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Environmental Protection Technology Series

Correlated Studies of Vancouver Lake - Water Quality Prediction Study

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November 1972

CORRELATED STUDIES OF VANCOUVER LAKE-WATER QUALITY PREDICTION STUDY

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ABSTRACT

This study deals with the restoration of water quality of shallow, polluted, and eutrophic lakes. Dredging and removing of lake bottom sediments and introducing better quality water are the restoration measures explored in this study. Vancouver Lake, Washington, was used as a test case.

Hydrologic, hydrographic, hydrodynamic, and water quality information provided by separate but correlated studies, was combined with the aid of mathematical simulation models. Dissolved oxygen was used as an indicator of the overall water quality in the system. Photosynthesis, atmospheric reaeration, biological respiration, and advection were the mechanisms considered in the computation of diurnal changes in dissolved oxygen level. In addition to the DO model, the aquatic life model for computing time-varying levels of phytoplankton and bacteria was also tried. The validity of these models was verified with the actual field data. After verifications of the models under the existing conditions, they were used to project and predict the water quality of Vancouver Lake as will be affected by dredged lake depths and introduced flows from the Columbia River.

This report was submitted in fulfillment of Project Number 16080ERQ under the partial sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. Without curtailing the present sources and amounts of pollution to Vancouver Lake and dredging the lake to provide 15 feet of water, a flow of about 750 cubic feet per second diverted from the Columbia River to Vancouver Lake will be required to raise the dissolved oxygen level in the lake to 8 mg/l. This diverted flow will also reduce the amount of pollution that enters the lake via the Lake River during high tides in the Columbia River.

2. Water quality simulation models are useful tools in studying, predicting and analyzing complex aquatic systems provided the models are verified with actual field data. Research is needed to establish numerical values of various coefficients and to refine the functional relationships that apply under a variety of environmental conditions. The accuracy of the models depends upon the accuracy of the values of coefficients used and the functional relationships assumed.

3. The sensitivity analysis conducted in this study strongly suggests that the diurnal variations in dissolved oxygen are very sensitive to the phytoplankton specific growth rates. Furthermore, in matching the computed values with the actual field data, the effect of temperature on the values of the specific growth rate could not be ignored as suggested in the literature. The specific growth rate value of 0.09 per day per degree centigrade best simulated the summer conditions in Vancouver Lake.

4. In verifying the validity of the water quality simulation models, actual field data should be available on a continuous basis for at least the critical periods in water quality.

SECTION II

RECOMMENDATIONS

It is recommended that the information developed in this study should be used as guidelines in the initial as well as final stages of modifications of the Vancouver Lake System. It is further recommended that the Environmental Protection Agency partially sponsor a study which would provide continuous monitoring of Vancouver Lake, under the post-modification period, of such water quality parameters as have been used in this simulation model study. The purpose of the recommended proposed study is to check the predicted results and then to make modifications in the water quality model so that the model can be used by others in analyzing other lakes by incorporating the changes corresponding to the conditions being studied.

SECTION III

INTRODUCTION

This study is one of several related studies conducted on Vancouver Lake which in its present condition is polluted and therefore is of limited value to the nearby communities of Vancouver, Washington and Portland, Oregon. However, this shallow inland body of water has the potential of becoming a useful multipurpose resource.

Description of the Study Area

Vancouver Lake (Figure 1) lies immediately northwest of the city of Vancouver, Washington and only four miles across the Columbia River from Portland, Oregon. The lake is bounded on the northwest, west and south by a low-lying ground area which separates the lake from the main channel of the Columbia River. To the east and the northeast, the lake is bounded by hills on which are located rapidly expanding residential areas. The lake has an average surface area of 2,600 acres. Except for periods of flooding, Vancouver Lake has an average depth of only three feet.

The principal inlet streams are Burnt Bridge Creek on the southeastern end and Lake River on the northern end of the lake. The Burnt Bridge Creek, containing high pollutional loads, drains from elevated hilly areas east of the lake where residential development is largely served with septic tanks. Lake River, which connects the lake with the Columbia River, reverses its flow direction with the change in the tides. The lake receives tidal flows from Lake River during high tides. Of the several tributaries that discharge into Lake River, Salmon Creek is the major tributary that receives significant loads of sediments and nutrients from the agricultural, industrial, and domestic activities located in its drainage basin. Seasonally, the inlet streams are heavily loaded with sediment, and organic and inorganic nutrients. The tidal flats at the north end of Vancouver Lake and the existing poor water quality are evidences of incoming pollution load.

Previous Studies

Prior to 1965, many agencies and individuals have made limited effort toward improving the usefulness of this lake through studies and various projects. A summary of these studies is included elsewhere.[(1)]

Vancouver Lake, Lake River and the separating lowlands constitute a 13,000 acre complex having 12 miles of Columbia River frontage. This complex has been and is being studied for recreational, industrial, agricultural and navigational development. One or more interconnecting channels between the lake and the Columbia River and dredging of

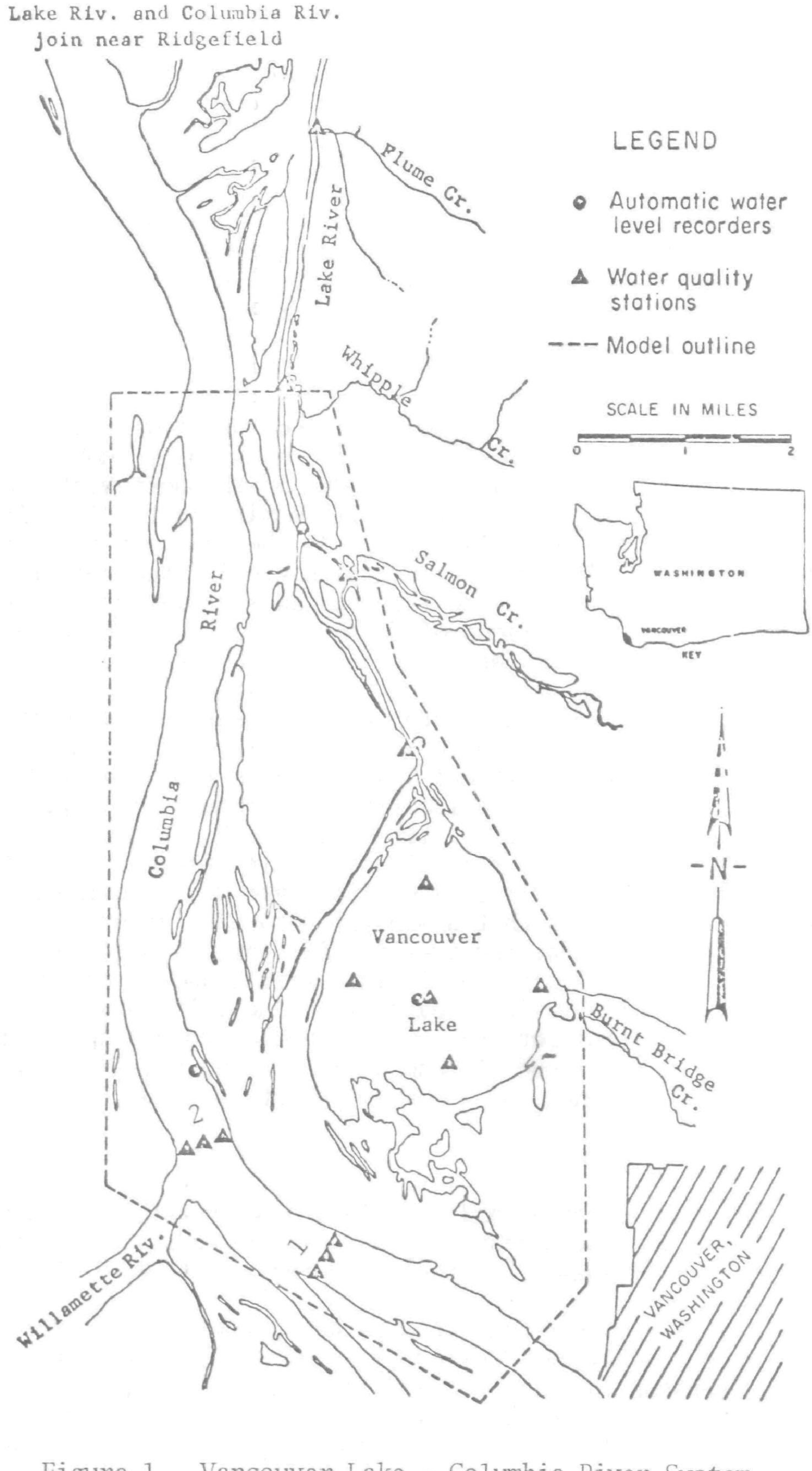


Figure 1. Vancouver Lake - Columbia River System

Vancouver Lake are being considered as possible methods of increasing lake use potential and as a water quality improvement measure. A study dealing with the development plan for the 13,000 acre complex was completed in September, 1967.[2] This study was sponsored by the Washington State Department of Commerce and Economic Development through a federal grant from the Department of Housing and Urban Development under the Urban Planning Assistance Grant Program authorized by Section 701 of the Housing Act of 1954, as amended. This study made an attempt to determine the location and the extent of land that should be assigned to the various uses of the complex. A wide variety of ideas for improving the quality of the water-land environment in order to enhance the usefulness of the area was proposed by this study and by others.

In 1966, the College of Engineering Research Division, Washington State University (WSU), was contacted by the Port of Vancouver to determine possible alternatives for restoring Vancouver Lake. After exploration, it was found that practically no water quality, hydrologic, hydrographic, and related water quantity data were available on Vancouver Lake, Lake River, or their tributaries. A preliminary proposal, indicating the need for various correlated studies which would establish a data base and then consider a broad range of alternative solutions for improving the quantity and quality of Vancouver Lake, was prepared. Between 1966 and 1969, separate proposals were submitted to the appropriate agencies and the funds were finally secured to undertake these studies. A flow chart of Vancouver Lake studies is shown in Figure 2 and a summary of the studies conducted by WSU is given below:

1. Hydroclimatic Study:[3] This study was sponsored by the Federal Water Pollution Control Administration and WSU, and it was completed in May, 1968. The primary purposes of the study were to determine: (a) the physical, chemical, biological and bacteriological water quality in Vancouver Lake-Lake River System, (b) the levels of nutrients and the types and populations of living organisms in the lake bottom sediments, and (c) the sources of pollution to the system.

2. Hydrologic Study:[4] This study was sponsored by the Port of Vancouver and WSU, and it was completed in September, 1971. The main purpose of this study was to determine the amount of water coming into and leaving Vancouver Lake under existing conditions.

3. Hydrographic Study:[5] This study was also sponsored by the Port of Vancouver and WSU and it was completed in September, 1971. The purpose of this study was to determine changes in depth and volume in the lake as a result of variations in inflow and outflow in the existing system.

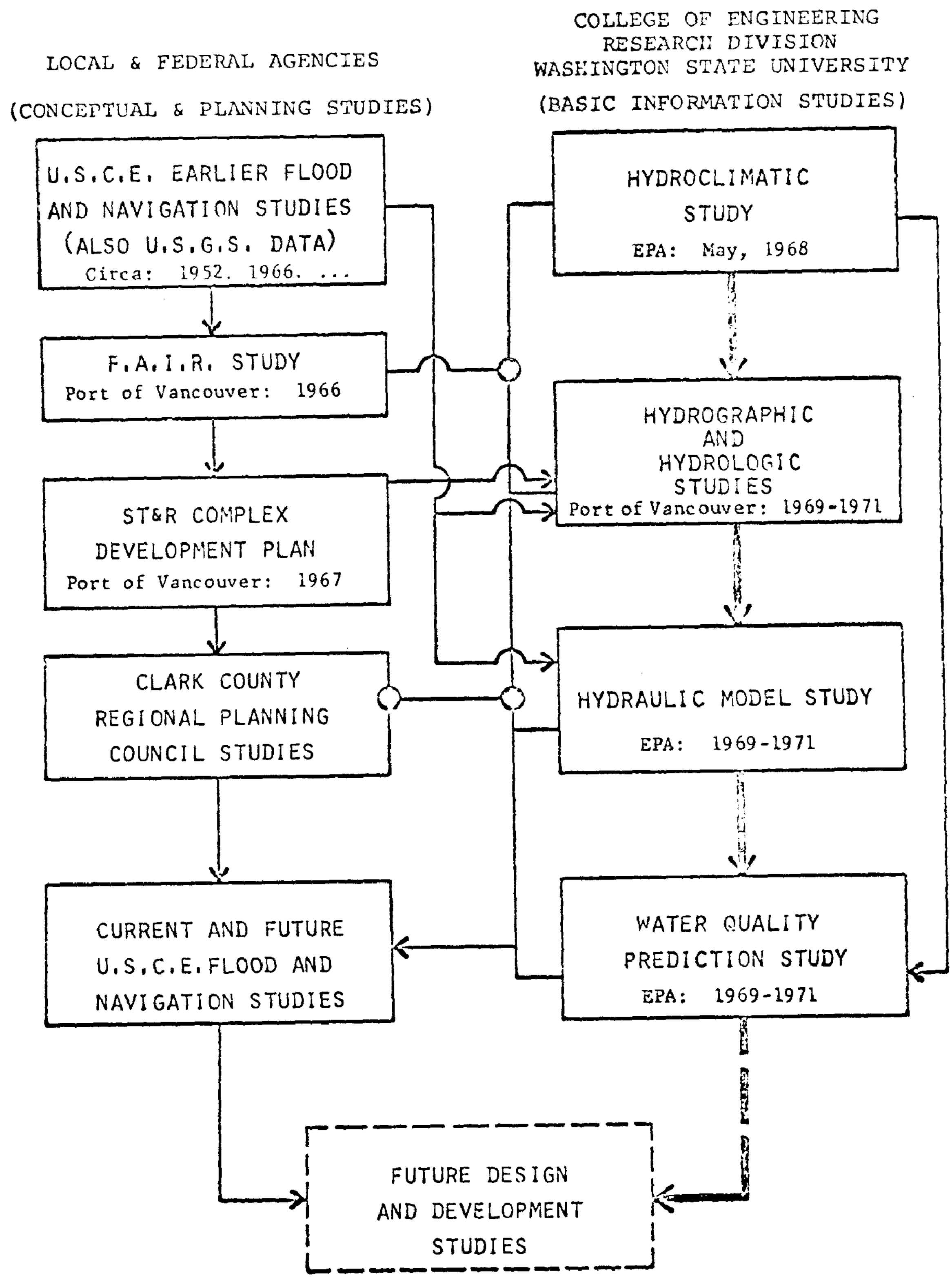


Figure 2. Flow Chart of Vancouver Lake Studies

4. Hydraulic Model Study:[6] This study was sponsored by Federal Water Quality Administration (now the Environmental Protection Agency) and WSU and it was completed in June, 1972. The main purpose of this study was to investigate the influence of alternate channel routes from the Columbia River into and out of Vancouver Lake on the flushing action in the lake, sedimentation and erosion patterns, detention times, river-lake stage relationships, and other factors which would influence flow into and out of Vancouver Lake.

Objectives

The purpose of this project was to combine the results of hydroclimatic, hydrologic, hydrographic, and hydraulic model studies with the quality of the proposed inflow from the Columbia River and evaluate the water quality which could be expected in Vancouver Lake. It was the intent of the project that water quality prediction techniques developed for Vancouver Lake could be applied to other shallow lakes.

Specific objectives included in this study are:

a. Determination of seasonal variations in water quality in the Columbia River in the vicinity of Vancouver, Washington,

b. Establishment of seasonal variations in water quality of Vancouver Lake under the present conditions,

c. Determination of diurnal variations in dissolved oxygen, temperature, etc. in Vancouver Lake during the critical conditions which generally occur in the month of August,

d. Determination of variations in nutrient levels in bottom sediments with sediment core depth, and

e. Development of a mathematical model for prediction of water quality in Vancouver Lake for the post-development conditions (dredging of the lake and connecting the south of the lake with the Columbia River through a channel or culverts).

SECTION IV

SAMPLING AND MEASUREMENTS

The Hydroclimatic Study,[3] which was completed in 1968, provided sufficient information on the seasonal variation of water quality in Vancouver Lake-Lake River System, the sources of pollution to the system, and the nutrient levels in the top few inches of the lake bottom sediments. However, additional information was necessary to achieve the objectives of this project and, hence, sampling and measurements were primarily directed toward determining the quality of water which might be diverted from the Columbia River to Vancouver Lake, determining the quality of the lake sediment core samples, and establishing the diurnal variations in water quality of Vancouver Lake.

Sampling

After careful study of the possible locations of Columbia River water diversion to the lake, two water quality sampling stations on the Columbia River were selected. These stations and the continuously monitoring station in the center of the lake are shown in Figure 1. Additional water quality stations shown in Figure 1 were used in the 1968 Hydroclimatic Study.

Based on low and high water levels and extreme seasonal changes, five detailed field water quality surveys of the Columbia River were made during December 1969, and in 1970 during the months of February, April, June and August. During each survey, water samples at surface, mid-depth and near bottom were taken at 1/4, 1/2, and 3/4 river widths at each station.

A self-propelled pontoon boat (Figure 3) was used for sampling and for some direct water quality measurements. The boat, having a deck area of 160 sq. ft., provided sufficient space for six people, storage of necessary equipment and instruments, and for on-the-spot measurement and analysis of some water quality parameters. The boat equipment included pH meters, dissolved oxygen probes and analyzers, thermisters, a sonar depth measuring instrument, conductivity meters, a VanDorn water sampler, homemade chemical kits for measuring alkalinity, hardness and dissolved oxygen (Winkler), turbidimeters, portable ice chests, portable bacteriological incubators, a submarine photometer, bottom organism sampling and identification equipment, various reagents for chemical testing and preserving of water and biological samples, a variety of sample containers and bottles, necessary glassware, bottom sediment coring equipment, etc.

Initially, the plan was to collect sediment core samples from five locations (north, south, east, west, and center) in the lake and three times during the study period. However, because of high water

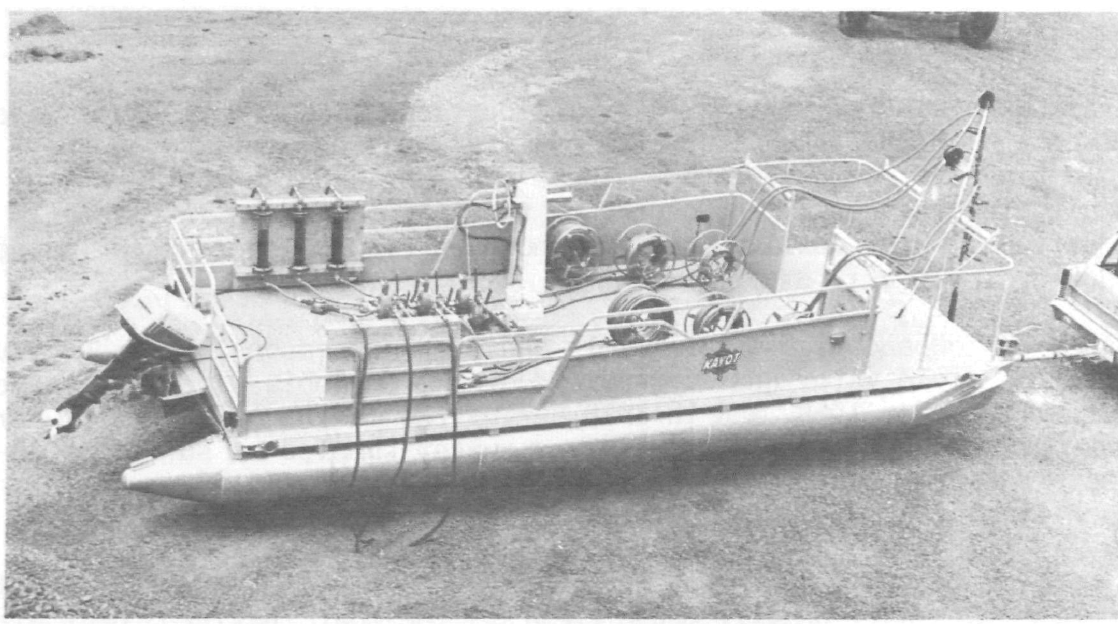


Figure 3. Pontoon Boat

conditions and the problem with the initial coring device, the extensive sampling of the lake was limited to the month of August in 1970. Sediment core sampler, which was borrowed from the Pacific Northwest Water Laboratory at Corvallis (now under EPA), did not prove to be entirely satisfactory for core sampling in Vancouver Lake. The bottom sediments in Vancouver Lake were rather compacted at places and were "soft" at other places. The Corvallis core sampler was designed for sampling soft bottoms. Therefore, a homemade coring device, which could be driven by hand or by hammering, was constructed. The device proved adequate for our needs. During the high water levels in the lake, the core sampling was limited to the shallow areas, and during the low water levels in August 1970, an extensive sediment core sampling was achieved.

Measurements

A variety of measurements, which provided information on the bacteriological, limnological, nutrient, and environmental aspects of water quality, was made during each of the field water quality surveys. Nearly all of the bacteriological, phytoplankton, physical, and some of the chemical analyses were made, within 12 hours of sampling, on the boat or in the nearby borrowed laboratories of Clark College and Sewage Treatment Plant of Vancouver. For other examinations and analyses, samples were properly stored and transported to Sanitary Engineering Laboratories in Pullman which is located about 350 miles east of Vancouver, Washington.

To acquire data, on a continuous basis, on the diurnal variations in levels of dissolved oxygen, temperature, pH, and conductivity in the lake during the critical period (low water levels and high water temperatures), the following setup was used. A floating wooden platform, 8' x 6', was installed in the center of Vancouver Lake. The platform was used to house instruments and a recorder which were operated on a continuous basis with rechargeable batteries. The calibration and operation of the system were checked once or twice a week. The system for monitoring dissolved oxygen, temperature, pH, and conductivity included a Hydro-lab water quality analyzer which consisted of five modules, housed in a main frame, for the simultaneous measurement of up to five water quality parameters, water quality sensing probes, a marine field scanner, and a strip chart recorder. The marine field scanner received output of each of the water quality variables from the main frame and it in turn transmitted this information to the strip chart recorder. The monitoring system (Figure 4) was completely portable.

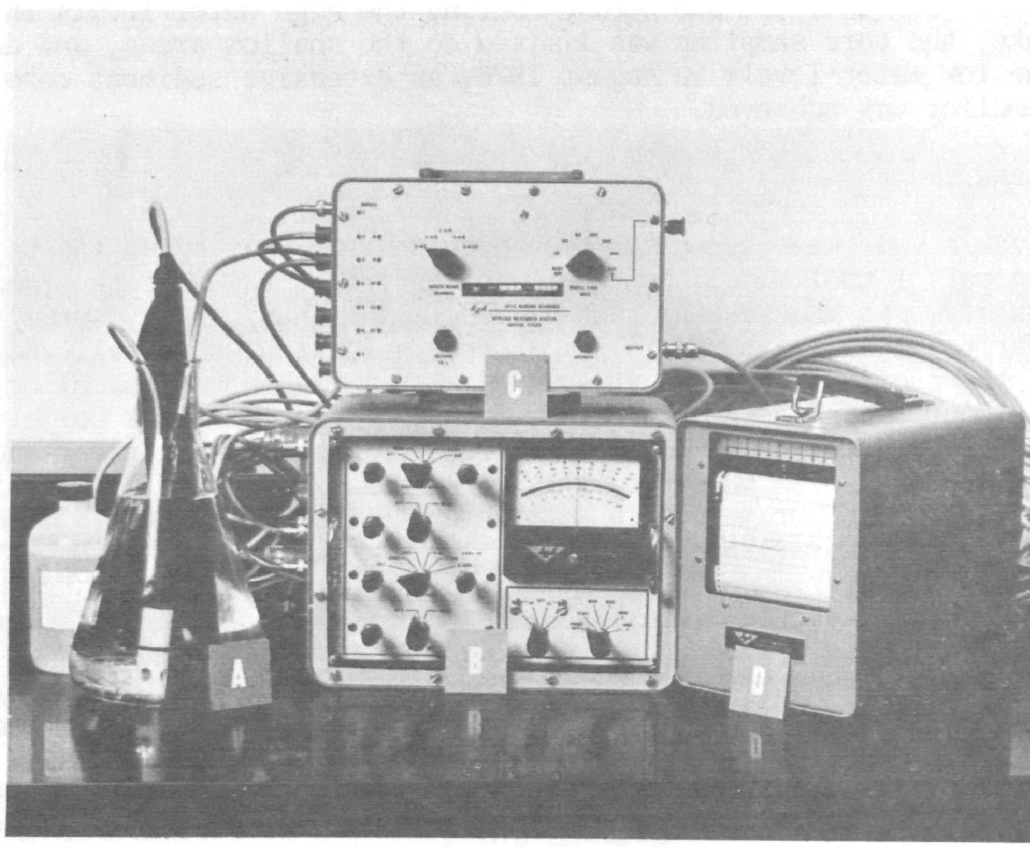


Figure 4. Portable Continuous Water Quality Monitoring System, A: sensing probes; B: main analyzer; C: scanner; D: strip chart recorder

SECTION V

WATER QUALITY OF THE COLUMBIA RIVER

Bacteriological Quality

The purpose of bacteriological examination of an aquatic environment has been, in the past and still is to a great extent, to measure the degree of potential hazard to public health. Public health consideration, beyond any doubt, should remain of high priority. However, water quality degradation caused by bacteria which do not directly affect public health but otherwise interfere with the normal uses of water should also be of concern. The case in point is the presence of bacteria of the genus Sphaerotilus, which are responsible for slime growths in streams. These slime growths have been known[7,8,9] to collect and clog the nets of fishermen, interfere with fish hatching by coating fish eggs, and smother aquatic flora and fauna that serve as food for fish.

Although bacterial water quality standards for most bodies of water in the U.S. are based on the total coliform density, it is believed by many public health bacteriologists that the widely used total coliform density is not adequate as the sole criteria for protecting public health. Geldreich[10] states that the fecal coliform density provides a better basis for protecting the public health during water-contact activities and that the fecal coliform test for monitoring water quality is the most accurate available. Measurements must be based on detection of fecal contamination by all warm-blooded animals. When fecal coliform densities are above 200 organisms per 100 ml, a sharp increase in the frequency of Salmonella detection is found in fresh water and estuarine pollution. According to Geldreich the recommended limit of 200 fecal coliforms per 100 ml for primary contact recreational water use is consistent with research findings. The State of Washington Class A interstate water quality standards state that total coliform organisms shall not exceed median values of 240 colonies per 100 ml with less than 20 percent of the samples exceeding 1,000/100 ml when associated with any fecal source. In accordance with the characteristic uses for Class A waters, the bacterial standards would permit water contact sports such as swimming, water skiing, etc., to be carried on without a hazard to public health.

