EPA-600/3-77-087
August 1977

Ecological Research Series

TROPHIC EQUILIBRIUM OF LAKE WASHINGTON

Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Corvallis, Oregon 97330

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial, and atmospheric environments.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/3-77-087
August 1977

TROPHIC EQUILIBRIUM OF LAKE WASHINGTON

by

W. T. Edmondson
Department of Zoology
University of Washington
Seattle, Washington 98195

R 8020 82-03-1

Project Officer

Charles F. Powers
Marine and Freshwater Ecology Branch
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

CORVALLIS ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97330

DISCLAIMER

FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Ccrvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report provides important documentation of the effects of reduced nutrient input in the control of culturally induced eutrophication.

A. F. Bartsch
Director, CERL

ABSTRACT

The purpose of this study was to help establish a description of the chemical condition of Lake Washington during 1973-1976 after recovery from diversion of sewage effluent. The condition during this period is compared with some of the results of extensive earlier studies. The hypothesis was that the lake would enter into a steady state in equilibrium with the new conditions in the watershed.

Sewage effluent was diverted progressively from the lake during 1963-1968, and the chemical conditions changed in close relation to the amount of sewage entering. The total phosphorus content of the lake decreased rapidly to 1971 after which year it varied around a value of about 50,000 kg (= 17 μg/l) with a slight decreasing trend. The lake has retained about 56% of the phosphorus that entered during 1971-1975.

Winter means of nitrate and the annual mean total content of Kjeldahl nitrogen has decreased at a slow rate during the entire period. Phytoplankton as measured by chlorophyll in the epilimnion during summer dropped to a low value in close proportion to phosphorus during diversion, but has decreased faster than phosphorus during 1971-1976.

A large increase in transparency occurred in 1976. A major change is taking place in the character of the zooplankton of Lake Washington in that *Daphnia* became very abundant in 1976. This event is probably not directly related to recovery from eutrophication, so the lake is entering a new phase.

This report was submitted in fulfillment of Grant No. R802082 by the University of Washington under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers the period 1 February, 1973 to 30 November, 1976, and work was completed 10 June, 1977.

CONTENTS

TABLES

FIGURES

ACKNOWLEDGEMENTS

Most of the data with which the results of this project are compared were collected with support by a series of grants from the National Science Foundation which also provided the equipment used. The 1950 data were collected with support from the State of Washington Research Fund in Biology and Medicine.

Thanks are due the many people who helped with the large amount of field and laboratory work on which this report is based, in particular Arni Litt, David E. Allison, Sally Bartley Abella, Deborah Hairston, Pamela Bissonnette and Diane Egan. John T. Lehman made some of the calculations of flow, loading and equilibrium.

SECTION 1

INTRODUCTION

The title of this project derives from the concept that with a given morphology and climate, the productivity of a lake is largely set by its nutrient supply. In a stable landscape and climate, the lake will be in trophic equilibrium with its watershed (Hutchinson and Wollack, 1940). Major changes in the watershed that affect the amount and character of the nutrients entering the lake will be reflected in the condition of the lake as expressed by its chemical content, biological productivity, and abundance of organisms. But, with steady, uniform conditions, as when the lake is surrounded by a climax forest, the lake will have a certain uniformity over a long span of time. Processes of ecological succession as an initially deep lake fills in will affect the way the lake distributes its nutrient income among the various parts of the community; these changes are most pronounced early and late in the lake's history and smallest in the long middle period. During this period the lake can be expected to vary around a steady mean from year to year in response to changes in rainfall, inflow, insolation and other influential factors. Secular changes in any of these factors can be expected to be matched by secular changes in the lake. The productivity and abundance of organisms in a lake will be determined by the combined action of a number of factors. A significant change in any one of these factors is expected to affect the productivity in the lake. Lake Washington is one of many lakes that have been observed to change greatly in response to an increase in nutrient income in the form of sewage effluent.

Starting in 1941, Lake Washington went through a period of eutrophication with secondary sewage effluent. The initial effects of increased abundance of algae and decreased transparency coupled with predictions of the consequences of further enrichment produced considerable concern among residents of the Lake Washington area. A public vote in 1958 established the Municipality of Metropolitan Seattle (METRO) which had the responsibility for improving the sewerage in the region, including the diversion of effluent from Lake Washington (Chasan, 1971; Edmondson, 1973). The amount of effluent entering the lake was progressively decreased during the period 1963-1968. With the first diversion of about one-third of the effluent, the lake stopped deteriorating, and with further diversion it began to recover, as measured by increasing transparency and decreasing amount of phytoplankton. By 1972 the lake appeared to be coming into equilibrium with its new circumstances with respect to the properties that produce the nuisance conditions associated with eutrophication (Edmondson, 1972a, b). In any case, the rate of change was much less than it had been.

A rather detailed limnological study had been made of the lake during part of its deterioration and all of its recovery, designed as an experimental study of lake fertilization (Edmondson, 1972a, 1973). The plan was to measure at appropriate times and places the chemical and biological properties of the lake that would be expected to respond to the major changes in nutrient income. The changes in the condition of the lake were then studied quantitatively as a function of the changes in the income of nutrients.

The major support for this study of Lake Washington has come from the National Science Foundation since 1958, after two initial years of support by the National Institutes of Health.

By 1972 the experiment could be described as being near completion in regard to field study (Edmondson 1977a). That is, the lake had reverted to a condition similar to that observed before eutrophication became publicly evident in that the concentration of phosphorus was close to that of 1933, and the transparency was comparable to that observed in 1950. Nevertheless, it seemed important to continue a study of the lake similar to the one made during eutrophication and recovery to establish definitely what the basic condition is. The lake can be expected to vary from year to year with the normal variation in inflow, nutrients and radiation. Thus, it was necessary to study the lake long enough to establish the range of variation of the properties that had been used in the earlier work. The results of such a study would provide a more secure description of the end-point of the Lake Washington experiment than would have otherwise been possible, and would also provide a stronger base against which to measure the response of the lake to any future changes in its circumstances. For example, a program of sewer separation is in progress. This will reduce the amount of dilute sewage entering in sewer overflow. Furthermore, while one can expect the lake to respond to the external conditions mentioned, the magnitude of the changes could not be predicted as closely as desired. Good advances in evaluation of phosphorus and water income are being made, but they depend on availability of appropriate data (Vollenweider and Dillon, 1974; Vollenweider, 1976). Since this study was beyond the available resources, it seemed appropriate to request funding from the Environmental Protection Agency to obtain information about chemical conditions that would permit a comparison of the present condition of the lake with that during the earlier period when the lake was still responding strongly to the changes in nutrition. A three-year grant was secured, extended to cover four summers. Ideally the work should have been continued long enough to encompass a very wide variation in conditions; ordinarily a three year period would not be enough. Fortunately, the actual period of study included a year with minimum inflow of water (1973) and a year with the largest flood in recorded history (1975-76); however, the range of annual input of solar radiation was only 44% that experienced during the past 25 years.

The principal purpose of this report then is to present a description of chemical conditions in the lake during the period when the work was partly supported by the Environmental Protection Agency. By itself, such a presentation would not be very useful, since the aim is to compare the different conditions of the lake and interpret the changes. Therefore, data are presented for the entire period 1971-1976, and comparison made with three earlier years, 1933 and 1950 when the condition of the lake was acceptable, and 1963 when its response to eutrophication was at a maximum (Scheffer and Robinson, 1938; Comita and Anderson, 1959; and Edmondson, 1972a). Because of the bulk, the entire set of data is not reproduced in this report, but a sampling is given in Tables 1 and 2. The present report is not an appropriate place to attempt a full analysis of the changes of the lake during eutrophication and recovery. Such an analysis is currently under way. Further, data are not presented on the plankton which has changed in a major way, with the near disappearance of *Oscillatoria* and the reappearance of *Daphnia* after an absence of at least 23 years (Edmondson, 1977).

SECTION 2

SUMMARY

During the period 1973-1976, Lake Washington was studied by measuring the same properties that had been used earlier to evaluate its response to increase and decrease in the amount of sewage effluent reaching the lake. The lake was considered to have shown most of its reaction to the diversion of sewage effluent by the beginning of the present study. During the period covered by this report, concentrations of phosphorus and nitrogen varied, but very much less than during and immediately after diversion of sewage effluent. Some of the variations observed could be related to changes in external factors, particularly silt brought in at times of high flow, but the lake seems relatively insensitive to the variations that existed during the period of study. Three properties of the lake did show a systematic trend during the period of study. The mean summer chlorophyll and annual total phosphorus values decreased from 1973 through 1976. Secchi disc transparency also showed a tendency to increase during the period, with a major increase in 1976. Thus the lake is still changing, but slowly. The reasons for the change will be found only by additional work.

SECTION 3

PLAN OF RESEARCH

The general plan was to sample the lake at a standard central station at intervals of time and depth close enough to define the changes in the condition with the sensitivity required by the aims of the project as described above. The chemical sampling, to which this report is devoted, was generally done at two-week intervals. Every second trip, or once a month, the samples were analyzed for all the components on the basic list ("complete chemistry"). On the alternate dates, a somewhat simplified scheme of analysis was done ("partial chemistry"). It is desirable to have more frequent measurements of some properties. Quantitative samples of phytoplankton and zooplankton were taken every week, and temperature and transparency were almost always measured on those trips. Additional trips were sometimes made when some special condition existed. Samples at the central station are adequate for defining the annual range of conditions and the year to year changes, but on a few dates, samples were collected at stations widely distributed around the lake to define the extent of horizontal variation.

The number of depths sampled varied with the stratification of the lake. When it was unstratified, usually from early December through April or May, three depths were sampled, surface, mid-depth (30 m) and just over the bottom (60 m). When it was stratified, usually 12 depths were sampled. Sometimes additional depths were sampled to permit more exact specification of the gradient of some substance. Examples of the different sampling schemes can be seen in Table 2, 5 February, 1974 and 16 May, 1974.

On each date of chemical sampling, samples were also collected from the two major inlets (Cedar River and Sammamish River) and from two minor inlets (Thornton Creek and Swamp Creek).

The area of Lake Washington is 87.615 km^2, its length 21 km and its maximum width 5.5 km. The maximum depth is about 62.5 m, the mean 32.9 m, and the volume 2853.0 million m^3. Over a 34-year period, the water renewal time, calculated from a hydrological model, varied between 1.72 and 6.18 years with a mean of 2.38 years. For more information on the lake and its watershed, see Edmondson 1977b.

SECTION 4

METHODS

The properties discussed in this report were selected because they are direct measures of nutrient input or because they give information about biological activity.

