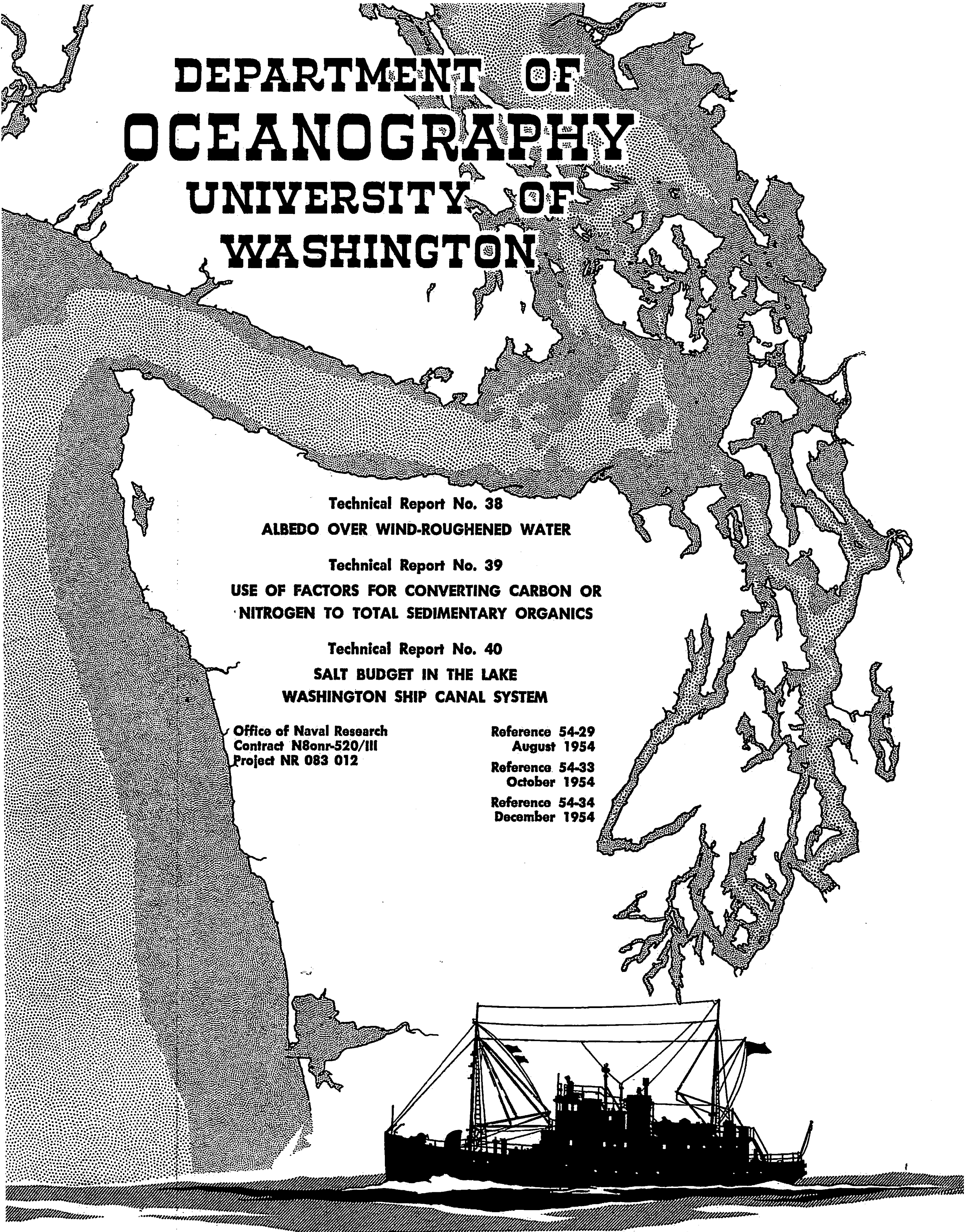
DEPARTMENT OF
OCEANOGRAPHY
UNIVERSITY OF
WASHINGTON



Technical Report No. 38

ALBEDO OVER WIND-ROUGHENED WATER

Technical Report No. 39

USE OF FACTORS FOR CONVERTING CARBON OR NITROGEN TO TOTAL SEDIMENTARY ORGANICS

Technical Report No. 40

SALT BUDGET IN THE LAKE WASHINGTON SHIP CANAL SYSTEM

Office of Naval Research
Contract N8onr-520/III
Project NR 083 012

Reference 54-29
August 1954

Reference 54-33
October 1954

Reference 54-34
December 1954

SEATTLE 5, WASHINGTON

UNIVERSITY OF WASHINGTON DEPARTMENT OF OCEANOGRAPHY
(Formerly Oceanographic Laboratories)
Seattle, Washington

Technical Report No. 38

ALBEDO OVER WIND-ROUGHENED WATER

by
Wayne V. Burt

Technical Report No. 39

USE OF FACTORS FOR CONVERTING CARBON OR NITROGEN TO TOTAL SEDIMENTARY ORGANICS

by
Richard G. Bader

Technical Report No. 40

SALT BUDGET IN THE LAKE WASHINGTON SHIP CANAL SYSTEM

by
Maurice Rattray, Jr., G. R. Seckel and C. A. Barnes

Office of Naval Research
Contract N8onr-520/III
Project NR 083 012

Reference 54-29
August 1954

Reference 54-33
October 1954

Reference 54-34
December 1954

RHFleming
Richard H. Fleming
Executive Officer

TECHNICAL REPORT NO. 40

SALT BUDGET IN THE LAKE WASHINGTON SHIP CANAL SYSTEM[1]

By

MAURICE RATTRAY, Jr., G. R. SECKEL[2] and C. A. BARNES

Department of Oceanography
University of Washington
Seattle 5, Washington

ABSTRACT

Salt water enters the freshwater system of Lake Washington, Montlake Canal, Lake Union, Fremont Canal, and Salmon Bay through the U. S. Government Locks at Ballard. During the summer season of heavy lock operation and small runoff this salt water accumulates in Lake Union and Lake Washington. Lake Union is flushed corresponding to the rates of flow during periods of high runoff, and Lake Washington is flushed only during the period of winter overturn. With increased chlorinity in the bottom waters, overturn and therefore flushing may be prevented. At present approximately 25% of the salt in Lake Washington is flushed out annually.

