Fraser River Estuary

The Fraser is one of the world's major rivers and no description of the Strait of Georgia region would be complete without a few specifics about the oceanographic setting of its estuary. Volumes could be written on this subject alone, but only some highlights will be touched on here.

Through an intricate network of tributaries, the Fraser River drains approximately 230,000 km^2 (90,000 mi^2) of British Columbia or about ¼ of the province. The river originates in the Rocky Mountains near Jasper, Alta., 1370 km from its mouth, descends rapidly until it reaches Hope, then spreads to a flat alluvial valley to begin a 160 km journey to the Strait of Georgia. In addition to the largest salmon runs of any river in North America, its silt-laden waters have formed the largest estuary on the Pacific Coast of Canada and support important fish and wildlife populations. The delta provides fertile agricultural land and building lots for the sprawling population of the lower mainland. Deep-sea vessels can navigate the main channel to New Westminster, 30 km upstream from the Strait (Fig. 10.26). (Millions of tonnes of sediment must be dredged annually to maintain a 9.8-m draught on a 3.7-m tide.) A northern arm separates from the main channel at New Westminster and is navigable to ships with a 3.7-m draught. The mouth of the Fraser River adjoins the Strait of Georgia along a 37-km delta-front from Point Grey to Point Roberts Peninsula. An abandoned portion of the delta-front extends 13 km east from Point Roberts and faces into Boundary Bay. Roughly 75% of the total river outflow into the Strait is discharged through the South (main) Arm, with the remaining outflow divided among the North Arm (15%), the Middle Arm (5%), and Canoe Pass (5%).

For geographical purposes, New Westminster can be considered the head of the estuary. At the end of the last ice age 8000 yr ago, it was there the river began to fan out as a deltaic plane. Since then, the delta has been adding sediments at a rate of 12 million m^3/yr and has formed deposits 100–200 m thick over glacial deposits. Estimates presently indicate that the front of the delta off Sturgeon Bank is advancing seaward at 2.3 m/yr at the low water mark and 4.6 m/yr at a depth of 30 m. By comparison, the southern end of Roberts Bank is thought to be retreating inland at around 12 m/yr at a depth of 30 m.

Winds

As with the Strait of Georgia proper, the Fraser River estuary is influenced by the large-scale pressure systems that develop over the coast. However, the valley and local mountains somewhat alter the winds associated with these systems. Thus, although maximum hourly winds blow from the northwest and occasionally from the southwest, the prevailing direction is easterly. During the summer, local winds are dominated by the sea–land breeze circulation; the eastward blowing sea breeze sets up around 10 A.M., strengthens until midafternoon to about 5.0–7.5 m/s (10–15 kn) and then dies away before sunset. The weaker land breeze blows onto the Strait until early morning. In winter, strong outflows of cold arctic air pour down the Harrison and main Fraser valleys to augment the comparatively light land breezes associated with nighttime cooling. Though the northern portions of the estuary, such as Sea Island, are partially protected from the full strength of these winds by local topography, northeast

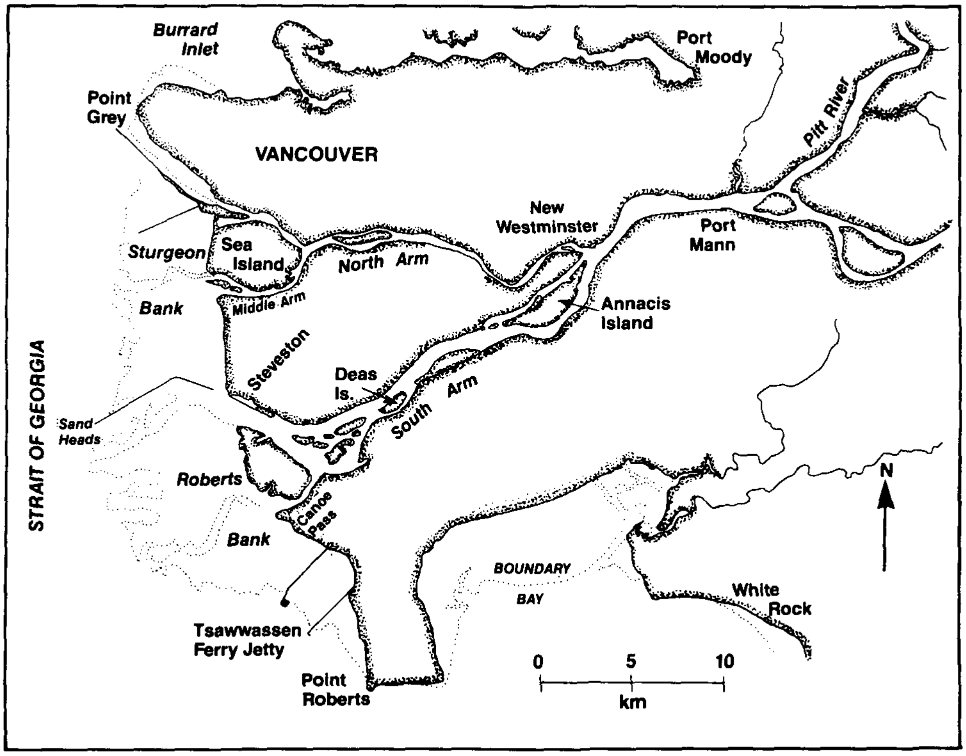


FIG. 10.26. Lower Fraser River valley.

winds in excess of 15 m/s (30 kn) often blow across the more exposed areas of the estuary to the south. The Tsawwassen Ferry causeway can be an especially chilly place in winter when cold Arctic air is sweeping the Fraser Valley.

Periods of calm airs occur less than 10% of the time over the estuary; they are twice as likely to occur in fall as in spring and are most frequent at night and early morning. Episodes of light winds (0–3 m/s) persist for days, and are most frequent in fall and winter (50%) and least frequent in spring (20%).