Phosphorus

- Total
- Total dissolved
- Phosphate phosphorus (inorganic, "reactive")
  (filtered and unfiltered)

Nitrogen

- Total Kjeldahl N
- Dissolved Kjeldahl N
- Nitrate
- Nitrite
- Ammonia

Oxygen

Carbon dioxide

Alkalinity

pH

Seston

Chlorophyll

Transparency

Temperature

In addition, the total study included properties not summarized in this report:

- Primary production by ^{14}C uptake and by oxygen production
- Quantitative phytoplankton counts
- Quantitative zooplankton counts
- Quantitative benthos counts
- Periphyton
- Sinking material caught by sediment traps (P, N, chlorophyll, dry weight, diatom counts).
- Chemical analysis of water from inlets

A summary of data on primary production and phosphorus loading has been prepared (Edmondson 1977b).

Data on insolation measured by a pyrheliometer near Lake Washington were obtained from the University of Washington Department of Atmospheric Sciences when available. Otherwise, data from the U. S. Weather Bureau were used. Measurements of stream flow were supplied by the U. S. Geological Survey, Tacoma, Washington. Flow data based on a hydrological model were supplied by METRO. In general, the chemical methods used for this study are based on standard methods published by Strickland and Parsons (1968), the U. S. Environmental Protection Agency (1971), and American Public Health Association (1960). Specific references are given for modifications of different methods. When filtering was necessary, Millipore HA (0.45 μ) filters were used. Most colorimeteric measurements were made with a Klett industrial model colorimeter with 5 cm. cell until 1973. Since then, the measurements have been made with a Brinkman probe colorimeter. Spectrophotometric measurements were made with a Perkin-Elmer Hitachi recording spectrophotometer.

Phosphorus (μg/l of the element P).

Dissolved inorganic phosphate-phosphorus ("reactive"). Ammonium molybdate reagent is reduced with stannous chloride (Robinson and Thompson, 1948). Precision is ± 5%, limit of detection 1 μg/l. The analysis is run on both filtered and unfiltered ("raw") samples with turbidity blank. The difference, if any, is acid soluble sestonic P.

Total phosphorus (μg/l). The same reaction as above is carried out on samples of unfiltered water digested with perchloric acid (Robinson, 1941). Two ml of 70% perchloric acid are added to a sample. Care is taken to avoid loss by overheating. The digest is made up to 50 ml and phosphate determined. The same procedure applied to filtered samples gives total dissolved phosphorus.

Nitrogen (μg/l of the element N).

Nitrate. Brucine-sulfanilic acid method, (U.S. Environmental Protection Agency, 1971; Kahn and Brezenski, 1967; Jenkins and Medsker, 1964). Precision is 5-10%, limit of detection 10 μg/l.

Nitrite. Sulfanilimide method, (Strickland and Parsons, 1968). Precision is ± 3%, limit of detection 0.2 μg/l.

Ammonia. (Solorzano, 1969). Precision ± 5% limit of detection 2 μg/l. This method has been in use since May, 1973. Between then and August 1966, ammonia was oxidized and measured as nitrite (Strickland and Parsons, 1968). Before that, it was measured by Nesslerization.

Organic nitrogen is done by a micro-Kjeldahl method similar to that described by the American Public Health Association (1960), using sulfuric acid and hydrogen peroxide. The digested samples are steam-distilled into 19% hydrochloric acid and the ammonia measured colorimetrically with Nessler's Reagent on filtered and unfiltered samples; the difference is particulate N.

Oxygen (mg/l). Winkler method, unmodified, similar to that described by American Public Health Association (1960), using a stronger alkaline iodide reagent (Carpenter, 1965). Precision ± 0.2 mg/l.

Carbon dioxide. Titration with 0.1 N sodium bicarbonate to phenolphthalein endpoint, Precision ± 10%. These data have been used in this report, but CO_2 can also be calculated from pH and alkalinity with greater precision for Lake Washington (John T. Lehman, University of Washington personal communication).

Alkalinity. Titration of 100 ml samples with 0.02 N sulfuric acid to mixed indicator endpoint (pH 4.5). When pH is above 8.3, the phenolphthalein endpoint is also recorded. The values in Table 2 are 10 times the volume of titrant, giving the $CaCO_3$ equivalent.

pH. Glass electrode

Seston. (mg/l dry weight). An appropriate amount of water (100-1000 ml) is filtered through a prerinsed weighed Millipore HA filter, dried to constant weight at 80°C. Blank filters are run with distilled water. Loss on ignition is done with a muffle furnace in porcelain crucibles at 500°C after preignition in air with alcohol.

Chlorophyll *a* (μg/l chlorophyll *a*). Water is filtered on Millipore HA filters with vacuum less than 500 mm mercury. Pigments are extracted with 80% acetone for 24 hours in a dark refrigerator. Until 1973 the optical density of the extract was read with a Klett colorimeter. Since then, spectrophotometric method described by Strickland and Parsons has been used with the SCOR/UNESCO equations giving precision of ± 0.2 μg/l. The two methods have been coordinated by reading many samples both ways. The calculation with Klett measurements was based on a calibration of a Klett in 1946 by Dr. Harold Haskins of Rutgers University with purified chlorophyll *a* and *b* supplied by Dr. Richard Goodwin of the University of Connecticut. Preliminary comparison with the spectrophotometric method, which uses improved knowledge of the specific absorption of chlorophyll, shows that the original values based on the Klett were low by a factor of 1.73 (Edmondson 1972a, p. 123 footnote). This correction has been applied in this report. Unfortunately, some earlier publications gave uncorrected values.

Temperature. Surface temperature is recorded to nearest 0.1°C with a mercury thermometer. Temperature at depth is taken with a bathythermograph.

Transparency (meters). A white 20 cm. Secchi disc is observed under standardized condition.

Total nutrient content of the lake was calculated by multiplying concentrations by area at depth and by volume of the layers between depths.

SECTION 5

RESULTS

The figures included in this report have been designed to substitute for lengthy verbal descriptions of the changes in Lake Washington, and the tables provide numerical values for a selection of representative dates that indicate the variations shown during the period of study. The present condition of the lake can be compared with the recovery stage by examining the means of certain properties that were sensitive to the changes in nutrient loading. One needs to be careful in evaluating trends. Minor variations from year to year produce what may look like new trends at a moment, but in the long run they turn out to be minor wobbles on the line describing the major trend (Figure 1).

In 1971, the transparency exceeded that of 1950. In 1972, the values of phosphorus were almost identical with those of 1933. These events could be regarded as indicating the recovery of the lake since its condition in 1933 was acceptable (Edmondson, 1972b). Change did not stop at that time. Winter values of dissolved inorganic phosphate varied widely after 1971, but winter nitrate showed a generally downward, oscillating trend. The annual mean concentration of total phosphorus in the top 10 m decreased during 1971-1976. The total phosphorus content of the lake decreased proportionally less during the same period, its mean value being about 50,000 kg, corresponding to a concentration of 17 µg/l. Between 1972 and 1976, summer chlorophyll showed a downward decreasing trend to 54% of its 1972 value. To some extent, variations above and below the trend lines for these substances are related.

The biggest change during the period of study has been in transparency (Figure 2). The maximum during the summer of 1976 was 8.2 meters, deeper than the Secchi disc had ever before been reported at any time of year. Observations in the preceding few years had suggested that the transparency was oscillating around a mean of about 3.8 m. Whether 1976 is an aberrant year, represents a continuing trend, or represents the new condition of the lake will not be known for some years. This change in transparency is not proportional to the changes in chlorophyll or seston, and must result at least in part from a change in the character of the plankton.

While the data on plankton are still under analysis, it is known that there have been substantial changes in recent years (Edmondson, 1977a). Blue green algae are still present, but the proportions of species and proportions in relation to other types of algae have changed, especially during 1973-1976. Filamentous blue greens (*Oscillatoria*, *Pseudanabaena*, *Lyngbya*) are very scarce during the summer. The ones that are present form chunky, tight colonies (Coelosphaerium, Anabaena flos aquae). Since the Secchi disc is very sensitive to the number of light-scattering particles rather than their volume, a given volume of algae collected together in large colonies will affect the transparency less than the same amount of material dispersed in many fine filaments and small cells. With the reduction in total amount of algae, diatoms have become relatively more prominent than blue greens, and the proportions of species have changed. After many years of relative stability, the zooplankton has changed importantly in that Daphnia reappeared in 1972, increased by the year, and became prominent in 1976 after an absence of more than 23 years (Edmondson 1977a).

The differences among the annual means of chemical properties are not clearly related in an obvious way to changes in some of the factors that are known to affect lakes. In the period 1971-1974, total phosphorus loading varied between 0.43 and 1.00 g/m^2 (Edmondson 1977). The high year was 1972 when floods and landslides in the Cedar River watershed caused delivery of a great deal of silt to the lake; dissolved phosphate was low during that time. Since probably most of the mineral phosphorus was not available biologically dissolved phosphorus is probably a more meaningful component for calculating loading. The low was 1973, a year of very low water flow (Table 3). Insolation varied more during the period of study than it had during the previous period of recovery (1963-1973). It was maximum in 1975, minimum in 1973, and intermediate in the other years (Table 3).

Examination of annual mean values gives only a partial understanding of the changes in the lake. To some extent, the annual change or the rate of change of a property may be more revealing than the absolute values. Thus, a study of the seasonal changes provides the context for the means (Figure 3).

Thermal stratification is important in the seasonal events in a lake. Lake Washington is monomictic, circulating freely all winter except during unusual calm spells when it may develop slight transitory stratification. Stable stratification usually begins to develop late in April or in May and establishes an epilimnion about 10 m thick and a metalimnion another 10 m. The surface water begins to cool late in August or early in September, the epilimnion progressively thickens, and the lake achieves homothermality late in November or during December. The minimum winter temperature observed during the period of study was 6.4°C and the maximum summer surface temperature was 22.9°C (Table 1).

Transparency has shown great variations (Figure 3C). The depth to which a Secchi disc can be seen is strongly affected by the amount of light scattered back by suspended particles. Thus, transparency will be reduced by input of silt or by increase of phytoplankton. The maximum inflow through the tributaries takes place in winter, with low flow usually occurring May-September; high concentrations of phosphorus tend to accompany high flow (Figure 3 G,H). Thus, during summer the opportunity for input of large volumes of silty water is at a minimum, and changes in transparency will be dominated by changes in phytoplankton (Figure 8 of Edmondson, 1972a). Despite the increased inflow during winter, the lake usually becomes much clearer as the phytoplankton declines during fall, and maximum transparency usually occurs sometime in the period December-March. Two exceptional events in recent years have reduced the winter transparency. In February, 1972, heavy local rains and high flow of the Cedar River coupled with landslides along the Cedar River and near the north end of the lake brought much silty water into the lake and the transparency was less than in the two bracketing years. Again in December 1975 and January, 1976, high flow brought in much silty water through the Cedar River, and the transparency was reduced to little more than half what it had been the winter before. As mentioned above, the following summer, the transparency broke all records, reaching 8.2 m on 4 August, 1976. The maximum, 10.2 m occurred in December.

