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Current Patterns and Distribution of River Waters in Inner Bristol Bay, Alaska

Richard R. Straty

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U.S. DEPARTMENT OF COMMERCE
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National Oceanic and Atmospheric Administration
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Current Patterns and Distribution of River Waters in Inner Bristol Bay, Alaska[1]

RICHARD R. STRATY[2]

ABSTRACT

Hydrographic studies to determine the distribution of the waters of the major sockeye-salmon-producing river systems in inner Bristol Bay show the net seaward flow of river water is along the northwest (right) side of inner Bristol Bay. The net motion of seawater toward the head of Bristol Bay transports with it the waters of Ugashik and Egegik rivers, which enter the bay on the southeast side. Near Egegik Bay to Middle Bluff, the mixed sea and river waters join the seaward flow of Kvichak and Naknek river waters, which enter at the head of Bristol Bay. Waters of these four rivers, along with the large volume of water from the rivers entering Nushagak Bay, are eventually transported to, and move seaward on, the northwest side of Bristol Bay. Waters of Naknek, Egegik, and Ugashik rivers are similar to each other in the courses followed during ebb and flood tides. Flood tide currents, along with the nontidal current, transport water from Egegik and Ugashik rivers above or north of the entrance to Egegik and Ugashik bays.

INTRODUCTION

The distribution and migratory behavior of juvenile and adult sockeye salmon, *Oncorhynchus nerka*, while in Bristol Bay are influenced by physical and chemical properties of the bay. The literature on salmon behavior indicates that certain features of a bay or estuary, such as salinity gradients (McInerney 1964), or physicochemical properties of home-river waters (Hasler and Wisby 1951; Wisby and Hasler 1954; Donaldson and Allen 1958; Hara et al. 1965; Hasler 1966), may provide directive cues to salmon during their seaward and homing migrations. In Bristol Bay, the distribution of home-river waters and the physicochemical properties they contain are the result of ocean currents.

In conjunction with investigations by the National Marine Fisheries Service of the early marine life of sockeye salmon (Straty 1974) and their later distribution during spawning migration (Straty 1975), data were collected to describe the current patterns and distribution of waters from the major sockeye-salmon-producing river systems in Bristol Bay. Such information was expected to provide a better understanding of the relationship between environmental factors and behavior of salmon while in Bristol Bay and to provide knowledge for predicting the distribution of pollutants which might be introduced into the bay or rivers during the critical period when salmon are present.

In this paper I describe the distribution of water from each major river system as it flows out of the bay and describe current patterns of the mixed sea and river waters within the bay.

BACKGROUND

Bristol Bay, the southeastern terminus of the shallow continental shelf of the Bering Sea, is considered to be the area east of a line drawn from Cape Sarichef on Unimak Island to the Kuskokwim River (Fig. 1). Unimak Island and the Alaska Peninsula bound Bristol Bay on the south and east and separate it from the North Pacific Ocean. The studies reported here were conducted in the inner bay between Kvichak and Cinder rivers (Fig. 1).

Most of the precipitation in Bristol Bay occurs from July through September. Total rainfall varies from 76.2 to 101.6 cm annually, August being the rainiest month (U.S. Coast and Geodetic Survey 1964). Mean air temperature is about 1.7°C. Fog occurs in every month of the year at most localities. Ice begins to form along shores of the bay in October or November and expands seaward until March. Although the ice pack usually begins to break up and melt in April, compact fields of drift ice may remain offshore until late May. Over much of Bristol Bay, winds are from the northeast from October to March and from the southeast in spring, summer, and early fall. Average wind velocity is 15 knots at Port Heiden in outer Bristol Bay and about 10 knots at Naknek at the head of the bay.

Movement of water in Bristol Bay is affected by ice, runoff, winds, tidal currents, density gradients, and movement of oceanic water off the continental shelf. The funnel-shaped configurations of the bay and of the river entrances create tidal currents with velocities up to 6 knots. Tides and currents in the bay are the mixed type in which two highs and two lows occur during a tidal day, generally with a significant diurnal inequality. The diurnal range of tide averages about 5.5 m at river entrances.

[1]Based in part on a thesis submitted to the graduate school of Oregon State University, Corvallis, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June 1969.

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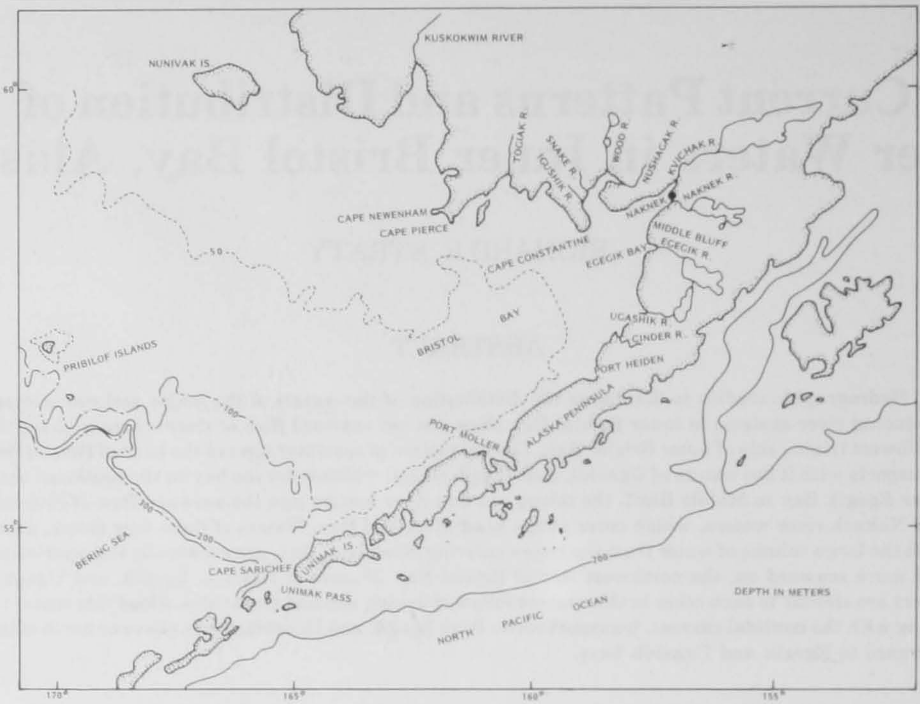

Figure 1.—Bristol Bay, showing locations of principal river systems.

Dodimead et al. (1963) depicted the pattern of the nontidal currents in a review of the general oceanographic conditions in Bristol Bay from May through August in 1938 and 1939. Dodimead et al. (1963) inferred from salinity and sigma-*t* distributions that water in the bay moved counterclockwise. Hebard (1959) determined that the average velocity of this current near Port Moller (Fig. 1) on the Alaska Peninsula was slightly less than 0.1 knot, or about 2 n.mi./day.

In spring (May and June) a temperature front occurs in the seawater across the bay and separates waters of the inner bay from those of the outer bay. In 1939 this front occurred along a line from Port Heiden to Cape Pierce; surface temperatures and salinities indicated the presence of counterclockwise gyres both shoreward and seaward of this front (Dodimead et al. 1963). The inshore gyre was apparently confined to the surface, and warm dilute river runoff was contained eastward of Cape Pierce and forced to recirculate shoreward of this front. By August the temperature front had disappeared, and a peripheral counterclockwise flow was evident throughout the bay.[3] These descriptions of water movement apply to the area seaward of a line between Cape Constantine and Egegik Bay (Fig. 1).

DISTRIBUTION OF RIVER WATERS

Three methods were used to determine the distribution of waters from individual river systems in inner Bristol Bay: 1) measuring vertical and horizontal distributions of salinity, 2) tracking river waters tagged with a fluorescent dye, and 3) tracking drift cards released at strategic locations in the bay.

Four Bristol Bay river systems were studied—Naknek, Kvichak, Egegik, and Ugashik (Fig. 1). These systems were chosen because their average combined production of sockeye salmon is more than 70% of the total annual Bristol Bay run. Moreover, a considerable amount of inshore mark-and-recovery data were available for adult salmon of stocks occurring along the southeast side of the inner bay where these rivers enter.

