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SYNTHESIS OF CURRENT MEASUREMENTS IN PUGET SOUND, WASHINGTON - VOLUME 1: INDEX TO CURRENT MEASUREMENTS MADE IN PUGET SOUND FROM 1908-1980, WITH DAILY AND RECORD AVERAGES FOR SELECTED MEASUREMENTS

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ABBREVIATIONS

C	--	Celsius
cm	--	centimeter
db	--	decibar
ENDECO	--	Environmental Devices Corporation
m	--	meter
MESA	--	Marine Ecosystems Analysis
mho	--	unit of conductance equal to the reciprocal of the standard measure of resistance, the ohm
NOAA	--	National Oceanic and Atmospheric Administration
NOIC	--	National Oceanographic Instrumentation Center
NOS	--	National Ocean Survey
o	--	degrees
OMPA	--	Office of Marine Pollution Assessment
PMEL	--	Pacific Marine Environmental Laboratory
PST	--	Pacific Standard Time
s	--	seconds
USACE	--	U.S. Army Corps of Engineers
USCGS	--	U.S. Coast and Geodetic Survey
UW	--	University of Washington

PREFACE

Puget Sound is an estuary in northwestern Washington consisting of three branches joined near their mouths to an entrance sill zone. In turn, this zone connects to the Pacific Ocean via the Strait of Juan de Fuca. The branches consist largely of basins embraced by sill zones; the largest or Main Basin accounts for half of Puget Sound's volume and the other half occurs mostly in three secondary basins. The estuarine flow is strongly modified by vertical mixing of surface and deep water over the sills as the water moves between the basins. As a result, the major portion of the surface flow is mixed downward and returned inland before exiting Puget Sound. This downwelling has raised concerns that primary fractions of municipal and industrial wastes are also refluxed inland and may be retained in the fjord complex for considerable periods.

To describe the characteristics of the circulation in Puget Sound, a synthesis of historical measurements of currents, water properties, and meteorological conditions has been undertaken. The results of this project are presented in three volumes:

Volume 1. Index to current measurements made in Puget Sound from 1908-1980, with daily and record averages for selected measurements.

Volume 2. Indices of mass and energy inputs into Puget Sound: runoff, air temperature, wind, and sea level.

Volume 3. Circulation in Puget Sound: an interpretation based on historical records of currents.

This volume (Volume 1) is an index to approximately 54 recorded years of current measurements which are available to the public; it supersedes a preliminary index (Cox et al., 1981), and includes all measurements known to the authors as of September, 1981.

Between 1908-1980, currents were measured at 340 sites in Puget Sound using 22 types of equipment. These measurements were collected by seven organizations: the 1) National Ocean Survey; 2) Pacific Marine Environmental Laboratory; 3) University of Washington; 4) CH_2M Hill Corporation; 5) U.S. Army Corps of Engineers; 6) URS Company; and 7) Crown-Zellerbach Corporation.

Included in this volume are: 1) references to original data sources; 2) maps showing locations of the measurements; 3) tables containing the date, depth, and length of each set of current measurements; and 4) averages over complete records and tidal days of current speed, direction, and when available, water temperature, salinity, and density.

Volume 2 describes indices of the mass and energy inputs into Puget Sound which may influence the water properties and circulation in Puget Sound. Volume 3 contains an interpretation of the circulation based on data presented in Volumes 1 and 2.

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1. INTRODUCTION

1.1 PROJECT OVERVIEW

Puget Sound is an estuary located in northwestern Washington (Fig. 1.1). The population near Puget Sound numbers several million people and a variety of wastes are discharged into the estuary. The dilution and distribution of these wastes is in part controlled by a complex circulation of water in Puget Sound.

In a gross perspective the estuary consists of a central or main basin, three secondary basins, and an entrance sill zone which connects to the Pacific Ocean via the Strait of Juan de Fuca (Fig. 1.2). The central axis is a chain of sills and basins. The prominent features of this chain are a seaward sill zone (Admiralty Inlet), a central basin (Main Basin), a secondary sill zone, and a terminal basin (Southern Basin). Appended to the central axis near its mouth are two other basins. One of these (Hood Canal) has a sill at its mouth; the other (Whidbey Basin) lacks an entrance sill, but contains an outlet to the Strait of Juan de Fuca at its head.

The circulation in the Main Basin is in part controlled by vigorous tidal mixing in the embracing sill zones (Ebbesmeyer and Barnes, 1980). As a consequence some of the water initially moving seaward in the estuary's upper layer is carried to depth within these zones, where it is then returned to the estuary's lower layer moving inland. This partial recycling of surface waters through Puget Sound has increased the concern regarding the fate of wastes discharged into the estuary. A common belief was that most of these wastes were rapidly removed from Puget Sound within the outflow of the upper layer. The recent study by Ebbesmeyer and Barnes (1980) suggests that these wastes will accumulate in the water column to some presently unknown

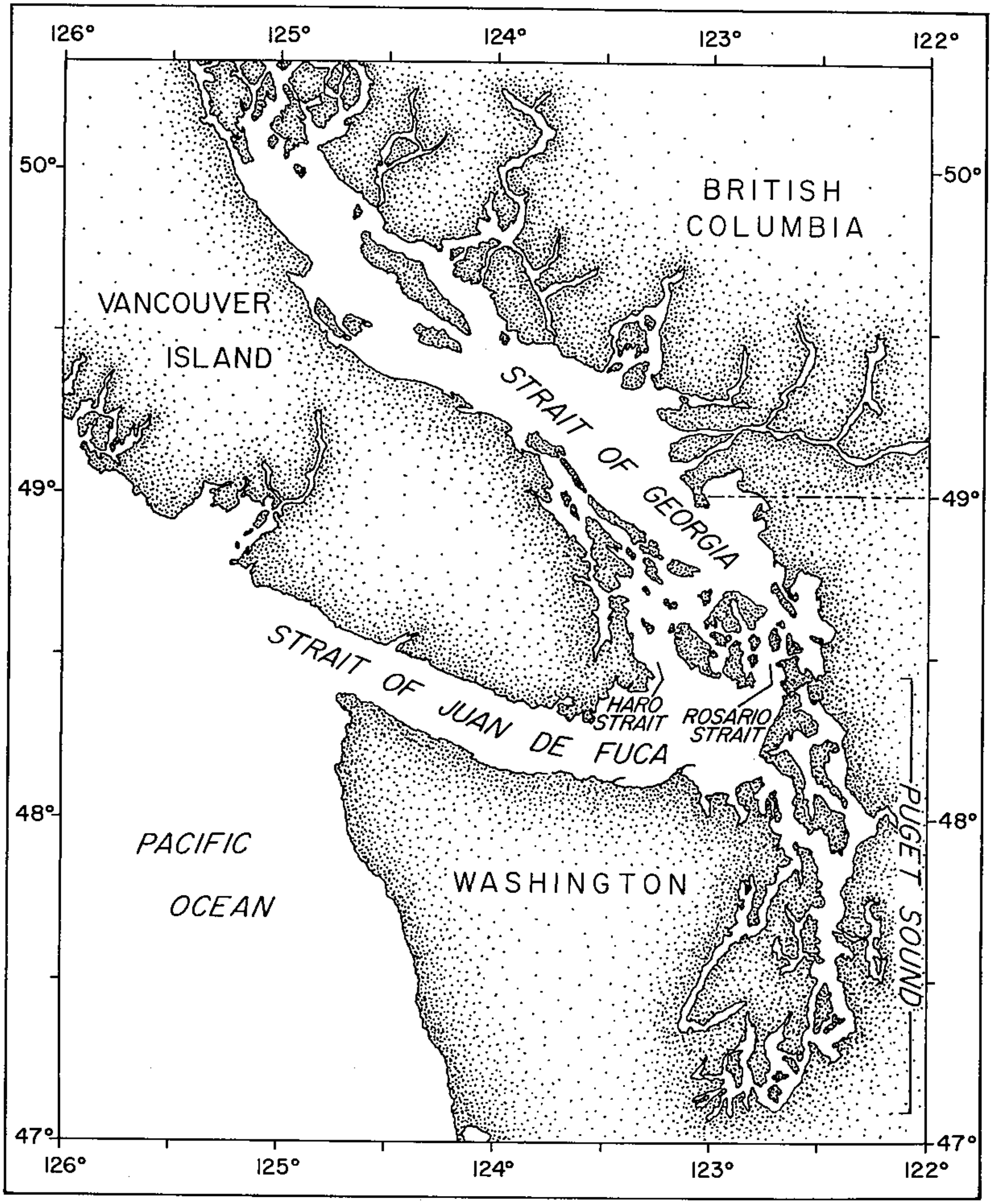

Figure 1.1. Inland marine waters of northwestern Washington and adjacent Canada.