INTRODUCTION

The Lake Washington Ship Canal extends from Puget Sound to Lake Washington via the U. S. Government Locks at Ballard, Salmon Bay, Fremont Canal, Lake Union, and Montlake Canal (see Fig. 1). Lake Washington is nominally a freshwater lake while Puget Sound contains slightly diluted ocean water. The navigation channel is dredged and maintained everywhere at a minimum depth of 9 m. Salmon Bay contains a catch basin 600 m long, 75 m wide, and 15 m deep from which a siphon 2.7 m^2 in cross section extends to the downstream side of the spillway, where water is discharged from the basin at an estimated 2.8 to 4.2 m^3/sec. Lake Union has an area of 3.7 km^2 with depths of 14 to 15 m in north and south basins and approximately 12 m over the separating sill. Lake Washington is 29 km long with an approximate area of 90 km^2 and a maximum depth of 65 m. The main tributaries are the Cedar and Sammamish Rivers which enter respectively at the south and north end of Lake Washington. The minimum discharge of each river, approximately the same, is less than 3 m^3/sec and occurs in either August or September. The maximum

---

[1] This work was supported in part by the Office of Naval Research under Contract No. N8onr–520/III with the University of Washington.

[2] Now with the U. S. Fish and Wildlife Service, Pacific Oceanic Fisheries Investigations, Honolulu, T. H.

Reprint from SEARS FOUND. JOURN. MAR. RES.

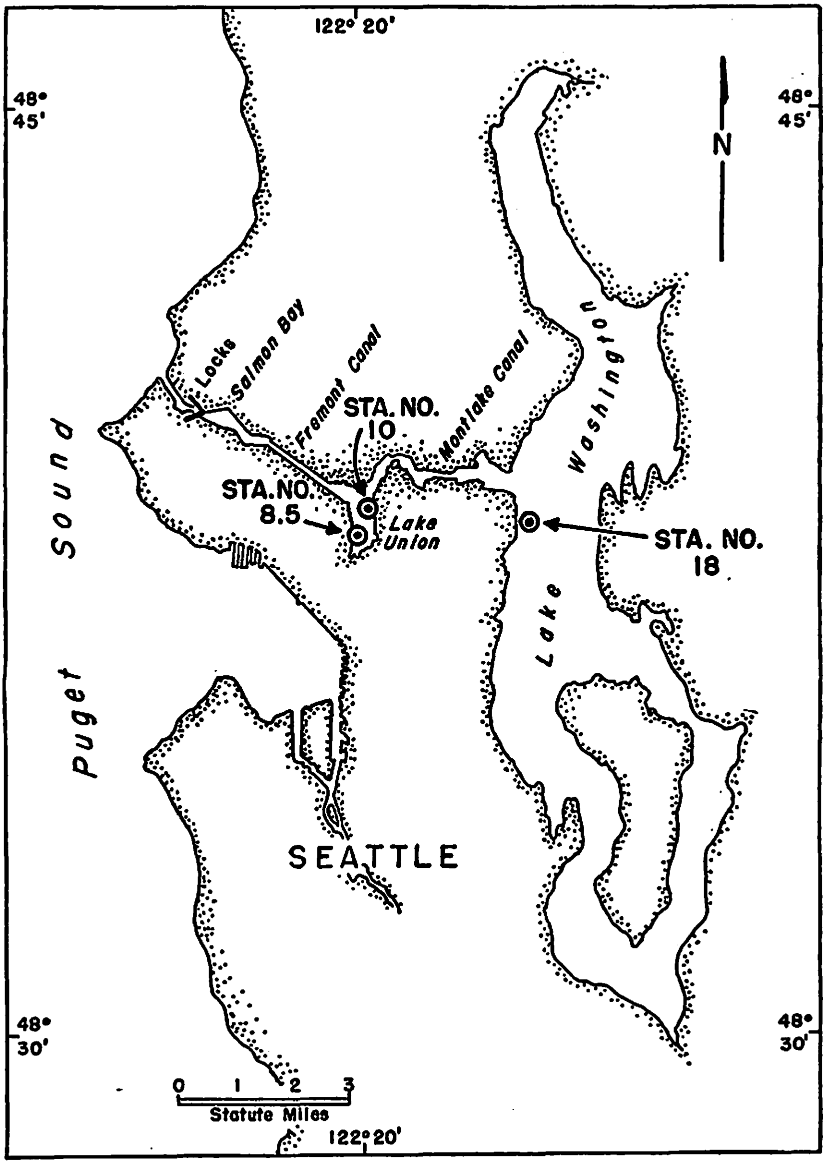


Figure 1. Location map showing hydrographic stations in Lake Union and Lake Washington.

discharge of the Cedar River is between 55 and 140 m^3/sec while that of the Sammamish River is 20 to 50 m^3/sec; the maxima occur in February or March.