Determining Salinity Distribution

Salinity was measured in 1966 at stations along six parallel transect lines across inner Bristol Bay. The stations were located at 8-km intervals along the offshore transect lines, which were 16 km apart, and at 1.6- and 3.2-km intervals along inshore transect lines, which were 8 km apart. Salinity was measured with a Beckman Model RS5-3 electrodeless induction salinometer at the surface and at 1- and 2-m intervals thereafter to the bottom at low tide and usually during the following high tide.

Data were collected on consecutive days in late July and August during periods when tidal conditions were as nearly similar as possible. Although transects could not always be run on the desired tide because of inclement weather and darkness, they could usually be run on the lowest and highest tides of the day. Coverage of a transect line usually began between 1 and 1½ h before low or high tide. The tracking vessel was kept on a constant compass course along a given transect line as it

[3] Recent data collected by the National Marine Fisheries Service, which are on file at the Auke Bay Laboratory, Auke Bay, Alaska, suggest that a temperature front occurs annually, but its location may vary from year to year.

traveled between stations so that it moved toward the head of the bay or seaward at a rate controlled by the speed of the tidal current. In this way the vessel was assumed to remain in water representative of water at the beginning of a transect run.

Transects were usually run when the wind velocity was 10 to 15 knots; speeds greater than 13 knots caused waves to become unstable and break into whitecaps, resulting in an increase in the mixing of the surface waters (Johnson 1960).

The vertical and horizontal profiles of salinity in inner Bristol Bay are used to interpret distribution of river waters in the inner bay where there is very little vertical variation in salinity (Fig. 2). Vertical mixing is caused by

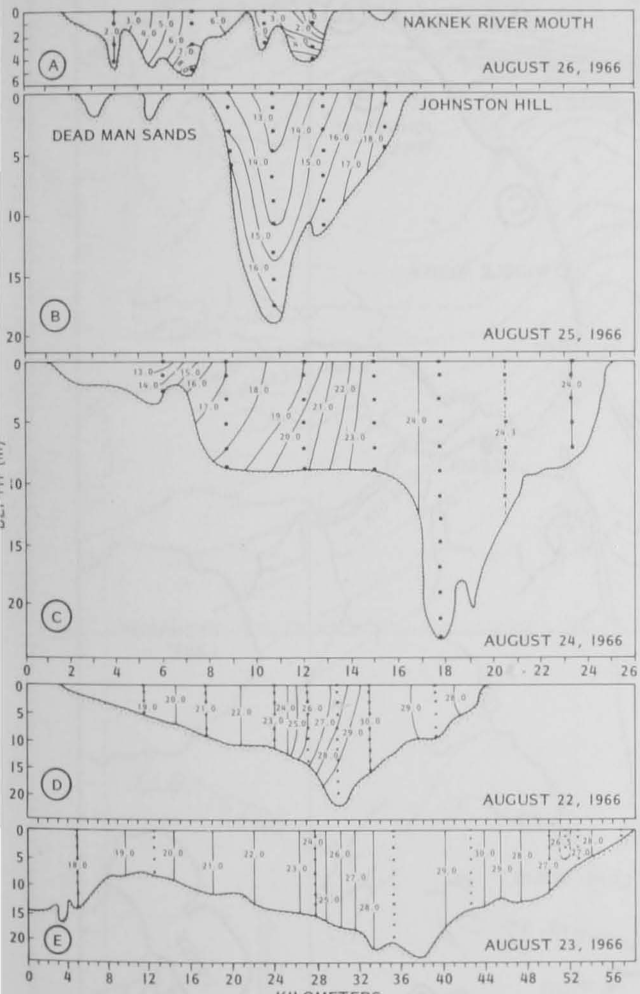

Figure 2.—Vertical profiles of salinity (‰) at 16-km intervals across inner Bristol Bay, August 1966.

the high velocities of the tidal current, shallow depth, and wind. Salinity in inner Bristol Bay varied horizontally, as shown by surface and bottom salinities at low and high tides (Figs. 3-6); salinity was low on the northwest side and high on the east side. Dodimead et al. (1963) found that this condition persisted farther offshore: low-salinity water moved seaward on the northwest side of the bay, and a countercurrent of high-salinity water was present on the southeast side. This current appeared as a wedge of high-salinity water between the river waters entering each side of the bay.

Dye Studies

To track water from individual rivers, I used a tracer technique utilizing a fluorescent organic pigment, Rhodamine B (alkyl aminophenol derivative).[4] This technique was first used by Pritchard and Carpenter (1960) to observe the movement and dispersion of water in various parts of Chesapeake Bay.

Ideally, a tracer is released into a river when a continuous flow is expected for a period of time long enough for the tracer to achieve equilibrium with its environment. However, the objectives of my study could be met by instantaneous release of enough Rhodamine B to trace its course over one or two tidal cycles. The dye was released only on days when wind velocities were less than 15 knots because the wind is considered to be an important agent of mixing and dispersion of a tracer in short-term studies such as mine. The dye was rapidly poured from plastic containers into the propeller wash of the tracking vessel while traveling at a speed of 5 knots. Approximately 9.5 to 18.9 liters of dye were released about 1 h after high slack tide along a continuous line 3 m wide across the main channel of the river. The channel was crossed three or four times with a line of dye laid down about 15 m upstream from the previous line. The dye mixed rapidly with the water to a depth of 2 m; within 1 h after release it had mixed to a depth of 4 m. Usually within 1 h, individual lines of dye had diffused horizontally and merged with one another, producing a visible patch across the channel 60 m or more wide. Dye was also released in a similar manner near the end of the ebb tide offshore across the course assumed by the dye previously released at the beginning of the ebb tide. The course of this release was followed during the following flood tide.

Paths of Fluorescent Dye.—Dye was released into Naknek, Egegik, and Ugashik rivers in July and August 1965 and 1966. No dye was released in the Kvichak River because the course and distribution of Kvichak River water in inner Bristol Bay could be logically deduced from results of the Naknek River study and the surveys to measure salinity. The tracks of 11 dye releases in the three rivers showed that river waters followed rather discrete and similar courses in the inner bay (Figs. 7, 8). The course of dye released near the end of ebb tide at the mouths of the three rivers indicated that a portion of the river water was carried north by the succeeding flood tide (Fig. 8). Water entering the bay from these rivers (and Kvichak River) near the end of ebb tide constitutes the greatest fraction of river water entering the bay during a tidal cycle. In most cases, dye was tracked on the flood

[4]Rhodamine B dye was purchased as a 40% (by weight) acetic acid solution. Because the density of the solution was greater than that of the water into which it was to be released, its specific gravity was adjusted to 1.00 by the addition of methyl alcohol.