Fog

Fog is infrequent in March through August but begins in September and is most likely to develop in October through February; 80% of all foggy days occur in these 5 mo. For the most part, fog is the radiation-type, formed by the ground cooling on clear, calm nights and, therefore, is usually most dense in early morning just before sunrise. The frequency of fog by industrial pollutants and domestic fuel consumption has decreased significantly in recent years. Periods of fog visibilities less than 1 km dropped from 104 days in 1943 to 35 days in the late 1960s, due perhaps to the changeover from sawdust to natural gas as the main source of heat for residential homes. There are fewer fine solid particles in the air for water drops to condense on, so "pea-soup" fogs are less common throughout the entire lower mainland.

River Discharge

As noted earlier, the volume of fresh water carried by the Fraser River varies considerably from year to year. It also changes with season and has marked fluctuations over periods of a few days. Snow-melt, which constitutes about two-thirds the total runoff, begins in April and runoff increases to a maximum in late May and early June (Fig. 10.19). By late August, the river discharge has significantly diminished and by early December has reached the low level it will maintain until the following spring. The average daily discharge measured at Hope between 1912 and 1956 ranged from 570 m^3/s (20,000 ft^3/s) in winter to 8800 m^3/s (310,000 ft^3/s) in summer. Discharge rates increase downstream of Hope; are approximately 20% greater at Mission, and 30% greater at Port Mann. The largest daily flow on record 15,200 m^3/s (536,000 ft^3/s) was on May 31, 1948, when over 220 km^2 of the lower Fraser Valley were flooded; the lowest daily flow of 340 m^3/s (12,000 ft^3/s) was Jan. 8, 1976.

Tides

As with any channel that opens onto a coastal basin, the lower portion of the Fraser River is influenced by the tide at its entrance. As it is moving into a river channel, however, the nature of the tide is affected by the volume of water carried downstream and by the relatively shallow depths of the channel. During the winter period of low discharge, for example, the tidal influence reaches as far as Chilliwack, 120 km upstream of Sand Heads, but during the high-discharge freshet it reaches only to Mission, 75 km upstream. The river discharge also affects the daily range of the tide along the river while the shallowness of the river causes a particular stage of the tide to be delayed compared with the tide in the Strait of Georgia. These features can be seen in *Canadian Tide and Current Tables*, Vol. 5, for the Fraser River, where the predicted tide heights at three river locations, Steveston, Deas Island, and New Westminster were determined on the basis of the corresponding tide height at Point Atkinson at four different runoff stages.

The main effects of river discharge on Fraser River tides can be summarized as follows: (1) like tides in the Strait of Georgia, the tide in the river is mixed, mainly semidiurnal, but there is a marked up-river decrease in the diurnal inequality associated with the up-river decrease in the daily range of the tide (Fig. 10.27). The greatest tidal

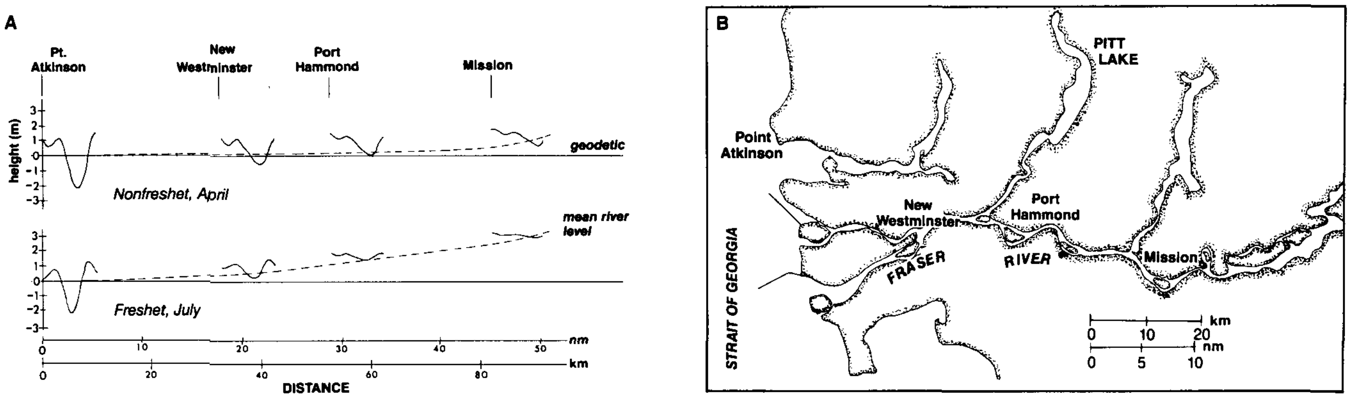


FIG. 10.27 (A) Upstream modification of tide in main arm of Fraser River. *(left)* tidal curve over a 24-h period at Point Atkinson, height measured in metres relative to geodetic (local mean sea level). Remaining curves show upstream alteration of tidal cycle as measured relative to mean river level (broken line) for both nonfreshet and freshet conditions. (B) Map of area. (Modified after Ages and Woollard 1976)

range at any one time is found near the river mouth at Sand Heads, which has a mean range of 3.1 m and a large (spring) tide range of 4.8 m; (2) the disparity between the tide range in the Strait and in the river is *least* at times of low runoff. During large spring tides of 4.9 m at Point Atkinson, for instance, the range at low runoff periods varies from 3.9 m at Steveston to 3.1 m at Deas Island, to 2.3 m at New Westminster; and, (3) the disparity between the tide range in the Strait and in the river is *greatest* at times of large runoff. For the above spring tide at Point Atkinson and a typically large discharge rate, the tidal range varies from 3.3 m at Steveston to 2.1 m at Deas Island, to 0.8 m at New Westminster.

