SOME ASPECTS OF THE OCEANOGRAPHY OF LITTLE PORT WALTER ESTUARY, BARANOF ISLAND, ALASKA

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ABSTRACT

In connection with studies on the survival of the pink salmon, *Oncorhynchus gorbuscha,* certain aspects of the oceanography of Little Port Walter estuary were investigated. Efforts were directed principally toward studies of the patterns and mechanisms of circulation; water exchange; flushing; and temporal and spatial distribution of salinity, temperature, transparency, and dissolved oxygen.

A shallow sill separates the estuary into two basins, the innermost possessing the structural and three-layered circulatory characteristics of a fiord. A net upbay movement of intermediate and deep water responded to a salt pump activated by the inflow from the estuary's single tributary stream, Sashin Creek. The rate of pumping increased materially during periods of heavy precipitation. The pattern of circulation in a shallow top layer containing the fresh water was strongly affected by the discharge from Sashin Creek but was not greatly affected by winds, since the estuary is well sheltered.

The average flushing time for the fresh water of the inner basin, computed by the method of Ketchum, Redfield, and Ayers (1951), showed a correlation with the rate of stream discharge: flushing time decreased as stream discharge increased. The total water exchange between the inner and outer basins varied in magnitude with the monthly tide range and fresh water runoff and showed some response to wind.

During the spring and summer of 1959, studies were made of certain aspects of the oceanography of the estuary of Little Port Walter, Alaska. These studies were supported by the Bureau of Commercial Fisheries and were based at the Biological Field Station at Little Port Walter. They constituted part of a series of investigations on the biology of pink salmon, *Oncorhynchus gorbuscha.* Little Port Walter estuary is the site of an annual spawning run of this commercially important species, and knowledge of environmental conditions within the estuary is pertinent to investigations of their biology.

The oceanographic studies were designed to obtain information on the following: spatial distribution of temperature and salinity, at high and low tides, under various conditions of freshwater runoff; temporal distribution of temperature, salinity, dissolved oxygen, and transparency at selected reference stations; circulation and flushing of the estuary and the relation of these factors to the discharge of Sashin Creek; and total water transport into and out of the estuary. The methods of studying these various features and parameters are presented in the discussion of methods of investigation and observation.

We were not equipped to operate in adjacent large open waters, although observations there would have been desirable and helpful. Work was therefore limited to the estuary.

The estuary is located near the tip of Baranof Island in southeastern Alaska, about 40 airline miles from Sitka. A stream, Sashin Creek, enters the inner end over a small waterfall which

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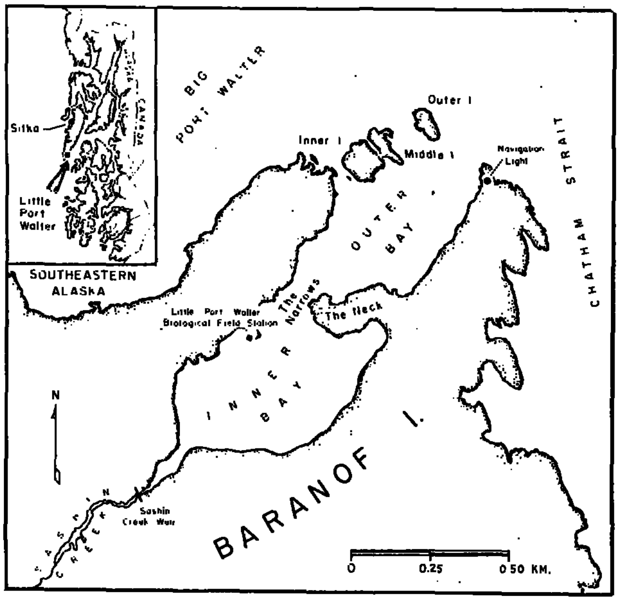

FIGURE 1.—Little Port Walter estuary, Baranof Island, southeastern Alaska.

marks the limit of salt-water intrusion. At its seaward end the estuary connects with Chatham Strait and Port Walter Bay (fig. 1).

The distance from the waterfall to Chatham Strait is 1.5 kilometers (km.); the distance across the widest part of the estuary is about 0.4 kilometer (km.). A peninsula, The Neck, extends from the south shore and divides the estuary into two bays of approximately equal area, Inner Bay and Outer Bay. These are connected by a short channel, the Narrows, between The Neck and the north shore.

The maximum observed depth of Inner Bay was 21 meters (m.) and of Outer Bay, 44 m. (referred to mean lower low water).[1] The depth at The Narrows, where a shallow sill is present, was almost 5 m. Because of this sill, Inner Bay has the structural characteristics of a fiord; Outer Bay does not, since it connects directly with Chatham Strait through a channel approximately 36 m. deep.

Three small rocky islands partially separate Outer Bay from Port Walter Bay to the north. Proceeding in a seaward direction, they are Inner, Middle, and Outer Islands. Three shallow channels connect with Port Walter Bay, but the channel between Inner and Middle Islands floods only during spring tides and has no functional significance.

The basins of both Inner and Outer Bays are steep sided, with practically no shelf formation except for a small shoal area at the head of Inner Bay. The surface area of the estuary consequently undergoes little change between low and high waters. Basins of this type are characteristic of Baranof Island as well as much of the rest of southeastern Alaska. The coastline is frequently indented by long narrow, deep embayments from which mountains rise sharply to heights of several thousand feet.

Tides in the estuary exhibit the exaggerated diurnal inequality typical of the west coast of North America. The range of spring tides at Little Port Walter was as much as 4.6 m., the range of neap tides less than half of this. Within the estuary the tide has the characteristics of a standing wave, with high and low slack waters occurring at about the same time over the entire basin.

The coastal region of southeastern Alaska is a zone of heavy precipitation. Little Port Walter receives an average of 221 inches per year.

John C. Ayers gave much valuable advice during the writing of this paper.

METHODS OF INVESTIGATION AND OBSERVATION

CRUISES

Five cruises were conducted to obtain basic oceanographic data over the entire estuary during different conditions of fresh-water runoff. Cruises were made at slack before ebb plus or minus one-half hour and at slack before flood plus or minus one-half hour. Eighty-nine stations were occupied during three cruises at slack before ebb, and 62 during two cruises at slack before flood. Station positions (fig. 2) were the same for all five cruises except where indicated. To show the stage of tide on which a particular cruise was conducted, cruise numbers bear the prefix "H" for slack before ebb and "L" for slack before flood. During each daily cruise period, as many stations as possible were visited at both slacks so that "H" and "L" cruises bearing the same number were conducted during the same time interval. Cruises H–1 and L–1 were made between June 25 and July 2, cruise H–2 between July 7 and 29,

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[1] In this discussion, all depths to bottom are referred to the datum of the U.S. Coast and Geodetic Survey: mean lower low water (U.S. Coast and Geodetic Survey, 1959).

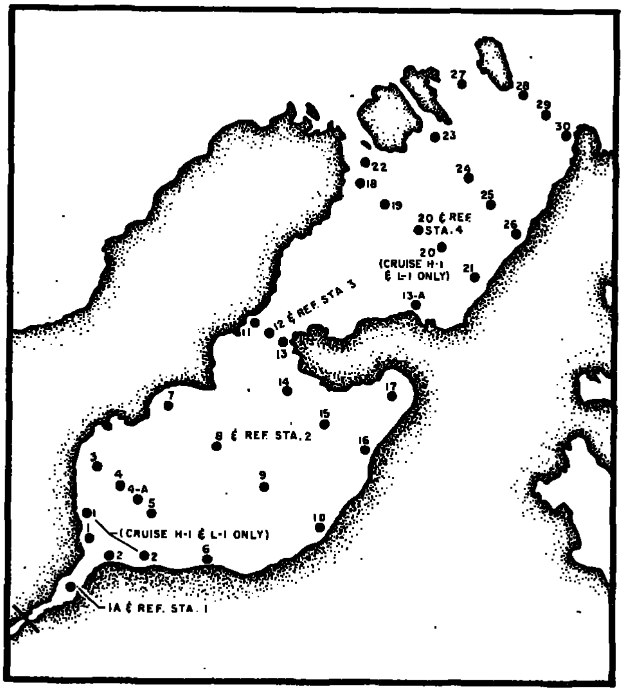

FIGURE 2.—Numbered stations for study of Little Port Walter estuary. Except where indicated, numbers refer to stations of cruises H–1, L–1, H–2, H–3, and L–3.

and cruises H–3 and L–3 between July 29 and August 4. Cruise L–2 was missed because of a series of boat engine failures. Cruise H–2 ended when about two-thirds completed because of rapidly changing conditions in the estuary, brought on by heavy rains.

At each of the 151 stations water samples for salinity determinations were obtained by Kemmerer bottle at selected depths, temperature was determined by bathythermograph, transparency was measured by white Secchi disk, and wind speed and direction and weather conditions were recorded. Wind speed was estimated, according to the Beaufort scale, from the condition of the water surface; whereas direction was estimated by reference to the geographical orientation of the axis of the estuary. Salinity was determined in the laboratory at the field station by hydrometry, and the results expressed in grams per kilogram (parts per thousand: ‰). Data from the cruise stations are on file at the laboratory at the Little Port Walter Field Station.

ANCHOR STATIONS

In addition to the stations included in the five cruises, anchor stations were occupied in The Narrows, in the two functional channels between Outer Bay and Port Walter Bay, and in the entrance to Chatham Strait. These stations furnished data on current profiles and water transport. At anchor stations hourly determinations of the current profile from surface to bottom were obtained throughout the complete tidal cycle with a von Arx current meter (von Arx, 1950). With each lowering of the meter, water samples, temperature determinations, and wind and weather observations were obtained in the same manner as described for cruise stations.

Data from all anchor stations are on file at the station laboratory.

REFERENCE STATIONS

To obtain knowledge of temporal changes in the parameters studied, four reference stations (fig. 2) were occupied each week. Stations 1 and 2 were located in Inner Bay—station 1 just below the mouth of Sashin Creek and station 2 in the deep part of Inner Bay. Station 3 was over the sill in The Narrows. The three stations were occupied on April 3 and thereafter at intervals of approximately 1 week until August 21. Salinity, temperature (by resistance thermometer), and transparency were determined, and wind and weather were noted. Dissolved oxygen was measured on June 6, and weekly from July 11 to August 21 at stations 2 and 3 only. On July 11 reference station 4 was added. Located in the center of Outer Bay at the deepest part, it was occupied weekly until August 21. The observations were the same as those made at stations 2 and 3, except that transparency was not measured, and temperature was measured by a bathythermograph which was calibrated against the resistance thermometer. Reference stations were always visited at slack before ebb, plus or minus one-half hour. The remaining data are on file at the station laboratory.