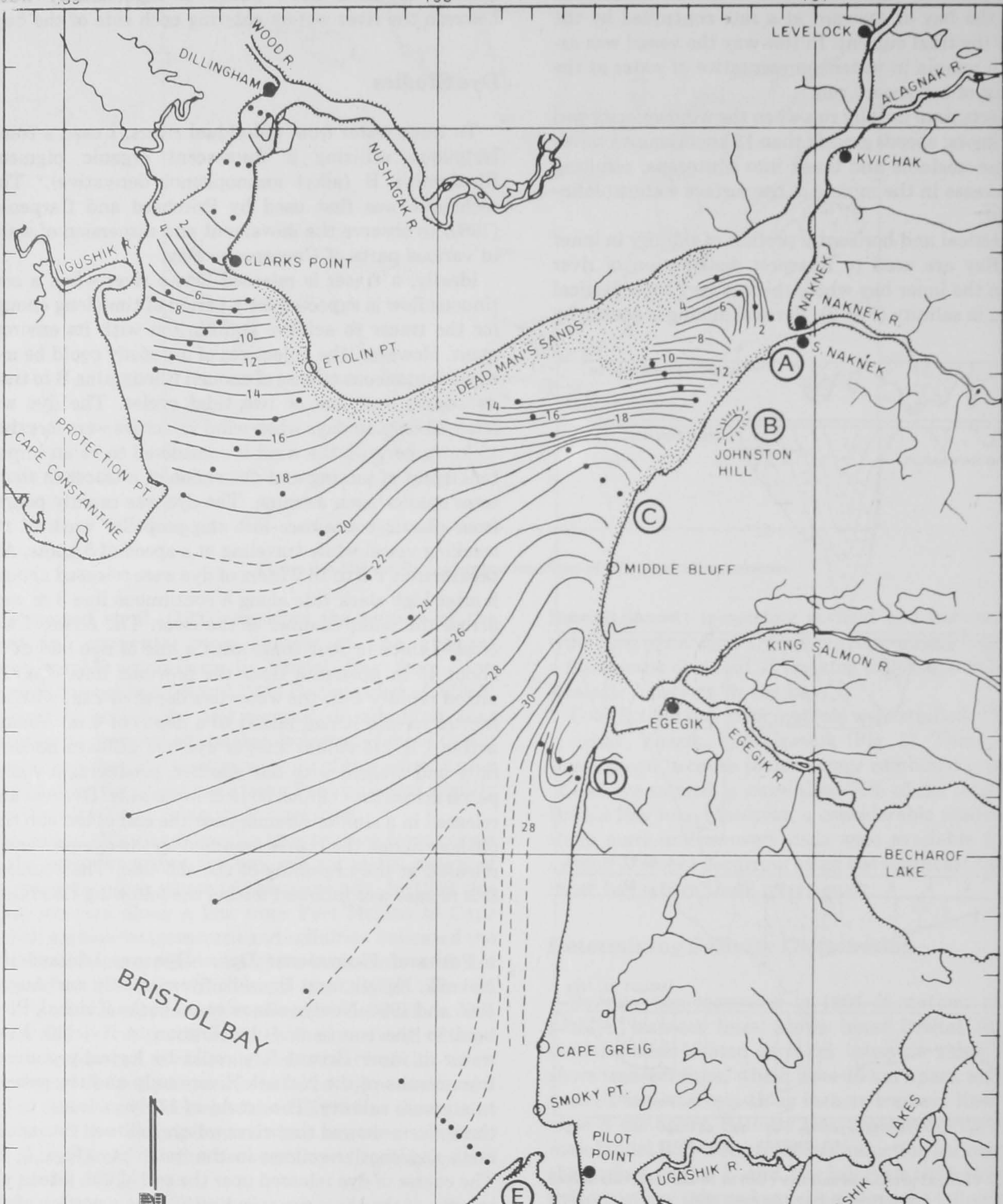

Figure 3.—Surface salinity (‰) at low tide, inner Bristol Bay, July and August 1966.

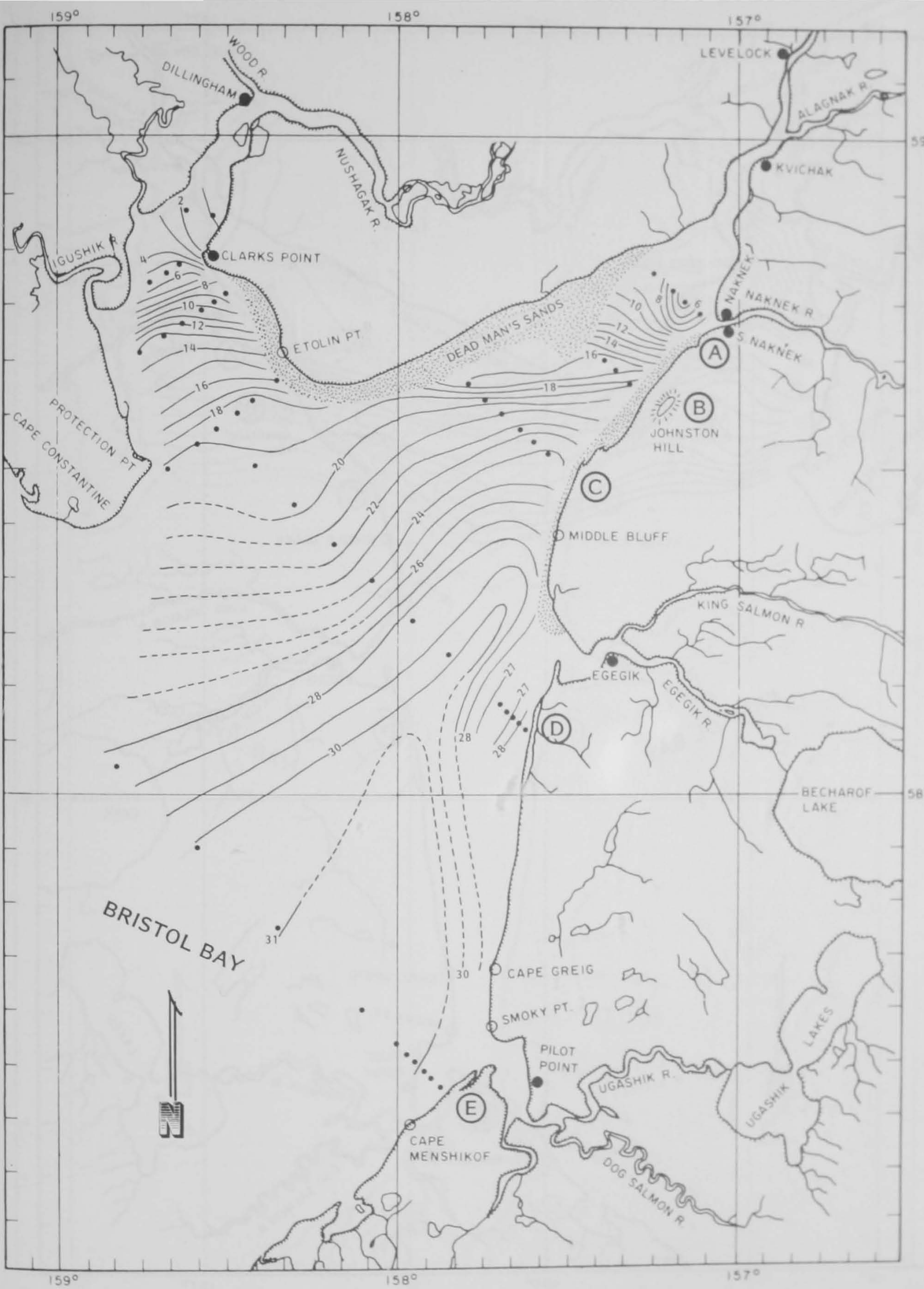

Figure 4.—Bottom salinity (‰) at low tide, inner Bristol Bay, July and August 1966.