Tides in the river are always delayed relative to the Strait of Georgia. Starting at Sand Heads, a particular stage of the tide occurs progressively later as the tidal wave progresses inland. Although it may seem strange at first, the magnitude of the river discharge has a negligible effect on this delay below New Westminster. The height of the tide at the river mouth is important. For example, a large spring tide of 5.0 m in the Strait will be delayed by only 5 min at Steveston, 10 min at Deas Island, and 50 min at New Westminster; on the other hand, a small neap tide of 0.5 m will be delayed 25 min at Steveston, 70 min at Deas Island, and 180 min at New Westminster. Curves in Fig. 10.28 give the time delay of the tide at three river locations referred to Point Atkinson. In general, high waters at New Westminster occur around 1 h later than those in the Strait of Georgia, and low waters about 2 h later. A portion of the increasing tides also propagates into Pitt Lake via Pitt River, a few kilometres upstream of New Westminster. Delays in high and low water are typically around 1–2 h in the lake relative to New Westminster; the range of the tide is commonly around 1 m.

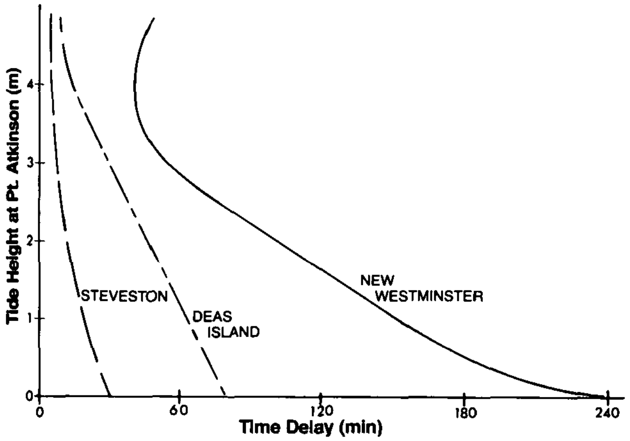


FIG. 10.28. Tidal heights and time differences in main arm Fraser River. Curves give time in minutes that low or high water at each location lags that at Point Atkinson for given tide height. In general, added time for tide to propagate up river from Strait of Georgia decreases as height of tide increases. (Adapted from *Canadian Tide and Current Tables* Vol. 5, 1979)

The previous features raise two important questions. Why are low tides delayed more than high tides? And, why doesn't the river rate affect the delay of the tides? Because the average depth, D, of the river channel is 10 m it should theoretically take slightly less than 1 h for the tidal wave to travel from Sand Heads to New Westminster at normal propagation speed, $C = \sqrt{gD}$. This alone accounts for delay of high water along the river; it is simply due to the finite time it takes the tide to propagate along the river channel. However, because adding or subtracting a few metres of tide to the river depth, D, doesn't significantly alter this speed, the longer delays of low waters are not directly due to changes in river depth. Instead, as the tide begins to fall below its mean level, bottom friction becomes increasingly important and acts to retard the seaward retreat of the water; the lower the tide the shallower the river and the greater the frictional drag. As a consequence, tides in the river rise much more quickly than they fall, though the whole process still takes just over 12 h (Fig. 10.29). Moreover, the tidal wave is unaffected by the runoff because associated tidal streams are independent of the river current. Flood currents associated with the rising tide at the river mouth oppose the river flow to cause a net slowdown in the downstream flow and a subsequent backing-up of water that travels upstream as a high-water bulge. Ebb currents formed at the river mouth on a falling tide augment the river flow to cause a net speed-up in the seaward flow and a subsequent lowering of the water level that moves upstream as a low water depression. The amount of runoff determines the average slope of the river surface but doesn't affect the strength of the tidal streams. In effect, the tide "diffuses" up-river as if the river flow were nonexistent.

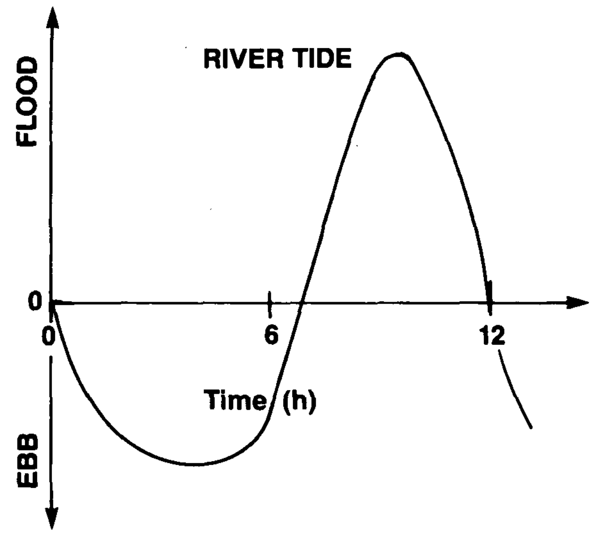


FIG. 10.29. Tidal streams in river. Ebb is weaker but longer duration than flood.

Flow Reversals

During the winter low-runoff period, moderate to strong flood streams can reverse the river flow as far as Mission; the strength of the reversal diminishes upstream. At times of large freshet, the flow is outward at all stages of the tide all the way to the mouth.

A unique feature of the river system is the negative delta that has formed at the southern end of Pitt Lake.