MEASURING RUNOFF

Except during periods of intense precipitation, the entire fresh-water runoff into the bay was from Sashin Creek. This stream was not gaged, but it was possible to estimate its volume of flow. From early spring until July 20, the stream was dammed near its mouth by a fish weir with two rectangular spillways. A recording gage continuously monitored the level of the water impounded by the weir. The gage record gave the head of water

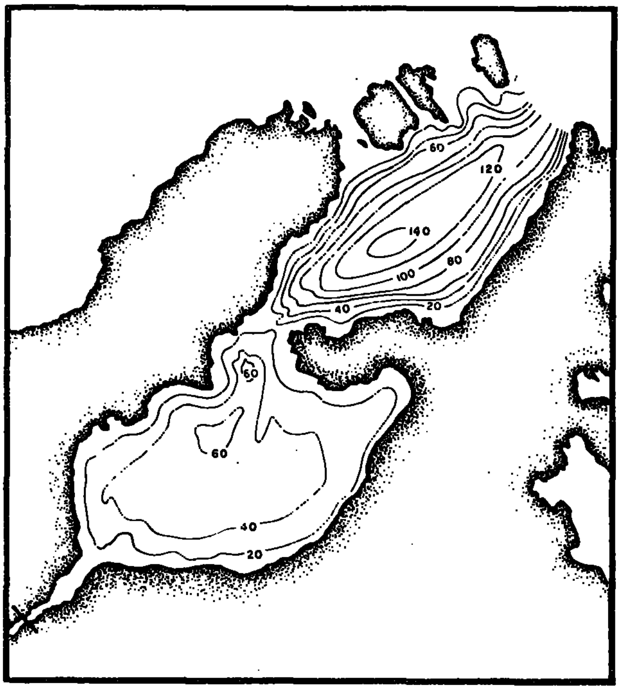

FIGURE 3.—Bathymetry in feet of Little Port Walter estuary, based on sonic soundings corrected to datum.

over the spillways, and from this the velocity of effluent through the spillways was computed by:

$$v=\sqrt{2gh}$$

where g was the acceleration due to gravity and h the head of water. Multiplying the velocity of effluent by the cross-sectional area of the spillways gave the volume of flow.

After the dam was removed on July 20, volume of flow was calculated by the method of Robins and Crawford (1954), utilizing cross-sectional area and timed observations of floats where the stream flowed through the open weir.

BATHYMETRY

Since navigation charts give only a sketchy bathymetry of the estuary a bathymetric chart was constructed (fig. 3). Sounding transects were made with a battery-powered portable recording echo sounder by running the boat at constant speed from one side of the estuary to the other between objects on shore whose positions were charted. Depths were corrected to datum before contouring, using predicted water levels for the days when the sounding operations were made (U.S. Coast and Geodetic Survey, 1959). These corrections are only approximate, their accuracy being limited by differences that may have existed between predicted and actual water levels.

METEOROLOGY

Meteorological data collected daily at Little Port Walter were maximum and minimum air temperatures and precipitation. These data, along with daily observed maximum and minimum temperatures of Sashin Creek, are presented graphically in figure 4.

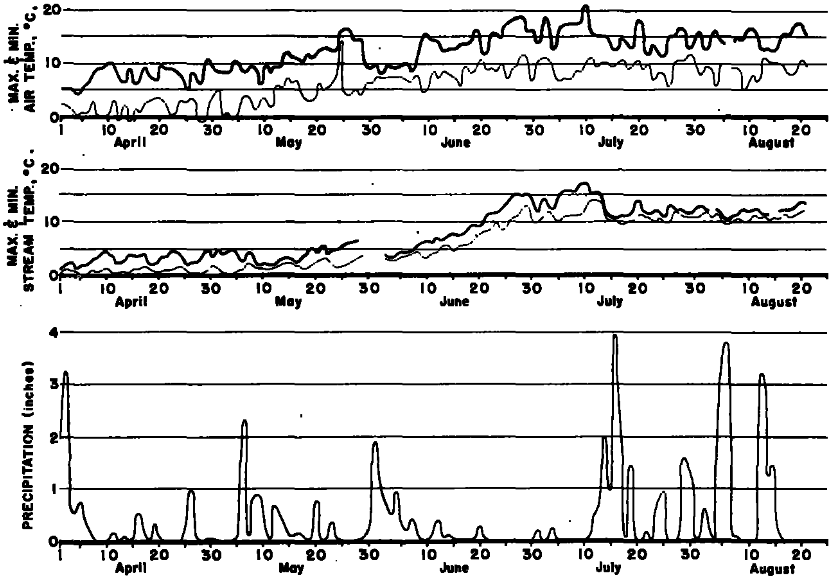

FIGURE 4.—Regimes of air temperature, stream temperature, and precipitation at Little Port Walter, April 1 to August 21, 1959.

Air temperature was measured with a sheltered glass-mercury maximum-minimum thermometer located near the station laboratory on Inner Bay. Temperature of the creek was taken daily just above the weir with a stem thermometer at approximately 0800 and1800 hours. Rainfall was measured with a standard U.S. Weather Bureau rain gage located near the laboratory.

Routine meteorological observations at the laboratory did not include wind conditions, but they were recorded at all stations and are on file at the station laboratory. Wind conditions for the five cruises and the concurrent precipitation regimes are shown in table 1. Velocities during the five cruises never exceeded Beaufort force 2, and, except for cruise L–1, at least the inner half of Inner Bay was always visited during periods of calm. No pronounced differences in distributions of temperature or salinity as a result of variations in wind direction were observed.

TABLE 1.—*Meteorological observations on five cruises in Little Port Walter estuary*

Cruise number and date	Station	Average wind direction and force	Precipitation (inches)
1959			
H–1:			
June 25	1A–7	Calm to SW.–1	0
June 26	16	Calm	0
June 27	11–15, 17	Calm	0
June 30	19–21	NE.–1	0
July 1	18, 22–24, 26	NE.–1	0. 20
July 2	25, 27–30	Calm to SW.–1	0
H–2:			
July 27	1A–7	Calm	0. 01
July 28	8–18, 21, 22	SE.–1 to SW.–1, 2	0. 05
July 29	19, 20	Calm	1. 57
H–3:			
July 30	1A–6	Calm	1. 43
July 31	7–10, 15	E. to SE.–1	0. 03
July 31	16, 17	NW.–1	---
Aug. 1	11–14	Calm to SSW.–2	0. 04
Aug. 1	18, 21, 22	Calm to W.–1	---
Aug. 2	19, 20, 23, 26	Calm	0. 60
Aug. 3	24	E.–2	0. 27
Aug. 4	25, 27–30	W.–1, 2	0. 01
L–1:			
June 25	1A–10	SE.–1, 2	0
June 26	11, 12	NNE.–1, 2	0
June 26	13–17	Calm to SE.–1	---
June 30	18–21	NE.–1, 2	0
July 1	26–30	SW.–1, 2	0
L–3:			
July 29	1A–7	Calm	1. 57
July 30	8–10, 15, 16	SE.–1, 2	1. 43
July 30	17	NW.–2	---
July 31	11–13	SW.–1	0. 03
July 31	14, 18, 21, 22	Calm	---
Aug. 1	13A, 19, 20	Calm to W.–1	0. 04
Aug. 2	23–26	E.–1	0. 60
Aug. 3	27–30	W.–2	0. 27

DROGUES AND DRIFT BOTTLES

Direct observations of surface current directions were made in Inner Bay with "drift bottles" and 2-foot-square (0.6 m.^{2}) sheet metal current drogues suspended from gallon glass jugs. The drift bottles were actually 1-pint motor oil cans ballasted with sand so that they floated nearly submerged.

OBSERVATIONS

SALINITY

Surface Salinity at Slack before Ebb

The lowest salinity in Inner Bay was generally found at the mouth of Sashin Creek, although during cruise H–2 it was found at station 17 in the small cove at The Neck. In cruises H–1 and H–3 (figs. 5 and 6) this freshened water showed a definite tendency to hold toward the north shore. This tendency was not as noticeable during cruise H–2 (fig. 7), probably as a result of reduced outflow of the stream at that time. Wind was not a causative factor in this distribution, since in all three "H" cruises the upper part of Inner Bay was visited during periods of calm.

The most prominent feature of the surface salinity in Inner Bay during cruises H–1 and H–3 was a large eddylike configuration of isohalines in the southeast quadrant (figs. 5 and 6). Salinity values on the side of the eddy toward the middle of the bay were continuous with those observed in The

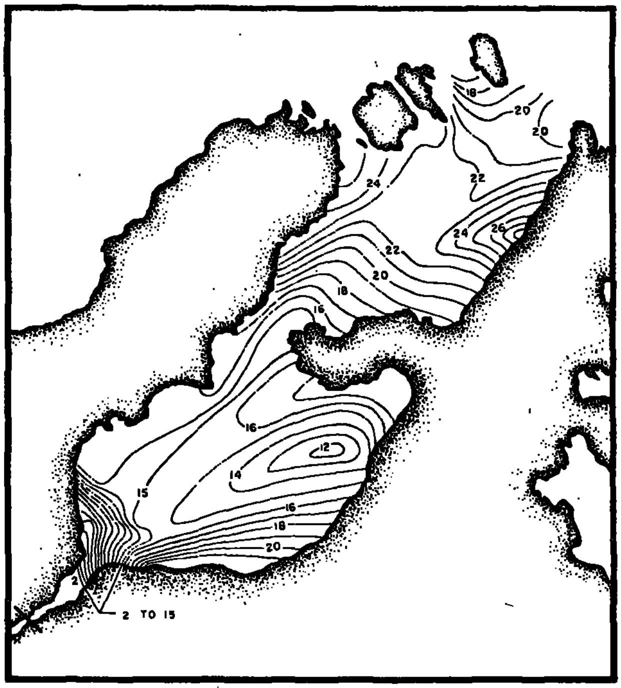

FIGURE 5.—Surface salinity; °/oo, slack before ebb. Cruise H–1, June 25 to July 2.

Narrows. During cruise H-2 the eddylike structure was not present, but a series of recurved isohalines bent around The Neck from The Narrows into Inner Bay (fig. 7).

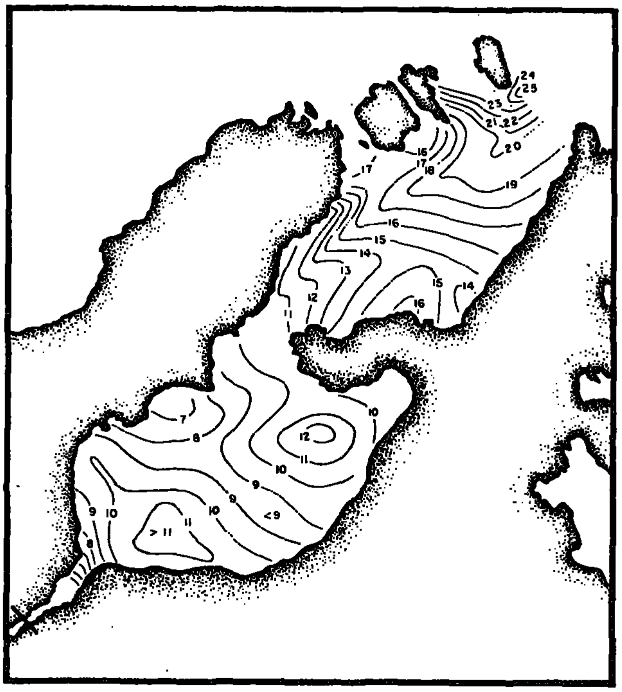

Figure 6.—Surface salinity; °/oo, slack before ebb. Cruise H-3, July 30 to August 4.