The bacterial quality of Columbia River (designated as Class A stream) was assessed by examining the water for total coliforms (TC), fecal coliforms (FC), fecal streptococci (FS), plate counts (PC), Sphaerotilus counts (Sphaer), and pigmented bacteria (Pig). The detailed results are given in Table 1. The variation of total coliform density, fecal coliform and fecal streptococci data, and the total plate counts for the two stations and for the two river widths (total plate count data plotted only for 1/2 river width) are shown in Figures 5, 6, 7, 8, and 9. The data presented in these figures are averages of bacterial counts

Table 1. Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #1 1/4 Channel Width Surface Sample	Dec. 4, 1969	560	90	21	4.3	84	96,000	~500	30,000	31
	Feb 4, 1970	310	50	17	2.9	84	72,000	~200	8,700	12
	Apr. 7, 1970	~10	~2	~3	~0.8	~80	66,000	*	22,000	33
	June 12, 1970	20	0	0	0.0	100	33,000	*	2,600	8
	Aug. 4, 1970	400	36	2	18.0	91	20,700	*	~6,000	13
Station #1 1/4 Channel Width Mid-Depth	Dec. 4, 1969	370	34	10	3.4	91	40,000	*	16,400	41
	Feb. 4, 1970	340	78	26	3.0	77	71,000	~60	23,000	32
	Apr. 7, 1970	~40	<10	~4	-	~75	68,000	*	35,000	51
	June 12, 1970	<10	0	0	0.0	-	26,000	*	2,500	10
	Aug. 4, 1970	700	39	5	7.8	94	45,000	*	7,000	16
Station #1 1/4 Channel Width Near Bottom	Dec. 4, 1969	440	55	30	1.8	87	85,000	*	22,000	26
	Feb. 4, 1970	110	18	9	2.0	83	68,000	~800	21,000	31
	Apr. 7, 1970	~10	~3	~4	~0.7	~70	44,000	*	11,000	25
	June 12, 1970	100	~3	~1	~3.0	97	39,000	*	1,500	4
	Aug. 4, 1970	200	11	1	11.0	94	45,000	*	6,000	13

Table 1 (cont.). Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #1 ½ Channel Width Surface Sample	Dec. 12, 1969	300	3	1	~3.0	99	26,000	*	9,500	36
	Feb. 4, 1970	~30	13	7	1.8	56	66,000	*	16,000	24
	Apr. 7, 1970	<10	0	0	0.0	-	20,600	~10	7,100	34
	June 12, 1970	<10	1	0	~1.0	-	6,900	*	1,500	20
	Aug. 4, 1970	800	8	2	4.0	99	7,500	~10	1,600	21
Station #1 ½ Channel Width Mid-Depth	Dec. 4, 1969	300	7	3	2.3	97	37,000	*	9,000	24
	Feb. 4, 1970	~12	12	13	0.9	0	61,000	*	7,000	11
	Apr. 7, 1970	<10	0	~1	-	-	36,000	*	13,000	36
	June 12, 1970	<10	2	2	~1.0	~80	7,700	*	2,300	30
	Aug. 4, 1970	300	10	4	2.5	97	10,600	*	2,100	20
Station #1 ½ Channel Width Near Bottom	Dec. 4, 1969	400	5	1	5.0	99	39,000	*	10,000	25
	Feb. 4, 1970	>9	9	7	1.2	0	70,000	*	14,000	20
	Apr. 7, 1970	<10	0	0	-	-	20,000	*	8,000	40
	June 12, 1970	<10	1	0	-	-	8,000	*	2,400	30
	Aug. 4, 1970	700	-	1	0.0	100	10,100	*	1,500	15

Table 1 (cont.). Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #2 1/2 Channel Width Surface Sample	Dec. 12, 1969	600	47	27	1.7	92	42,000	~200	11,000	26
	Feb. 4, 1970	~20	17	5	3.4	15	62,000	*	18,000	29
	Apr. 7, 1970	<10	~2	0	~2.0	-	400,000	*	190,000	47
	June 12, 1970	<10	3	0	~3.0	-	220,000	*	4,200	19
	Aug. 4, 1970	3,100	200	14	14.3	94	179,000	*	27,000	15
Station #2 1/2 Channel Width Mid-Depth	Dec. 12, 1969	300	8	0	1.0	97	31,000	*	14,000	45
	Feb. 4, 1970	80	63	11	5.7	21	87,000	~200	20,000	22
	Apr. 7, 1970	~40	~1	~3	~0.3	~97	100,000	*	37,000	37
	June 12, 1970	<10	1	0	~0.1	-	21,000	*	3,600	17
	Aug. 4, 1970	2,300	180	12	15.0	92	143,000	*	18,000	13
Station #2 1/2 Channel Width Near Bottom	Dec. 12, 1969	100	10	22	0.45	90	34,000	*	13,000	38
	Feb. 4, 1970	150	56	11	5.0	62	89,000	~100	22,000	25
	Apr. 7, 1970	~10	~3	0	~3.0	~70	87,000	*	37,000	42
	June 12, 1970	100	2	0	~2.0	98	27,000	*	5,000	19
	Aug. 4, 1970	5,000	~200	20	10.0	96	187,000	*	20,000	11

Table 1 (cont.). Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #2 1/4 Channel Width Surface Sample	Apr. 7, 1970	~50	~50	~40	~1.2	0	125,000	~200	52,000	41
	June 12, 1970	30	18	4	4.5	40	32,000	*	2,300	7
	Aug. 4, 1970	5,600	268	17	15.7	95	120,000	*	14,000	11
Station #2 1/4 Channel Width Mid-Depth	Apr. 7, 1970	>70	~70	~5	~14.0	0	97,000	~100	41,000	42
	June 12, 1970	20	9	0	~9.0	55	41,000	~100	5,500	13
	Aug. 4, 1970	8,700	280	24	11.6	97	220,000	*	21,000	9
Station #2 1/4 Channel Width Near Bottom	June 12, 1970	90	12	0	~12.0	87	64,000	*	9,000	14
	Aug. 4, 1970	9,200	273	30	9.1	97	212,000	*	48,000	23

Table 1 (cont.). Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #1 3/4 Channel Width Surface Sample	Apr. 9, 1970	<10	0	0	0.0	-	3,400,000	*	2,680,000	78
	June 12, 1970	<10	4	0	~4.0	-	8,000	*	2,300	29
	Aug. 4, 1970	700	22	~4	~5.5	97	10,900	~100	2,200	20
Station #2 3/4 Channel Width Surface Sample	Apr. 4, 1970	<10	0	0	0.0	-	31,000	*	6,000	19
	June 12, 1970	10	0	1	0.0	~100	16,900	*	4,800	28
	Aug. 4, 1970	4,200	189	10	18.9	96	65,000	*	10,000	15
Station #2 3/4 Channel Width Mid-Depth	Aug. 4, 1970	7,500	192	12	16.0	97	82,000	*	4,500	5

Table 1 (cont.). Bacteriological Water Quality of Columbia River at Vancouver - Portland

Sampling Station	Date	TC	FC	FS	FC/FS	%NFC	PC/ml	Sphaer/ml	Pig/ml	%Pig
Station #2 3/4 Channel Width Near Bottom	Aug. 4, 1970	3,100	140	~5	~28.0	95	41,000	*	3,600	9

TC = Total Coliforms No./100mls
FC = Fecal Coliforms No./100mls
FS = Fecal Streptococci No./100mls
FC/FS = Ratio of Fecal Coliforms to Fecal Streptococci
%NFC = Percent of Nonfecal Coliforms
PC/ml = Total Count/ml
Sph/ml = Sphaerotilus/ml
Pig/ml = No. Pigmented Bacteria/ml
%Pig = Percent of Pigmented Bacteria

* Below level of detection at 1:10 dilution
- No calculated value

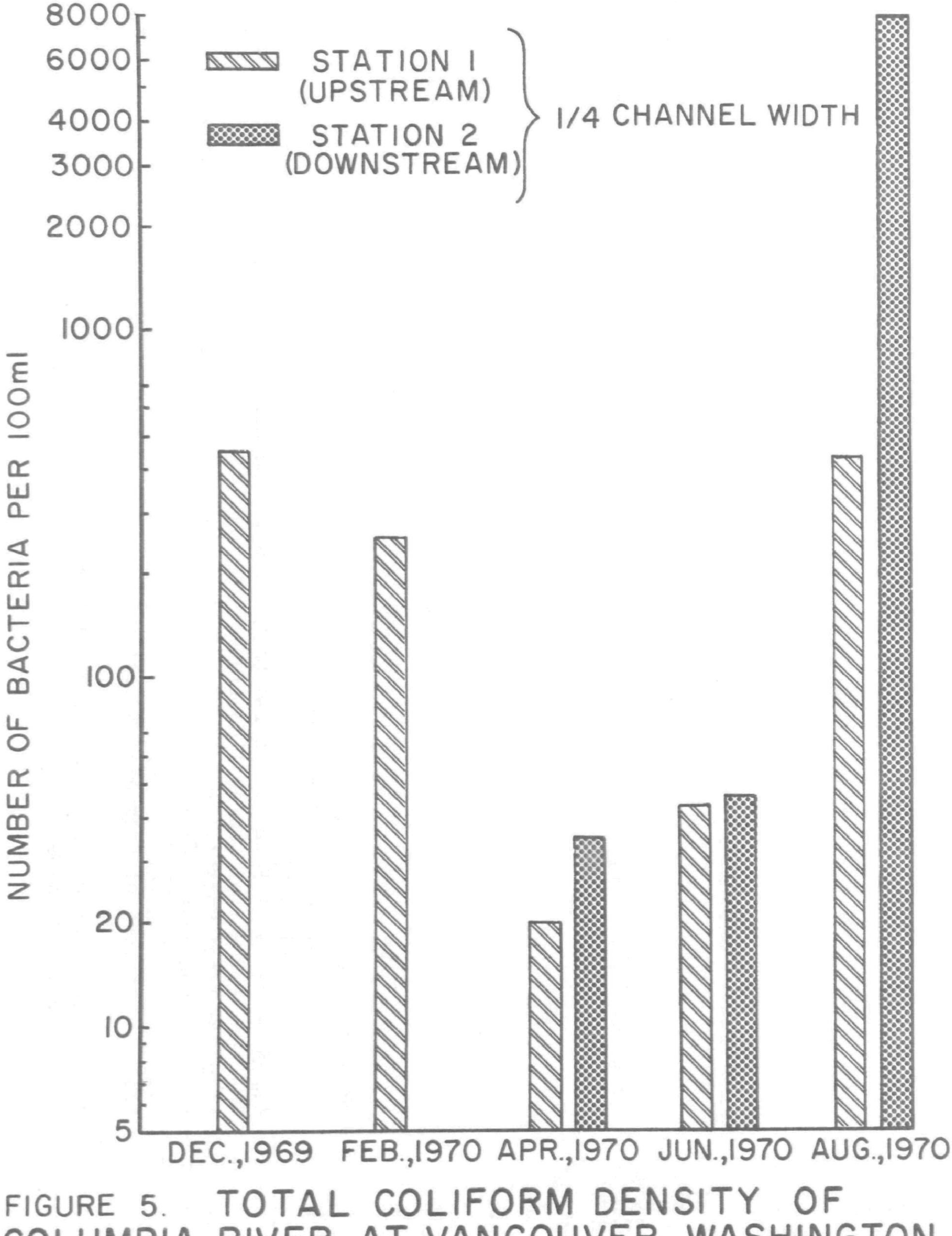


FIGURE 5. TOTAL COLIFORM DENSITY OF COLUMBIA RIVER AT VANCOUVER, WASHINGTON

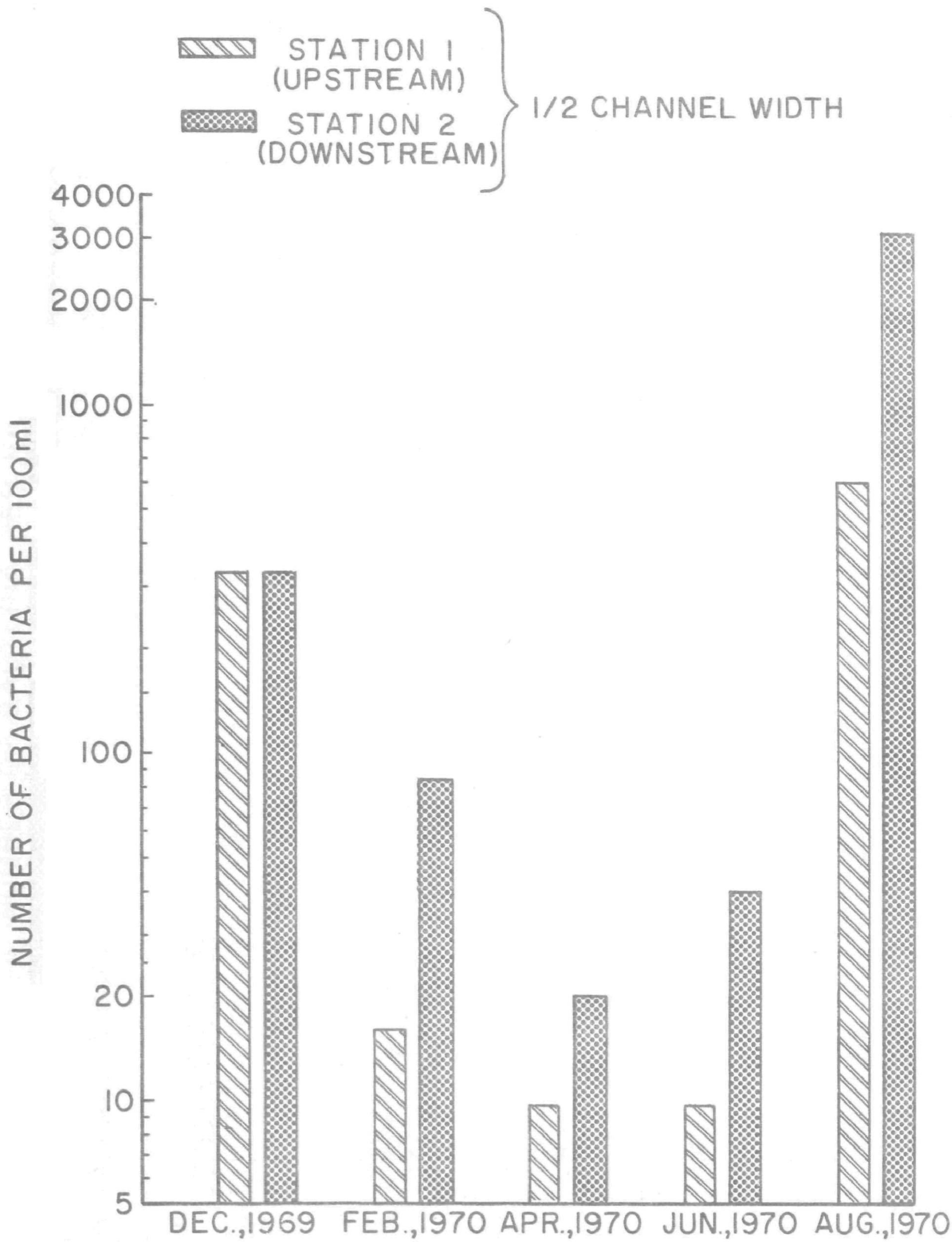


FIGURE 6. TOTAL COLIFORM DENSITY OF COLUMBIA RIVER AT VANCOUVER, WASHINGTON

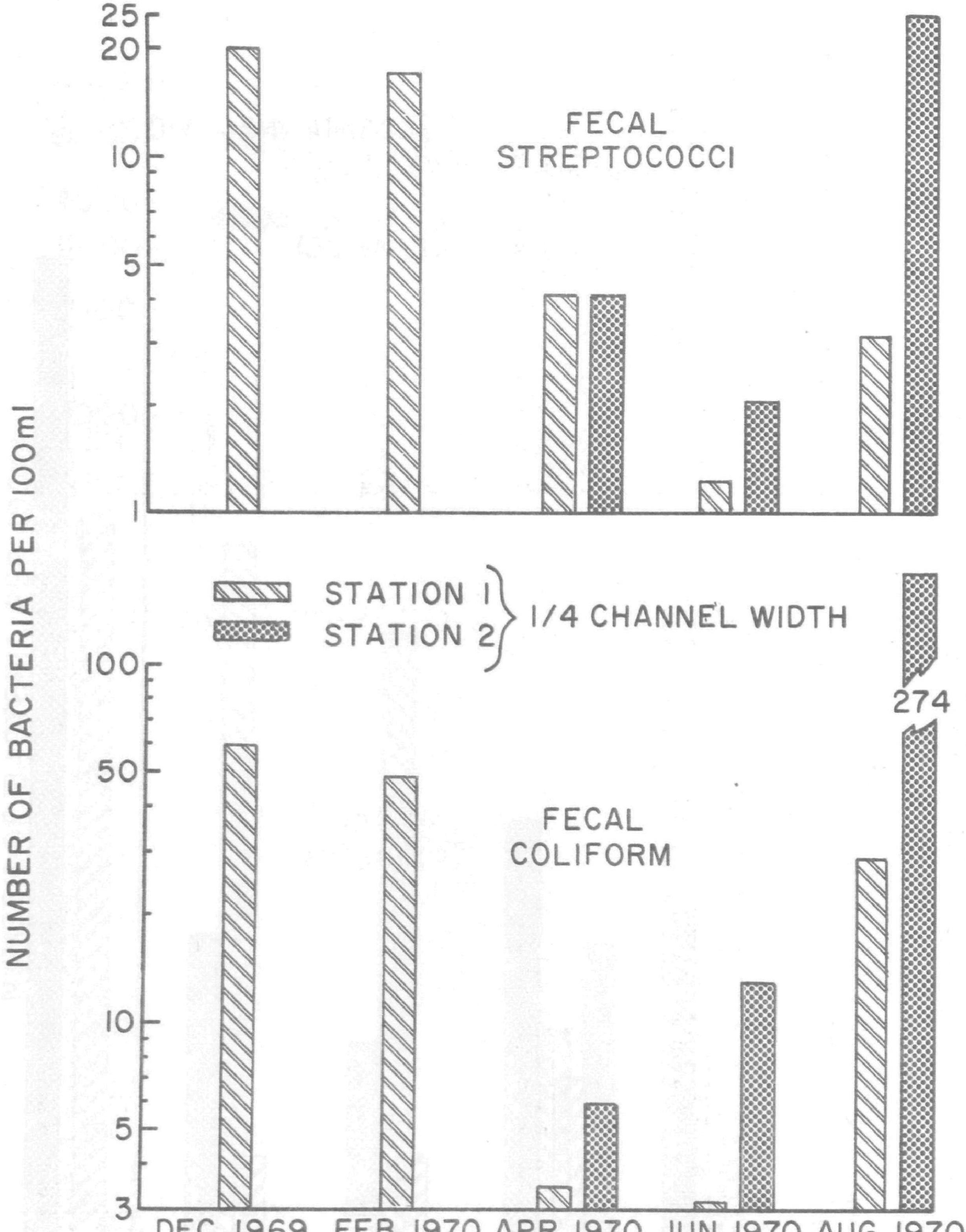


FIGURE 7. FECAL COLIFORMS AND FECAL STREPTOCOCCI DATA OF COLUMBIA RIVER AT VANCOUVER, WASHINGTON

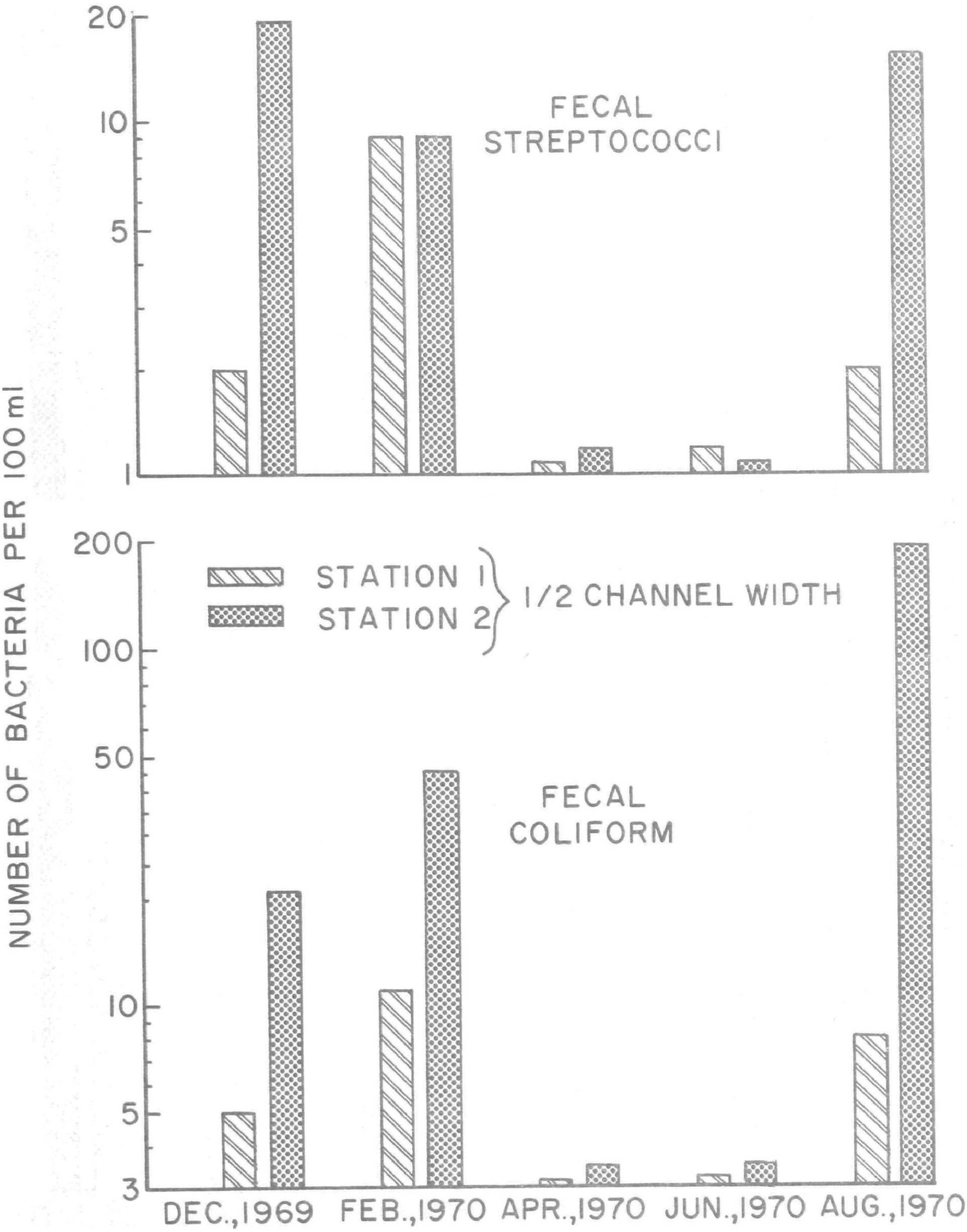


FIGURE 8. FECAL COLIFORMS AND FECAL STREPTOCOCCI DATA OF COLUMBIA RIVER AT VANCOUVER, WASHINGTON

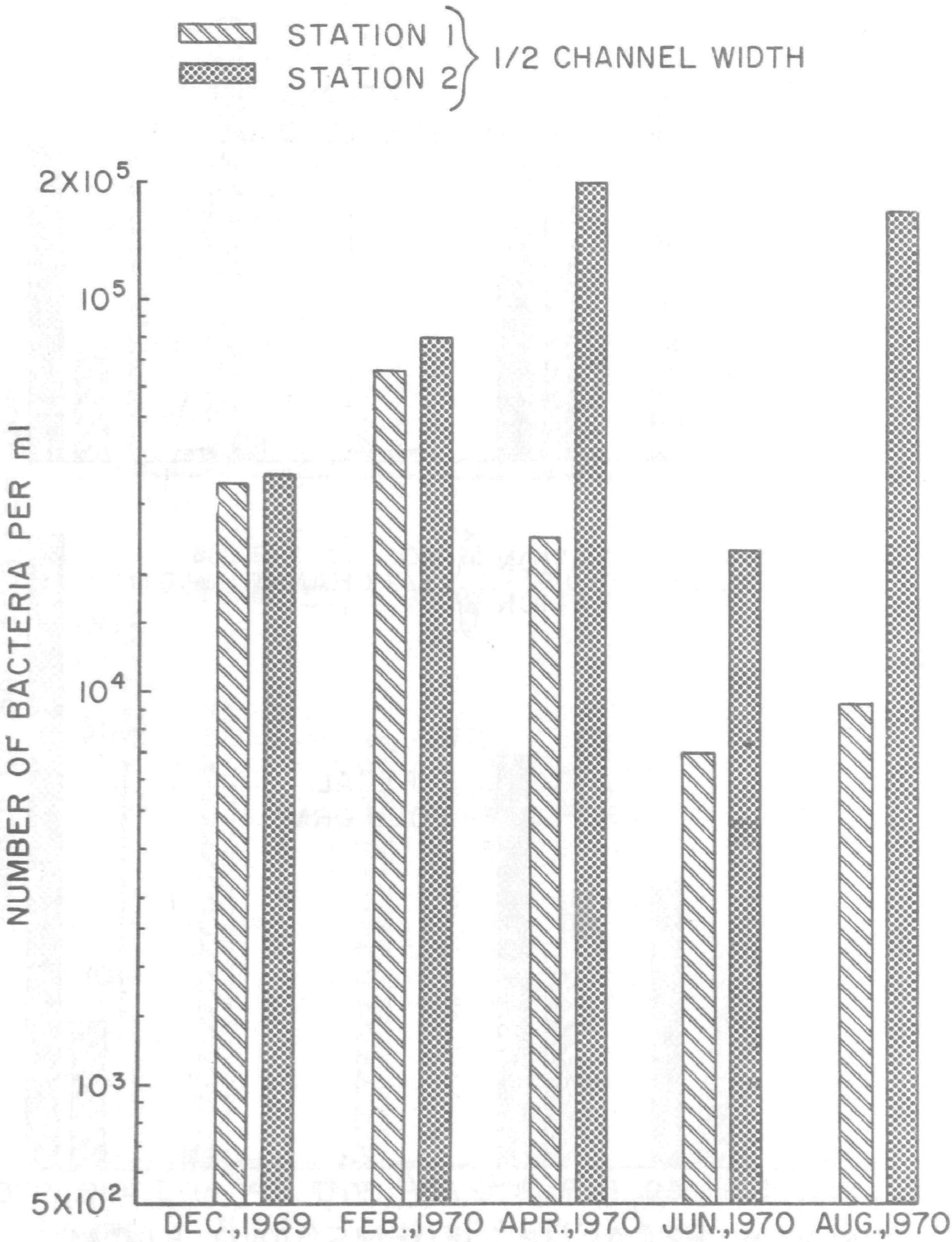


FIGURE 9. TOTAL PLATE COUNT DATA OF COLUMBIA RIVER AT VANCOUVER, WASHINGTON

measured at water surface, mid-depth, and near bottom. Generally, the bacterial counts at station 2, the downstream station, were higher than at station 1, the upstream station. Also, the counts were generally higher in winter months and late summer period than in early summer months. It appears that the bacterial intensity is inversely proportional to the flow in the Columbia River. The flow of the Columbia River varies considerably during the year with flow increasing gradually during March and April, increasing abruptly during May and June, and decreasing again in July. The flow normally remains low during the fall and winter months, although high water can occur during the winter months.

In examining Figures 5 and 6, it can be seen that the median value for TC is well within the Class A stream standards. It should be noted, however, that the TC counts were excessively high during August. The counts of FC were below 200 organisms per 100 ml in all cases except in August at 1/4 channel width at station 2 (Figures 7 and 8). Also, the ratio of FC/FS, in most cases, was greater than 0.6 (Table 1) indicating that contamination was largely from domestic sewage. Geldreich et al.[11] and Kenner et al.[12] report that the ratio of FC/FS for man is 4.4 and that for other warm-blooded animals it is 0.6 or less. Table 1 further indicates that, in most cases, the fecal coliforms constituted less than 30% of the total coliforms. In summary, bacterial quality of the Columbia River as it exists today should present no health hazard to the public in its use of the river for water-contact recreation.

Generally, the presence of Sphaerotilus in the Columbia River water was measurable in winter months and the levels in summer months were generally below the detectable limit. The significance of 10 to 800 Sphaerotilus organisms per ml that have been detected in our sampling in the Columbia River has not been determined so far as proposed diversion of river water to Vancouver Lake is concerned.

The chromogenic or pigmented bacteria are comprised of those bacteria able to form visible pigmented colonies on modified Henrici's agar at room temperature in 2 days. Chromogenic colonies ranged in color from light yellow through yellow orange and red orange and from pink to red with some purple colonies. Preliminary identification placed them in the genera Flavobacterium, Xanthomonas, Pseudomonas, Brevibacterium, and Micrococcus. Most of the isolants were gram negative rods. Some colonies produced a melanin-like diffusible black pigment. The significance of the organisms is not known at present.

The numbers of chromogenic bacteria are indicative of the overall quality of surface waters. The populations of chromogenic bacteria in the Columbia River was in agreement (Table 1) with the findings of other investigators.[13,14,15] Plating media with reduced amounts of nutrients are in many instances replacing the standard plate count agar (Standard Methods). Chromogenesis is more evident when the organisms are grown on a low nutrient medium. The numbers chromogenic bacteria usually comprise are about 20 to 40% of the total populations capable of growing on low nutrient media.[14,15,16] The pigmented average 24% of the total colony count with a range of 4 to 78% in Columbia River waters. Waters of exceptionally high quality (arctic lakes) may exhibit only 5% of the total population as chromogenic.[17] During our investigation, a 5% figure was observed only once (Table 1).

It is desirable in a comprehensive bacteriological survey of surface waters to enumerate not only the bacteria of sanitary significance but also to enumerate those indigenous to the stream. The results of previous studies indicate that total counts in relatively unpolluted streams average 4.0×10^4 bacteria per ml.[13,18,19] The average total count for Columbia River waters is 6.0×10^4 bacteria/ml (Table 1). This average is not significantly higher than those of previous investigations. High quality waters usually exhibit values of approximately 3.0×10^3 bacteria per ml.[19,20] The difference in total counts from station 1 to station 2 can be attributed to urban influences. This type of impact has been well documented.[13,18] When the higher counts are considered with respect to the usual numbers encountered in highly polluted water (1.0×10^7), their significance is unimportant.[18,21]

Phytoplankton

At each of the two stations on the Columbia River, algae measurements were made at three equal river widths and at three water depths (surface, mid-depth, and near bottom) for each river width. The data indicated no major variations in the species and their numbers with respect to depth, width, or station but there were definite changes in species and their numbers with respect to time. These algae data are summarized in Table 2. It can be seen that the peak algae concentrations occurred in the month of June when the numbers reached 4,700 cells per ml. In April and in August the concentration ranged between 1,000 and 2,000 cells per ml whereas the concentration remained below 300 cells per ml during the months of December and February.

Table 2. ALGAE DISTRIBUTION IN THE COLUMBIA RIVER

	1969	1970			
	December	February	April	June	August
Total cells/ml	256	88	1060	4691	1682
Diatoms (%)	68.0	71.6	84.9	77.0	73.0
Greens (%)	15.2	14.8	0.0	15.2	11.0
Blue Greens (%)	0.0	0.0	0.0	0.4	0.7
Others (%)	16.8	13.6	15.1	7.4	15.3

Table 2 further shows the distribution of algae into the three groups--diatoms, greens, and blue greens. Diatoms were the predominant algae present in the Columbia River throughout the year, making up 68 to 85% of total algae. The greens constituted from 0 to 15%, blue greens less than 1%, and other unidentified species 7 to 17% of the total algae. The blue greens were observed only in the months of June and August.

Detailed tabulations of the algal species observed in the Columbia River are given in Appendices A and B. The relative abundance of algal forms observed in the months of December, February, April, June, and August are shown in Figures 10, 11, 12, 13 and 14, respectively. In December 1969, the most prevalent form was Asterionella and other prominent diatoms were Fragilaria, Melosira, and Stephanodiscus. Tribonema, belonging to the yellow greens, was the only other identifiable form present. All these forms were also observed in February 1970, but in smaller numbers, and the dominant form was Fragilaria which increased in numbers and remained dominant by April 1970. At that time another form, Melosira, was observed and by June this genus had surpassed other algae and showed a concentration of about 2,000 cells per ml at station 2. Other identified algae observed, in considerable numbers, in the month of June were Fragilaria, Tribonema, Asterionella, Stephanodiscus, Tabellaria, Scenedesmus, and Oscillatoria. A decrease in concentration of algae was observed in August 1970 and the forms identified in decreasing order were Tabellaria, Fragilaria, Stephanodiscus, Tribonema, Asterionella, Melosira, Scenedesmus, and Oscillatoria.

The fact that 85% of the algae that make up the phytoplankton population of the Columbia River are diatoms strongly indicates that the water quality of this stream is presently in good condition. This fact, coupled with the observation that blue greens make up only about 0.4 to 0.7% of the populations and these occur during the warmer months of late June through August, is another indication that these waters are in good condition. It is recognized that some blue greens are present in waters of excellent condition as well as certain diatoms are present in polluted waters, but the wide variety of clean water species is indicative of the overall water conditions. Over 50 different species of diatoms were represented--25-30 species of greens and only 5 species of blue greens--which gives an indication as to the variety of phytoplankton present. This variety and number of clean water species present would indicate that the body of water is in a mesotrophic state of nutrition.