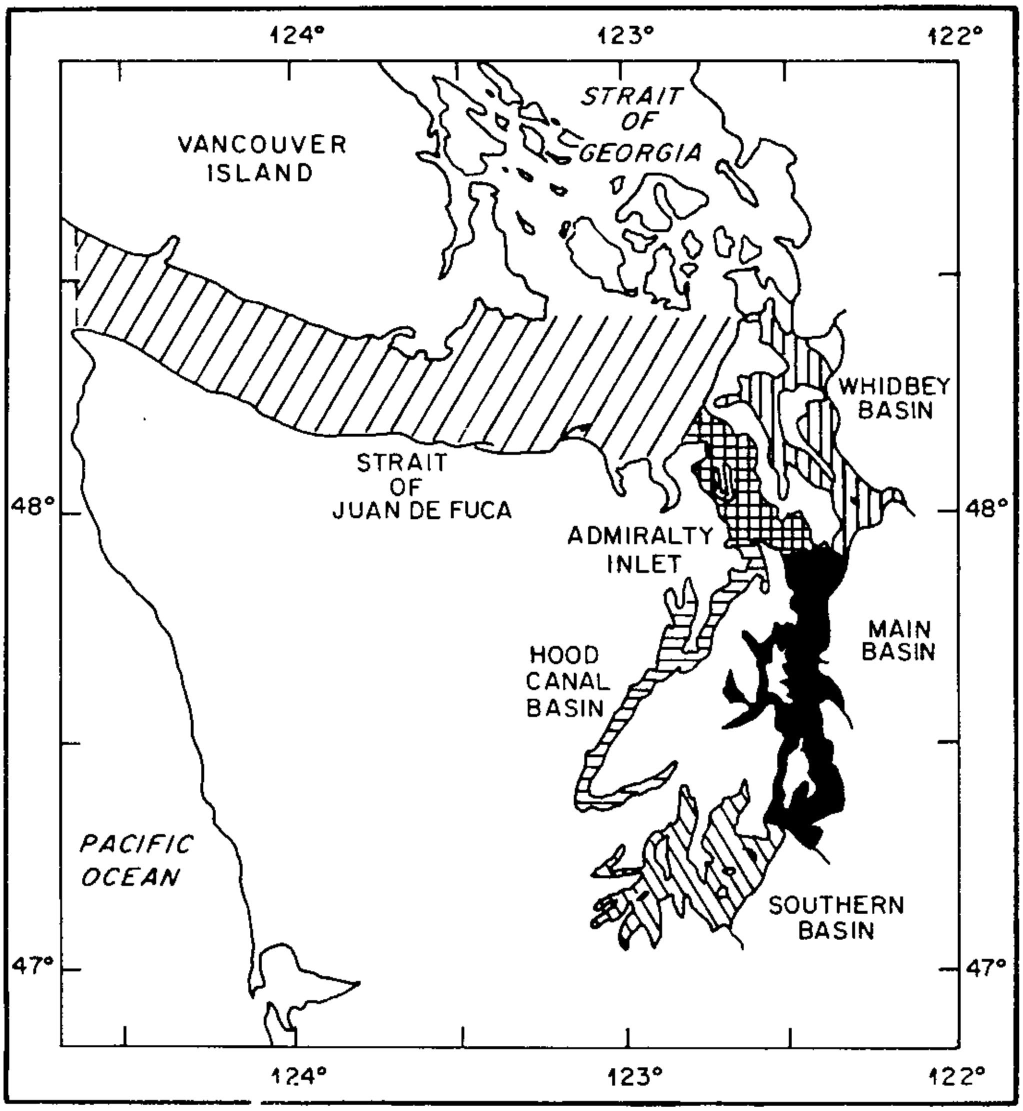

Figure 1.2. Puget Sound and approaches. The Sound consists of the Main Basin (darkened), three secondary basins (Whidbey Basin, Hood Canal Basin, and Southern Basin), and an entrance sill zone (cross-hatched) which are attached to the ocean via the Strait of Juan de Fuca.

background concentration depending upon the rate of their input to the estuary, and the rate of their removal by the combined effects of: escape to the Strait of Juan de Fuca; chemical and biological decomposition; and settling to the bottom.

To predict the background concentration of the wastes for particular rates of discharge, one needs to know the composition of the waste, its settling characteristics, and its biological and chemical removal rates. For some wastes these rates may be small compared to those associated with the physical removal of the waste from the estuary by circulatory features. Hence, an accurate estimate of the amount of surface water (and its waste content) recycled through the estuary is a primary concern.

For the Main Basin, a rough estimate of the recycled fraction is currently available; estimates for the secondary basins remain undetermined. Based upon hydrographic data taken from 1932-1975, Ebbesmeyer and Barnes (1980) estimated that approximately two-thirds of the surface water flowing seaward in Admiralty Inlet was mixed downward and returned landward within the Main Basin's lower layer.

To further describe this circulation, we have undertaken a synthesis of water property, current, and related measurements (runoff, air temperature, wind, and sea level) taken in and around Puget Sound. Observations of the water's physical characteristics (temperature, salinity, and nutrients) have been sampled at many locations and times since the 1930's. These data have been indexed by Collias (1970) and presented in atlas form by Collias, McGary and Barnes (1974). These data have also been combined and interpreted in order to deduce the quantities and patterns of water movement (Friebertshauser and Duxbury, 1972; Barnes and Ebbersmeyer, 1978; and Ebbesmeyer and Barnes, 1980). The full citations are given in the references in Volume 3.

Currents have been measured at various times and locations in Puget Sound since 1908, and although many observations were available, no systematic exploration of the various observations had been undertaken to complement the analysis of water properties. An analysis had not previously been performed because of the formidable amount of data, and because the data had been stored in various forms in scattered locations.

Specific objectives of the present synthesis are: 1) estimate the portion of surface water that is refluxed into Puget Sound; 2) examine the response of currents to inputs of mass and energy; and 3) describe seasonal variations of the circulation.

The data gathered for this project and the results of the synthesis have been organized into three volumes as follows:

Volume 1. Index to current measurements made in Puget Sound from 1908-1980, with daily and record averages computed for selected measurements.

Volume 2. Indices of mass and energy inputs into Puget Sound: runoff, air temperature, wind, and sea level.

Volume 3. Circulation in Puget Sound: an interpretation based on historical records of currents and water properties.

Volume 1 contains an index to current measurements made in Puget Sound from 1908-1980. Daily and record averages and standard deviations of net currents, and water properties where available, are presented for measurements spanning at least one tidal day (approximately 25 hours).

Volume 2 provides daily and monthly averages of runoff, air temperature, wind, and sea level.

Volume 3 describes selected aspects of Puget Sound's general circulation, but also examines the variability within the Main Basin.

This study was initiated by the Marine Ecosystems Analysis (MESA) Puget Sound Project within the Office of Marine Pollution Assessment (OMPA) of the National Oceanic and Atmospheric Administration (NOAA). The MESA Puget Sound Project was established to focus scientific research on environmental problems relating to Puget Sound. The primary objective of the Project is to document the occurrence and fluxes of contaminants of special concern, the dynamic processes influencing their physical and chemical transport and fate, and their biological and ecological effects.

1.2 VOLUME 1 OVERVIEW

This volume is an index to current measurements taken in Puget Sound and also includes record and daily averages of currents and water properties for selected records. Criteria applied to the selection of indexed measurements are as follows: 1) the measurements were taken primarily at fixed locations, i.e., floating instrumentation used over large distances were not used; and 2) the measurements are available to the public. Measurements meeting these criteria date from 1908-1980. The measurements were taken and contributed by seven organizations; twenty-two types of instrumentation were used to take the measurements. The combined total duration of the indexed measurements (i.e., assuming one instrument was used to take all measurements) equals approximately half a century.

To insure the completeness of the index, numerous contacts were made with individual investigators, private companies, public institutions, and government agencies, both state and federal. An extensive review of available literature was conducted and, where possible, original data were obtained for cited measurements. In addition, a preliminary version of this index (Cox et al., 1981) was published in which unlisted measurements were requested. The present index supersedes the preliminary version and references in addition all new or previously unlisted measurements that reached the authors by September 1981. Moreover, corrections have been made to previously listed measurements; locations of measurements have been renumbered; the index has been reorganized; and record and daily averages of current velocities and water properties have been added for selected measurements.

Within this Volume are provided: an estimate of the quality and quantity of the measurements; methods by which record and daily averages of the data were computed; and descriptions of the measurements and of instrumentation used to collect the measurements. Sources of the data are given in Appendix A; locations of the measurements are shown in Appendix B; pertinent information concerning each measurement is given in Appendix C; averages and standard deviations of complete records are provided in Appendix D; and averages and standard deviations of tidal days (24.84 hours) within each record are given in Appendix E.

2. QUALITY AND QUANTITY OF MEASUREMENTS

2.1 DATA QUALITY

Measurements have not been indexed when an investigator's log book or publication states that an instrument malfunctioned and no data were recovered. All other measurements have been indexed.

The quality of the indexed measurements varies. A few measurements contain data taken after a current meter lost its rotor, vane, or otherwise became inoperable. The questionable data within these records has been deleted so as not to affect the record and daily averages presented in Appendices D and E, respectively. A few additional measurements lack obvious sections of bad data, but have been described by original investigators as questionable in quality, yet probably useful if carefully edited. These measurements have been identified in Appendices C, D, and E.

The remaining indexed measurements are considered to be accurate given the limitations of the respective instruments. For certain instruments estimates of uncertainties have been developed from laboratory testing. Instrument errors which occur during fieldwork may be substantially higher. Moreover, sensor drift, calibration uncertainties, data processing, and human errors may combine to give total measurement uncertainties much greater than instrumentation errors determined under laboratory conditions (see Frey and Appell, 1981). However, the information necessary to estimate the total measurement uncertainty for each indexed measurement generally was not recorded in the field. Therefore, we were not able to estimate total measurement uncertainties. Instead, so as to give the reader some feeling for the quality of each measurement, we have provided brief descriptions of the contributors, instruments, and instrument uncertainties developed from laboratory tests.

Finally before computing record and daily averages, the measurements were screened for spurious data using criteria described in Section 3.

2.2 DATA QUANTITY

The indexed measurements were taken at 340 sites within five regions of Puget Sound (Fig. 2.1; Appendix B). Assuming one meter was used to take all the measurements, their combined length equals approximately 54 years. The total amount of data collected within each region is as follows: Whidbey Basin, 5.3 years at 47 sites; Admiralty Inlet, 9.2 years at 78 sites; Main Basin, 24.5 years at 101 sites; Hood Canal, 4.8 years at 31 sites; and Southern Basin, 10.1 years at 83 sites. The periods when observations were taken at each site are presented in Figure 2.2. Specific information concerning each measurement at each site is given in Appendix C.