The seasonal changes of phytoplankton as reflected by the chlorophyll content of surface water show the common pattern of a rapid increase from a winter low to a maximum in April or May, and a subsequent decrease in summer (Figure 3D). In 1973, there was a slight indication of a resurgence in fall, and a much more pronounced fall bloom in 1974. The year 1963 had maximum chlorophyll development, reaching its peak in June, and maintaining high concentrations all summer and fall.

Of all the nutrients, phosphorus is given particular attention since it has been shown to be especially important in controlling the abundance of phytoplankton in several lakes including Lake Washington (Edmondson, 1972a). In general, inorganic phosphate is at a maximum during the first three or four months each year, decreasing in the surface water rapidly during April and May as the phytoplankton increases (Figure 3A). As shown earlier, a strong correlation exists between the concentration of phosphate in the winter and the amount of phytoplankton developed and maintained the next summer as measured by chlorophyll and particulate phosphorus (Edmondson, 1972a). Total phosphorus varies somewhat during the year, but tends to be more uniform than phosphate. While in most years it tends to decrease during stratification, it does not decrease nearly as much as phosphate because it is held by the plankton.

In the years of heavy eutrophication, phosphorus was in excess relative to use by phytoplankton, and substantial concentrations of phosphate were left in the surface water at the end of the spring, but in 1933 and in recent years, phosphate approached closely to zero (Table 1).

Phosphorus remains in the hypolimnion during the summer at about the same concentration it had at the beginning of stratification, generally with some tendency to increase (Table 2 and Edmondson 1972a, 1977a).

The phosphate concentration was distinctly lower during the first three months of 1972 than it was during the preceding winter or any of the following winters. This minimum came after the flood that brought silt into the lake. It seems likely that the settling clay absorbed part of the phosphate and carried it to the bottom. The phosphate in the early months of 1976, also following a flood and period of silty inflow, was less than in the preceding two years, but higher than in 1972.

The pattern of annual changes of nitrogen are similar to those of phosphorus (Figure 3B). Nitrate is at a maximum during winter and decreases during the growth of the spring phytoplankton. Total Kjeldahl nitrogen varies irregularly within a rather narrow range. Ammonia and nitrite are always very small compared to nitrate (Table 2). The ratio of nitrogen to phosphorus has changed greatly over the years (Edmondson 1972a). In its unpolluted state, Lake Washington had an excess of nitrate in the sense that during the growth of the plankton in spring, phosphate came close to zero values while nitrate still maintained significant concentrations. During the years of heavy eutrophication, significant concentrations of phosphate were left when nitrate was nearing zero. This was attributed to the fact sewage has a large excess of phosphorus relative to the proportion in natural waters and in organisms. This characteristic was accentuated by the use of detergents based on phosphorus. Thus, during eutrophication, the lake developed a very unnatural N:P ratio, and during recovery it reverted to a condition in which phosphorus is limiting.

Oxygen is well known to be a sensitive indicator of changes in productive conditions in stratified lakes. Each summer, the oxygen concentration in the hypolimnion progressively decreases, but in recent years the concentration in most of the water remained above 5 or 6 mg/l at the end of summer (Table 2). In contrast, during the years of eutrophication, values less than 4.0 were common in much of the hypolimnion at the end of summer (Edmondson 1963, 1972a).

Changes in rate of development of the hypolimnetic oxygen debt were used as strong indicators of approaching deterioration in the early studies of the eutrophication of Lake Washington but its usefulness was lessened by qualitative changes in the phytoplankton (Edmondson, 1966).

During the summer, carbon dioxide increases in the hypolimnion, in strong inverse correlation with oxygen (Table 2).

SECTION 6

DISCUSSION

The aim of this study was to help establish a description of the condition of Lake Washington after the diversion of secondary sewage effluent which took place over a five year period. In 1963 about 28% of the effluent was diverted, about half had been diverted by 1965, and the project was completed early in 1968, although most of the effluent had been diverted early in 1967. The lake responded sensitively to each stage of diversion and rapidly returned to a condition comparable in some ways with the condition before eutrophication had become a problem. The rapidity of response probably results from several features. Although the mean residence time of water is 2.38 years, it was only 2.08 years during 1968-1971. The lake has steep sides in most parts and there is relatively little littoral development with dense growths of rooted plants. Less than 8% of the bottom area is less than 5 m deep. Even at the height of eutrophication, large volumes of hypolimnion did not become anoxic for long periods.

Using the total phosphorus content of the entire lake as a criterion of the effect of diversion of effluent, we can identify a period of recovery after diversion, 1968-1970, and a post-recovery period during which the phosphorus content varied above and below a mean value of about 50,000 kg with only a slight decreasing trend during the period (Figure 1). Since the volume of the lake is 2853.0 million m^3, the corresponding concentration is about 17 μg/l.

The interpretation of these data on phosphorus is somewhat subjective, being influenced by the selection of the beginning of the post-recovery period. The year 1971 is a reasonable choice since it was in that year that a major prediction about the rate of recovery of the lake was confirmed (Edmondson, 1972b). A linear regression fitted to the individual measurements on which the means of Figure 1C are based for 1971-1976 has a slope of minus 2700 kg/year, significantly different from zero at the 0.03 level by the *t* test. In view of the magnitude of the year to year differences in phosphorus and hydraulic loading and the small number of years involved, a horizontal line may be a satisfactory description of the data (Figure 1C).

These figures suggest that Lake Washington has come into or is about to come into equilibrium with the present conditions in the watershed in terms of its phosphorus content. The assumption behind this statement is that conditions in the watershed that affect phosphorus are not changing in a secular manner.

Considerable attention has been given to the budgetary relations of phosphorus in terms of input, sedimentation and output, and a variety of models or computational schemes elaborated (Piontelli and Tonolli, 1964; Vollenweider 1969, 1976). On the basis of the mean annual inflow of water and input of phosphorus for the period 1971-1975, the equilibrium value for the total phosphorus content of the lake can be calculated using one of the simpler methods (Piontelli and Tonolli, 1964; Vollenweider, 1969). Phosphorus input was 52,600 kg and water was 1352 million m^3 per year. (These figures may become subject to slight revision on the basis of improved knowledge of hydrological conditions, probably about 10% upward.) Since the area of the lake is 87.615 km^2, the mean areal loading during the period was 0.67 $g/m^2 \cdot$ year. With retention values of 50%, 60% and 70%, the equilibrium values for total phosphorus would be 57,500, 46,000 and 34,500 kg respectively (Fig. 3C). The observed total retention during 1971-1975 was 56.1% of the phosphorus that entered the lake, corresponding closely to the observed mean of about 50,000 kg.

Nitrogen has continued to decrease during the entire so-called post-recovery period, so the lake cannot be said to have achieved full trophic equilibrium. This may be a result of the biogeochemical versatility of nitrogen in contrast to phosphorus. At least three differences are involved. Nitrate is more mobile than phosphate, and more easily displaced from the soil when land is developed. The nitrate concentration of the Cedar River increased after 1957 (Edmondson 1972a). The diversion of sewage would have affected nitrogen less than phosphorus because the N:P ratio of secondary sewage effluent is very much lower than in tributary waters (Edmondson 1969). Finally, Lake Washington contained significant amounts of nitrogen-fixing blue green algae. Thus there is no reason to have expected the nitrogen content of the lake to have changed in the same way as that of phosphorus.

Chlorophyll has continued to decrease during the post-recovery period, but phytoplankton is strongly affected by zooplankton, and zooplankton has been changing since 1972 for reasons probably unrelated to diversion of sewage (Edmondson, 1977a). Lake Washington is entering a new phase, and more time must pass and work be done before we can understand the changes that are happening now.

REFERENCES

American Public Health Association. 1960. Standard Methods for the Examination of Water and Wastewater. (11th edition, earlier editions were used in the 1950's).

Carpenter, J. H. 1965. The Chesapeake Bay Institute Technique for the Winkler Dissolved Oxygen Method. Limnol. Oceanog. 10:141-143.

Chasan, D. J. 1971. The Seattle Area Wouldn't Allow Death of Its Lake. Smithsonian 2:6-13.

Comita, G. W., and G. C. Anderson. 1959. The Seasonal Development of a Population of Diaptomus ashlandi Marsh, and Related Phytoplankton Cycles in Lake Washington. Limnol. Oceanogr. 4:37-52.

Edmondson, W. T. 1963. Pacific Coast and Great Basin, p. 371-392 In D. G. Frey (ed.) Limnology in North America. University of Wisconsin Press, Madison, Wisconsin.

Edmondson, W. T. 1969. Eutrophication in North America. pp. 124-149 in Eutrophication: Causes, Consequences, Correctives. National Academy of Sciences Publication No. 1700.

Edmondson, W. T. 1972a. Nutrients and Phytoplankton in Lake Washington. pp. 172-193 In Nutrients and Eutrophication, G. Likens (ed.). American Society of Limnology and Oceanography, Special Symposia No. 1.

Edmondson, W. T. 1972b. The Present Condition of Lake Washington. Verh. Internat. Verein. Limnol. 18:284-291.

Edmondson, W. T. 1973. Lake Washington. pp. 281-298 in Environmental Quality and Water Development. C. R. Goldman, James McEvoy III and Peter J. Richerson, eds. Freeman. (Originally published as a report to the National Water Commission.)

Edmondson, W. T. 1977a. The Recovery of Lake Washington from Eutrophication. pp. 102-109 in Recovery and Restoration of Damaged Ecosystems. ed. J. Cairns, Jr., R. L. Dickson and E. E. Herricks. University Press of Virginia.

Edmondson, W. T. 1977b. Lake Washington in: North American Project--A Study of U.S. Water Bodies: a Report for the Organization for Economic Cooperation and Development. Published by Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency (in press).

Hutchinson, G. E., and A. Wollack, 1940. Studies on Connecticut Lake Sediments. II. Chemical Analyses of a Core from Linsley Pond, North Branford. Am. Jour. Sci. 238:493-517.

Jenkins, D., and L. L. Medsker. 1964. Brucine Method for Determination of Nitrate in Ocean, Estuarine and Fresh Waters. Anal. Chem. 36:610:612.

Kahn, L., and F. T. Brezenski. 1967. Determination of Nitrate in Estuarine Waters. Envir. Sci. and Technol. 1:488- 491

Piontelli, R., and V. Tonolli. 1964. Il Tempo di Residenza Acque Lacustri in Relazione ai Fenomeni di Arricchimento in Soztanze Immesse, con Particolare Riguardo al Lago Maggiore. Mem. Ist. Ital Idrobiol. 17:247-266.