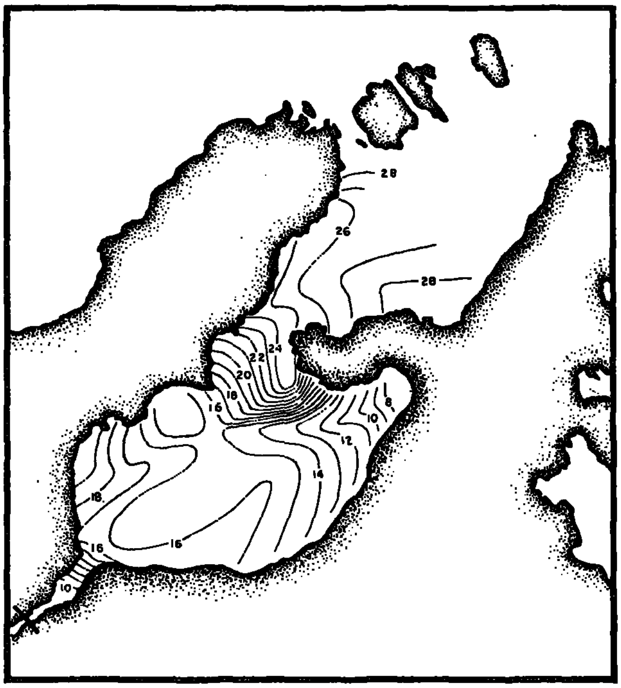

Figure 7.—Surface salinity; °/oo, slack before ebb. Cruise H-2, July 27–29.

Although salinity was low at the head of Inner Bay along the north shore, it was relatively high in a comparable position on the south shore and did not appear to be appreciably affected by the direct outflow of the stream (figs. 5, 6, and 7).

During all three cruises isohalines in Outer Bay tended to parallel the north shore between the mainland-Inner Island channel and The Narrows (figs. 5, 6, and 7). Over the rest of Outer Bay, salinity tended to increase in the direction of Chatham Strait, with generally higher values in the southern portion.

Surface salinity in Outer Bay was generally higher than in Inner Bay. Average surface values for the three cruises at slack before ebb were as follows:

	Inner Bay	*Outer Bay*
Cruise H-1	14.2	22.0
Cruise H-2	15.0	27.4
Cruise H-3	10.1	18.3

The notably lower average values of surface salinity observed during cruise H-3, as compared with the previous cruises, appeared to reflect prevailing precipitation regimes. Cruise H-1 was begun June 25 and ended July 2. Precipitation was extremely low during that period, with the only measurable amount (0.20 inch) recorded July 1.

Cruise H-2 was carried out on July 27 and 28 and the morning of the 29th. Precipitation was negligible, although 1.57 inches of rain fell on the 29th after the cruise was terminated.

Cruise H-3 was begun July 30 and completed August 4. Precipitation was only slightly less on July 30 (1.43 inches) than on the 29th. During the remainder of the cruise it varied between 0.03 inch on July 31 and 0.60 inch on August 2. The heavy rains of July 29 and 30, however, appeared to be sufficient to greatly reduce surface salinity throughout the cruise.

Surface Salinity at Slack before Flood

Stations at slack before flood were occupied during cruises L-1 and L-3.

The lowest salinity of Inner Bay was found during cruises L-1 and L-3 at the head of the estuary where the fresh water from Sashin Creek entered. It remained low along the north shore for about two-thirds of the distance to The Narrows (figs. 8 and 9). From that point, it increased both across and down the bay. In cruise L–3 (fig. 9), isohalines within this ascendant exhibited definite protrusions toward the cove at The Neck and toward The Narrows. Such protrusions were present, but less pronounced, in cruise L–1 (fig. 8). Near the south shore, just downbay from the shoal at the head of the bay, isohalines bent sharply and extended past the middle of the bay in the direction of the opposite shore (figs. 8 and 9).

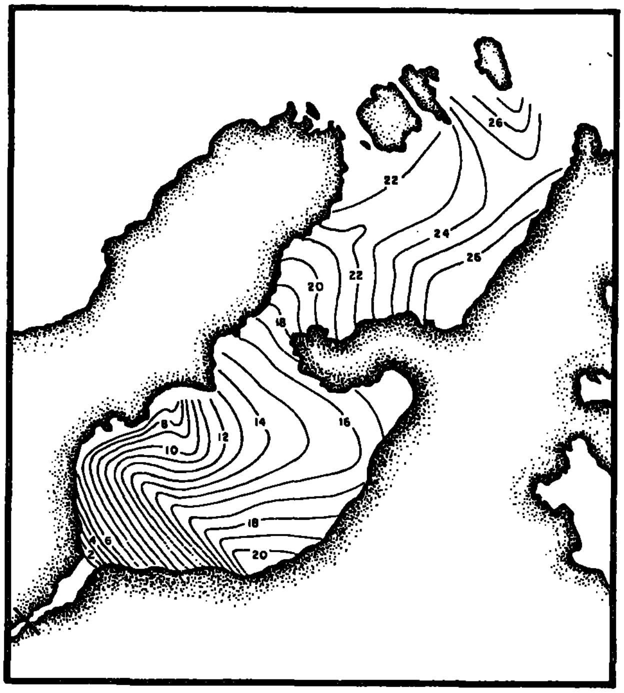

Figure 8.—Surface salinity; °/oo, slack before flood. Cruise L–1, June 25 to July 2.

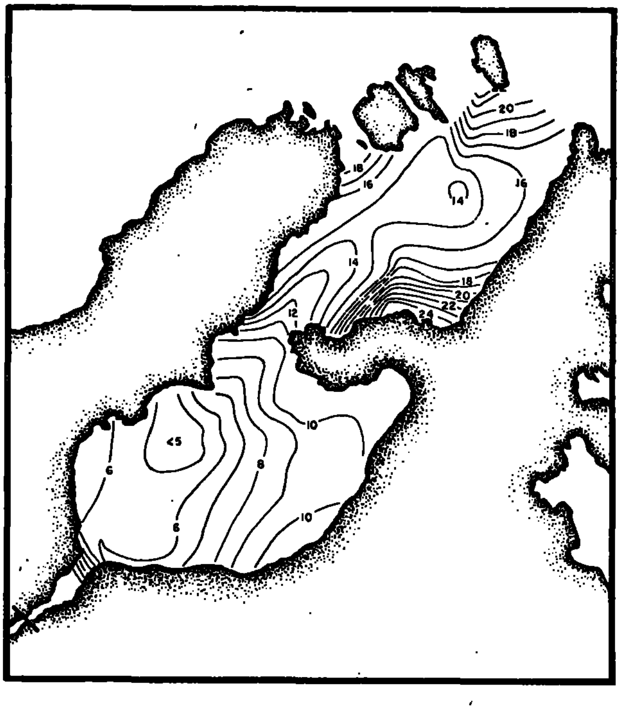

Figure 9.—Surface salinity; °/oo, slack before flood. Cruise L–3, July 30 to August 4.

On both cruises, the downbay increase in salinity observed in Inner Bay continued through The Narrows and into Outer Bay as a seaward-protruding tongue of isohalines. In Outer Bay this tongue occupied the north half of the bay as far as Inner Island. The south side of the tongue was continuous with a crossbay ascendant which attained maximum values in the embayment on the seaward side of The Neck.

Seaward of Middle Island, salinity increased rapidly to the end of the bay.

Average surface salinity at slack before flood was consistently greater in Outer Bay.

Values for cruises L–1 and L–3 were as follows:

	Inner Bay	*Outer Bay*
Cruise L–1	13. 8	24. 3
Cruise L–3	6. 8	17. 9

The greatly lowered average surface salinity of cruise L–3 was similar to the lowering observed during cruise H–3 and again appeared to reflect the effects of the heavy rains of July 29 and 30.

Vertical Salinity Distribution during Cruises at Slack before Ebb

Salinity along the axis of the estuary, as observed at slack before ebb during cruises H–1, H–2, and H–3 (figs. 10, 11, and 12), was strongly stratified. In Inner Bay, water of less than 30°/oo was usually found in the upper 2 m. and never below a depth of 5 m. At greater depths the salinity was nearly constant, varying only between 30 and 32°/oo.

In Outer Bay stratification was generally less intense than in Inner Bay. The 30 and 31°/oo isohalines rose from depths of about 20 and 30 m. in Outer Bay to about 5 m. in Inner Bay on cruise H–1. During cruise H–3, the 30°/oo isohaline was near the surface over the entire estuary, but the 31°/oo isohaline rose from about 35 m. in Outer Bay to less than 5 m. at the head of Inner Bay.

At depths below the superficial top layer, vertical salinity distribution at slack before flood differed little from that at slack before ebb and is not discussed here.

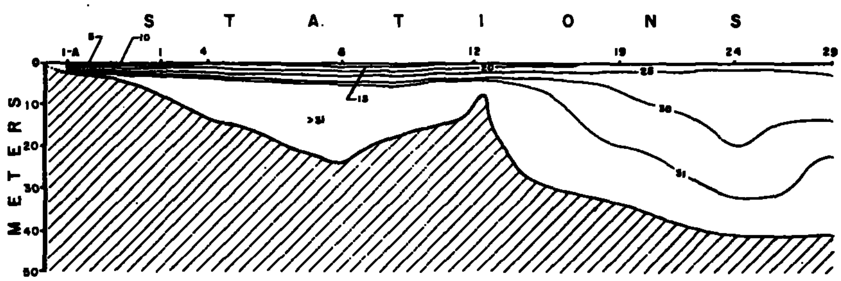

FIGURE 10.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H-1, June 25 to July 2. (Data of station 8 missing.)

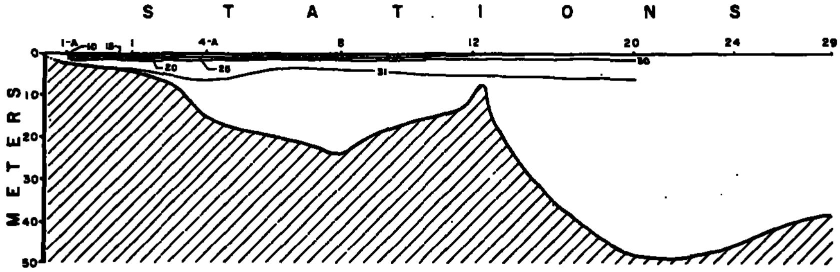

FIGURE 11.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H-2, July 27–29.

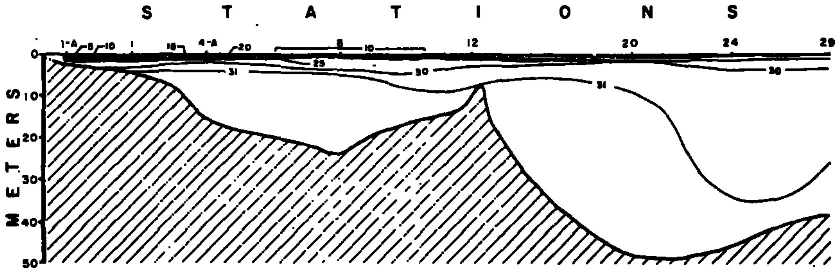

FIGURE 12.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H-3, July 30 to August 4.

Temporal Salinity Distribution

The temporal variation of salinity for Inner Bay, as observed at reference station 2 between April 3 and August 21, and daily precipitation for the period are shown in figure 13.

A strong halocline lay between the surface and 1 m. throughout most of the observation period. It was notably weakened between April 24 and May 22, probably by the mixing effects of a northeastern storm which began on April 28 and continued into the first week of May. Winds during this period attained velocities estimated at Beaufort force 6 to 7. Although heavy rains began on May 6 and continued intermittently until May 24, they or the associated heavy runoff from Sashin Creek were probably not the cause of the partial breakdown of the halocline, which remained strongly intact during prolonged periods of much heavier precipitation during July and August. A comparison of precipitation and surface salinity (fig. 13) shows that surface salinity lowered appreciably with heavy rainfall. The effect of the increased fresh-water input always appeared to be restricted to a superficial surface layer. Most of the column was consistently of salinity of 30°/₀₀ or more.