Nutrients and Other Parameters

The detailed data on 5-day biochemical oxygen demand (BOD), chemical oxygen demand (COD), total solids (TS), total volatile solids (TVS), suspended solids (SS), volatile suspended solids (VSS), total phosphorus and soluble phosphorus expressed as PO_4, organic nitrogen, ammonia nitrogen, and nitrate nitrogen are given in Appendix C. A summary of

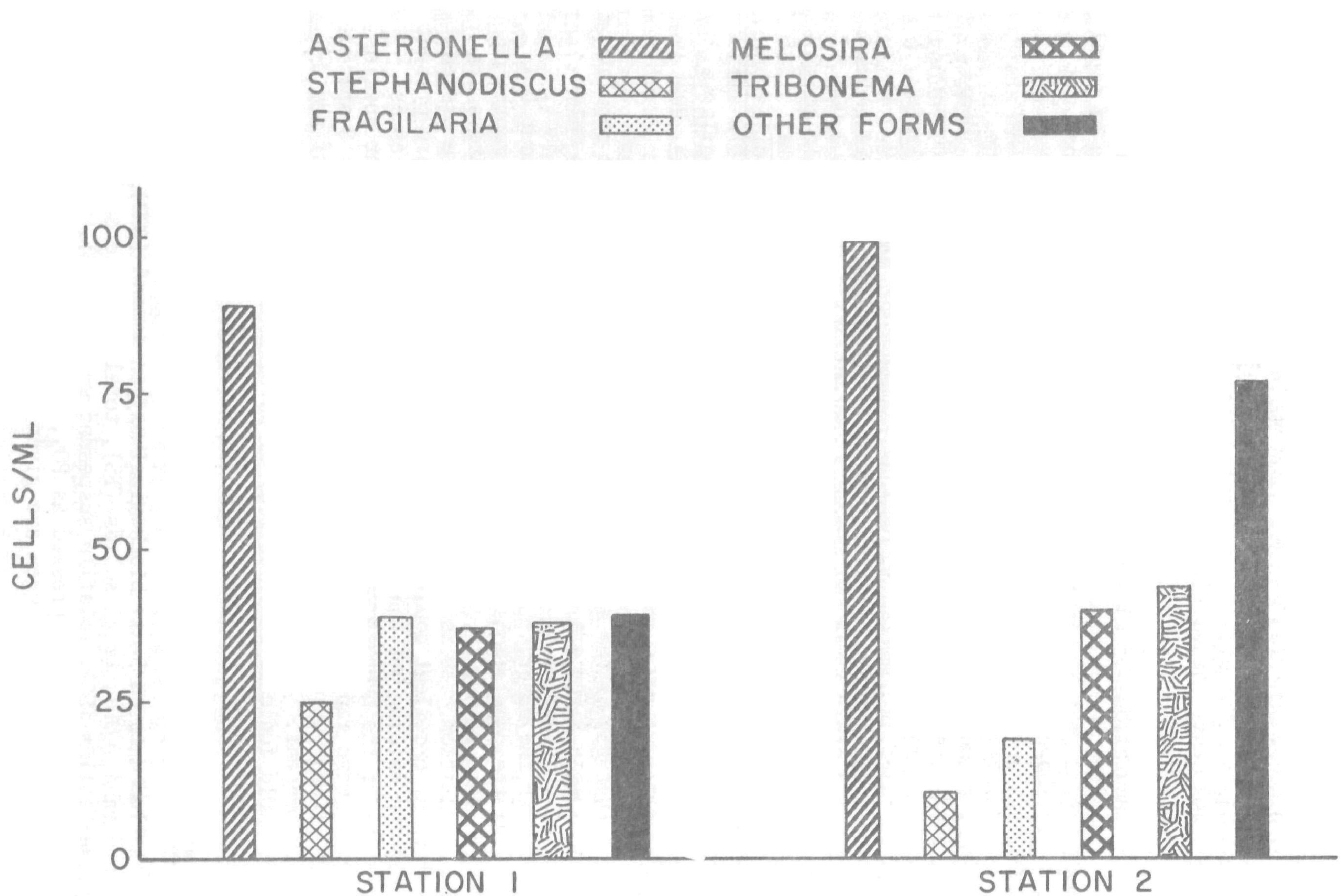


FIGURE 10. ALGAE OBSERVED IN COLUMBIA RIVER IN DECEMBER, 1969

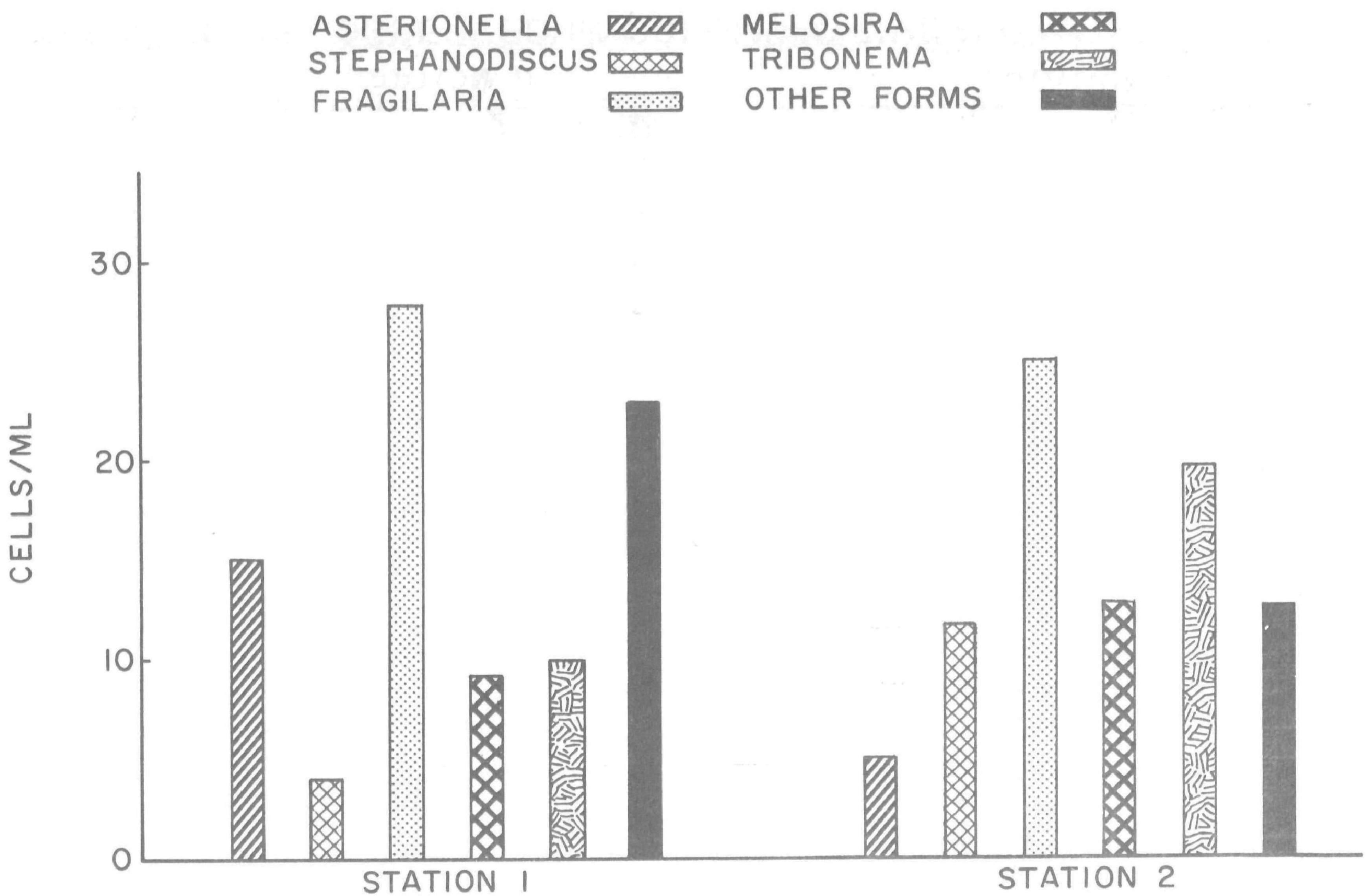


FIGURE 11. ALGAE OBSERVED IN COLUMBIA RIVER IN FEBRUARY, 1970

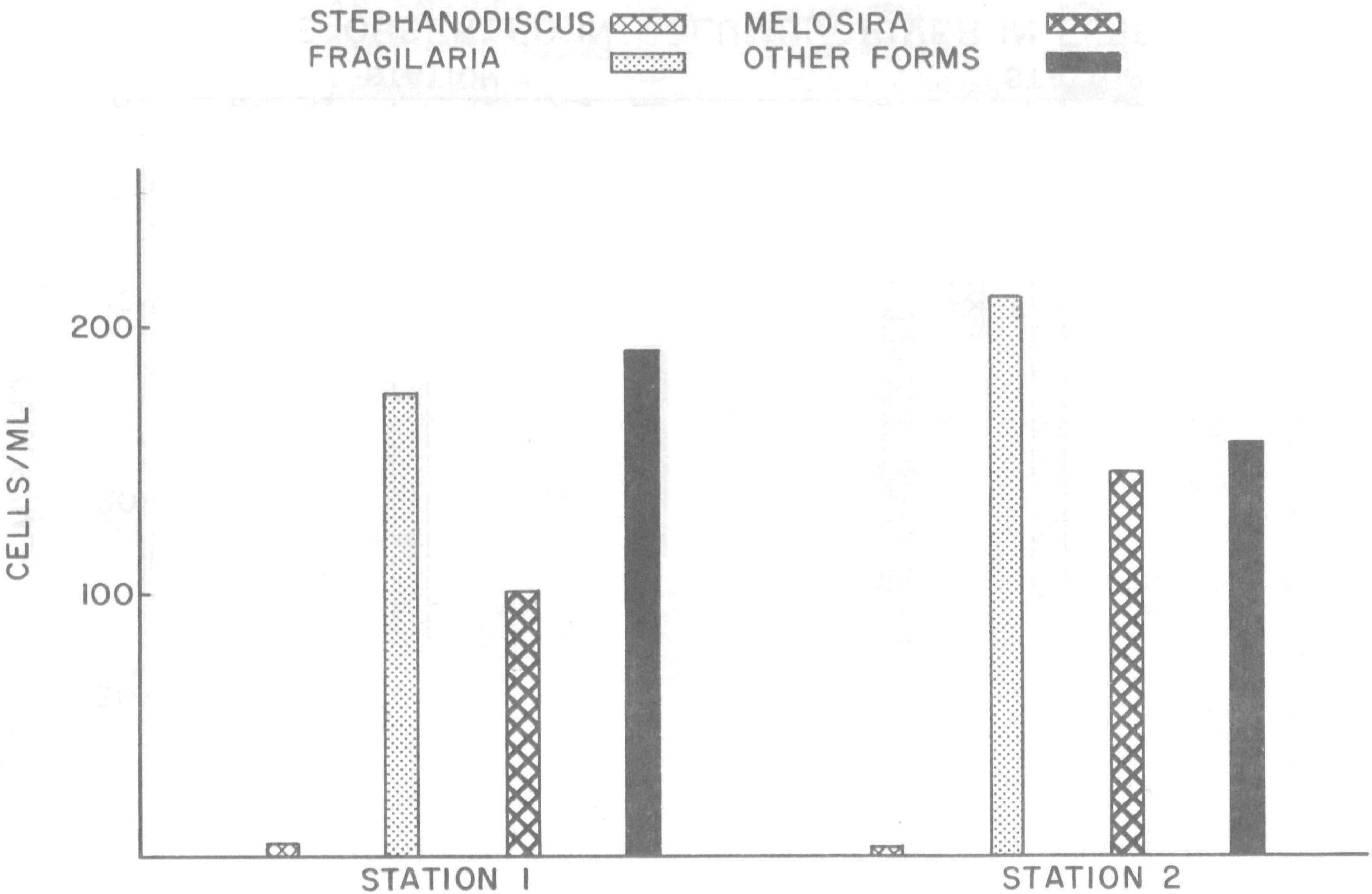


FIGURE 12. ALGAE OBSERVED IN COLUMBIA RIVER IN APRIL, 1970

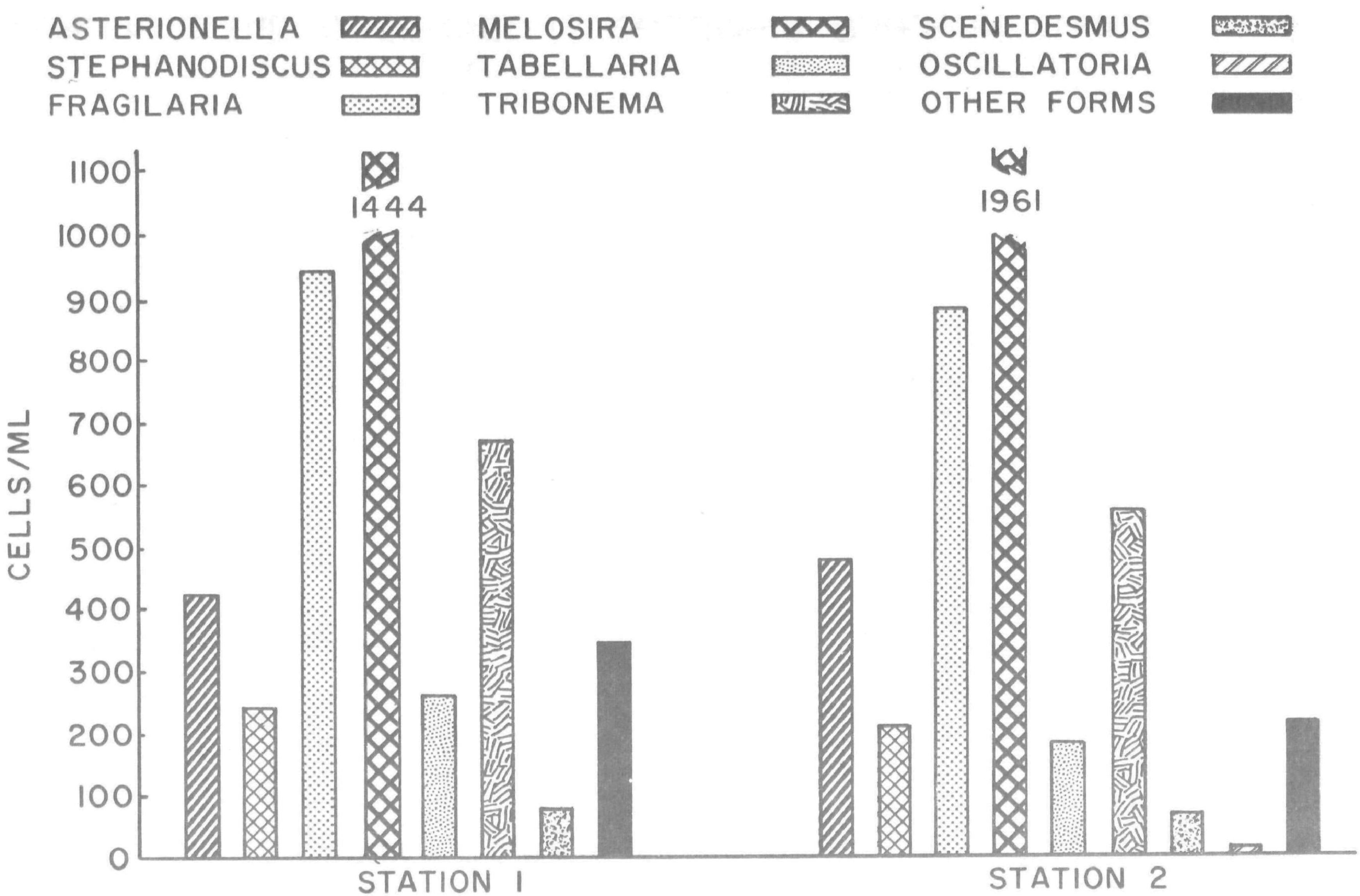


FIGURE 13. ALGAE OBSERVED IN COLUMBIA RIVER IN JUNE, 1970

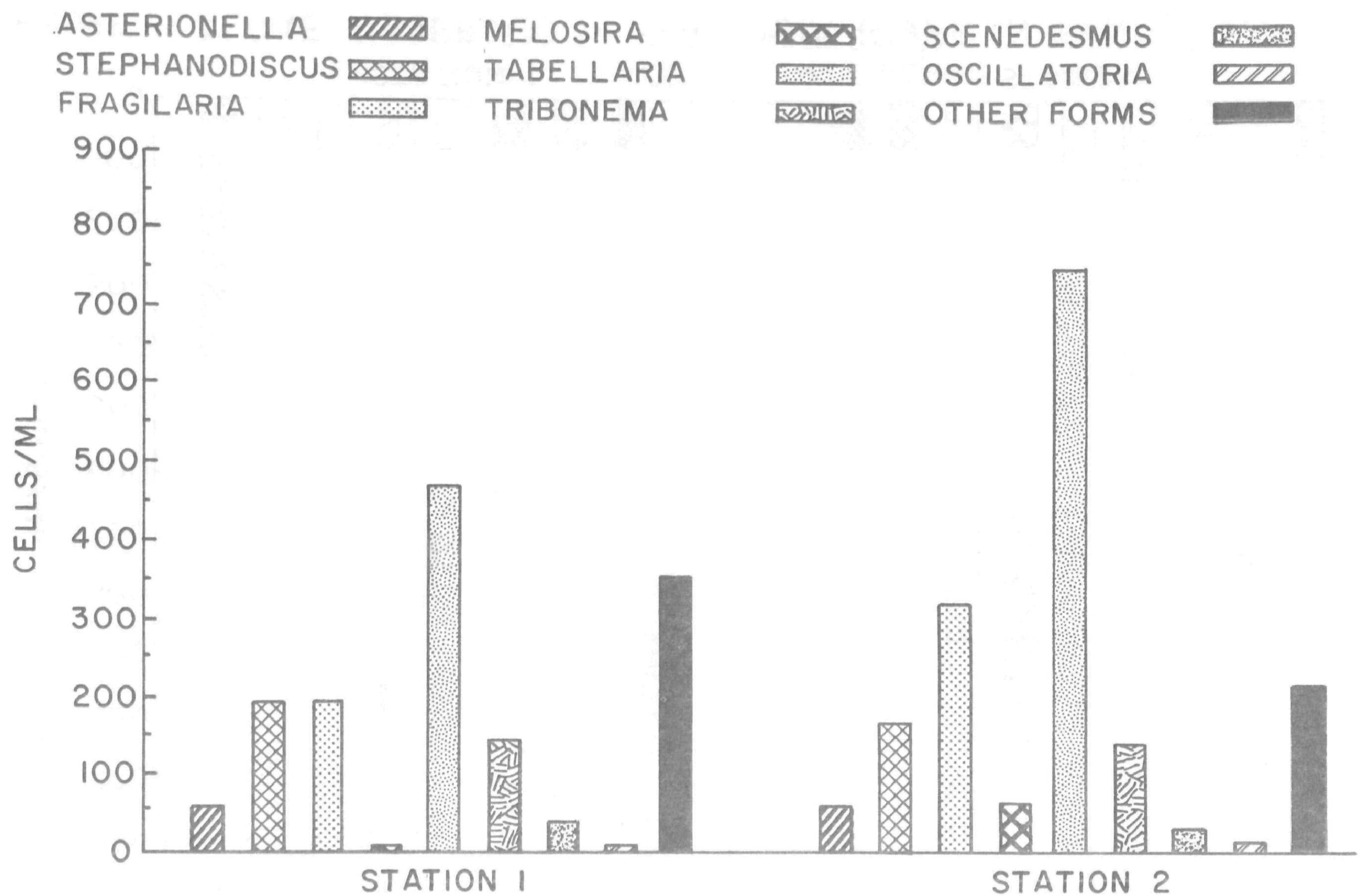


FIGURE 14. ALGAE OBSERVED IN COLUMBIA RIVER IN AUGUST, 1970

these parameters and also of other water quality parameters such as alkalinity, pH, hardness, sulfates, Pearl-Benson index (PBI), chlorides, dissolved oxygen, temperature, and conductivity is presented in Table 3. The values included in Table 3 are derived for the most part from the entire data collected at the two stations, three river widths at each station, and three depths for each river width.

The 5-day BOD values measured were always less than 2.0 mg/1 and the average was about 1.0 mg/1. The COD values ranged from 2.5 to 14.0 mg/1 with 5.8 mg/1 as the average.

Total nitrogen varied from 0 to 1.38 mg/1 and the average was about 0.35 mg/1 (Table 3). Most of the nitrogen measured was in the forms of nitrates and organic nitrogen. The nitrate levels gradually increased from December to April and then there was an abrupt drop from April to June (Figure 15). The organic nitrogen remained about constant from December to February and then gradually decreased from February to June. The ammonia levels stayed about constant during the study period.

The total phosphate levels ranged from 0.04 to 0.85 mg/1 as PO_4 with an average value of 0.23 mg/1. On the average, 50% of the phosphorus measured was in the soluble form and the remaining 50% was associated with the suspended solids.

Generally, the nitrogen and phosphorus levels were low (Figure 15) during the summer months when high biological activity was noticed (Table 2).

The concentration of total solids ranged from 68 to 180 mg/1 with an average value of 116 mg/1. On the average, about 30% of the total solids were volatile solids. The concentration of suspended solids varied from 0 to 35 mg/1 and the average was about 18 mg/1. On the average, about 33% of the suspended solids were volatile.

The measurements summarized in Table 3 indicate that the water quality of the Columbia River, at present, is in good condition and the river can be used for recreational and other purposes. The levels of phosphorus are higher than 0.01 mg/1 as P, the border-line level recognized by some and disputed by others, between eutrophic and non-eutrophic waters.

Table 3. SUMMARY OF COLUMBIA RIVER WATER QUALITY

	Concentration, mg/1			
	Minimum	Maximum	Average	σ
BOD	0	2.1	1.0	0.44
COD	2.5	14.0	5.8	2.50
NH_3-N	0	0.15	0.05	0.036
Org-N	0	0.53	0.11	0.072
NO_3-N	0	0.70	0.19	0.18
Total P-PO_4	0.04	0.85	0.23	0.13
Soluble P-PO_4	0.01	0.72	0.12	0.11
TS	68	180	116	23
TVS	18	64	34	9
SS	0	35	18	8
VSS	0	15	6	4
pH	7.6	8.2	8	
Alk-$CaCO_3$	18	79	47	20
Hardness-$CaCO_3$	18	78	63	13
SO_4	0	11	6.6	2
PBI	0	0.52	0.1	0.13
Cl	2.3	5.5	4.1	1
DO	8	12	9	
+Temp.	4	21		
*Conductivity	65	210	167	36

*Conductivity is given in units of μ mhos

+Temp. is given in °C

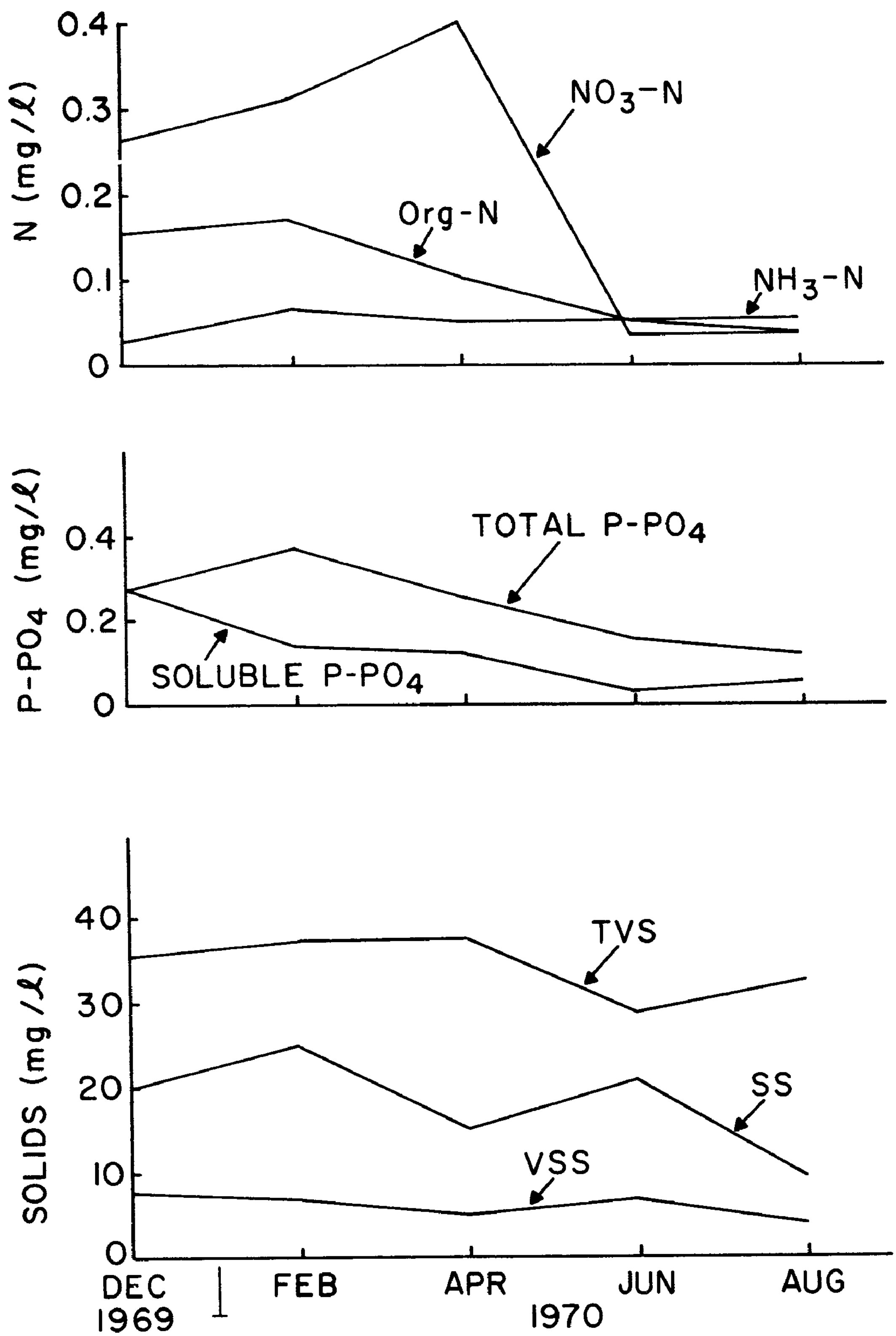


FIGURE 15. NUTRIENT LEVELS IN COLUMBIA RIVER AT VANCOUVER, WASHINGTON

SECTION VI

QUALITY OF VANCOUVER LAKE SEDIMENTS

Quality of Vancouver Lake bottom sediments was assessed by measuring the organic matter, phosphorus, and nitrogen levels in the sediment core samples collected throughout the lake. Also, the potential of these sediments to support phytoplankton populations was evaluated on a qualitative basis. A few samples were analyzed by the method of neutron activation analysis to determine the levels of some of the trace elements available in the lake sediments. Data on bottom organisms as collected previously(3) are also summarized.

Nutrients

Generally, the nutrient levels in the top six inches of bottom sediments were higher than in the remaining core. There were some pockets of high nutrient levels observed even at deeper than six inches of core depth. Typical vertical profiles of nutrient levels in Vancouver Lake bottom sediments, as observed in August 1970, are shown in Figure 16. It should be noted that the ammonia-nitrogen levels increased with core depth whereas organic nitrogen, phosphorus, COD and volatile solids, generally, decreased with core depth.

It should also be mentioned that previous findings(3) indicate that the levels of nutrients in the top layers of Vancouver Lake bottom sediments were the highest in the winter months and the lowest in the late summer period.

The minimum, maximum, and average values of organic carbon, nitrogen, and phosphorus derived from the 43 Vancouver Lake sediment analyses are summarized in Table 4. A similar analysis of "sewage sludge in river" as found by others(22) is also included in this table for comparison. It can be seen that the bottom sediments of Vancouver Lake come close to resembling "sewage sludge in river."

Table 4. CARBON, NITROGEN, AND PHOSPHORUS IN VANCOUVER LAKE BOTTOM SEDIMENTS

				Ratio	
	%C	%N	%P	C:N	N:P
Maximum	2.66	0.31	0.14	20	4
Minimum	0.40	0.05	0.06	4	0.5
Average	2.00	0.20	0.10	10	2
Sewage Sludge in River(22)	5.8	0.28	0.18	21	2

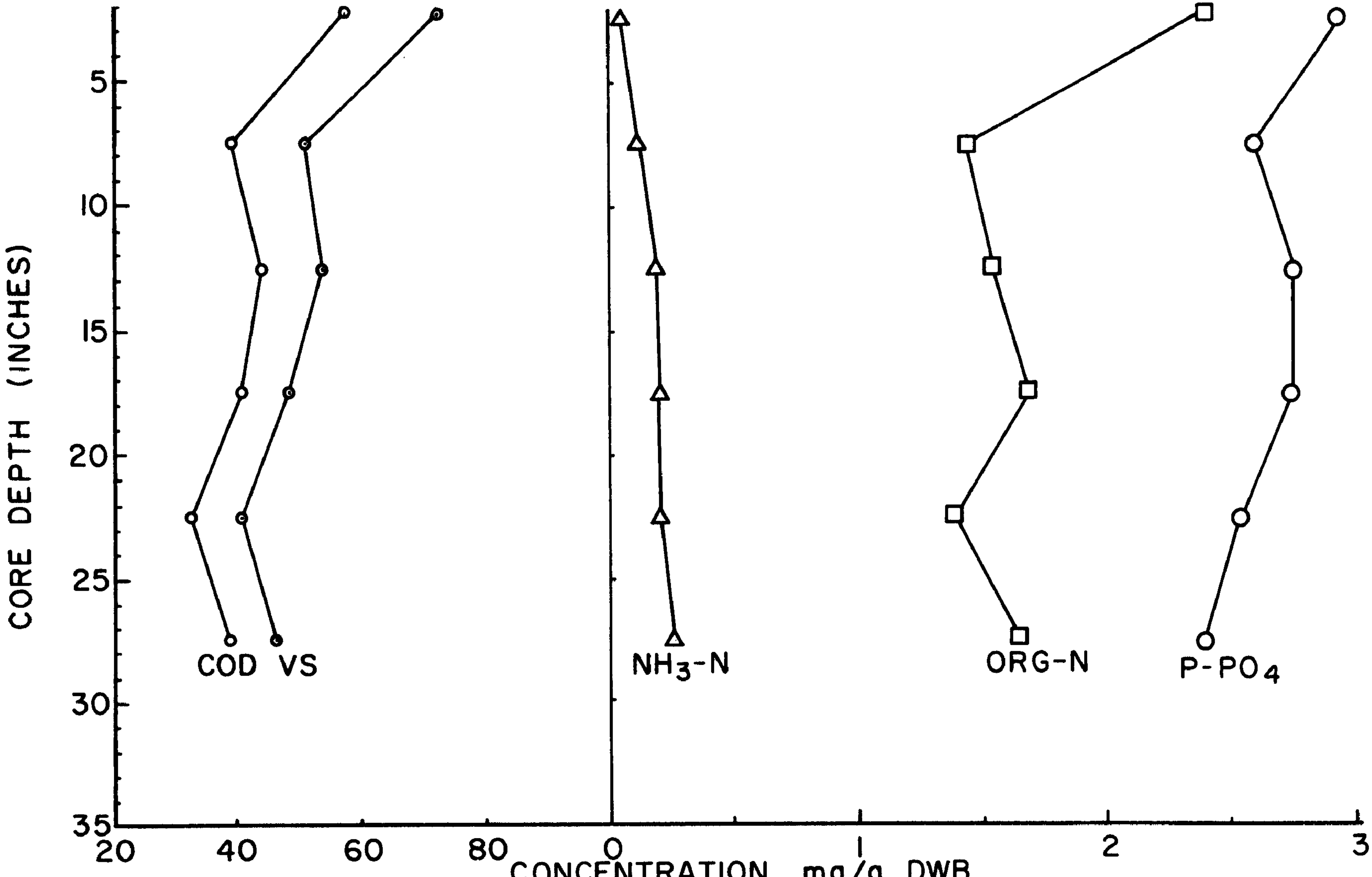


FIGURE 16. VERTICAL NUTRIENT PROFILE OF VANCOUVER LAKE BOTTOM SEDIMENTS

Also, organic sediment index (OSI), which is a product of percent organic nitrogen and percent carbon measurements of sediments, was computed and the values of OSI for Vancouver Lake sediments varied from 0.02 to 0.82 with an average value of 0.4. According to the classification suggested by Ballinger and McKee,[23] the Vancouver Lake sediments fall between type I and type II sediments. The type I sediments represent sand, clay, and old stable sludge, and the type II sediments represent organic detritus, peat, and partially stabilized sludge.