Robinson, R. J. 1938. The Data of Lake Washington. Typewritten, University of Washington Library. For summary, see Scheffer and Robinson (1938).

Robinson, R. J. 1941. Perchloric Acid Oxidation of Organic Phosphorus in Lake Waters. Anal. Chem. 13:465-466.

Robinson, R. J., and T. G. Thompson. 1948. The Determination of Phosphates in Sea Water. J. Mar. Res. 7:33-41.

Scheffer, V. B., and R. J. Robinson. 1939. A Limnological Study of Lake Washington. Ecol. Mongr. 9:95-143.

Solorzano, L. 1969. Determination of Ammonia in Natural Waters by the Phenolhypochlorite Method. Limnol. Oceanog. 14:799-801.

Strickland, J. D. H., and T. R. Parsons. 1968. A Practical Handbook of Seawater Analysis. Bull. 167 Fish. Res. Bd. Canada. (second edition).

U.S. Environmental Protection Agency. 1971. Methods for Chemical Analysis of Water and Wastes.

Vollenweider, R. A. 1969. Möglichkeiten und Grenzen Elementarer Modelle der Stoffbilanz von Seen. Arch. Hydrobiol. 66:1-36.

Vollenweider, R. A. 1976. Advances in Defining Critical Loading Levels for Phosphorus in Lake Eutrophication. Mem. Ist. Ital. Idrobiol. 33:53-83.

Vollenweider, R. A., and P. Dillon. 1974. The Application of the Phosphorus Loading Concept to Eutrophication Research. NRCC Report No. 13690, 42 pp.

BIBLIOGRAPHY

Carlson, R. E. 1977. A Trophic State Index for Lakes. Limnol. Oceanog. 22:361-369.

Chapra, S. C., and S. T. Tarapchak. 1976. A Chlorophyll a Model and Its Relationship to Phosphorus Loading Plots for Lakes. Water Resources Research. 12:1260-1264.

Chen, C. W., and G. T. Orlob. 1975. Ecologic Simulation for Aquatic Environment. pp. 476-588., in B. C. Patten ed. Systems Analysis and Simulation in Ecology. Vol. III.

Davis, M. B. 1973. Pollen Evidence of Changing Land Use Around the Shores of Lake Washington. Northwest Science. 47:133-148.

Dillon, P. J., and F. H. Rigler. 1974. The Phosphorus-Chlorophyll Relationship in Lakes. Limnol. Oceanog. 19:767-773.

Edmondson, W. T., G. C. Anderson and D. R. Peterson. 1956. Artificial Eutrophication of Lake Washington. Limnol. Oceanog. 1:47-53.

Edmondson, W. T. 1961. Changes in Lake Washington Following an Increase in the Nutrient Income. Verh. Internat. Verein. Limnol. 14:167-175.

Edmondson, W. T. 1966. Changes in the Oxygen Deficit of Lake Washington. Verh. Internat. Limnol. Verein. 16:153-158.

Edmondson, W. T. 1968. Water Quality Management and Lake Eutrophication: The Lake Washington Case. pp. 139-178 in Water Resources Management and Public Policy. T. H. Campbell and R. O. Sylvester (eds.) University of Washington Press.

Edmondson, W. T. 1969b. Cultural Eutrophication with Special Reference to Lake Washington. Mitt. Internat. Verein. Limnol. 17:19-32.

Edmondson, W. T. 1970. Phosphorus, Nitrogen and Algae in Lake Washington after Diversion of Sewage. Science 196:960-691.

Edmondson, W. T. 1974a. Review of The Environmental Phosphorus Handbook. Limnol. Oceanog. 19:369-375.

Edmondson, W. T. 1974b. The Sedimentary Record of the Eutrophication of Lake Washington. Proc. Nat. Acad. Sci. 71:5093-5095.

Kemmerer, H., J. F. Bovard and W. R. Boorman. 1924. Northwestern Lakes of the United States: Biological and Chemical Studies with Reference to Possibilities in Production of Fish. Bull. U. S. Bureau Fish. 39:51-140.

Oglesby, R. T., W. R. Schaffner and E. L. Mills. 1975. Nitrogen, Phosphorus and Eutrophication in the Finger Lakes. Tech Rep. No. 94, Cornell Univ. Water Resources and Marine Sciences Center.

Shapiro, J., W. T. Edmondson and D. E. Allison. 1971. Changes in Chemical Composition of Sediments of Lake Washington, 1958-1970. Limnol. Oceanog. 16:437-452.

Snodgrass, W. J. and C. R. O'Melia. 1975. Predictive Model for Phosphorus in Lakes. Environ. Sci. Technol. 9:937-944.

Thut, R. 1969. A Study of the Profundal Bottom Fauna of Lake Washington. Ecol. Mongr. 39:79-100.

Wydowski, R. S. 1972. Annotated Bibliography on the Ecology of the Lake Washington Drainage. Coniferous Forest Biome Bull. No. 1, Seattle. Fisheries Research Institute, University of Washington, Seattle.

TABLE 1. TRANSPARENCY, TEMPERATURE AND CONCENTRATION OF SELECTED SUBSTANCES IN SURFACE WATER OF LAKE WASHINGTON

A. Total P
B. Phosphate-P (unfiltered)
C. Total Kjeldahl N
D. Nitrate-N
E. Seston, dry weight
F. Chlorophyll a
G. Transparency, m (Secchi disc)
H. Surface temperature

Note: Chlorophyll, phosphorus and nitrogen as μg/l, seston as mgm/l, transparency in meters, temperature, degrees Celsius. Blanks mean no determination. Zeros mean the concentration was below the level of detection. Transparency and temperature were measured on 171 trips when no chemical samples were taken.

Date	A	B	C	D	E	F	G	H
1973								
Jan 2	19.7	10.9	214	315	1.1	1.7	5.0	8.4
18	-	10.5		301		1.2		8.1
30	18.4	11.1	204	333	1.2	1.0	4.6	7.8
Feb 13	-	13.6		321		1.2	6.2	8.6
Mar 8	20.3	9.3	250	316	1.4	1.0	6.0	9.0
20	-	10.0		329		1.0	5.9	7.4
Apr 3	19.9	2.2	230	262	3.0	4.4	4.0	10.2
17	-	2.0		250		6.6	3.6	8.7
May 8	14.5	1.2	301	213	1.7	2.3	6.5	10.8
22	-	4.2		113		4.5	3.5	14.7
Jun 6	14.8	1.2	235	89	2.4	3.2	4.0	16.5
19	-	2.4		49		3.6	3.0	15.6
Jul 3	12.6	0	301	25	3.5	2.9	3.0	18.1
17	-	0		35		2.4	3.5	21.7
Aug 1	14.0	1.1	308	6	2.2	3.8	3.2	21.3
14	-	0		20		2.4	3.4	20.3
29	9.7	0	402	19	2.6	1.2	3.6	18.8
Sep 11	-	1.1		38		2.4	3.4	19.0
25	20.0	2.0	264	50	1.6	1.6	3.6	17.3
Oct 10	-	0.6		30			4.5	15.3
23	8.6	0.8		46	1.2	2.8	5.0	14.0
Nov 6	-	1.7		118		1.2	5.0	11.5
20	20.0	8.2	231	202		1.5	5.5	9.7
Dec 4	-	12.7		251		0.6	5.5	9.0
11	19.3	16.4	169	261	0.6	1.3	6.0	8.6

(continued)

TABLE 1 (continued)

Date	A	B	C	D	E	F	G	H
1974								
Jan 8	20.0	19.2	194	355	1.4	1.3	6.0	7.2
22	-	19.3		360		1.3	4.5	
Feb 5	26.9	20.7	168	350	1.7	1.3	4.5	6.6
21	-	19.7		390		1.4	5.0	6.5
Mar 5	32.0	20.4	217	353	1.7	2.0	5.0	6.4
21	-	17.1		321		4.3	5.3	7.1
Apr 4	25.2	11.6	273	278	2.4	7.2	5.0	7.6
18		5.9		274		7.0	4.5	9.4
May 2	15.9	6.1	218	307	2.1		5.5	9.3
16	-	0		220		10.0	4.0	10.2
29	20.7	0.2	170	180	3.0	5.0	4.0	13.8
Jun 13		0		110		5.5	3.0	18.2
27	7.6	0.3	265	99	2.8	5.3	3.5	15.6
Jul 10	-	1.5		50		5.1	3.3	16.7
24	10.0	0.9	298	33	2.1	4.2	2.7	19.8
Aug 8	-	0.5		26		2.1	4.2	21.9
22	6.3	0	233	32	2.6	3.1	4.5	20.5
29							4.7	22.3
Sep 4	-	1.0		36		2.3	5.5	20.9
17	11.4	0	238	27	2.4	4.2		19.8
Oct 2	-	0		24		4.8	5.5	18.1
15	3.2	1.6	214	31	2.0	5.8	4.8	16.4
29	-	0		54		5.3	4.4	14.7
Nov 12	9.7	0.5	294	73	1.8	5.8	4.7	12.6
25	-	3.4		108		5.4	5.5	11.1
Dec 5							5.4	10.1
10	10.0	8.0	227	168	1.3	4.3	5.7	9.8
23	-	9.5		209		4.5	5.7	9.4
1975								
Jan 7	15.2	14.4	224	267	1.4	3.5		8.3
21	-	16.9		277		2.4	6.2	8.2
Feb 4	17.2	15.4	188	314	1.6	1.9	6.2	8.0
18	21.2	15.5		317		2.2	7.5	7.5
Mar 4	21.2	13.3	186	304	1.2	2.1	7.3	7.2
19	-	14.8		333		4.0		7.4
27	22.1	10.6				3.9	6.4	7.4
Apr 1	22.6	10.0	228	324	2.2	6.8	6.0	7.8
8	16.2	4.1		201		13.0	4.4	9.1
15	-	0.6		177		12.9	3.3	9.7
29	13.6	1.6	341	149	4.5	16.9	4.0	9.9
May 14	11.3	1.8		103		15.4	2.8	13.2
23	14.7					10.3	3.4	12.7
27	12.8	0	258	101	2.6	6.7	3.3	14.1
Jun 6	9.4	0		66		1.4	3.4	16.4
10	10.0	1.3		55		5.8	2.9	16.4
18	8.6	0.5		50		2.7	4.4	16.8
24	9.4	0	256	37	2.6	6.2	4.0	16.2

(continued)

TABLE 1 (continued)

