean	0.011	0.012	0.004	0.005	0.006	0.012	0.014	0.019	45.3
max.	0.32	0.40	0.017	0.014	0.027	0.032	0.025	0.061	84.4
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	25.7
NO_2-N									
mean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.18
max.	0.0	0.015	0.0	0.0	0.001	0.0	0.0	0.0	0.27
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.04

TABLE 3. Ratios of chemical concentrations of the sewage effluent, Station S, and Station I

	meq/meq Sewage/off sew	meq/meq off sew/ave lake	meq/meq off sew/Sta I
O_2	0.66	0.98	0.93
pH	1.66	0.56	1.14
CO_2	8.33	0.57	1.17
Cond	6.52	0.95	0.94
Na	5.93	0.96	0.94
K	8.86	0.95	1.00
Ca	3.73	0.70	1.00
Mg	2.32	0.87	0.93
HCO_3	4.98	1.02	1.02
SO_4	6.27	0.85	0.91
Cl	10.13	1.01	0.95
PO_4	376.5	1.18	1.13
NO_3	530.0	1.67	0.67
NO_2	----	----	----
NH_3	2380	2.37	1.73

FIGURE 3

Dissolved Oxygen Concentration (mg/l) Profiles
During Summer Stratification, West Thumb, 1972

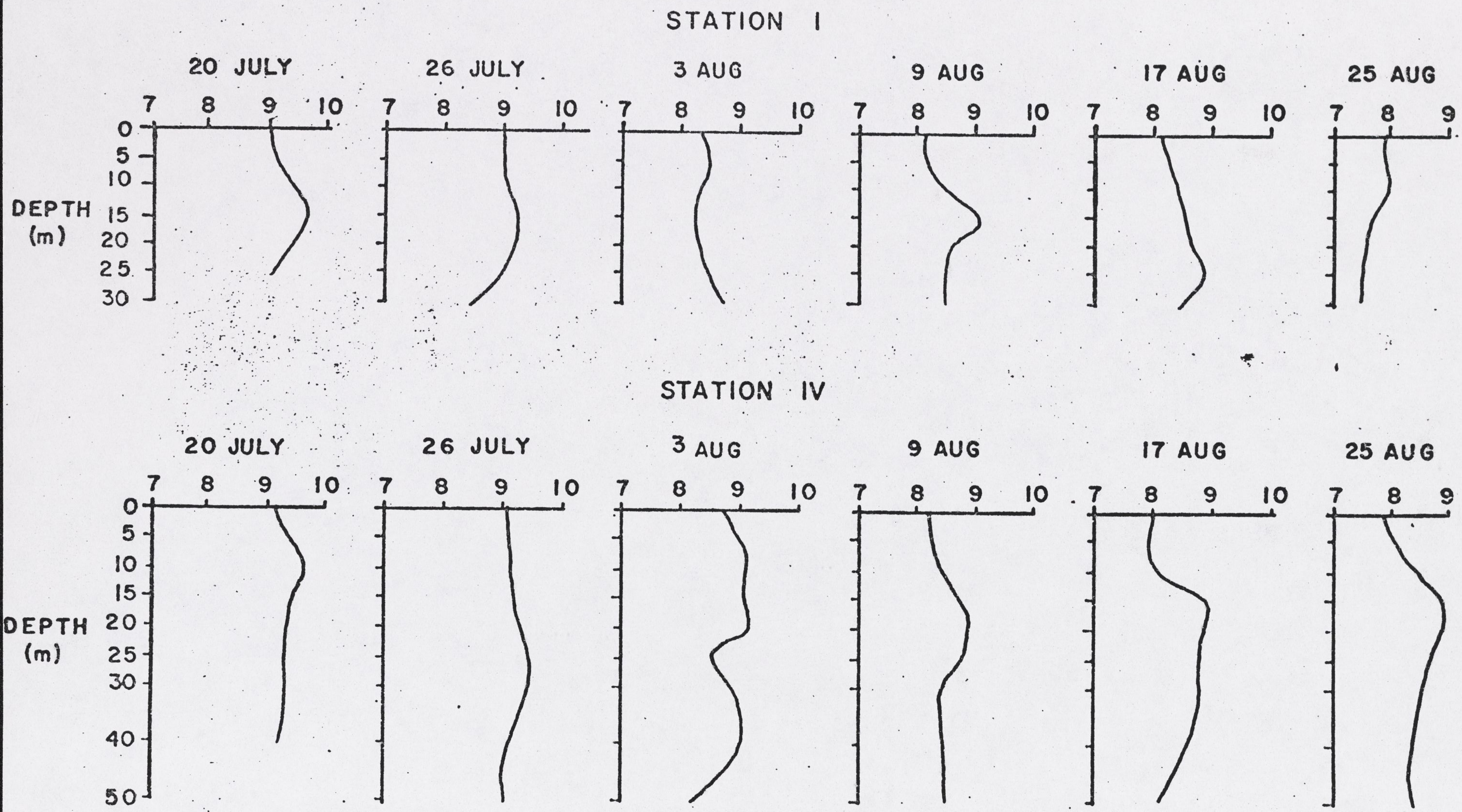


TABLE 4. Profiles of concentrations of PO_4-P, NO_3-N, NH_3-N in $mg \cdot m^{-3}$. Values are averaged for all samples taken at that depth. Values for 40m and below are for single samples at Station IV.

DATE	Depth (m)	PO_4-P	NO_3-N	NH_3-N
14 June	0	17	0	0
	5	13	0	0
	10	13	0	10
	15	19	0	0
	20	22	6	0
	30	20	6	0
	40	20	12	0
	50	26	18	0
	60	24	22	0
	70	18	29	22
12 July	0	10	1	2
	5	11	2	0
	10	11	3	0
	15	16	2	2
	20	14	4	3
	30	17	8	27
	40	21	5	18
	50	21	8	10
26 July	0	11	0	0
	5	22	0	10
	10	22	0	1
	15	29	4	5
	20	17	3	8
	30	29	6	16
	40	20	17	--
	50	--	28	16
9 Aug	0	14	1	14
	5	14	1	15
	10	14	1	14
	15	17	3	8
	20	20	6	17
	30	24	28	15
	40	24	32	7
	50	25	36	18
25 Aug	0	29	0	5
	5	22	1	12
	10	27	2	9
	15	34	2	17
	10	23	8	19
	30	28	31	16
	40	33	33	32
	50	28	38	32
29 Sep	0	28	18	4
	5	22	21	2
	10	21	16	2
	15	21	--	3
	20	19	22	0
	30	21	25	0
	40	25	32	0
	50	26	37	3
	60	26	39	--
	70	22	23	--

Fig. 4 shows the actual mean concentrations of NO_3-N, NH_3-N, total inorganic N (NO_3 + NH_3), and PO_4-P in the epilimnion and hypolimnion. These were calculated based on volumes determined for 20 meter intervals on the morphometric map of Benson (1961). For consideration of the nutrient balance, the epilimnion is defined to coincide with the euphotic zone and the 20 meter countour line of Benson (1961). The hypolimnion includes all water strata below 20 meters.

NH_3-N and NO_3-N increased in the hypolimnion throughout the summer. PO_4-P increased irregularly in the hypolimnion, but did not decrease in the epilimnion.

Estimates of the total amount of NH_3-N, NO_3-N, and PO_4-P were calculated for different water strata in West Thumb (Table 5). There was a net gain in total, inorganic N (NH_3 + NO_3) of about 27,000 kilograms from 26 July to 25 August, compared to a maximum calculated annual input from the sewage plant of 3500 kilograms (based on 90 days operation at 180,000 gpd; EPA, 1971). When compared to the maximum "standing crop" of total inorganic nitrogen of 66,300 kg (25 August), the maximum annual sewage input assumes an even smaller order of magnitude. The maximum "standing crop" of PO_4-P was 55,700 kg, compared to a maximum annual input of 949 kg from the sewage plant. The maximum weekly change in PO_4-P amounted to 28,500 kg (from 17-25 August), 30 times the maximum annual input of phosphorus from the sewage.

If the total amount of N and P in West Thumb Waters and the weekly changes in these values are compared to the input of N and P from sewage, it is apparent that the rate of nutrient loading has been very low. Especially in view of current patterns in West Thumb, which continually remove surface water into which the sewage disperses.

Phytoplankton

Chlorophyll "a" has been proven a rapid and reliable index to standing crop of phytoplankton (Parsons and Strickland, 1960). Chlorophyll "a" concentrations were determined at Stations I - V and at Station S. The results are summarized in Table 6, which shows chlorophyll "a" concentrations for 13 June, 1973, a date on which sewage was not entering the lake, and an average for the sampling period 12 July to 7 September, 1972. Chlorophyll "a" concentrations obatined were very low, as compared to eutrophic lakes such as Lake Washington, which may obtain 20-25 µg Chl_a/liter (Edmondson, 1959). The maximum value obtained for a single sample was 20.4 µg/l, on the surface at Station IV, 25 August. This was during the Anabaena pulse. However, the

FIGURE 4

Actual Mean Nutrient Concentrations (mg/m^3), West Thumb, 1972

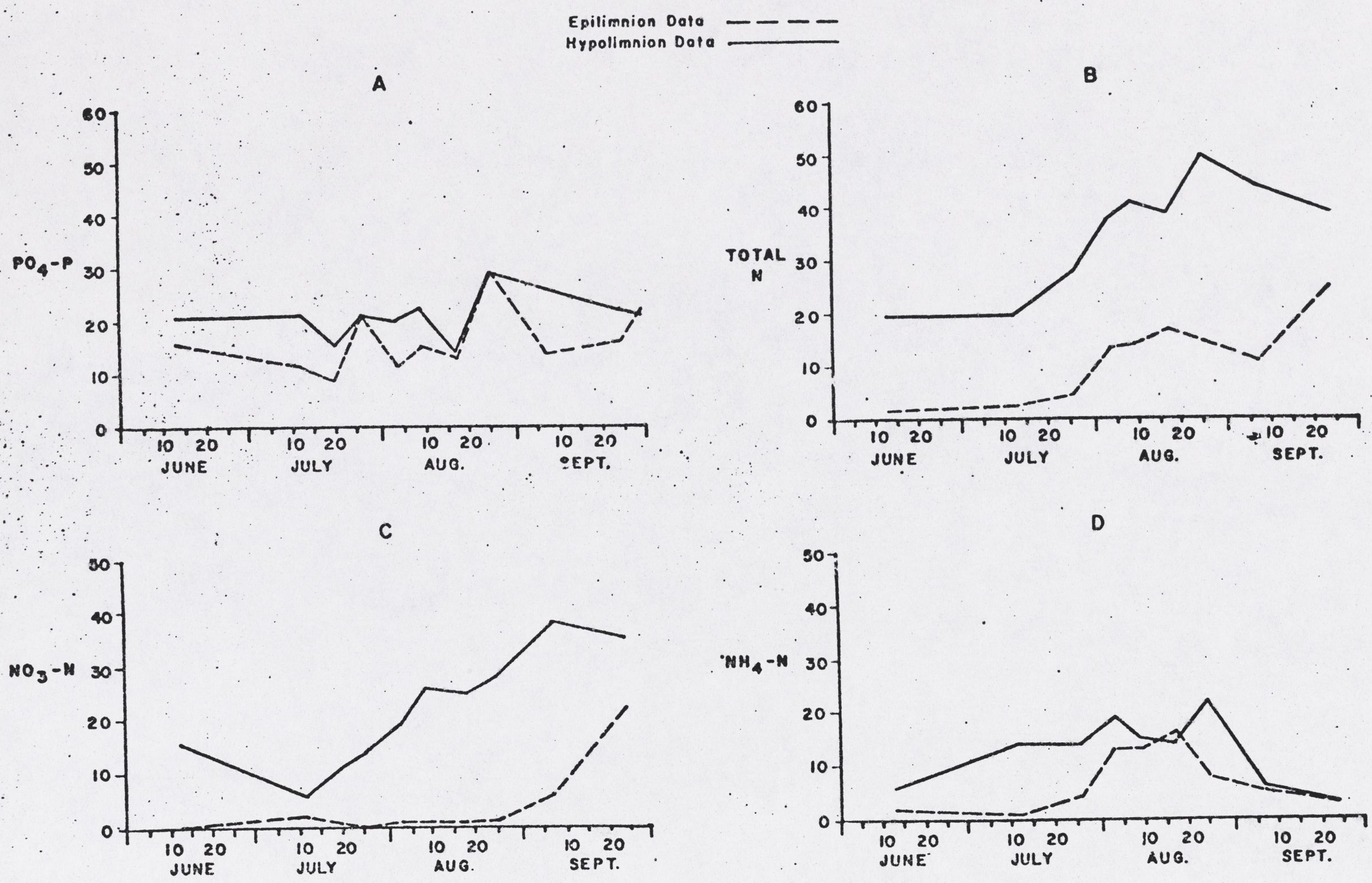


TABLE 5. Total amounts of PO_4-P, NO_3-N, and NH_3-N as 10^2 kg, estimated from chemical profiles (Part of which are presented in Table 4) and volumes calculated from a morphometric map in Benson (1961).

	PO_4-P			NO_3-N			NH_3-N			$(NH_3 + NO_3)$-N		
DATE	E	H	Σ	E	H	Σ	E	H	Σ	E	H	Σ
Jul 7	54	161	214	---	---	---	---	---	---	---	---	---
12	121	250	371	16	76	92	8	164	172	24	240	264
20	72	185	257	16	137	153	---	---	---	---	---	---
25	169	262	431	8	171	179	32	166	148	40	337	377
Aug 3	96	244	340	0	222	222	104	224	328	104	446	550
9	120	276	396	8	307	315	104	179	283	112	486	599
18	104	167	271	8	295	303	129	172	301	137	467	603
25	225	332	557	8	331	339	64	260	324	72	591	664
Sep 7	113	303	416	48	448	496	40	66	106	88	514	602
24	129	259	388	177	415	592	24	32	56	201	446	647
29	184	268	452	145	345	490	---	---	---	---	---	---
Jun 13	129	255	384	0	149	149	16	72	88	16	221	237

next highest value was 8.4 μg/l, at Station V on 7 July. The average chlorophyll "a" concentration in the euphotic zone on 25 August was 3.2 μg/l.