Laboratory studies[24] with lake bottom sediments from three lakes in west-central Minnesota indicated that the sediments can act as reservoirs of orthophosphate and that the release of orthophosphates from the sediment to the water takes place when the phosphate concentration in the overlying waters is low. In evaluating the nutrient concentrations measured in sediments, it is important to know the nutrient fraction that is available for biological reactions and the fraction that is not available. Although the determination as to what fraction of nutrients in sediments is available for biological activity was not in the scope of this study, a small qualitative study to gain information related to this topic was undertaken. This study involved 25-250 ml glass flasks, each of which contained five grams of Vancouver Lake sediment and 100 ml of the Columbia River water, and 3-250 ml glass flasks, each of which contained 100 ml of the Columbia River water only to serve as controls. The sediments used in this study were taken from the five locations (north, south, east, west, and center of the lake) in Vancouver Lake and from five core depths at each location. The flasks were exposed to about 300-foot candles fluorescent light intensity in a room maintained at 20°C. The experiment was continued for seven weeks, and the results of algae growth observations are summarized in Table 5.

Table 5. ALGAE GROWTH* POTENTIAL OF VANCOUVER LAKE BOTTOM SEDIMENTS - COLUMBIA RIVER WATER

Time (Weeks)	Control**	Sediment Core Depth (inches)				
		0-5	5-10	10-15	15-20	20-25
0	NG	NG	NG	NG	NG	NG
1	NG	NG	NG	NG	NG	NG
2	NG	SG	NG	NG	NG	NG
3	NG	SG	NG	NG	NG	NG
5	NG	AG	SG	SG	LG	LG
7	NG	AG	SG	SG	SG	LG

*Algae growth observations denoted as: NG - no growth, LG - little growth, SG - sparse growth, and AG - abundant growth.
**Columbia River water with no Vancouver Lake sediments added.

It appears that the nutrients in the top five inches of the lake sediments were sufficiently "available" to produce abundant algae growth which took place after the 3rd week and before the 5th week of the experiment. It can also be concluded from this experiment that the "availability" of nutrients in sediments at depths greater than about five inches was scarce.

Trace Elements

Neutron activation analysis technique was used to determine the levels of some of the trace elements present in the sediments and water. The results are summarized in Table 6. The levels of nine elements found in Vancouver Lake sediments are of the same magnitude as present in average basalt rocks. Cobalt is one of the trace elements that has been recognized as essential for the growth of blue green algae and it is required in concentration of 0.5 mg/l.[25] It appears from Table 6 that there is no deficiency of cobalt in the Vancouver Lake system.

Table 6. SOME TRACE ELEMENTS IN VANCOUVER LAKE-COLUMBIA RIVER SYSTEM

	Concentration in ppm		
	Vancouver Lake		Columbia River
Element	Sediments	Water	Water
Iron	5×10^4	ND*	ND
Cobalt	18.5	1.02	0.58
Chromium	57.5	8.9	8.9
Barium	500-700	ND	ND
Scandium	18.5	0.95	0.14
Europium	1.42	0.06	0.06
Hafnium	7.35	ND	ND
Thorium	17.10	0.60	0.12
Rupidium	90.2	ND	ND

*ND = not determined

Bottom Organisms

The number of organisms per square meter of the lake bottom area ranged from 0 to 2,451. Aquatic earthworms, chironomids, and nematodes were three predominant organisms in the lake sediments. Most of the organisms detected were aquatic earthworms of the family Naididae which are characteristic of shallow and turbulent waters. Chironomid worms were sparingly present in areas where organic solids were present in the mud. They were conspicuously absent in locations where log rafts were formerly tied up. At these locations (in the Lake River), a great deal of bark and wood chips were sieved from the bottom sediments but relatively few living organisms were found.

The significance of the biological inventory of the bottom organisms lies in the fact that these organisms are more or less fixed in their habitat and cannot move to more favorable surroundings when pollutional conditions become critical. Therefore, these organisms should be good indicators of the past and present environmental conditions.[26]

SECTION VII

WATER QUALITY PREDICTION APPROACH

Dredging of Vancouver Lake to make it deeper and introducing Columbia River water into the lake through a channel or culverts are being considered as possible methods of both increasing lake use potential and as a water quality improvement measure. To predict the effect of the above measures on the final water quality in the lake, the following information and steps were considered essential in approaching this problem:

Water Quality in the Columbia River - Vancouver Lake System

It was essential to establish the available water quality in the Columbia River and the existing water quality in the lake in order to predict the obtainable water quality in the lake if the Columbia River water were diverted into the lake. The available water quality in the Columbia River has been established in Section V. The existing water quality in Vancouver Lake was established in a previous study.[1,3] A summary of the water qualities in the two systems is given in Table 7.

Hydrodynamic Characteristics of Columbia River - Vancouver Lake System

In addition to the information on water quality, the information on the hydrodynamic characteristics of the system under the present conditions as well as under the proposed modification of the Columbia River-Vancouver Lake system was equally important.

The information on the hydrodynamic characteristics of the system was obtained through concurrent but three separate studies.[4,5,6] These studies were involved in acquiring hydrologic and hydrographic field data which were then used in the construction, operation, and verification of the hydraulic model.

A summary of the results is presented here, and the readers should refer to the above mentioned three studies for detailed information. During August, the water quality conditions were critical because of low flows and high temperatures. Therefore, the conditions for the month of August were emphasized:

- The tidal relationships in the Columbia River-Vancouver Lake-Lake River system are very important factors in the evaluation of the flow rates into and out of Vancouver Lake. Seasonal changes in depth of Vancouver Lake associated with net tidal flows in Lake River are shown in Figure 17.

Table 7. COMPARISON OF AVERAGE WATER QUALITY OF VANCOUVER LAKE AND COLUMBIA RIVER (Units are mg/l unless otherwise specified)

	Vancouver Lake	Columbia River
BOD_5	8.0	1.0
COD	12.0	5.8
Kjeldahl - N	2.25	0.16
NO_3 - N	0.17	0.19
Total P as PO_4	0.70	0.23
TS	200	116
TVS	90	34
Conductivity (μ-mhos)	170	167
pH	6.7-9.3	7.6-8.2
Hardness as $CaCO_3$	104	63
SO_4	14.5	6.6
Cl	4.0	4.1
Temperature (°C)	4-26	4-21
DO	5.7-14.8	8-12
Coliform Bacteria (median value - No/100 ml)	3000	>200
% Fecal Coliforms	10-40	>30
Blue-Green Algae (% of total algae)	95	0.5
State of Nutrition	eutrophic	mesotrophic

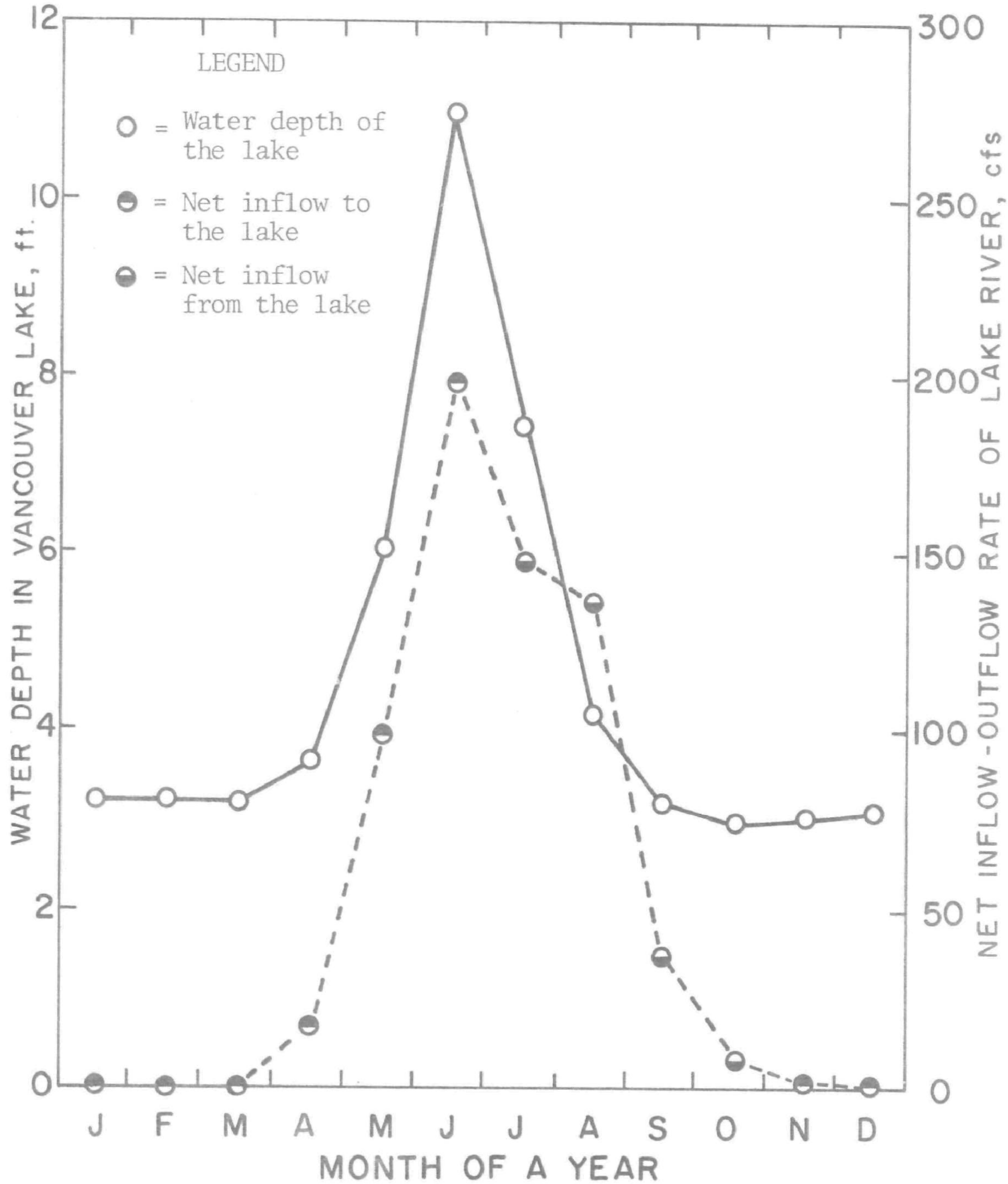


Figure 17. Mean Seasonal Variations in Lake Depths and Net Inflow-Outflow Rates of Lake River to Vancouver Lake for Existing Conditions.

- Statistical analysis of field water stage data indicated that in August the average high elevations of the Columbia River, Vancouver Lake, and Lake River (at Felida) were 5.78, 4.41, and 4.91 feet above mean sea level.

- The average value of the differences in peak water surface elevations between the Columbia River and Vancouver Lake during August was about 1.8 feet, while the average values of the tidal fluctuations in the Columbia River and Vancouver Lake were 2.25 and 0.15 feet, respectively. This information was the basis of the sinusoidal tide variations in the Columbia River and Lake River as used in the water quality simulation study.

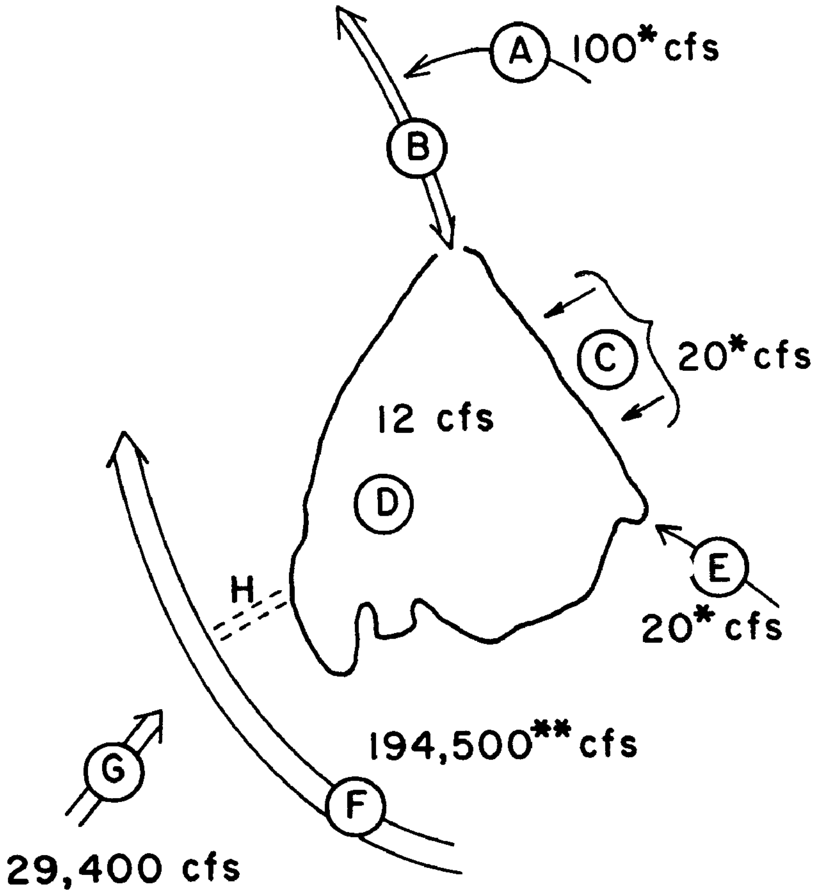
- The difference in elevation between the Columbia River and Vancouver Lake is influenced by the general rising and falling trend in the Columbia River stage. This relationship shows that Vancouver Lake rarely goes below a stage of about four feet due to the tidal flat at the entrance to Lake River, and the Columbia River maximum elevation is sometimes less than the Vancouver Lake minimum elevation.

- The main rivers and creeks which play an important role in influencing the quantity and quality of Vancouver Lake are: (a) the Columbia River, (b) the Willamette River, (c) the Lake River, (d) Salmon Creek and Burnt Bridge Creek. The estimated flows of these streams and the approximate contribution of groundwater and precipitation are shown in Figure 18.

- The hydraulic model study indicated that introduction of the Columbia River water into the lake produced near complete mixing conditions. The results of a typical test are shown in Figure 19. In this test, a precalculated dose of a fluorescent dye was completely mixed with the lake water and then the Columbia River water was introduced into the lake. The dye concentration in the model was measured as function of time at seven stations in the lake and at the inlet to Lake River. A total of 22 tests were conducted under various conditions of stream flows, tidal variations and dredged depth.

- It was established that in order to prevent the tidal flow from Lake River into Vancouver Lake, the width of the proposed channel connecting the Columbia River and Vancouver Lake should be 150 feet or greater.

- The relationship of average detention time in the lake of the average inflow introduced into the lake under various lake bottom dredged conditions is shown in Figure 20.



A Salmon Creek--100* cfs. Flow moves upstream or downstream depending on tidal action and stage trend in Columbia River.

B Lake River--300* cfs in and out. Tidal flow plus Salmon Creek half of the time.

C 20* cfs ground water

D Vancouver Lake--12 cfs precipitation on lake

E Burnt Bridge Creek--20* cfs

F Columbia River--194,500** cfs

G Willamette River--29,400 cfs

H Proposed Site for Diversion of the Columbia River Water into Vancouver Lake

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*Estimated

**At Dalles, longer record

Figure 18. Average Annual Flows

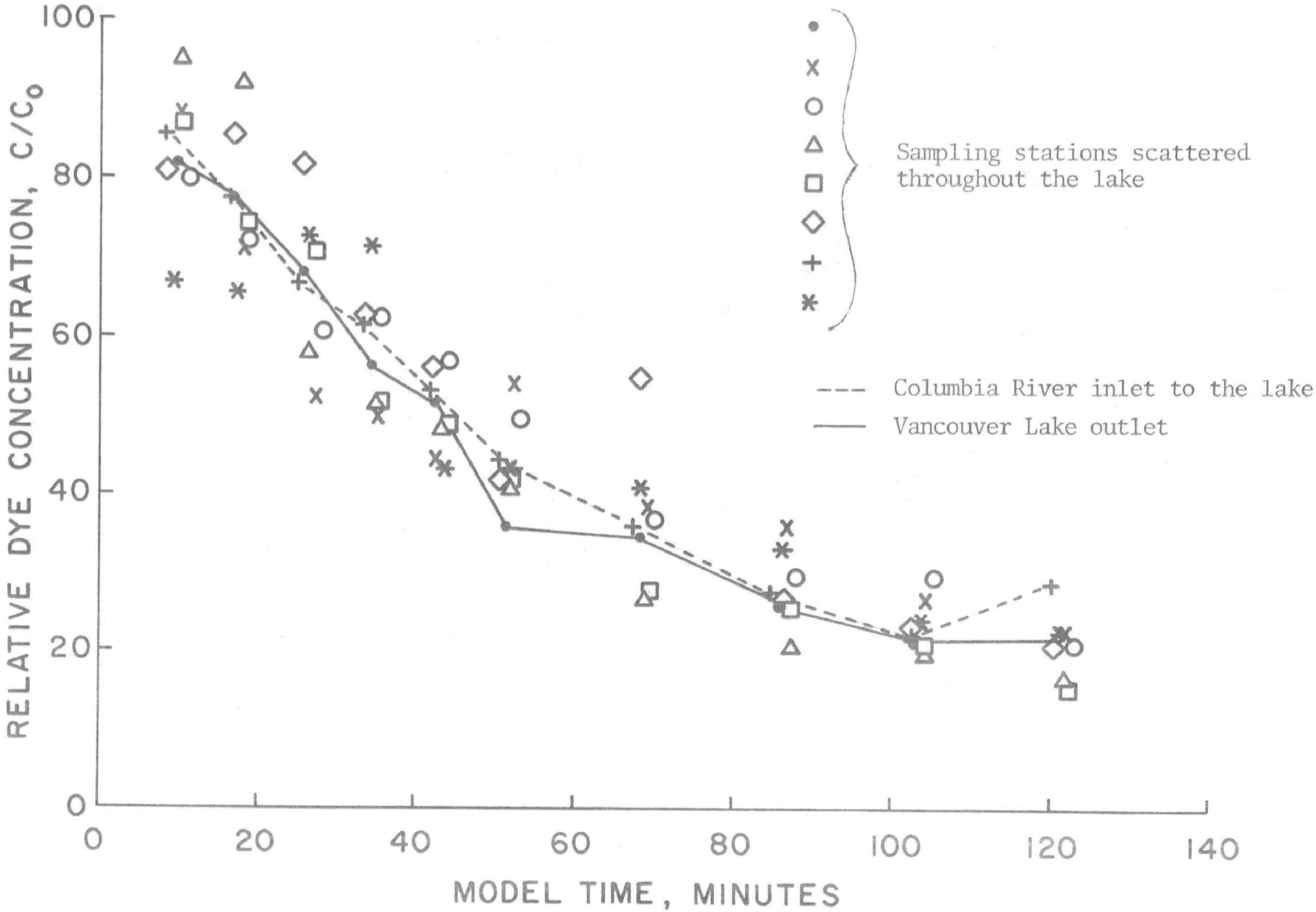

Figure 19. Relative Concentration of Dye in Vancouver Lake Model as Function of Time

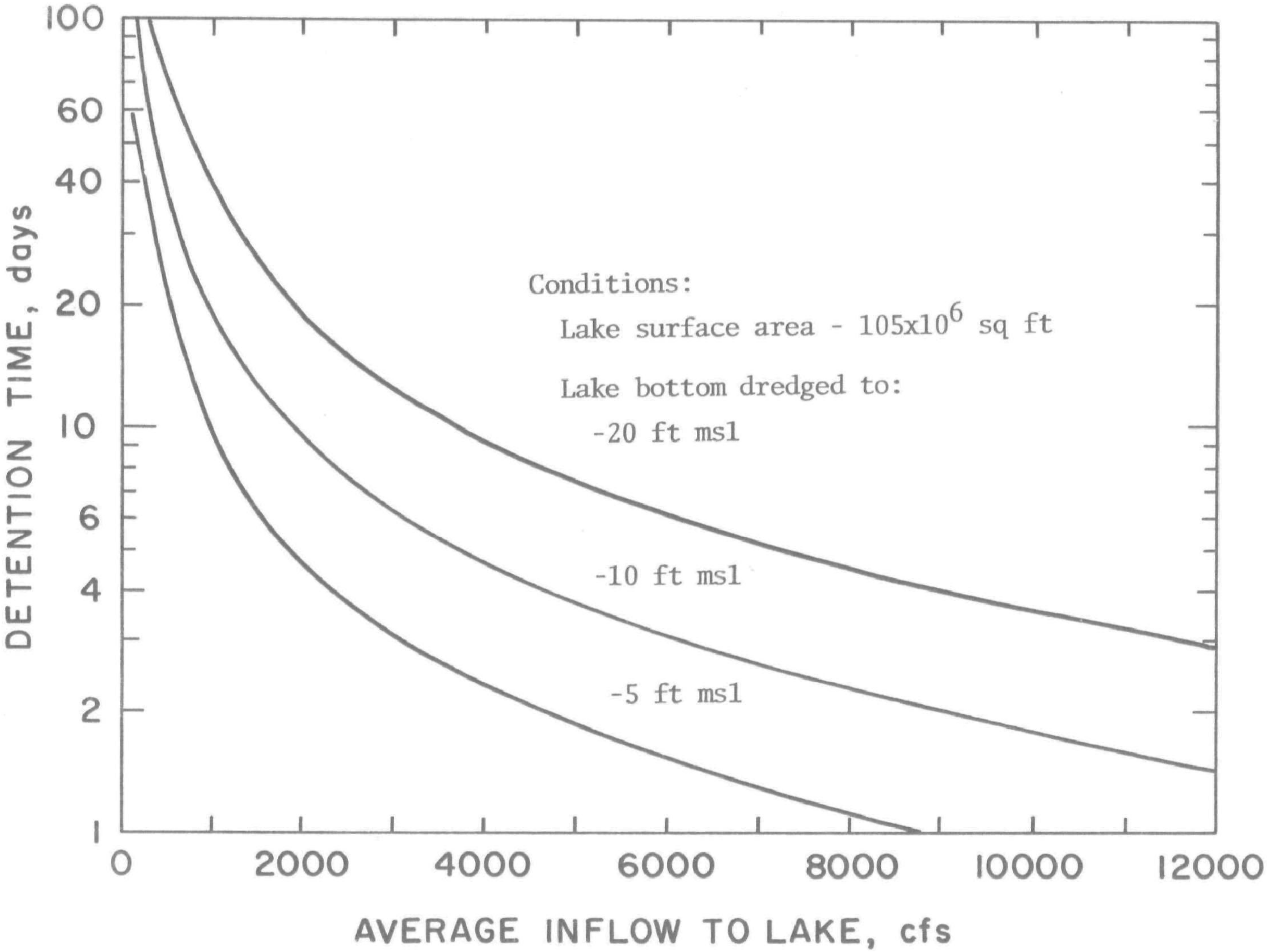

Figure 20. Lake Detention Time and Average Inflow through Any Kind of Conduit(s)

Water Quality Indicator

After acquiring the water quality and quantity information, the next step was to select a water quality parameter which would be indicative of the overall water quality in the lake and at the same time the parameter selected could be described mathematically in terms of its relationship with other factors affecting it. Dissolved oxygen was the water quality parameter selected as an indicator of the overall water quality in the lake because of the following reasons:

a. dissolved oxygen is essential for aquatic life,

b. aquatic plant photosynthesis and atmospheric reaeration are the sources of dissolved oxygen in an aquatic system, and the addition of dissolved oxygen by these processes can be described mathematically,

c. the sinks of dissolved oxygen in an aquatic system are respiration by microorganisms and other aquatic life and decomposition of organic matter. These sinks can also be written into approximate mathematical equations,

d. the fact that interaction of phosphorus, nitrogen, carbon dioxide, other trace nutrients, sunlight, temperature, etc. with phytoplankton results in the production of photosynthetic oxygen; that the atmospheric reaeration of aquatic systems depends upon the wind action, temperature, water depth, and the dissolved oxygen deficit; that the depletion of dissolved oxygen is related to biochemical oxygen demand of aqueous and benthic zones including respiration of bacteria, algae, zooplankton, fish, and other organisms suggest that the dissolved oxygen is indeed a water quality parameter which indicates a composite effect of many of the dominant processes that take place in a dynamic aquatic ecosystem,

e. the measurement of dissolved oxygen can be made easily and accurately, and

f. dissolved oxygen is one of the most important water quality standards.

Therefore, the main emphasis in this study was placed on the dissolved oxygen model although phytoplankton and bacteria models were also attempted.

Water Quality Model

Computer programming and digital computers have made it possible to build simulation models of dynamic ecosystems. The accuracy of these models depends largely on the accuracy of the various coefficients used, the assumptions made, and the functional relationships incorporated.

The water quality model considered in this study consists of two main parts: DO Model and Aquatic-Life Model. The emphasis in this study has been placed on the DO Model because of the better understanding as well as the wide acceptance of the mathematical relationships involved. Although the two models are interrelated, the response in terms of change in population of organisms as related to changes in environmental and nutritional factors is difficult to predict under the present state of knowledge, and it becomes even more difficult to predict the number of biological species and the population of each of the species. On the other hand, dissolved oxygen as related to environmental and nutritional changes can be estimated.

DO Model: Several modifications and improvements to the earlier DO model by Streeter-Phelps(27) have been suggested.(28,29,30,31,32,33) The DO model considered in this study was primarily based on the work of Chen(34) and Chen and Orlob.(35) However, we found that we could not verify the model with the actual field data unless the temperature dependence of phytoplankton growth rate (μ) was included. The temperature effect was especially important for predicting diurnal variations in dissolved oxygen.

The mechanisms considered which affect the DO concentration are advection (oxygen in inlet streams minus outlet streams to Vancouver Lake); photosynthesis as affected by nutrients, light availability, and temperature; biological respiration and deoxygenation; and atmospheric reaeration. A mass-balance type formulation which incorporates major processes that affect dissolved oxygen is presented:

Rate of Change of DO Mass		Rate Change in DO Mass Due To				
$\frac{d(VO)}{dt}$	=	T_o +	$(\mu - r)pVT/R$ −	$K_1 V\ell$ −	$K_4 DA$ +	$K_2(O_s - O)V$
		Advective Transfer	Net Photosynthesis	Biochemical Oxygen Demand in Water	Benthic Oxygen Demand	Reaeration

$$\frac{d(VO)}{dt} = T_o + (\mu - r)pVT/R - K_1 V\ell - K_4 DA + K_2(O_s - O)V \quad [1]$$

where V = the volume of the lake;
t = time;
T_o = the total advective transfer of oxygen defined as the summation of $Q_B O_B$, $Q_C O_C$, and $Q_L O_L$, in which O_B, O_C, and O_L are the oxygen levels of Burnt Bridge Creek, the channel or culverts, and Lake River, respectively;
T = the lake water temperature;
O = the dissolved oxygen concentration in the lake;
R = the conversion factor between oxygen and algal biomass;

ℓ = the biochemical oxygen demand;
K_1 = the decay coefficient for BOD;
K_2 = the reaeration coefficient;
K_4 = the oxygen uptake by detritus;
μ = the specific growth coefficient of phytoplankton (algae);
r = the respiration coefficient of phytoplankton;
D = detritus concentration accumulated at the lake bottom;
p = the biomass concentration of phytoplankton; and
O_s = the dissolved oxygen saturation concentration.

The correlated components which directly or indirectly affect the dissolved oxygen are biomass of phytoplankton, organic and inorganic nutrients, and zooplanktons. These components are described by a series of mass balance equations as follows:

Biomass of phytoplankton. The biomass of phytoplankton is transported by the movement of water--advection. In addition, phytoplankton growth rate is determined by light, temperature, and nutrient conditions. It decreases as a result of continuous respiration, settling, and grazing by zooplankton. Those terms must be included in the mass balance equation to form a differential equation for phytoplankton which directly affect the DO level in equation [1].

Rate of Change of Phytoplankton Mass	Rate Change in Phytoplankton Mass Due To		
	Advective Transfer	Net Growth After Settling	Grazing of Phytoplankton by Zooplankton

$$\frac{d(Vp)}{dt} = T_p + [(\mu - r)T]pV(1 - s) - gTzV/Y_z \qquad [2]$$

where T_p is the total advective transfer of biomass of phytoplankton, s the fraction of settling of phytoplankton, g the specific growth coefficient of zooplankton, Y_z the yield coefficient of zooplankton, z the total count of zooplankton, and μ is the specific growth coefficient of phytoplankton which is assumed to follow the Michaelis-Menton kinetics for the uptake of limiting nutrients or light. In this study, nitrogen, phosphate, and light intensity are considered as possible limiting factors

$$\mu = \hat{\mu}\left(\frac{L}{K_L + L}\right)\left(\frac{N}{K_N + N}\right)\left(\frac{P}{K_P + P}\right) \qquad [3]$$

in which $\hat{\mu}$ is the maximum possible growth rate; K_L, K_N, and K_P are the Michaelis-Menton constants and are respectively the concentration of light, nitrogen, and phosphate at which μ equals $0.5\ \hat{\mu}$.