(1975 cont.)	A	B	C	D	E	F	G	H
Jul 2	10.2	0.8		23		4.7	4.1	16.4
8	11.5	1.1		16		2.2	4.8	20.5
9							5.6	21.7
15	12.7	0		19			4.4	20.4
22	13.6	0.7	239	23	2.0	4.2	3.8	21.0
Aug 5	13.3	0.9		32		3.3	3.8	20.4
12	12.0	0.4		11			3.4	20.7
19	5.1	0.2	319	36	2.0	3.5	4.0	19.4
Sep 3	7.4	0.7		24		4.4	4.1	17.8
16	-	0.2	247	25	1.8	4.1	4.0	18.0
24	-	1.4		19		2.1	4.0	18.3
30	11.2	0.5		21	1.7	0	4.0	17.5
Oct 14	11.9	0.8	291	33	1.1	1.0	5.6	15.2
22	12.4	1.0		37		5.6	6.5	14.2
29	12.8	1.4		68	1.6	6.2	6.0	12.6
Nov 4	12.6	2.0		104		4.7	6.0	12.9
11	12.1	5.2	231	151	1.3	3.3	6.2	10.8
18	14.8	7.8		182		4.2	6.5	10.0
25	21.9	10.8	221	217	1.3	0.7	6.8	9.5
Dec 9	22.2	11.6	202	254	1.4	2.9	5.3	8.8
17	22.5	14.2		282		2.6		
23	11.1	14.1	198	277	3.0	3.6	2.5	8.0
30	17.5	12.3		276		2.3		
1976								
Jan 6	19.5	12.8	250	319	2.8	2.4	3.3	7.6
20	19.5	14.4		321	2.3	2.4	4.2	7.2
28	20.6	12.3		311		2.8	4.6	7.2
Feb 3	16.1	14.2	197	308	1.9	3.3	4.5	7.0
17	23.4	13.3		295	3.1	4.2	4.9	6.7
Mar 2	20.8	11.1	196	296	3.2	6.9	5.2	6.4
9	18.2	7.6		272		6.9	5.0	6.5
16		6.4		257	2.9	6.8	5.5	7.0
30	16.6	4.5	276	275	3.4	7.6		8.3
Apr 8	14.6	1.1		216		7.6	4.2	8.1
14	15.3	1.9		213	4.2	6.8		8.8
21	11.4	1.0		201		6.9	4.4	9.3
28	11.5	2.4	228	196	2.0	6.4	4.6	10.7
May 6	8.8	1.1		177		3.9	5.4	12.7
11	12.4	1.0		184	2.2	4.6	4.9	11.0
19	11.4	1.2		138			4.2	12.7
Jun 1	10.6	0	243	130	2.3		4.2	12.2
15	19.4	1.4		100	0.7		4.1	15.5
23	11.5			74			4.3	15.6

(continued)

TABLE 1 (continued)

(1976 cont.)	A	B	C	D	E	F	G	H
Jul 1	9.7	0.5	258	134	1.1			
8	10.0	0.5				4.0	6.0	17.9
15	14.5	0.3		53	1.8	2.3	6.3*	19.2
21	11.1			52		4.3	5.5	19.4
27	9.4	0.5	231	32	1.8	5.1	4.8	19.9
Aug 4	14.2	0.6		32		2.7	5.0	20.5
10	10.3	0		27	2.1	3.2	5.4	20.1
18						2.3	5.7	19.6
24	9.7	0.5	213	31	2.8	3.1	4.6	18.9
Sep 2	7.8	0		23			5.1	20.4
7	10.0	0		8	2.1	1.9	5.4	18.8
15	7.8	0.3				3.0	5.5	
21	9.7	1.8	246	73	1.7	2.3	6.5	18.3
30	7.1	0		44		2.5	8.2	18.5
Oct 6	8.1	0		55	0.8	2.7	8.4	17.2
13	6.7	0.5		54		1.5	9.2	16.9
20	4.8	1.0	197	55	1.1	2.8	9.2	15.6
27	7.8	0		54		2.7	8.9	14.5
Nov 2	6.8	1.0		83	0.8	3.9	9.8	13.8
10	6.9	0.5		89		3.4	9.2	13.3
17	7.9	1.6	207	108	0.9	2.9	9.2	12.6
23	9.6	2.9		110		3.4	9.8	12.0
30	10.3	5.3		162	0.7	2.4	9.8	10.8
Dec 9	11.9			186		1.8	9.0	10.0
15	11.3	7	195	207	0.7	2.6	9.5	9.8
21	14.5	10.3		103		1.8	10.2	9.5
28	14.3	10.0		266	0.8	1.4	9.4	9.0

* 8.2 on 13 July

TABLE 2. CHEMICAL PROPERTIES OF LAKE WASHINGTON MEASURED AT VARIOUS DEPTHS ON SELECTED DATES

A. Chlorophyll a
B. Total phosphorus
C. Dissolved phosphorus
D. Phosphate-phosphorus (unfiltered)
E. Phosphate-phosphorus (filtered)
F. Total Kjeldahl nitrogen
G. Dissolved Kjeldahl nitrogen
H. Nitrate nitrogen
I. Nitrite nitrogen
J. Ammonium nitrogen
K. Oxygen
L. Carbon dioxide
M. Alkalinity
N. Seston
O. pH
P. Total alkalinity

Note: Chlorophyll, phosphorus and nitrogen as μg/l, other concentrations as mg/l. Data are from two stations, the usual main station at Madison Park (MP) and a station north of the Evergreen Point Bridge (NEPB), occupied when strong winds are blowing from the south. Surface temperature is given in degrees Celsius and Secchi disc transparency in meters.

30 January, 1973 NEPB Temp. 7.8° Trans. 4.6 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.7	18.4	13.1	11.1	10.0	204	191	333	0.7	0.0	10.97	2.24	30.2	1.20	7.35
30	1.6	20.6	11.9	10.7	10.0	229	148	326	0.7	0.0	10.99	2.08	30.1	1.48	7.35
59	1.7	21.6	13.1	11.1	11.1	208	166	314	0.6	0.0	10.85	2.20	30.2	1.44	7.30

8 March, 1973 MP Temp. 9.0° Trans. 6.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.0	20.3	10.9	9.3	9.3	250	163	316	0.0	0.0	11.83	1.40	30.7	1.36	7.80
30	0.8	19.5	12.8	12.7	12.7	228	172	329	0.0	0.0	11.22	2.32	30.4	0.96	7.45
60	0.8	23.0	14.4	16.0	14.0	222	202	345	0.0	0.0	10.51	2.48	30.4	0.96	7.30

(continued)

TABLE 2 (continued)

3 April, 1973 MP Temp. 10.2° Trans. 4.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	4.4	19.9	6.7	2.2	2.2	230	162	262	0.6	0.0	12.92	0.20	30.9	3.04	8.00
5	6.2	19.9	6.4	2.8	2.2	270	254	287	0.6	0.0	12.56	0.68	31.3	3.60	7.95
15	4.3	20.2	8.9	7.8	4.4	217	175	329	0.8	0.0	11.81	1.12	21.3	2.44	7.65
30	2.4	18.9	12.0	8.9	8.3	322	171	343	1.8	0.0	11.32	0.60	30.5	1.28	7.50
60	1.5	20.8	15.4	13.3	12.2	322	166	364	0.0	0.0	10.50	2.00	30.3	1.08	7.30

6 June, 1973 NEPB Temp. 16.5° Trans. 4.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0	3.2	14.8	4.6	1.2	1.2	235	157	89	2.2	2.1	10.99	0.0	28.5	2.40	8.20	32.9
5	2.4	12.2	3.0	1.2	0.6	225	114	96	1.9	0.1	10.99	0.0	28.1	2.48	8.45	33.1
10	4.3	13.5	3.7	1.9	1.2	190	114	155	1.2	6.2	10.32	0.20	32.5	2.32	8.00	
15	1.4	11.6	4.0	2.5	1.9	181	105	277	0.8	9.0	9.80	2.20	31.2	0.96	7.50	
20	1.2	11.3	6.2	5.0	3.8	171	119	319	0.1	0.2	9.76	2.60	30.9	0.72	7.40	
30	0.7	16.7	13.8	12.2	12.2	148	138	366	0.3	1.0	9.52	2.96	30.6	0.60	7.30	
40	0.6	16.7	13.8	13.3	12.8	119	90	378	0.3	0.0	9.38	3.60	30.6	0.60	7.30	
50	0.4	23.1	16.7	16.7	15.6	181	105	394	0.6	2.4	8.93	4.24	30.4	0.64	7.20	
59	0.5	23.1	16.7	16.7	14.6	181	105	394	0.6	2.4	8.22	4.60	30.5	0.76	7.20	

25 September, 1973 NEPB Temp. 17.3° Trans. 3.6 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.6	20.0	11.1	2.0	0.2	264	138	50	0.5	3.0	9.84	0.60	33.3	1.55	8.02
5	1.6	-	-	1.7	0.0	217	132	55	0.5	4.5	9.66	0.80	33.5	1.86	8.20
10	2.0	15.6	-	1.5	0.5	231	138	50	0.5	4.8	9.54	0.80	33.4	1.81	8.11
12	2.0	13.3	4.7	1.2	1.7	302	154	57	0.5	3.3	9.50	1.00	33.2	1.65	8.12
15	1.2	13.3	4.0	1.0	0.2	207	154	110	0.0	5.0	7.88	4.20	32.0	1.17	7.30
18	0.6	8.0	4.7	2.2	0.7	231	149	330	0.6	1.3	8.00	7.60	30.3	0.56	7.07
20	0.0	15.6	9.3	6.1	4.1	192	127	353	0.5	2.0	6.05	7.80	30.0	0.64	7.01
25	0.0	17.8	12.2	8.5	7.6	122	149	377	9.5	1.3	7.18	-	30.0	0.44	7.04
30	0.6	25.0	20.7	15.0	13.3	159	122	385	0.7	2.3	6.77	7.00	29.8	0.52	7.04
40	0.0	25.0	22.9	16.9	15.3	186	176	406	0.2	1.5	7.20	7.00	20.5	0.70	7.07
50	0.0	32.1	27.9	21.9	18.3	202	202	416	0.6	0.5	6.85	7.80	29.4	0.52	7.00
55	0.0	32.1	27.1	23.3	18.3	186	132	431	0.6	1.8	6.09	8.80	29.5	0.64	6.96
59	0.4	40.0	30.0	26.1	21.7	192	192	436	0.1	15.0	4.20	10.20	29.5	0.80	6.82

(continued)

TABLE 2 (continued)