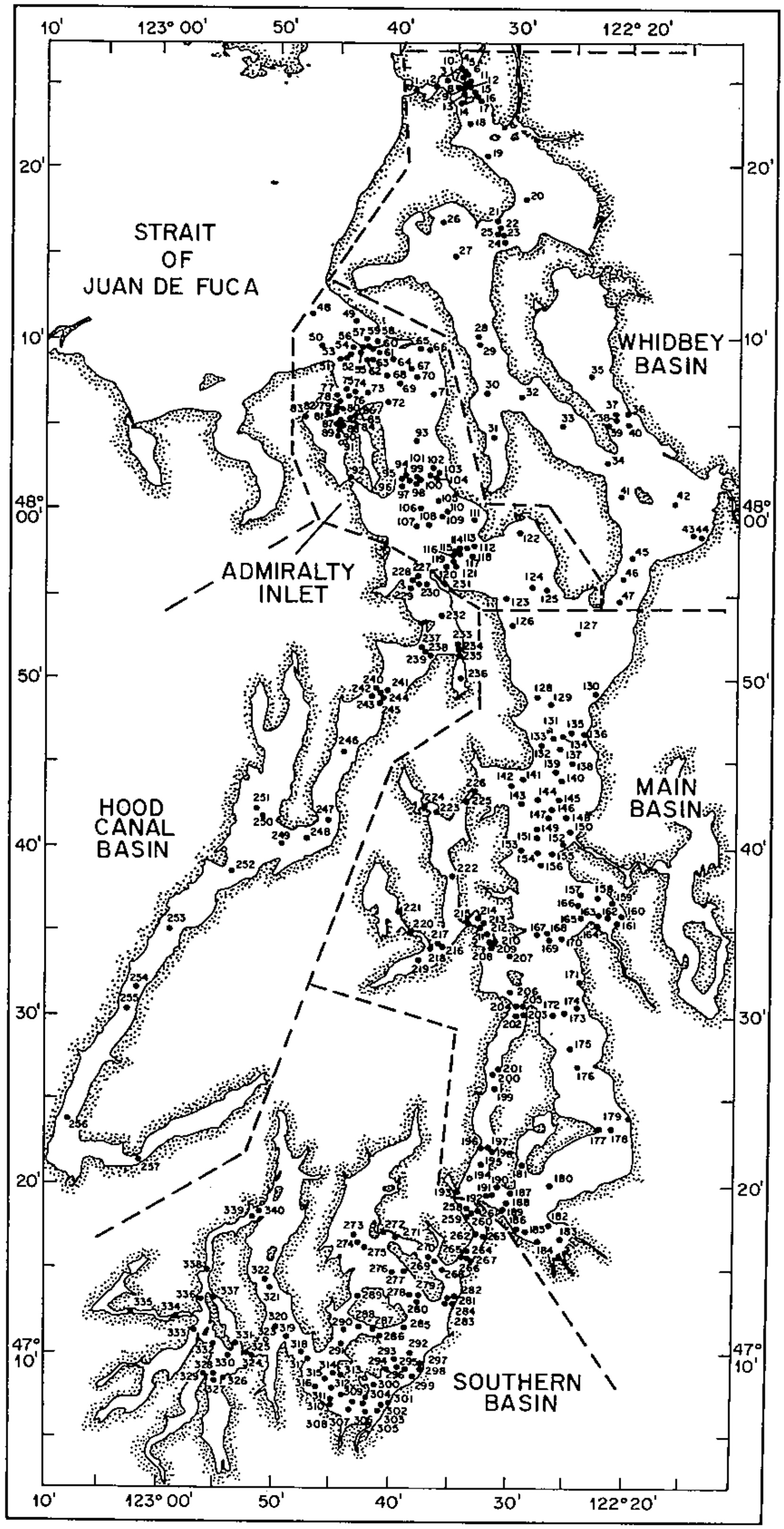

Figure 2.1. Sites of current measurements in Puget Sound. Dashed lines denote boundaries by which sites are also shown in Appendix B.

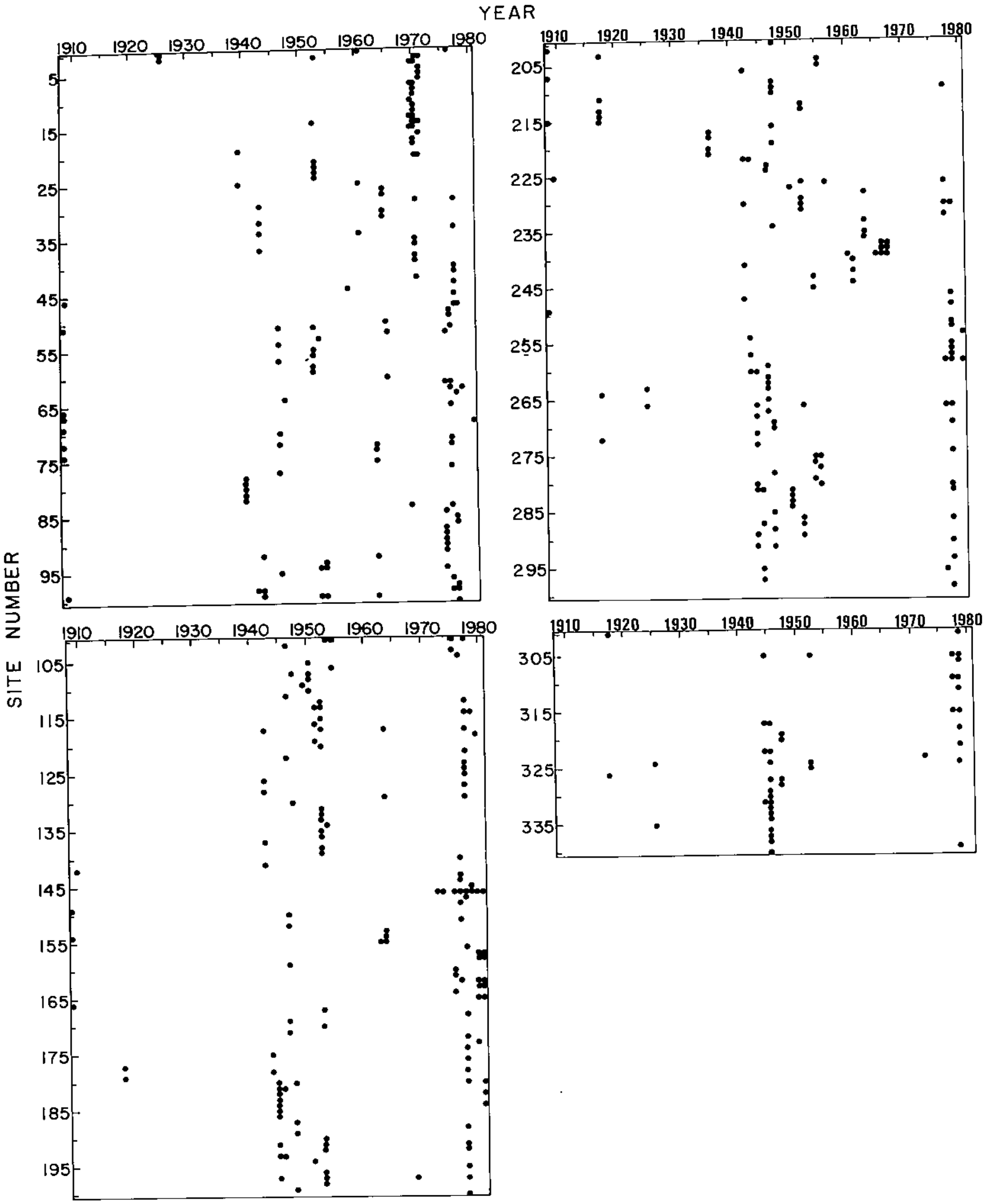

Figure 2.2. Intervals when current observations were made at each site in Puget Sound.

3. RECORD AND DAILY AVERAGES OF THE DATA

Record and daily averages of current and (if taken) water property data are provided for measurements which meet the following criteria: 1) we were able to obtain original data (i.e., averages computed and published by original investigators were not used); 2) both speed and direction were recorded; 3) the speed measurement was consistently above the threshold recording value of the instrument; and 4) the measurements lasted at least 1 tidal day (24.84 hours).

Inspection of these records revealed a number of obviously spurious data and gaps longer than one hour between data points, both of which we desired to eliminate. The following editing procedure was adopted to make these deletions. First, records were visually reviewed for obviously bad data (such as when a current meter rotor became inoperable). These data were removed from the records. Second, records were segmented into subrecords whenever gaps of one hour or greater between data points were found. Third, means and standard deviations of temperature, salinity, and the zonal and meridional components of current speed were computed for the maximum number of whole tidal days within a record or subrecord. Finally, points which lay beyond four standard deviations were deleted, and the means and standard deviations were recomputed for each record or subrecord. These values are presented in Appendix D with net current speed and direction given in place of the zonal and meridional components of current speed.

Means and standard deviations of temperature, salinity, and net current speed and direction were also computed for tidal days within each subrecord using data which passed the four-standard-deviation filter. Tidal days are centered about local noon of calendar days and overlap adjoining days by approximately one-half hour. Means and standard deviations for tidal days within each subrecord are given in Appendix E.

4. CONTRIBUTORS OF THE MEASUREMENTS

Three government agencies, one university, and three private companies have taken the measurements listed in this Volume. Table 4.1 summarizes the periods when intensive fieldwork was undertaken by each organization; the type of instrumentation that was used; the number of sites occupied; and the amount of data collected. The total amount of data obtained by each contributor is summarized by region in Table 4.2. Following are brief descriptions of the measurements taken by each organization.

4.1 NATIONAL OCEAN SURVEY

The National Ocean Survey (NOS) has periodically measured currents in Puget Sound since 1908 (see Table 4.1) for the purpose of annually predicting currents in the Tidal Current Tables (e.g., NOS, 1980). A total of 18 years of data, or 33% of the data indexed, has been collected by the NOS. This data was taken at 283 sites; some sites were occupied several times during different years. This is by far the largest number of sites occupied by any organization.

Generally measurements were taken at a few primary sites for thirty days or longer, and at secondary sites for three to five days. Samples were collected twice per hour. During their most recent measurements (1976-1978) the observational period at all sites was extended to fifteen days and six samples per hour were obtained.

A variety of equipment was used to take these measurements. From 1908-1940 measurements were made exclusively with captive drift poles and Price current meters. During 1942-1965 Roberts Radio current meters were used to take the majority of the NOS measurements, although captive drift poles and Price current meters were used to some extent. In 1960 a limited amount of data was also obtained using floats released over short distances. The use of this equipment is described in detail by the U.S. Coast and Geodetic Survey (USCGS; 1950a, 1961).

Current observations taken from 1908-1965 are presently available as graphs of current speed versus time. Current direction is handwritten in degrees beside each speed measurement. Reproductions of these graphs were obtained from the NOS and digitized on computer magnetic tape. Measurements taken from 1976-1978 were obtained using Aanderaa current meters. These measurements generally pass through three phases of processing before release to the public. This process has been described by Parker and Bruce (1980). The measurements were obtained on computer magnetic tape.