SALT INTRUSION

The mechanism of salt intrusion into the Lake Washington Ship Canal system by lockage operations has been discussed previously by Smith and Thompson (1927), who showed that the water in the locks, just prior to raising the level, is always sea water. In raising the water in the locks from sea to lake level, lake water, introduced into the locks through culverts at the bottom of the chamber, actually "bubbles" through the sea water. Although mixing is not complete, the water introduced from Salmon Bay becomes more saline and the sea water becomes diluted. After the lock level is raised to that of the lake, the upper gates are opened to the canal side. The impounded water, being denser than that at the same level on the lake side, flows rapidly into Lake Union and is replaced by lighter surface water. The volume of Salmon Bay water used in each lockage is approximately twice that required to raise the lock level. During periods of light runoff and heavy lockages, the salt water in Lake Union may rise above sill level and spill over into Lake Washington.

To investigate the salt budget of this system, water samples were taken every two or three weeks in Lake Washington (depth 63 m) and in the two deep parts of Lake Union (depths 15 m). Sampling began in October 1950.

LAKE UNION

To illustrate the annual salt intrusion and flushing, the isochlors of 0.5, 1, 2, 5, and 7 ‰ at the northern Lake Union station are plotted in Figs. 2*a*, 2*b* and 2*c* from January 1951 through September 1953; shown also is the total rate of discharge through the canal system, averaged over a five-day period. Since computations on the exact amount of water used in lockage operations for 1953 were not available, the average monthly amounts for lockages in 1952 were used for 1953. The error is not significant during periods of large runoff, but a dashed line indicates the approximate nature of the curve after July. The dashed line in the chlorinity profiles indicates the approximate depth at and below which dissolved oxygen was absent and hydrogen sulfide generally present.

Starting with 10 January 1951, the 0.5 ‰ isochlor was at 12.5 m; subsequently it rose to 11 m and then disappeared completely during mid-February. During this period the isochlors were rather closely spaced, and the stagnant water which was present in the lower layers also disappeared in February.

The curve for total flow, which also showed some variation during January, reached a peak during February, when a flow of more than 100 m³/sec lasted for 13 days. The highest 5-day average flow during this time was 290 m³/sec, with the peak flood of 300 m³/sec on 13 February.

Soon after the lake was flushed, salt water began to reappear more or less in steps. These steps of sharp increases in chlorinity seemed to coincide with decrease in flow, which remained generally above 49 m³/sec for the first 25 days of March. After March, as the runoff through the system decreased, the amount of salt increased rapidly, particularly in concentrations between 1 and 2 ‰. Dissolved oxygen also decreased rapidly, and at the end of April hydrogen sulfide began to reappear.

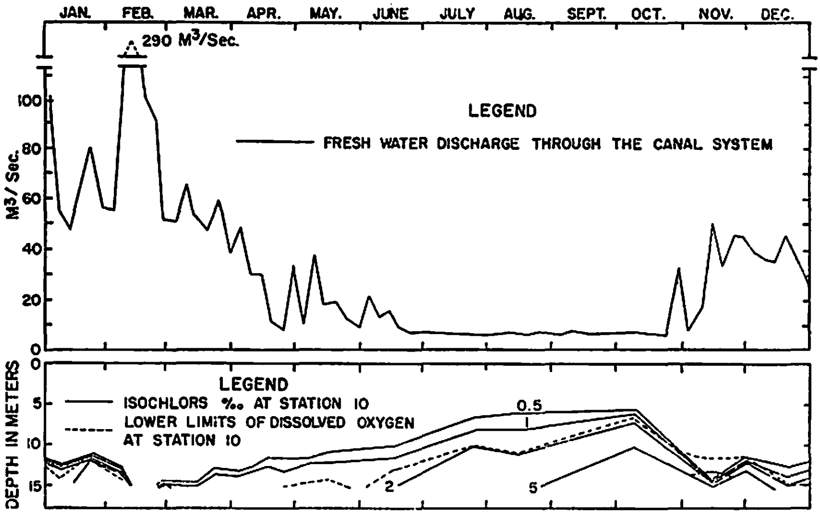


Figure 2a. Chlorinity (‰) variation at station 10 in Lake Union, and freshwater discharge (m³/sec) through the Canal, 1951.

After 16 June no more water was wasted either over the spillway or through the culverts, and the intrusion of salt water was indicated by a steady increase of chlorinity in the lake throughout the summer and early autumn. At the same time the amount of stagnant water increased at approximately the same rate.

With the return of the rainy season in early October, water is again wasted at the locks, depending on the lake level. In 1951, as soon as the flow had increased to approximately 33 m³/sec (14 November), the

5 ‰ isochlor dropped sharply to 14 m; by 29 November it was back at 11 m.

This general pattern of flushing during the winter and of increasing chlorinity during the summer was repeated in 1952 and 1953 except for the complete flushing that took place in February 1951. Precipitation during the winter and spring of 1952 was below average, and as can be seen in Fig. 2, wastage of water was well distributed throughout the first six months of the year, the amounts being considerably below 50 m^3/sec most of the time. Only once, for a brief period of 16 days in February, did discharge exceed this. Though the isochlors dipped for this period, they rose again shortly thereafter during a rather low runoff period. During April and May there were three brief periods of flow greater than 40 m^3/sec which were reflected in a lowering of the interface by approximately 1 m.