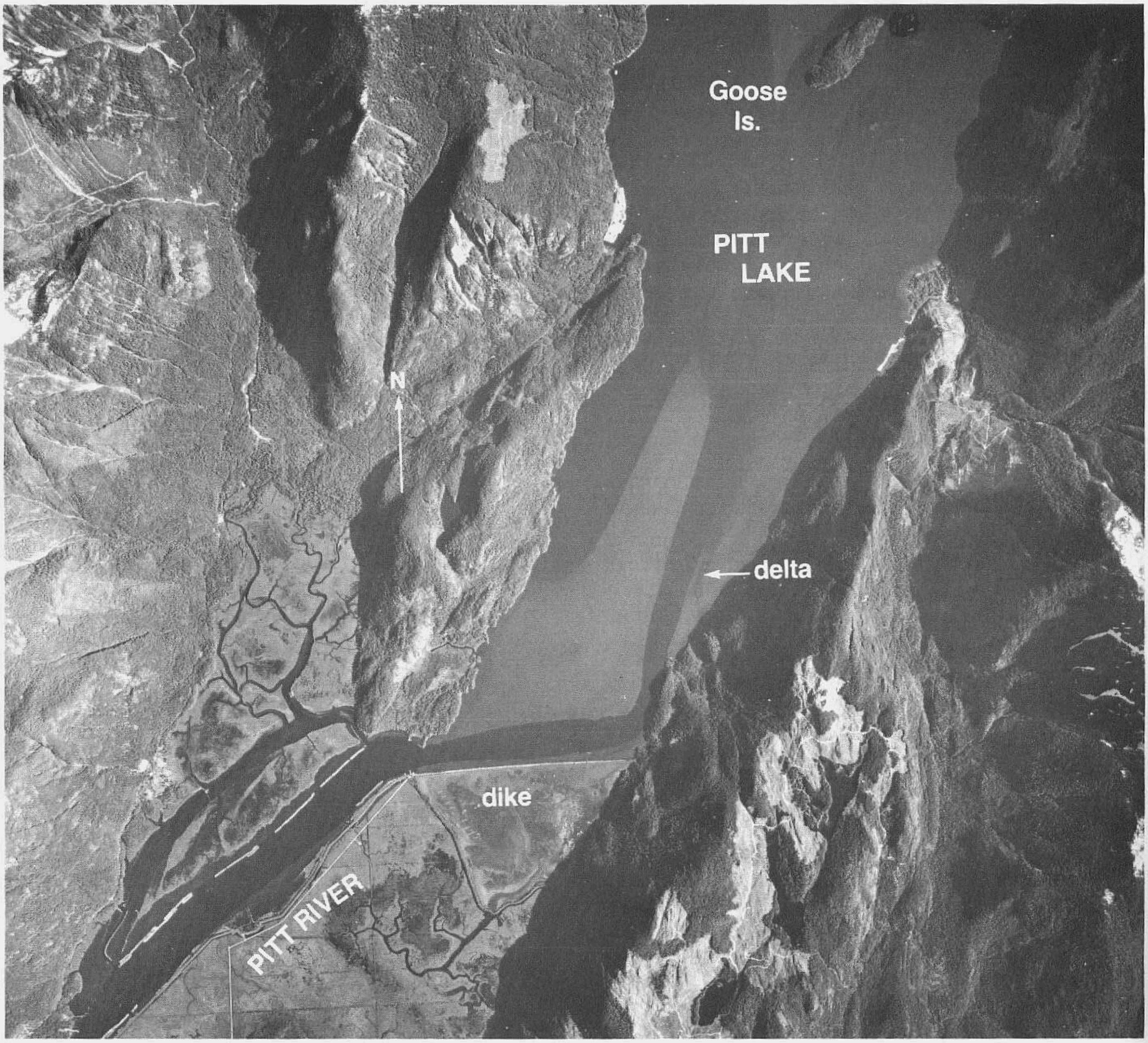


FIG. 10.30. Aerial photograph of lower Pitt system. Delta formed at south end of Pitt Lake by upstream movement of Fraser River sediments along Pitt River to lake. Pitt tidal delta has advanced 6 km into lake in last 4700 yr, average rate 1.28 m/yr. (Ashley 1977; British Columbia Government Photo 1954)

Sediment is carried into the lake at its seaward end contrary to the direction of the Pitt River (Fig. 10.30). The reason for this apparent paradox is that flood streams associated with the tide that enters the lake create stronger currents than the combined ebb stream and river flow, though the latter are of longer duration. As the stronger flood currents can move the sediments more readily than the weaker ebb currents, sand moves upstream into the lake. Maximum floods occur in winter and can attain speeds of 50 cm/s (1 kn) at the entrance to the lake; in summer the larger flood streams are only a fraction of this speed.

Salt Wedge

Currents in the tidally influenced region of the Fraser River below New Westminster regularly have characteristics of an intensified version of the estuarine-type circulation in fiords. On a large flood, a wedge of clear, salty water from the Strait of Georgia will work its way up-river along the bottom, despite the fact that the fresh silty water above is flowing swiftly downstream (Fig. 10.31). On occasion, this salt wedge may penetrate as far as Annacis Island, 22 km upstream of Steveston, before it is swept out with the ebb. The time of maximum intrusion appears to lag behind high water at the river mouth by 60–80 min.

Reversals in the direction of the currents with depth at the seaward end of the estuary may be quite abrupt when the salt wedge is in the river. Within the lower reaches of the Main Arm, 100 cm/s (2 kn) down-river flow at the surface is often accompanied by a 50 cm/s (1 kn) up-river flow at a depth of only 6 m or so (Fig. 10.32).