During thermal stratification when current patterns are effected by the epilimnion, chlorophyll "a" concentrations are higher at Stations IV and V. This would be expected if surface water were piling up on the eastern side of West Thumb. Comparisons of values for Station S (near the effluent) to those obtained for other stations reveals no apparent differences. However, slightly higher values at Station S could be due to the littoral nature of the stations itself, rather than any effect by the sewage.

Concentrations of nutrients and phytoplankton chlorophyll "a" values have been plotted against time in Fig. 5. Phytoplankton standing crops were high in June and continually decreased through the summer. The only substantial increase in phytoplankton standing crop was on 25 August at the height of the pulse of Anabaena flos-aquae, also observed by Benson (1961).

During the entire summer, phosphate concentrations in the epilimnion and hypolimnion remained fairly constant with little difference in concentrations between the two strata of water, indicating that the phytoplankton had little effect on phosphate concentrations.

However, nitrogen values steadily increased in both the hypolimnion and epilimnion throughout the summer with substantial differences between the two layers. This indicates nitrogen is effected by the phytoplankton. Increase of nitrogen in the hypolimnion was probably due to the aerobic decomposition of settled phytoplankton removed from the epilimnion. Nitrogen concentrations remained depleted in the epilimnion until 26 July, where ammonia nitrogen (see Fig. 4) was being accumulated in the epilimnion. Since very little diffusion occurs through the metalimnion, the increase in ammonia nitrogen in the epilimnion was probably due to two factors. First, aerobic decomposition of unsettled phytoplankton in the epilimnion was undoubtedly occurring. Second, at the time of ammonia nitrogen increase, Anabaena flos-aquae was also increasing. Anabaena flos-aquae is a known nitrogen fixer, converting gaseous nitrogen to inorganic, ionic nitrogen (PAAP, Joint Industry/Government Task Force on Eutrophication, 1969). Thus Anabaena is capable of growing in nitrogen deficient waters, whereas other nitrogen-dependent algae are unable to sustain a steady growth rate, and therefore decline.

After stratification ended, 30 August, the phytoplankton standing crop again increased when nutrients, particularly nitrogen, became available in the euphotic zone.

TABLE 6. Average surface chlorophyll "a" concentration (µg/l).

	mg Chl_a 14 June 1973	mg Chl_a (mean) (12 July-7 Sep, 1972)	Range
10 - 15 off sewage effluent	2.3	2.3	1.09 - 5.50
Station I	2.1	1.5	0.8 - 1.9
Station II	1.2	1.6	0.9 - 4.0
Station III	---	1.0	1.0 - 1.3
Station IV	1.5	3.4	0.6 - 20.4
Station V	---	2.3	0.7 - 8.4

1.96

2.017 mg/l

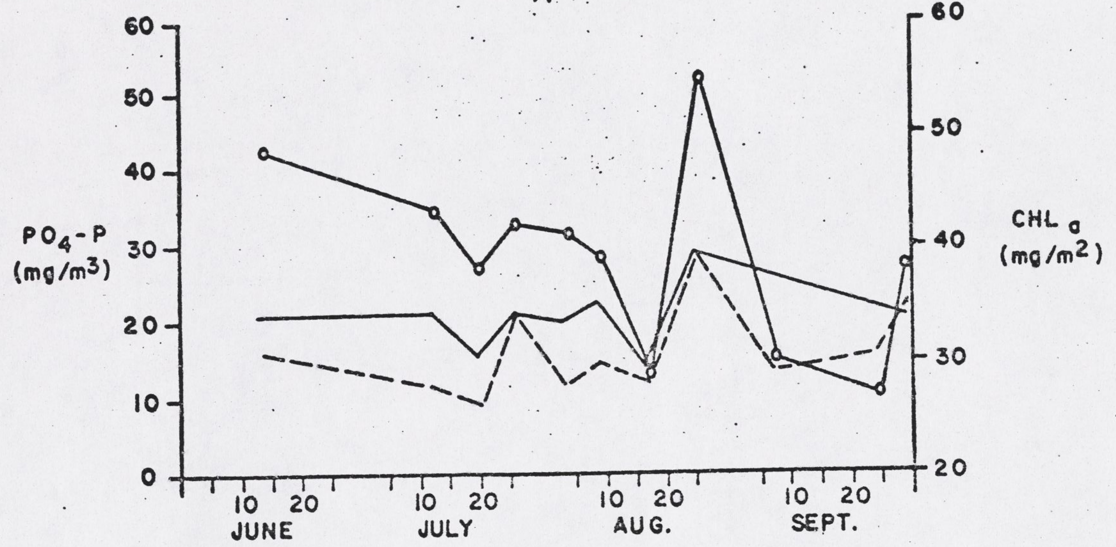
= 2.0 mg/m^3

FIGURE 5

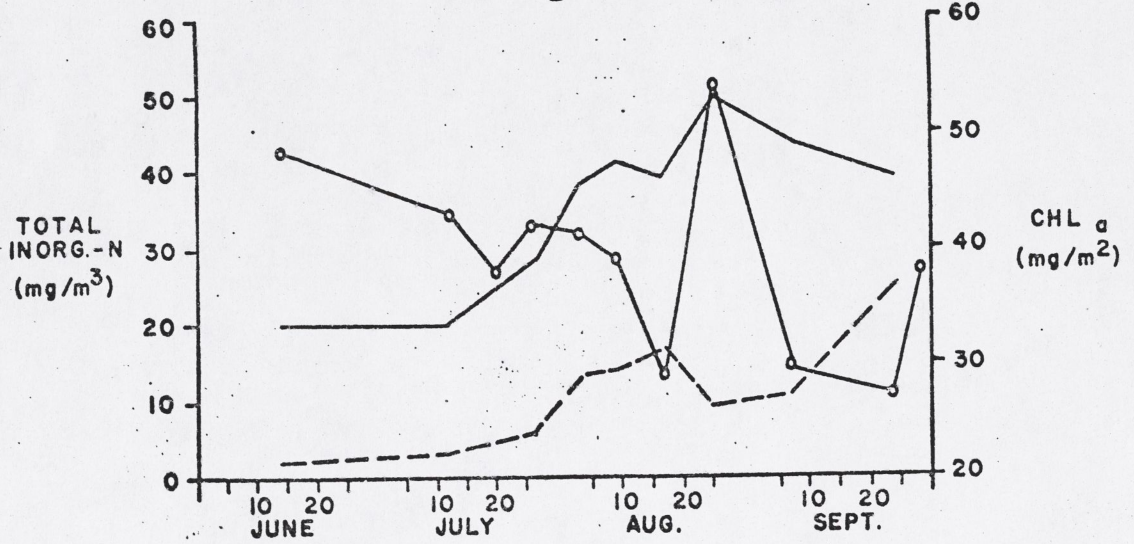
Seasonal Chlorophyll$_a$ and Nutrient Concentrations, West Thumb, 1972

Epilimnion Nutrient Data
Hypolimnion Nutrient Data
Chlorophyll$_a$ Data

A



B



Zooplankton

The species composition of the zooplankton fauna was substantially the same as that described by Benson (1961). Diaptomus shoshone and Diaptomus minutus were still the dominant copepods, although some Cyclops were also found. D. minutus appeared to comprise 50% of copopodite and nauplius numbers, whereas Benson (1961) reported that D. shoshone composed over 90% of copepods and nauplii taken. Daphnia schoedleri was the only clacoceran and was present only in small numbers in oblique tows at offshore stations. Daphnia were observed swarming in the littoral areas, but samples were not analyzed. Conochilus unicornis accounted for over 99% of the rotifers collected, other genera being Keratella, Kellicottia, and Notholca.

Density and seasonal distribution of zooplankters are shown in Figures 6 through 9. Copepodite and nauplius numbers include Diaptomus sp., Daphnia, and Cyclops. The general trend in numbers of copepodites and nauplii seems to be an early summer peak followed by a gradual decline through early August, with a late August-early September increase (Fig. 9). The late summer increase in probably due to recruitment of D. minutus nauplii, as gravid females of this species were observed in samples throughout the summer. Gravid D. shoshone females were observed only in samples taken during September.

Rotifers did not appear in zooplankton samples before 12 July or after 7 September. Numbers reached a first peak about 3 August, declined slightly, then increased to a maximum density of 268/1 (average) on 25 August.

The distribution of organisms between stations (Fig. 6 through 8) indicates the same current patterns during summer as shown by physical data. Stations V and IV have the highest densities of nauplii, Stations V, I, and IV the highest densities of rotifers, on 2 August, indicating a concentration of organisms in these areas. Station II, an area of upwelling, had lowest densities of these organisms, but had the highest densities of copepodites on 7 September.

Periphyton

Table 7 shows the µg chlorophyll "a" accumulated per square meter per day. These units were used since the slides were incubated for various time periods. It is difficult by observing Table 7 to discern a difference at particular locations or depths. Therefore, Table 8 shows the p-values of the paired observations obtained using Student's-t test (Snedecor and Cochran, 1967). This procedure indicated no significant difference between any of the locations. Also, Table 9a and 9b show no statistical difference in the periphyton chlorophyll "a" accum-

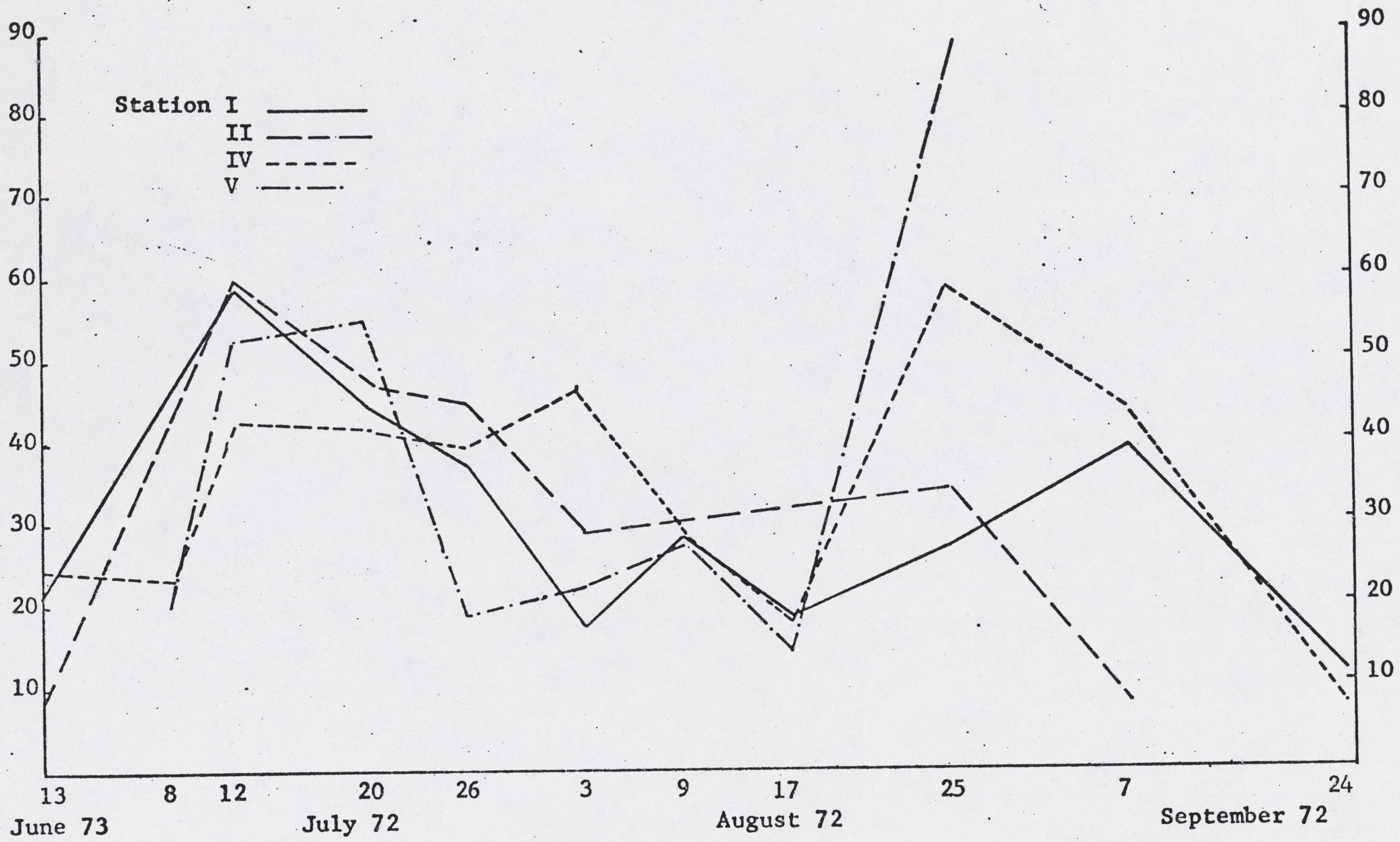


FIGURE 6. Seasonal concentration of copepod nauplii as organisms/l (ordinate) in the euphotic zone (0-20m) at Stations I, II, IV, and V.