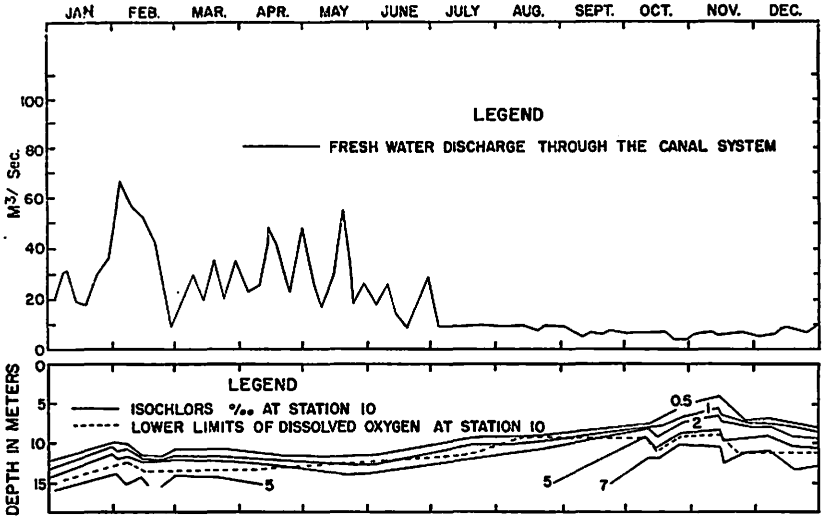


Figure 2*b*. Chlorinity (‰) variation at Station 10 in Lake Union, and freshwater discharge (m^3/sec) through the Canal, 1952.

After mid-May 1952 the isochlors began to rise steadily. From July through the rest of the year the water flowing through the system was only that used in lockage operations, fish ladder, and siphon. As in 1951, the 5 ‰ isochlor appeared at the end of August. Subsequently, however, the chlorinity increased rapidly and the 7 ‰ isochlor appeared below 10*m*. The complete closure of the saltwater siphon from 5 to 19 September and its partial closure from 19 September to 5

December probably account for the appearance of this abnormally high chlorinity.

Noteworthy is the sudden drop of the 0.5 ‰ isochlor after 12 November 1952 and its continuation downward throughout December, although no wastage of water occurred until 7 January 1953. Notwithstanding a flow greater than 80 m^3/sec for 30 days, the interface level did not drop below 10 m until March. The 7 ‰ isochlor level dropped slowly during the first three months of 1953 until May, when it disappeared. The 0.5, 1, and 2 ‰ isochlors began to rise during May, as in previous years, while the 5 ‰ isochlor continued to decline.

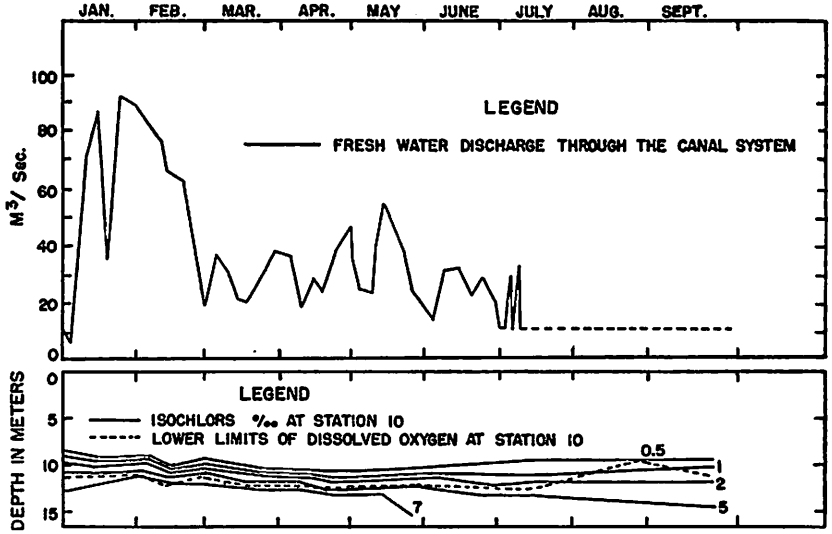


Figure 2c. Chlorinity (‰) variation at Station 10 in Lake Union, and freshwater discharge (m^3/sec) through the Canal, 1953.

It is concluded that Lake Union will be flushed completely when the discharge through the system is in excess of 100 m^3/sec for several days, as was the case in February 1951. Partial flushing, which takes place when the discharge is greater than 50 m^3/sec, seems to depend not only on the density difference between the upper and lower zones but also on the density gradient below the interface. For example, since the density gradient in October 1951 was considerably smaller than it was during the following winter and spring, a rate of flow of 50 m^3/sec produced a greater dip in the interface than did 65 m^3/sec the following February. It is assumed that the water above sill level (10 m) drained out when the flow increased, while flushing by the process of mixing extended to 4 m below that depth.

The importance of density difference can be seen in a comparison of observations for February 1952 with those for February 1953 (Fig. 2). In each case the interface was at approximately the same depth, but the chlorinity in the saltwater layer in 1953 was higher than that in 1952. A flow of more than 82 m^3/sec in 1953 did not flush the lake any more than the 65 m^3/sec in the previous year.

Apparently a flow of 30 to 50 m^3/sec does some flushing over a period of two to three months, as was the case in April and May of 1952 and 1953, when the interface was lowered by approximately 1 m. However, this rate of flow does not prevent new salt water from flowing into the lake, as was the case during the spring of 1951 and apparently during December 1951 and January 1952.

Three phenomena require special explanation. First, the rapid reappearance of salt water after the initial flushing in November, as indicated by lack of oxygen, is due to drainage from the southern part of the lake rather than to inflow from the lock system. Second, the decrease in the level of the interface commencing in November 1952 could not be caused by mixing, considering the small flow during this period. The maintenance of salt water above sill level must result from a balance between the inflow from the locks and outflow into both Salmon Bay and Lake Washington, due to the salt water head. Thus the decrease in lockage volume, especially on the 13th, 16th and 20th, explains the observed drop in the interface level. Third, the disappearance of the 7 ‰ isochlor in May 1953 while the interface level was rising indicates internal mixing within the saltwater layers while there is little or no mixing across the interface. This mixing probably results from the initial energy of the incoming salt water.