20 November, 1973 NEPB Temp. 9.7° Trans. 5.5 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.5	20.0	11.4	8.2	7.1	231	171	202	1.0	9.1	9.38	3.00	31.1		7.21
5													31.3		7.57
10		21.8	6.9	7.4	6.8	220		200	0.5	3.4	9.25	3.12	31.1		7.32
20	1.5	25.4	10.0	7.9	6.8	242	165	196	0.5	1.7	9.15	3.40	31.2		7.31
30		21.8	10.0	8.2	7.6	220	128	200	0.6	0.0	9.11	3.40	31.2		7.30
40		41.8	29.1	29.7	24.3	236	160	409	0.1	1.1	4.87	8.00	29.7		6.92
50		49.0	30.9	35.6	27.0	187		440	0.5	0.0	4.19	10.44	29.5		6.91
55	0.6	50.9	36.4	37.6	28.9	181	144	437	0.1	8.2	3.89	10.96	29.5		6.88
59		50.9	38.2	35.9	30.6	214	155	447	0.2	2.0	3.89	10.64	29.4		6.72

5 February, 1974 MP Temp. 6.6° Trans. 4.5 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.3	26.9	20.6	20.7	18.9	168	162	350	0.5	0.0	11.54	2.00	30.0	1.67	7.22
5												2.00			7.13
30	1.2	29.6	20.2	20.0	18.9	141	200	342	0.5	0.0	11.44	1.96	30.1	1.55	7.08
60	1.0	27.1	19.0	21.4	17.9		114	336	1.0	0.0	11.50	1.96	29.1	2.29	7.29

16 May, 1974 MP Temp. 10.2° Trans. 4.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	10.0			0.0	0.0			220	2.3	0.0	12.08				
5	9.9			0.8	0.0			228	2.1	0.0	12.12				
10	7.6			1.1	0.0			288	2.9	0.0	11.78				
20	7.1			1.4	1.4			283	3.0	0.0	11.70				
25	6.8			1.7	2.3			316	3.7	0.0	11.67				
30	2.6			7.6	6.8			349	8.6	0.0	11.37				
40	1.3			14.1	13.0			379	8.6	0.0	11.00				
50	0.7			20.7	18.0			397	0.7	1.9	10.29				
60	0.8			19.7	19.1			426	0.6	1.0	10.22				

(continued)

TABLE 2 (continued)

27 June, 1974 NEPB Temp. 15.6° Trans. 3.5 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0	5.3	7.6	1.2	0.3	0.6	265	167	99	4.2	31.0	10.33	0.0	27.5	2.82	8.58	29.5
5	5.8	12.3	3.6	0.6	0.9	270	167	101	4.5	23.0	10.27	0.0	27.6	2.66	8.58	29.5
10	4.2	13.9	13.2	1.8	0.9	270	209	99	4.8	31.0	10.07	0.84	28.1	2.84	8.12	29.6
15	1.6	10.4	3.7	3.3	1.2	226	184	213	3.2	35.0	9.79	2.20	29.7	1.40	7.49	
20	0.6	9.7	4.8	3.9	3.0	184	145	281	1.2	9.0	9.81	3.16	29.7	1.09	7.48	
25	0.4	13.8	9.4	9.7	9.1	167	194	332	0.5	1.0	9.81	3.84	29.4	0.97	7.38	
30	0.4	9.3	6.8	7.0	6.7	151	156	315	0.6	4.0	9.77	3.84	29.5	0.67	7.37	
40	0.5	19.6	13.8	14.1	14.9	151	184	351	0.5	9.0	9.63	4.40	29.5	0.89	7.36	
50	0.5	31.3	18.1	22.1	19.7	209	167	371	0.5	2.0	9.05	6.48	20.5	0.65	7.15	
55	0.4	33.5	18.4	20.3	19.4	222	226	366	1.0	3.0	8.89	7.64	29.6	1.09	7.12	
60	0.4	26.8	32.2	21.4	21.0	172	184	374	1.1	7.0	8.83	6.00	20.6	1.01	7.20	

17 September, 1974 MP Temp. 19.8° Trans. 4.3 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0	4.2	11.4	3.7	0.5	1.0	238	187	27	0.2	5.0	9.55	0.0	29.9	2.37	8.54	31.9
5	4.4	10.3	3.9	1.0	1.0	238	167	26	0.0	0.0	9.22	0.0	30.3	2.27	8.67	31.9
10	4.7	15.7	3.9	1.0	1.0	244	156	21	0.2	2.0	7.38	0.36	30.7	2.22	8.21	31.3
12.5											7.16					
15	1.3	9.1	3.0	1.4	1.4	182	172	204	0.3	3.0	5.70	5.56	29.6	1.34	7.29	
17.5											6.71					
20	0.2	10.0	7.6	5.7	5.2	177	167	330	0.3	6.0	7.06	5.52	29.5	0.63	7.21	
25	0.3	17.3	3.9	11.6	11.6	197	157	364	0.2	2.0	8.07	4.28	29.0	0.75	7.21	
30	0.1	21.4	15.9	15.8	15.3	203	116	345	0.2	0.0	9.26	4.92	29.5	0.67	7.21	
40	0.1	16.5	19.2	18.9	18.9	197	167	398	0.3	1.0	8.70	5.64	20.5	0.51	7.20	
50	0.2	37.1	31.4	24.6	24.2	167	172	410	0.3	8.0	6.86	6.96	29.5	0.55	7.09	
55	0.3	54.8	39.5	30.0	28.3	182	157	451	0.7	7.0	5.91	9.40	29.4	1.03	6.98	
60	0.3	47.1	39.5	36.1	29.6	249	228	459	0.5	8.0	4.37	9.60	29.7	1.50	6.92	

(continued)

TABLE 2 (continued)

12 November, 1974 MP Temp. 12.6° Trans. 4.7 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	5.8	9.7	2.4	0.5	0.7	294	159	73	0.8	0.0	0.58	1.60	31.5	1.76	7.65
5	5.9	9.4	5.8	0.2	0.2	253	334	63	0.5	1.0	9.56	1.72	32.0	1.92	7.74
10	5.6	12.9	0.0	0.5	1.2	235	153	59	0.5	2.0	9.50	1.52	31.7	1.78	7.70
12.5											9.60				
15	6.1	5.8	1.5	0.7	1.4	226	125	89	0.5	1.0	9.50	1.80	31.6	1.67	7.72
17.5											9.54				
20	1.2	12.9	7.0	5.1	5.1	187	147	350	0.5	3.0	6.48	6.24	29.5	0.96	7.13
25	0.4	27.1	22.5	18.3	18.5	176	164	387	0.0	0.0	6.78	6.40	29.6	0.56	7.05
30	0.6	23.3	15.5	14.5	14.5	170	170	381	0.0	0.0	6.54	6.60	30.0	0.60	7.10
40	0.2	30.4	31.2	23.5	22.9	243	187	894	0.2	0.0	6.60	6.64	29.9	0.56	7.05
50	0.1	40.4	38.7	30.9	29.4	147	159	408	0.8	1.0	4.96	5.88	30.4	0.76	7.00
55	0.1	54.2	42.1	37.4	32.0	217	170	436	0.6	2.0	3.64	10.80	30.5	1.04	6.92
60	0.4	52.1	37.9	36.0	32.3	193	198	442	0.8	5.0	3.14	10.40	30.5	1.36	6.88

4 February, 1975 MP Temp. 8.0° Trans. 6.2 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.9	17.2	14.8	15.4	16.1	188	156	314	0.2	3.0	10.64	2.8	30.3	1.6	7.50
5												3.0	30.3		7.53
30	1.9	22.3	17.8	16.8	17.1	202	167	303	0.3	3.0	10.56	2.8	30.5	1.6	7.52
60	2.0	23.1	19.5	17.8	17.6	179	172	306	0.3	4.0	10.56	3.0	30.7	1.8	7.50

20 April, 1975 MP Temp. 9.9° Trans. 4.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0	16.9	13.6	5.6	1.6	2.4	341	194	149	1.9	2.0	13.62	0.0	23.6	4.5	9.00	31.0
5	18.1	17.9	4.1	4.2	3.2	358	189	157	1.6	3.0	13.32	0.0	25.0	4.6	9.28	31.2
20	18.1	15.2	2.6	3.2	3.2	276	174	166	1.6	5.0	12.75	0.0	26.0	4.2	9.08	31.0
30	13.5	3.2	4.4	4.2	4.2	289	206	200	1.7	8.0	12.30	0.2	31.0	3.6	7.75	
35	10.1	17.6	6.2		6.3	380	207	247	2.7	14.0	11.90	0.8	31.0	2.9	7.74	
40	8.2	20.0	10.0	10.0	10.0	216	229	274	4.1	6.0	11.58	1.92	30.5	2.2	7.45	
60	5.1	21.5	14.5	17.2	17.2	289	165	300	6.3	6.0	10.68	2.40	30.5	1.6	7.45	

(continued)

TABLE 2 (continued)

24 June, 1975 MP Temp. 16.2° Trans. 4.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0	6.2	9.4	0.0	0.0	0.0	256	175	37	4.1	8.0	10.28	0.00	29.8	2.61	8.19	32.0
5	6.0	11.2	11.5	0.0	0.0		161	41	4.1	10.0	10.28	0.00	30.4	2.19	8.31	32.0
10	5.6	10.3	2.1	0.0	0.0	247	147	40	4.2	13.0	10.06	0.00	31.2	1.86	8.25	32.0
15	1.7	7.6	0.7	0.0	0.0	199	142	178	4.2	7.0	9.88	3.40	31.5	1.17	7.29	
20	1.6	5.9	1.4	0.5	0.5	180	85	273	0.8	8.0	9.74	3.52	31.0	0.25	7.08	
25	1.4	0.3	3.4	2.6	3.2	170	175	276	0.8	5.0	9.60	3.64	30.8	0.81	7.01	
30	1.4	9.0	2.8	4.7	3.7	161	194	298	0.8	4.0	9.78	3.80	30.9	0.97	7.01	
40	1.0	11.2	11.2	6.3	5.8	194	142	219	0.7	5.0	9.70	4.20	30.1	0.69	6.99	
50	0.9	14.7	9.6	7.4	7.4	207	170	324	1.2	7.0	9.27	4.80	30.7	0.93	6.95	
55	0.9	14.4	10.6	10.6	8.9	194	52	332	0.8	5.0	8.55	4.00	32.0	0.89	6.79	
60	0.8	18.8	13.2	12.7	11.7	207	189	349	0.6	21.0	7.38	7.08	31.4	1.33	6.82	