The maximum upstream distance of penetration of

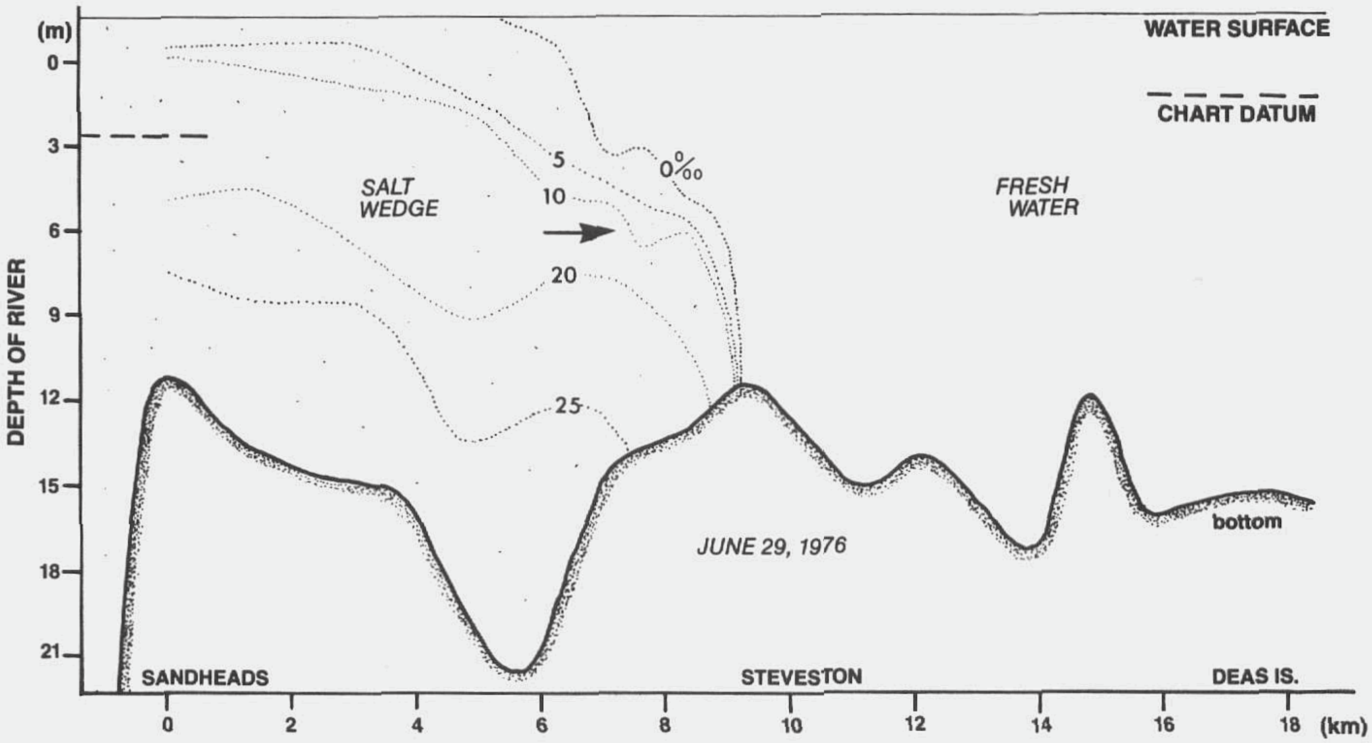


FIG. 10.31. Position of salt wedge in main arm Fraser River near high tide in freshet runoff conditions, June 1976; River depth (m), salinity (‰). During nonfreshet (winter) runoff, same salt wedge could penetrate upstream past Deas Island. (Adapted from Ages 1979)

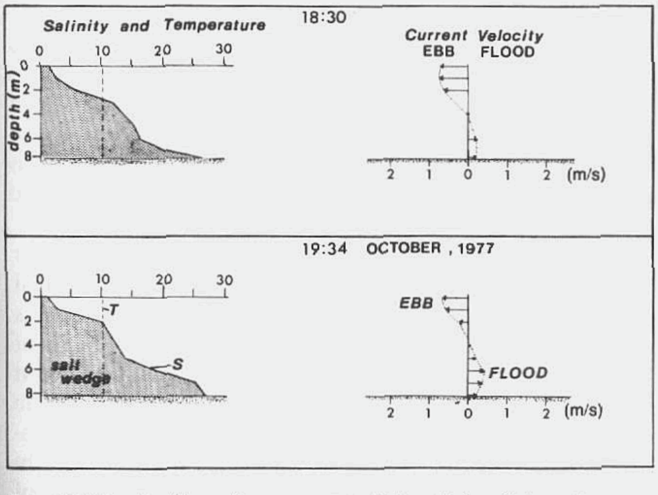


FIG. 10.32. Profiles of temperature (°C), salinity (‰), and current velocity (m/s) in Fraser River near mid-channel south of Steveston, Oct. 17, 1977, at 18:30 and 19:34 (PST). Water temperature uniform from top to bottom but salt wedge present. Currents reverse from outflow at surface to inflow at depth. (Adapted from Ages 1979)

the salt wedge depends on the strength of the river discharge. At low discharges, it may reach Annacis Island in the main channel and penetrate halfway along the shallower North Arm; at intermediate discharges the upstream penetration is limited to Deas Island tunnel in the Main Arm and the Oak Street Bridge in the North Arm. During large runoff peaks in summer, the salt wedge can penetrate only a short distance into the river.

Provided that river discharge is not so great nor the tide so low to prevent the salt wedge from entering, a deeply keeled vessel can actually drift upstream against the surface current of the river. To quote Dawson (1920) ". . . a deep-draught vessel which was being towed in, at a certain stage of the tide, was carried forward by the undercurrent faster than the tug with half the draught could make against the swift-running surface water. The tug had thus difficulty to avoid being over-run by the vessel it was towing."

Buoyancy

Ocean water is a few percent more dense than fresh water and, consequently, more buoyant. A swimmer floats higher in the "salt chuck" than in a lake because his body needs to displace a smaller volume of water to support his weight. By the same token, a boat proceeding into the Fraser River from the Strait of Georgia will experience a decrease in buoyancy when it encounters the river water and, if loaded to the gunwhales, may suddenly find its deck awash as its hull rides deeper in the water.

Burrard Inlet–Indian Arm

Unlike most west coast inlets, Burrard Inlet lacks a sill at the seaward entrance, is relatively shallow, is not bounded by steep, precipitous cliffs, and receives considerable fresh water from an external source, the Fraser River. Only at its eastern extremity does this marine indentation transform into a truly fiordlike setting (Indian Arm) nestled in the heart of the Coast Mountains (Fig. 10.33). But, what the inlet lacks in rugged beauty is compensated for by its socio-economic importance to British Columbia.