According to Beer's law, the solar energy reaching the water surface is attenuated exponentially with water depth influenced by the suspended silt and phytoplankton population. A sinusoidal model as the function of photoperiod was used in this study.

$$L = L_o \exp\left[-(a + bp)y\right] , \qquad [4]$$

and

$$L_o = L_n(1 - 0.65\ C_1^2) \sin\left(\frac{\pi(t - t_{sr})}{t_{ss} - t_{sr}}\right) \ldots ; \; t_{sr}<t<t_{ss} \qquad [5a]$$

$$= 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; t_{sr}>t>t_{ss} \qquad [5b]$$

where L is the light intensity in Langleys/day* at the depth y measured downward from the water surface, L_o the solar energy at water surface at time of day t, L_n the solar energy at noon time, C_1 the degree of cloud cover, t_{sr} the time at sunrise, and t_{ss} the time at sunset.

For the completely mixed model in the lake of H feet in depth, the average value of light intensity, $\bar{L}$, was calculated by

$$\bar{L} = \frac{1}{H}\int_o^H L dy = L_o \frac{1 - \exp\left[(-a - pb)H\right]}{H(a + pb)} . \qquad [6]$$

Biomass of zooplankton. The growth and death rates due to natural causes were presumed to be directly proportional to the water temperature. Mass conservation for biomass of zooplankton may be expressed as follows:

Rate of Change of Zooplankton Number	Rate Change in Zooplankton Number Due To			
$\frac{d(Vz)}{dt}$ =	T_z +	$gzVT$ −	$mzVT$ −	$\gamma FV/y_f$ [7]
	Advective Transfer	Growth	Mortality	Predation by Fish

---

*One foot-candle = 3.2675×10^{-2} Langleys/day. Calibration of the instrument used in the Vancouver Lake study is 4 micro-amp for 1 foot-candle. Therefore, 1 micro-amp = 8.1686×10^{-3} Langleys/day.

in which T_z is the total advective transfer of zooplankton, m the mortality of zooplankton, γ the specific growth rate of fish, F the biomass of concentration of fish, and Y_f the yield coefficient of fish. Predation of zooplankton by fish was excluded in the simulation study.

Biochemical oxygen demand. The mass balance equation for BOD which directly affects the DO level may be written as

Rate of Change of BOD Mass		Rate Change in BOD Mass Due To		
$\frac{d(V\ell)}{dt}$	=	T_ℓ	$- K_1 V\ell$	$- K_3 V\ell$
		Advective Transfer	Removal of BOD by Aerobic Bacteria	Removal of BOD by Settling

$$\frac{d(V\ell)}{dt} = T_\ell - K_1 V\ell - K_3 V\ell \qquad [8]$$

where T_ℓ is the total advective transfer of BOD, K_3 the rate of BOD removal by sedimentation and/or adsorption, and ℓ the BOD concentration.

Nutrient level. Nutrients can be consumed by phytoplankton (sinks), but released by zooplankton and recycled by bacteria from lake bottom deposits (sources). The conservation of mass for any given nutrient becomes:

Rate of Change of Nutrients		Rate Change in Nutrient Due To			
$\frac{d(Vn)}{dt}$	=	T_n	$+ \alpha zV$	$+ \beta DA$	$- \mu pVT/y_{pn}$
		Advective Transfer	Recycling by Zoo-plankton	Recycling by Bottom Sediments	Conversion of Nutrient to Phytoplankton

$$\frac{d(Vn)}{dt} = T_n + \alpha zV + \beta DA - \mu pVT/y_{pn} \qquad [9]$$

in which n is the concentration of nutrient at time t, T the advective transfer of nutrient, α the return coefficient of nutrient from zooplankton, β the recycle coefficient from bottom deposits depending upon the rate of bacteria metabolism, and Y_{pn} the yield coefficient of phytoplankton for a specific nutrient.

Dissolved oxygen saturation concentration. The dissolved oxygen saturation concentration is a function of temperature, barometric pressure, and salinity of water. The changes in DO concentrations in Vancouver Lake due to fluctuations in barometric pressure were assumed to be negligible. However, if one wishes to include this effect, the following equation can be used:

$$O_s^1 = O_s \frac{p^1 - P_w}{760 - p_w} \quad [10]$$

where p_w is the water saturated pressure in mm o Hg at a particular water temperature T in °C, O_s^1 is the saturated value of dissolved oxygen at barometric pressure of p^1 in mm of Hg, and O_s is the dissolved oxygen saturation concentration at a barometric pressure of 760 mm of Hg.

An empirical formula for O_s as a function of temperature as given below for fresh water was used in this study.

$$O_s = 14.652 - x.1002 \times 10^{-1}T + 7.9971 \times 10^{-3}T^2 - 7.7774 \times 10^{-5}T^3 \quad [11]$$

Aquatic Life Model: Parker's(36) work on modeling of Kootenay Lake in British Columbia was the basis of the aquatic life model attempted in this study. Some modifications of Parker's model to correspond to conditions in Vancouver Lake were made.

The available quality data indicate that Vancouver Lake is currently undergoing rapid eutrophication. Therefore, the seasonal variations in quantity of algae as well as bacteriological level are of importance and are described as follows:

Algae. The seasonal variations of algae and its affected factors such as zooplankton and phosphate density are represented as:

Rate of Change of Algal Mass	Rate Change in Algal Mass Due To		
$\frac{dp}{dw} = p\{$	$p_1 \exp\left[-0.5\left(\frac{T-26}{3}\right)^2\right] P_p P$	$- \; p_2 T$	$- \; p_3 z T\}$
	Growth	Natural Death	Grazing of Algae by Zooplankton

$$\frac{dp}{dw} = p\left\{p_1 \exp\left[-0.5\left(\frac{T-26}{3}\right)^2\right] P_p P - p_2 T - p_3 z T\right\} \quad [12]$$

Rate of Change of Zooplankton Number — Rate Change in Zooplankton Number Due To

$$\frac{dz}{dw} = z\left\{z_1 \exp\left[-0.5\left(\frac{T-13}{8}\right)^2\right] P_p PG(P_p) - z_2 TG(P_p)\right\} \qquad [13]$$

Growth — Natural Death

Rate of Change of Phosphate Concentration — Rate Change in Phosphate Concentration Due To

$$\frac{dp}{dw} = \frac{Q_B P_B + Q_L P}{V} - P_2 \frac{dz}{dw} - P_3 \frac{dp}{dw} \qquad [14]$$

Advective Transfer — Conversion to Zooplankton — Conversion to Phytoplankton

where w is the week of the year; Q_L the net flux to the lake; p_1, p_2, p_3, z_1, z_2, P_2, and P_3 are constants; P_B the phosphate of the incoming flow; P_p the photoperiod (or daylight hour); $G(P_p)$ the function of photoperiod; and T the water temperature of the lake. Some of these are represented as:

$$P_p = 12.2 + 4.1 \sin\left[2\pi\left(\frac{38 - w}{52}\right)\right] \qquad [15]$$

$$G(P_p) = 0.82 + 0.343 \sin\left[2\pi\left(\frac{P_p - 7.2}{10.4}\right)\right] \qquad [16]$$

From the available field data, the incoming flow rate of Burnt Bridge Creek, Q_B; phosphate content of Burnt Bridge Creek, P_B; and the lake water temperature were found to be represented as the following functional relationships.

$$Q_B = 28.32\left\{16.2 - 15.7 \exp\left[-0.5\left(\frac{w - 24}{9}\right)^2\right]\right\} \qquad [17]$$

$$P_B = 150 + 750 \exp\left[-0.5\left(\frac{w - 24}{3}\right)^2\right] \qquad [18]$$

$$T = 4.0 + 22 \exp\left[-0.5\left(\frac{w - 24}{6}\right)^2\right] \qquad [19]$$

Equations [18] and [19] are for w (time in weeks) greater than or equal to 8; otherwise w is replaced by (w + 52) in the equations.

Total bacteria. It is assumed that the bacteria depend on BOD as the food source. The mass balance for bacteria and substrate is given as:

Rate of Change of Bacteria Mass		Rate Change in Bacteria Mass Due To		
$\frac{dB}{dw}$	=	$(\bar{\mu} - k_2T)B$	+	$\frac{Q_BB_B + Q_LB}{V}$
		Net Growth		Advective Transfer

$$\frac{dB}{dw} = (\bar{\mu} - k_2T)B + \frac{Q_BB_B + Q_LB}{V} \qquad [20]$$

Rate of Change of Substrate

$\frac{dS}{dw}$	=	$\frac{Q_BS_B + Q_LS}{V}$	-	$\left(\frac{\bar{\mu} - k_2T}{Y_S}\right)B$	+	$\bar{p}qk_sTB$
		Advective Transfer		Conversion to Bacteria		Release of Substrate Due to Bacteria Death and Lysis

$$\frac{dS}{dw} = \frac{Q_BS_B + Q_LS}{V} - \left(\frac{\bar{\mu} - k_2T}{Y_S}\right)B + \bar{p}qk_sTB \qquad [21]$$

where B and S are the total bacteria count and substrate concentration, respectively, k_2 the rate of die-off of bacteria, S_B the substrate concentration of the incoming flow, $\bar{p}$ the fraction of cells which die in the lake, q the fraction of exogenous substrate released per unit cell lysed, and Y_S the effective yield coefficient of substrate. The specific growth rate of bacteria $\bar{\mu}$ is expressed as:

$$\bar{\mu} \quad \hat{\bar{\mu}} \exp\left[-0.5\left(\frac{T - 26}{5.5}\right)^2\right] \qquad [22]$$

in which $\hat{\bar{\mu}}$ is the maximum specific growth rate of bacteria. An approximate maximum value of $\bar{p}q$ has been reported by Postgate[37] to be 0.004. Sayer[38] and Gellman and Heakelekian[39] have shown that 0.5 gram volatile suspended solids is synthesized per gram of BOD_5 removed. Therefore, the value of 0.5 for Y_S is used.

Method of Solution

Following the formulation of water quality model for the simulation study, the numerical solution to a set of differential equations was obtained in a step-by-step manner with the aid of a digital computer. The finite difference method was applied to the solution of DO model and a third order Runge-Kutta method was used for the aquatic life model. Initial conditions were required for solving the mathematical models and to simulate the various subsequent behaviors in the system. Initial lake water quality, climatological data, flow quality and quantity, rate constants of biological activities, physical dimensions of the lake, etc., were necessary.

When the initial input data were ready, the explicit technique of numerical integration was used by substituting all the conditions corresponding to the initial time in the right-hand side of equations [1], [2], [7], [8], and [9], and for the time derivatives on the left-hand side. Once the time derivative of a given variable was known, it was evaluated for some short time interval by assuming a constant rate of change in this interval. The new values became the initial conditions for calculating the next set of conditions over the next time interval. The solution was thus obtained in time increments Δt until the desired total simulated time had been reached. The detailed steps of the method are given in Appendix D.

Table 8 summarizes the values of various reaction rate constants and other coefficients used in the solution of the water quality model.

A number of assumptions were made in the solution of mathematical models:

- Complete mixing conditions were assumed in Vancouver Lake. Previous studies[3] indicate that the lake is unstratified most of the year because of its shallowness and mixing induced by wind action. It is believed that even if the lake is dredged to a water depth of 15 feet, complete mixing assumption will still prevail.

- The euphotic zone exists to a depth of three feet. Field data indicated that the penetration of sunlight was limited to water depths less than three feet.

- The biochemical and biological reactions follow first order equations.

- The transport mechanism of diffusion is small compared to advection and other transport mechanisms for non-conservative soluble substances.

- Daily sinusoidal cyclic variation of tides in the Columbia River and Lake River was assumed. Magnitudes of the mean tidal amplitude were obtained by statistical analysis of the field hydrographic data.

Table 8. FUNCTIONAL OR ESTIMATED COEFFICIENTS FOR WATER QUALITY MODEL

Parameter		Functional Relationship or Estimated Coefficients	Reference and Remark
A. DO MODEL			
Light Extinction			
a:	Background, per foot	0.09	Chen[34]
b:	Algal suspension, per foot per mg/l	0.006	Chen[34]
C_1:	Degree of cloud cover	0.40	Assumed in this study
$\bar{L}$:	Average light intensity, Langleys/day	$L_o\left(\frac{1 - \exp[(-a-bp)H]}{H(a+bp)}\right)$	Calculated from Beer's Law
L_n:	Solar energy at noon time, Langleys/day	400	Computed from data by Bhagat and Funk[3]
P_p:	Photoperiod, day	0.5	Assumed in this study
t_{sr}:	Time of sunrise, day	0.2917	Assumed in this study
Evaporation			
C_2:	Empirical constant	0.394	Jaske[40]
C_3:	Empirical constant	-0.098	Jaske[40]
Nutrient			
α:	Return coefficient of nutrient from zooplankton	0.01	Assumed in this study

Table 8. Continued

Parameter	Functional Relationship or Estimated Coefficients	Reference and Remark
β: Recycle coefficient from bottom deposits depending on the rate of bacteria metabolism	0.01	Assumed in this study
Y_{pN}: Yield coefficient of phytoplankton for nitrogen	12.0	McGauhey et al.[41]
Y_{pP}: Yield coefficient of phytoplankton for phosphate	24	Deduced from Parker[36]
K_1, BOD decay coefficient, per day	$(K_1)_T = (K_1)_{20}\theta_1^{T-20}$	Temperature dependent
	$\theta_1 = 1.047$	Streeter and Phelps[27]
	$(K_1)_{20} = 0.231$	Pence et al.[42]
	$K_1 = 0.25$	Chen[34]
	$K_1 = 0.20$	Orlob et al.[43]
K_2, reaeration coefficient, per day	$(K_2)_T = (K_2)_{20}\theta_2^{T-20}$	Temperature dependent
	$\theta_2 = 1.046$	O'Connor and Dobbins[44]
	$K_2 = 0.25$	Orlob et al.[43]
	$K_2 = 0.40$	Chen[34]
K_3, rate of BOD removal by sedimentation and/or absorption, per day	0.1	Assumed in this study

Table 8. Continued

Parameter		Functional Relationship or Estimated Coefficients	Reference and Remark
Phytoplankton			
r:	Respiration coefficient, /day/degree	0.025	Assumed in this study
s:	Settling fraction	0.07	Bella[45]
R:	Oxygen and algae conversion factor, mg algae per mg O_2	0.633	Chen[35]
$\hat{\mu}$:	Maximum possible growth coefficient, per day per degree	0.090	Estimated from data by Bhagat and Funk[3]
K_L:	Coefficient in Langleys/day	43.2	Chen[34]
K_N:	Coefficient in mg/l	0.0088	McGauhey[41]
K_p:	Coefficient in mg/l	0.005	McGauhey[41]
Zooplankton			
m:	Mortality, per day per degree	0.025	Chen[34]
Y_z:	Yield coefficient of zooplankton, no. of zooplankton per mg algae	12.0	Assumed
g:	Specific growth coefficient of zooplankton, per day per degree	0.02	Assumed
K_4:	Decay of bottom deposits, per day	0.007	Camp[46]

Table 8. Continued

Parameter		Functional Relationship or Estimated Coefficients	Reference and Remark
O_s:	Saturated dissolved oxygen, mg/1	$14.652 - 0.41002\ T + 0.0079971\ T^2 - 0.000077774\ T^3$	Fair[47]
B. AQUATIC LIFE MODEL			
P_p:	Photoperiod, hr	$12.2+4.1\sin\left[2\pi\left(\frac{38-w}{52}\right)\right]$	Parker[36]
$G(P_p)$:	Function of photoperiod	$0.82+0.343\sin\left[2\pi\left(\frac{P_p-7.2}{10.4}\right)\right]$	Parker[36]
Q_B:	Flow rate in Burnt Bridge Creek, liter/sec	$28.32\left\{16.2-15.7\ \exp\left[-0.5\left(\frac{w-24}{9}\right)^2\right]\right\}$	Calculated for this study
P_B:	Phosphate content in Burnt Bridge Creek, micro-gm/1	$150+750\ \exp\left[-0.5\left(\frac{w-24}{3}\right)^2\right]$	Calculated from data by Bhagat and Funk[3]
T:	Water temperature in the lake, °C	$4.0+22\ \exp\left[-0.5\left(\frac{w-24}{6}\right)^2\right]$	Calculated from data by Bhagat and Funk[3]
$\hat{\mu}$:	Maximum specific growth rate of bacteria, per day	0.055	Assumed in this study
$\bar{p}q$:	Substrate release by bacteria	0.004	Postgate[37]
k_2:	The coefficient of die-off bacteria, per day per degree	0.0088	Assumed in this study

Table 8. Continued

Parameter		Functional Relationship or Estimated Coefficients	Reference and Remark
Y_S:	The effective yield coefficient of the substrate, mg bacteria per mg substrate released	0.5	Gellman et al.[39]
p_1:	Growth rate coefficient of algae	0.00012	Parker[36]
p_2:	Natural death coefficient of algae	0.002	Parker[36]
p_3:	Predation death coefficient of algae by zooplankton	0.006	Parker[36]
Z_1:	Growth rate coefficient of zooplankton	0.0015	Parker[36]
Z_2:	Natural death coefficient of zooplankton	0.03	Parker[36]
P_2:	Phosphate utility rate by zooplankton	0.6	Parker[36]
P_3:	Phosphate utility rate by algae	20.00	Parker[36]

- A constant lake surface area was assumed. This was verified by comparing tidal inflow with volume change in the lake.

- The change in the dissolved oxygen saturation concentration due to the local barometric pressure fluctuations is negligible.

- Average evaporation rates for each incremental period were used in the analyses.

- The effect of fish biomass on the zooplankton population was neglected.

- Atmospheric aeration and photosynthesis mechanisms were limited to the upper three feet of the lake water even after dredging of bottom sediments.

- Deoxygenation coefficient (K_1) and reaeration coefficient (K_2) vary with temperature according to the accepted relationship

$$K_T = K_{20}\theta^{T-20}$$

- Numerical values of various constants and reaction rates as given in Table 8 were used in this study.

Verification of Water Quality Model

After formulation of mathematical equations and the establishment of the method of solution of these equations, the next step was to generate the theoretical data with the aid of a digital computer and to check the validity of the mathematical model. The validity of the model was evaluated by comparing the theoretical values with the observed field data. It is obvious that the mathematical model is not of much value unless it is verified with the actual field observations. If the difference between the computed and the observed values is significant, then the modification of the mathematical model should be continued until this difference is reduced to a minimum value. This procedure was followed in this study and, hence, involved trials of several numerical values of a coefficient until the difference between the computed and observed data reached a minimum. It should be pointed out that the values of some of the coefficients were available for the Vancouver Lake System, whereas the values of other coefficients suited to this system were derived from the literature. Trial procedure was essential in order to arrive at a value characteristic of the Vancouver Lake System in the case of a coefficient the magnitude of which was reported in the literature to vary over a wide range. These trials were also helpful in revealing the relative sensitivity of the coefficients tried.

For the purpose of verification of the DO model, dissolved oxygen concentration and temperature readings were recorded on a continuous basis for the month of August, 1970. This month was selected because the water quality in Vancouver Lake generally reaches a low point during this time because of low water level and high temperatures. A typical comparison between computed and observed DO levels is shown in Figure 21. On the whole, the computed values were very close to the observed values. The peak DO values observed in the afternoons of summer months which are typical of eutrophic lakes and other bodies of water were at times significantly different from the corresponding simulated values. Generally, we are concerned with the lowest dissolved oxygen concentration reached in a system and the difference between the lowest simulated and observed values was less than 1.0 mg/l.

The aquatic life model was verified against the limited observed data collected in 1967.(3) The results are shown in Figures 22 and 23. The hallow circles represent data at different locations in Vancouver Lake observed on the same date, whereas the solid black circles represent average values for the entire lake. Because of the limited field data available, there is a further need of verification of the aquatic life model.

Upon verification of the water quality model under the existing prototype conditions, the model is ready for application to the predictions of water quality that can be expected under variety of modifications to the Vancouver Lake-Lake River-Columbia River System.

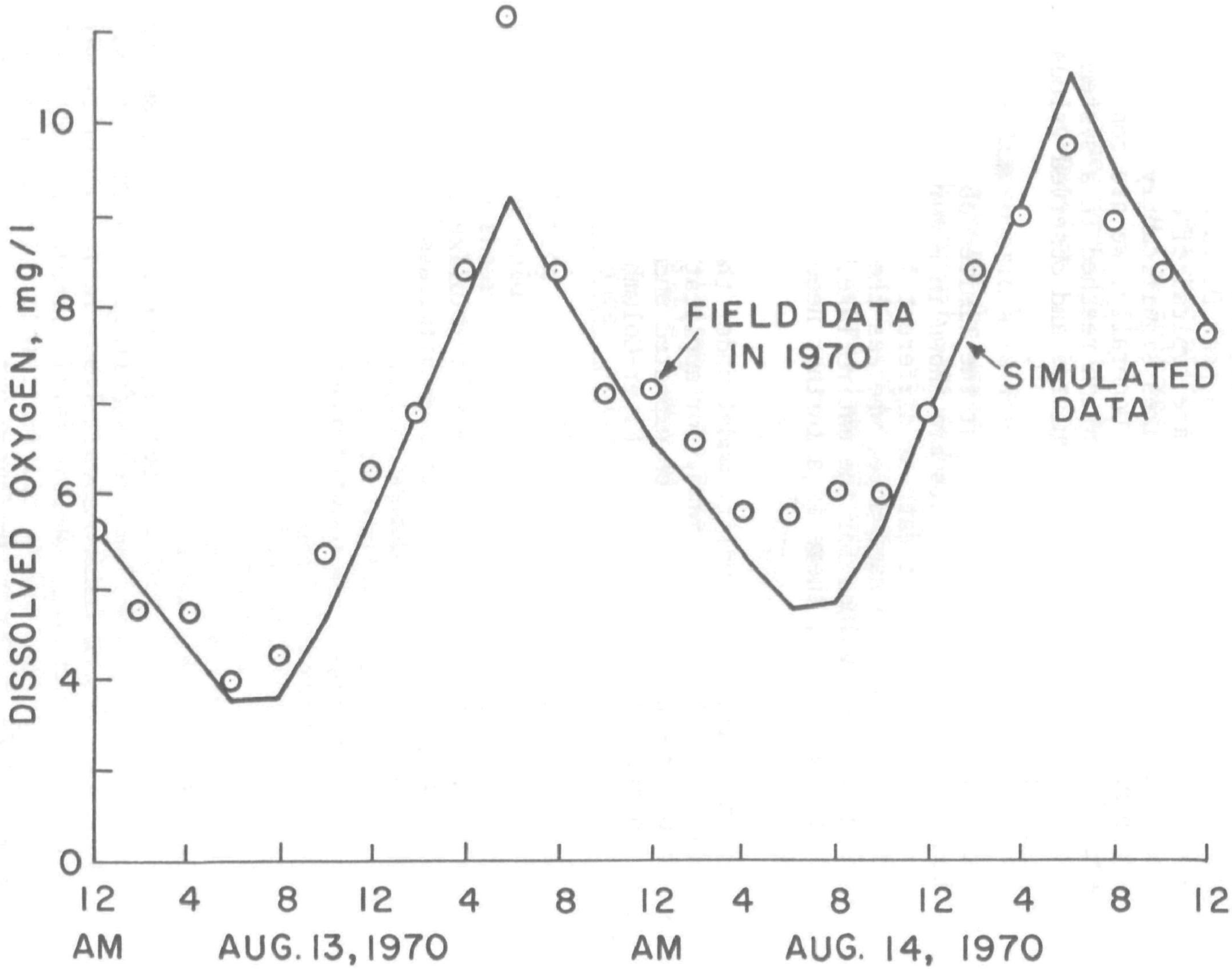

Figure 21. Comparison between Simulated and Observed Dissolved Oxygen Concentration in Vancouver Lake.

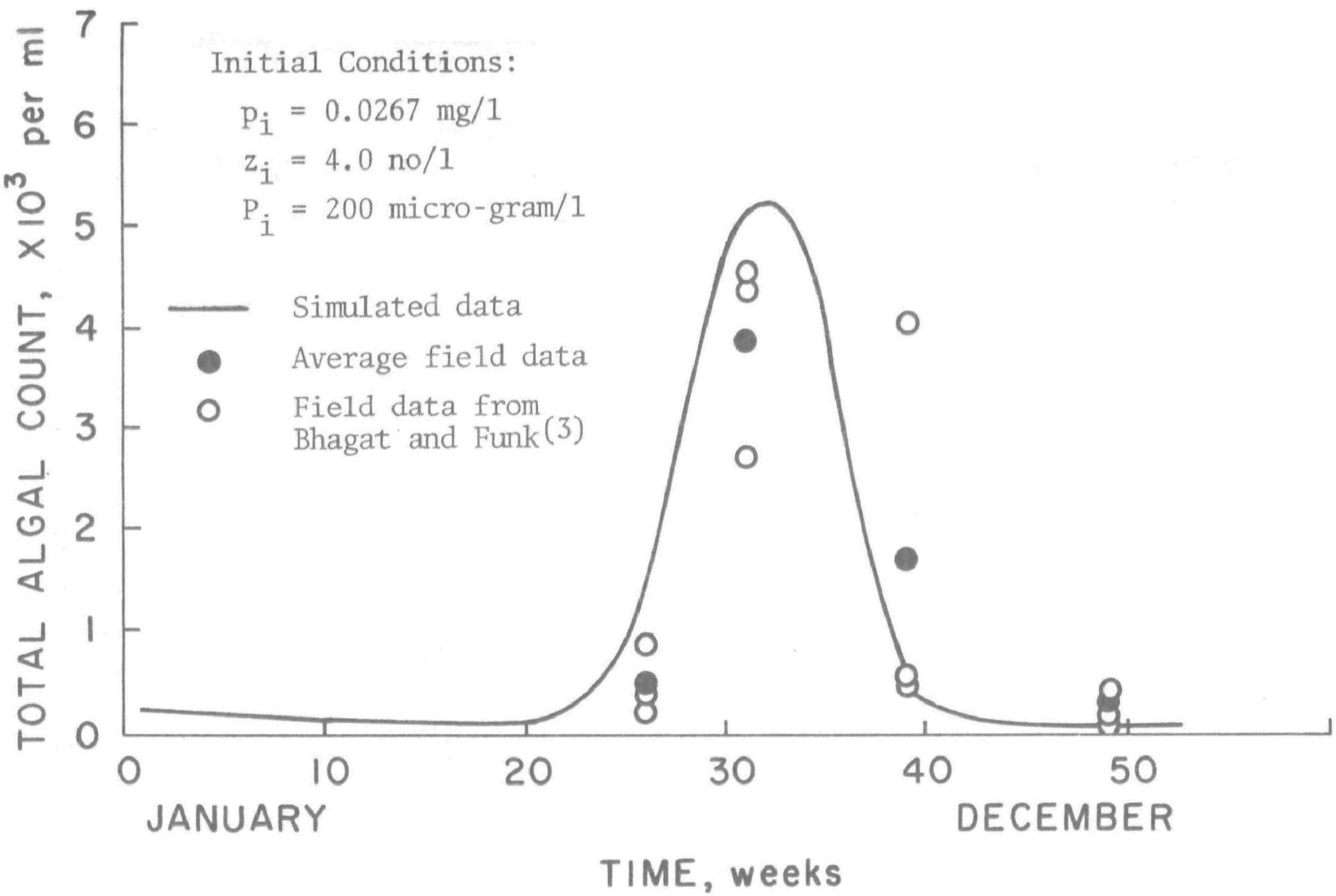

Figure 22. Comparison between Simulated and Observed Algal Concentration in Vancouver Lake.

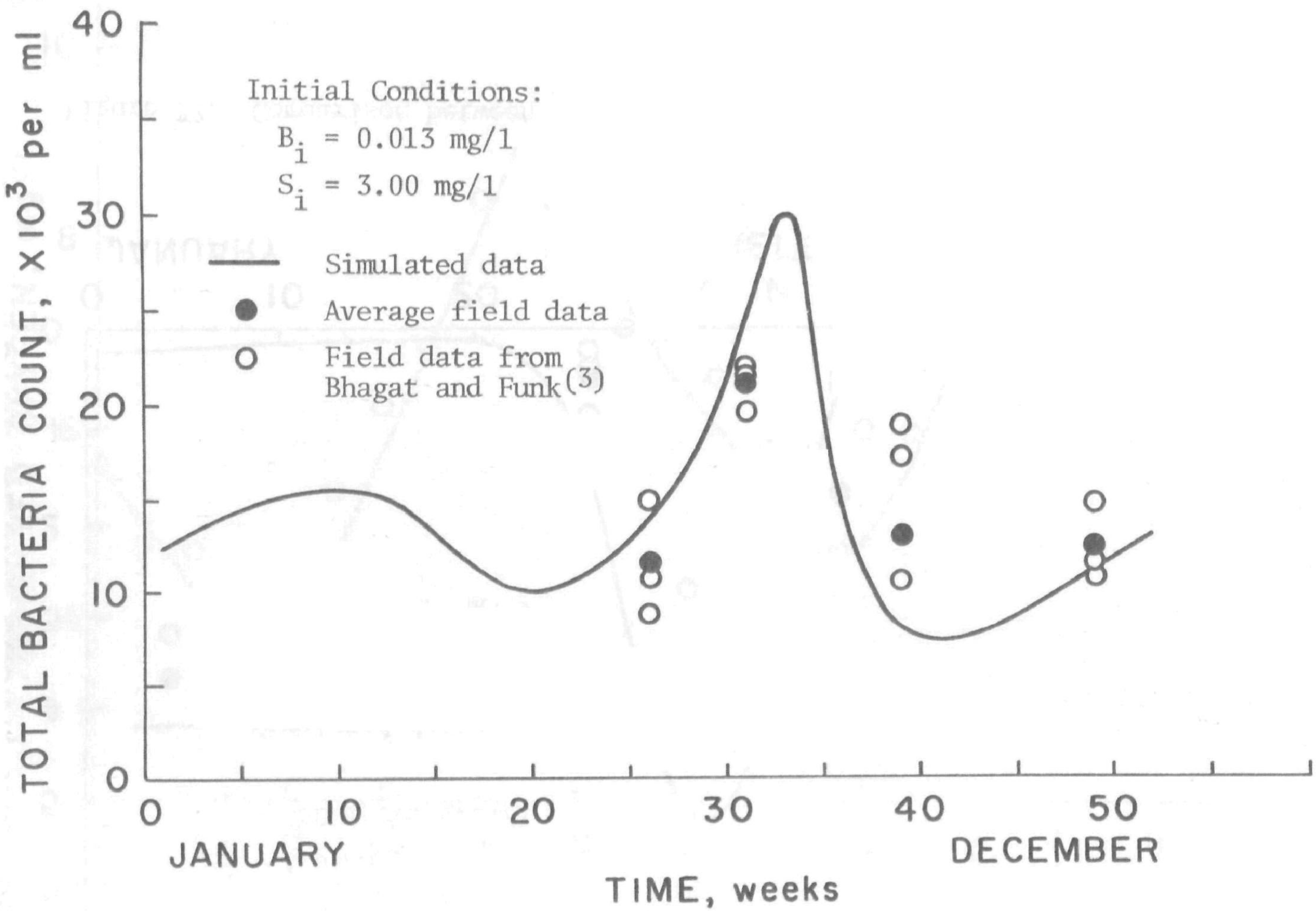

Figure 23. Comparison between Simulated and Observed Total Bacteria Concentration in Vancouver Lake.