LAKE WASHINGTON

The limnology of Lake Washington has been discussed by Sheffer and Robinson (1939). Lake Washington, a typical freshwater lake, has minimum temperatures of approximately 6° to 8° C, depending on the climatic conditions of the year. Because of these high minimum temperatures, the lake overturns during one extended period each year, beginning approximately in December and lasting through February or March. After March the lake rapidly becomes stratified and maximum surface temperatures of 20° to 25° C occur during August.

Chlorinities reported in early studies of this lake were very low. The chlorinity reported by Sheffer and Robinson was approximately 2 p.p.m. in 1933 while that listed by Smith and Thompson (1927) did not exceed 4 p.p.m. The latter authors also listed the total salt analysis made by J. G. Priestley, chemist for the city of Seattle, from

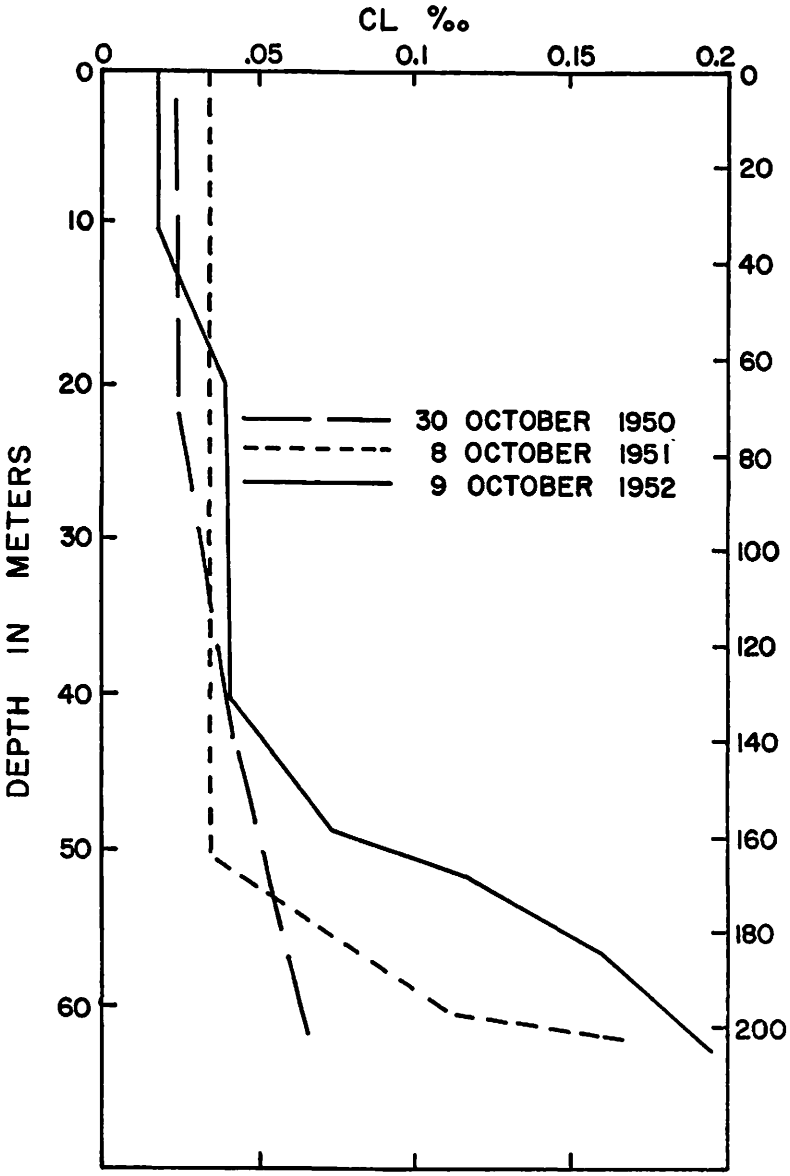


Figure 3. Chlorinities (‰) in Lake Washington (Station 18) for 30 October 1950, 8 October 1951, 9 October 1952.