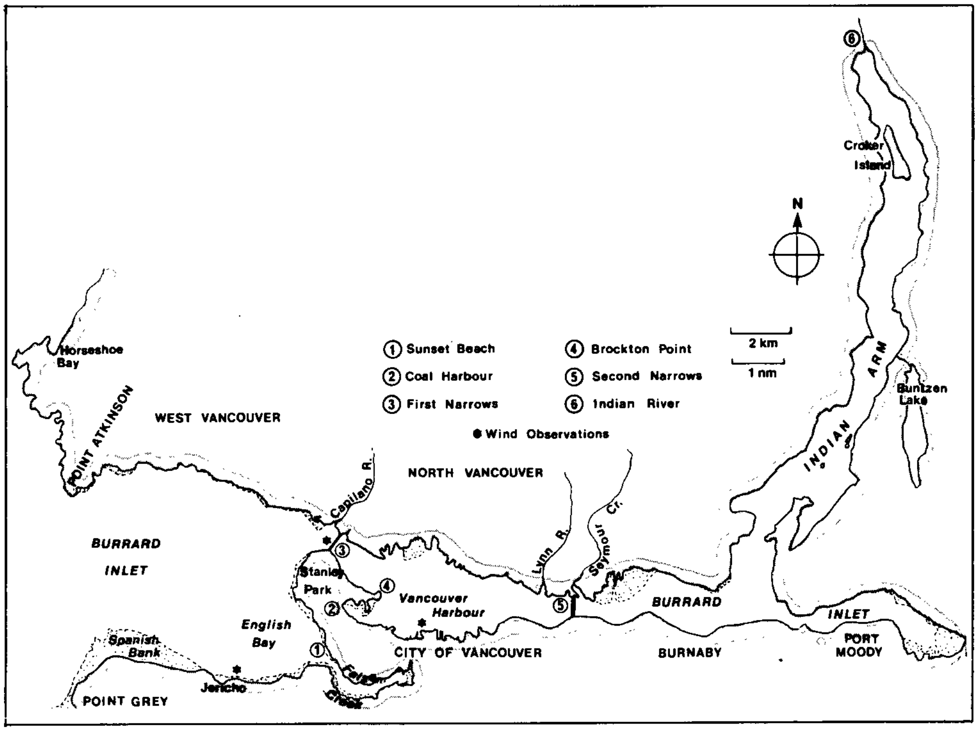


FIG. 10.33. Map of Burrard Inlet-Indian Arm. Also shown are wind observation locations for Table 10.1–10.3.

Burrard Inlet is divisible into an "inner" and "outer" basin. The relatively wide outer basin has a maximum breadth of 7 km and extends about 9 km from Point Atkinson to the First Narrows (Pl. 12) through one of the more densely populated areas of the province. The narrower, 3.5-km wide inner basin, Vancouver Harbour, extends a further 8.5 km eastward to the Second Narrows through the highly commercialized and industrialized sectors of Vancouver. Sandy beaches along much of the perimeter of the outer basin, against the backdrop of the local mountains and the skyline of the city, create a scenic recreational shoreline that is actively used throughout the year. This portion of the inlet is also heavily used by pleasure craft and provides an essential marine highway for commercial vessels. English Bay at the eastern extremity of the basin provides anchorage for as many as 16 deep-sea ships waiting to load or unload cargo at the ports of greater Vancouver. Within the inner basin, the foreshore has been greatly modified by landfill and dredging, and the few recreational areas that remain haven't been improved by industrialization.

Bathymetry

Water depths in the outer basin of Burrard Inlet decrease steadily eastward from a maximum of around 100 m in midchannel south of Point Atkinson to about 15 m over the sill at the First Narrows under the Lions Gate Bridge. There are extensive shallows less than 10 m deep along the southern shore at Spanish Bank and English Bay from Jericho Beach to the vicinity of Second Beach in Stanley Park. The deepest parts of the basin are within a broad trough that begins well into the Strait of Georgia and cuts eastward to the vicinity of First Narrows. An isolated, 30-m deep depression is located immediately outside the Narrows.

There are few dangerous shoals in the outer inlet and these are well charted. This does not, however, deter groundings. One of the most frequented grounding spots is the small shoal off Sunset Beach near the entrance to False Creek (Fig. 10.33). More than once, cutters from the nearby Coast Guard Station have had to free stranded sailboats in this area; on one occasion a "mariner" is reported to have navigated himself aground by a road map!

Within Vancouver Harbour, extensive shoals fan out from Stanley Park, and there is an isolated offshore shoal area near the eastern end. The maximum depth of 66 m is in the center of the basin. A wide swath from south of Capilano Creek to the vicinity of Brockton Point has been dredged to 15 m, to allow deep-sea shipping access to the harbor. Another 15-m deep dredged area is located adjacent to Neptune Terminals west of the mouth of Lynn Creek, and two lesser dredged areas near the mouth of Mackay Creek. Within Indian Arm, depths are more typical of coastal fiords, and average 120 m with a maximum of 245 m to the south of Croker Island. The Indian River at the head of the fiord provides the main source of fresh water and the broad sill-like shallows at the southern end restrict exchange of salt water with Burrard Inlet. As with most fiords, the total length of Indian Arm (22 km) greatly exceeds its average width (1.3 km).

Winds

Because of the funneling effect of the northshore mountains and the ridges of the southern shore, winds in Burrard Inlet are predominantly east–west. Recorded winds from Point Atkinson, First Narrows Bridge, Jericho, and Centennial Pier in Vancouver Harbour show that easterlies occur most often and that the wind strength, regardless of direction, is greatest in winter and least in summer. Somewhat surprisingly, periods of persistently light winds longer than 24 h are most prevalent in the autumn and winter and least prevalent in the spring.

Table 10.1 shows the speeds and percentage occurrence of winds from the prevailing east–west directions, averaged over each month, at the First Narrows Bridge. Roughly speaking, easterly winds occur about 40% of the time from November to January, 35% of the time from August to October and February to March, and 30% of the time from April to July. Easterly winds occur most frequently in winter and least frequently in summer in Burrard Inlet. If northeast and southeast winds are included in the above totals, winds from easterly quadrants occur about 70% of the time in December and January, 60% of the time during October, November, February, and March, and about 50% of the time from March to September.

Westerly winds occur most often from late spring to summer (20–30% of the time) and least often in winter. Winds from the north, south, southwest, and northwest, on the other hand, occur less than 5% of the time throughout the year. The average speeds of westerlies exceed those of easterlies for all months, and are strongest in January and weakest in August. Strong westerlies in winter are associated with storm fronts that pass across southwestern British Columbia on their way inland and last 24–36 h. In spring and summer, westerly winds are associated with the sea-breeze effect set up by solar heating of the land. On more than 60% of the days during these months there is a shift to westerly winds about 3–5 h after sunrise, followed by a return to predominantly easterly winds (land breeze) near sunset. Calm periods and light winds occur generally a few hours before sunrise and a few hours after sunset.