TABLE 4.1. PERIODS OF INTENSIVE CURRENT MEASUREMENTS IN PUGET SOUND.

Survey Period	Instrumentation	No. Sites Occupied	Days of Data Obtained
I. NATIONAL OCEAN SURVEY			
1908-1909	captive drift pole	18	111.0
1917	captive drift pole	11	55.7
1925	captive drift pole Price current meter	6	27.0
1936	captive drift pole	4	6.4
1939-1940	captive drift pole	2	17.6
	Price current meter	6	3.6
1942-1945	Roberts Radio current meter	58	403.1
1946-1947	captive drift pole Price current meter Roberts Radio current meter	47	261.7
1952	Roberts Radio current meter	40	574.4
1960	captive drift pole, floats, Price current meter	3	37.8
1961	Price current meter Roberts Radio current meter	3	27.5
1963-1965	Price current meter Roberts Radio current meter	21	187.6
1976-1978	Aanderaa current meter	64	4835.8
Total		283	6529.1
Years			17.9
Percentage of Total Measurements			33.1%
II. PACIFIC MARINE ENVIRONMENTAL LABORATORY			
1970-1971	Braincon current meter	8	565.1
1972	Braincon current meter Aanderaa current meter	1	137.8
1973	Aanderaa, Geodyne, and AMF Vector Averaging current meters	1	307.8
1975-1976	Aanderaa current meters	6	2797.2
1977-1978	Aanderaa current meters	15	2639.8
1979-1980	Aanderaa current meters	13	3467.0
Total		44	9914.7
Years			27.2
Percentage of Total Measurements			50.3%

TABLE 4.1 (continued).

Survey Period	Instrumentation	No. Sites Occupied	Days of Data Obtained
III. UNIVERSITY OF WASHINGTON			
1932-1948	unknown	unknown	Not available
1948-1955	captive drift pole, biplane, and Price, Ekman, Gemware, Magnesyn and Roberts current meters	34	198.1
1956	Lincoln current meter	1	0.3
1958	Price, Gemware, and Lincoln current meters	1	16.8
1960	Ekman current meter	1	unknown
1962	Price, Ekman-Mertz, Kelvin-Hughes, and Magnesyn current meters	1	50.8
1965-1967	Kelvin-Hughes, Hydro-Products, Magnesyn, Marine Advisors, Roberts Radio, and Braincon current meters	3	194.5
1968	Magnesyn current meter	1	4.8
1969-1971	Braincon and unknown current meters	18	375.3
1972	Hydro-Products, Magnesyn, and Sternberg current meters	1	19.0
1975	General Oceanics and Aanderaa current meters	3	21.0
1976	Aanderaa current meters	1	27.6
1977	Price, Magnesyn, and Aanderaa current meters	3	113.7
1979-1980	Aanderaa and Larsen current meters	1	215.0
Total		69	1236.9
Years			3.4
Percentage of Total Measurements			6.3%
IV. CH_2M HILL COMPANY			
1977-1978	Endeco Type 105 and 110 current meters	22	1984.1
Total			1984.1
Years			5.4
Percentage of Total Measurements			10.1%

TABLE 4.1 (continued).

Survey Period	Instrumentation	No. Sites Occupied	Days of Data Obtained
V. U.S. ARMY CORPS OF ENGINEERS			
1975	unknown	3	10.5
1976	Braincon and General Oceanics current meters	1	12.0
Total		4	22.5
Years			0.1
Percentage of Total Measurements			0.1%
VI. URS COMPANY			
1975	General Oceanics current meter	6	7.7
Total		6	7.7
Years			0.02
Percentage of Total Measurements			0.04%
VII. CROWN ZELLERBACH CORPORATION			
1969	Magnesyn current meter	1	0.9
1976	Magnesyn current meter	1	2.6
Total		2	3.5
Years			0.01
Percentage of Total Measurements			0.02%
Total for all Contributors		430*	19698.5
Years			54.0

*Some sites (as listed in Appendix C) were occupied by more than one contributor, and sometimes several times by each contributor.

TABLE 4.2. QUANTITY OF DATA (DAYS) OBTAINED BY EACH CONTRIBUTOR WITHIN FIVE REGIONS OF PUGET SOUND.

Contributor	REGION Whidbey Basin	Admiralty Inlet	Main Basin	Hood Canal	Southern Basin	Total by Contributor Days	Years	%
NOS	961.5	1746.2	1431.7	1093.1	1296.6	6529.1	17.9	33.1
PMEL	565.1	1476.0	7056.6	434.0	383.0	9914.7	27.2	50.3
UW	392.1	140.2	444.5	223.5	36.6	1236.9	3.4	6.3
USACE	0	0	22.5	0	0	22.5	0.1	0.1
CH_2M Hill	0	0	0	0	1984.1	1984.1	5.4	10.1
URS	0	7.7	0	0	0	7.7	0.02	0.04
Crown Zellerbach	0	3.5	0	0	0	3.5	0.01	0.02
Total by								
Days	1918.7	3373.6	8955.3	1750.6	3700.3	19698.5		
Years	5.3	9.2	24.5	4.8	10.1		54.0	
%	9.7	17.1	45.5	8.9	18.8			100.

In some instances data that are considered of questionable quality due to accuracy or timing problems were not completely processed by the NOS; however, these data are available to the public with the understanding that deficiencies occur which must be checked and corrected. While we have not provided averages for these data in Appendices D and E, they have been included in the index in Appendix C.

4.2 PACIFIC MARINE ENVIRONMENTAL LABORATORY

The Pacific Marine Environmental Laboratory (PMEL) was formed in the early 1970's. Since that time it has conducted several major current surveys. These measurements have been taken primarily in an effort to describe the estuarine circulation of Puget Sound. Measurements generally spanned a month or more and were taken at several (up to eight) depths simultaneously. Three, four, or six samples were collected per hour. A total of approximately 27 years of data were obtained by PMEL, or 50% of the data indexed. These data were taken at a total of 44 sites.

Four types of moored, internally recording current meters were used to collect these measurements. Measurements taken during 1970-1971, and some data taken in 1972, were obtained using Braincon current meters. Aanderaa current meters were used to take measurements from 1972-1980. During 1973, Geodyne and AMF Vector Averaging meters were also used. All these measurements were obtained from PMEL on computer magnetic tape.

4.3 UNIVERSITY OF WASHINGTON

The University of Washington (UW) began taking measurements in Puget Sound in 1932. Until 1948 these measurements were primarily exploratory and lasted only a few hours. These data apparently were not published and are not presently available to the public.

From 1948 through 1980 various investigators from the UW have conducted several current measurement programs from which a total of approximately three years of data have been taken at a total of 69 sites. Sampling intervals have ranged from once every few hours to six samples per hour. These measurements amount to 6% of the data indexed.

Seventeen types of instrumentation have been used to obtain the UW measurements. These data were obtained in either tabular form as printed in technical reports, as punched computer cards, or in the case of Aanderaa instrumentation, on computer magnetic tape.

4.4 CH_2M HILL COMPANY

The CH_2M Hill Company obtained approximately five years of data at 22 sites using Endeco Type 105 and 110 current meters. Data taken with the Endeco Type 105 meter were obtained on computer magnetic tape; data taken with the Endeco Type 110 meter are available in graphical form, but were not obtained. The Endeco Type 105 meter collected four samples per hour. The sampling interval of data collected with Endeco Type 110 meter is unknown.

4.5 U.S. ARMY CORPS OF ENGINEERS

Investigators working for the U.S. Army Corps of Engineers (USACE) have obtained approximately 23 days of data at four sites. Ten and one-half days of this data were taken with an unknown type of instrumentation. Braincon and General Oceanics current meters were used to obtain 12 days of measurements. The Braincon current meter sampled three times per hour; the General Oceanics current meter sampled eight times per hour. The data were obtained in tabular form.

4.6 URS COMPANY

The URS Company has obtained approximately eight days of data at six sites using General Oceanics current meters. Approximately ten samples per hour were collected. The data were obtained in tabular form.

4.7 CROWN ZELLERBACH CORPORATION

The Crown Zellerbach Corporation has obtained approximately four days of data at two sites using a Magnesyn current meter. Two samples per hour were collected. The data were obtained in tabular form.

5. INSTRUMENTATION

Twenty-two types of instrumentation have been used to measure currents in Puget Sound. They consist of two types of drifting apparatus, ten types of instrumentation lowered over-the-side from anchored platforms, seven types of current meters suspended from moored buoys, and three types of current meters mounted on tripods set on the bottom. Each type of instrumentation is listed in Table 5.1. The amount of data taken with each instrument is summarized in Table 5.2.

Brief descriptions of the instruments are provided below along with references to more detailed information. Specifications listed are those developed from laboratory tests and published in data reports, National Oceanographic Instrumentation Center (NOIC) Instrument Fact Sheets, or instrument manuals provided by manufacturers.

5.1 DRIFTING APPARATUS

Observations taken with two types of drifting apparatus have been included in this index because the observations were taken in such a manner as to be representative of nearly one location.

5.1.1 Captive Drift Pole

The captive drift pole was the standard instrument used to obtain current measurements near the water surface at a single location prior to the development of reliable current meters. Later the drift pole was used simultaneously with current meters lowered to depth.

The drift pole consists of a wooden pole measuring approximately 0.08 m in diameter and 4.5 m in length. It is weighted so as to float upright with approximately 0.3 m protruding above the water surface (USCGS, 1950a). In use, the pole is released near an anchored vessel and the distance and direction it drifts in one minute is measured. The distance is recorded by a line attached to the drift pole (referred to as a log line) that is graduated such that the length of line carried away from the vessel in one minute equals the current speed expressed in knots. Current direction is determined from the angle of the log line with respect to the vessel's compass. The pole is normally retrieved and redeployed at half-hour intervals. Assuming a 5 knot current, which is about the maximum encountered in Puget Sound, the measurements are representative over a distance of at most 150 m.

No estimates of accuracy were located.

TABLE 5.1. INSTRUMENTS USED TO MEASURE CURRENTS IN PUGET SOUND.