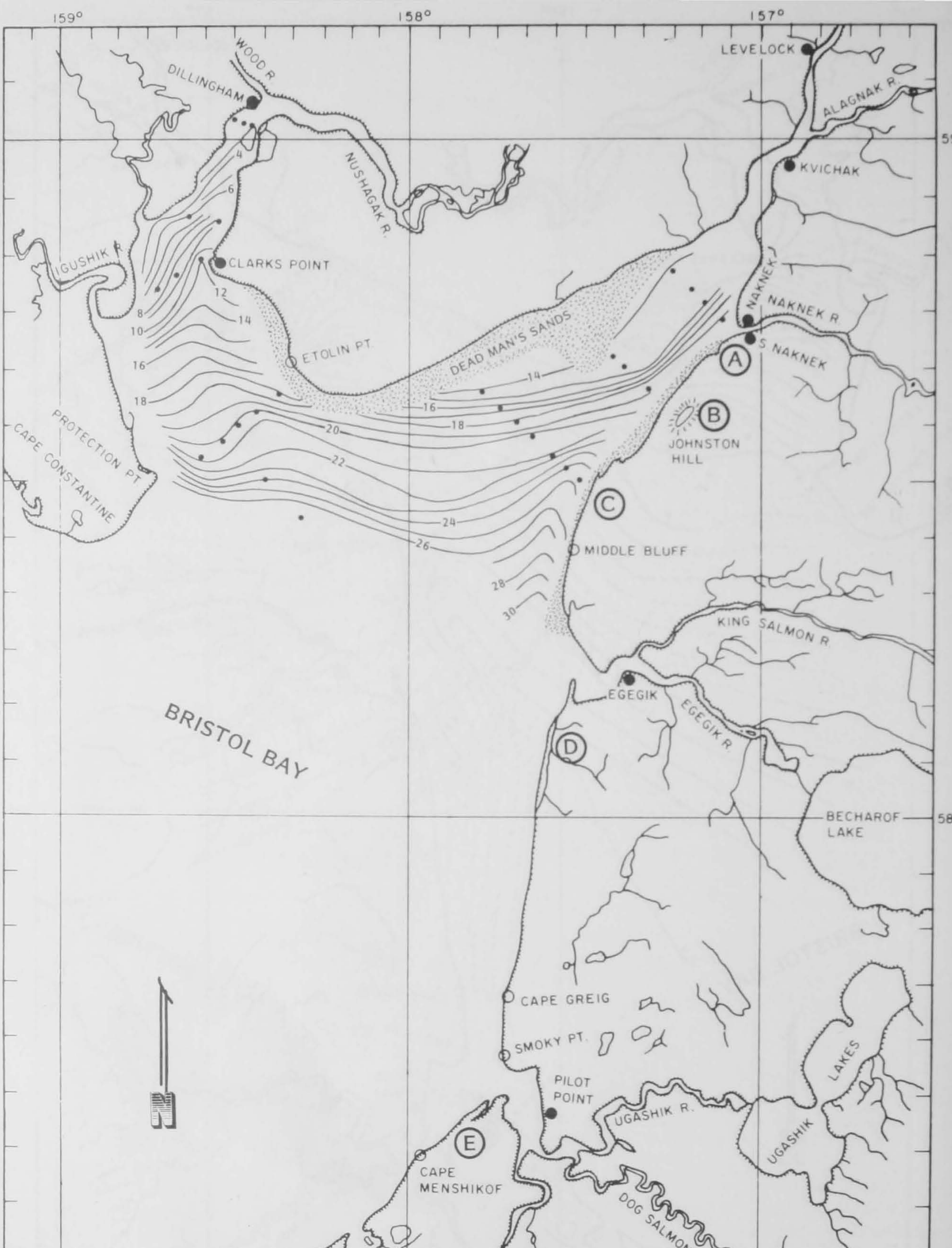

Figure 5.—Surface salinity (‰) at high tide, inner Bristol Bay, July and August 1966.

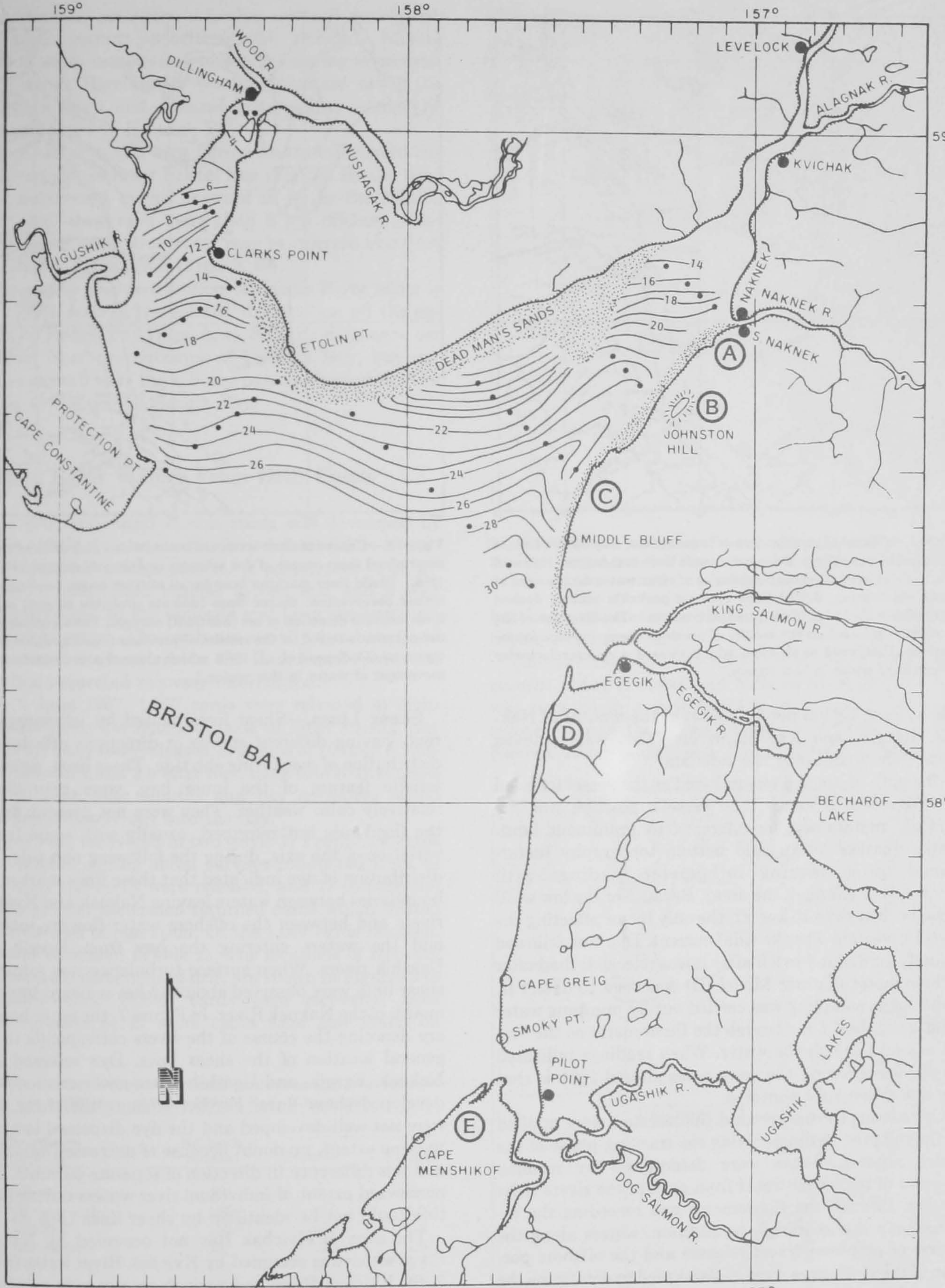

Figure 6.—Bottom salinity (‰) at high tide, inner Bristol Bay, July and August 1966.

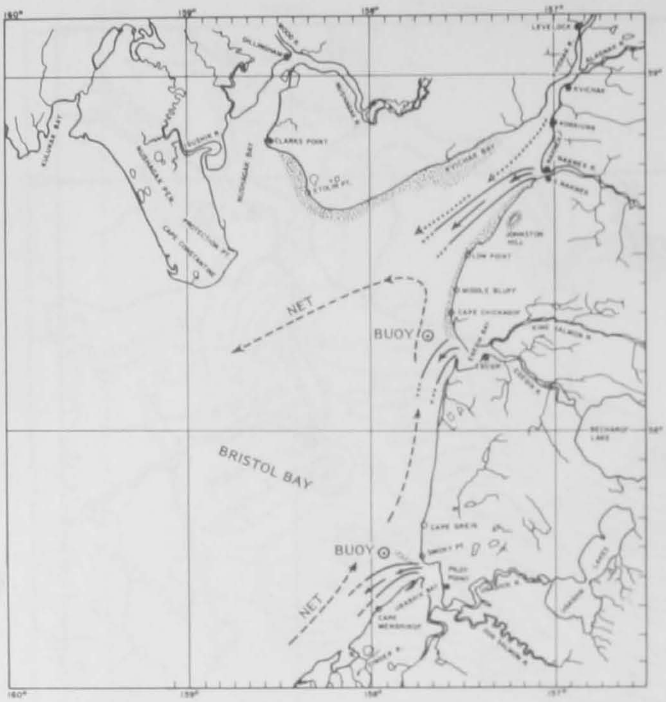

Figure 7.—Course of river waters in inner Bristol Bay on ebb tide as determined from course of dye releases in July and August 1965 and 1966. [Solid lines marking boundaries of river water denote area of actual observation; dotted lines indicate probable course; dashed lines indicate direction of net (nontidal) current. The direction of the net current is based on the results of previous oceanographic investigations (Dodimead et al. 1963) which showed a counterclockwise movement of water in this region.]