Because of the local topography, prevailing winds along the southern side of the outer basin are from the southeast and northwest, a slight modification from conditions on the northern shore. The land-sea breeze effect in summer (June, July, and August) is the reason that winds from the eastern quadrant (and calms) are most

TABLE 10.1. Winds at First Narrows (Lion's Gate) Bridge, Vancouver. Percentage occurrence of winds from 8 directions for each month (e.g. June westerly winds occur 25% of time). Also percentage of calms and mean wind speed for each month regardless of direciton. Data from January 1969 to June 1974.

DIRECTION		MONTH											
		J	F	M	A	M	J	J	A	S	O	N	D
N		2	1	1	1	2	1	1	0	1	1	2	2
NE		17	15	16	14	9	8	5	6	10	12	17	16
E		38	36	35	31	28	33	30	33	33	35	39	43
SE		13	10	8	9	9	12	11	11	9	9	8	12
S		3	2	2	3	1	1	1	1	1	1	2	2
SW		2	2	2	3	4	3	3	2	3	2	2	2
W		11	12	19	22	27	25	29	26	20	17	10	7
NW		1	1	1	2	1	1	1	1	1	1	1	1
Calm		13	21	16	15	19	16	19	20	22	22	19	15
Mean speed	*(m/s)*	3.5	3.5	3.6	3.6	3.2	3.1	2.9	2.9	3.1	3.1	3.4	3.6
	(kn)	6.8	6.8	7.1	7.1	6.3	6.1	5.7	5.7	6.1	6.1	6.7	7.0

prevalent in the morning hours, whereas western quadrant winds prevail in the afternoon (Table 10.2). Easterlies and southeasterlies, for example, occur on 59% of the days at 7 A.M.; westerlies and northwesterlies on 55% of the days at 3 P.M. Aside from those winds associated with passing frontal systems, summer winds on the average are strongest in the early afternoon and weakest around midnight. Moreover, Table 10.2 shows that 41% of the wind shifts from morning easterlies to afternoon westerlies occur between 10 and 11 A.M. During periods of polar outbreaks, however, strong and easterly outflow conditions will be maintained along the south shore despite the clear skies. Easterly winds also can be expected to prevail in winter during periods of inclement weather prior to the passage of a front or low-pressure system.

The wind pattern in Vancouver Harbour is similar to that in the outer basin with a few modifications (Table 10.3). Easterly winds, for instance, occur more frequently throughout the year in the inner basin and summer westerlies are turned more to the northwest. The sea-breeze effect is again quite noticeable and strongest westerlies are linked to passing winter storms. Calms are less frequent within the inner basin; winds from the west, southwest, and southeast blow less than 10% of the time each month.

There is no detailed wind information for Indian Arm, though it is expected that funneling of air by the rugged surrounding land leads to intensified winds. Northerly winds in Indian Arm presumably accompany easterlies in Burrard Inlet and southerly winds accompany westerlies.

The air lifted by the northshore mountains and the convergence of winds that flow up the local valleys lead to significantly greater annual precipitation on the northern side of the inlet than the southern side. The first effect causes approximately a 4½-cm increase in precipitation for every 300-m rise in elevation above sea level on the north shore. Along the axes of the two main valleys, Capilano and Seymour, the added effect of the wind convergence causes a 6-cm increase in annual precipitation for every 30-m rise in elevation; this is equivalent to an increase in annual precipitation of 2 cm/km for Seymour Valley and 3 cm/km for Capilano Valley.

Tides

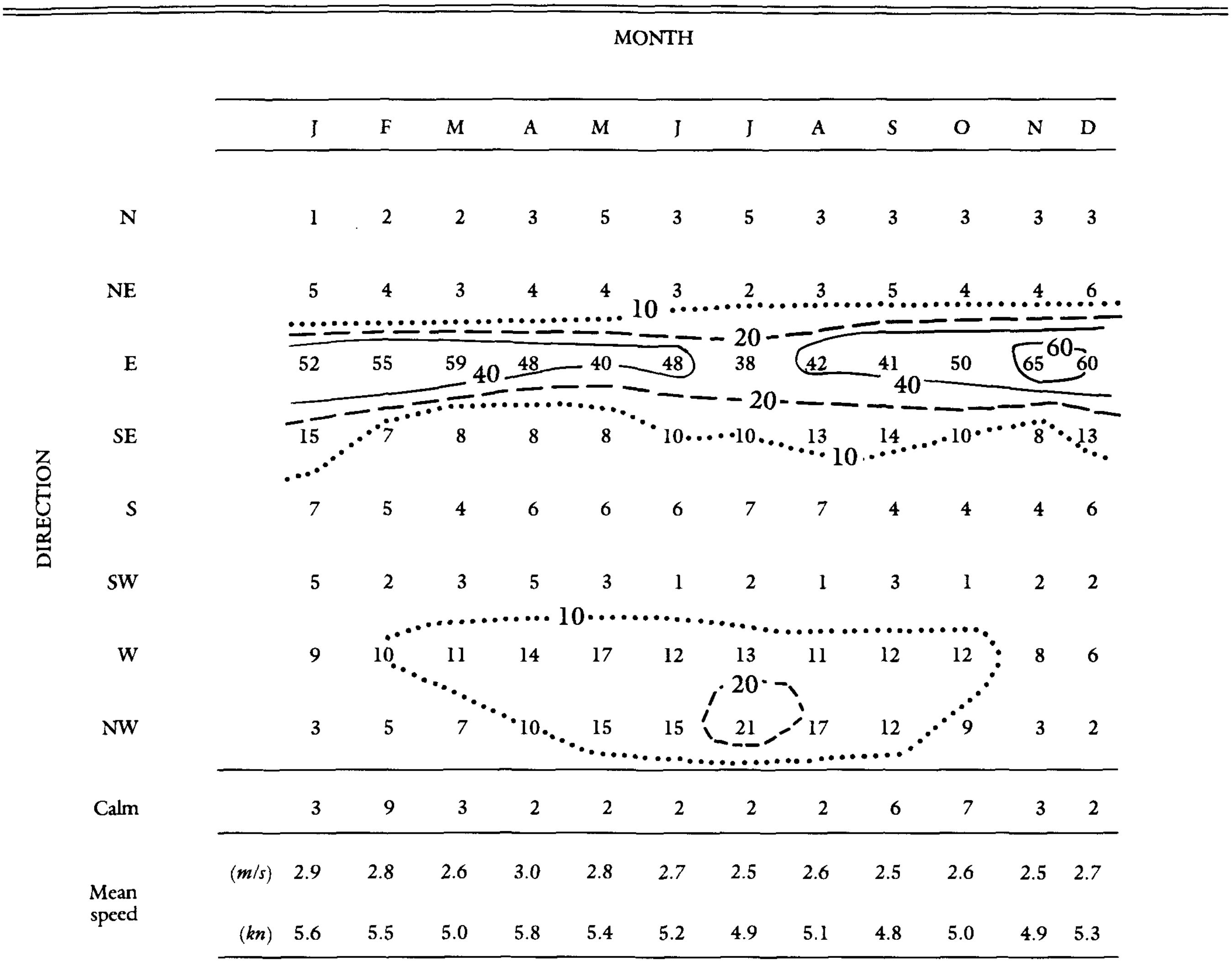
From Point Atkinson to the head of Indian Arm the tides are mixed, mainly semidiurnal with a strong declinational variation over 2 wk. There is a slight increase in the tidal range eastward of Second Narrows to a maximum in Port Moody and an accompanying delay of Higher High Water by approximately 30 min relative to Vancouver Harbour. Lower Low Water, on the other hand, occurs almost simultaneously throughout the entire inlet system.