Code*	Instrument	Instrument Type
1.	Captive drift pole	Drifting Apparatus
2.	Captive float	
3.	Biplane	Instrumentation lowered over-the-side from anchored platforms
4.	Price current meter	
5.	Ekman current meter	
6.	Ekman-Mertz current meter	
7.	Gemware current meter	
8.	Kelvin-Hughes current meter	
9.	Hydro Products current meter	
10.	Magnesyn current meter	
11.	Marine Advisors current meter	
12.	Endeco Type 110 current meter	
13.	Roberts Radio current meter	Instrumentation suspended on moored buoys
14.	Braincon current meter	
15.	General Oceanics current meter	
16.	Geodyne current meter	
17.	Aanderaa current meter	
18.	AMF Vector Averaging current meter	
19.	Endeco Type 105 current meter	
20.	Lincoln Pressure Plate current meter	Instrumentation mounted on Tripods placed on the bottom
21.	Sternberg current meter	
22.	Larsen current meter	

*Instrument code used in Appendix C.

TABLE 5.2. QUANTITY OF DATA (DAYS) OBTAINED USING EACH TYPE OF INSTRUMENT WITHIN FIVE REGIONS OF PUGET SOUND.

Instrument Code (see Table 4.1)	SUBREGION Whidbey Basin	Admiralty Inlet	Main Basin	Hood Canal	Southern Basin	Total Each Instrument Days	Total Each Instrument Years	% Total
1	22.1	65.8	110.0	3.0	20.7	22.1	0.6	1.1
2	7.2	0	0	0	0	7.2	0.02	-
3	0	9.2	0	0	2.9	12.1	0.03	0.1
4	48.5	41.0	41.5	10.8	38.4	180.2	0.5	0.9
5	0	46.1	22.6	12.1	0	80.8	0.2	0.4
6	0	0	3.6	0	0	3.6	0.01	-
7	12.6	46.7	6.2	10.5	0	76.0	0.2	0.4
8	0	0	30.7	1.2	0	31.9	0.1	0.2
9	0	0	0	1.2	12.0	13.2	0.04	0.1
10	0	4.3	19.3	1.2	6.3	31.1	0.1	0.2
11	0	0	0	162.0	0	162.0	0.4	0.8
12	0	0	0	0	0	*	-	-
13	160.1	373.7	310.2	115.5	390.4	1349.9	3.7	6.8
14	929.2	0	78.7	0	0	1007.9	2.8	5.1
15	0	14.7	9.0	0	0	23.7	0.1	0.1
16	0	0	79.1	0	0	79.1	0.2	0.4
17	726.8	2772.1	8169.5	1404.2	1241.6	14,314.2	39.2	72.6
18	0	0	37.1	0	0	37.1	0.1	0.2
19	0	0	0	0	1984.1	1984.1	5.4	10.1
20	1.0	0	0.3	0	0	1.3	-	-
21	0	0	0	0	3.9	3.9	0.01	-
22	0	0	27.0	0	0	27.0	0.1	0.1
*	11.2	0	10.5	28.9				
Total by subregion								
Days	1918.7	3373.6	8955.3	1750.6	3700.3	19,698.5		
Years	5.3	9.2	24.5	4.8	10.1		54.0	
%	9.7	17.1	45.5	8.9	18.8			100.

*Unknown

5.1.2 Captive Float

In channels where currents precluded anchoring a ship, a float was used in place of a drift pole. Each float consists of two horizontal, perpendicular wooden poles attached at their intersection to a vertical pole, where each member measured approximately 0.05 m in diameter and 0.5 - 1.0 m in length (USCGS, 1950a). Current speed is determined by timing the passage of the float between two lines of sight set onshore a known distance apart (approximately 400 m) and perpendicular to the channel as shown in Figure 5.1. Current direction is normally noted as in or out channel, or if the channel is sufficiently straight, the direction may be given in degrees. The float was normally captured at the downstream line of sight and redeployed upstream at half-hour intervals.

No estimates of accuracy were located.

5.2 INSTRUMENTS LOWERED OVER-THE-SIDE FROM ANCHORED PLATFORMS

Described are instruments that are generally lowered on electrical or hydrographic cables from surface platforms.

5.2.1 Biplane

A biplane, or current cross, was used to make a few measurements at 30 m depth during 1954 and 1955 (Paquette and Barnes, 1955). The instrument consists of two perpendicular planes (0.9 x 1.2 m) of paraffin-coated plywood which are weighted at the bottom and lowered at the end of a cable. By theory and calibration, the angle which the supporting wire is deflected from vertical is proportional to the current speed. Current direction is estimated by the direction in which the wire is deflected.

Wire angles were measured with a precision inclinometer accurate to 0.5^{o} (Paquette and Barnes, 1955); this represents an uncertainty in speed of approximately 3 cm s^{-1} above a threshold of 4 cm s^{-1}. Directional accuracy was estimated as $\pm 15^{o}$ at wire angles greater than 0.5^{o}, and about $\pm 30^{o}$ at wire angles less than 0.5^{o}.

5.2.2 Price Current Meter

Price current meters were first used in Puget Sound in 1925. The meter was designed by W.G. Price, an engineer with the USACE. The Price current meter senses current speed but not direction and is normally lowered from an anchored vessel by a conducting cable attached to a heavy weight (USCGS, 1950a; Fig. 5.2). Speed is measured using a set of rotating cups attached to a vane which orients the cups upstream into the current. The rotation of the cups creates electrical pulses which are recorded by an observer using earphones or by an automatic recording device described by Liddy (1932) The speed of the current is calculated by comparing with calibration tables the number of electrical pulses generated during a selected interval.

No estimates of accuracy were obtained.

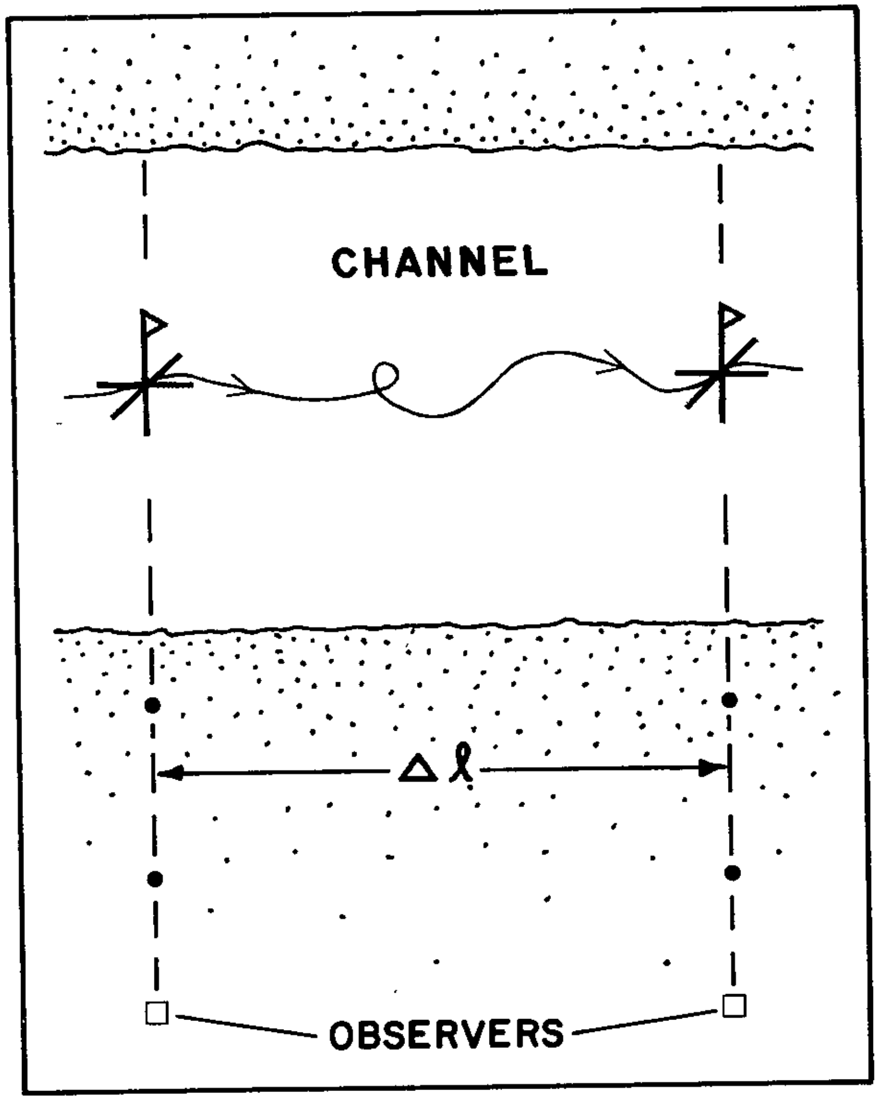

Figure 5.1. Current speed determined by timing the passage of a float (triangle) between two parallel lines of site (dashed lines) set onshore a known distance apart and oriented perpendicular to a channel. Each line of sight is established by two markers (dots) along which observers note the passage of the float.