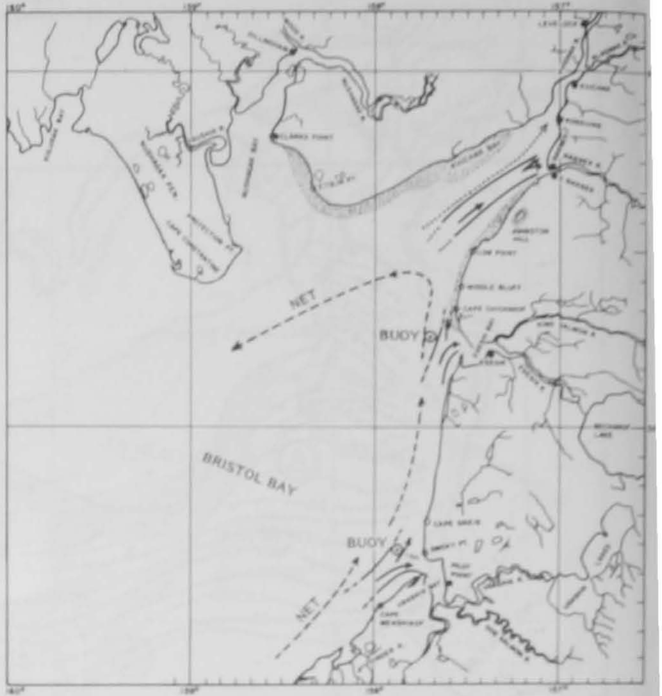

Figure 8.—Course of river waters in inner Bristol Bay on flood tide as determined from course of dye releases in July and August 1965 and 1966. [Solid lines marking boundaries of river water denote area of actual observation; dotted lines indicate probable course; dashed lines indicate direction of net (nontidal) current. The direction of the net current is based on the results of previous oceanographic investigations (Dodimead et al. 1963) which showed a counterclockwise movement of water in this region.]

tide at least 4.8 km north (above) of the mouths of Naknek, Egegik, and Ugashik rivers. This water moved toward shore and over the tideflats.

The path of the dye was followed as the vessel traveled at a speed of 3 knots. The vessel's position was accurately maintained by reference to prominent landmarks, marker buoys, and bottom topography (determined by comparing fathometer readings with navigational charts of the area). Because of the low wind velocity (less than 15 knots), the only factor affecting the vessel's position was the tidal current. Dye was followed visually for about 1 to 2 h after it was released; thereafter a fluorometer (Turner Model III) was used to detect it. Continuous sampling was carried out by pumping water from a depth of 1 m through the fluorometer as the vessel moved through the water. When readings indicated no dye was present, the course was altered 180° so that the dye patch was reentered.

Corrections for background fluorescence were applied to fluorometer readings during the tracking phase of the tracer studies. These were determined by running samples of pure river water from each of the rivers to be studied through the fluorometer and recording the instrument's dial readings. In addition, waters along the course of proposed tracer releases and the offshore portion of the study area were also sampled to determine the level of possible interfering background fluorescence. Only fluorometer dial readings above these background levels were considered to indicate the presence of dye.

Shear Lines.—Shear lines caused by adjoining currents having different speeds or directions affected the distribution of dye during ebb tide. These lines, a characteristic feature of the inner bay, were seen during relatively calm weather. They were not present during the flood tide but reformed, usually with some lateral variation of the axis, during the following ebb tide. The distribution of dye indicated that these lines marked the boundaries between waters leaving Naknek and Kvichak rivers and between the offshore water flowing seaward and the waters entering the bay from Egegik and Ugashik rivers. When surface turbulence was minimal, shear lines were observed about 6.5 km seaward from the mouth of the Naknek River. In Figure 7, the outer boundary denoting the course of the rivers corresponds to the general location of the shear lines. Dye released into Naknek, Egegik, and Ugashik rivers never crossed well-developed shear lines. Farther offshore the shear lines were not well developed and the dye dispersed laterally to some extent, no doubt because of decreased velocities and less difference in direction of separate currents. The northward extent of individual river waters during flood tide could not be identified by shear lines (Fig. 8).

The area of Kvichak Bay not occupied by Naknek River water was occupied by Kvichak River water (Figs. 7, 8). Kvichak River had a much greater volume of discharge than Naknek River, as indicated by the lower salinity on the northwest side of Kvichak Bay (Figs. 3, 6). Undoubtedly, waters of these two rivers mixed along their interface, particularly farther seaward during ebb tide when current velocities were reduced. Mixing between water masses also took place during flood tide, but Kvichak River water was predominant along the northwest shore and Naknek River water along the southeast shore of Kvichak Bay.

River runoff in this area moved southwest toward the northwest side of inner Bristol Bay (Fig. 7). By the time these waters had moved seaward as far as the Middle Bluff area, they were more than 8 km offshore. This movement of less saline water may be inferred also from the salinity distribution (Figs. 3, 6).

The course and distribution of Egegik River water is also clearly seen in the salinity distribution off the entrance to Egegik Bay (Figs. 3, 4). Salinity data were not obtained from the entrance of Ugashik Bay, but dye studies showed that the salinity pattern there should be similar to the one off Egegik Bay.

Plotting River Waters From Drift Cards

The drift card used in this study was developed by Martin (1967). It is made of a folded sheet (22 × 28 cm) of international orange plastic. A polystyrene float attached by galvanized staples to one end and a lead weight attached to the opposite end keep the card vertical in the water. The cards are serially numbered and bear printed instructions to the finder and spaces for recording requested recovery information.

On 2 June 1967, 1,007 cards were released at eight locations along the northeast side of inner Bristol Bay (Table 1). They were released in groups of 10 from an aircraft between 1 and 2 h after high slack tide so that those released near river mouths and bay entrances would move immediately out into the bay.

Cards were recovered in two ways: 1) I collected cards from beaches during aerial surveys conducted 6 wk or more after the cards were released, and 2) commercial salmon gill net fishermen returned cards which drifted into their area of operation. Of the 1,007 cards released, 141 were recovered (Table 1). The locations of recovery and resultant directions of drift are shown in Figures 9 to 16. Eighty-nine (8.8%) cards were recovered from beaches; parts of 31 more cards were also found on beaches but were unusable because they had lost identifying serial numbers.

Table 1.—Number and percent of drift cards recovered from releases in eight areas of inner Bristol Bay, 2 June 1967.