14 October, 1975 NEPB Temp. 15.2° Trans. 5.6 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	1.0	11.9	5.2	0.8	1.0	291	182	33	0.3	31.0	9.19	3.60	32.4	1.12	7.48
5	3.6	11.0	5.0	1.0	1.0	271	182	25	0.2	30.0	9.11	3.92	32.0	1.03	7.58
10	4.0	13.0	0.0	0.5	1.0	238	192	15	0.5	31.0	9.11	3.76	32.6	1.09	7.50
15	3.7	13.0	4.0	1.0	1.0	267	197	23	0.3	29.0	8.88	6.00	32.3	1.12	7.49
20	2.6	11.0	7.0	4.0	4.0	308	172	233	0.5	8.0	6.20	8.80	20.7	0.76	6.86
25	1.2	17.0	14.0	10.7	10.0	197	197	296	0.2	6.0	6.06	10.60	30.0	0.64	6.90
30	0.8	18.0	14.0	12.7	12.0	172	182	295	0.2	5.0	6.40	7.40	31.4	0.68	6.88
40	0.7	21.0	16.0	16.0	14.7	172	197	216	0.2	6.0	6.89	9.04	29.5	0.56	6.82
50	0.6	21.0	18.0	18.0	16.0	157	192	320	0.2	7.0	6.59	8.80	29.5	0.56	6.82
55	0.9	25.0	18.0	21.3	18.7	153	213	340	0.0	3.0	5.41	11.60	30.0	0.84	6.74
60	0.4	31.0	15.0	25.3	13.3	279	201	357	0.8	24.0	3.93	12.80	30.2	1.44	6.69

(continued)

TABLE 2 (continued)

9 December, 1975 NEPB Temp. 8.8° Trans. 5.3 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	2.9	22.0	17.0	11.6	11.1	202	161	254	0.0	8.8	10.18		30.7	1.36	7.11
5													30.7		7.21
10	2.7	28.0	18.0	10.5	9.6	209	148	264	0.0	8.0	9.88		30.5	1.23	7.21
20	2.5	23.0	17.0	10.5	9.6	178	174	261	0.0	6.0	9.98		30.0	1.36	7.21
30	2.6	24.0	18.0	10.0	9.6	174	148	264	0.0	6.0	9.98		30.7	1.48	7.20
45	2.4	19.0	18.0	10.0	9.1	174	148	259	0.0	5.0	9.94		30.5	1.80	7.20
50	0.9	26.0	18.0	11.9	10.0	178	153	270	0.0	9.0	9.70		30.3	3.44	7.21
55	2.0	37.0	20.0	20.5	9.6	200	170	374	0.7	17.0	9.77		28.2	13.60	7.07
60	1.9	34.0	17.0	25.0	8.7	204	120	288	0.0	7.0	10.14		27.0	27.40	7.05

6 January, 1976 NEPB Temp. 7.6° Trans. 3.3 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	2.4	19.5	13.5	12.8	11.7	250	182	219	0.3	6.0	10.71	4.88	30.0	2.77	7.20
5												4.00	29.6		7.12
30	2.8	21.0	15.0	13.6	11.9	202	187	311	0.3	4.0	10.81	4.60	30.1	2.88	7.13
60	3.0	20.5	14.0	13.8	11.9	216	169	317	0.3	3.0	10.62	5.04	29.8	2.93	7.11

30 March, 1976 MP Temp. 8.3° Trans. 5.0 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	7.6	16.6	6.7	4.5	3.1	276	172	275	0.3	9.0	12.65	2.40	29.3	3.40	7.91
5	11.7	21.2	4.1	3.8	3.3	249	141	259	0.2	9.0		2.15	29.5	3.76	7.98
10	11.3	18.6	7.6	3.8	3.8	257	179	251	0.2	3.0	12.55	1.80	29.4	3.68	7.90
15	9.9														
20	10.3	15.8	3.3	5.7	5.2	232	179	264	0.3	12.0	12.14	2.40	29.3	3.60	7.74
30	10.8	13.8	4.6	4.8	4.8	236	184	263	0.2	4.0	12.14	2.20	29.3	3.52	7.68
60	11.9	17.2	2.8	5.2	4.3	270	179	267	0.3	7.0	11.94	3.84	29.6	4.08	7.65

(continued)

TABLE 2 (continued)

1 June, 1976 MP Temp. 13.8° Trans. 11.5 m

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0		10.6	5.4	0.0	0.0	243	158	130	5.9	7.0	10.99	1.60	30.0	2.29	7.87
5		12.5	3.3	0.0	0.0	223	256	121	6.0	8.0	10.91	1.80		2.05	7.98
10		9.1	5.4	0.0	0.0	256	185	130	6.0	10.0	10.99	1.80	30.4	2.21	7.99
15		12.7	3.0	0.0	0.0	252	169	128	6.0	8.0	10.89	1.76	30.1	2.21	7.90
20		11.1	3.6	0.0	0.0	289	169	129	6.0	7.0	10.89	1.48	30.5	2.21	7.83
25		7.6	2.6	0.0	0.0	235	190	185	2.0	14.0	10.35	3.68	30.1	1.25	7.48
30		8.8	5.4	0.7	0.3	177	173	247	0.3	4.0	10.29	3.48	29.6	0.93	7.31
40		7.9	6.7	2.3	1.7	165	160	262	0.3	5.0	10.39	3.80	29.6	0.93	7.30
50		10.5	7.6	4.0	3.3	173	152	265	0.3	9.0	10.23	4.20	29.5	0.85	7.20
55		12.7	8.8	5.3	4.7	173	148	287	0.2	5.0	10.19	4.20	29.5	1.01	7.21
60		14.1	9.7	5.7	5.3	177	219	295	0.6	9.0	9.88	5.60	30.0	1.09	7.14

TABLE 3. MEAN VALUES OF SELECTED PROPERTIES OF LAKE WASHINGTON

A. Total phosphorus, annual mean, whole lake
B. Total phosphorus, annual mean, top 10 m.
C. Phosphate-P, January-March mean, top 10 m.
D. Nitrate-N, January-March mean, top 10 m.
E. Chlorophyll *a*, July-August mean, top 10 m.
F. Solar radiation, annual total, thousands cal./$cm^2 \cdot$year
G. Total inflow in streams, millions m^3/year

Radiation data from University of Washington Department of Atmospheric Sciences and U.S. Weather Bureau. Flow data from U.S. Geological Survey, Tacoma, Washington and Municipality of Metropolitan Seattle. Data for 1933 from Robinson (1938), for 1950 from Comita and Anderson (1959). Flow data subject to slight revision. Concentrations, μg/l.

Year	A	B	C	D	E	F	G
1933	18.0	16.0	7.8	120	-	-	-
1950	-	-	14.3	-	2.7	99.1	1682
1963	70.3	65.7	55.3	425	34.8	109.5	964
1971	17.6	18.4	14.6	375	6.1	95.3	1540
1972	16.1	16.0	8.8	310	7.2	101.4	1514
1973	18.8	16.8	11.3	255	4.7	96.5	898
1974	19.4	14.8	18.9	350	4.3	98.7	1329
1975	15.8	14.5	15.3	305	3.9	110.6	1480
1976	14.4	13.4	10.1	295	4.0	112.1	-

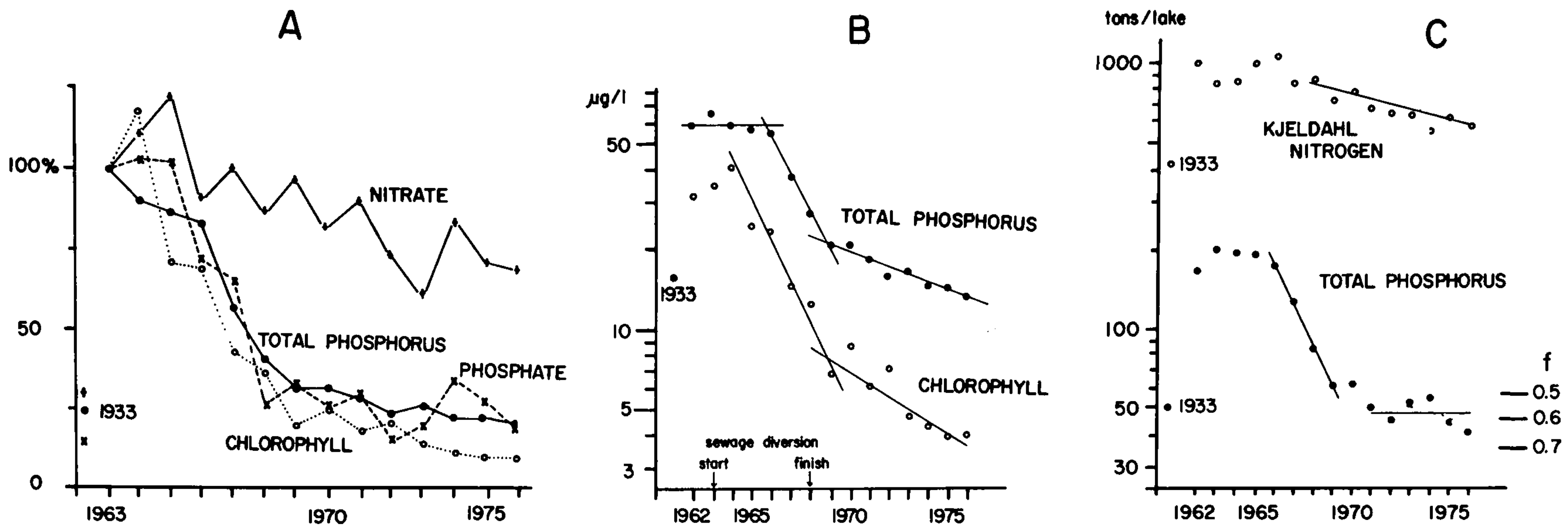

Figure 1. Summary of changes in phosphorus, nitrogen and chlorophyll during the recovery of Lake Washington

A. Mean values for the top 10 meters, related to the absolute values in 1963, shown in parentheses as 100%
Total phosphorus for whole year (65.7 µg/l).
Dissolved inorganic phosphate phosphorus, January-March (55.3 µg/l).
Nitrate nitrogen, January-March (425 µg/l).
Chlorophyll, July-August (34.8 µg/l).
The symbols at the left show values for 1933 (Scheffer and Robinson, 1939). Note that the winter values are for a slightly different time from those published earlier (Edmondson, 1970). Sewage diversion started in February, 1963 and ended in February, 1968, but most sewage had been diverted by March, 1967. Winter phosphate phosphorus can exceed the annual mean for total phosphorus when the latter decreases considerably during the summer as in 1974 (see Fig. 2). This is an updated modification of a graph used previously to report on the progress of the recovery of Lake Washington (Edmondson, 1970, 1976b).

B. Total phosphorus and chlorophyll as in A, on a logarithmic scale. Lines fitted by eye.
For details of sewage diversions, see C.

C. Annual means of total content of lake of Kjeldahl nitrogen and total phosphorus on a logarithmic scale.
The equilibrium values are shown for three different retention fractions (f) at right (see text).