TEMPERATURE

Surface Temperature at Slack before Ebb

During cruise H-1 (fig. 14), water of > 12.5° C. protruded sharply into the southeastern quarter of Outer Bay from Chatham Strait. This extension reached to station 25, where temperatures decreased slightly to a low of < 11° C. at The

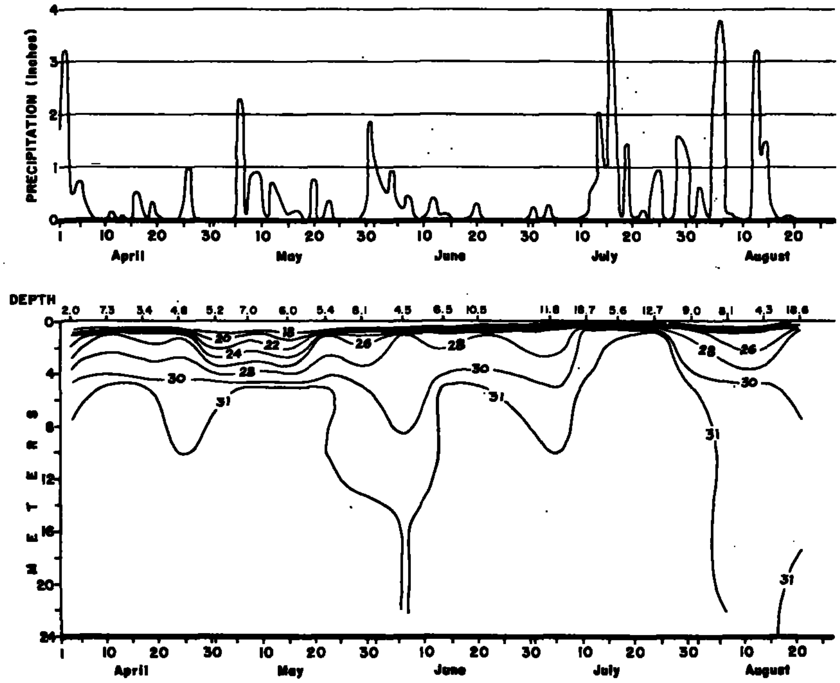

FIGURE 13.—Upper: Daily precipitation (inches of rainfall) at Little Port Walter, April 1 to August 21, 1959. Lower: Temporal sequence of salinity, °/₀₀, at reference station 2, April 3 to August 21, 1959. Contours representing values less than 18 °/₀₀ are omitted. Numbers at top are observed surface salinities.

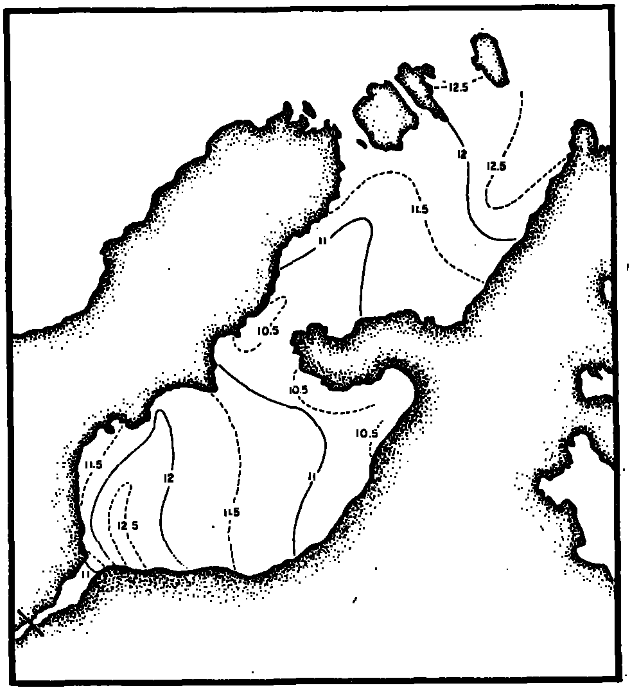

FIGURE 14.—Surface temperature, degrees C., slack before ebb, cruise H-1, June 25 to July 2.

Neck. Water of < 11° C. extended through The Narrows into the outer end of Inner Bay, then gradually warmed toward the head of the bay. Maximum temperatures in Inner Bay (> 12.5° C.) occurred as a narrow tongue extending from station 2 to station 4. Temperatures fell to < 11° C. at the mouth of Sashin Creek.

In cruise H-2 (fig. 15) a tongue of < 11° C. water extended into The Narrows from Outer Bay. This tongue was separated from the north shore by > 11° C. water that extended from the mainland-Inner Island channel into The Narrows. Slightly cooler surface waters characterized most of Inner Bay, with lows of < 10° C. in the cove at The Neck and in a narrow band in the northwest quadrant.

The nearest approach to homogeneity of surface temperatures was observed on cruise H-3 (fig. 16). The greater part of Outer Bay was occupied by water of > 10.5° C. Along the north shore a narrow band of < 10.5° C. water extended from the mainland-Inner Island channel through The Narrows, and a wider band of like temperature extended along The Neck and through The

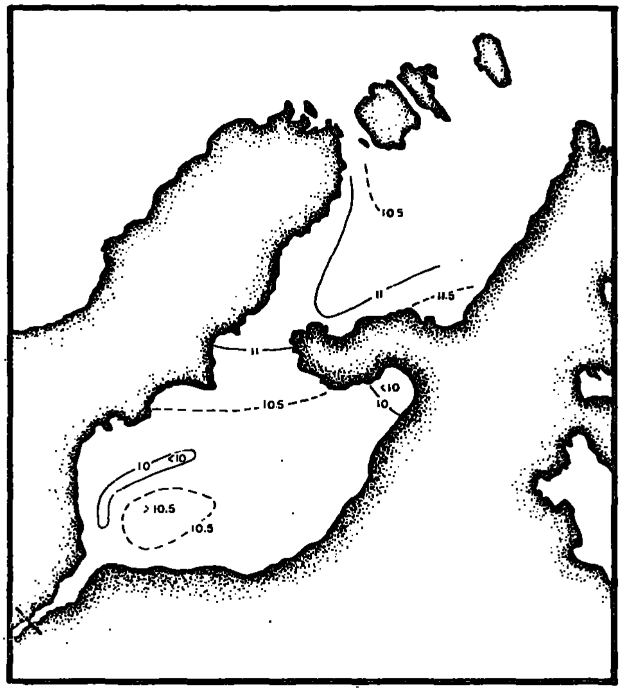

FIGURE 15.—Surface temperature, degrees C., slack before ebb, cruise H–2, July 27–29.

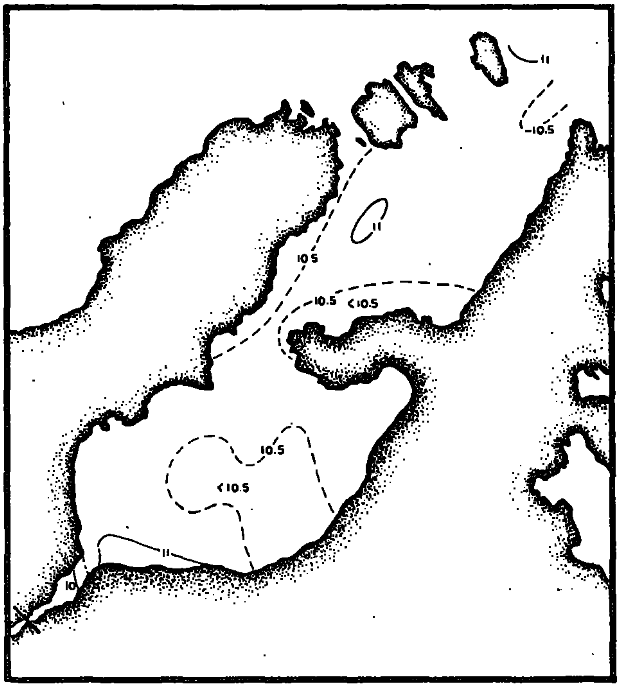

FIGURE 16.—Surface temperature, degrees C., slack before ebb, cruise H–3, July 30 to August 4.

Narrows. The $<$ 10.5° C. water continued through The Narrows from Outer Bay and occupied a large part of Inner Bay. A large bilobed area of $<$ 10.5° C. water protruded from the south shore. Temperatures of $>$ 11° C. lay over the shoal at the head of the bay; at the mouth of the stream they decreased to $<$ 10° C.

Surface Temperature at Slack before Flood

During cruise L–1 (fig. 17) a fairly large mass of $<$11.5° C. water extended from the mouth of Sashin Creek to the northwest quarter of Inner Bay. The southern half of Inner Bay was occupied by a small body of $>$12° C. water that surrounded station 6 and an adjacent area of $<$11.5° to $<$10.5° C. water that reached to the cove at The Neck, where it warmed to $>$12.5° C. A band of $>$12° C. water extended from the vicinity of station 7 near the north shore, through the south side of The Narrows, and into Outer Bay where it turned back toward the north shore. It then protruded in a downbay tongue to station 24 where it recurved to the south to terminate at the south shore near station 22. The tonguelike formation was continued to the center of the Outer Island-Light Point passage by the 12.5° and 13° C. isotherms. Warmer water lay on either side of this tongue; temperature was $>$13.5° C. along the south shore, and increased to 15° C. in the Middle Island-Outer Island channel.

Surface temperature structure during cruise L–3 (fig. 18) was much less complex than during cruise L–1. A large eddylike structure of $>$11° C. water lay in the southern half of Inner Bay, and $>$11° C. water was also found along the north shore. Water of $<$11° C. ran in a wide band from the head of the bay to and through The Narrows and also extended along shore through the southern half of Inner Bay to completely surround the eddy of $>$11° C. water.

From The Narrows the band of $<$11° C. water reached to Chatham Strait. It was partially separated from the north shore by a narrow band of $<$10.5° C. water that lay between The Narrows and the Mainland-Inner Island channel. In the southern half of the bay the extent of the $<$11° C. water was interrupted by a tongue of $>$11° C. water that ran from The Neck to the center of the bay, and by a cooler area of $<$10.5° C. water between Light Point and Inner Island.

Vertical Temperature Distribution during Cruises at Slack before Ebb

Vertical distribution of temperature along the central axis of the estuary at slack before ebb

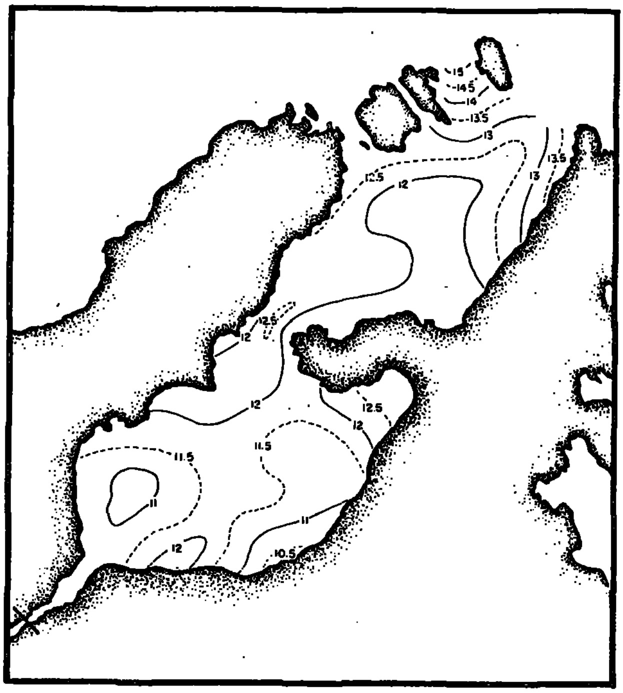

FIGURE 17.—Surface temperature, degrees C., slack before flood, cruise L-1, June 25 to July 2.