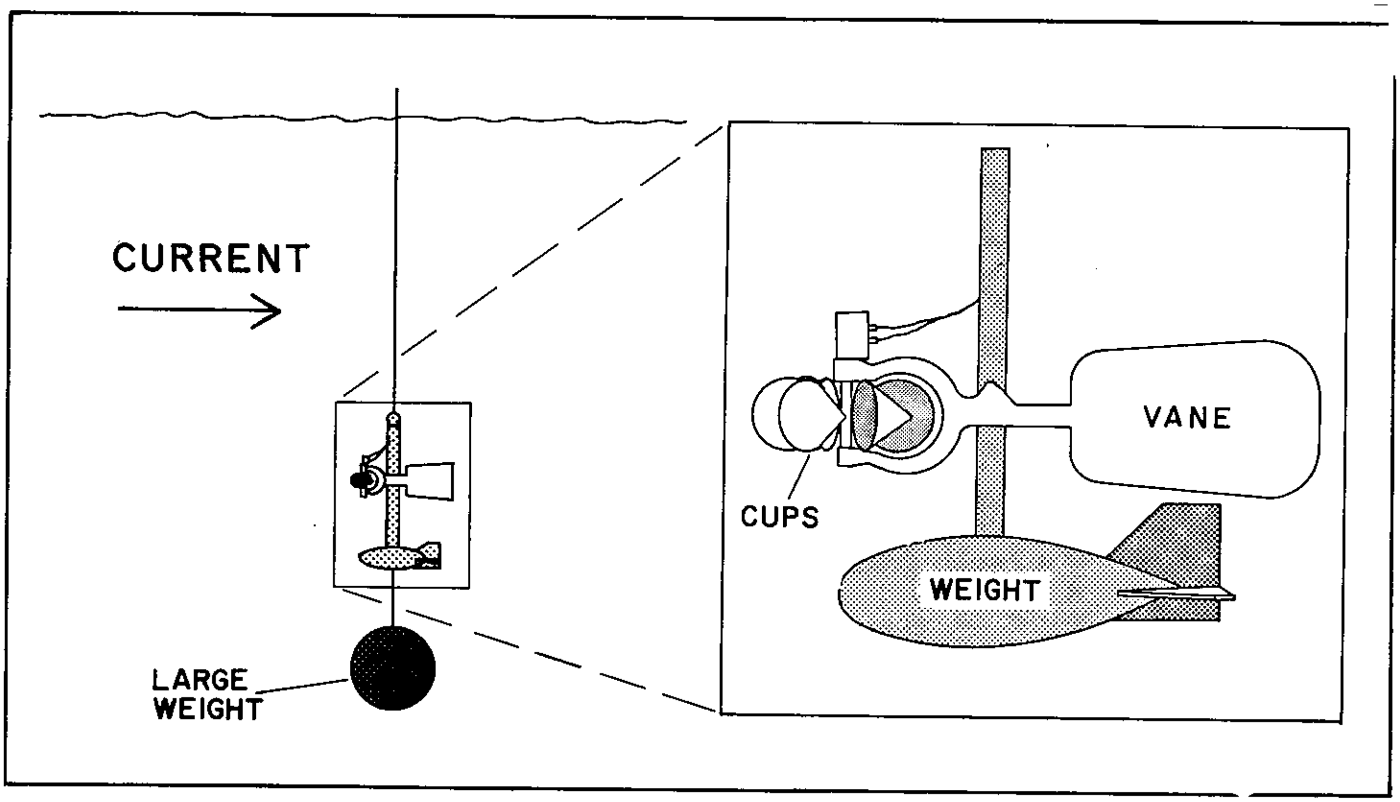

Figure 5.2. Deployment of a Price current meter. Inset shows profile view of meter.

5.2.3 Ekman Current Meter

The first mechanical current meter to be used in Puget Sound was developed by V.W. Ekman (1932). The meter measures both speed and direction but must be returned to the surface in order to record each measurement. Speed is determined from the number of revolutions made by a propeller during a given interval of time; this number is registered by dials mounted on the instrument. Direction is sensed by an internal compass. For every thirty-three revolutions a lead shot is released and oriented by the compass towards magnetic north. The shot drops into one of thirty-six compartments (each representing ten degrees of direction) which are oriented by the vane. As the meter is generally suspended on a hydrographic wire, messengers are used to control the start and completion of each measurement.

The meter, as originally designed and tested, records current speeds between 2 - 80 cm s^{-1} with an accuracy of 0.5 cm s^{-1}; directional accuracy was not given (Ekman, 1932). Estimates of accuracy by more recent users were not located.

5.2.4 Ekman-Mertz Current Meter

The Ekman-Mertz current meter is a modified version of the Ekman current meter and is operated in a similar fashion (Collias, 1963). Differences in accuracy between the Ekman and Ekman-Mertz current meters were not found.

5.2.5 Gemware Current Meter

The Gemware current meter is similar to the Ekman current meter with the advantage that several can be used concurrently on a single hydrographic wire (Kahl Scientific Instrument Corporation, undated). Details concerning accuracy were not found, but it is believed to be approximately the same as for the Ekman current meter.

5.2.6 Kelvin-Hughes Current Meter

The Kelvin-Hughes current meter is a modified version of the Roberts Radio current meter described later in section 5.3.1. Normally the Roberts Radio current meter is suspended below a moored buoy and current measurements are transmitted as electrical pulses to a nearby observer aboard a ship. In contrast the Kelvin-Hughes meter is used over-the-side from an anchored ship (Collias, 1963). Current velocity is read directly on a deck unit as direction and speed.

The accuracy of the meter as used in Puget Sound is unknown, but is believed to be comparable to that of the Roberts Radio current meter.

5.2.7 Hydro Products Current Meter

The Hydro Products Model 451 current meter was one of the first used in Puget Sound to measure current speed with a Savonius rotor. Speed is determined by the number of closures per unit of time of a reed switch which is magnetically activated by the Savonius rotor. Direction is sensed by a small vane (0.1 x 0.1 m) which is compared to an internal magnetic compass using a potentiometer. The measurements are telemetered via cable to voltage meters aboard ship and are recorded either manually from a deck or automatically on a strip chart.

The meter is capable of measuring speeds between 3 - 360 cm s^{-1}. Two speed scales (0 - 51 cm s^{-1}; 0 - 360 cm s^{-1}) are provided for increased resolution. The accuracy of the speed is approximately ± 3% of full scale (M. Keeham of Hydro Products, Inc., personal communication); however, ±5% accuracies were reported by Taylor (1968). Direction can be obtained between 0 - 355° with an accuracy of ± 10% of full scale (M. Keehan, personal communication). No directions can be obtained between 356 - 360°.

5.2.8 Magnesyn Current Meter

Two types of Magresyn current meters have been deployed by the University of Washington Department of Oceanography. The first version was an experimental model designed by R.G. Paquette in the early 1950's and was used in Puget Sound prior to 1955. The meter uses an internal Magnesyn compass to sense direction, but little else is known about the meter.

The second version of Magnesyn current meter was developed in 1967 by P.L. Taylor (1968). A Savonius rotor is used to sense speed; direction is sensed with an internal Magnesyn compass coupled to a potentiometer. The meter is connected with an electrical cable to a deck readout unit. The meter is designed to remain vertical.

The meter can measure current speeds between 3 - 130 cm s^{-1} using two speed scales (0 - 51 cm s^{-1}; 0 - 360 cm s^{-1}). The accuracy of speed is given by Taylor (1968) as ± 5% of full scale. Current direction can be measured between 0 - 360° with an accuracy of ± 3% of full scale (Taylor, 1968).

5.2.9 Marine Advisers Current Speed Sensor

The Marine Advisers Model B-1a current speed sensor measures only speed using a Savonius rotor. Six electrical pulses are generated during each revolution of the rotor. The meter is normally calibrated such that an output of ten pulses per second equals a current speed of 50 cm s^{-1}. The sensor measures speed over a range of 3 - 300 cm s^{-1} with an accuracy of ± 2% of full scale (Creeden, 1968).

5.2.10 Endeco Type 110 Current Meter

The Environmental Devices Corporation (Endeco) Type 110 current meter measures current speed and direction, water temperature, and depth, and displays these values on a portable deck unit. The meter, which is neutrally buoyant and tethered at its nose to a cable, operates by swivelling around the cable unit in the direction of the current. Speed is sensed by an impeller; direction is determined from the orientation of the meter with respect to an internally mounted magnetic compass.

The meter has a speed range of 0 - 257 cm s^{-1} with a threshold of 3 cm s^{-1}. Accuracy of speed is ± 3% of full scale. At speeds above threshold, current direction is measureable between 0 - 360° with an accuracy of ± 3% of full scale. Temperature between 0 - 40°C can be measured with an accuracy of ± 0.5°C. Depth is measurable between 0.5 - 30 m with an accuracy of ± 2% of full scale (Endeco, 1980). In addition, Endeco claims that the operation of the tether and the impeller isolate the meter from mooring motion, thus eliminating surface wave-induced errors that occur using most other types of current meters.

5.3 INSTRUMENTATION SUSPENDED FROM MOORED BUOYS

Following is a description of current meters that were suspended on moorings attached to either surface or subsurface buoys. The advantage of the surface buoy is that measurements can be taken very near the water surface (i.e., several meters depth), but its disadvantage is that wave energy may contaminate the measurements. While wave energy is greatly reduced using subsurface buoys, currents near the surface cannot be measured.

5.3.1 Roberts Radio Current Meter

The first observations made using moored buoys were taken with Roberts Radio current meters as originally developed in 1942 by E.B. Roberts of the USCGS (see Roberts, 1947; and USCGS, 1950a). At that time, the main advantage of these meters was that a single operator could measure currents at several locations simultaneously because the measurements were transmitted via radio signals to the observer. The original type of meter was normally suspended below a single surface buoy at approximately 5 m depth (Fig. 5.3). A later model was developed (see USCGS, 1950b, 1961) which could be deployed concurrently at three depths (Fig. 5.4). Both models sense speed as the time interval between two electrical pulses generated by the rotation of a propeller during a sampling interval. Direction is determined by two sets of electrical contacts whose positions are controlled by a vane. The electrical signals are transmitted via the surface buoy to a nearby recording instrument where they are manually converted into speed and direction. Measurements in Puget Sound were normally taken every half-hour.

No estimates of accuracy were found.