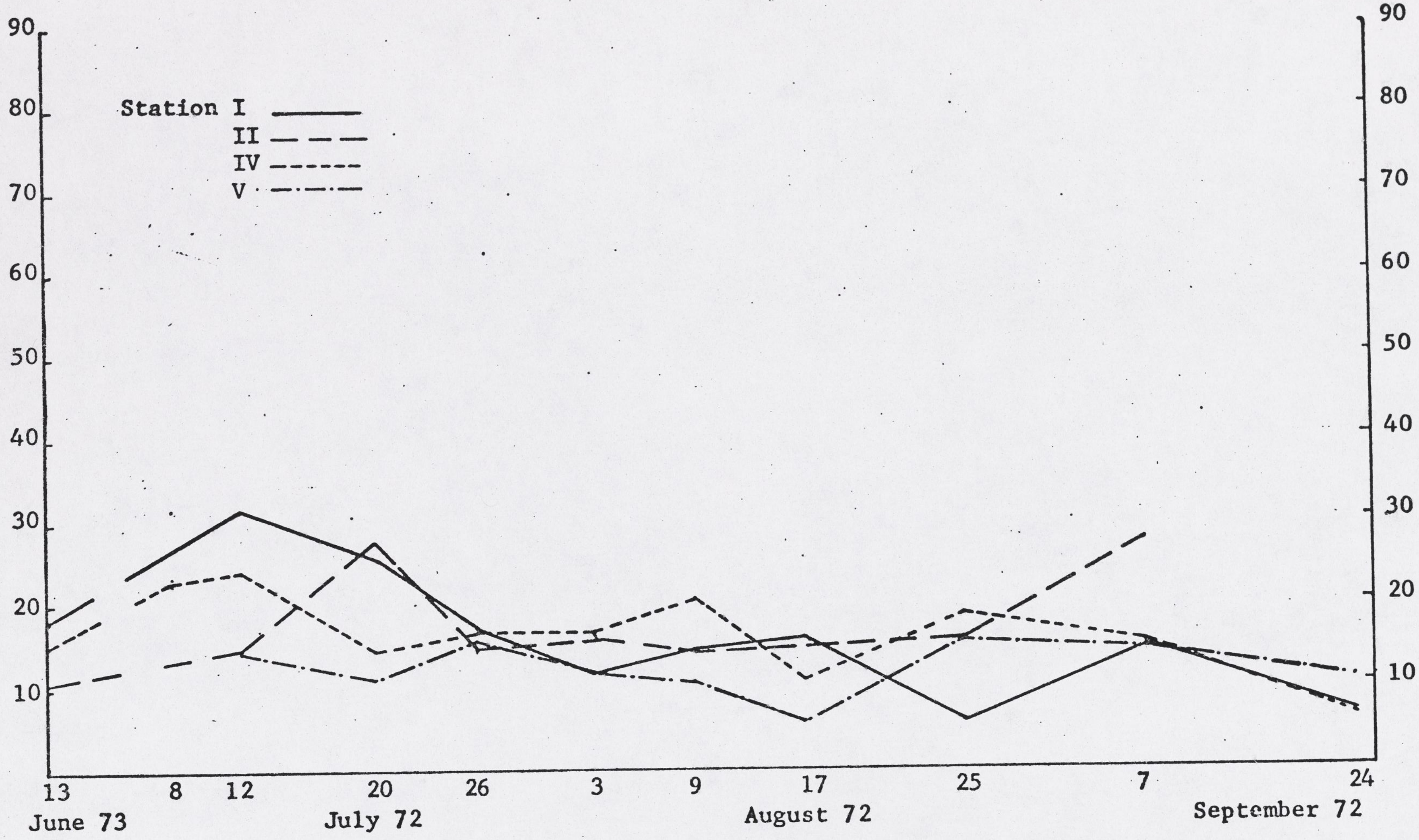


FIGURE 7. Seasonal concentration of copepod copepodites (including Cyclops and Daphnia) as organisms/l (ordinate) in the euphotic zone (0-20m) at Stations I, II, IV, and V.

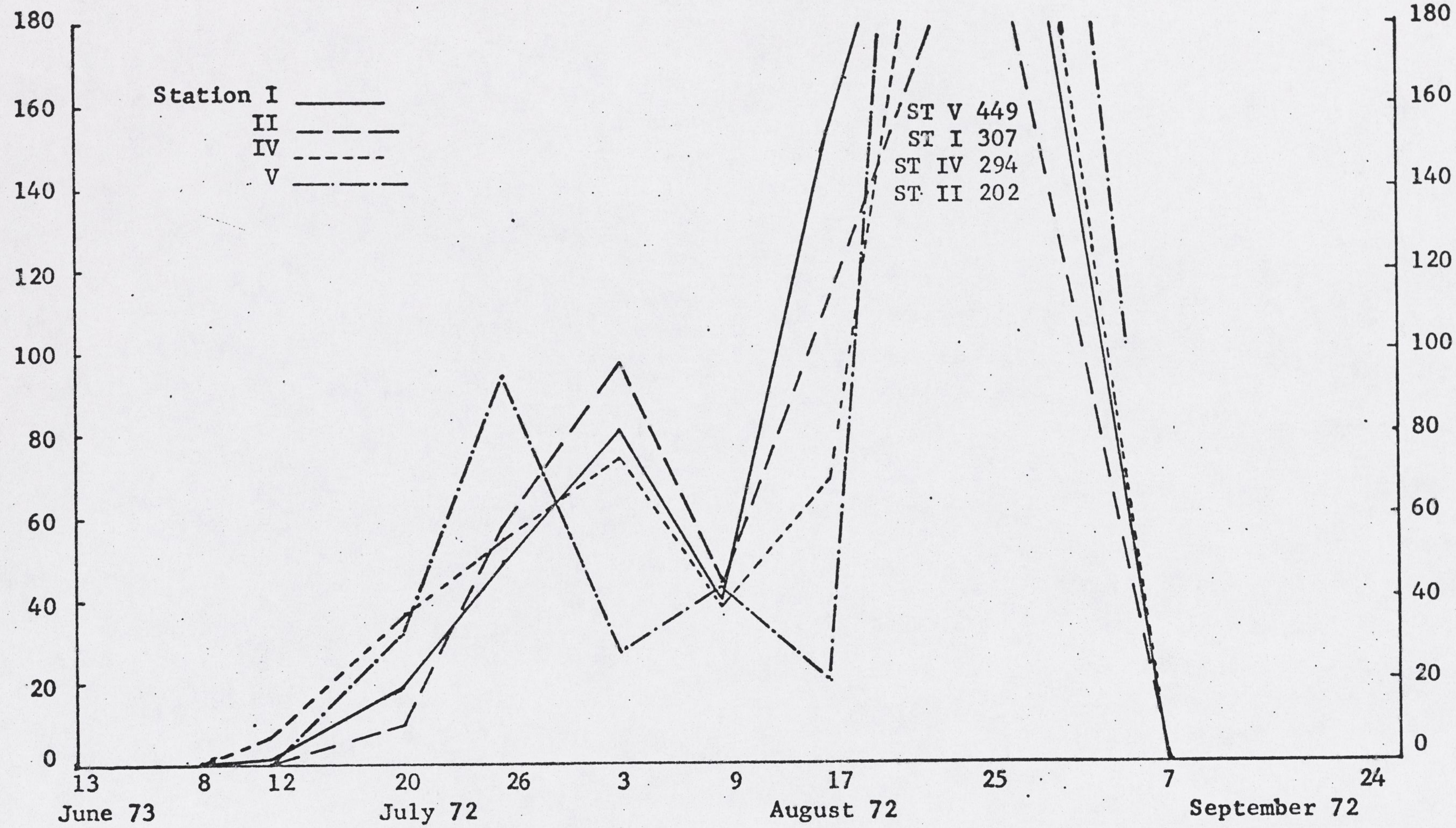


FIGURE 8. Seasonal concentration of rotifers as organisms/l in the euphotic zone (0-20m) at Stations I, II, IV and V.

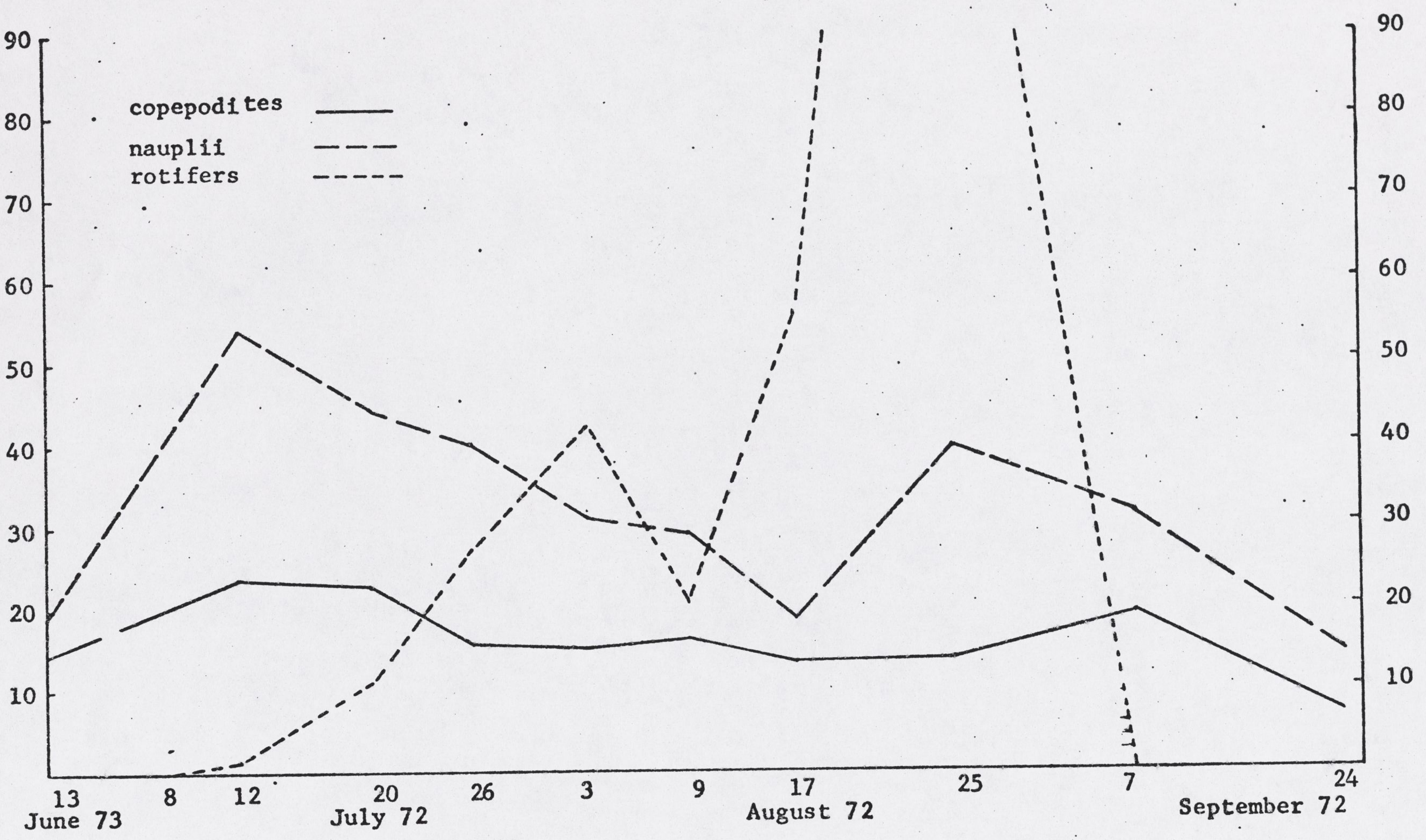


FIGURE 9.— Mean concentrations with respect to time of organisms/l (ordinate) in the euphotic zone of West Thumb.

TABLE 7. Mg/Chl_a accumulated per m^2/day.

Location	mean mg Chl_a per m^2/day	range mg Chl_a per m^2/day
off sewage effluent		
east at 2 meters	95.4	---
west at 2 meters	176.0	118.1-231.4
north at:		
2 meters	60.7	11.8-114.7
4 meters	33.2	11.6-63.5
6 meters	60.7	54.1-67.3
Station A (west shore)		
2 meters	107.7	33.5-273.3
4 meters	33.1	5.0-56.4
Station B (Breeze Point)		
2 meters	124.4	103.2-145.7
4 meters	101.1	80.0-122.3
6 meters	140.5	---

TABLE 8. p-values of paired individual observations using Student's-t test on mg Chl_a per m^2/day.

	Sewage North			Sewage East	Sewage West	West Shore		Breeze Point		
	2 m	4 m	6 m	2 m	2 m	2 m	4 m	2 m	4 m	6 m
Sewage North										
2 meters	---	---	---	---	---	---	---	---	---	---
4 meters	<0.25	---	---	---	---	---	---	---	---	---
6 meters	1.0	<0.25	---	---	---	---	---	---	---	---
East										
2 meters	<0.25	<0.25	<0.25	---	---	---	---	---	---	---
West										
2 meters	<0.1	<0.05	<0.1	<0.25	---	---	---	---	---	---
West Shore										
2 meters	<0.25	<0.2	<0.25	<0.25	<0.2	---	---	---	---	---
4 meters	<0.25	1.0	<0.25	<0.25	<0.05	<0.1	---	---	---	---
Breeze Point										
2 meters	<0.25	<0.2	<0.25	<0.25	<0.25	<0.25	<0.2	---	---	---
4 meters	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	---	---
6 meters	<0.25	<0.2	<0.25	<0.25	<0.25	<0.25	<0.2	<0.25	<0.25	---

TABLE (9)a. p-values of paired station observations using Student's-t test on mg Chl_a per m^2/day.

	off sewage effluent	West Shore	Breeze Point
Off sewage efflent	---	---	---
West shore	< 0.25	---	---
Breeze Point	< 0.25	< 0.25	---

TABLE (9)b. p-values of paired depth observations using Student's-t test on mg Chl_a per m^2/day.

	2 meter	4 meter	6 meter
2 meter	---	---	---
4 meter	< 0.05	---	---
6 meter	< 0.25	< 0.25	---

ulations, either between stations, or between depths.

The highest rate of chlorophyll "a" accumulation was observed at the west shore location, Station A. This could be taken as an indication that the sewage is having little, if any, effect on the growth of benthic algae.

Benthos

A total of 18 benthic samples were examined on a comparative basis, 14 from Station S and 4 from Station W. Species composition, approximate numbers of individuals per taxa and standing crop of biomass (dry wgt.) were tabulated to determine if a localized effect of the sewage effluent could be detected.