SECTION VIII

PREDICTION RESULTS AND DISCUSSION

Under the present conditions, the dissolved oxygen level in Vancouver Lake frequently goes down to about 6 mg/l during the night and sometimes the level is as low as 4 mg/l. If the lake is dredged to 10 feet below mean sea level to provide 15 feet of water depth and there is no curtailment in the existing levels of inflow pollution loads to the lake, then the water quality in the lake will become worse and the DO model predicts that the dissolved oxygen level in the lake will frequently go down to 4 mg/l. On the other hand, if Columbia River water is also introduced, then the water quality in the lake is predicted to improve according to Figure 24. Here the dissolved oxygen concentration in the lake is plotted as a function of the detention time in the lake of the introduced Columbia River water. The detention time is inversely proportional to the flow rate of the introduced water (Figure 20). In order to raise the present level of dissolved oxygen in the lake to 8 mg/l (as required for class A lakes), an average flow of 750 cubic feet per second will be required to be diverted from the Columbia River to Vancouver Lake near its southwest corner. This prediction is based on the assumption that the water quality of the Columbia River will remain of as high quality as is today. The Columbia River is an interstate stream and is regulated by state agencies from Washington and Oregon through federally approved water quality standards and plans of implementation. It is therefore believed that the water quality of the Columbia River will be maintained and possibly improved.

A summary of the water quality input data used in the water quality model for model verification and for prediction analysis is given in Table 9. These data were used as the initial values in the generation of theoretical values of time-varying water quality parameters for the subsequent time periods. The average concentrations of nitrogen and phosphorus, in the Columbia River, that are considered easily available to plankton were used. The easily available forms of nitrogen considered were NH_3, NO_2, and NO_3, and the similar form of phosphorus considered was the orthophosphate. In the case of present nutrient levels in Vancouver Lake, high total phosphorus values and average total nitrogen values were used in order to compensate for the recycling of nutrients from bottom sediments. High phosphorus values rather than average values were chosen to simulate the critical conditions in the lake, and phosphorus is considered to be the most important of the limiting nutrients for the blue green algae (Aphanizomenon Flos-Aquae) which are prevalent in Vancouver Lake.

Attempts were also made to predict the concentrations of algae and bacteria in Vancouver Lake for the post-modification of the system. The results are shown in Figures 25 and 26. These results are based on the organism concentrations in the Columbia River water as shown in these figures and, for other concentrations than these, proper modification of the predicted results will be required.

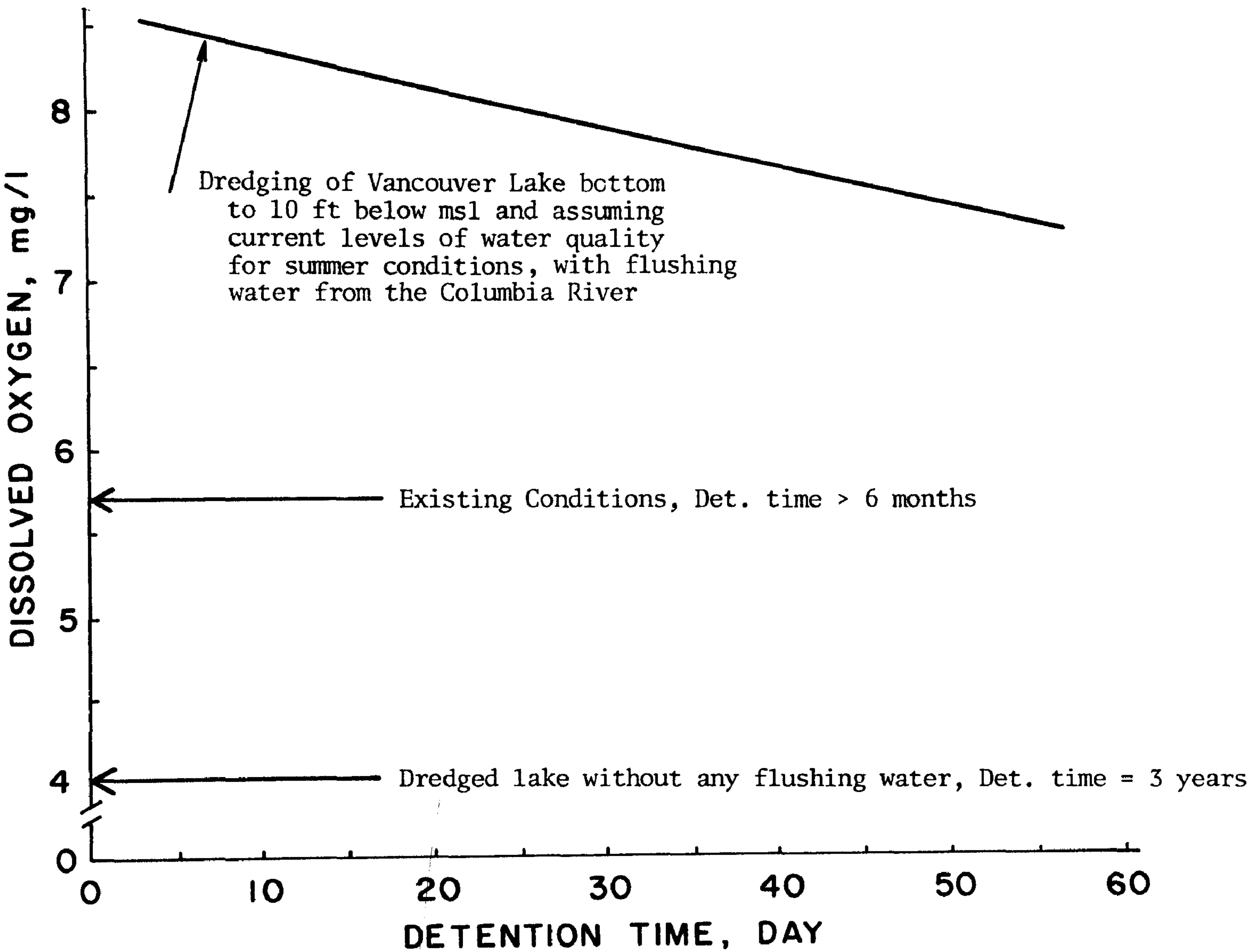

Figure 24. Predicted Water Quality in Vancouver Lake

Table 9. WATER QUALITY INPUT DATA USED IN WATER QUALITY MODEL FOR VERIFICATION AND PREDICTION

Water Quality	Burnt Bridge Creek	Vancouver Lake	Columbia River[a]
Total phytoplankton (mg/1)	8.0	8.0	4.0
Nitrogen (mg/1)	4.22	2.3	0.24
Phosphate (mg/1)	6.34	1.6	0.12
Dissolved oxygen (mg/1)	8.6	5.7	9.0
Total zooplankton (no/1)	20.0	20.0	2.0
BOD_5 (mg/1)	10.0	8.0	2.0

[a]Used for prediction after the Columbia River water is diverted into the lake.

There are three interrelated steps which can be taken to improve the quality and quantity of water in Vancouver Lake:

(1) curtail the sources and amounts of pollution entering the lake,

(2) dredge the lake to remove the nutrient rich bottom sediments and to increase the depth, and

(3) introduce an additional flow of better quality water into the lake to improve and then to maintain its quality.

The study of the last two steps and their effect on the water quality in Vancouver Lake was the main emphasis of this study and, although step number one was not in the scope of this study, a few comments may be in order. The sources of pollution to Vancouver Lake include Burnt Bridge Creek, Lake River, and drainage from livestock and agricultural areas. Burnt Bridge Creek has been receiving drainage from septic tanks which serve approximately 20,000 people. Today about 45% of the area population is served with municipal sewers and within the next five years the remaining population of the area is expected to be sewered. Therefore, the completed and the planned sewer installation programs and completed and planned facilities for treatment of wastewaters should reduce the level of pollution in Burnt Bridge Creek and hence should reduce the amount of human waste entering Vancouver Lake. To control the drainage from livestock areas, better management of livestock wastes is needed. By introducing the Columbia River water into the lake, the tidal inflow to the lake from the Lake River will be reduced. At present, Lake River transports into the lake, during high tidal cycles, sediment and nutrient loads which it receives primarily from Salmon Creek.

One of the potential uses of a simulation model is to perform sensitivity analyses of variables operating on a system. Once the accuracy of the model has been verified, the relative significance of the different

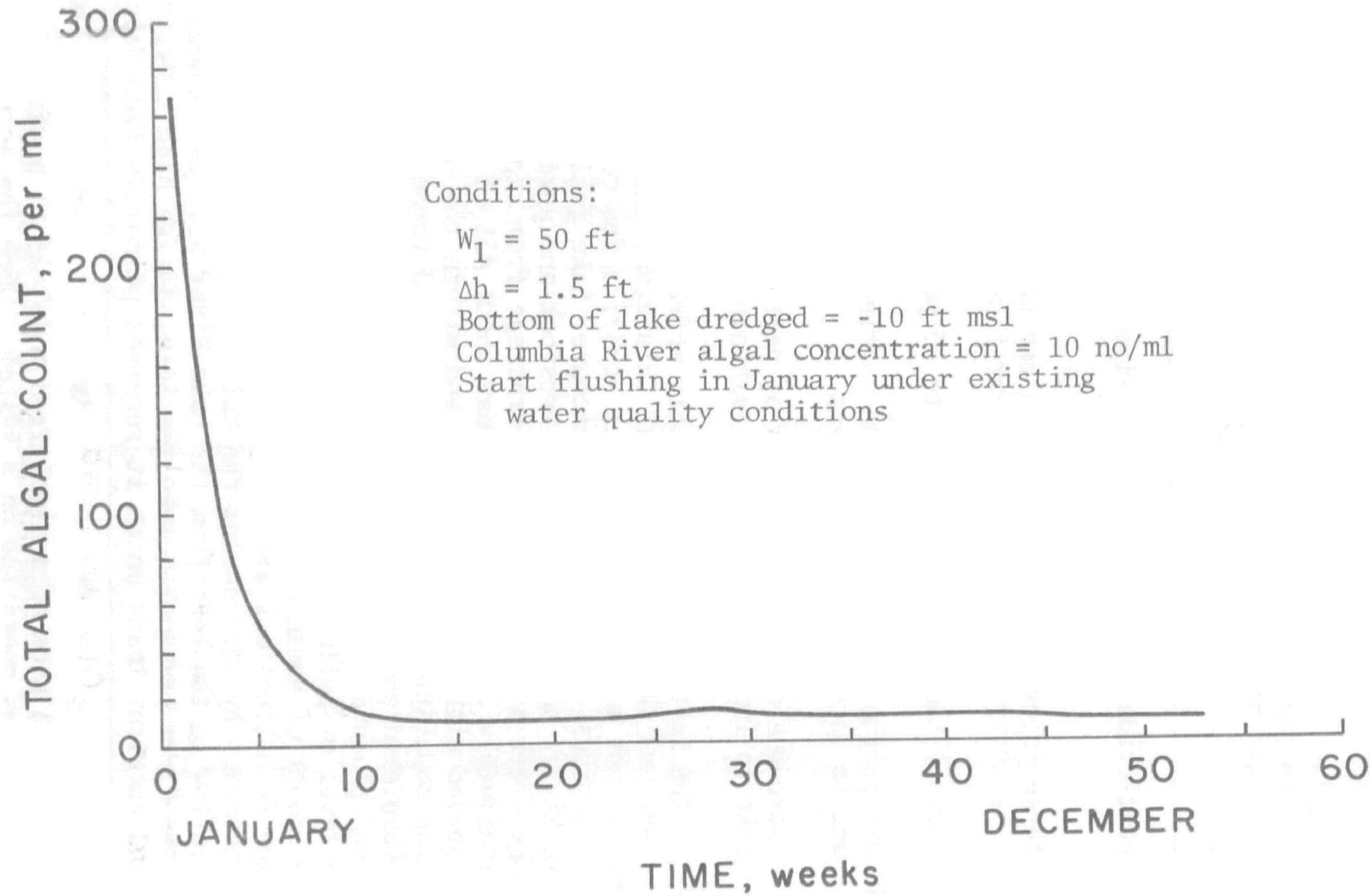

Figure 25. Predicted Effects of Dredging and Flushing on Total Algal Count in Vancouver Lake.

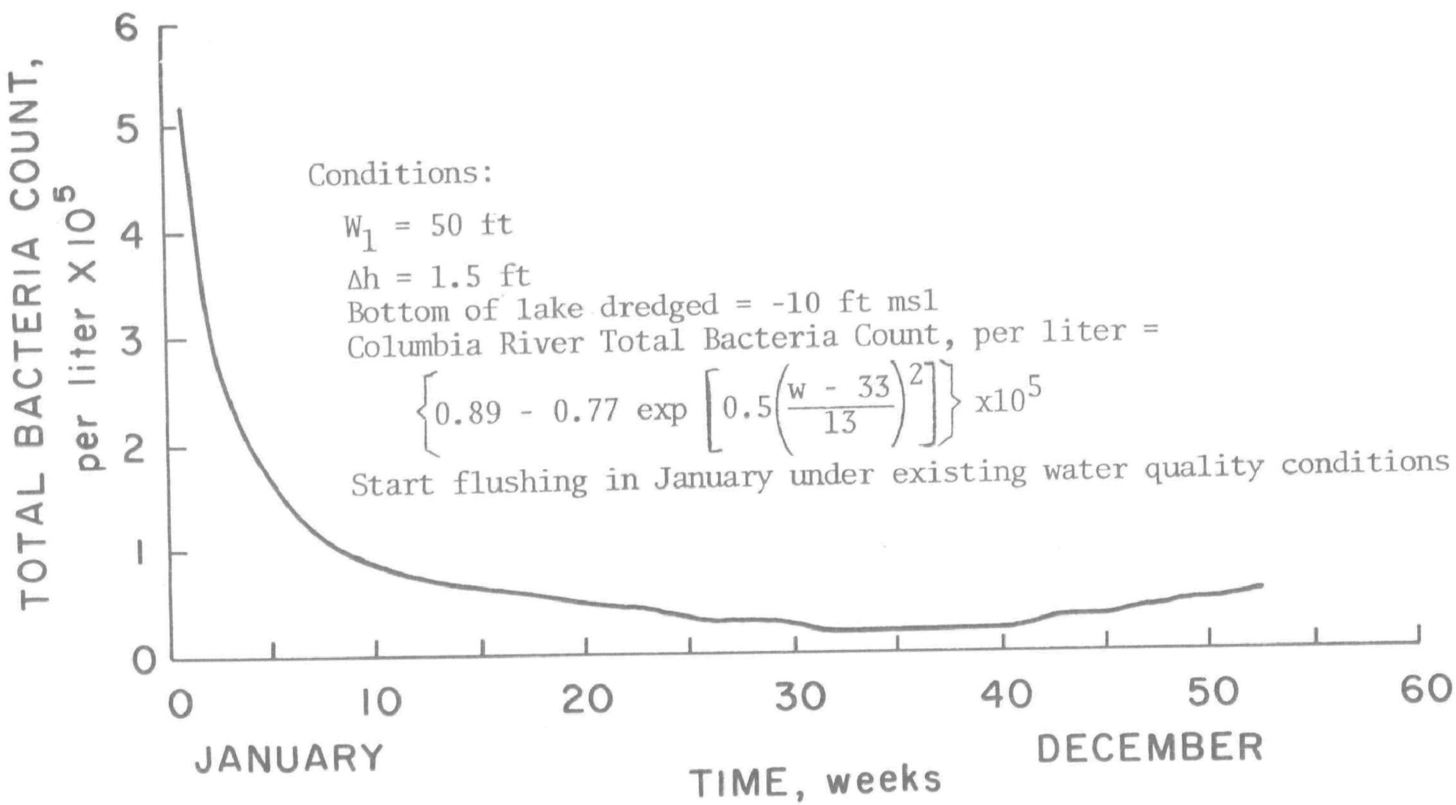

Figure 26. Predicted Effects of Dredging and Flushing on Total Bacteria Count in Vancouver Lake.

parameters may be assessed. In the DO model, it was found that the diurnal variation of dissolved oxygen was very sensitive to the phytoplankton specific growth rate (μ) parameter. An example of this is shown in Figure 27. The numerical values of μ were varied from 0.05 to 0.15 per day per degree centigrade and the μ value of 0.09/day-°C best simulated the conditions in Vancouver Lake and hence this value was used in the prediction analysis of Vancouver Lake.

This study though directed to the specific case of Vancouver Lake, the systems analysis techniques developed, the models used, and the approaches taken should be useful in the investigations dealing with the improvement of water quality of polluted lakes. It is believed that the results of this study will be valuable in the initial as well as in the final development stages of Vancouver Lake System.

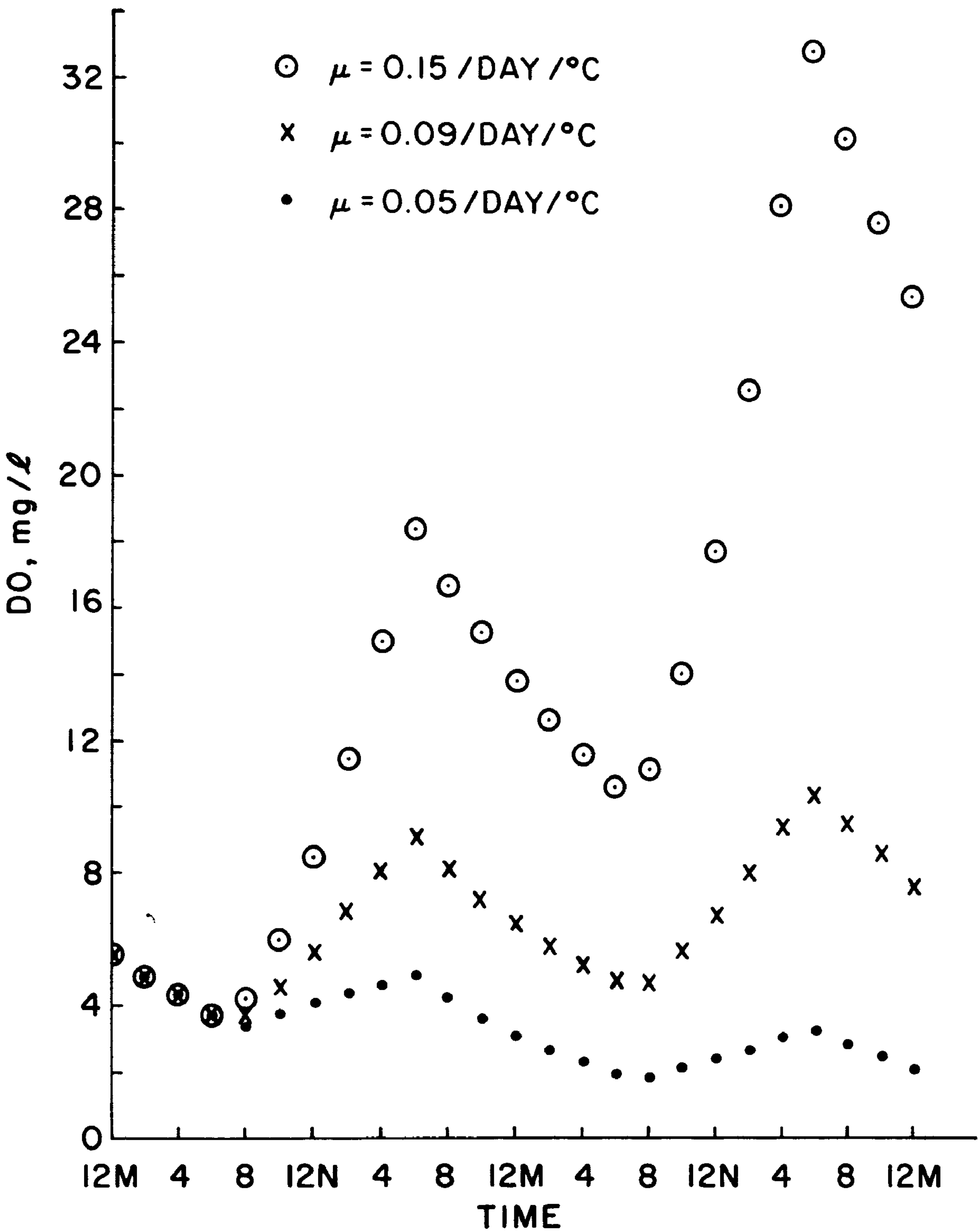

Figure 27. Sensitivity of Dissolved Oxygen to Phytoplankton Specific Growth Rate, μ

SECTION IX

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SECTION X

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APPENDICES

APPENDIX A

ALGAE FOUND IN COLUMBIA RIVER AT STATION #1

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Diatoms					
Achanathes sp.	--	--	--	1	--
Asterionella formosa	--	--	--	421	61
Asterionella sp.	89	15	483	30	--
Caloneis sp.	--	--	--	<1	--
Cocconeis sp.	--	--	--	2	<1
Cocconeis placentula	--	--	--	--	--
Cyclotella sp.	--	--	--	45	54
Cymbella sp.	<1	1	3	6	<1
Diatoma sp.	--	3	--	5	1
Diatoma hiemale	--	--	--	1	--
Fragilaria crotonensis	38	--	175	860	104
Fragilaria sp.	--	28	--	80	86
Frustulia sp.	--	--	--	<1	--
Gomphoneis sp.	--	--	--	<1	--
Gomphonema sp.	1	--	1	5	5
Gomphonema lanceolata	--	--	--	--	--
Gyrosigma sp.	1	1	--	<1	--
Hannea arcus	2	--	<1	3	--
Melosira varians	--	--	--	18	--
Melosira sp.	32	9	100	1426	4
Meridon sp.	--	--	--	<1	--
Navicula sp.	--	--	7	31	--
Navicula minus	--	--	--	--	--
Neidium sp.	--	--	--	--	--
Nitzchia sp.	4	1	--	--	--
Opephoea martyi	--	--	--	1	--
Pinnularia acuminata	--	--	--	<1	--
Rhizosolenia sp.	--	--	--	--	--
Rhoicosphenia curvata	--	--	--	1	--
Stauroneis sp.	--	--	--	3	--
Stephanodiscus sp.	25	4	7	249	190
Surirella sp.	--	--	--	1	--
Synedra amphicephala	--	--	--	<1	--
Synedra incisa	--	--	--	4	--
Synedra filiformis	--	--	--	1	--
Synedra sp.	14	4	19	68	40
Synedra ulna	--	--	--	30	--
Tabellaria flocculosa	--	--	--	186	477

APPENDIX A

ALGAE FOUND IN COLUMBIA RIVER AT STATION #1
(cont.)

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Tabellaria asteroides	--	--	--	80	--
Tabellaria sp.	--		71	--	55
Tetracyclus elliptica	--	<1	--	--	--
Unident. diatoms	--	--	134	64	36
<u>Yellow Greens</u>					
Tribonema	36	10	--	692	146
<u>Greens</u>					
Actinastrum sp.	--	--	--	1	--
Ankistrodesmus falcatus	11	1	--	7	8
Chlorella sp.	--	--	--	6	16
Chlorococcum sp.	--	--	--	--	1
Closteridium sp.	--	--	--	1	<1
Closteriopsis longissima	--	--	--	--	4
Closterium sp.	--	--	--	10	29
Coelastrum sp.	<1	<1	--	2	5
Docidium sp.	--	--	--	--	--
Echinosphaerella	--	--	--	--	<1
Eudorina sp.	--	--	--	--	1
Genicularia sp.	--	--	--	--	--
Gloeocystis sp.	--	--	--	--	--
Gonatozygon sp.	--	--	--	<1	--
Micractinium sp.	--	--	--	--	<1
Netrium sp.	--	--	--	4	--
Pandorina morum	--	--	--	1	1
Pedistrum duplex	--	--	--	--	2
Pediastrum sp.	--	--	--	--	3
Phacus sp.	--	--	--	--	--
Pleurotaenium sp.	--	--	--	1	--
Protococcus sp.	--	--	--	--	--
Rhizochonium	--	--	--	--	<1
Scenedesmus quadricauda	--	--	--	64	51
Scenedesmus sp.	--	<1	--	31	--
Sphaerocystis schroeteri	--	--	--	--	3
Staurastrum sp.	--	--	--	--	1

APPENDIX A

ALGAE FOUND IN COLUMBIA RIVER AT STATION #1
(cont.)

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Ulothrix sp.	--	--	--	11	1
Volvox sp.	--	--	--	--	<1
Blue-Greens					
Anacystis	--	--	--	--	--
Microspora	--	--	--	20	18
Nostoc	--	--	--	10	--
Oscillatoria sp.	--	--	--	--	5
Oscillatoria angustissima	--	--	--	--	--

APPENDIX B

ALGAE FOUND IN COLUMBIA RIVER AT STATION #2

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Diatoms					
Achanathes sp.	1	2	--	4	--
Asterionella formosa	--	--	--	490	57
Asterionella sp.	99	5	534	24	--
Caloneis sp.	--	--	--	--	1
Cocconeis sp.	--	--	--	2	--
Cocconeis placentula	--	--	--	--	<1
Cyclotella sp.	--	--	--	24	58
Cymbella sp.	4	--	1	9	2
Diatoma sp.	10	--	--	3	1
Diatoma hiemale	--	--	--	--	--
Fragilaria crotonensis	<21	--	215	787	249
Fragilaria sp.	--	25	--	108	76
Frustulia sp.	--	--	--	<1	--
Gomphoneis sp.	--	--	--	--	--
Gomphonema sp.	<1	--	--	4	--
Gomphonema lanceolata	--	--	--	<1	--
Gyrosigma sp.	<1	--	--	--	1
Hannea arcus	3	<1	1	4	--
Melosira varians	--	--	--	29	--
Melosira sp.	37	13	147	1932	67
Meridon sp.	--	--	--	--	--
Navicula sp.	--	--	6	37	1
Navicula minus	--	1	--	--	--
Neidium sp.	--	--	--	--	<1
Nitzchia sp.	9	2	--	--	--
Opephoea martyi	--	--	--	1	--
Pinnularia acuminata	--	--	--	--	--
Rhizosolenia sp.	--	--	--	<1	--
Rhoicosphenia curvata	--	--	--	<1	--
Stauroneis sp.	--	<1	--	<1	--
Stephanodiscus sp.	12	12	5	212	168
Surirella sp.	--	--	--	3	<1
Synedra amphicephala	--	--	--	--	--
Synedra incisa	--	--	--	8	--
Synedra filiformis	--	--	--	1	--
Synedra sp.	27	3	44	84	32
Synedra ulna	--	--	--	27	7
Tabellaria flocculosa	--	--	--	87	755
Tabellaria asteroides	--	--	--	84	--

APPENDIX B

ALGAE FOUND IN COLUMBIA RIVER AT STATION #2
(cont.)

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Tabellaria sp.	--	6	81	--	48
Tetracyclus elliptica	--	--	--	--	--
Unident. diatoms	--	--	95	61	44
<u>Yellow Greens</u>					
Tribonema	46	20	--	563	134
<u>Greens</u>					
Actinastrum sp.	--	--	--	1	--
Ankistrodesmus falcatus	2	--	--	8	4
Chlorella sp.	--	--	--	6	5
Chlorococcum sp.	--	--	--	--	3
Closteridium sp.	--	--	--	--	<1
Closteriopsis longissima	--	--	--	<1	--
Closterium sp.	--	--	--	10	29
Coelastrum sp.	--	1	--	1	6
Docidium sp.	--	--	--	1	--
Echinosphaerella	--	--	--	--	--
Eudorina sp.	--	--	--	--	1
Genicularia sp.	--	--	--	12	--
Gloeocystis sp.	--	--	--	--	1
Gonatozygon sp.	--	--	--	3	--
Micractinium sp.	--	--	--	--	<1
Netrium sp.	--	--	--	--	--
Pandorina morum	--	--	--	1	1
Pedistrum duplex	--	--	--	<1	2
Pediastrum sp.	--	--	--	<1	1
Phacus sp.	--	--	--	--	1
Pleurotaenium sp.	--	--	--	1	--
Protococcus sp.	--	--	--	--	<1
Rhizochonium	--	--	--	--	--
Scenedesmus quadricauda	--	--	--	36	33
Scenedesmus sp.	1	--	--	40	5
Sphaerocystis schroeteri	--	--	--	--	--
Staurastrum sp.	--	--	--	--	<1
Ulothrix sp.	--	--	--	6	2
Volvox sp.	--	--	--	--	--

APPENDIX B

ALGAE FOUND IN COLUMBIA RIVER AT STATION #2
(cont.)