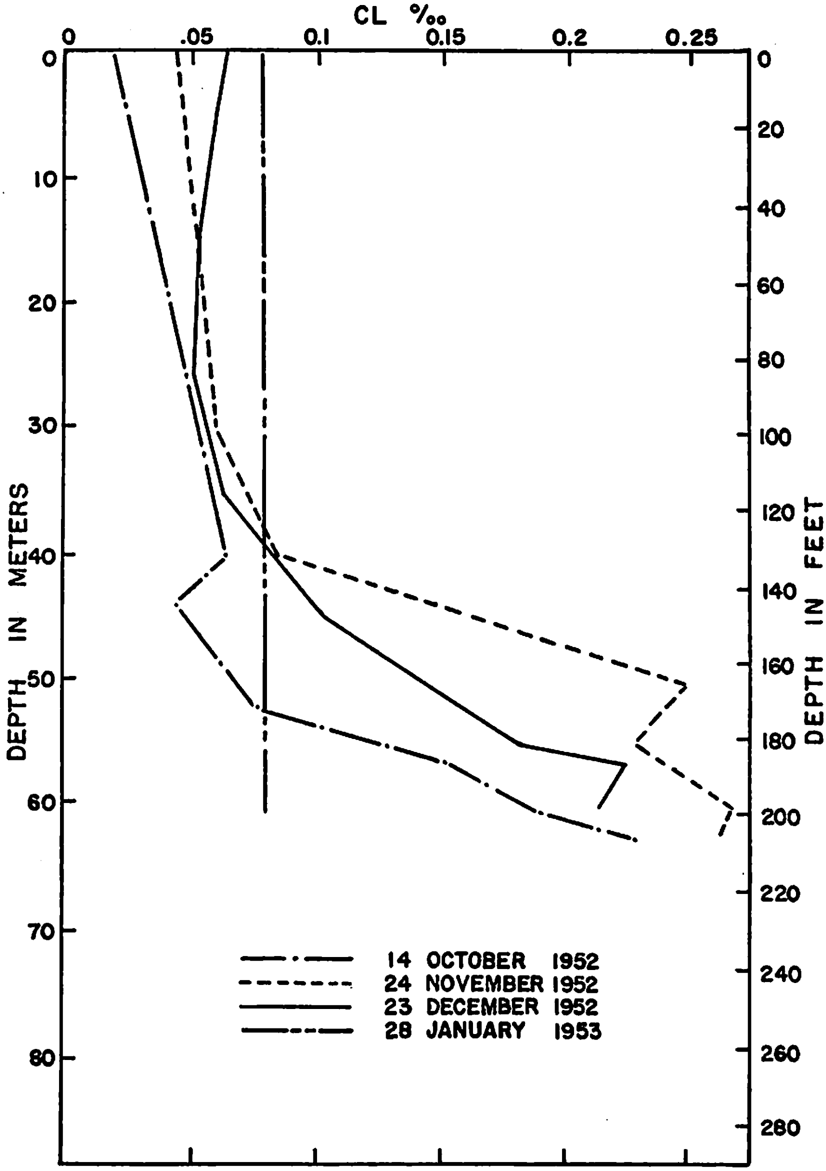


Figure 4. Chlorinities (‰) in Lake Washington (Station 18) for 14 October, 24 November 23 December 1952, 28 January 1953.

whose data the sulfate-chlorinity ratios were computed to be 4.2 and 6 for the north and south ends of the lake respectively. These ratios are typical for fresh water, and it is safe to say that at least until 1933 there was no appreciable saltwater intrusion into Lake Washington.

During the past few years the minimum chlorinity of the lake has been at least five times that found by Smith and Thompson. In Fig. 3 the chlorinity profiles for October 1950, 1951 and 1952 indicate this growth in total salt content, both the maximum chlorinity at the bottom and the height of the brackish water layer having increased each succeeding year. This increase occurs when the interface in Lake Union is above sill level and the rate of discharge of fresh water is too low to prevent the flow of saline water eastward along the bottom of Montlake Canal. At higher freshwater discharge rates, mixing and shearing stresses across the interface prevent salt water from reaching Lake Washington. Stagnation, which will occur when the bottom layers become sufficiently dense to prevent overturn during the winter season, is thus likely in following years.

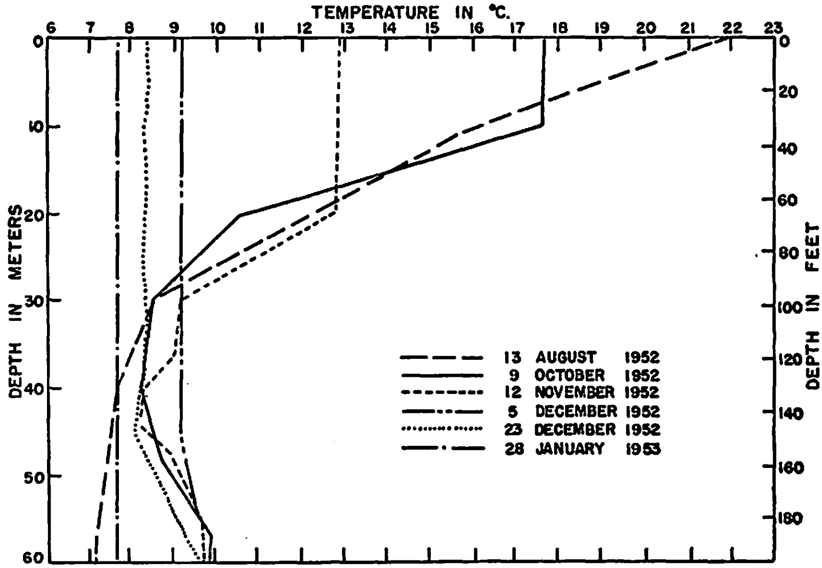


Figure 5. Temperatures (° C) in Lake Washington (Station 18), Autumn 1952.

The minimum requirements for prevention of overturn are at present unknown, but some light can be thrown on them by examination of the temperature and salinity profiles in Lake Washington during the autumn of 1952 and winter of 1953 (Figs. 4 and 5). With the bottom water at 10° C and about 0.25 ‰ chlorinity and with the surface water at 8.4° C and 0.05 ‰, no overturn occurred; however, when the surface temperatures reached 7.7° C on 28 January, an overturn did occur. Since 7.7° C is within a few degrees of the minimum lake temperature and since the density of the water varies slowly with temperature near that of maximum density, the chlorinity of the bottom water must be close to that which is sufficient to prevent overturn. Knudsen's Tables (1901), while not suitable for determining actual density values for low chlorinities, will give satisfactory results for the density difference between surface and bottom waters; therefore they can be used to estimate the maximum allowable chlorinity of the bottom waters. From the above chlorinity and temperature values, we find that overturn occurred between top to bottom density differences of 1.3×10^{-4} and 0.7×10^{-4} g cm^{-3}. If we assume that overturn occurs at a density difference of 1.0×10^{-4} g cm^{-3}, and if we consider a minimum surface temperature of 6° C while that at the bottom remains at 10° C, then the maximum bottom chlorinity for overturn would be 0.28 ‰. We can set a definite upper limit for the density difference at 1.3×10^{-4} g cm^{-3}, which then allows a bottom chlorinity of 0.30 ‰. Of course, at lower values of bottom chlorinity, a mild or less stormy winter might fail to cause overturn. The problem of salt water intrusion into Lake Washington is thus critical with regard to the annual flushing process of the lake.