A definite difference was noticeable in species composition of macroflora from Stations S and W. Musci (mosses), Isoetes, Myriophyllum, Ranunculus, Lemna trisculca, Elodea, Chara, and Nostoc were common to both. Potamogeton sp. were collected only at Station S.

In depths of 0-2 meters, Isoetes and Nostoc were the most prominent plants at both stations. At Station W, Musci (Fontinalis sp.) were the dominant plants in samples from depths of 4-6 meters, growing in a thick carpet. At Station S, Potamogeton sp. and Elodea dominated the macroflora in water deeper than 2 meters.

Physical differences between Stations S and W may be sufficient to cause the observed distribution (Sculthorpe, 1967). Station W, being near the west shore, is protected from the prevailing westerly winds, thus is not as turbulent as Station S. Also, Station W is an area of upwelling. Water there would have a high free CO_2 content, which is the only form of carbon available to mosses for photosynthesis.

The influence of turbulence is supported by the distribution of dry weights with depth (Table 10). At Station S, the average dry weight in 0-2 meter water is 2.6 gm. At Station W the 2 meter sample obtained a weight of 9.8 gm. Station W obtained a higher standing crop than did Station S, 29.2 gm at 5 meters. Station S obtained maximum average standing crop at 6-7 meters, 10.5 gm.

The dry weights for samples from Station S showed no pattern of distribution relative to the sewage point discharge, other than in the immediate area (within 10 meters laterally). A sample taken at the point of discharge contained only Isoetes and Nostoc. This distribution may be a result of substrate, which was composed of finely divided, detrital, material, in which Isoetes could firmly anchor itself with its well-developed, tuberous root.

Numbers of macroinvertebrates were counted in 8 samples. For the remainder, numbers of individuals were estimated using the following categories.

TABLE 10. Distribution of average standing crop of biomass at Stations S and W with depth, biomass in grams per sample. Ranges and individual values in parentheses.

Depth (m)	STATION S	W
0 - 2	2.5 (.3 - 4.3)	(9.8)
4 - 5	8.8 (4 - 14.7)	(5.1) (5.0)
6 - 7	10.5 (4 - 13.6)	(29.2) (9.2)

Abundant	(A)	100+
Numerous	(N)	50-100
Common	(C)	20-50
Present	(P)	5-20
Rare	(R)	less than 5

This method has been shown to be accurate within the stated limits with practice (Garrett, unpub. Ms. thesis, 1973). The 8 counted samples served as a check.

Invertebrates collected included Gammaridae (Gammarus and Hyalella), Ephemeroptera (Ephemerella), Diptera (Chironomidae), Hirudinea, Lumbriculidae, Porifera, and Gastropoda. The zoobenthos was dominated in numbers and biomass by Gammaridae. Insect nymphs and larvae were relatively uncommon, except for Diptera, probably due to prior emergence, although many Trichoptera cases (Limnephilidae) were found in samples from both stations.

Table 11 shows the relative abundance and frequency of invertebrate taxa in samples from stations S and W. The highest density of Gammaridae obtained was 425/sample, 2 meters deep at Station W on 8 August. The highest density of Gammaridae obtained at Station S was 119 per sample, 4 meters, on 8 August. The average number of Gammaridae in the counted samples was 107 (range 25-425).

At Station S, no distributional pattern of macroinvertebrates relative to the sewage effluent was discernable, other than in the immediate vicinity of the outlet pipe (within 5-10 meters). A sample taken at the outlet pipe contained only Diptera (Chironomidae), which were abundant, and Lumbriculidae (Rare).

It does not appear that the sewage has significantly altered the macrobenthic community, other than in the very restricted area of the outfall pipe, which is covered with a small sludge deposit.

Sewage Movement and Dispersion

Figure 10 illustrates the results of the Rhodamine-B dye tracings of the effluent under three varying wind directions and speeds. Generally, very little sewage moves out into the lake, but rather moves along the shoreline in the direction of the prevailing wind.

The rate of sewage movement appears to depend solely on the velocity of the wind. The stronger the wind, the greater the rate of removal from the effluent discharge, but the amount of dispersion is greatly reduced. As winds become stronger, the sewage moves as a 'slug', rather than dispersing. As Benson (1961)

TABLE 11. Relative abundance and frequency of occurrence of benthic macroinvertebrates in samples at Stations S and W. Total samples = 18.

TAXA	ABUNDANT S	ABUNDANT W	NUMEROUS S	NUMEROUS W	COMMON S	COMMON W	PRESENT S	PRESENT W	RARE S	RARE W	Total Occurences
Gammaridae	4	2	3	2	3	0	0	0	1	0	15
Ephemeroptera	0	0	0	0	0	0	0	0	4	1	5
Diptera	1	0	2	3	1	0	3	1	1	1	13
Hirudinea	0	0	0	0	0	0	2	3	6	1	12
Lumbriculidae	0	0	0	0	0	0	1	2	0	2	5
Porifera	0	0	0	0	0	0	1	0	3	2	6
Gastropoda	0	0	0	0	0	0	0	0	0	1	1

Figure 10

Predominate Sewage Movement (Direction and Rates) at Three Variable Wind Speeds and Directions

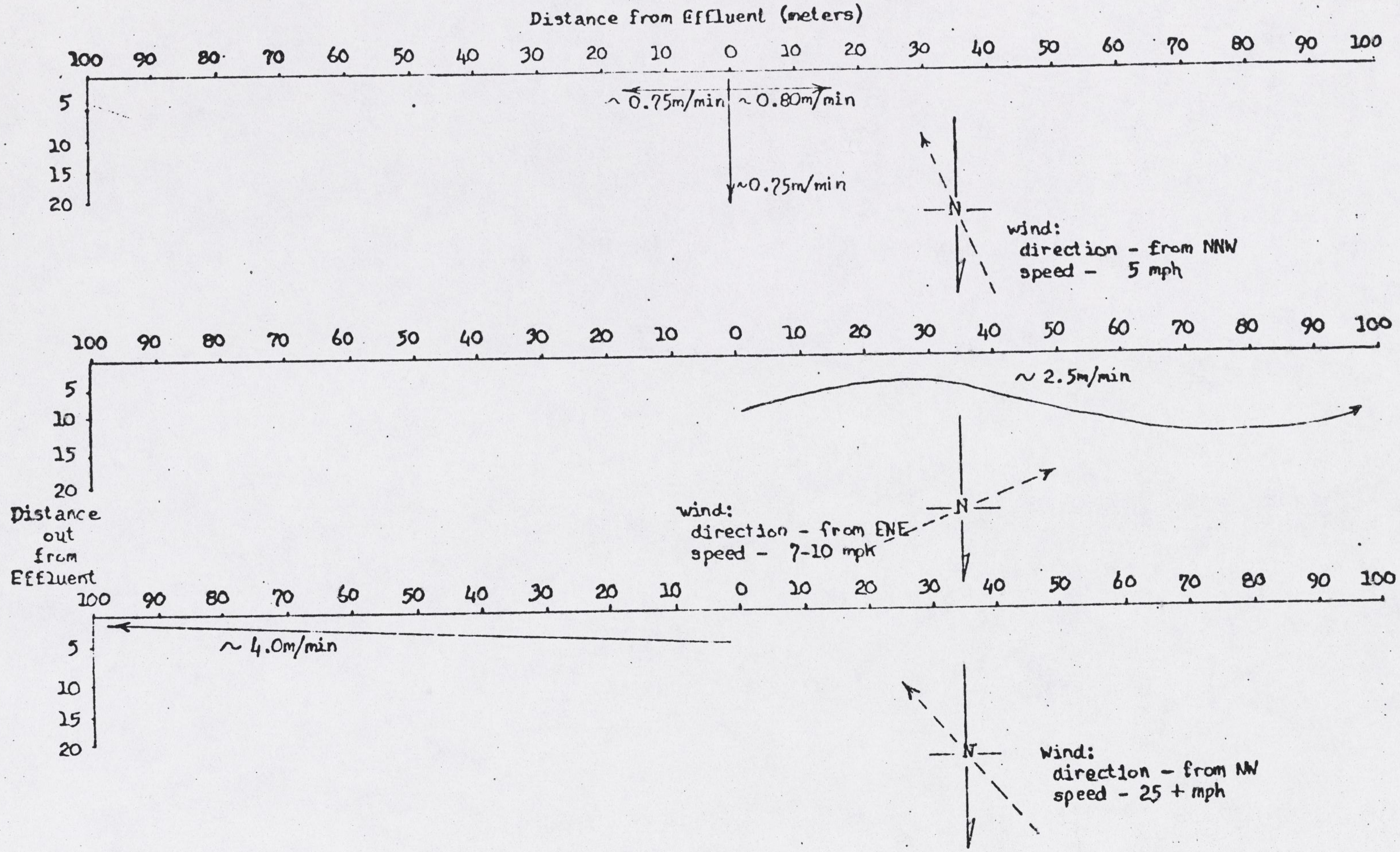
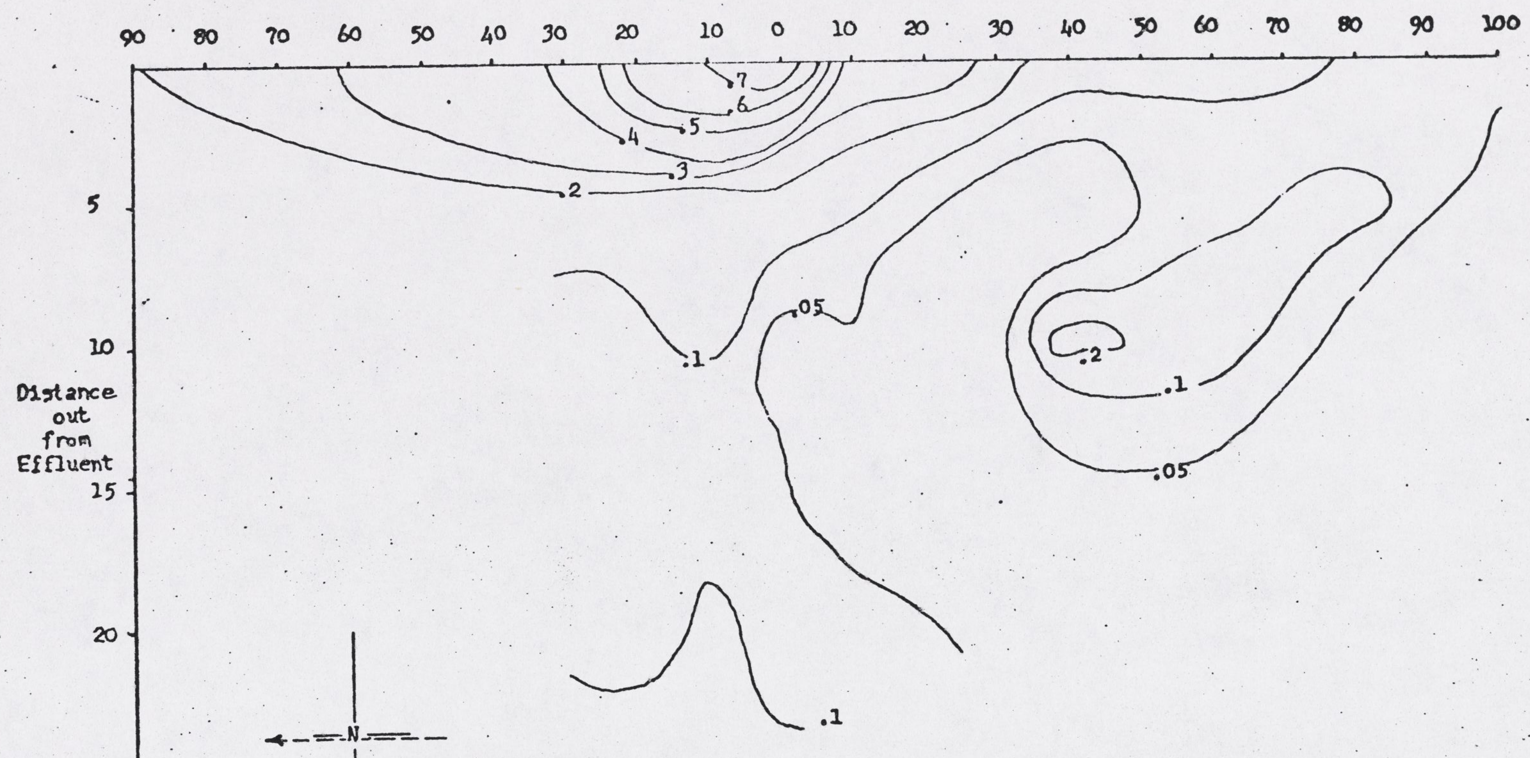


Figure 11

SEWAGE DISPERSAL
(based on mean phosphate concentrations (mg/1))