Phytoplankton	Average Cell Concentration, No./ml				
	December	February	April	June	August
Blue-Greens					
Anacystis	--	--	--	--	1
Microspora	--	--	--	8	4
Nostoc	--	--	--	9	--
Oscillatoria sp.	--	--	--	9	3
Oscillatoria angustissima	--	--	--	--	18

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #1 $\frac{1}{4}$ Channel Width Surface Sample	Dec. 1969	0.0	3.5	115	33	27	6.4	0.28	0.16	0.16	0.06	0.10
	Feb. 4, 1970	0.45	6.3	156	36	22	7.0	0.33	0.15	0.20	0.02	0.34
	Mar. 13, 1970	--	--	--	--	--	--	0.26	0.24	0.53	0.03	0.20
	Apr. 7, 1970	0.0	4.7	132	43	17	3.0	0.32	0.05	0.14	0.06	0.34
	June 12, 1970	1.60	9.5	105	29	17	7.0	0.13	0.01	--	0.05	0.03
	Aug. 4, 1970	1.0	4.1	85	33	6	0.0	0.05	0.03	0.04	0.02	0.01
Station #1 $\frac{1}{4}$ Channel Width Mid-Depth	Dec. 1969	0.4	4.7	120	28	23	2.0	0.26	0.17	0.13	0.03	0.35
	Feb. 4, 1970	1.5	6.2	160	32	27	7.0	0.32	0.12	0.24	0.02	0.30
	Apr. 7, 1970	1.2	4.5	126	39	14	3.0	0.29	0.13	0.12	0.03	0.37
	June 12, 1970	1.5	9.0	109	25	20	13.0	0.13	0.03	0.00	0.09	0.04
	Aug. 4, 1970	0.5	3.4	94	29	21	15.0	0.08	0.02	0.04	0.02	0.01
Station #1 $\frac{1}{4}$ Channel Width Near Bottom	Dec. 1969	0.7	6.0	112	23	18	2.0	0.25	0.18	0.13	0.00	0.10
	Feb. 4, 1970	1.0	5.9	160	40	35	10.0	0.37	0.13	0.21	0.08	0.31
	Apr. 7, 1970	1.4	4.7	129	37	16	1.0	0.28	0.11	0.14	0.05	0.37
	June 12, 1970	1.4	9.8	125	31	10	0.0	0.12	0.01	0.07	0.02	0.03
	Aug. 4, 1970	0.8	4.3	94	35	14	4.0	0.04	0.03	0.00	0.10	0.01

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER
(cont.)

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #1 1/2 Channel Width Surface Sample	Dec. 12, 1969	0.3	5.3	126	38	30	13	0.22	0.22	0.12	0.01	0.20
	Feb. 4, 1970	<1.1	5.2	152	36	30	10	0.30	0.15	0.11	0.09	0.32
	Mar. 13, 1970	--	--	--	--	--	--	0.34	0.36	0.53	0.03	0.33
	Apr. 7, 1970	--	3.4	135	29	13	2	0.52	0.14	--	0.06	0.36
	June 12, 1970	1.2	8.3	116	25	15	10	0.08	0.02	0.03	0.05	0.03
	Aug. 4, 1970	0.7	3.2	103	31	12	4	0.10	0.03	-0.40	0.21	0.00
Station #1 1/2 Channel Width Mid-Depth	Dec. 12, 1969	0.7	4.1	125	43	22	1.6	0.24	0.26	--	0.00	--
	Feb. 4, 1970	1.0	5.7	168	56	30	10	0.40	0.13	0.15	0.02	0.33
	Apr. 7, 1970	0.8	3.2	131	40	13	3	0.26	0.10	0.02	0.15	0.38
	June 12, 1970	1.4	8.5	105	25	16	10	0.10	0.05	0.02	0.04	0.05
	Aug. 4, 1970	0.8	2.8	108	34	10	1	0.12	0.03	0.08	0.01	0.00
Station #1 1/2 Channel Width Near Bottom	Dec. 12, 1969	0.9	3.4	132	41	22	5	0.10	0.27	0.07	0.04	0.19
	Feb. 4, 1970	1.4	5.4	180	64	28	8	0.38	0.12	0.20	0.03	0.34
	Apr. 7, 1970	1.0	4.0	136	29	20	0	0.36	0.11	0.12	0.05	0.38
	June 12, 1970	1.5	8.9	120	28	20	7	0.16	0.04	0.04	0.02	0.03
	Aug. 4, 1970	0.6	4.3	110	46	15	4	0.13	0.03	0.05	0.01	0.00

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER
(cont.)

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #1 3/4 Channel Width Surface Sample	Dec. 1969	0.1	5.1	128	18	18	3.4	0.21	0.29	0.10	0.05	0.15
	Feb. 4, 1970	<1.8	5.8	168	28	28	8	0.46	0.18	0.18	0.09	0.32
	Mar. 13, 1970	--	--	--	--	--	--	0.30	0.44	0.47	0.03	0.45
	Apr. 7, 1970	0.8	2.5	136	44	23	1	0.22	0.18	0.10	0.10	0.41
	June 12, 1970	1.4	8.2	110	26	20	10	0.18	0.03	0.07	0.04	0.03
	Aug. 4, 1970	0.8	3.4	112	48	12	0	0.14	0.09	0.03	0.08	0.00
Station #1 3/4 Channel Width Mid-Sample	Dec. 1969	0	4.2	132	34	18	3.4	0.21	0.36	0.14	0.02	0.15
	Feb. 4, 1970	<1.9	6.3	160	42	30	5	0.4	0.18	0.21	0.09	0.31
	Apr. 7, 1970	0.8	2.6	130	44	17	2	0.28	0.15	0.11	0.06	0.40
	June 12, 1970	1.4	8.6	100	27	20	9	0.22	0.02	0.02	0.07	0.04
	Aug. 4, 1970	1.0	3.4	107	21	12	2	0.25	0.1	0.04	0.09	0.00
Station #1 3/4 Channel Width Near Bottom	Dec. 1969	0.9	3.7	115	44	188	6	0.29	0.32	0.17	0.01	0.15
	Feb. 4, 1970	0.9	6.9	156	28	25	10	0.45	0.18	0.24	0.08	0.32
	Apr. 7, 1970	0.9	3.6	91	34	13	6	0.23	0.20	0.10	0.07	0.40
	June 12, 1970	1.4	10.9	102	22	30	10	0.17	0.03	0.05	0.04	0.05
	Aug. 4, 1970	0.8	4.7	112	30	24	0	0.25	0.09	0.05	0.08	0.01

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER (cont.)

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #2 1/4 Channel Width Surface Sample	Dec. 1969	0.6	4.3	108	32	15.4	12.4	0.22	0.12	0.15	0.02	0.58
	Feb. 4, 1970	1.0	6.0	152	24	20	10	0.39	0.15	0.21	0.05	0.34
	Apr. 7, 1970	1.0	4.3	100	42	18	8	0.28	0.13	0.08	0.09	0.36
	June 12, 1970	1.6	10.6	104	26	23	9	0.14	0.02	0.03	0.05	0.03
	Aug. 4, 1970	0.8	5.4	96	34	0	0	0.08	0.03	0.02	0.04	0.01
Station #2 1/4 Channel Width Mid-Sample	Dec. 1969	0.6	4.5	105	49	15.2	14	0.15	0.20	0.16	0.02	0.02
	Feb. 4, 1970	--	--	--	--	--	--	--	--	--	--	--
	Apr. 7, 1970	-1.0	4.2	87	37	--	--	0.13	0.15	Total Kjeldahl 0.18		0.42
	June 12, 1970	1.5	10.2	108	41	23	3	0.13	0.02	0.04	0.04	0.03
	Aug. 4, 1970	0.5	4.7	108	42	7	7	0.09	0.06	0.08	0.02	0.01
Station #2 1/4 Channel Width Near Bottom	Dec. 1969	0.9	6.1	112	49	20	13.4	0.23	0.22	0.11	0.04	0.04
	Feb. 4, 1970	1.5	6.2	120	36	20	5	0.32	0.12	0.18	0.06	0.32
	Apr. 7, 1970	--	--	--	--	--	--	--	--	--	--	--
	June 12, 1970	1.5	10.8	104	34	27	12	0.20	0.03	0.10	0.04	0.03
	Aug. 4, 1970	1.0	5.1	104	33	5	5	0.09	0.04	0.08	0.03	0.00

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER
(cont.)

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #2 $\frac{1}{2}$ Channel Width Surface Sample	Dec. 1969	1.3	3.4	108	43	14	14	0.40	0.17	0.08	0.04	--
	Feb. 4, 1970	<2.1	5.7	162	36	20	5	0.37	0.16	0.18	0.07	0.34
	Apr. 7, 1970	0.6	4.2	90	37	11	5	0.21	0.08	0.16	0.01	0.45
	June 12, 1970	1.4	9.0	110	28	21	0	0.17	0.03	0.05	0.06	0.03
	Aug. 4, 1970	0.4	5.1	96	28	5	5	0.10	0.03	0.09	0.02	0.01
Station #2 $\frac{1}{2}$ Channel Width Mid-Depth	Dec. 1969	0.4	2.5	109	42	13	12	0.21	0.28	0.11	0.04	0.15
	Feb. 4, 1970	--	--	--	--	--	--	--	--	--	--	--
	Apr. 7, 1970	0.5	4.7	95	47	14	14	0.15	0.14	0.09	0.02	0.47
	June 12, 1970	1.0	8.4	106	33	21	1	0.17	0.02	0.13	0.02	0.04
	Aug. 4, 1970	0.9	4.5	93	32	4	4	0.12	0.04	0.06	0.02	0.00
Station #2 $\frac{1}{2}$ Channel Width Near Bottom	Dec. 1969	0.6	2.5	128	20	16	0	0.23	0.27	0.14	0.02	0.28
	Feb. 4, 1970	1.1	6.0	152	38	25	10	0.31	0.10	0.14	0.06	0.32
	Apr. 7, 1970	0.4	4.9	98	34	16	6	0.10	0.03	0.08	0.02	0.46
	June 12, 1970	1.2	8.2	97	22	25	7	0.19	0.02	0.06	0.08	0.04
	Aug. 4, 1970	0.6	4.5	95	33	6	6	0.09	0.06	0.05	0.02	0.01

APPENDIX C

WATER QUALITY OF THE COLUMBIA RIVER (cont.)

Sampling Station	Date	BOD	COD	TS	TVS	SS	VSS	Total-P as PO_4	Soluble-P as PO_4	Kjeldahl-N Org-N	Kjeldahl-N NH_3-N	NO_3 as N
Station #2 3/4 Channel Width Surface Sample	Dec. 1969	1.0	10.6	76	25	10	10	0.23	0.20	0.23	0.04	--
	Feb. 4, 1970	0.8	8.6	68	20	15	0	0.42	0.08	0.09	0.11	0.26
	Apr. 7, 1970	1.2	3.4	124	30	15	9	0.50	--	0.05	0.02	0.31
	June 12, 1970	1.2	7.7	103	28	20	0	0.15	0.02	0.00	0.14	0.04
	Aug. 4, 1970	0.4	3.6	93	30	4	4	0.11	0.07	-0.02	0.10	0.00
Station #2 3/4 Channel Width Mid-Depth	Dec. 1969	1.4	12.7	102	38	30	15	0.44	0.42	0.23	0.03	0.36
	Feb. 4, 1970	--	--	--	--	--	--	--	--	--	--	--
	Apr. 7, 1970	0.9	5.2	121	32	--	--	0.22	0.12	Total Kjeldahl 0.1		0.50
	June 12, 1970	1.3	8.5	100	40	24	2	0.18	0.02	0.10	0.04	0.03
	Aug. 4, 1970	0.6	4.1	89	23	5	5	0.11	0.06	0.07	0.03	0.00
Station #2 3/4 Channel Depth Near Bottom	Dec. 1969	1.6	14.0	101	36	29	9	0.85	0.72	0.44	0.03	0.70
	Feb. 4, 1970	1.6	6.8	120	52	30	10	0.32	0.10	0.32	0.12	0.55
	Apr. 7, 1970	1.0	4.1	--	--	9	4	0.05	0.07	0.07	0.02	--
	June 12, 1970	1.4	8.1	104	27	24	14	0.18	0.05	0.10	0.05	0.04
	Aug. 4, 1970	0.8	5.1	81	21	4	4	0.11	0.06	0.04	0.04	0.00

APPENDIX D

METHOD OF SOLUTION OF MODELS

Hydrodynamic Model

1. Identify initial values of H_i, Y_i, and Z_i; then calculate $(Q_L)_i$ by Equation [15],* and $(Q_C)_i$ by Equation [16]* for open channel calculation and Equation [21]* for pipe flow calculation.

2. Calculate the subsequent values by using initial values. At time $t_{i+1} = t_i + \Delta t$, use Equations [17]* and [18]* to obtain Y_{i+1} and Z_{i+1}. Calculate $(Q_L)_{i+1}$ and $(Q_C)_{i+1}$ by using Equations [15],* [16],* or [21], and then obtain the change in lake depth by Equation [8]* as

$$\Delta H = [(Q_L)_i + (Q_C)_i + Q_B + Q_{in} + P_r - E_v - Q_{ou}] \; \Delta t/A \; .$$

Therefore, we can evaluate

$$H_{i+1} = H_i + \Delta H \; .$$

*These equations are given elsewhere.(48)

3. Using the results of the previous steps as initial values, the procedure is repeated.

Actual tidal records were used instead of assuming the sinusoidal tidal cycle. Tabulated field data were used in input information and the same procedure of calculation was followed. Simulated results are shown in the verification of the hydrographic data of Vancouver Lake in Chapter 5 for existing prototype conditions.(48)

DO Model

Dissolved oxygen and its correlated components were solved by the finite difference approximation. Results of the hydrodynamic analysis were incorporated into this model. Procedures were similar to those used in the hydrodynamic model.

1. Identify the initial values of V_i, o_i, p_i, z_i, ℓ_i, n_i, L_i, and μ_i. Then evaluate the values of $(Vo)_i$, $(Vp)_i$, $(Vz)_i$, $(V\ell)_i$, and $(Vn)_i$ by Equations [1], [2], [7], [8], and [9].

2. Calculate the subsequent values of $(Vo)_{i+1}$, $(Vp)_{i+1}$, $(Vz)_{i+1}$, $(V\ell)_{i+1}$, and $(Vn)_{i+1}$ by using Equations [1] through [9] as follows:

$$(Vo)_{i+1} = (Vo)_i + [T_{o_i} + (\mu_1 - r)(Vp)_i\ T_i/R - K_1(V\ell)_i - K_4(AD)_i + K_2 V_i o_{s_i} - K_2(Vo)_i]\ \Delta t$$

$$(Vp)_{i+1} = (Vp)_i + [T_{p_i} + (\mu_i - r)\ T_i\ (Vp)_i(1 - s) - g(Vz)_i\ T_i/Y_z]\ \Delta t$$

$$(Vz)_{i+1} = (Vz)_i + [T_{z_i} + (Vz)_i\ g\ T_i - m(Vz)_i\ T_i]\ \Delta t$$

$$(V\ell)_{i+1} = (V\ell)_i + [T_{\ell_i} - (K_1 + K_3)(V\ell)_i]\ \Delta t$$

$$(VN)_{i+1} = (VN)_i + [T_{N_i} - \mu_i\ (VN)_i\ T_i/Y_{pN} + \alpha(Vz)_i + \beta(AD)_i]\ \Delta t$$

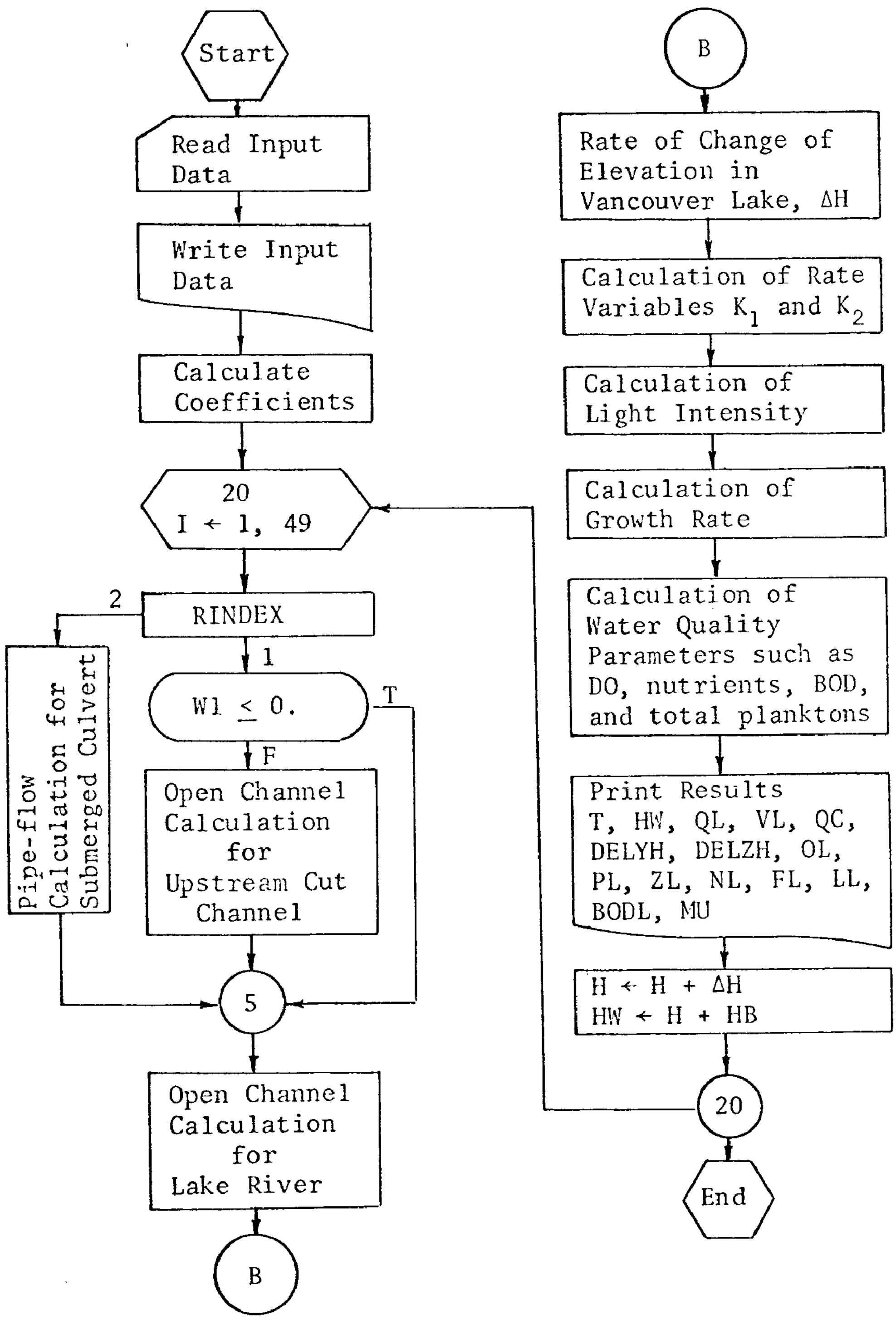
$$(VP)_{i+1} = (VP)_i + [T_{P_i} - \mu_i\ (VP)_i\ T_i/Y_{pP} + \alpha(Vz)_i + \beta(AD)_i]\ \Delta t$$

V_{i+1}, $(Q_L)_i$, and $(Q_c)_i$ were obtained from the hydrodynamic model. Therefore T_{o_i}, T_{p_i}, T_{z_i}, T_{ℓ_i}, T_{N_i}, and T_{P_i} can be determined, and o_{i+1}, p_{i+1}, z_{i+1}, ℓ_{i+1}, N_{i+1}, and P_{i+1} are evaluated by dividing by V_{i+1}.

3. The procedure was repeated by using values calculated from the previous step as initial values. A flow chart is shown on the next page and computer programs are included in Appendix E. The time was incremented by 0.0417 day (one hour) until equilibrium conditions were reached.

APPENDIX D

METHOD OF SOLUTION OF MODELS (cont.)



Flow Chart for Hydrodynamic and/or DO Computer Models

Runge-Kutta Third Order Method

The differential equation has its solution extended forward from known conditions by an increment of the independent variable without using information outside of this increment. By evaluating the slope at initial, one-third, and two-thirds points of the time increment, the unknown point can be calculated by weighting the values at those points. The numerical solutions of Equations [12] through [22] for the aquatic life model were obtained by using the Runge-Kutta third-order method by Hildebrand.[49] The method is applied to the aquatic life model for numerical solution as follows:

1. Identify the initial values of p_i, z_i, P_i, B_i, and S_i at time w_i with time increment Δw. Then, from Equations [12], [13], [14], [20], and [21], evaluate the Runge-Kutta first, second, and third values as follows.

2. Runge-Kutta first value:

$$u_1 = \Delta w p_i \left\{ p_1 \exp\left[-0.5\left(\frac{T_i - 26}{5.5}\right)^2\right] P_{p_i} P_i - p_2 T_i - p_3 z_i T_i \right\}$$

$$v_1 = \Delta w z_i \left\{ z_1 \exp\left[-0.5\left(\frac{T_i - 13}{8}\right)^2\right] P_{p_i} P_i G(P_{p_i}) - z_2 T_i G(P_{p_i}) \right\}$$

$$w_1 = \Delta w \frac{Q_{B_i} P_{B_i} + Q_{L_i} P_i}{V_i} - P_2 v_1 - P_3 u_1$$

$$X_1 = \Delta w \left[(\bar{\mu}_i - k_2 T_i) B_i + \frac{Q_{B_i} B_{B_i} + Q_{L_i} B_i}{V_i} \right]$$

$$Z_1 = \Delta w \left[\frac{Q_{B_i} S_{B_i} + Q_{L_i} S_i}{V_i} - (\bar{\mu}_i - k_2 T_i) B_i / Y_S + 0.004\, k_2 T_i B_i \right]$$

where the following expressions were obtained from Equations [15], [16], [17], [18], [19], and [22], respectively.

$$P_{p_i} = 12.2 + 4.1 \sin\left[2\pi\left(\frac{38 - w_i}{52}\right)\right]$$

$$G(P_{p_i}) = 0.82 + 0.343 \sin\left[2\pi\left(\frac{P_{p_i} - 7.2}{10.4}\right)\right]$$

$$Q_{B_i} = 28.32\left\{16.2 - 15.7 \exp\left[-0.5\left(\frac{w_i - 24}{9}\right)^2\right]\right\}$$

$$P_{B_i} = 150 + 750 \exp\left[-0.5\left(\frac{w_i - 24}{3}\right)^2\right]$$

$$T_i = 4.0 + 22.0 \exp\left[-0.5\left(\frac{w_i - 24}{6}\right)^2\right]$$

$$\bar{\mu}_i = \hat{\mu} \exp\left[-0.5\left(\frac{T_i - 26}{5.5}\right)^2\right]$$

3. Runge-Kutta second value:

$$u_2 = \Delta w(p_i + u_1/3)\left\{p_1 \exp\left[-0.5\left(\frac{T_{i+1/3} - 26}{5.5}\right)^2\right] P_{p_{i+1/3}} \right.$$
$$\left. x(P_i + w_1/3) - p_2 T_{i+1/3} - p_3(z_i + v_1/3) T_{i+1/3}\right\}$$

$$v_2 = \Delta w(z_i + v_1/3)\left\{z_1 \exp\left[-0.5\left(\frac{T_{i+1/3} - 13}{8}\right)^2\right] P_{p_{i+1/3}} \right.$$
$$\left. x(P_i + w_1/3)\ G(P_{p_{i+1/3}}) - z_2 T_{i+1/3}\ G(P_{p_{i+1/3}})\right\}$$

$$w_2 = \Delta w\ \frac{(Q_B P_B)_{i+1/3} + Q_{L_{i+1/3}}(P_i + w_1/3)}{V_{i+1/3}} - P_2 v_2 - P_3 u_2$$

$$X_2 = \Delta w \left[(\bar{\mu}_{i+1/3} - k_2 T_{i+1/3}) (B_i + X_1/3) + \frac{(Q_B B_B)_{i+1/3} + Q_{L_{i+1/3}} (B_i + X_1/3)}{V_{i+1/3}} \right]$$

$$Z_2 = \Delta w \left[\frac{(Q_B S_B)_{i+1/3} + Q_{L_{i+1/3}} (S_i + Z_1/3)}{V_{i+1/3}} - (\bar{\mu}_{i+1/3} - k_2 T_{i+1/3}) (B_i + X_1/3)/Y_S + 0.004\ k_2 T_{i+1/3} (B_i + X_1/3) \right]$$

where

$$P_{P_{i+1/3}} = 12.2 + 4.1 \sin \left[2\pi \left(\frac{38 - w_i - \Delta w/3}{52} \right) \right]$$

$$G(P_{P_{i+1/3}}) = 0.82 + 0.343 \sin \left[2\pi \left(\frac{P_{P_{i+1/3}} - 7.2}{10.4} \right) \right]$$

$$Q_{B_{i+1/3}} = 28.32 \left\{ 16.2 - 15.7 \exp \left[-0.5 \left(\frac{w_i + \Delta w/3 - 24}{9} \right)^2 \right] \right\}$$

$$P_{B_{i+1/3}} = 150 + 750 \exp \left[-0.5 \left(\frac{w_i + \Delta w/3 - 24}{3} \right)^2 \right]$$

$$T_{i+1/3} = 4.0 + 22 \exp \left[-0.5 \left(\frac{w_i + \Delta w/3 - 24}{6} \right)^2 \right]$$

$$\bar{\mu}_{i+1/3} = \hat{\mu} \exp\left[-0.5\left(\frac{T_{i+1/3} - 26}{5.5}\right)^2\right]$$

4. Runge-Kutta third value:

$$u_3 = \Delta w(p_i + 2u_2/3\left\{p_1 \exp\left[-0.5\left(\frac{T_{i+2/3} - 26}{5.5}\right)^2\right]P_{p_{i+2/3}}\right.$$

$$\left. x(P_i + 2w_2/3) - p_2 T_{i+2/3} - p_3(z_i + 2v_2/3)\ T_{i+2/3}\right\}$$

$$v_3 = \Delta w(z_i + 2v_2/3) \left\{z_1 \exp\left[-0.5\left(\frac{T_{i+2/3} - 13}{8}\right)^2\right] P_{p_{i+2/3}}\right.$$

$$\left. x(P_i + 2w_2/3)\ G(P_{p_{i+2/3}}) - z_2 T_{i+2/3}\ G(P_{p_{i+2/3}})\right\}$$

$$w_3 = \Delta w \quad \frac{(Q_B P_B)_{i+2/3} + Q_{L_{i+2/3}}(P_i + 2w_2/3)}{V_{i+2/3}} - P_2 v_3 - p_3 u_3$$

$$X_3 = \Delta w\left[(\bar{\mu}_{i+2/3} - k_2 T_{i+2/3})(B_i + 2X_2/3) + \right.$$

$$\left.\frac{(Q_B B_B)_{i+2/3} + Q_{L_{i+2/3}}(B_i + 2X_2/3)}{V_{i+2/3}}\right]$$

$$Z_3 = \Delta w\left[\frac{(Q_B S_B)_{i+2/3} + Q_{L_{i+2/3}}(S_i + 2Z_2/3)}{V_{i+2/3}} - \right.$$

$$(\bar{\mu}_{i+2/3} - k_2 T_{i+2/3})(B_i + 2X_2/3)/Y_S +$$

$$0.004\ k_2 T_{i+2/3}(B_i + 2X_2/3)\Big]$$

where

$$P_{p_{i+2/3}} = 12.2 + 4.1 \sin\left[2\pi\left(\frac{38 - w_i - 2\Delta w/3}{52}\right)\right]$$

$$G(P_{p_{i+2/3}}) = 0.82 + 0.343 \sin\left[2\pi\left(\frac{P_{p_{i+2/3}} - 7.2}{10.4}\right)\right]$$

$$Q_{B_{i+2/3}} = 28.32\left\{16.2 - 15.7 \exp\left[-0.5\left(\frac{w_i + 2\Delta w/3 - 24}{9}\right)^2\right]\right\}$$

$$P_{B_{i+2/3}} = 150 + 750 \exp\left[-0.5\left(\frac{w_i + 2\Delta w/3 - 24}{3}\right)^2\right]$$

$$T_{i+2/3} = 4.0 + 22 \exp\left[-0.5\left(\frac{w_i + 2\Delta w/3 - 24}{6}\right)^2\right]$$

$$\bar{\mu}_{i+2/3} = \hat{\mu} \exp\left[-0.5\left(\frac{T_{i+2/3} - 26}{5.5}\right)^2\right]$$

5. Weigh those values and obtain the subsequent values as

$$p_{i+1} = p_i + 0.25\ u_1 + 0.75\ u_3$$

$$z_{i+1} = z_i + 0.25\ v_1 + 0.75\ v_3$$

$$P_{i+1} = P_i + 0.25\ w_1 + 0.75\ w_3$$

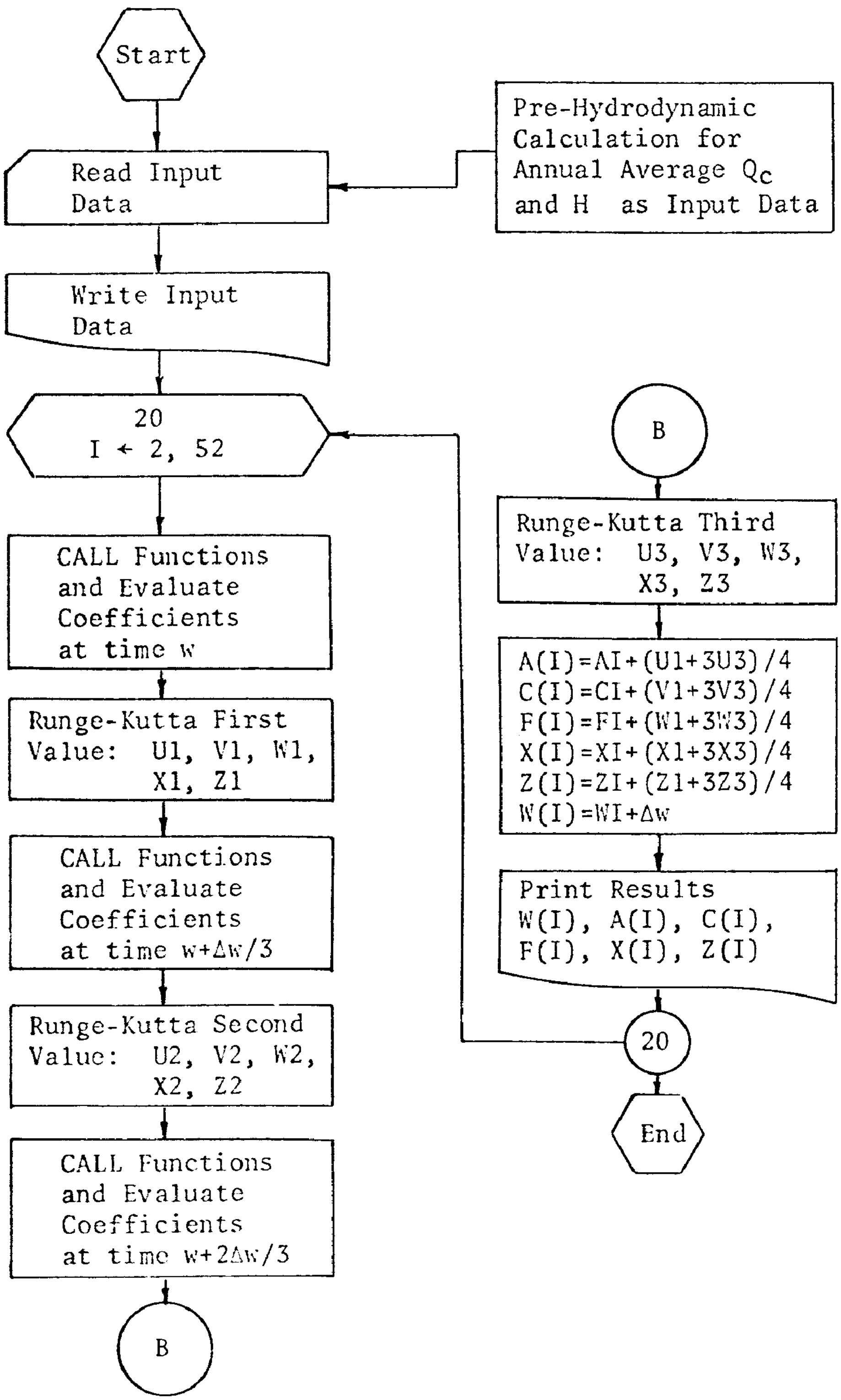
$$B_{i+1} = B_i + 0.25\ X_1 + 0.75\ X_3$$

$$S_{i+1} = S_i + 0.25\ Z_1 + 0.75\ Z_3\ .$$

By iteration the procedure is repeated until a desired time limit is reached. A flow chart is shown on the next page and computer programs are included in Appendix E. In this program the time was incremented by 1 week from w equals 1 to 52.