5.3.2 Braincon Current Meter

The Type 381 histogram current meter manufactured by Braincon, Inc. senses speed, direction, and meter tilt, and records the data internally on 16 mm photographic film. Speed is sensed using a Savonius rotor and is internally recorded on the film as an arc, the length of which is proportional to the number of revolutions made by the rotor during a sampling period. Direction is sensed with a magnetic compass and a large vane and is recorded on film as the angle of an arc between two reference points (magnetic north and the position of the vane). Tilt and tilt direction are determined from the orientation of the current meter housing with respect to the plane of the compass card, and are recorded on film as two

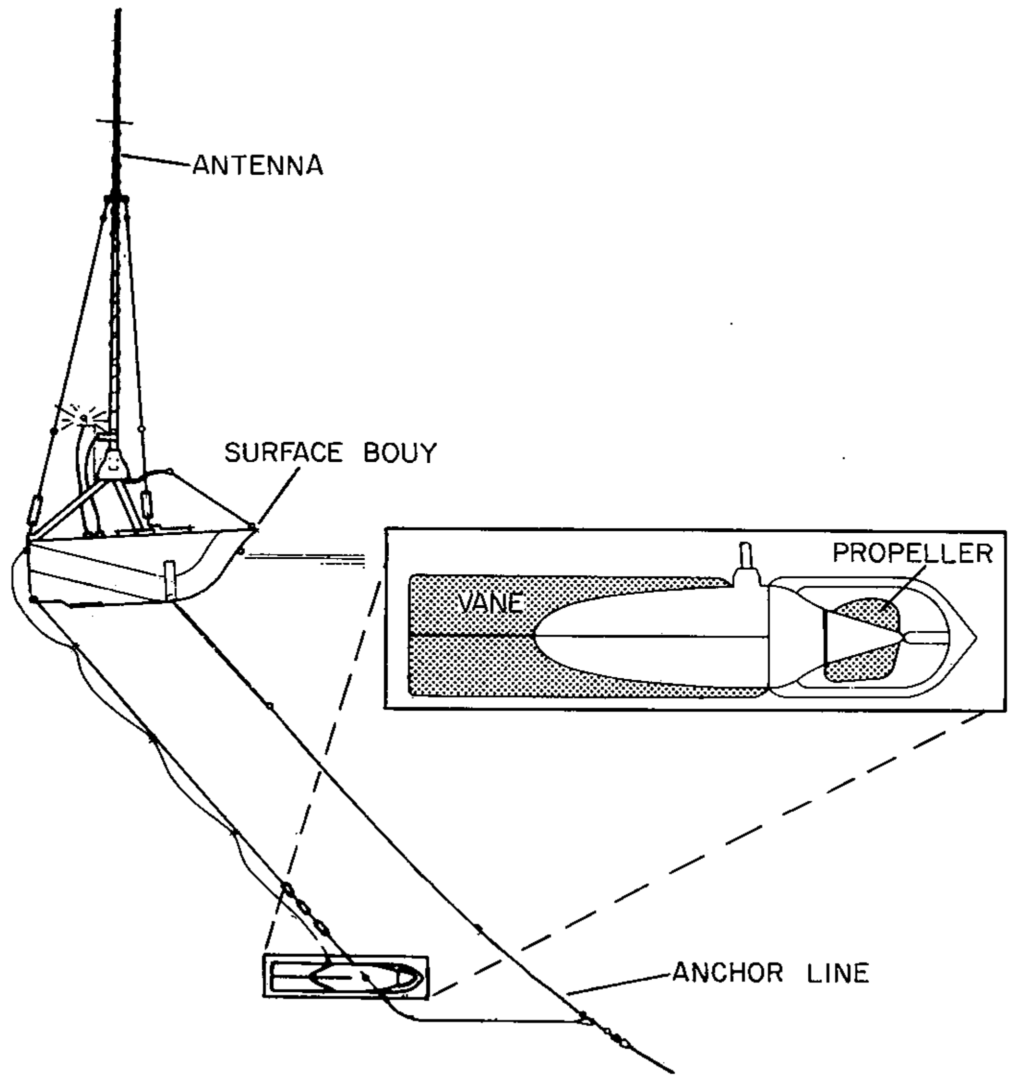

Figure 5.3. Deployment of the original version of the Roberts Radio current meter (adapted from USCGS, 1950a). Only one meter could be moored below each surface buoy. Inset shows profile view of meter.

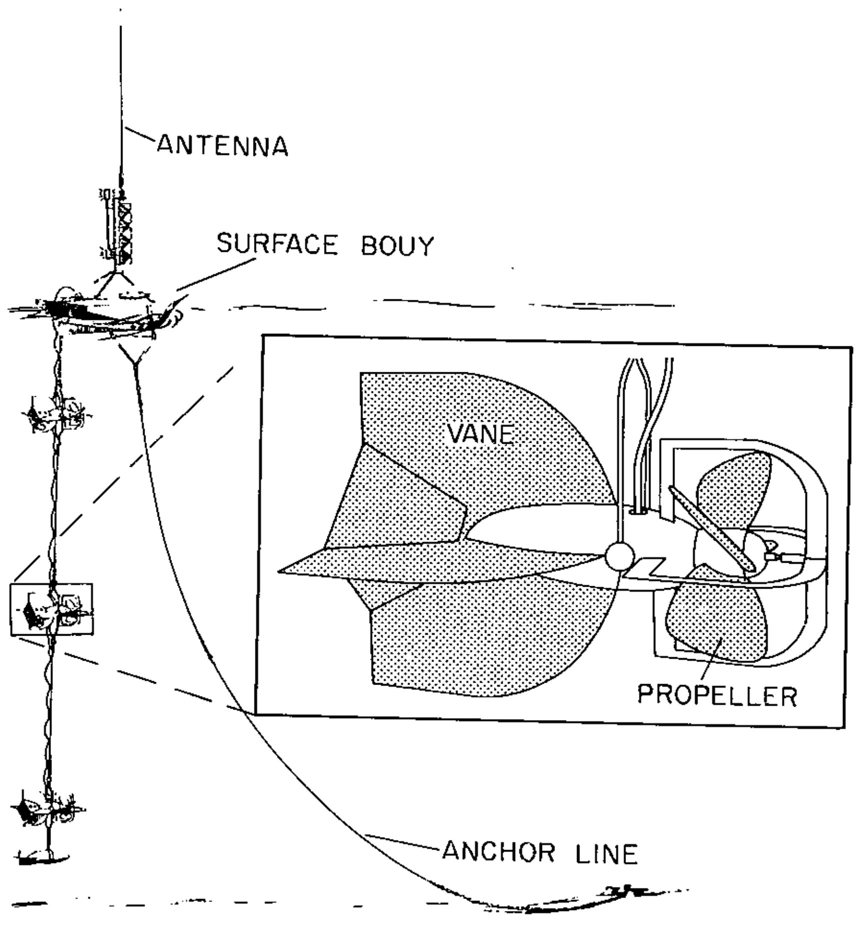

Figure 5.4. Deployment of Roberts Radio current meters modified to measure currents simultaneously at three depths below a single surface buoy (adapted from USCGS, 1961). Inset shows side view of the modified version of the meter.

dots which coincide when the meter is vertical, and separate when it tilts. Current speed and direction, and meter tilt must be visually read off the developed film. Measurements are averages over 9.5 minutes taken within consecutive ten minute intervals. The sampling interval is adjustable and can be set to record during a maximum interval of fifty days.

The meter is designed to record speeds between 0 - 257 cm s^{-1} above a threshold of 3 cm s^{-1} with an accuracy of $\pm$ 3% at full scale. Current direction is measurable between 0-360^{o} with an accuracy of approximately $\pm$ 1% of full scale. Tilt amplitude is measurable between 0-30^{o} relative to vertical with an accuracy of $\pm$ 3^{o}; tilt direction is measurable between 0 - 360^{o} with an accuracy of $\pm$ 10^{o} (Hammond and Rosebrook, 1970; see also NOIC, 1970).

5.3.3 General Oceanics Current Meter

The Model 2011 current meter manufactured by General Oceanics, Inc. uses the principle that a buoyant object tethered at one end will be deflected by the current at an angle and direction that are functions of the speed and direction of the flow, respectively. The buoyant meter is attached at its base to a mooring and the current deflects the meter from the vertical in the downstream direction. Speed is determined from the tilt angle, and both the angle and direction of the tilt with respect to a magnetic compass are photographically recorded internally on Super 8 film at selected intervals. A total of 3500 photographs can be obtained during a deployment. Measurements must be visually transcribed for later numerical analysis.

The meter can measure current speeds between 0 - 200 cm s^{-1} with an accuracy of $\pm$ 4% above an unknown threshold (General Oceanics, Inc., undated). Directional accuracy is unknown.

5.3.4 Geodyne Current Meter

The Model A850-2 current meter manufactured by Geodyne, Inc. measures speed and direction and records these data internally on magnetic tape. Speed is sensed using a Savonius rotor which magnetically activates reed switch closures. Each speed measurement is the number of switch closures counted over a five second interval. Current direction is sensed as the orientation of a large external vane with respect to a magnetic compass mounted within the current meter housing. The meter is capable of sampling continuously for approximately 8.5 days or at timed intervals for up to 156 days.

The meter can measure speeds between 0 - 257 cm s^{-1} above a threshold of 3 cm s^{-1}. Direction is measureable between 0 - 360^{o} (NOIC, 1971). Accuracies of speed and direction were not obtained.

5.3.5 Aanderaa Current Meter

Two models (RCM-4 and RCM-5) of Aanderaa current meters have been used in Puget Sound; both are manufactured by Aanderaa Instruments. The Model RCM-5 current meter is similar to the Model RCM-4 in all aspects except that it is contained within a pressure case capable of withstanding pressures of up to 5000 db, whereas the Model RCM-4 is designed to withstand pressures of up to 2000 db.

The Aanderaa meters measure speed and direction and internally record these data on magnetic tape. These meters are normally attached by gimbals to a mooring held taut with a subsurface buoy. The gimbals allow the meter to remain vertical when the mooring is tilted by drag from the current up to 23^{o} from vertical. Both the meter and mooring (Fig. 5.5) have been described by Parker and Walker (1978) and Parker and Bruce (1980). Speed is determined by counting the number of revolutions of a Savonius rotor and direction is sensed as the orientation of an internal compass to the meter body and large vane. Speed is averaged during a selected sampling interval after which an instantaneous reading of the current direction is recorded. The sampling interval is adjustable, but normally six samples of speed and direction are taken per hour. At this sampling interval the meter can record for up to two months. The meter can be equipped with additional sensors to measure temperature, pressure, and conductivity which are then internally recorded along with speed and direction.

Manufacturer's specifications (as published by the NOIC, 1974a) state that the meter can measure currents between - 250 cm s^{-1} above a threshold of 1.5 cm s^{-1} with an accuracy of ± 1 - 4%. Direction is measurable between 0 - 360^{o} with an accuracy of ± 5^{o}. The meter can measure temperatures over a variety of ranges with an accuracy of ± 0.1^{o}C. Conductivity is measurable from 0 - 60 mho cm^{-1} x 10^{-3}; accuracy is not known. Pressure is measurable in various ranges from 0 - 5500 db with an accuracy of better than ± 1% over the selected full scale. A more detailed account of the meter's performance and errors is given by the NOIC (1974a).