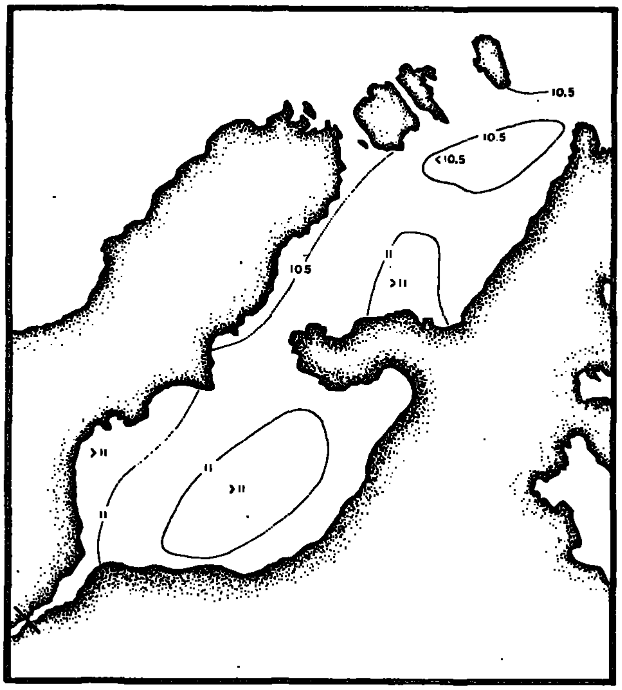

FIGURE 18.—Surface temperature, degrees C., slack before flood, cruise L-3, July 30 to August 4.

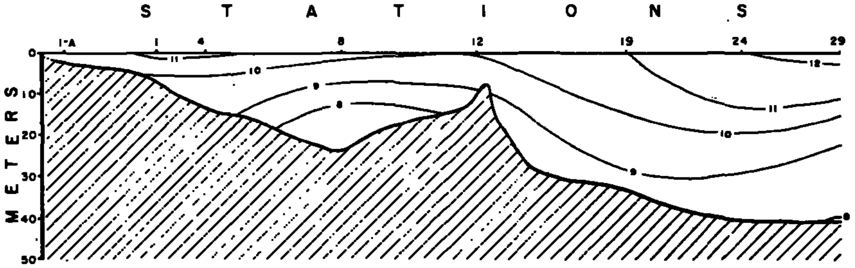

FIGURE 19.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H-1, June 25 to July 2. (Data of station 8 missing.)

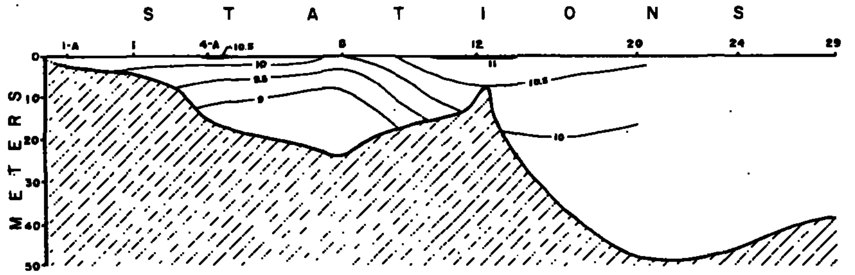

FIGURE 20.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H-2, July 27-29.

during cruises H-1, H-2, and H-3, (figs. 19, 20, and 21) exhibited only slight gradients. Although much greater depths existed in Outer Bay, bottom temperatures remained within 1° C. of those in Inner Bay.

On cruises H-1 and H-3, all subsurface isotherms in Outer Bay sloped upward toward the sill at The Narrows. Since cruise H-2 was not completed, slopes of isotherms in Outer Bay for that cruise could not be determined.

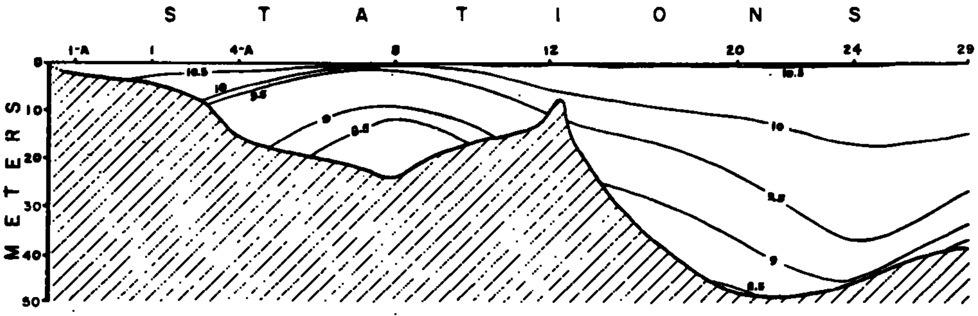

FIGURE 21.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H-3, July 30 to August 4.

Vertical temperature distribution at slack before flood differed little from that at slack before ebb and is not discussed here.

Temporal Temperature Distribution

Figure 22 depicts the temporal variation of temperature for Inner Bay at reference station 2 between April 3 and August 21. It also includes daily maximum air temperature and daily observed maximum temperature of Sashin Creek. Conditions at reference station 2 during the first half of April were nearly isothermal, with some slight stratification appearing during the latter part of the month and persisting into June.

Until early June, surface waters were colder than those immediately below the surface. Highest temperatures (6° to 7° C.) began at a depth of about 2 meters. Comparatively rapid warming occurred in June and July. The highest temperature of the entire period of observation (12.2° C. at the surface) was recorded on July 11. This

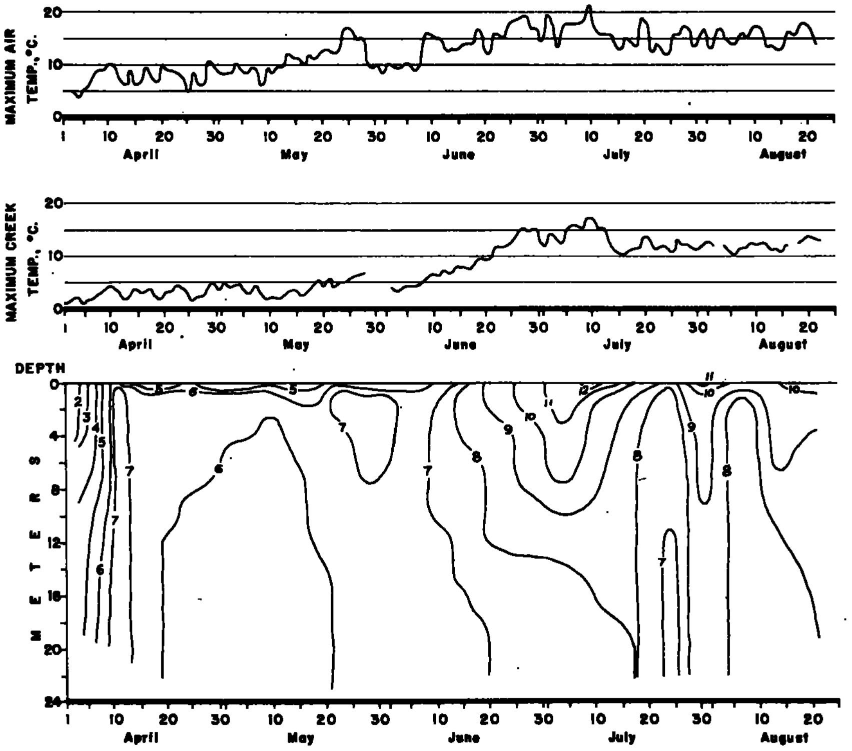

FIGURE 22.—Upper: Maximum daily air temperature, degrees C., Little Port Walter, April 1 to August 21, 1959. Center: Maximum observed daily temperature of Sashin Creek, degrees C., April 1 to August 21, 1959. Lower: Temporal sequence of water temperature, degrees centigrade, at reference station 2, April 3 to August 21, 1959.

warming trend coincided with a similar increase in air temperature which culminated in a high of 21.1° C. on July 10. Fluctuating air temperatures during the rest of the observation period were reflected in alternate warming and cooling of the water, particularly evidenced by changes in position of the 8° and 9° C. isotherms.

TRANSPARENCY AND OXYGEN IN INNER BAY

Transparency was measured weekly at reference stations 1, 2, and 3, and at all cruise and anchor stations between April 3 and August 31. Observations of this parameter at reference station 2 are presented temporally in figure 23.

Vertical distribution of oxygen was observed at reference stations 2 and 3 on June 6, and weekly at reference stations 2, 3, and 4 from July 11 to August 21. Temporal distribution at station 2 is presented in figures 23 and 24. Oxygen concentration was greater than 6 p.p.m. at all depths in all three stations except station 2 (located at the deepest part of Inner Bay). There, oxygen at depths of 20 m. and greater (22 to 24.5 m., depending on height of tide and exact point of sampling) was usually less than 6 p.p.m. The week-to-week variations in oxygen at 20 m. at station 2 are shown in table 2 (oxygen at 15 m. is included for comparison).

TABLE 2.—*Comparison of week-to-week variation in oxygen at 15 and 20 m., reference station 2*

Date	P.p.m. at 20 m.	P.p.m. at 15 m.
June 6	9.50	9.00
June 13, 20, July 4	(1)	(1)
July 11	2.75	7.68
July 17	7.34	6.81
July 24	7.66	7.87
July 31	5.28	7.18
August 7	5.45	6.78
August 14	5.58	7.22
August 21	4.15	6.58

[1] No observations.

At 15 m. oxygen showed no tendency to become depleted, fluctuating between 6.58 and 9.00 p.p.m. At 20 m., however, changes of considerable magnitude occurred. Highest observed oxygen content at that depth was 9.50 p.p.m. on June 6. It decreased by 6.75 to a low of 2.75 p.p.m. on July 11, then increased sharply to 7.34 p.p.m. on July 17. A further slight increase of 0.32 p.p.m. during the following week resulted in a secondary high of 7.66 p.p.m. on July 24. Between July 24 and 31 it decreased by 2.38 p.p.m. to a value of 5.28, then rose gradually to 5.58 on August 14. A week later it again appeared to be decreasing rather rapidly, having fallen to 4.15 p.p.m. on August 21.

Both transparency and 20-m. oxygen, as observed at reference station 2, exhibited temporal variations which correlated with the corresponding precipitation regime. In figure 23, the trend of the transparency curve correlates directly with the precipitation trends. Periods of increased precipitation corresponded with increased transparency, and periods of decreased precipitation

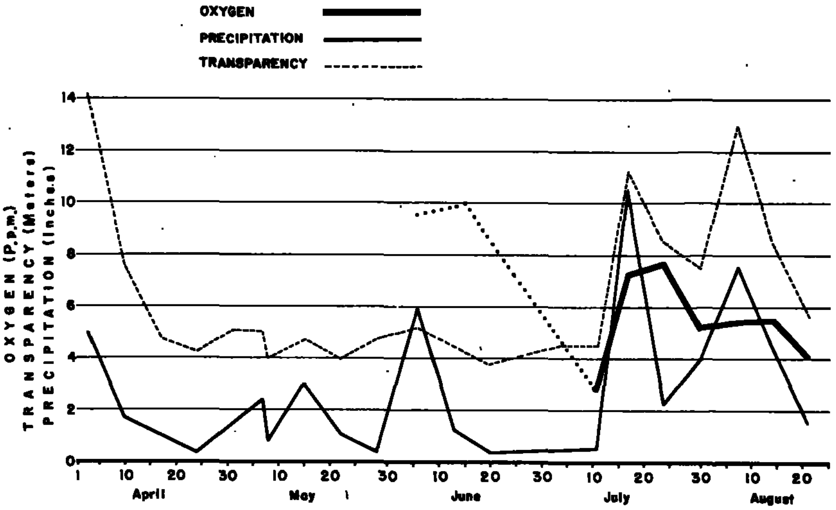

FIGURE 23.—Regimes of transparency and 20 m. oxygen at reference station 2, and precipitation as observed at Little Port Walter, April 3 to August 21, 1959. Each point on the precipitation curve represents the total for that day plus the 6 preceding days.