APPENDIX D

METHOD OF SOLUTION OF MODELS (cont.)



Flow Chart for Aquatic Life Computer Model

APPENDIX E

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C
C
C
C                         ***************************
C                         *  DISSOLVED OXYGEN MODEL  *
C                         ***************************
C
C
C
C    ......................................................................
C    .  UNDER THE COMPLETE MIXING ASSUMPTION, THE WATER QUALITY PREDICTION .
C    .  MODELS WERE APPLIED TO VANCOUVER LAKE, WASHINGTON.  THIS PROGRAM WAS .
C    .  PREPARED BY MARCUS C. N. LIN IN FEB., 1971 AT WSU.                 .
C    ......................................................................
      REAL MU,MUM,KN,KF,KL,K1,K2,K3,K4,NL,NC,NB,LL,LN,MT,MF
      DIMENSION TEMP(400),ZW(400),YW(400),V(400),QCC(400),QLL(400)
      READ (5,1) (TEMP(I),I=1,49)
      READ (5,1) (ZW(I),I=1,49)
100   READ(5,1,END=1000) ZG,YB,HW,HB,F1,F2,W1,W2,D1,D2,A
      READ (5,1) RC,R,YZ,G,KL,KN,KF,S,MT,K3,YPN,YPF,ALPHA,BETA,MUM,A1,
     1B1,C1,LN,PP,TSR,K4
      READ (5,1) PB,PL,PC,NB,NL,NC,FB,FL,FC,OB,CL,OC,ZB,ZL,ZC,BODB,BODL,
     1BODC,DL
1     FORMAT (8F10.2)
      WRITE (6,300) ZG,YB,HW,HB,F1,F2,W1,W2,D1,D2,A
300   FORMAT (1H1,'HYDRAULIC CHARACTERISTICS OF LAKE-RIVER SYSTEM  ',//,
     1' ZG =',F7.2,10X,'YB =',F8.2,10X,'HW =',F7.2,10X,'HB =',F7.2,//,
     2' F1 =',F7.3,10X,'F2 =',F8.3,10X,'W1 =',F7.2,10X,'W2 =',F7.2,//,
     3' D1 =',F10.2,7X,'D2 =',F10.2,8X,' A =',F14.2)
      WRITE (6,301) (TEMP(I),I=1,49)
301   FORMAT (////,' AVERAGE DAILY VANCOUVER LAKE WATER TEMPERATURE IN A
     1UG. (FOR 60 MIN. TIME INTERVAL)',10(//,10F10.2))
      WRITE (6,302) (ZW(I),I=1,49)
302   FORMAT (////,' STAGE HYDROGRAPH OF FELICA IN LAKE RIVER (MSL) ON A
     1UG. 13, 1970 (FOR 60 MIN. TIME INTERVAL)',10(//,10F10.2))
      WRITE (6,303) RC,R,YZ,G,KL,KN,KF,S,MT,K3,YPN,YPF,ALPHA,BETA,MUM,A1
     1,B1,C1,LN,PP,TSR,K4
303   FORMAT (////,' RATE CONSTANTS AND COEFFICIENTS FOR WQ PREDICTION',
     1//,'  RC =',F7.3, 8X,' R =',F8.3, 8X,'YZ =',F7.2, 8X,' G =',F7.4,
     28X,'KL =',F7.1, 8X,'KN =',F7.4, 8X,'KF =',F7.4,//,'    S =',F7.3, 8
     3X,'MT =',F8.4, 8X,'K3 =',F7.3,7X,'YPN =',F7.3,7X,'YPF =',F7.3, 5X,
     4'ALPHA =',F7.3,6X,'BETA =',F7.3,//,' MUM =',F7.5, 8X,'A1 =',F8.3,
     58X,'B1 =',F7.3, 8X,'C1 =',F7.3, 8X,'LN =',F7.2, 8X,'PP =',F7.3,7X,
     6'TSR =',F7.4,//,'   K4 =',F7.3)
      WRITE (6,304) PB,PL,PC,NB,NL,NC,FB,FL,FC,OB,OL,OC,ZB,ZL,ZC,BODB,
     1BODL,BODC,DL
304   FORMAT (////,' INITIAL WQ CONDITIONS FOR PHYTOPLANKTON, NITROGEN,
     1PHOSPHATE, DO, ZOOPLANKTON, BOD AND DETRITUS',/,' IN BURNT BRIDGE
     2CREEK, VANCOUVER LAKE AND COLUMBIA RIVER RESPECTIVELY',
     37(//,3F20.3))
      PR=0.
      OOU=0.
      QB=50.
      Q3=QB*86400.
      EV=-16.65
      TSS=TSR+PP
```

```
      DT=0.01041667*4.
      QIN=20.
      CV1=(1.49*W1)/(F1*D1**0.5*2.**1.6667)
      CV2=(1.49*W2)/(F2*D2**0.5*2.**1.6667)
      CVI=1.1*CV2
      CVC=0.9*CV2
      DB1=YB-HB
      DB2=ZG-HB
      H=HW-HB
      WRITE (6,10)
10    FORMAT (1H1,'OUTPUT OF BOTH HYDRODYNAMIC AND WATER QUALITY CONDITI
     1ONS',//' IN VANCOUVER LAKE SYSTEM')
      DO 20 I=1,49
      RI=I
      T=(RI-1.)*DT
      III=I-1
C     ......................................................................
C     .  HYDRODYNAMIC PROGRAMMING --- WATER BUDGET FOR VANCOUVER LAKE-     .
C     .  RIVER SYSTEM BY MAKING USE OF THE MANNING FORMULA (IN FT-SEC UNIT) .
C     .  AND THE CONTINUITY CONCEPT OF THE LAKE.  WATER SURFACE SLOPE WAS USED .
C     .  AS THE FIRST APPROXIMATION FOR EVALUATING THE ENERGY SLOPE.       .
C     ......................................................................
      Z=ZW(I)-ZG
      DELZH=ZW(I)-HW
      IF (W1 .LE. 0.) GO TO 55
C
C     FLOW RATE AND VELOCITY IN THE UPSTREAM CUT CHANNEL
C
      Y=YW(I)-YB
      DELYH=YW(I)-HW
      AC=W1*(Y+H)/2.
      TD1=Y-H+DB1
      COQ=(W1/(W1+Y+H))**0.6667
      IF (TD1 .LT. 0.) GO TO 4
C
C     FIRST APPROXIMATION IN UPSTREAM CUT CHANNEL
C
      QC=CV1*(Y+H)**1.6667*TD1**0.5
      IF (W1 .GT. 200.) GO TO 405
      QC=CC*COQ
C
C     FINAL CALCULATION IN THE UPSTREAM CUT CHANNEL
C
405   VC1=QC/(W1*Y)
      VC2=QC/(W1*H)
      DV=(VC1+VC2)*(VC1-VC2)/64.4
      TEST=TD1+DV
      IF (TEST .LT. 0.) GO TO 11
      QC=CV1*(Y+H)**1.6667*(TEST)**0.5
      IF (W1 .GT. 200.) GO TO 12
      QC=CC*COQ
      GO TO 12
11    QC=-CV1*(Y+H)**1.6667*(-TEST)**0.5
      IF (W1 .GT. 200.) GO TO 12
      QC=QC*COQ
12    VC=QC/AC
```

APPENDIX E

DISSOLVED OXYGEN MODEL
(cont.)

```
      GO TO 5
4     QC=-CV1*(Y+H)**1.6667*(-TD1)**0.5
      IF (W1 .GT. 200.) GO TO 410
      QC=QC*COQ
410   VC1=QC/(W1*H)
      VC2=QC/(W1*Y)
      DV=(VC1+VC2)*(VC1-VC2)/64.4
      TEST=-TD1+DV
      IF (TEST .LT. 0.) GO TO 22
      QC=-CV1*(Y+H)**1.6667*(TEST)**0.5
      IF (W1 .GT. 200.) GO TO 23
      QC=QC*COQ
      GO TO 23
22    QC=CV1*(Y+H)**1.6667*(-TEST)**0.5
      IF (W1 .GT. 200.) GO TO 23
      QC=QC*COQ
23    VC=QC/AC
      GO TO 5
55    QC=0.
      VC=0.
      DELYH=0.
C
C     FLOW RATE AND VELOCITY IN LAKE RIVER
C
5     AL=W2*(Z+H)/2.
      AI=1.1*AL
      AO=0.9*AL
      TD2=Z-H+DB2
      IF (TD2 .LT. 0.) GO TO 6
C
C     FIRST APPROXIMATION IN THE LAKE RIVER
C
      QL=CVI*(Z+H)**1.6667*TD2**0.5
C
C     FINAL CALCULATION IN THE LAKE RIVER
C
      VL1=QL/(W2*Z)
      VL2=QL/(W2*H)
      DV=(VL1+VL2)*(VL1-VL2)/64.4
      TEST=TD2+DV
      IF (TEST .LT. 0.) GO TO 44
      QL=CVI*(Z+H)**1.6667*(TEST)**0.5
      VL=QL/AI
      GO TO 45
44    QL=-CVO*(Z+H)**1.6667*(-TEST)**0.5
45.   VL=QL/AO
      GO TO 7
6     QL=-CVO*(Z+H)**1.6667*(-TD2)**0.5
      VL1=QL/(W2*H)
      VL2=QL/(W2*Z)
      DV=(VL1+VL2)*(VL1-VL2)/64.4
      TEST=-TD2+DV
      IF (TEST .LT. 0.) GO TO 33
      QL=-CVO*(Z+H)**1.6667*(TEST)**0.5
      VL=QL/AO
      GO TO 34
```

APPENDIX E

DISSOLVED OXYGEN MODEL
(cont.)

```
33    QL=CVI*(Z+H)**1.6667*(-TEST)**0.5
34    VL=QL/AI
C
C     CHANGE OF ELEVATION IN VANCOUVER LAKE
C
7     DH=DT*(QIN+QC+QL+QB+PR+EV+QOU)*86400./A
      V(I)=A*H
      QCC(I)=QC
      QLL(I)=QL
C     ......................................................................
C     .  WATER QUALITY PREDICTION PROGRAMMING --- MATERIAL BALANCE FOR     .
C     .  CELLS AND SUBSTRATE IN VANCOUVER LAKE WATER BY THE CONTINUITY     .
C     .  CONCEPT.                                                          .
C     ......................................................................
      TP=TEMP(I)
      IF (TP .LT. 20.) GO TO 200
      K1=0.2*1.047**(TP-20.)
      K2=0.25*1.047**(TP-20.)
      GO TO 201
200   K1=0.2/1.047**(20.-TP)
      K2=0.25/1.047**(20.-TP)
201   OSL=14.652-0.41002*TP+0.0079971*TP**2.-0.000077774*TP**3.
C
C     LIGHT INTENSITY CALCULATION
C
      ARG=(-A1-B1*PL)*H
      TL=T
      II=T
      RII=II
      IF (TL .GT. RII) GO TO 88
      GO TO 89
88    TL=T-RII
89    THETAL=3.14159*(TL-TSR)/PP
      IF ((TL .GE. TSR) .AND. (TL .LE. TSS)) GO TO 66
      LL=0.
      GO TO 77
66    LL=LN*(1.-0.65*C1**2.)*SIN(THETAL)*(1.-EXP(ARG))/(-ARG)
C
C     GROWTH RATE OF PHYTOPLANKTON
C
77    MU=MUM*NL/(KN+NL)*FL/(KF+FL)*LL/(KL+LL)
      MF=MU*TP
      RMUTP=(MU-R)*TP
      GMTP=(G-MT)*TP
      IF (T .LE. 0.) GO TO 600
      Q1=QCC(III)*86400.
      Q2=QLL(III)*86400.
      IF (VC .LT. 0.) GO TO 500
C
C     DISSOLVED OXYGEN (DO) CALCULATION
C
      VOL=V(III)*OL+((Q1*CC+Q2*OL+Q3*OB)+ RMUTP*V(III)*PL/RC-K1*V(III)*B
     1ODL+K2*V(III)*(OSL-CL)-K4*A*OL)*DT
      OL=VOL/V(I)
C
C     CALCULATION FOR NUTRIENT CONCENTRATION OF NITROGEN AND PHOSPHATE
```

```
C
      VNL=V(III)*NL+((Q1*NC+Q2*NL+Q3*NB)-MF*PL*V(III)/YPN+ALPHA*V(III)*Z
     1L+BETA*A*CL)*DT
      NL=VNL/V(I)
      VFL=V(III)*FL+((Q1*FC+Q2*FL+Q3*FB)-MF*PL*V(III)/YPF+ALPHA*V(III)*Z
     1L+BETA*A*CL)*DT
      FL=VFL/V(I)
C
C     TOTAL PHYTOPLANKTON IN VANCOUVER LAKE
C
      VPL=V(III)*PL+((Q1*PC+Q2*PL+Q3*PB)+RMUTP*V(III)*PL*(1.-S)-G*TP*V(I
     1II)*ZL/YZ)*DT
      PL=VPL/V(I)
C
C     ZOOPLANKTON CALCULATION
C
      VZL=V(III)*ZL+((Q1*ZC+Q2*ZL+Q3*ZB)+V(III)*ZL*GMTP)*DT
      ZL=VZL/V(I)
C
C     BIOCHEMICAL OXYGEN DEMAND (BOD) CALCULATION
C
      VBODL=V(III)*BODL+((Q1*BODC+Q2*BODL+Q3*BODB)-(K1+K3)*V(III)*BODL)*
     1DT
      BOCL=VBODL/V(I)
      GO TO 550
C
C     DISSOLVED OXYGEN (DO) CALCULATION
C
500   VOL=V(III)*OL+((Q1*OL+Q2*OL+Q3*OB)+ RMUTP*V(III)*PL/RC-K1*V(III)*B
     1ODL+K2*V(III)*(OSL-OL)-K4*A*DL)*DT
      CL=VOL/V(I)
C
C     CALCULATION FOR NUTRIENT CONCENTRATION OF NITROGEN AND PHOSPHATE
C
      VNL=V(III)*NL+((Q1*NL+Q2*NL+Q3*NB)-MF*PL*V(III)/YPN+ALPHA*V(III)*Z
     1L+BETA*A*DL)*DT
      NL=VNL/V(I)
      VFL=V(III)*FL+((Q1*FL+Q2*FL+Q3*FB)-MF*PL*V(III)/YPF+ALPHA*V(III)*Z
     1L+BETA*A*DL)*DT
      FL=VFL/V(I)
C
C     TOTAL PHYTOPLANKTON IN VANCOUVER LAKE
C
      VPL=V(III)*PL+((Q1*PL+Q2*PL+Q3*PB)+RMUTP*V(III)*PL*(1.-S)-G*TP*V(I
     1II)*ZL/YZ)*DT
      PL=VPL/V(I)
C
C     ZOOPLANKTON CALCULATION
C
      VZL=V(III)*ZL+((Q1*ZL+Q2*ZL+Q3*ZB)+V(III)*ZL*GMTP)*DT
      ZL=VZL/V(I)
C
C     BIOCHEMICAL OXYGEN DEMAND (BOD) CALCULATION
C
      VBODL=V(III)*BODL+((Q1*BODL+Q2*BODL+Q3*BODB)-(K1+K3)*V(III)*BODL)*
     1DT
```

```
      BODL=VBODL/V(I)
C
C     PRINT AND LIST RESULTS
C
550   IF ((I/2*2-I) .EQ. 0) GO TO 560
600   WRITE(6,30) T,HW,QL,VL,QC,VC,DELYH,DELZH,CL,PL,ZL,NL,FL,BODL,LL,MU
30    FORMAT(/,' TIME =',F8.4,//,10X,'HW =',F8.4,9X,'QL =',F9.2,9X,'VL =
     1',F8.4,9X,'QC =',F9.2,9X,'VC =',F8.4,/,9X,'Y-H =',F8.4,8X,'Z-H =',
     2F8.4, /,10X,'OL =',F7.3,10X,'PL =',F8.4,    10X,'ZL =',F8.4,9X,'NL
     3=',F8.4,10X,'FL =',F8.4,/,8X,'BODL =',F7.3,10X,'LI =',F8.2,10X,'MU
     4 =',F8.4)
560   H=H+DH
      HW=H+HB
20    CONTINUE
      GO TO 100
1000  WRITE (6,40)
40    FORMAT (////,' END OF CALCULATION')
      RETURN
      END
```

APPENDIX E

```
C
C
C
C                                    ************************
C                                    *  AQUATIC LIFE MODEL  *
C                                    ************************
C
C
C
C      ..................................................................
C      . WATER QUALITY PROGRAMMING: FOR BACTERIA, ALGAE AND THEIR       .
C      . AFFECTED PARAMETERS CONSIDERED IN THE DIFFERENTIAL             .
C      . EQUATIONS, THEN SOLVED BY RUNGE-KUTTA THIRD ORDER METHOD.      .
C      . THE FOLLOWING MATRICES ARE:                                    .
C      .       A: ALGAE                                                 .
C      .       C: ZOOPLANKTON                                           .
C      .       F: PHOSPHATE                                             .
C      .       X: BACTERIA                                              .
C      .       Z: BOD                                                   .
C      .       W: TIME                                                  .
C      . THIS PROGRAM WAS PREPARED BY MARCUS C. LIN IN APRIL, 1971 AT HSU .
C      ..................................................................
      DIMENSION A(100),C(100),F(100),Z(100),W(100),X(100),HL(52)
      DIMENSION QCAVG(55)
      READ (5,3) (QCAVG(I), HL(I),I=1,52)
3     FORMAT (4(2F10.2))
100   READ (5,1,END=1000) AI,CI,FI,XI,ZI,A1,A2,A3,C1,C2,F2,F3,
     1RK2,RMUM,Y,AREA
1     FORMAT (8F10.2)
      WRITE (6,2) AI,CI,FI,XI,ZI,A1,A2,A3,C1,C2,F2,F3,RK2,RMUM,Y,AREA
2     FORMAT (1H1,'INPUT DATA ARE :',///,6X,'AI =',F10.4, 6X,'CI =',
     1F10.4,6X,'FI =',F10.2,6X,'XI =',F10.4,6X,'ZI =',F10.4,6X,'A1 =',
     2F10.6,//,6X,'A2 =',F10.4,6X,'A3 =',F10.4,6X,'C1 =',F10.4,
     36X,'C2 =',F10.4,6X,'F2 =',F10.4,6X,'F3 =',F10.4,//,
     46X,'K2 =',F10.4,6X,'MU =',F10.4,7X,'Y =',F10.4,E20.4,///)
      WRITE (6,4) (QCAVG(I),HL(I),I=1,52)
4     FORMAT (2F20.3)
      FC=120.
      ZC=2.0
      CC=1.
      AC=0.01
      DW=1.0
      WI=1.
      XB=0.0354
      A(1)=AI*1000.
      C(1)=CI
      F(1)=FI
      X(1)=XI*1000000.
      Z(1)=ZI
      W(1)=WI
      WRITE (6,48)
48    FORMAT (1H1,'THE TABULAR RESULTS ARE :',///,' TIME (WEEK)',   10X,
     1'ALGAE (NO/ML)',9X,'ZOOPLANKTON (NO/L)',4X,'PHOSPHATE (MIG/L)',
     25X,'TOT BACT (NO/ML)',4X,'BOD (MG/L)')
      WRITE (6,49)  W(1),A(1),C(1),F(1),X(1),Z(1)
      DO 20 I=2,52
```

APPENDIX E

AQUATIC LIFE MODEL
(cont.)

```
C
C     RUNGE-KUTTA FIRST VALUE
C
      V=AREA*28.32*HL(I-1)
      CONST=QCAVG(I)*28.32*604800./V
      AUG11=WI
      AUG21=P(AUG11)
      AUG31=T(AUG11)
      RAMDA1=Q(AUG11)*604800.*FR(AUG11)/V
      RAMDAA=QL(AUG11)*FI*604800./V
      RAMDAX=CONST*(FC-FI)
      F11I=RAMDA1+RAMDAA+RAMDAX
      VALU1=-0.5*((AUG31-26.)/5.5)**2
      VALU2=-0.5*((AUG31-13.)/3.)**2
      QLR=QL(AUG11)
      XC=XCC(AUG11)
      ALPHA1=(Q(AUG11)*XB+QLR*XI)*604800./V+CONST*(XC-XI)
31    BETA1=(Q(AUG11)*SR(AUG11)+QLR*ZI)*604800./V+CONST*(ZC-ZI)
      DELTA1=RMUM*EXP(VALU1)*ZI-RK2*AUG31
      U1=DW*(AI*(A1*EXP(VALU1)*AUG21*FI-(A2+A3*CI)*AUG31-CONST)+CONST*AC
     1)
      V1=DW*(CI*(C1*EXP(VALU2)*AI*FI*G(AUG21)-C2*AUG31*G(AUG21))+CONST*(
     1CC-CI))
      W1=DW*F11I-F2*V1-F3*U1
      X1=DW*(XI*DELTA1+ALPHA1)
      Z1=DW*(BETA1-DELTA1/Y*XI+0.004*RK2*AUG31*XI)
C
C     RUNGE-KUTTA SECOND VALUE
C
      AUG12=WI+DW/3.
      AUG22=P(AUG12)
      AUG32=T(AUG12)
      RAMDA2=Q(AUG12)*604800.*FR(AUG12)/V
      RAMDAB=QL(AUG12)*(FI+W1/3.)*604800./V
      RAMDAY=CONST*(FC-FI-W1/3.)
      F12I=RAMDA2+RAMDAB+RAMDAY
      VALU1=-0.5*((AUG32-26.)/5.5)**2
      VALU2=-0.5*((AUG32-13.)/3.)**2
      QLR=QL(AUG12)
      XC=XCC(AUG12)
      ALPHA2=(Q(AUG12)*XB+QLR*(XI+X1/3.))*604800./V+CONST*(XC-XI-X1/3.)
33    BETA2=(Q(AUG12)*SR(AUG12)+QLR*(ZI+Z1/3.))*604800./V+CONST*(ZC-ZI-Z
     11/3.)
      DELTA2=RMUM*EXP(VALU1)*(ZI+Z1/3.)-RK2*AUG32
      U2=DW*((AI+U1/3.)*(A1*EXP(VALU1)*AUG22*(FI+W1/3.)-(A2+A3*(CI+V1/3.
     1))*AUG32-CONST)+CONST*AC)
      V2=DW*((CI+V1/3.)*(C1*EXP(VALU2)*(AI+U1/3.)*(FI+W1/3.)*G(AUG22)-C2
     1*AUG32*G(AUG22))+CONST*(CC-CI-V1/3.))
      W2=DW*F12I-F2*V2-F3*U2
      X2=DW*((XI+X1/3.)*DELTA2+ALPHA2)
      Z2=DW*(BETA2-DELTA2/Y*(XI+X1/3.)+0.004*RK2*AUG32*(XI+X1/3.))
C
C     RUNGE-KUTTA THIRD VALUE
C
      AUG13=WI+2.*DW/3.
      AUG23=P(AUG13)
```

```
      AUG33=T(ALG13)
      RAMDA3=Q(AUG13)*604800.*FR(AUG13)/V
      RAMDAC=QL(AUG13)*(FI+2.*W2/3.)*604800./V
      RAMDAZ=CONST*(FC-FI-2.*W2/3.)
      F13I=RAMDA3+RAMDAC+RAMDAZ
      VALU1=-0.5*((AUG33-26.)/5.5)**2
      VALU2=-0.5*((AUG33-13.)/8.)**2
      QLR=QL(AUG13)
      XC=XCC(AUG13)
      ALPHA3=(Q(AUG13)*XB+QLR*(XI+2.*X2/3.))*6C4800./V+CONST*(XC-XI-2.*X
     12/3.)
35    BETA3=(C(AUG13)*SR(AUG13)+QLR*(ZI+2.*Z2/3.))*6C4800./V+CONST*(ZC-Z
     1I-2.*Z2/3.)
      DELTA3=RMUM*EXP(VALU1)*(ZI+2.*Z2/3.)-RK2*AUG33
      U3=DW*((AI+2.*U2/3.)*(A1*EXP(VALU1)*AUG23*(FI+2.*W2/3.)-(A2+A3*(CI
     1+2.*V2/3.))*AUG33-CONST)+CONST*AC)
      V3=DW*((CI+2.*V2/3.)*(C1*EXP(VALU2)*(AI+2.*U2/3.)*(FI+2.*W2/3.)*G(
     1AUG23)-C2*AUG33*G(AUG23))+CONST*(CC-CI-2.*V2/3.))
      W3=DW*F13I-F2*V3-F3*U3
      X3=((XI+2.*X2/3.)*DELTA3+ALPHA3)
      Z3=DW*(BETA3-DELTA3/Y*(XI+2.*X2/3.)+0.004*RK2*AUG33*(XI+2.*X2/3.))
      AI=AI+0.25*U1+0.75*U3
      CI=CI+0.25*V1+0.75*V3
      FI=FI+0.25*W1+0.75*W3
      XI=XI+0.25*X1+0.75*X3
      ZI=ZI+0.25*Z1+0.75*Z3
      WI=WI+DW
      A(I)=AI*1000.
      C(I)=CI
      F(I)=FI
      X(I)=XI*1C00000.
      Z(I)=ZI
      W(I)=WI
      WRITE (6,49)  W(I),A(I),C(I),F(I),X(I),Z(I)
49    FORMAT ( //,F9.2,10X,E10.4,17X,E10.4,9X,E10.4,11X,E10.4,8X,E10.4)
20    CONTINUE
      GO TO 100
1000  WRITE (6,70)
70    FORMAT (///,' END OF JOB')
      RETURN
      END
C
C
C
C     ----------------------------------------------------------------
      FUNCTION T(X)
      IF (X .LE. 8.) GO TO 10
      T=4.+22.*EXP(-0.5*((X-24.)/6.)**2)
      RETURN
10    T=4.+21.*EXP(-0.5*((X+28.)/6.)**2)
      RETURN
      END
C     ----------------------------------------------------------------
      FUNCTION P(X)
      IF (X .LE. 8.) GO TO 20
      P=12.2+4.1*SIN(6.28318*(38.-X)/52.)
```

APPENDIX E

AQUATIC LIFE MODEL
(cont.)

```
      RETURN
20    P=12.4+4.1*SIN(6.28318*(-14.-X)/52.)
      RFTURN
      END
C     ------------------------------------------------------------------
      FUNCTION G(X)
      G=C.82+0.343*SIN(6.28313*(X-7.2)/10.4)
      PFTURN
      END
C     ------------------------------------------------------------------
      FUNCTION Q(X)
      Q=28.32*(16.2-15.7*EXP(-0.5*((X-24.)/9.0)**2))
      RETURN
      END
C     ------------------------------------------------------------------
      FUNCTION QL(X)
      IF (X .GT. 33.) GO TO 10
      QL=28.32*200.*EXP(-0.5*((X-33.)/4.5)**2)
      RETURN
10    QL=-28.32*200.*EXP(-0.5*((X-33.)/4.5)**2)
      RETURN
      END
C     ------------------------------------------------------------------
      FUNCTION FR(X)
      FR=150.+750.*EXP(-0.5*((X-24.)/3.)**2)
      RETURN
      END
C     ------------------------------------------------------------------
      FUNCTION SR(X)
      SR=5.0+5.6*EXP(-0.5*((X-24.)/4.)**2)
      RETURN
      END
C     ------------------------------------------------------------------
      FUNCTION XCC(X)
      XCC=0.089-0.077*EXP(-0.5*((X-33.)/13.)**2)
      RFTURN
      END
```


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SELECTED WATER RESOURCES ABSTRACTS

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16. *Abstract*

This study deals with the restoration of water quality of shallow, polluted, and eutrophic lakes. Dredging and removing of lake bottom sediments and introducing better quality water are the restoration measures explored in this study. Vancouver Lake, Washington, was used as a test case.

Hydrologic, hydrographic, hydrodynamic, and water quality information, provided by separate but correlated studies, was combined with the aid of mathematical simulation models. Dissolved oxygen was used as an indicator of the overall water quality in the system. Photosynthesis, atmospheric reaeration, biological respiration, and advection were the mechanisms considered in the computation of diurnal changes in dissolved oxygen level. In addition to the DO model, the aquatic life model for computing time-varying levels of phytoplankton and bacteria was also tried. The validity of these models was verified with the actual field data. After verifications of the models under the existing conditions, they were used to project and predict the water quality of Vancouver Lake as will be affected by dredged lake depths and introduced flows from the Columbia River.

This report was submitted in fulfillment of Project Number 16080ERQ under the partial sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

17a. *Descriptors*

Water Quality Modeling, Simulation, Lake Restoration, Water Quality Control, Eutrophication, Flushing of a lake, Dredging of bottom muds.

17b. *Identifiers*

Vancouver Lake (WA)

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