Release location (Figs. 9-16)	No. cards released	Cards recovered	
		Number	Percent
Kvichak River mouth	102	33	32.4
Naknek River mouth	100	44	44.0
Cape Chichagof	150	11	7.3
Egegik Bay entrance	101	5	4.9
Lat. 58°N	152	14	9.2
Cape Greig	151	21	13.9
Ugashik Bay entrance	101	4	4.0
Cape Menshikof	150	9	6.0
Total	1,007	141	14

Figure 9.—Recovery locations of drift cards released across Kvichak River mouth, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

The direction of drift for cards released across the mouths of the Kvichak and Naknek rivers (Figs. 9, 10) was seaward in a southwesterly direction. Most cards recovered from these two releases were found between Naknek River mouth and Johnston Hill. The concen-

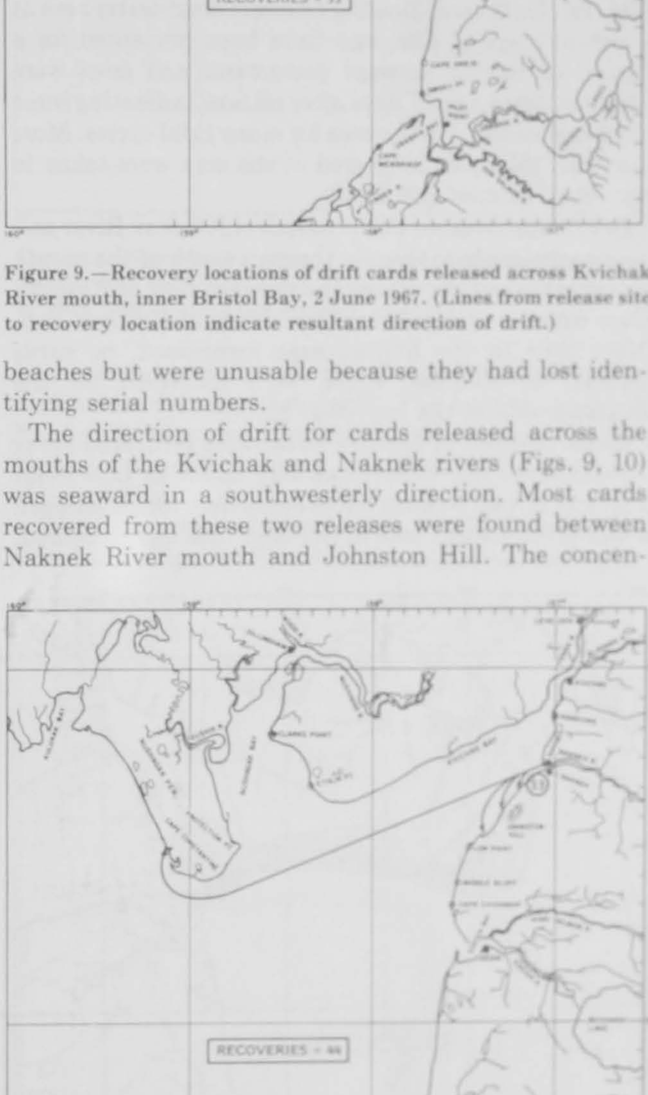

Figure 10.—Recovery locations of drift cards released across Naknek River mouth, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

tration of cards in this area was probably due to several factors. Water leaving Naknek River during the first several hours after high slack water moves seaward along the southeast side of Kvichak Bay. This movement must also occur for water above the Naknek River mouth along the east side of Kvichak River. Once the water level has dropped enough, the influence of a gravel bar off the entrance to Naknek River causes the main stream of Naknek River water to be directed farther offshore, and the water moving seaward along the east side of Kvichak River is also directed farther offshore. These flows converge and cause the shear line in the Naknek River mouth mentioned earlier. The emergence of the gravel bar at ebb tide also causes an eddy seaward of the bar which extends as far as the northern end of Johnston Hill (Fig. 10). Drift cards floating into this dead-water area at a certain stage of tide may have been prevented for a time from further seaward movement, and most were recovered from 2 to 17 days after release, indicating some had been confined in the area for many tidal cycles. More than half the cards recovered in the area were taken in stationary salmon gill nets.

Drift cards released in the mouth of Kvichak River and recovered elsewhere than in the area south of the mouth of Naknek River show that the seaward flow of Kvichak River water is along the northwest side of Kvichak Bay. Other than in the limited area mentioned, no cards released in Kvichak River were recovered on the southeast side of the bay (Fig. 9).

Cards released in Naknek River were recovered along the southeast side of Kvichak Bay as far as Low Point (Fig. 10), but no Naknek River cards were found seaward of this point on this side of the bay. One was recovered, however, on the west side of Nushagak Peninsula, indicating that the route of Naknek River water is offshore and toward the northwest side of inner Bristol Bay.

Drift cards released off Cape Chichagof and the entrance to Egegik Bay (Figs. 11, 12) show that movement of these waters is across and toward the northwest side of inner Bristol Bay; one card from each release was recovered north of the release site.

An eddy similar to the one at the Naknek River mouth probably exists south of Egegik River also. Most cards released between Egegik and Ugashik rivers were eventually recovered on beaches south of Egegik Bay (Figs. 13, 14).

Recoveries of cards from releases along lat. 58°N (Fig. 13), off Cape Greig (Fig. 14), at the entrance to Ugashik Bay (Fig. 15), and off Cape Menshikof (Fig. 16) show the course of the water to be north along the coast and ultimately toward the northwest side of Bristol Bay. No cards from any of these four releases were recovered to the south.

The distribution of drift cards furnished direct evidence on the courses followed by Kvichak, Naknek, Egegik, and Ugashik river waters in Bristol Bay and on the influence of the net or nontidal current on this pattern. The course followed is consistent with the course inferred from the horizontal salinity distribution in the area and from results of the tracer studies.

SYNOPSIS OF DISTRIBUTION OF RIVER WATERS

Results of the three methods of investigation permit a reasonable synopsis of the distribution of waters of the

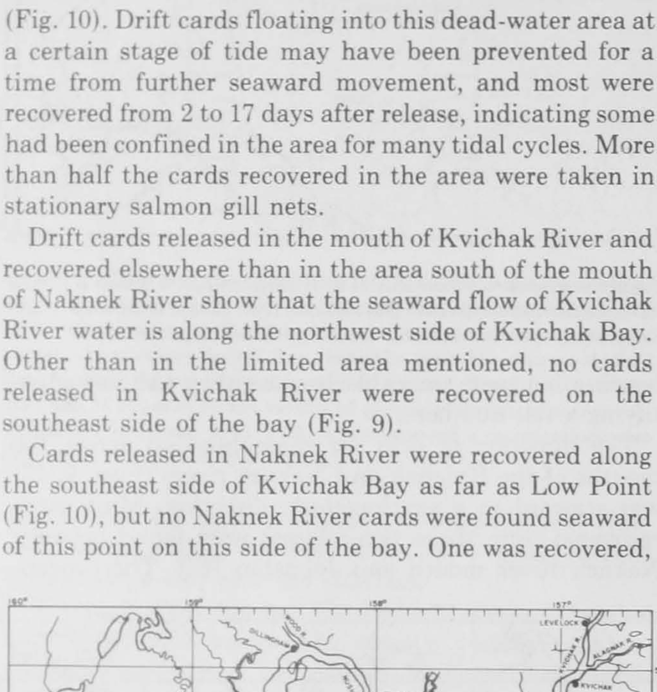

Figure 11.—Recovery locations of drift cards released off Cape Chichagof, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

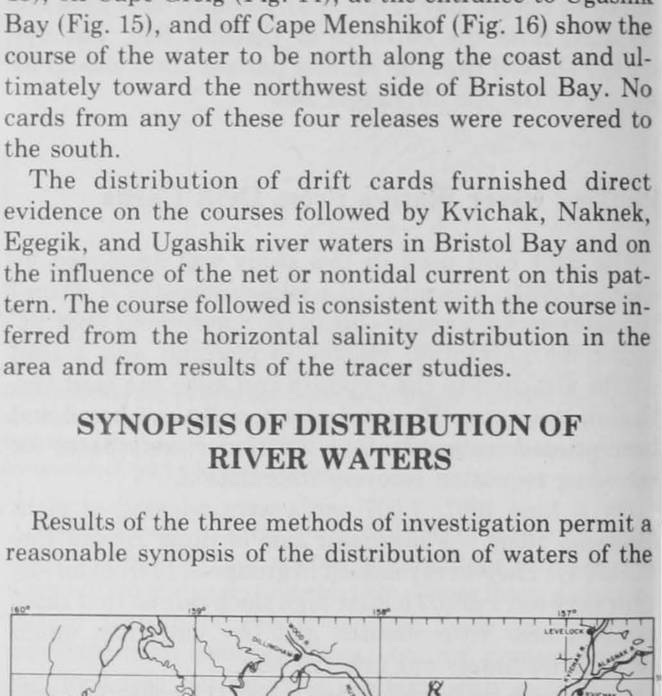

Figure 12.—Recovery locations of drift cards released across entrance to Egegik Bay, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