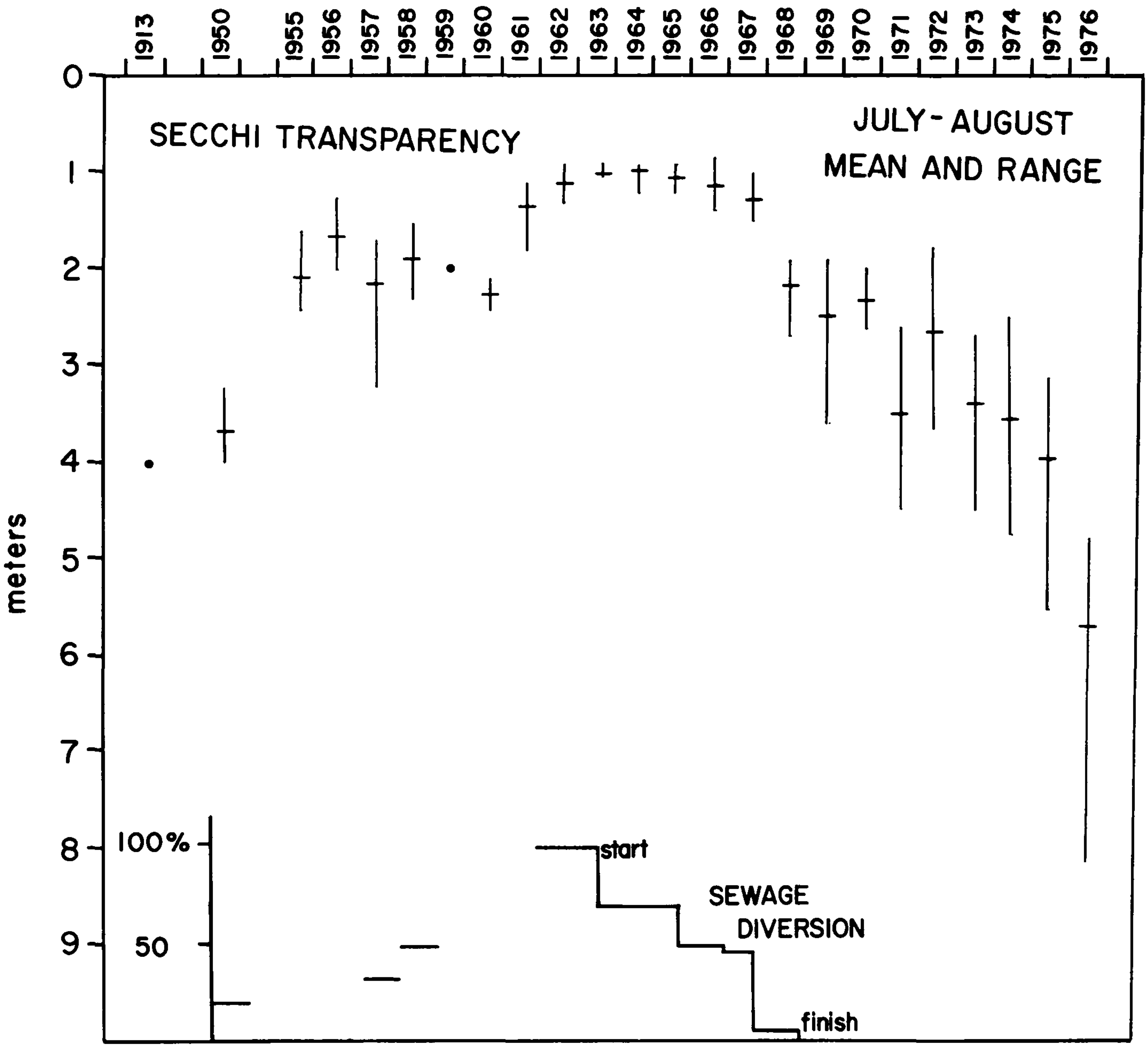

Figure 2. Minimum, mean and maximum Secchi disc transparency during summer in Lake Washington. Dots are single observations; the one for 1913 is from Kemmerer et al. (1924). This is an updated version of a graph published earlier (Edmondson, 1973).

Figure 3. Summary of seasonal changes in Lake Washington. The condition in the post-recovery period 1971-1975 is compared with that in two years before eutrophication was a problem (1933 and 1950), one year at the height of eutrophication (1963), and 1976.

A. Total phosphorus (dots) and phosphate-phosphorus (x).
B. Total Kjeldahl nitrogen (dots) and nitrate-nitrogen (x).
C. Secchi disc transparency, mean, maximum and minimum.
D. Chlorophyll *a*.
E. Surface temperature.
F. Solar radiation.
G. Flow of Cedar River.
H. Phosphorus in Cedar River (symbols as in A.)

The values are monthly means, based on all observations made during the month. For N, P and chlorophyll, this was usually about 4 per month in recent years, less frequently in earlier years. Temperature and transparency were measured more frequently. Radiation and water flow are based on daily measurements. Phosphorus in the Cedar River was measured every two weeks.

Concentrations as μg/l. Transparency, meters. Temperature, degrees Celsius. Radiation, $cal/cm^2 \cdot day$ (data from University of Washington Department of Atmospheric Sciences and U.S. Weather Bureau). Flow $m^3/min.$ (data from U.S. Geological Survey, Tacoma, Washington).

Note. Total nitrogen means for 1963 varied between 160 and 690 μg/l, and most points would be off scale on this graph. Data for 1933 from Robinson (1938), for 1950 from Comita and Anderson (1958).

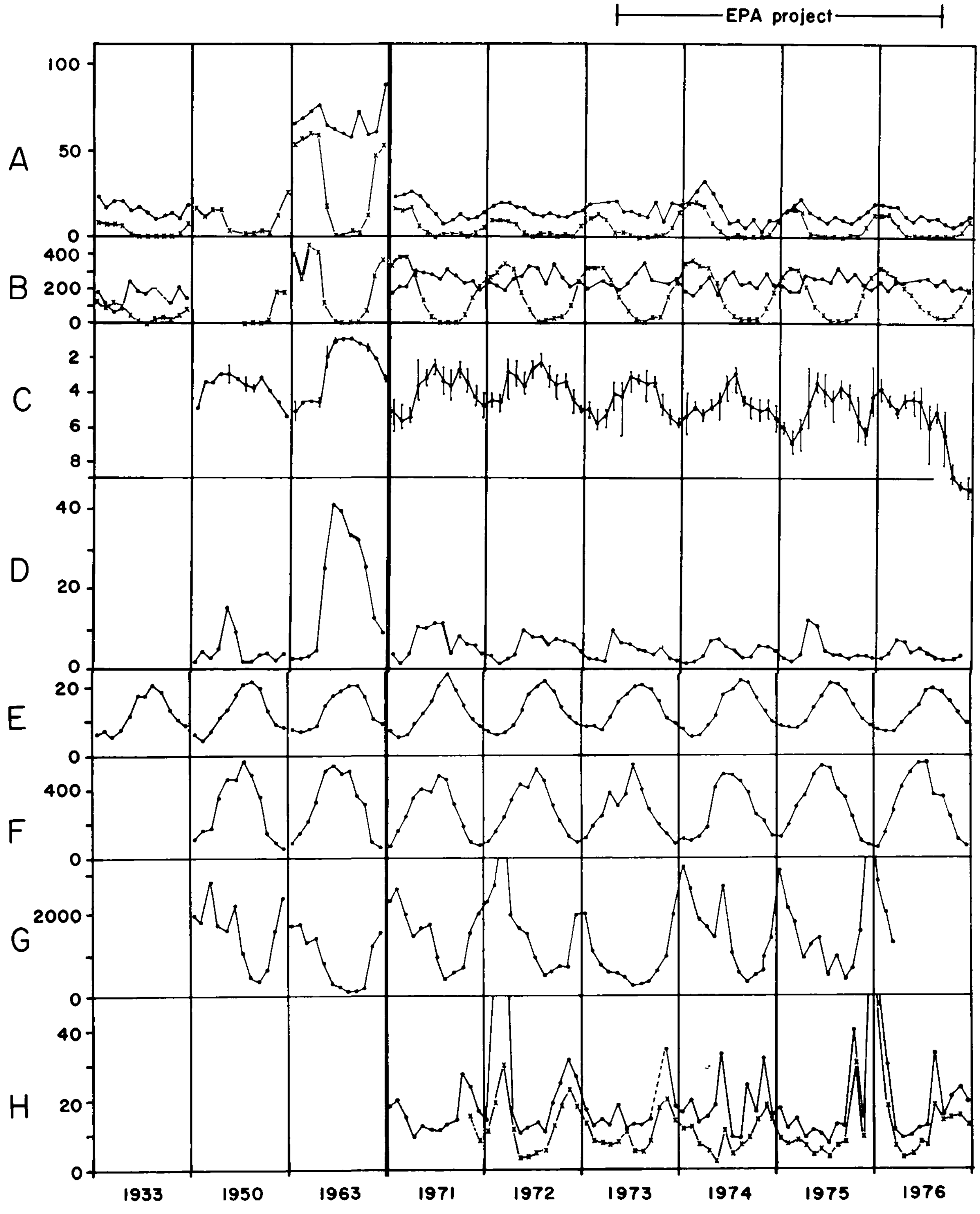
EPA project
A
B
C
D
E
F
G
H
100
50
0
400
200
2
4
6
8
40
20
2000
1933
1950
1963
1971
1972
1973
1974
1975
1976

Figure 3

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-77-087	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Trophic Equilibrium of Lake Washington		5. REPORT DATE August 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) W. T. Edmondson		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Zoology, University of Washington, Seattle, Washington 98195		10. PROGRAM ELEMENT NO. 1BA608
		11. CONTRACT/GRANT NO. R 8020 82-03-1
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory-Corvallis, U.S. Environmental Protection Agency, 200 S.W. 35th Street, Corvallis, OR 97330		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Sewage effluent was diverted progressively from Lake Washington during 1963-1968, and the chemical conditions changed in close relation to the amount of sewage entering. The total phosphorus content of the lake decreased rapidly to 1971 after which year it varied around a value of about 50,000 kg (= 17 µg/l) with a slight decreasing trend. The lake has retained about 56% of the phosphorus that entered during 1971-1975.

Winter means of nitrate and the annual mean total content of Kjeldahl nitrogen has decreased at a slow rate during the entire period. Phytoplankton as measured by chlorophyll in the epilimnion during summer dropped to a low value in close proportion to phosphorus during diversion, but has decreased faster than phosphorus during 1971-1976.

A large increase in transparency occurred in 1976. A major change is taking place in the character of the zooplankton of Lake Washington in that Daphnia became very abundant in 1976. This event is probably not directly related to recovery from eutrophication, so the lake is entering a new phase.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Limnology, Lakes, Plankton blooms, Phosphorus	eutrophication lake restoration	08 H

18. DISTRIBUTION STATEMENT Release unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 44
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

☆ U. S. GOVERNMENT PRINTING OFFICE: 1977—798-505/198 REGION 10