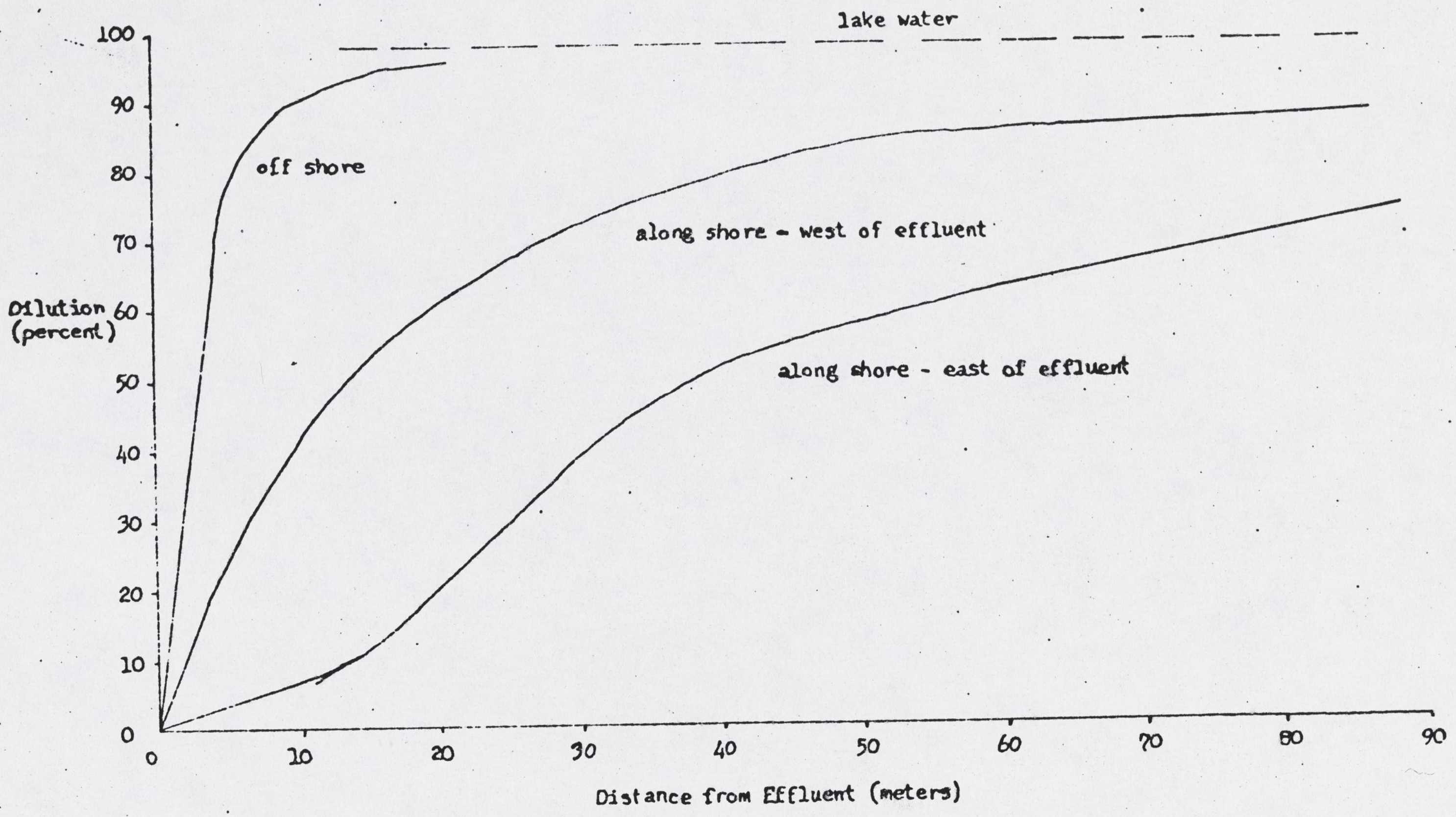
wind:
direction was variable,
ranging from the west to almost east,
however, predominately from the west

gusting from 8 - 10 mph to less than 1 mph

31 August 1972

Figure 12

SEWAGE DILUTION RATES
(based on mean phosphate concentrations (mg/l))



note: zero percent dilution is the effluent pointed out, the prevailing winds on West Thumb are from the westerly direction. This would tend to move more sewage to the east of the discharge point.

Figure 11 shows the degree of sewage dispersion based on phosphate concentrations made from the grid plot. Nitrate was not detected other than within 5 meters from the effluent. The data corresponds with observations of the dye tracings, namely, that the sewage moves in the direction of the prevailing winds.

Figure 12 was plotted using the phosphate concentrations shown in Fig. 11. Even though the sewage moves in a 'slug' with stronger wind speeds, Fig. 12 shows the high rate of sewage dilution. Within 10-30 meters off shore, the sewage is diluted to approximately 95-100%, yielding phosphate concentrations similar to that of the lake (Table 2.) The dilution rate is less in the easterly direction, but within 90-100 meters from the discharge point, the sewage was diluted to 75-80%.

Laboratory Algal Assays

Water collected on 26 July, 1972 was spiked with several concentrations of phosphorus and nitrogen. The inital nutrient concentration of the water was 0.019 mg/l P and 0.001 mg/l N. The growth response became greater with the successively increasing concentrations of phosphorus and nitrogen (Table 12). At the highest concentrations used, the maximum standing crop was nearly identical to that found for the algal nutrient medium.

Water collected on 9 August was spiked individually with separate concentrations of phosphorus and nitrogen. The initial concentrations were 0.019 mg/l P and 0.001 mg/l N. Increased growth occurred as the phosphorus concentrations were increased but there was no response to nitrogen (Table 13). The growth response to phosphorus alone was not nearly as great as that observed with phosphorus plus nitrogen.

Since there was no response to nitrogen, another run was made on 7 September water to see if a response to phosphorus alone could be detected. The initial nutrient concentrations were 0.012 mg/l P and 0.002 mg/l N. In this case there was no significant response to P; however, the growth in the control was significantly greater than that observed in the two previous runs (Table 14).

It would appear that both nitrogen and phosphorus are limiting in West Thumb. Some unknown factor caused a significant increase in maximum standing crop and maximum specific growth rate for the control of the run of 9 September.

TABLE 12. Treatment, maximum standing crop and specific growth rate for lake-water spiked with both phosphorus and nitrogen (July 26, 1972).

Treatment	Maximum Standing Crop	Maximum Specific Growth Rate
Control (no spike)	$2.2 \times 10^4 \pm 0.31 \times 10^4$ cells/ml	0.871 ± 0.03 day^{-1}
0.02 mg/l P + 0.42 mg/l N	$2.9 \times 10^5 \pm 1.6 \times 10^5$ cells/ml	1.36 ± 0.27 day^{-1}
0.06 mg/l P + 1.26 mg/l N	$1.1 \times 10^6 \pm 2.9 \times 10^5$ cells/ml	1.52 ± 0.09 day^{-1}
0.09 mg/l P + 2.10 mg/l N	$1.4 \times 10^6 \pm 0.42 \times 10^6$ cells/ml	1.68 ± 0.02 day^{-1}
0.13 mg/l P + 2.94 mg/l N	$1.8 \times 10^6 \pm 2.1 \times 10^6$ cells/ml	1.69 ± 0.35 day^{-1}
0.19 mg/l P + 4.20 mg/l N	$3.6 \times 10^6 \pm 2.0 \times 10^6$ cells/ml	1.64 ± 0.16 day^{-1}
Algal nutrient medium	$3.2 \times 10^6 \pm 0.12 \times 10^6$ cells/ml	1.82 ± 0.24 day-1

TABLE 13. Treatment, maximum standing crop and maximum specific growth rate for lake-water spiked separately with nitrogen and phosphorus (August 9, 1972).

Treatment	Maximum Standing Crop	Maximum Specific Growth Rate
Control (no spike)	$7.4 \times 10^3 \pm 1.1 \times 10^3$ cells/ml	0.713 ± 0.24 day^{-1}
0.02 mg/l P	$1.7 \times 10^4 \pm 0.15 \times 10^4$ cells/ml	0.910 ± 0.18 day^{-1}
0.06 mg/l P	$3.0 \times 10^4 \pm 0.35 \times 10^4$ cells/ml	0.819 ± 0.20 day^{-1}
0.19 mg/l P	$32. \times 10^4 \pm 2.00 \times 10^4$ cells/ml	0.769 ± 0.009 day^{-1}
0.42 mg/l N	$6.5 \times 10^3 \pm 0.85 \times 10^3$ cells/ml	0.860 ± 0.28 day^{-1}
1.26 mg/l N	$6.9 \times 10^3 \pm 1.2 \times 10^3$ cells/ml	0.570 ± 0.04 day^{-1}
4.2 mg/l N	$7.5 \times 10^3 \pm 1.5 \times 10^3$ cells/ml	0.752 ± 0.105 day^{-1}
Algal nutrient medium	$4.1 \times 10^6 \pm 0.40 \times 10^6$ cells/ml	2.12 ± 0.23 day^{-1}

TABLE 14. Treatment, maximum standing crop and maximum specific growth rate for lake-water spiked with phosphorus (September 7, 1972).

Treatment	Maximum Standing Crop	Maximum Specific Growth Rate
Control	$2.2 \times 10^5 \pm 0.35 \times 10^5$ cells/ml	1.25 ± 0.21 day^{-1}
0.02 mg/l P	$2.4 \times 10^5 \pm 0.32 \times 10^5$ cells/ml	1.37 ± 0.20 day^{-1}
0.06 mg/l P	$2.5 \times 10^5 \pm 0.20 \times 10^5$ cells/ml	1.84 ± 0.38 day^{-1}
0.19 mg/l P	$2.3 \times 10^5 \pm 0.20 \times 10^5$ cells/ml	1.55 ± 0.13 day^{-1}
Algal nutrient medium	$3.9 \times 10^6 \pm 0.12 \times 10^6$ cells/ml	2.01 ± 0.59 day^{-1}

In stimulating algal growth with inorganic nutrients, the concentration of nutrients is the important value. Thus in considering the nutrient loading required in the West Thumb to cause concentrations near the assay values, the availability of the nutrients to phytoplankton in the euphotic zone is critical. The only time at which the lake's entire nutrient resource is available is during overturn, since it has been demonstrated that the nutrients are uniformly distributed at this time, while nitrogen does accumulate in the hypolimnion during thermal stratification. The amount of nitrogen required to bring the West Thumb to the spike concentration is approximately 0.42 mg/l - 0.04 mg/l = 0.38 mg/l. $0.38 \text{ mg/l} \times 2\text{x}10^9 \text{ m}^3 = 76 \times 10^4 \text{ kg}$. This value is over 200 times the present maximum annual rate of sewage input. The volume of sewage at the operating concentration necessary to introduce this much nitrogen would also raise the phosphorus concentration of West Thumb waters to approximately 0.035 mg/l.

Summary

West Thumb exhibits typical characteristics of an oligotrophic, temporate lake draining from rhyolite areas.

a. Orthograde dissolved oxygen curve

b. Orthograde distribution of nutrients during summer stratification

c. High light transparency, with the euphotic zone to 20 meters; secchi disc depth averages 8 meters

d. Low standing crops of phytoplankton, with chlorophyll "a" concentrations from 1-3 µg/l, with the exception of a natural Anabaena flos-aquae bloom in late August

e. Low conductivity values of 95-100 µmhos, with sodium and bicarbonate being the major anions.

The combined physical, chemical, and biological data failed to reveal any effect of the sewage input on the West Thumb biota and chemistry, with the exception of the benthic invertebrate composition within 5 meters of the discharge point. Differences in the macroflora between sites seems to be a function of natural physical characteristics, such as light and turbulence. The chemical data reveals no effect of the sewage within the immediate area of the effluent, nor any part of West Thumb. Phytoplankton and benthic algal populations are also uneffected by the sewage effluent.

These findings are in agreement with the observations based on the extremely high rate of effluent dispersion, which is effectively diluted to lake water concentrations within 100 meters of the discharge point. The rate of sewage movement is entirely dependent upon the strength and direction of the wind.

Data on nutrient chemistry and chlorophyll "a" concentrations indicate that the natural plankton association in the lake is nitrogen-limited. However, the algal assay organism, Selenastrum capricornutum, showed a significant growth response only when both nitrogen and phosphorus were added.

The past rate of sewage input does not appear sufficient to cause significant nutrient loading and enrichment. Surface currents tend to remove the surface water and dispersed sewage from the West Thumb.

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THE LIMNOLOGY OF THE WEST THUMB OF YELLOWSTONE LAKE, YELLOWSTONE NATIONAL PARK, WYOMING

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Botany

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February, 1975

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VITA

Jonathan Charles Knight was born 16 July 1949 at Watertown, Wisconsin, to Mr. and Mrs. William J. Knight. He attended elementary, junior and senior high schools in Fond du Lac, Wisconsin. In June 1967, he graduated from L.P. Goodrich High School in Fond du Lac.

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On 21 August 1971 he married Barbara Sue Catlin. A son, Adam Charles, was born in September 1973.

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Special gratitude is felt for my wife Barb, for her patience, understanding, motivation and cooperation in typing the manuscript.

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The Effects of a Century of Human Influences on the Cutthroat Trout of Yellowstone Lake

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Abstract

Over the past century man has had a definite impact on the cutthroat trout of Yellowstone Lake. Direct effects include exotic species introductions, hatchery operations and angler harvests. It would appear that thus far, the latter two activities have been the most deleterious.

Three exotic species introduced to the system have apparently filled empty niches in the lake ecosystem, and there is no evidence of direct competition with native cutthroat trout. Although egg-taking and hatchery operations have been closed for over 25 years, it is now apparent that egg removal, genetic mixing and greatly reduced natural spawner escapement all led to a gradual reduction in reproductive potential and undermined the complex mosaic of reproduction and recruitment. Angler harvest also had a significant negative impact when it was allowed to rise to extreme levels. During the past decade increasingly restrictive regulations have helped to restore population numbers and age-class structure. Current policies which prohibit exotic species introductions, rely on natural wild stocks and restrict angler harvests are products of continued effort to manage the lake as an ecological unit.

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Although whiteman first visited the area of Yellowstone Park near the turn of the nineteenth century, it was not until the latter part of that century when his presence began to produce substantial impact to the area and specifically to Yellowstone Lake. Most human use impacts, such as pollution and degenerative land use practices which have negatively affected many other fisheries, have not been a factor in the Yellowstone Lake basin.

The one possible exception was the active suppression of natural fires (mostly lightning caused) from 1885-1972 (Sellers and Despain 1976). Although this program was rather ineffective until the late 1940's, the reduction of fire released nutrients and maintenance of a rather unproductive terrestrial vegetative mosaic throughout the watershed may have reduced lake productivity during this period. The effects of fire suppression are complex and must be analyzed in context with long term climatic and vegetational trends, the natural range of these parameters and the variation in timing and site of fire ignition; such an analysis is beyond the scope of this paper. It is evident, however, that even if suppression activities caused significant deviations, changes would be totally masked by population fluctuations directly attributable to other human activities in the past century.