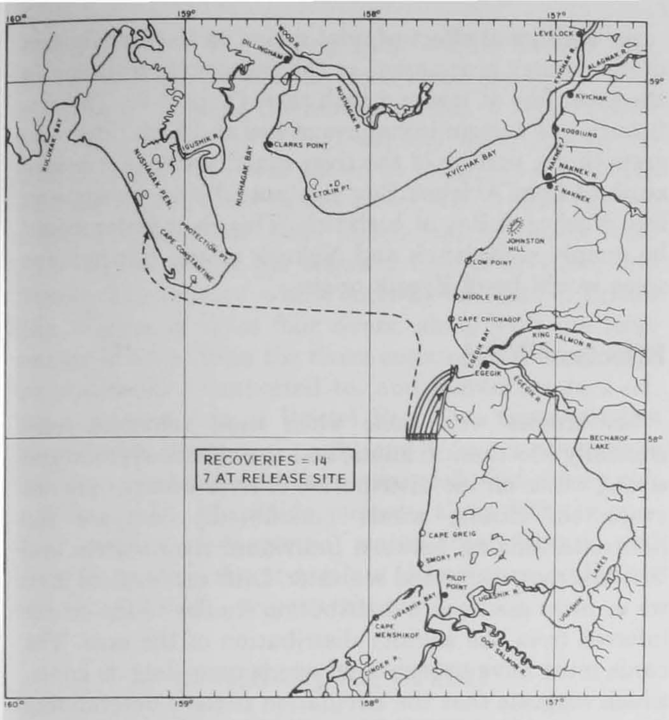

Figure 13.—Recovery locations of drift cards released along lat. 58°N, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

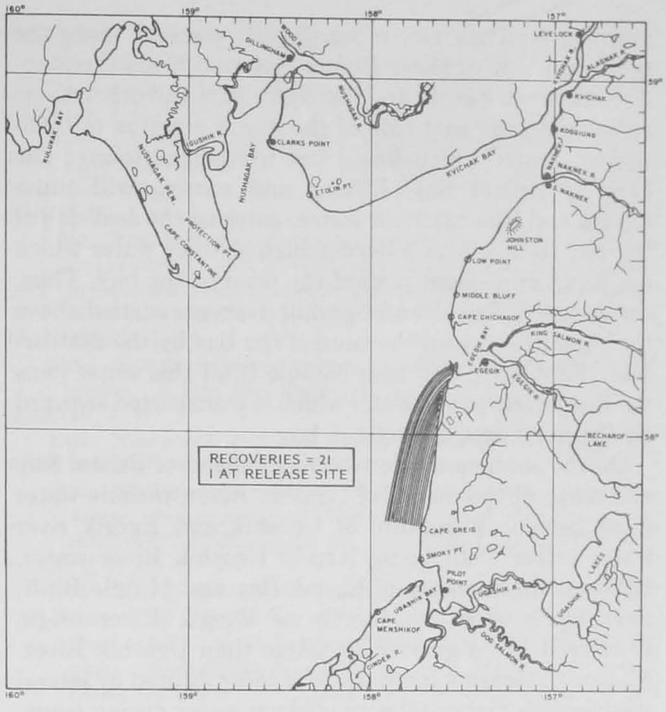

Figure 14.—Recovery locations of drift cards released off Cape Greig, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

major sockeye-salmon-producing river systems in inner Bristol Bay. The net seaward flow of river runoff water is along the northwest side of the bay, and the apparent net motion of seawater is toward the head of the bay on the southeast side.

The vertical distribution of salinity shows that the inner bay and the lower reaches of the rivers are vertically homogeneous. As a result, the circulation pattern in this region does not vary with depth. The motion toward the head of the bay, as pointed out earlier, extends to and perhaps somewhat above the Middle Bluff area in Kvichak Bay.

The distribution of salinity (Figs. 3-6) and the routes of drift cards (Figs. 9-16) both indicate that waters of rivers

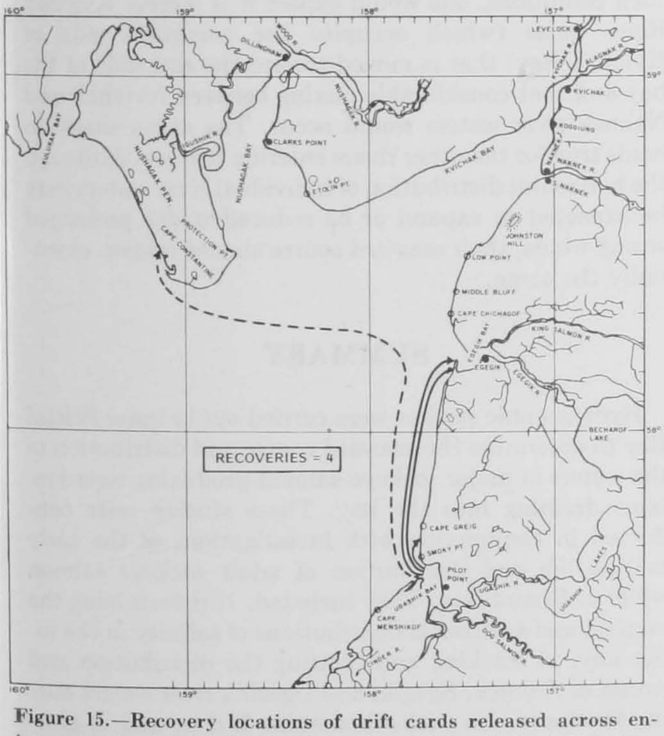

Figure 15.—Recovery locations of drift cards released across entrance to Ugashik Bay, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

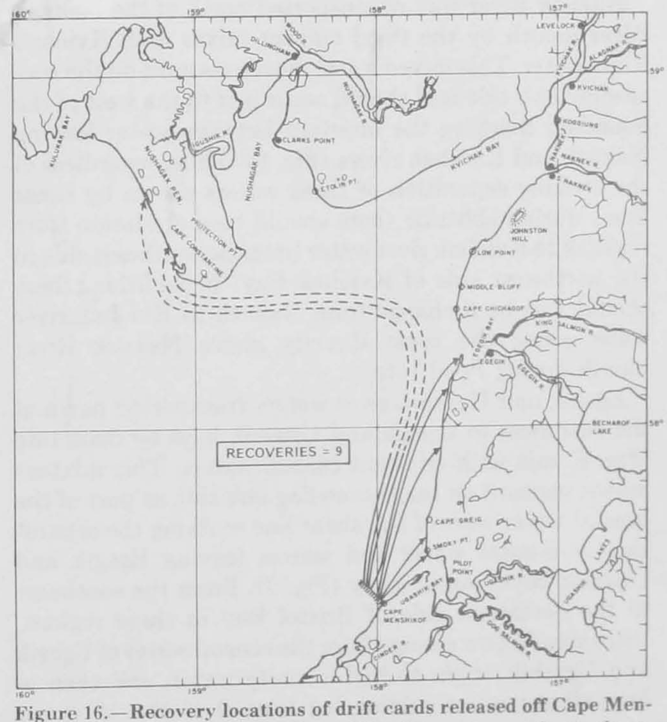

Figure 16.—Recovery locations of drift cards released off Cape Menshikof, inner Bristol Bay, 2 June 1967. (Lines from release site to recovery location indicate resultant direction of drift.)

draining Kvichak Bay move directly seaward along the northwest side of inner Bristol Bay past Cape Constantine. Between Egegik and Ugashik rivers and other rivers entering on the east side of the bay is a region of high-salinity water which has a net movement toward the head of Bristol Bay. Mixing and stirring will cause Egegik and Ugashik river waters entering the east side of the bay to mix with adjacent high-salinity water which has a net movement toward the head of the bay. Thus, the waters of Egegik and Ugashik rivers are carried above their mouths toward the head of the bay by the net current (Figs. 7, 8), and near Middle Bluff this water joins the flow of less saline water which is transported seaward on the northwest side of the bay.