Since the total chloride content of the lake showed an increase each year during this survey, it is possible that problems of salt water contamination might arise regardless of overturn. To investigate this phase of the problem, the annual salt budget for the lake is given. Since the salt content of the entire lake is determined from measurements at only one station, some error is inevitable. However, there are two times of the year when observation should give a fairly high degree of accuracy: first, in December or January when the water has become homogeneous due to overturn and wind mixing and before much water has been discharged; second, in July after wastage of water has ceased and thermal stratification has set in. Since the major flushing action occurs between December and July when there is no salt inflow, a comparison of total chloride content should give a reasonable approximation for the total flushing of the lake; Table I gives the total chloride content and the percent flushing from winter to summer for the years 1951–1953. The flushing, about 20% for the winter-to-summer period each year, is apparently unrelated to the total salt content. An independent check on this value can be made if it is assumed that the salt removal is accomplished by the outflow of surface

TABLE I. LAKE WASHINGTON TOTAL CHLORIDE CONTENT AND PERCENT FLUSHING

	Cl *1000 tons*	*winter-summer*
27 December 1950	88	17
24 July 1951	73	
19 December 1951	102	20
18 July 1952	81	
28 January 1953	230	20
15 July 1953	183	

TABLE II. LAKE WASHINGTON FLUSHING BASED ON SURFACE OUTFLOW

1953	10^6 m^3	*1000 tons Cl*
January	158	12.8
February	167	13.1
March	76	4.0
April	79	4.5
May	82	4.9
June	62	3.7
July	31	1.8

water through the Montlake Canal. Table II gives the monthly outflow and flushing for the first seven months of 1953, the figures being based on the mean monthly chlorinity of the upper 15 m. These values are also plotted as a dashed line in Fig. 6 for 7 January, when it is assumed that salt intrusion ceased, through 28 January 1953 (230,000 tons). The curve based on data from station 18 approaches the computed curve in July and finally meets it in November after salt intrusion has taken place. Since the two curves join in January and then approach each other closely in July, the salt flushing can be explained by the surface runoff, hence the flushing over a twelve-month period can be determined on this basis. Thus the total chloride flushed out of the system (approximately 57,000 tons) is computed to be 24% of the maximum chloride content (240,000 tons) at the beginning of the year. This is a reasonable figure when it is considered that the annual flow through the lock system is approximately 30% of the lake volume.

An expression for the maximum salt content of the lake during any one year can be written in terms of the salt content during some initial year and the inflow for each intervening year. If we use a figure of 25% for the annual flushings, we obtain

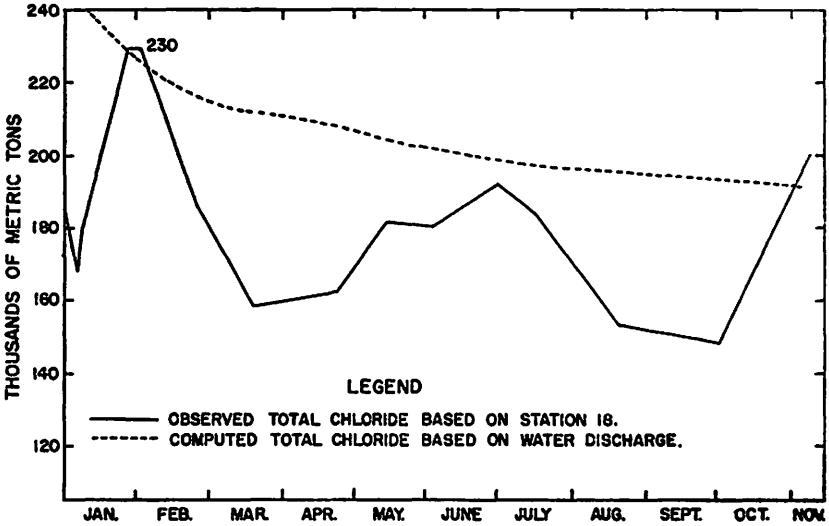


Figure 6. Total chloride (metric tons) in Lake Washington (Station 18), 1953

$$C_i = (0.75)^i C_0 + \sum_{j=0}^{i-1} (0.75)^j B_{i-j},$$

where C_i is the maximum content at the end of the ith year, C_0 is the initial content, and B_j is the inflow during the jth year.

This relation can be used to illustrate the extent of the present rate of salt inflow into the lake. For example, if we consider a 150,000-ton annual rate of inflow, as in 1952, then the equilibrium content will be 600,000 tons or more than 2½ times that which actually occurred in 1952. Or, if a maximum content of 230,000 tons is used, then the annual inflow will be restricted to 57,500 tons. Now, if the content were to reach 400,000 tons and if the annual inflow were to drop to 50,000 tons per year, the content after four years would be decreased only to 263,000 tons. Thus it is evident that one bad year requires four or five years of less inflow to bring the content back down to its original level.

REFERENCES

KNUDSEN, MARTIN
1901. Hydrographical tables. G. E. C. Gad, Copenhagen, Denmark. 63 pp.
SCHEFFER, V. B. AND R. J. ROBINSON
1939. A limnological study of Lake Washington. Ecol. Monogr., *9:* 95–143.
SMITH, E. V. AND T. G. THOMPSON
1927. Salinity of the Lake Washington Ship Canal. Bull. Engng. Exp. Sta., Seattle, No. 41. 104 pp.