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Therefore, considering that the environment is pristine and relatively constant, the cutthroat trout on Yellowstone Lake provides an interesting study of direct human manipulation. Large scale spawn-taking operations, commercial fishing and a 100 year history of almost unabated increases in sport fishery harvests have, both singly and in combination, significantly impacted the cutthroat population. At various times, trout stocks have been altered radically from the original state; there are also wide variations in population numbers and age-size structure of these altered states. In order to better understand these effects, a brief introduction to the ecology of the lake is necessary prior to discussing these effects separately.

Description of the Lake and Fishery

At an elevation of 2,357 m, Yellowstone Lake (Figure 1) is a large (35,391 ha), oligotrophic lake with an average depth of 40 m (Benson 1961). Annual growing season is short; the lake usually freezes by late December and remains covered with about 1 m of ice until late May or early June. Summer surface temperatures rarely exceed 18° C.

Lodgepole pine forests and subalpine meadows dominate the drainage basin which has an estimated area of 261,590 ha (Benson 1961). The bedrock geology is characterized by volcanic rock; andesite predominates in the eastern and southern portion of the drainage while rhyolite covers most of the west and north (USGS 1972). Chemically, the lake

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is a dilute sodium bicarbonate type (TDS: 52-80 ppm), typical of water originating from drainages of volcanic composition.

The siliceous nature of the watershed is also evidenced in the phytoplankton community. Diatoms are the major phytoplankters except for a brief pulse of the blue-green algae *Anabaena flos-aquae*, a nitrogen fixer, during periods of stratification (Garrett and Knight 1973, Benson 1961). The productivity is low, with chlorophyll "a" concentrations in West Thumb (one of the most productive portions of the lake, Benson 1961) from 1-3 μg/l (Garrett and Knight 1973). Production appears to be limited by nitrogen during the annual stratification and by water temperature and sunlight during the remainder of the year (Knight 1975).

The zooplankton is dominated by three species, *Diaptomus shoshone*, *Daphnia schoedleri* and *Conchilus unicornis*. Despite relatively low zooplankton densities, these forms are important as food for juvenile trout. Mature trout diets consist of zooplankton, two crustaceans (*Gammarus lacustris* and *Hyallela azteca*) and several families of Diptera, Ephemeroptera and Trichoptera. Depth distribution, feeding and movements of cutthroat trout were found to be related to food abundance (Benson 1961) and spawning migrations.

Yellowstone Lake currently supports the largest inland population of cutthroat trout in the world. Although the only native fishes were

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the Yellowstone cutthroat trout (*Salmo clarki bouvieri*) and the longnose dace (*Rhinichthys cataractae*), two exotic species, the redside shiner (*Richardsonius balteatus*) and the longnose sucker (*Catostomus catostomus*) are now abundant in the lake. Additionally, the exotic lake chub (*Couesius plumbeus*) is present in small numbers.

From May-July, cutthroat trout spawners ascend 140 direct tributaries to Yellowstone Lake. Most are initial spawners (ages IV+ and V+), although a substantial number of repeat spawners are also present.

Larger trout enter the streams first and appear to run higher in the tributaries than smaller individuals. The amount of time that spawners remain in these streams varies (1-3 weeks), but in most cases males stay longer than females (Ball and Cope 1961).

Fry emerge approximately 30 days after deposition. Although some fry may remain in the natal stream for one or two years, most migrate to the lake within two months of emergence. There is some evidence that after entering the lake, fry use the pelagic waters as a nursery area.

Larger trout (primarily mature) are found predominately in the littoral zone throughout the year, but this is especially evident during spawning migrations when trout appear to travel to and from spawning streams along the shoreline. The littoral orientation of mature trout has played an important role in the mode of angler exploitation. Since the majority of angling has been directed at littoral stocks, mature trout are highly vulnerable to exploitation. Conversely, juvenile trout (through age II) have

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never entered the fishery in significant numbers because of their presumed pelagic habitation.

The Yellowstone Lake sport fishery has been studied intermittently throughout this century. Annual data have been gathered since 1948. These long term records of angler use, effort and harvest provide an excellent data base for assessing the sport fishery impact on Yellowstone Lake.

Exotic Species Introductions

From the standpoint of native cutthroat preservation, official attempts at species introduction into Yellowstone Lake were fortunate failures. Varley (1980) reports that mountain whitefish (*Prosopuim williamsoni*) were stocked in the Yellowstone River below the lake in 1889 and 1890 (2,000 and 10,000, respectively). Rainbow trout (*Salmo gairdneri*) were planted twice in the lake (3,000 in 1902 and 3,800 in 1907) and once in the river (an unknown number of fingerling in 1929). Two plantings of landlocked salmon (*Salmo salar*), 7,000 in 1908 and 5,000 in 1909, were also unsuccessful.

Some fish introductions, official or otherwise, were successful. According to Benson (1961), records from the fish cultural station at Lake indicated that the longnose sucker was first introduced in 1923 or 1924. Redside shiners were first collected from the lake in 1957 (Cope 1958). In that same year, lake chubs were reported in Squaw

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Lake (within 300 m of Yellowstone Lake), but this species was not collected from Yellowstone Lake until several years later (Cope 1958). Although it has long been assumed that these introductions were made by releases of bait fish by anglers, at least one source (Kelly 1928) states that the longnose sucker may have been part of an authorized stocking of forage "minnows" in 1923.

The longnose sucker has been found in all portions of the lake including the three major islands; however, the redside shiner is currently restricted to shallow water along the margin of the entire lake. Collection of lake chubs has been limited to a small area in the northern portion of the lake. The native longnose dace appear to be confined to areas near the mouths of tributary streams.

Although populations of the longnose dace and lake chub are believed to be quite small and inconsequential, the sucker and shiner have been the subject of numerous studies centering on possible competition with the cutthroat trout. Of special concern was the great increase in numbers and distribution of the longnose sucker between the early 1950's and the late 1960's.

Despite a certain amount of diet overlap (Benson 1961, Biesinger 1961), there is currently no evidence of direct competition between the cutthroat trout and these exotic species. Apparently spacial separation within the lake, and both temporal and spacial separation in spawning

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streams has led to a rather stable association of fishes in the lake during the past decade. It seems likely that both the shiner and the sucker have filled previously vacant niches within the Yellowstone Lake ecosystem.

Hatchery Operations

The first egg collecting activities on Yellowstone Lake occurred on West Thumb Creek in 1899 under supervision of personnel from the Spearfish National Fish Hatchery, South Dakota. From this initial collection grew an immense operation which included a permanent hatchery at Lake Village and fish traps on 14 of the largest streams entering the lake. From 1899-1956, over 818 million eggs were gathered from cutthroat trout spawners entering lake tributaries (Varley 1979). A single year high of 43.5 million eggs were taken in 1940. Although many of the resulting fry were returned to the lake, eggs and fry were shipped worldwide as the Yellowstone Lake operation became what may have been the world's leading supplier of an inland wild trout species.

It is unfortunate that a program conceived in good will and carried out with a dedication for the resource became one of the most serious human threats to the cutthroat trout of Yellowstone Lake. The spawning runs in several of the larger tributary streams were totally blocked annually. Despite the return of fry to the lake, there was unquestionably genetic mixing of up to 140 reproductive entities and the subsequent demise of smaller discrete spawning populations.

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In some streams, reduced spawner escapement (coupled with intense angler harvest) resulated in the virtual collapse of some spawning runs. At Clear Creek (Figure 1), for example, annual spawner counts dropped from approximately 16,000 from 1945-1948 to an annual mean of 7,000 from 1956-1961; only 3,353 spawners were counted in 1954 (Benson and Bulkely 1963)(Figure 2). Of special significance is the increase of spawners after the cessation of spawn-taking activities in 1953; spawner counts in the past decade have ranged from 47,000 to 70,000 with a mean of almost 57,000 trout annually for the past five years. The initial increase of spawners in the 1960's, which occurred during a period when other measures of the fishery were declining rapidly (Figures 2, 3, 4 and 5), clearly indicated the impact of the spawn-taking operation.

Another reflection of the effect of the spawn-taking operation was the dramatic increase in mean length of cutthroat spawners in Clear Creek during the late 1950's after these operations were halted (Figure 3). It is difficult to determine the exact mechanism involved, but mean length in the angler catch (Figure 4) also increased after the hatchery program ceased. Apparently, mortality of stripped spawners, reduced production due to egg removal and questionable survival of returned fry and fingerling combined to vastly alter the size structure of the cutthroat population.

Angler Use and Harvest

With the exception of wars and depressions, angler use on Yellowstone

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Lake has increased steadily since the 1870's. Associated with these increases have been concomitant increases in annual harvests and declines in catch per unit effort (Figure 5). It is estimated that over 2 million trout had been harvested by 1920. Reports of substantial declines in angler success in that year led to a reduction in the creel limit to 20 trout daily. Commercial fishing operations which supplied fresh trout for hotel guests were also curtailed. Our estimates suggest that over 7 million trout had been harvested by 1954, a figure which may be unprecedented for an inland trout sport fishery.

In response to public and official concern during the 1950's, research biologists attempted to determine the number and sizes of cutthroat trout which could be harvested annually without deleterious effects to the population (Benson and Bulkley 1963). Management philosophy during this period was based on maximum sustained yield (MSY)(Gresswell in press). Estimates by Benson and Bulkley (1963) suggested that annual average MSY for Yellowstone Lake was 325,000 trout with a range of 290,000-340,000. It is now evident that these values were exceeded during the late 1950's and early 1960's. As a result of overharvest, the catch rate dropped between 1963-1968 to a low of 0.5 trout/hour; the harvest in 1968 was at a historic low point (Figure 5). Mean length of trout captured by anglers and those measured during spawning runs plummeted, and the mean age for spawners at Clear Creek

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dropped to a low of 3.9 years during the mid-1960's (Figures 3, 4 and 6).

Beginning in 1969, a series of increasingly restrictive regulations were implemented in an effort to support the ailing fishery (Gresswell 1980). Bait restrictions, reduction of creel limit from three trout to two, a 356 mm minimum size limit and the closure of Fishing Bridge to angling combined to foster stock recovery. Annual harvests dropped from 370,000 in 1958 to an average of 100,000 by 1974, and catch rate rose to about one trout/hour (Figure 5).

Despite these significant signs of resurgence, it became evident that the 356 mm minimum size limit was actually hastening the decrease of older and larger trout in the population. This result was viewed with great apprehension because of recruitment instability often associated with single age spawning stocks (Ricker 1954). Although estimates utilizing the Walford Line (Ricker 1975) indicated a historical maximum of 11 age groups, trout of age V+ and older were statistically absent from the catch by 1973. Experimental gillnetting data indicated that by 1974, the average size of cutthroat prespawners had begun to decrease to pre-minimum size regulation (1969) levels (Figure 7).

In order to prevent further deterioration of the population structure and the fishery in general, regulations changed from a 356 mm minimum size limit to a 330 maximum size limit in 1975. The effects of the first five years (1975-1980) are promising (Gresswell 1980). Average age

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of Clear Creek spawners was 4.8 years in 1980, and average length in the catch and experimental gillnets continued to rise. It is important to note that these changes have occurred while use and effort (about 150,000 angler-days and 350,000 angler-hours annually) remain high, and yet, the landing rate (averaging almost 1.0 trout/hour since 1975) is excellent.

Despite the encouraging results, it must be remembered that these data indicate changes are still occurring. It is expected that angler use will continue to rise, necessitating continual reevaluation of current regulations. With increased use and effort, harvest may again reach levels which will require further restrictions in order to continue to support high quality angling while providing adequate protection to this unique natural resource.

Summary

Over the past century, man has had a decided impact on the cutthroat trout of Yellowstone Lake. Direct effects include exotic species introductions, hatchery operations and angler harvest. It would appear that thus far, the latter two activities have been the most deleterious.

Within the past 60 years three exotic species have been successfully introduced to the lake, but attempted introductions of rainbow trout, landlocked salmon and mountain whitefish were failures. The redside shiner and the longnose sucker have thrived in favorable habitat.

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It appears that these species have filled empty niches in the lake ecosystem and do not compete directly with the native cutthroat. Perhaps the best method to insure that these exotics do not have future deleterious effects is to maintain a healthy, robust cutthroat trout population in the lake (Benson and Bulkley 1963).

The hatchery and egg-taking operation, one of the greatest threats to the integrity of the trout population in Yellowstone Lake, has been closed for over 25 years. Egg removal, genetic mixing and greatly reduced natural spawner escapement all led to a gradual reduction in reproductive potential and undermined the complex mosaic of reproduction and recruitment. Combined with overharvest, this overzealous program led to the collapse of the fishery during the early 1960's. Since the development of discrete, perhaps unique genetic characters is measured in geologic time, our losses may be virtually irretrievable.

Angler harvest also has proved to have a significant negative impact when it was allowed to rise to extreme levels and later when it was directed to older and larger trout. Since the collapse of the cutthroat fishery, increasingly restrictive regulations have helped to restore population numbers and age-size structure. It may yet be far from its historic potential, and data indicate equilibrium has not been reached. The continued rise in angler use is cause for concern, since overharvest may commence even under regulations which only allow a minimal creel

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limit. The problem in the past, and one yet to be addressed, is the aspect of unlimited entry of anglers into the sport fishery.

Despite its great size and once seemingly inexhaustable trout population, man has had, and continues to have, a significant impact on the Yellowstone Lake cutthroat fishery. Perhaps incredible trout abundance and early high-quality angling led to an attitude of invulnerability toward the lake's cutthroat population. Silvert (1977) has noted this phenomenon in commercial fisheries and concluded "the larger the initial population, the greater the danger of extinction!"

It is fortunate that the data record based on both historical records and experimental research is available for the continued evaluation of the Yellowstone Lake fishery. As we better understand past shortcomings, we can continually reassess management programs to ensure the proper protection for the resource while allowing high quality angling experiences for Park visitors. Current policies which allow natural fires, prohibit exotic species introduction, rely on natural wild stocks and restrict angler harvest are products of continued effort to manage the lake as an ecological unit.