On the southeast side toward the head of Bristol Bay and north of the mouth of Ugashik River, inshore water must become a mixture of Ugashik and Egegik river water rather than being largely Ugashik River water. Between the entrance of Egegik Bay and Middle Bluff, river water must be largely of Egegik River origin because it has a greater discharge than Ugashik River. Moreover, Ugashik River water is being diluted by lateral mixing with higher salinity offshore water during transport toward the head of the bay. In the Middle Bluff area, Egegik River water should predominate, but some Naknek River water could also be present. Kvichak River water must be well offshore in this area.

Tidal Influence

Flood tidal currents carry some Naknek, Egegik, and Ugashik river waters north or above their respective outlets into Bristol Bay, which cover tideflats exposed at low tide (Fig. 8).

Naknek River water transported north of the Naknek River mouth by the flood current mixes with Kvichak River water. This mixed water moves seaward on the succeeding ebb tide and should occur just to the west of the boundary marking the interface between water leaving Naknek and Kvichak rivers (Fig. 9). Thus, regardless of the striking separation of these waters shown by shear lines, during ebb tide there should be a gradation from Naknek to Kvichak river water from the southeast side to the northwest side of Kvichak Bay. In addition, there should also be a change from Naknek to Kvichak river water along the coast directly above Naknek River mouth during flood tide.

Egegik and Ugashik river waters transported north of the entrances to Egegik and Ugashik bays by flood tide (Fig. 8) mix with adjacent coastal waters. This mixture moves seaward on the succeeding ebb tide as part of the coastal water west of the shear line marking the separation of coastal water and waters leaving Egegik and Ugashik bays, respectively (Fig. 7). From the southeast to the northwest side of Bristol Bay in these regions, there should be a change from the coastal water of Egegik and Ugashik origin to high-salinity water, and then to low-salinity water originating from 9 of the 10 major sockeye-salmon-producing rivers entering inner Bristol Bay.

An additional effect of tidal action on the distribution of river water is apparent in the salinity distribution in the inner bay at low and high tides (Figs. 3-6). The distribution of certain isohalines at low and high tides suggests that a portion of the river runoff water that moves seaward from Kvichak Bay may actually be transported into Nushagak Bay at high tide. This river water would be mainly of Kvichak and Naknek origin, but perhaps some would be of Egegik origin.

Effects of Wind

My studies were done when wind velocities were generally less than 15 knots, and the effects of prolonged strong winds on the distribution of river waters were not evaluated. Strong winds undoubtedly increase the horizontal mixing between individual river waters and between river water and seawater. Drift cards afloat for 6 wk or more assumed a distribution similar to the course inferred from the salinity distribution of the area. The cards must have encountered winds exceeding 30 knots, which suggests that the circulation pattern determining the course followed by all river waters to the northwest side of inner Bristol Bay may not have changed during periods when winds exceeded 15 knots.

In the summer months, winds in Bristol Bay are generally from the southeast, and because the movement of surface water is to the right of wind direction in the Northern Hemisphere (Sverdrup et al. 1942), these southerly winds move water onshore or toward the head of Bristol Bay. Prolonged periods of strong winds may be expected then to expand or reduce the horizontal distribution of given river waters in the inner bay. Under such conditions, one would expect it is largely Kvichak River water (which occupies the northwest side of Kvichak Bay) that is moved toward the east side of the bay and that considerable mixing between Kvichak and Naknek river waters would occur. The same situation holds true for the other rivers entering the bay. Although the horizontal distribution of individual river waters may be expected to expand or be reduced under prolonged strong winds, their seaward course should remain essentially the same.

SUMMARY

Hydrographic studies were carried out in inner Bristol Bay to determine the seaward course and distribution of the waters of major sockeye-salmon-producing river systems draining into the bay. These studies were conducted in conjunction with investigations of the early marine life and distribution of adult sockeye salmon while in Bristol Bay. They included: 1) determining the vertical and horizontal distributions of salinity in the inner bay; 2) tracking and plotting the distribution and course of Naknek, Egegik, and Ugashik river waters during flood and ebb with Rhodamine B dye; and 3) plotting the seaward course of plastic drift cards released at several locations in inner Bristol Bay.

The results of the hydrographic studies showed that the net seaward flow of the lighter and less saline river runoff water is along the northwest side of inner Bristol Bay. The net motion of high-salinity water toward the head of Bristol Bay was shown to transport with it the waters of Ugashik and Egegik rivers, which enter the bay on the southeast side. Near Egegik Bay to Middle Bluff these waters joined the seaward flow of Kvichak and Naknek river waters, which enter at the head of Bristol Bay. Waters of these four rivers, along with the large volume of water from the rivers entering Nushagak Bay, are eventually transported to, and moved seaward on, the northwest side of Bristol Bay. Dye tracer studies showed that Naknek, Egegik, and Ugashik rivers were similar to each other in the courses followed during ebb and flood tides. Flood tide currents, along with the nontidal current, transported water from Egegik and Ugashik rivers above or north of the entrance to Egegik and Ugashik bays, respectively.

LITERATURE CITED

DODIMEAD, A. J., F. FAVORITE, and T. HIRANO.
1963. Salmon of the North Pacific Ocean, Part II. Review of oceanography of the Subarctic Pacific region. Int. North Pac. Fish. Comm., Bull. 13, 195 p.

DONALDSON, L. R., and G. H. ALLEN.
1958. Return of silver salmon, *Oncorhynchus kisutch* (Walbaum), to point of release. Trans. Am. Fish. Soc. 87:13-22.

HARA, T. J., K. UEDA, and A. GORBMAN.
1965. Electroencephalographic studies of homing salmon. Science (Wash., D.C.) 149:884-885.

HASLER, A. D.
1966. Underwater guideposts; homing of salmon. Univ. Wis. Press, Madison, 155 p.

HASLER, A. D., and W. J. WISBY.
1951. Discrimination of stream odors by fishes and its relation to parent stream behavior. Am. Nat. 85:223-238.

HEBARD, J. F.
1959. Currents in southeastern Bering Sea and possible effects upon king crab larvae. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 293, 11 p.

JOHNSON, J. W.
1960. The effect of wind and wave action on the mixing and dispersion of wastes. *In* E. A. Pearson (editor), Proceedings of the First International Conference on Waste Disposal in the Marine Environment, p. 328-343. Pergamon Press, N.Y.

McINERNEY, J. E.
1964. Salinity preference: an orientation mechanism in salmon migration. J. Fish. Res. Board Can. 21:995-1018.

MARTIN, J. W.
1967. New plastic drift card. Limnol. Oceanogr. 12:706-707.

PRITCHARD, D. W., and J. H. CARPENTER.
1960. Measurements of turbulent diffusion in estuarine and inshore waters. *In* Symposium on Tidal Rivers, Helsinki, p. 1-14. [John Hopkins Univ., Chesapeake Bay Inst., Collect. Repr. 4:101-114.]

STRATY, R. R.
1974. Ecology and behavior of juvenile sockeye salmon (*Oncorhynchus nerka*) in Bristol Bay and the eastern Bering Sea. *In* D. W. Hood and E. J. Kelley (editors), Oceanography of the Bering Sea with emphasis on renewable resources, p. 285-320. Proc. Int. Symp. Bering Sea Study. Univ. Alaska, Inst. Mar. Sci., Occas. Publ. 2.
1975. Migratory routes of adult sockeye salmon, *Oncorhynchus nerka*, in the eastern Bering Sea. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-690, 32 p.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING.
1942. The oceans, their physics, chemistry, and general biology. Prentice-Hall, N.Y., 1087 p.

U.S. COAST and GEODETIC SURVEY.
1964. U.S. Coast Pilot 9, Pacific and Arctic coasts, Alaska, Cape Spencer to Beaufort Sea. 7th ed. U.S. Dep. Commer., Coast and Geodetic Survey, 348 p.

WISBY, W. J., and A. D. HASLER.
1954. Effect of olfactory occlusion on migrating silver salmon (*O. kisutch*). J. Fish. Res. Board Can. 11:472-478.