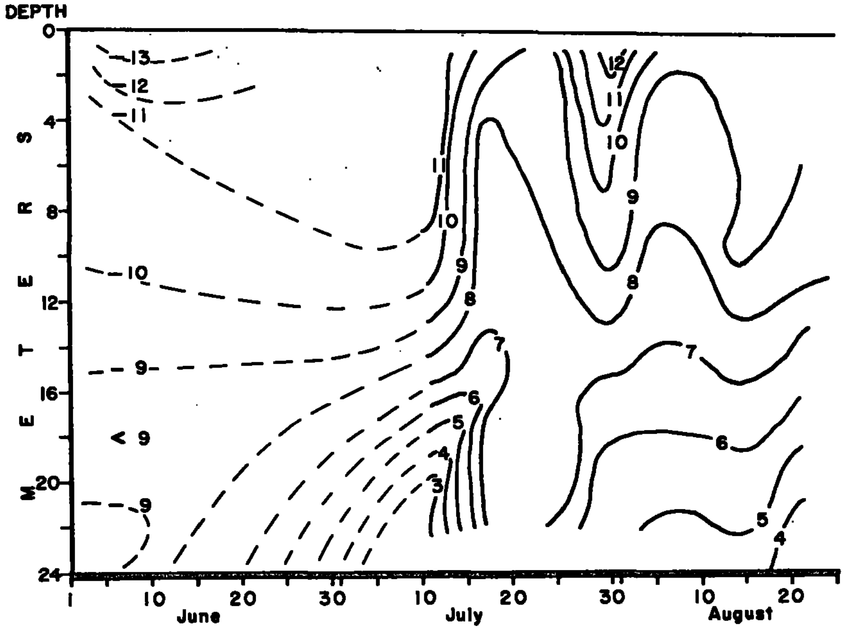

FIGURE 24.—Temporal sequence of dissolved oxygen, p.p.m., at reference station 2, June 6 and July 11 to August 21, 1959. Uppermost samples taken at depth of 1 meter.

with decreased transparency. Oxygen at 20 m. increased during two 1-week periods of heavy precipitation, continued to increase slowly during ensuing 1-week intervals of greatly reduced precipitation, and then decreased as precipitation remained low.

Between July 11 and 17, extremely heavy rainfall, 10.5 inches, coincided with large increases in transparency and 20-m. oxygen. From July 18 to 24, a period of very light precipitation, 2.4 inches, transparency decreased, while oxygen continued to increase slightly. During the week of July 25 to 31, precipitation measured a comparatively light 4.02 inches, and both transparency and oxygen decreased.

Relatively heavy precipitation (7.6 inches) between August 1 and 7 coincided with a large increase in transparency and a small increase in oxygen. Precipitation and transparency declined during the succeeding week (until August 14), while oxygen increased slightly. Precipitation was light during the last week in which observations were made, August 15–21, and both transparency and oxygen declined.

Two 3-week cycles were thus described: one between July 11 and 31, the other from August 1 to 21. Each was characterized by: (1) a week of heavy rainfall followed by 2 weeks of relatively light precipitation, (2) changes in transparency correlating directly with intensity of precipitation, and (3) 2 weeks of increasing oxygen values at 20 m. followed by a week of decrease. In each case, the increase in oxygen corresponded with the week of heavy precipitation.

On the basis of these two cycles, the probable trend of the oxygen curve between June 6 and July 4 is shown as a dotted line on figure 23.

DROGUES AND DRIFT BOTTLES

During the summer, drogues and drift bottles were released in Inner Bay at both high and low flows of Sashin Creek.

On August 5 the rate of flow of Sashin Creek rose sharply because of heavy rains. Estimated flows on the 4th, 5th, 6th and 7th were 0.096, 0.688, 0.728, and 0.329 million cubic meters per day respectively. The direction of flow in approximately the upper meter was observed on August 7, utilizing drift bottles and drogues. The drift bottles measured the movement of the top 0.25 m. of the water column; the drogues measured the 0.60-m. layer immediately below the 0.25-m. layer. Eight bottles and one drogue (*A*) were released at cruise station 4, seven bottles at station 4-A, and eight bottles at station 5. All releases were made about 1½ hours after the beginning of floodtide.

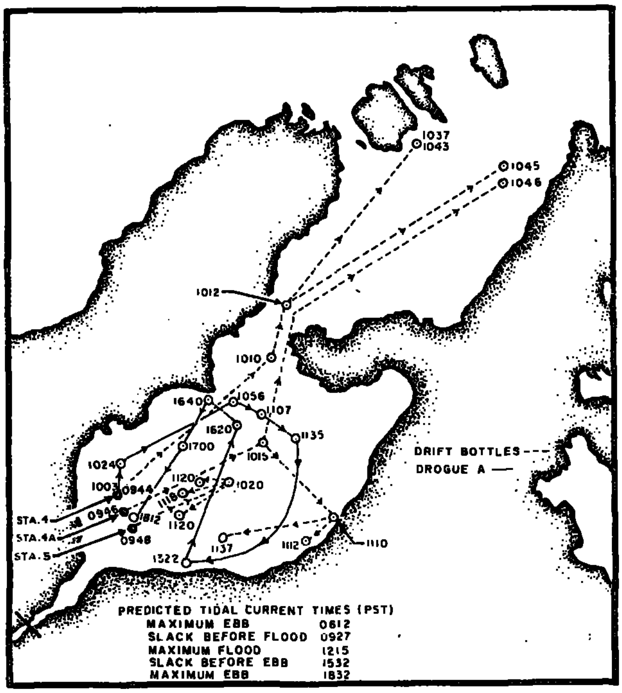

FIGURE 25.—Paths of travel of drift bottles and drogue *A*, August 7, 1959. Times of position fixes are indicated. Zero winds during entire period.

Wind was calm during the entire period of observation. Paths of travel of the bottles and of drogue *A* are presented in figure 25.

All bottles released at station 4, in the north side of the bay, moved nearly straight downbay toward the tip of The Neck, curved into The Narrows, and passed through Outer Bay to Chatham Strait in about an hour. Drogue *A*, released simultaneously with these bottles, did not enter The Narrows. Upon approaching the tip of The Neck it swung to the right, followed a curved path toward station 16 on the south shore, and continued upbay to the vicinity of station 10. It then moved away from shore toward The Narrows, and by the end of flood was about 150 m. southwest of the tip of The Neck. During the first 3 hours of ebb it moved toward the head of the estuary through the northern part of Inner Bay to a position near cruise station 4.

All drift bottle observations were made during floodtide (fig. 25).

The seven bottles released at station 4-A moved along the axis of the bay to between 90 and 140 m. of The Neck. Here two of them turned to the left and passed out through The Narrows, while the remaining five turned right and moved to station 16 near the south shore. From there they drifted slowly along shore in an upbay direction. These five bottles, from their initial point of release, followed a path similar to that of the drogue, rather than that of the bottles released at station 4.

All bottles from station 5 moved downbay, paralleling the paths of those from 4-A. After drifting about 230 m., they reversed direction and fanned out, moving very slowly back toward the head of the bay.

During periods of reduced fresh-water runoff the surface layer did not run out of the estuary on floodtides. Drogues were released in Inner Bay under conditions of low streamflow to ascertain whether the basic circulation pattern was otherwise similar to that observed during high streamflow.

On August 11, when the stream was discharging about 0.07 million cubic meters per day, single drogues were released during early flood at stations 8 (drogue *B*) and 9 (drogue *C*) and recovered several hours later before the end of flood (fig. 26). Drogue *B* pursued a circular, clockwise course, while drogue *C* moved diagonally upbay and acrossbay toward the north shore.

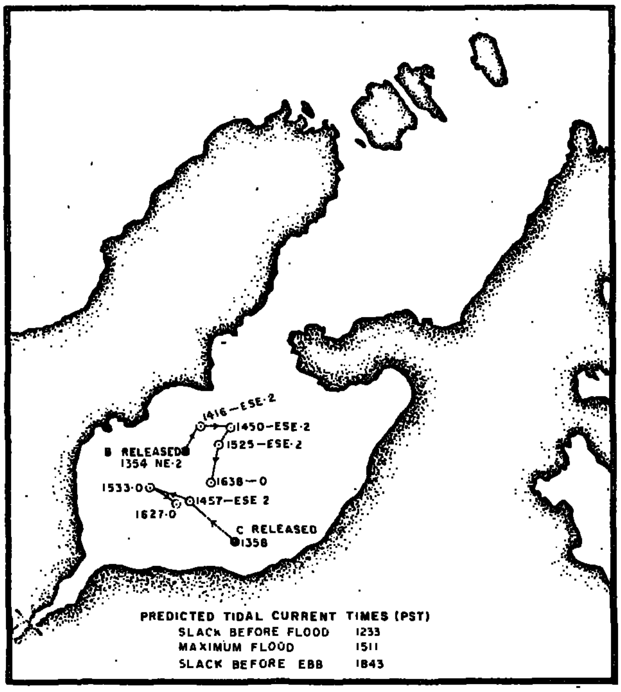

FIGURE 26.—Paths of travel of drogues *B* and *C*, August 11, 1959. Time and wind indicated at each position fix.

On August 19, when stream discharge was 0.10 million cubic meter per day, single drogues were again released at stations 8 (drogue D) and 9 (drogue E). Set adrift during early flood, they were observed until late ebb (fig. 27). Drogue *D* followed a net clockwise path. During flood it moved toward the south shore, thence to the head of the bay near the mouth of the stream, from where it started downbay shortly before the beginning of ebb. During ebb it continued to move down through the northern part of the bay toward The Narrows. Drogue *E* followed a rather aimless spiral drift during its first several hours of travel, eventually moving very close to the south shore, along which it passed in a northeasterly direction to eventually ground shortly after the beginning of ebb. After being re-released near shore, it moved upbay along shore during the remainder of its drift. Drogues *D* and *E* were both recovered at the fifth hour of ebb.