Department of Oceanography
University of Washington

UNCLASSIFIED TECHNICAL REPORT DISTRIBUTION LIST

4 Chief of Naval Research
Department of Navy
Washington 25, D. C.
Attention: Code 466 (1)
446 (1)
416 (2)

6 Director, Naval Research Laboratory
Washington 25, D. C.
Attention: Technical Information Officer

1 Office of Naval Research Branch Office
346 Broadway
New York 13, New York

1 Office of Naval Research Branch Office
Tenth Floor, John Crerar Library Building
86 East Randolph Street
Chicago 1, Illinois

1 Office of Naval Research Branch Office
1030 East Green Street
Pasadena 1, California

1 Office of Naval Research Branch Office
1000 Geary Street
San Francisco 9, California

1 Office of Naval Research Resident Representative
University of Washington
Seattle 5, Washington

3 Officer-in-Charge
Office of Naval Research
London Branch Office
Navy #100, Fleet Post Office
New York, New York

2 Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.
Attention: Code 847

1 Chief, Bureau of Yards and Docks
Department of the Navy
Washington 25, D. C.

1 Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attention: Op-533D

1 Chief Scientist
U. S. Navy SOFAR Station
APO 856, c/o Postmaster
New York, New York

1 Commanding Officer, Naval Ordnance Laboratory, White Oak
Silver Spring 19, Maryland

1 Department of Aerology
U. S. Naval Post Graduate School
Monterey, California

2 Director, U. S. Navy Electronics Laboratory
San Diego 52, California
Attention: Codes 2240, 2242

8 Hydrographer
U. S. Navy Hydrographic Office
Washington 25, D. C.
Attention: Division of Oceanography

1 Project Arowa
U. S. Naval Air Station
Building R-48
Norfolk, Virginia

2 Project Officer
Laboratory of Oceanography
Woods Hole, Massachusetts

5 Armed Services Technical Information Center
Documents Service Center
Knott Building
Dayton 2, Ohio

1 Assistant Secretary of Defense
(Research and Development)
Pentagon Building
Washington 25, D. C.
Attention: Committee on Geophysics and Geography

20 October 1954

1 Chief, Bureau of Aeronautics
Washington 25, D. C.
Attention: Code MA-S

1 Commandant (OAO)
U. S. Coast Guard
Department of the Treasury
Washington 25, D. C.

1 Commanding General
Research and Development Division
Department of the Air Force
Washington 25, D. C.

1 Commanding General
Research and Development Division
Department of the Army
Washington 25, D. C.

1 Commanding Officer
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts
Attention: CRHSL

1 Director, U. S. Coast & Geodetic
Survey
Department of Commerce
Washington 25, D. C.

2 Director, U. S. Fish & Wildlife Service
Department of the Interior
Washington 25, D. C.
Attention: Dr. L. A. Walford

1 Dr. F. Møller, Norwegian Defense
Research Institute
Akershus, Oslo, Norway

1 National Research Council
2101 Constitution Avenue
Washington 25, D. C.
Attention: Cimmittee on Undersea Warfare

1 Office of Technical Services
Department of Commerce
Washington 25, D. C.

1 Pacific Oceanographic Group
c/o Pacific Biological Station
Nanaimo, British Columbia, Canada

1 South Pacific Fishery Investigations
U. S. Fish & Wildlife Service
P. O. Box 271
La Jolla, California

1 U. S. Army Beach Erosion Board
5201 Little Falls Road N.W.
Washington 16, D. C.

1 U. S. Fish & Wildlife Service
Fort Crockett
Galveston, Texas

1 U. S. Fish & Wildlife Service
P. O. Box 3830
Honolulu, T. H.

1 U. S. Fish & Wildlife Service
Woods Hole, Massachusetts

1 Allen Hancock Foundation
University of Southern California
Los Angeles 7, California

1 Bingham Oceanographic Foundation
Yale University
New Haven, Connecticut

1 Department of Conservation
Cornell University
Ithaca, New York
Attention: Dr. J. C. Ayers

1 Department of Engineering
University of California
Berkeley, California

1 Department of Meteorology &
Oceanography
College of Engineering
New York University
University Heights, New York 53, N.Y.
Attention: Dr. W. J. Pierson

1 Department of Zoology
Rutgers University
New Brunswick, New Jersey
Attention: Dr. H. K. Haskins

1 Director, Bermuda Biological Station
for Research
St. George's, Bermuda

1 Director, Chesapeake Bay Institute
Box 426A, R.F.D. #2
Annapolis, Maryland

1 Director, Hawaii Marine Laboratory
University of Hawaii
Honolulu, T. H.

1 Director, Lamont Geological
Observatory
Torrey Cliff
Palisades, New York

1 Director, Marine Laboratory
University of Miami
Coral Gables, Florida

1 Director, Narragansett Marine
Laboratory
University of Rhode Island
Kingston, Rhode Island

1 Director, National Institute of
Oceanography
Wormley, Near Godalming
Surrey, England

2 Director, Scripps Institution of
Oceanography
La Jolla, California

2 Director, Woods Hole Oceanographic
Institution
Woods Hole, Massachusetts

1 Head, Department of Oceanography
Texas A & M College
College Station, Texas

1 Institute of Oceanography
University of British Columbia
Vancouver, British Columbia, Canada

~~1 The Oceanographic Institute~~
Florida State University
Tallahassee, Florida

1 DR. WAYNE V. BURT

OREGON STATE COLLEGE

CORVALLIS, OREGON