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Figure Captions

Figure 1. Map of Yellowstone Lake illustrating the major sections and several of the larger tributaries.

Figure 2. Cutthroat trout spawner counts at Clear Creek, Yellowstone Lake, during various sampling years, 1945-1980.

Figure 3. Mean length of cutthroat trout spawners entering Clear Creek, under various angling restrictions, Yellowstone Lake, 1953-1980.

Figure 4. Mean length of angler captured cutthroat trout, under various angling restrictions, Yellowstone Lake, 1949-1980.

Figure 5. Total effort (hours), total trout removals (inclucing a hooking mortality estimate after 1962) and catch per hour estimates for Yellowstone Lake, 1941 and 1950-1980.

Figure 6. Age distribution histograms and mean age of cutthroat trout spawners at Clear Creek, Yellowstone Lake, during various sampling years, 1953-1980.

Figure 7. Mean length of cutthroat trout prespawners (judged as ready to spawn the following spring) captured in experimental gillnets, under various angling restrictions, Yellowstone Lake, September, 1969-1980.

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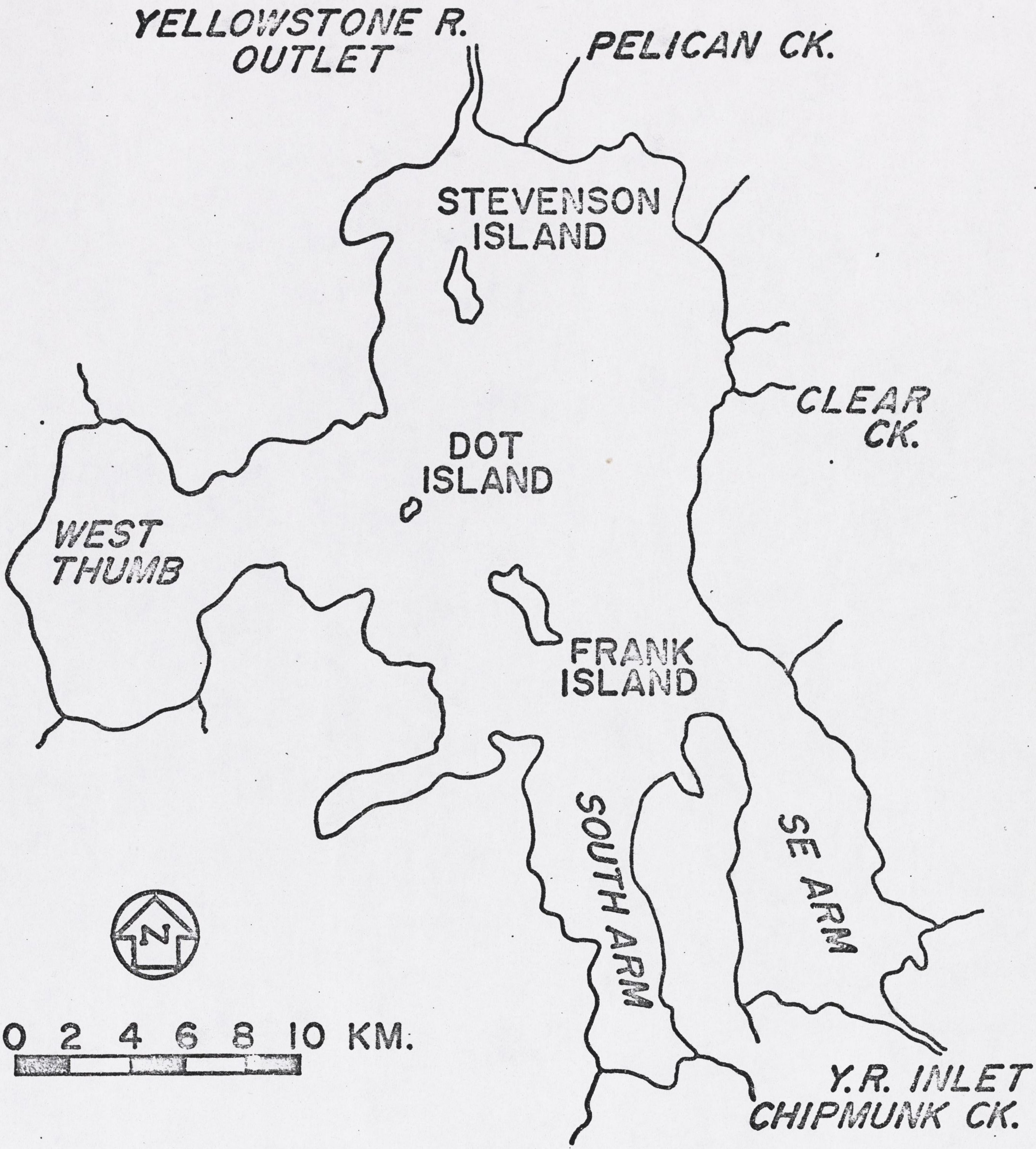

Gresswell and Varley Figure 1

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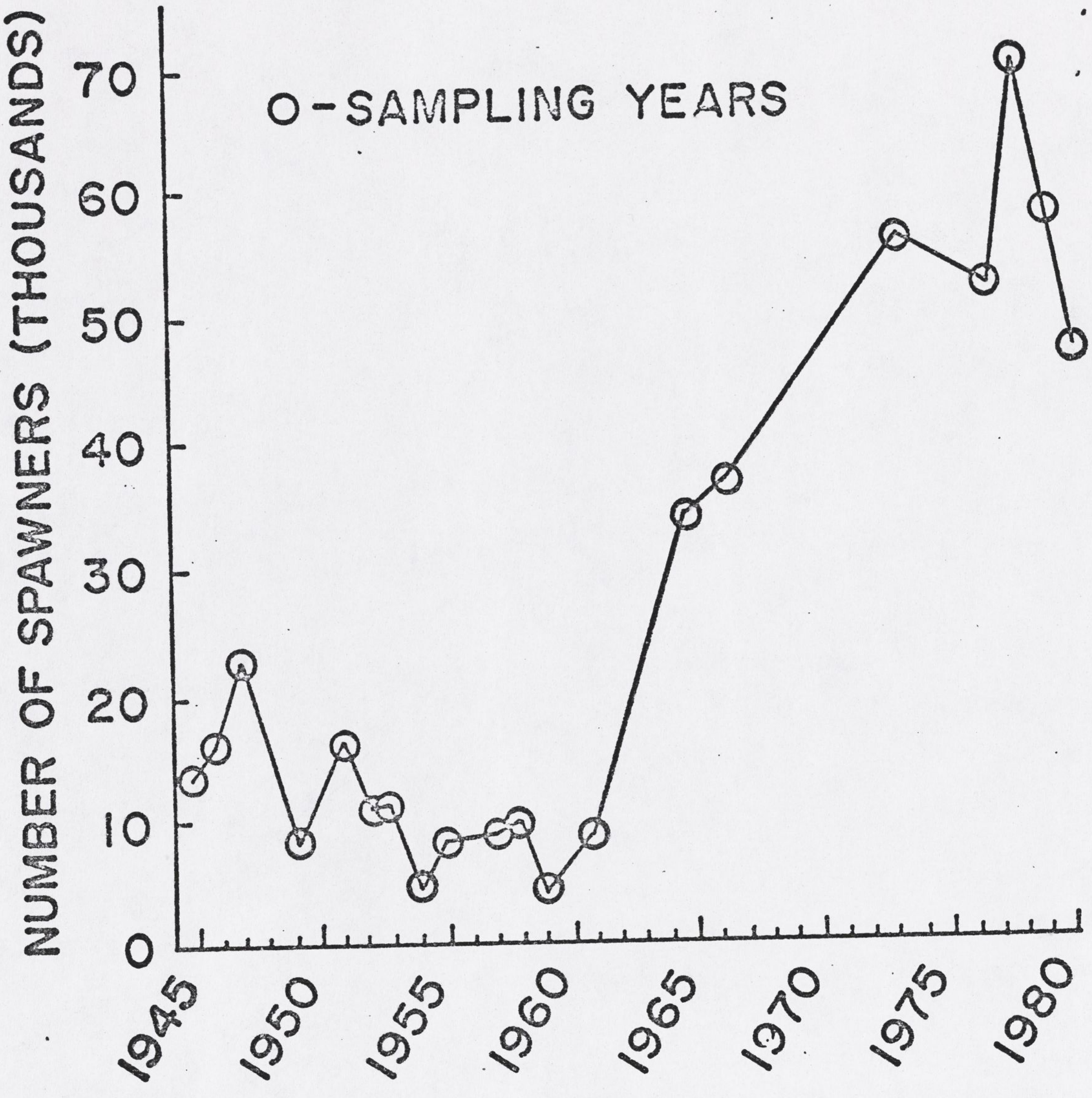

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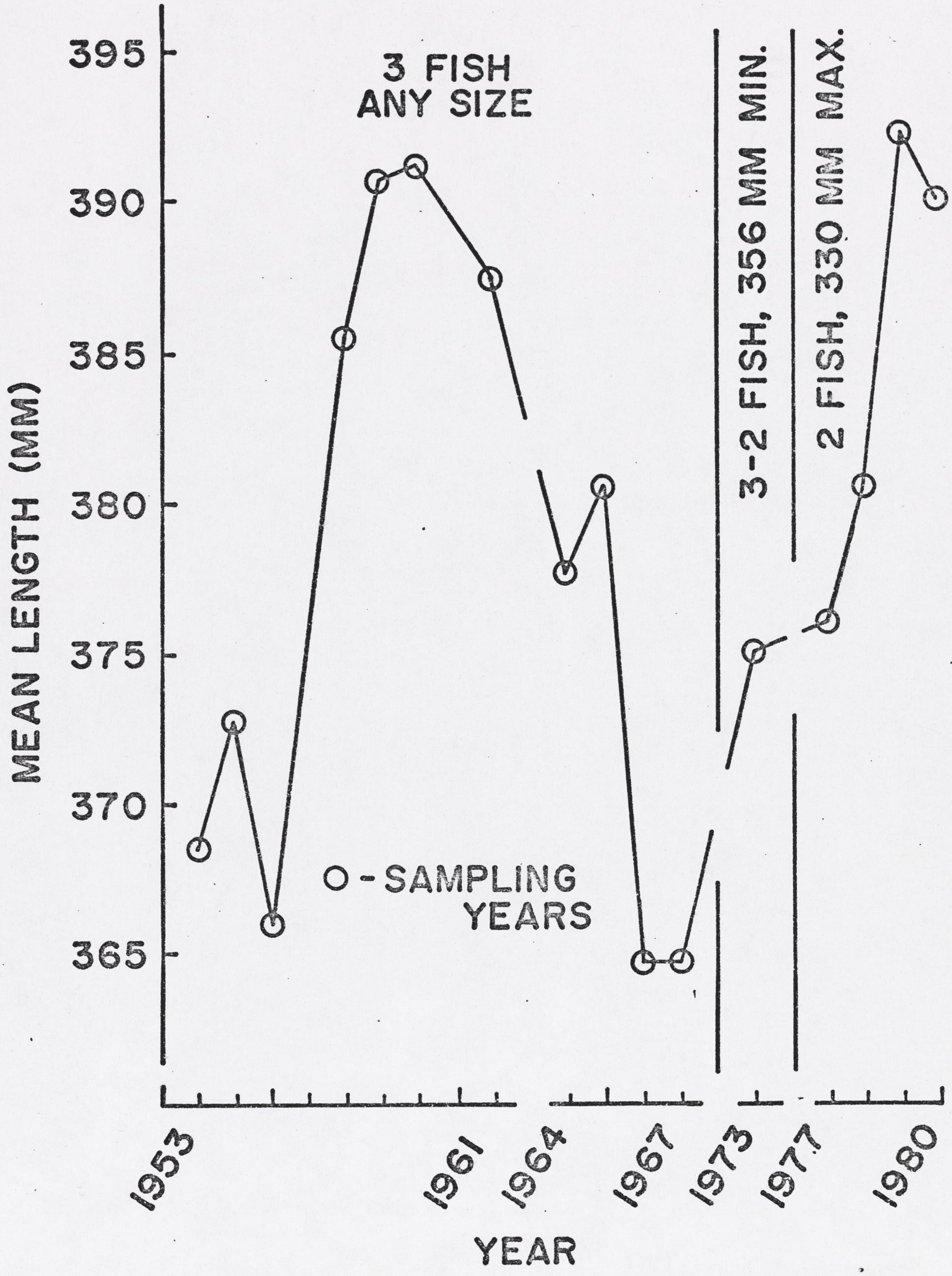