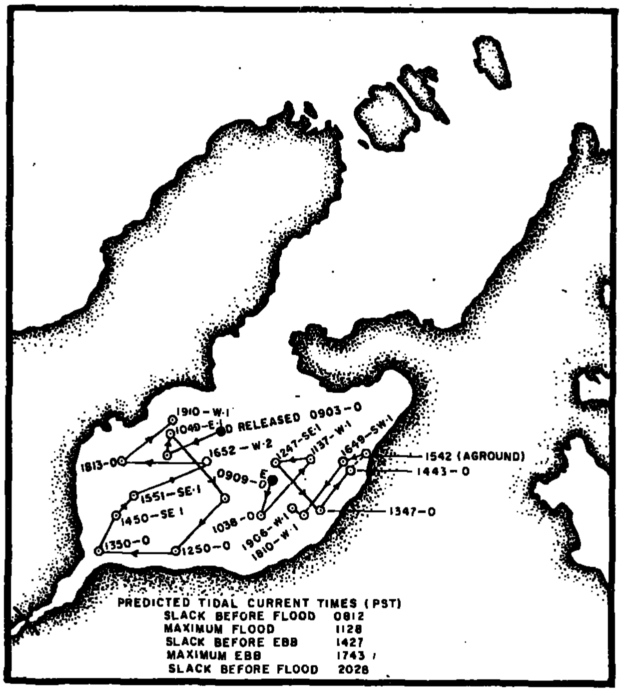

FIGURE 27.—Paths of travel of drogues *D* and *E*, August 19, 1959. Time and wind indicated at each position fix.

Medusae were in the estuary throughout the summer, usually in large numbers. They were never found in the upper freshened layer, appearing to come no closer to the surface than the top of the intermediate layer. Repeated visual observation indicated that these planktonic animals were effective neutrally buoyant drogues, and observations of their drift were helpful in discerning water movements. During times of greatly increased stream discharge, they were found in abnormally large concentrations at the extreme head of Inner Bay. Under such conditions the bottom in that region was covered with dead medusae. Their death was apparently caused by rupturing resulting from osmotic imbalance. A recent paper (Marshall and Hicks, 1962) substantiates my opinion that the medusae did not control their horizontal movements, but moved as freely floating bodies directed by the current.

DISCUSSION

CIRCULATION IN THE ESTUARY

Little Port Walter estuary exhibited normal oscillating tidal movements, which took the form of a standing wave. Slack waters coincided with high and low water, with maximum flows occurring approximately halfway between slacks. With the exception of the top 0.3 to 0.6 m. of water, which frequently ran out of Inner Bay throughout the tidal cycle, bidirectional currents were unusual, and movement of the entire water column through The Narrows was into Inner Bay during flood and out during ebb. Similar movements appeared to be the normal regime in the passages connecting Outer Bay with Port Walter Bay and Chatham Strait. For the most part, an equilibrium was apparently maintained by an excess of ebb transport over flood transport which was sufficient to carry off the fresh-water drainage. The discussion of basic circulation features which follows therefore refers to a net circulation achieved as a net product of the oscillating tidal movements.

Basic Features of Circulation

Inner Bay has the basin characteristics of a fiord. It is separated from Outer Bay by a sill at 5 m. and has a maximum depth of 21 m. The average depth is about 12 m., or approximately 2½ times the sill depth. (All depths are referred to datum.)

The fundamental net circulation of Inner Bay in the summer of 1959, as inferred from distribution of parameters and corroborated by direct observation, corresponded to that described for fiords by Pritchard (1955) and Tully (1949). The fresh-water runoff was contained in a shallow top layer (figs. 10, 11, 12, and 13). This layer was a region of mixing between the fresh water and the underlying sea water. Salinity increased rapidly with depth in the upper few meters. The 30 °/₀₀ isohaline was rarely found deeper than 5 m. At greater depths the water was of nearly constant salinity, varying only between 30 and 32 °/₀₀. This water possessed the salinity and temperature characteristics of the deep water of Outer Bay (figs. 10, 11, 12, 19, 20, and 21). In figures 10 and 12, the 30 and 31 °/₀₀ isohalines, which rose from deep positions in Outer Bay to approximately the 5-m. depth in Inner Bay, probably marked the lower limit of the intermediate layer (Pritchard, 1955) in which the net flow is directed up the estuary. The upper portion of this layer was probably delimited by the 25 °/₀₀ isohaline, which was never observed to come to the surface in Inner Bay. Sea water entrained in the intermediate layer extended to the waterfall at the head of the estuary, where bottom salinities greater than 30 °/₀₀ were routinely observed in 2 m. of water. Progressive seaward surfacing of isohalines less than 25 °/₀₀ probably indicated that they were contained in the upper layer in which net flow is seaward. According to Pritchard (1955), in this layer "the salt content increases in the seaward direction as a result of advection and mixing of saltier water from below."

Deep-Water Movement in Inner Bay

The deep water below the intermediate layer exhibited an irregular upbay movement. The precipitation-transparency-oxygen cycles of July 11–31 and August 1–21 suggested a sequence of periods of alternating increase and decrease in rate of movement of this deep water. Although the increases in transparency and in oxygen at 20 meters coincided with heavy precipitation, the only appreciable lowering of salinity was confined to a very shallow surface layer (fig. 13). It was therefore evident that the increased oxygen content of the deep water was not a result of downward mixing of the additional fresh water. The increased transparency likewise could not be ascribed directly to the presence of the runoff water, the turbidity of which was greater than that of the runoff during the immediately previous conditions of low flow.

The replenishment of oxygen and increase in transparency must therefore be attributed to a movement across the sill of deep water from Outer Bay. On July 17 oxygen content near the bottom of reference station 4 in Outer Bay was higher (9.88 p.p.m.) than at any other depth sampled in that station on that day. Since this observation coincided with the increase of oxygen at 20 m. in reference station 2, it further suggested an upbay movement of deep water which could have ridden over the sill and into Inner Bay.

The relationships between precipitation, transparency, and oxygen suggested that the movement of subsurface water across the sill from Outer Bay was in response to the mechanism of a salt pump. Hachey (1934) and others described such a mechanism in which the addition of fresh water resulted in a mixed layer of lowered salinity moving seaward (away from the mixing area) and a compensating current at a deeper level moving landward (toward the mixing area). Such differential movements are usually the net result of flows occurring over a complete tidal cycle. The rate of such a pumping is directly dependent upon the rate of fresh-water discharge into the estuary. In each of the observed precipitation-transparency-oxygen cycles, a regime of decreasing oxygen values at 20 m. was transformed to one of increasing values coincident with a change from light to heavy precipitation. After rainfall and runoff had decreased, oxygen continued to increase for another week before it declined. The intermediate layer and the deep water responded differentially to the pumping mechanism. Significantly increased rates of deep circulation were probably related to an effective frictional coupling of the deep layer to the intermediate during periods of high runoff resulting from periods of very heavy precipitation. Coupling of the two layers was likely insignificant when precipitation was light and runoff small. The movement of deep water at such times was sluggish or negligible, as shown by the observed tendency toward oxygen depletion. The lag period shown by oxygen may be due to replenishment during the momentum die-out of the deep layer.

Further evidence of increased subsurface flow toward the head of the bay during periods of heavy runoff was furnished by the abnormally large concentrations and deaths of medusae at the extreme head of the bay during times of greatly increased stream discharge. The medusae were apparently transported to the head of the bay within a counterflow that had increased its upbay rate of movement in response to the increased fresh-water discharge. Upwelling due to turbulent vertical mixing would tend to carry them into the freshened layers to which they were osmotically incompatible.

The action of a salt pump in Inner Bay was also indicated by the upbay ebbtide movements of drogue A on August 7 (fig. 25). The drogue was observed at a time when stream discharge had been quite heavy for several days. On the day the drogue was set, stream discharge was 0.33 million cubic meters per day, and the day before it was 0.73 million cubic meters per day, the greatest rate measured during the entire summer. It is difficult to explain the movement of the drogue, which was counter to the direction of the tide, on any basis other than that it was contained within a counterflow maintained by the salt pump. Water in the upper 0.3 m. was moving rapidly out of the bay at the time, and there was a complete absence of wind. Although the concept of the salt pump is generally based on net movement of water over a complete tidal cycle, it does not seem unlikely that, in a severely stratified situation such as occurred in Inner Bay, the rapid outward movement of the top layer of freshened water could have initiated and maintained an upbay movement of the more saline intermediate layer even during ebb. A somewhat analogous situation was found in Lake Ontario by Anderson and Rodgers (1959), where the flow of the warm water of the Niagara River into the lake induced a counterflow of colder bottom water from the lake toward shore.

Relation of Surface Circulation to Stream Discharge

It is evident from the foregoing discussion that the discharge rate of Sashin Creek markedly influenced the circulation of the estuary, particularly in Inner Bay. This was true not only with the vertically oriented water movements associated with the salt pump, but also with the horizontal pattern of surface circulation.

Floodtide, high stream discharge.—The paths of travel of the drift bottles and drogue A on August 7 (fig. 25) indicated vertical differences in circulation within the northern part of Inner Bay and horizontal differences between the northern and southern parts of the bay. From the northern third of Inner Bay, that part of the water column contained within the top 0.25 m. passed out through The Narrows, through Outer Bay, and into Chatham Strait, even though the tide was flooding. Water in the 0.6 m. layer directly below did not escape but passed into the southern part of Inner Bay. Surface water from the southern two-thirds of Inner Bay did not pass into The Narrows during flood tide, but appeared to enter an eddy.

The most striking aspect of this circulation was that it indicated at least part of the surface layer escaped throughout the tidal cycle. This continuous outflow appeared to result from the hydraulic pressure caused by increased stream discharge. Under all conditions of runoff the effluent of the stream tended to be diverted to the north side of Inner Bay by the shoal on the south side of the stream mouth. There was always an intense vertical salinity stratification, with most of the fresh water contained in a shallow surface layer. On August 7 this superficial freshened layer was subjected to sufficient head from the stream discharge to force its passage out of the northern portion of Inner Bay during both ebbtide and floodtide. That portion of the downbay surface flow which impinged upon The Neck was deflected into a clockwise eddy which occupied the southeastern quarter of the bay. Hence, only that surface water moving through approximately the northern one-third of the bay was able to escape through The Narrows. The motion of drogue A on August 7 indicated that during floodtide on that day, no water below a depth of 0.3 m. escaped from any part of Inner Bay, but that the deeper layers responded to the normal floodtide forces rather than to the force exerted by the fresh-water discharge.

The distribution of surface salinity during cruises H–1 and H–3 (when stream discharge was high and hence similar to conditions of August 7) confirmed the positioning of the fresh-water effluent in the north side of Inner Bay and the presence of the eddy in the southern portion.

A similar condition of continuous outflow of the surface layer throughout the tidal cycle was found during a current meter anchor station in The Narrows on June 22 when melt water influx had raised the volume of flow of Sashin Creek to about 0.34 million cubic meter per day. Observations of the vertical current profile showed that the flow in the upper 0.3 to 0.6 m. was out of Inner Bay during floodtide. Below this depth movement of water was into the bay during flood. The wind was light and variable.

Floodtide, low stream discharge.—Drogues *B*, *C*, *D*, and *E* (figs. 26 and 27), when released under conditions of reduced stream discharge drifted in the same clockwise eddy movement as they did during conditions of high stream discharge. This eddy seemed to be a dominant feature of Inner Bay under all conditions of runoff. On the day that drogue *E* was released the clockwise eddy had apparently shifted, possibly moving to a more centrally located upbay position and initiating by coupling action a counterclockwise eddy in the southeastern portion of the bay. The surface salinity of cruise H–2 (when stream flow was only 0.08 million cubic meter per day and hence comparable to that of August 11 and 19 when drogues *B*, *C*, *D*, and *E* were observed) tentatively confirmed such a shift of the clockwise eddy. The long, recurving tongue formed by the 16 °/₀₀ isohaline in the inner central part of the bay was suggestive of eddy motion. Such an eddy might account for the relatively high salinity found near the north shore (<19 °/₀₀ at station 3), since its motion could transport to that position the water of high salinity observed protruding in through The Narrows during the same cruise. A counterclockwise eddy geared to the clockwise motion could in turn account for the low salinity which lay in the southeast part of the bay. As the fresh water left the stream it could readily pass along the north side of the clockwise eddy and subsequently be carried south and thence downbay toward The Neck by the contiguous counterclockwise motion.