5.3.6 AMF Vector Averaging Current Meter

The vector averaging current meter, developed by the Woods Hole Oceanographic Institution, was previously manufactured by AMF, Inc. Speed is sensed using a Savonius rotor and direction is sensed using a vane and magnetic compass; both are recorded internally on magnetic tape. Temperature may also be recorded. The meter has been used in Puget Sound, attached to a mooring beneath a surface float. Eight samples of speed and direction are taken during each revolution of the rotor yielding, for example, approximately 11 samples per second at a current speed of 51 cm s^{-1}. The length of operation is dependent upon current speed; for example, the meter can operate for approximately six months in areas where current speeds average 154 cm s^{-1} Its major advantage is that because of its high sampling rate, contamination of the current spectrum by mooring motion or noise caused by surface way energy is reduced compared to Aanderaa current meter records (Halpern and Pillsbury, 1976; and Saunders, 1976).

Manufacturer's specifications (AMF, Inc., 1972) indicate that the meter can measure speeds between 3 - 309 cm s^{-1} with an unstated accuracy. Halpern (1980) has estimated speed accuracy of ± 2 cm s^{-1} near the water surface in the open ocean. Directions are measurable between 0 - 360^{o} with an accuracy of about ± 5^{o}. Temperature is accurate to ± 0.01^{o}C if the observations are

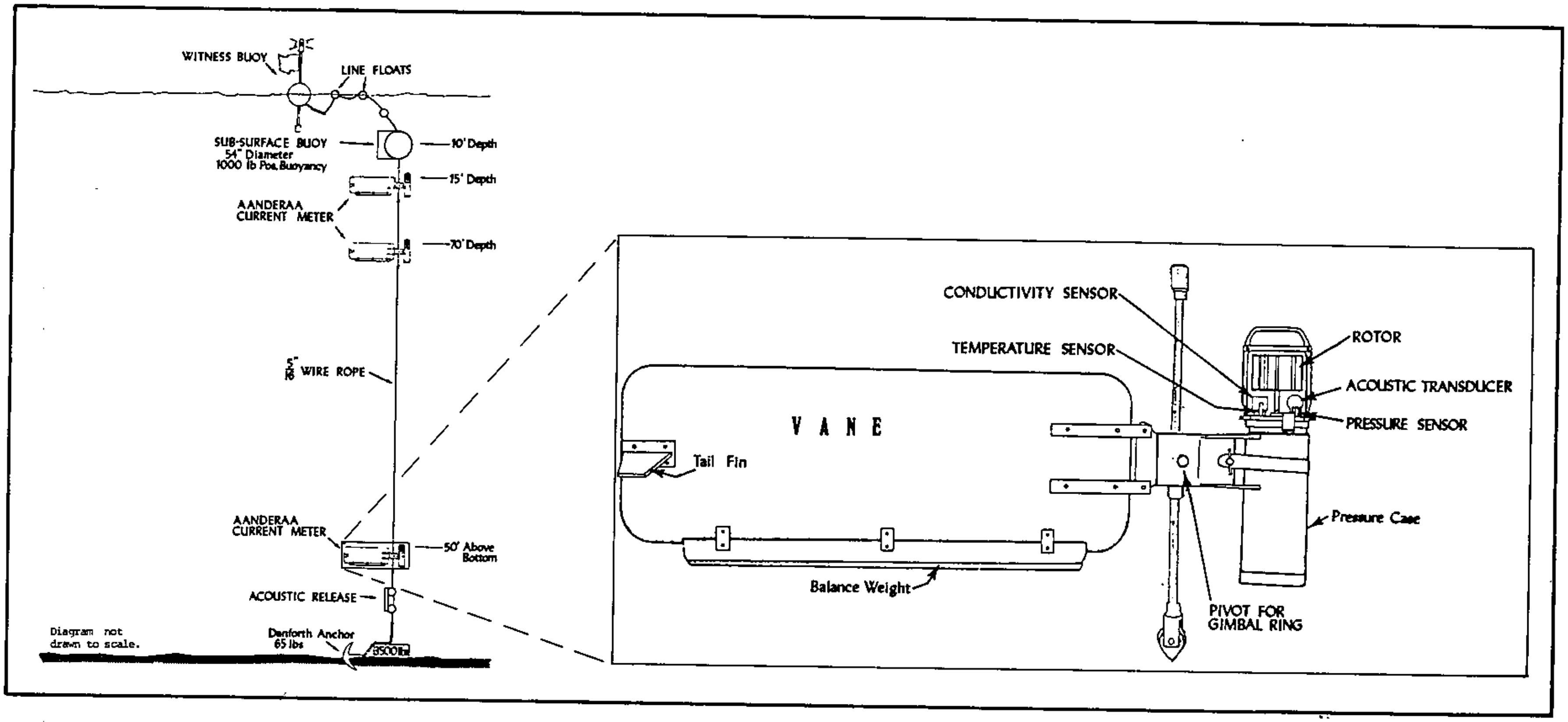

Figure 5.5. Configuration of a National Ocean Survey taut wire mooring using Aanderaa current meters (adapted from Figures 14 and 15 by Parker and Bruce, 1980). Inset shows profile view of Aanderaa Model RCM-4 current meter.

taken using a calibrated thermistor. Speed and direction accuracies also have been determined by the NOIC (1974b).

5.3.7 Endeco Type 105 Current Meter

The Endeco Type 105 current meter measures current speed and direction in the same manner as the Type 110 described earlier, and records these data internally on 16 mm photographic film. Speed and direction values are averaged over a 30 minute interval (CH_2M Hill, 1978).

Manufacturer's specifications (Endeco, 1979) indicate that the meter can measure speeds between 0 - 90, 0 - 180, or 0 - 360 cm s^{-1} above a threshold of 3 cm s^{-1} with an accuracy of ± 3% of full scale. Directions are measurable between 0 - 360° with an accuracy of ± 2% of full scale at speeds above threshold.

5.4 INSTRUMENTS MOUNTED ON TRIPODS PLACED ON THE BOTTOM

Three types of instruments were mounted on tripods placed on the bottom.

5.4.1 Lincoln Pressure Plate Current Meter

The Lincoln pressure plate current meter was designed and constructed by J.H. Lincoln of the University of Washington Department of Oceanography. The instrument measures instantaneous current speed near the bottom. The meter works on the principle that the force exerted by flowing water against a spring loaded disk held normal to the current will depress the disk into its housing an amount proportional to the current speed (Lincoln, 1956). The instant the tripod is lifted off the bottom, the position of the disk is locked by clamps so that the amount of depression can be recorded. To record the measurement the instrument has to be brought to the surface. Up to three disks were mounted on a tripod and were tripped simultaneously.

The meter also measures the inclination of the current flow relative to horizontal using a freely moving pendulum attached to a vane, both of which are securely clamped in position the instant the meter is raised from the bottom.

The range of speed that the meter can measure depends upon the size of the disks. By varying disk size, speeds between 18 - 150 cm s^{-1} can be measured (Lincoln, 1956) with an accuracy of ± 0.2 cm s^{-1} (Duxbury, 1956). The range and accuracy of the inclination were not found.

5.4.2 Sternberg Current Meter

R.W. Sternberg of the University of Washington Department of Oceanography, developed a current meter as part of an extensive, tripod-mounted, instrumentation package designed to measure physical and geological conditions near the bottom. The meter senses speed using a Savonius rotor; direction is sensed as the orientation of a vane relative to a magnetic compass. The rotation of the rotor is sensed optically in a manner that produces distinct wave forms on a strip chart recorder. Direction is recorded as the direction of the vane relative to the zero position of a potentiometer; the magnetic orientation of the zero position is established from photographs of the bottom showing a magnetic compass (Sternberg and Collias, 1973).

The meter can measure speeds between 0.5 - 100 cm s^{-1}; no accuracy is given (Sternberg et al., 1973). The direction of the vane is measured between 0 - 360° with an accuracy of ± 5°. The accuracy of the photographed magnetic compass was not found.

5.4.3 Larsen Current Meter

L.H. Larsen of the University of Washington Department of Oceanography mounted an Aanderaa Model RCM-5 current meter on a tripod. The meter is identical in operation, range, and accuracy to the Model RCM-5 described earlier with the exception that current direction was not recorded (Hinchey et al., 1980).

6. CONCLUSION

In summary, seven organizations have obtained a total of 54 years of record at 340 sites. While at first glance this data set may appear rather extensive, many additional measurements are needed to understand water motion in Puget Sound. Several examples of deficiencies are listed below.

First, Figure 2.1, which shows the locations of all measurements, is deceptive. This occurs because several sites are based upon short records which span less than a tidal day. These records are not sufficient to determine the net movement of water at these locations. Moreover, many additional sites are based upon records which span approximately five days. A large number of these records contain gaps greater than one hour, and sometimes greater than six hours, effectively creating two or more shorter length records in place of the original five day record. While rough estimates of net currents are possible to calculate from these records, it is not possible to accurately compute the tidal harmonics of the records.

Second, several of the records lasting five days or less were obtained with earlier types of instrumentation having fairly high threshold speeds. As a result, comparatively weak residual currents at many sites cannot be resolved.

Third, the coverage of records lasting fifteen days or longer, from which accurate residual currents can be established, is incomplete in space and time in major sections of Puget Sound For example, a majority of these measurements are taken toward midchannel. In contrast outfalls from human facilities mainly discharge near the shore. It is clear that the siting of new outfalls at specific locations will probably require additional current measurements to describe the movement of waters near the shore.

The vertical distribution of these measurements is also insufficient to completely describe residual currents. In some areas of Puget Sound there may be thin (~5 m depth) flows proceeding seaward which have not been measured. Examples of these areas include Hood Canal and many of the secondary inlets throughout Puget Sound.

While records lasting fifteen days or longer are sufficient to accurately estimate residual currents at the particular time of the measurements, insufficient measurements have been taken to describe the seasonal variations of the residual currents. At present there are only two locations where the currents have been measured throughout a year; the Main Basin (site 146), and the Southern Basin (site 305). Additional measurements of this type need to be taken in Admiralty Inlet, Whidbey Basin, and Hood Canal as well as within the secondary inlets to the major basins.

The deficiencies just described are important, and need to be corrected by future research efforts. Nevertheless the present data base as given in this volume (1) allows us to make some interpretations of the gross behavior of Puget Sound's circulation. These interpretations are the subject of Volume 3.

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