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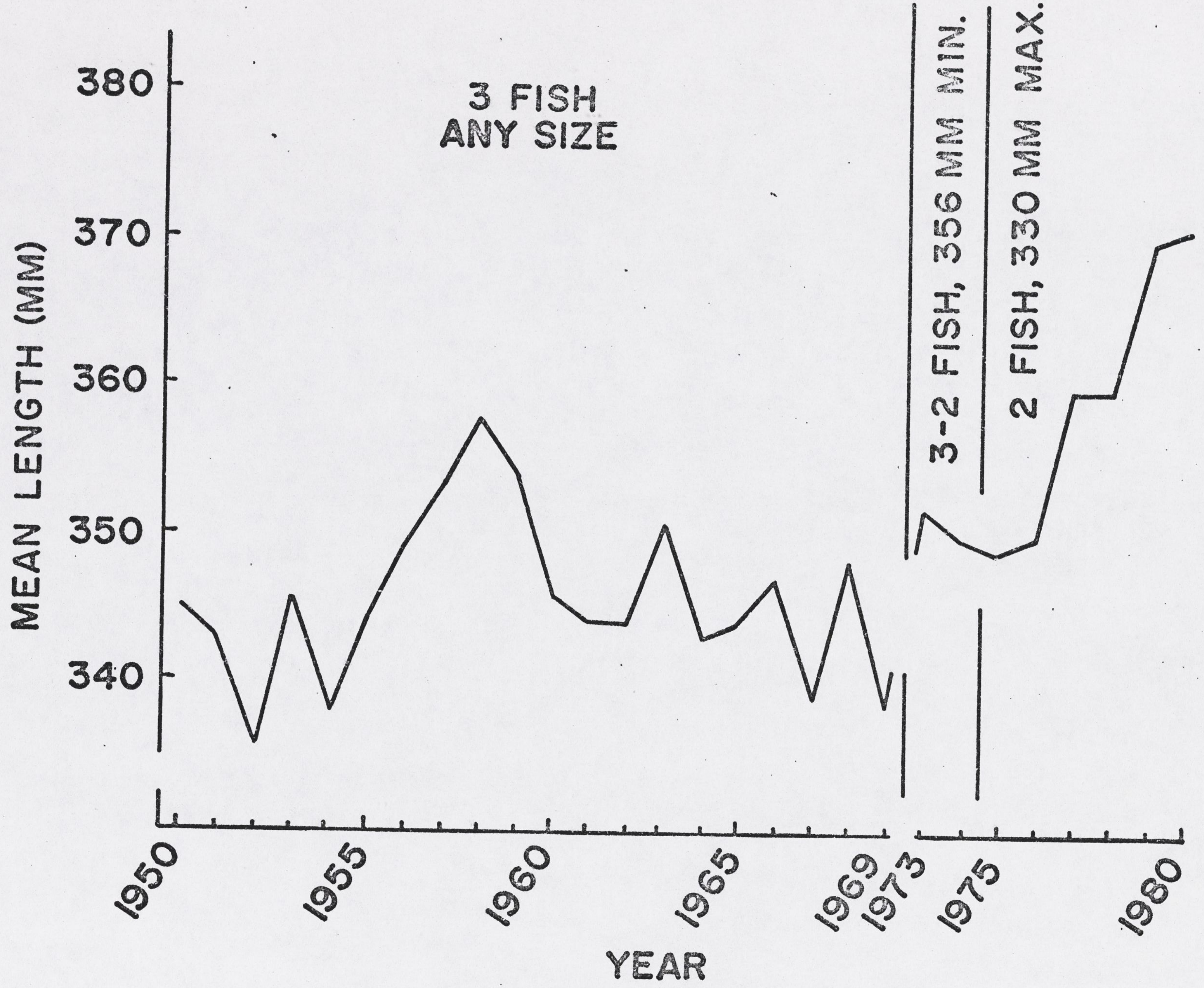

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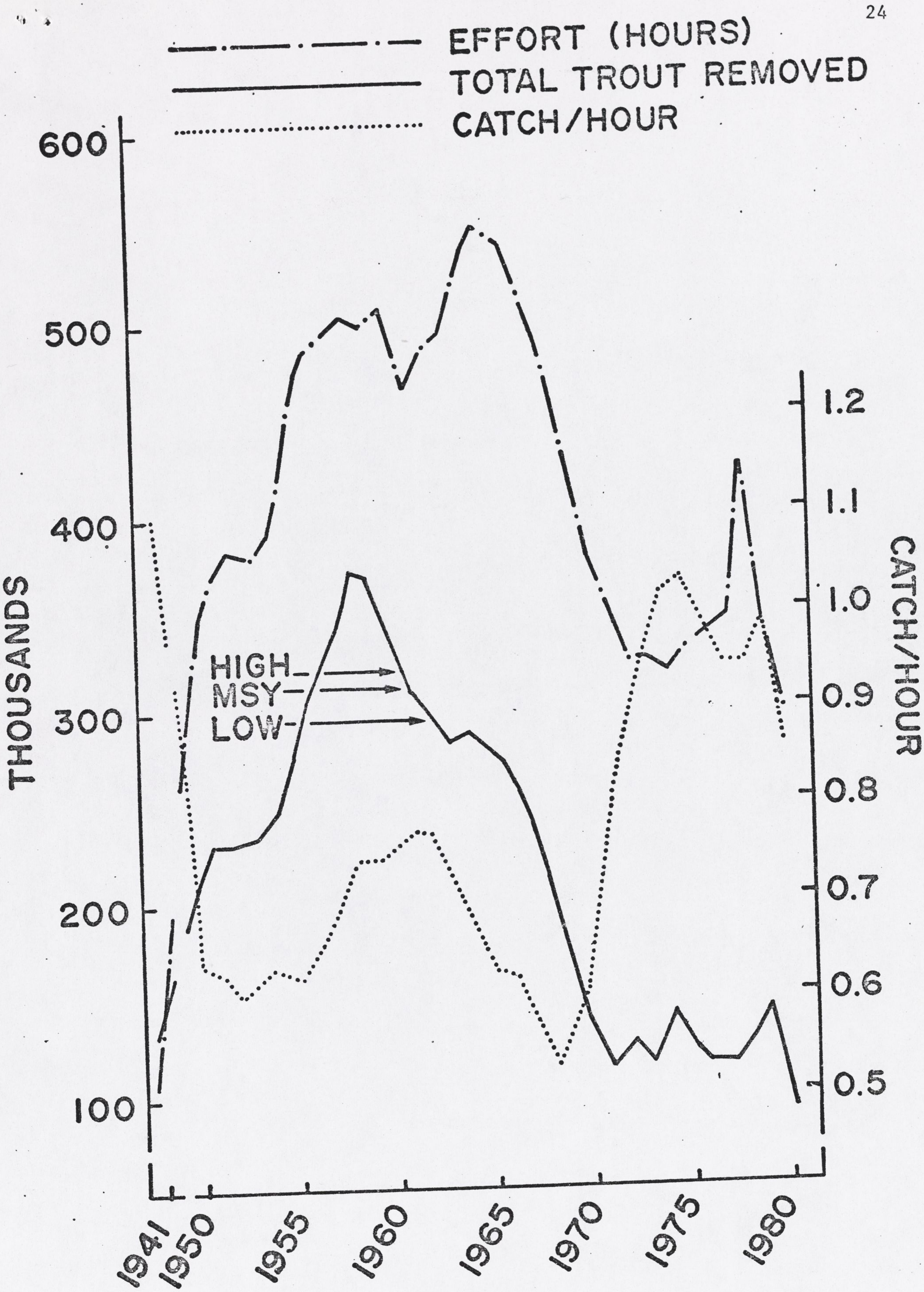

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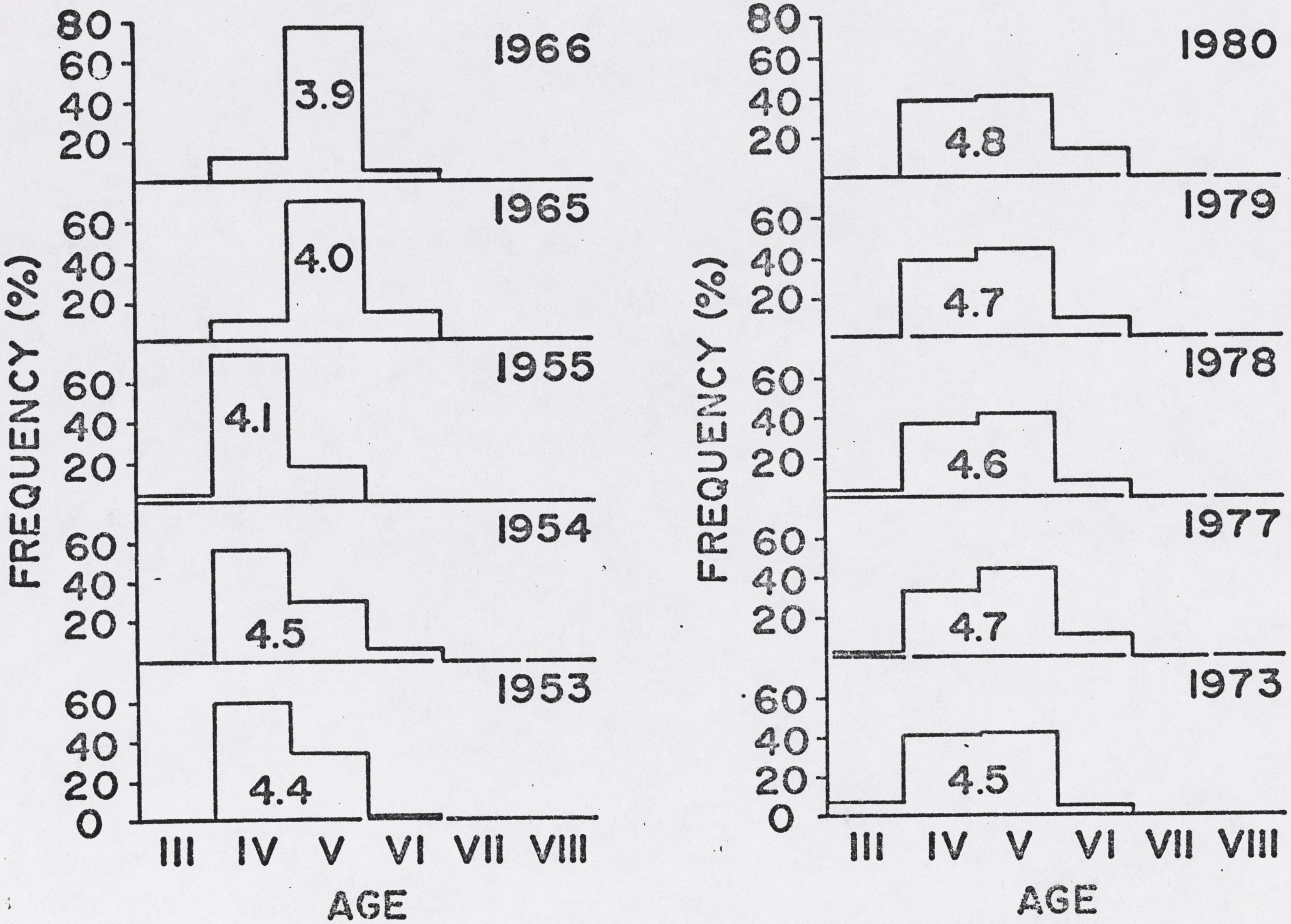

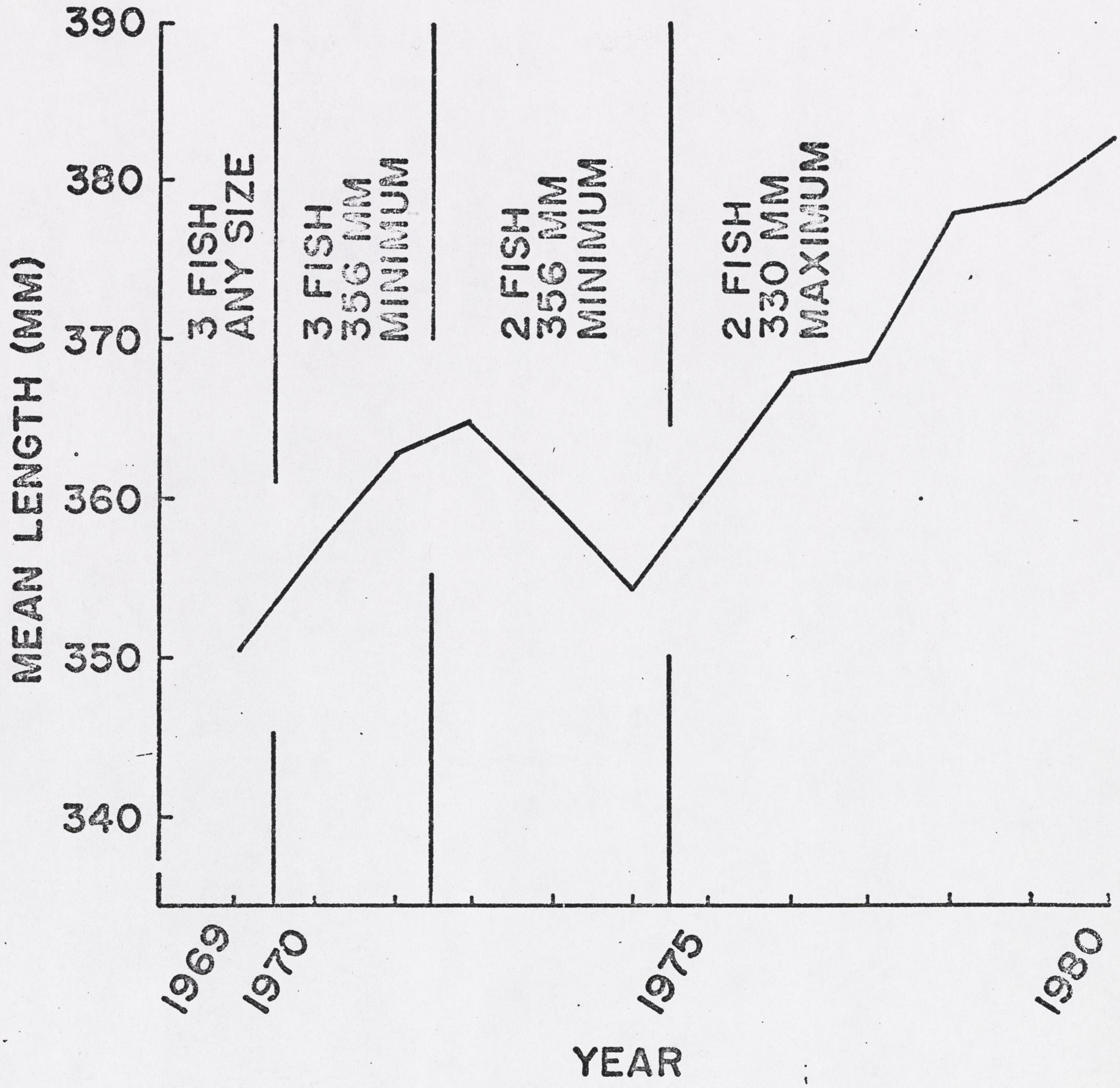

Gresswell and Varley Figure 7