Ebbtide.—During ebbtide there was no evidence of a reversal of currents leading to counterclockwise circulation under any conditions of freshwater runoff. Drogue *E* moved upbay along the south shore as though contained in the southern edge of the clockwise eddy. Drogue *D* moved down through the northern part of the bay toward The Narrows in a clockwise pattern. The drift of drogue *A*, which appeared to be counter to the direction of ebb, has been discussed.

The distribution of surface salinity at slack before flood (cruises L–1 and L–3) tended to confirm the ebbtide circulation pattern inferred from movements of the drogues. During both cruises, salinity tended to be lower in the northern part of Inner Bay, with isohalines of greater values occupying the south shore between The Neck and the shoal at the head of the bay. Such a distribution suggested that an admixed stream effluent moved through the northern portion of the bay toward The Narrows, and a counterflow that contained lesser amounts of fresh water moved to the southern portion. The result was a clockwise motion.

Abnormal Circulation in Outer Bay

Anchor stations confirmed that the normal ebbtide pattern in Outer Bay was outflow through the three functional channels into Port Walter Bay and Chatham Strait. Occasionally, however, a reversal of flow through the Outer Island-Light Point channel took place during the first several hours of ebb. This reversal was, at least in part, caused by strong southerly currents in Chatham Strait and was not observed to occur with any degree of regularity.

The ebb current in Chatham Strait runs south. The mouth of the estuary faces partially into this current, making it possible for Chatham Strait water to flow into Outer Bay through the channel between Outer Island and Light Point. Such inflows were occasionally observed shortly after the beginning of ebb. On some ebbtides no unusual currents were observed near the mouth of the bay; on others, strong currents passed close to the mouth of the bay without actually entering; and on some the current penetrated well into the bay. This intruding current had the appearance of a typical rip current, with attendant surface ripples and swirls.

When the inflow from the strait did take place, it had the effect of damming that portion of the outflow from the estuary which normally ran between Outer Island and Light Point. Strong currents then flowed from Outer Bay into Port Walter Bay through the mainland-Inner Island and Middle Island-Outer Island channels. The escapement through these two channels was entrained in the ebbing current in Port Walter Bay and carried to the strait.

The phenomenon described was particularly evident on August 17. A line of floating kelp and other flotsam marked the advancing front of water from the strait, which penetrated through the Outer Island-Light Point channel into Outer Bay as far as a line between Middle Island and the southeast shore halfway between stations 21 and 26. This intruding water escaped into Port Walter

Bay through the Middle Island-Outer Island channel at velocities up to 80 cm./sec. (1.6 knots). The ebbing Outer Bay current passed into Port Walter Bay through the mainland-Inner Island channel at velocities of 50 to 60 cm./sec. (slightly over 1 knot). Only a weak ebb current was present at The Narrows at this time, indicating that the strong flow through the mainland-Inner Island channel was composed principally of water from Outer Bay.

The inflow from the strait began at the beginning of ebb. At the end of 1 hour, the kelp line that marked the intrusion had passed back out to the entrance of the bay, although strong currents were still running between the mainland and Inner Island and between Middle and Outer Islands. In 2 more hours the system had dissipated, and normal outflow from the estuary had become established.

On another occasion (July 8) a strong current from Chatham Strait, with surface velocities up to 50 cm./sec., was observed to approach the mouth of Outer Bay, but, although it passed just to seaward of Outer Island, it did not enter the bay and did not appear to obstruct normal outflow. This occurred during a period of spring tides, as did the events previously described when the large intrusion of water from the strait took place.

On June 22, also during spring tides, observations at anchor stations at the three channels in Outer Bay failed to reveal any operation of this system of currents.

FRESH-WATER FLUSHING OF INNER BAY

Although the feasibility of computing flushing rates for such incompletely mixed estuaries as Inner Bay has been questioned, such an operation seems logical if one carefully defines what is implied by the term "flushing." As computed here, the flushing of Inner Bay refers strictly to the flushing out of the contained fresh water, and the flushing time is the length of time required to rid the bay of an amount of fresh water equal to that of the accumulated fresh water contained within it on any given high tide (i.e., at slack before ebb). Even in this restricted sense, the flushing of an estuary has definite biological implications in that it has a direct effect upon any suspended materials or planktonic organisms which enter the bay via a stream.

The flushing time of Inner Bay was computed for each of the three cruises at slack before ebb (cruises H–1, H–2, and H–3) after the method of Ketchum, Redfield, and Ayers (1951). From contoured cross sections of salinity distribution, the cross-sectional areas of water of various salinities were determined by planimetry. The fraction of fresh water in each of these areas was calculated from the salinity, using as a reference the highest salinity observed in the entire estuary during the cruise. From the fresh-water fraction, the area of fresh water contained in the cross section was determined, and, using the known distance between sections, the volume of fresh water contained within the bay was calculated. This volume of accumulated fresh water, when divided by the average daily volume of flow of Sashin Creek during the cruise period, gave the flushing time in days. The results are:

Cruise	Fresh-water accumulation (cubic meters)	Streamflow (cubic meters/day)	Flushing time (days)
H–1	0.35×10⁶	0.33×10⁶	1.1
H–2	0.20×10⁶	0.08×10⁶	2.5
H–3	0.32×10⁶	0.24×10⁶	1.3

The computed flushing times correspond rather closely, varying only between 1.1 and 2.5 days. The correlation between magnitude of streamflow and flushing time, with flushing time decreasing as streamflow increases, is obvious. When flushing time is plotted against streamflow for the three cruises, the points fall nearly on a straight line. While more observations are desirable, the results are highly suggestive of a direct dependence of flushing time of Inner Bay upon volume of flow of Sashin Creek. The probability of such a relationship is enhanced by the observations and conclusions regarding surface circulation of Inner Bay, where it appeared that the pressure exerted by the flow of the stream was one of the chief determinants of the pattern of circulation of the upper layers.

WATER TRANSPORT THROUGH THE NARROWS

On August 12 and again on August 19, an anchor station was occupied in The Narrows to obtain data on water exchange between Inner and Outer Bays. The station, located in midchannel, appeared to sample adequately currents passing through The Narrows. The bottom in that constricted passage shoaled rather rapidly toward both shores, and dense kelp beds, particularly on the south side, restricted water movements occurring outside the midchannel region.

According to Sverdrup, Johnson, and Fleming (1946, p. 568), the velocity of midchannel current in a cross section is about one-third higher than the average velocity for the entire cross section. Current velocities observed at the anchor station have accordingly been lowered by one-third to make them more nearly representative of the probable average velocity through the section. Independent estimates of total water transport through the section, using tide range and surface area of Inner Bay in the relationship

$$V = A \times 2_{\eta 0}$$

(Sverdrup et al., 1946, p. 568), indicated that this adjustment was realistic. In the above equation, V is the volume of the tidal prism (hence the volume of water that must move through The Narrows through one-half tidal cycle), A the surface area of Inner Bay, and $2_{\eta 0}$ the average tide range.

On August 12 the predicted mean tide range for Port Walter was 2.1 m. The current in the upper one-half meter ran out during the entire cycle of flood and ebb. The outflow during flood appeared to be caused by south to southwest winds of force 1–2, rather than by the pressure of stream discharge which measured only 0.07×10^6 cubic meters per day. The greatest observed velocity was 15 cm./sec. Below a depth of one-half meter currents were too weak to operate the current meter, which required a minimum current velocity of 7.5 cm./sec. for activation. Directional orientation of the meter, which was usually visible to the bottom, indicated that the water below one-half meter did move out of the bay during the ebb and in on the flood.

Since movement of inflowing water was not measurable, inflow was calculated from

$$S_o V_o = S_i V_i$$

where S is the weighted average salinity over one phase of tide (ebb or flood), V is volume of water, and the subscripts "*o*" and "*i*" are out and in, respectively.

Under steady state conditions, a salt balance is maintained, that is, the estuary becomes neither fresher nor saltier. Assuming such conditions, the calculated inflow represents the volume of incoming water needed to replace the measured outflow in the upper one-half meter to the extent that net salt transport through the section is zero. Any outflow which may have taken place below one-half meter could not be taken into account in this computation, since it was not known. This necessary omission had the effect of systematically lowering the estimates of total transport throughout the complete tidal cycle.

TABLE 3.—*Observations at anchor stations in The Narrows, August 12 and 19*

Item	August 12	August 19
Total transport out through The Narrows, m³/tide	0.32×10^6	0.915×10^6
Total transport in through The Narrows, m³/tide	*0.26×10^6	0.89×10^6
Excess, out less in (net transport), m³/tide	0.06×10^6	0.025×10^6
Volume of flow, Sashin Creek, m.³/tide	0.035×10^6	0.07×10^6
Difference, net transport minus streamflow, m.³/tide	0.02×10^6	$(-)0.04 \times 10^6$
Weighted average salinity, incoming water, °/oo	29.4	27.9
Weighted average salinity, outgoing water, °/oo	23.9	25.6
Salt transport, in through The Narrows, kg./tide	7.9×10^6	25.3×10^6
Salt transport, out through The Narrows, Kg./tide	7.9×10^6	23.9×10^6

*Calculated.

On August 19 greater total transports through The Narrows were observed than on August 12. Tide ranges on August 19 were also greater; the average range during the observed cycle was 3.6 m. During the first 3 hours of flood the entire water column moved into Inner Bay, despite the fact that observed streamflow was nearly twice that observed for August 12 (0.07×10^6 m³/tide vs. 0.035×10^6 on August 12). On the 19th, however, wind was absent during most of flood, with only occasional slight gusts from the northeast. By the fourth hour of flood the upper one-half meter was running out and continued to do so until the end of ebb. The remainder of the column flowed in until slack before ebb. Current velocities were appreciably greater than those observed on August 12, with peaks of 23.5 cm./sec. and 24.0 cm./sec. at maximum flood and maximum ebb, respectively. Current velocities were consistently of sufficient magnitude for direct observation by current meter.

The results of August 12 and 19 are shown in table 3.

As a check on the results for August 12, transport was estimated from $V=A\times 2_{\eta o}$. The average given by this method was 0.49×10^6 m.^{3}/tide, and is appreciably greater than, but of the same order of magnitude as, the measured-calculated average of 0.295×10^6. This difference probably resulted from the inability to measure that outflow which took place below a depth of one-half meter and not from the lowering of observed current velocities by one-third. This conclusion is substantiated by the excellent agreement between the two methods obtained on August 19, when current velocities were sufficiently strong for direct measurement at all depths.

The results for August 19 were checked in the same manner. Calculated average transport was 0.93×10^6m.^{3}/tide, in excellent agreement with the measured average of 0.90×10^6.

Under steady state conditions, the excess of outflow over inflow should equal the fresh-water contribution to Inner Bay. Such an ideal balance was not obtained from the observations of either August 12 or 19. However, on both dates the estimated volume of flow of Sashin Creek must, realistically, be accepted as an approximation only. In addition, total transport in through The Narrows on August 12 could not be measured directly, and it is believed that the total transport out was only partially measured. In consideration of these factors, as well as the realization that water transport measurements of this type give, at best, approximate figures, the discrepancies between estimated streamflow and the net transport out of Inner Bay are not disturbing. The degree of agreement that was obtained is probably about all that should be expected.

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