Within Burrard Inlet, mean Higher High Water is 4.4 m and mean Lower Low Water 1.1 m, a mean tidal range of 3.3 m. Large tides by comparison have a range of 5.0 m, and vary from a high-water level of 5.0 m near midnight in late December to a low-water level of 0.0 m (chart datum) near noon in late June. Extreme tides in Burrard Inlet have attained high-water marks of 5.6 m and

TABLE 10.2. Winds at RVYC, Jericho (See Fig 10.33). Percentage occurrence of winds from 8 directions averaged over each hour during June, July, and August (1975–78), with percentage calms and mean wind speed. Bottom line gives hour at which wind shifted from land breeze (easterly) to sea breeze (westerly) expressed as percentage of total wind shifts. (From Emslie 1979)

			TIME (PDT) (*h*)																						
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
DIRECTION	N		1	1	0	0	0	0	0	0	2	3	2	2	3	3	3	5	6	5	5	6	4	3	0	0
	NE		4	5	1	3	3	2	3	3	5	5	8	6	3	5	5	4	5	4	4	2	4	3	3	3
	E		19	19	18	18	16	16	15	19	20	22	18	13	17	11	10	8	9	8	7	9	9	13	16	19
	SE		33	32	38	37	39	39	41	40	36	30	27	29	19	19	19	19	16	17	17	19	20	21	25	28
	S		6	8	5	9	9	7	8	5	2	2	2	2	5	4	2	2	5	5	6	5	5	6	7	6
	SW		5	4	5	4	3	5	4	4	3	3	3	4	4	6	6	6	9	12	14	13	13	10	7	7
	W		6	5	5	4	5	5	5	6	8	10	14	16	19	17	17	19	18	20	21	23	20	17	3	7
	NW		1	1	2	2	2	2	2	4	4	11	17	25	28	34	37	36	31	28	24	18	17	10	4	3
Calm			25	25	26	23	23	24	22	19	20	14	9	3	2	1	1	1	1	1	2	5	8	17	25	27
Mean speed		(*m/s*)	1.7	1.7	1.7	1.9	1.9	2.0	2.0	2.1	2.2	2.5	2.7	3.0	3.3	3.5	3.7	3.6	3.4	3.3	3.2	2.9	2.5	2.1	1.7	1.7
		(*kn*)	3.3	3.4	3.3	3.6	3.6	3.7	3.8	4.0	4.3	4.9	5.3	5.9	6.5	6.9	7.1	7.0	6.7	6.5	6.3	5.6	4.8	4.0	3.4	3.3
% wind shift			–	–	–	–	–	–	1	3	10	15	22	19	14	10	3	3	–	–	–	–	–	–	–	–

TABLE 10.3. Winds in Vancouver Harbour as measured at Centennial Pier (March 1969 to February 1974). Values are percentage occurrence of winds from a particular direction for each month. (See caption Table 10.1.)



DIRECTION		J	F	M	A	M	J	J	A	S	O	N	D
N		1	2	2	3	5	3	5	3	3	3	3	3
NE		5	4	3	4	4	3	2	3	5	4	4	6
E		52	55	59	48	40	48	38	42	41	50	65	60
SE		15	7	8	8	8	10	10	13	14	10	8	13
S		7	5	4	6	6	6	7	7	4	4	4	6
SW		5	2	3	5	3	1	2	1	3	1	2	2
W		9	10	11	14	17	12	13	11	12	12	8	6
NW		3	5	7	10	15	15	21	17	12	9	3	2
Calm		3	9	3	2	2	2	2	2	6	7	3	2
Mean speed	(*m/s*)	2.9	2.8	2.6	3.0	2.8	2.7	2.5	2.6	2.5	2.6	2.5	2.7
	(*kn*)	5.6	5.5	5.0	5.8	5.4	5.2	4.9	5.1	4.8	5.0	4.9	5.3

low-water marks of –0.4 m. Therefore, tides within the inlet system only rarely fall below chart datum though such conditions might occur during strong easterly blows in midwinter at low spring tide. Within Indian Arm the mean tidal range is 3.3 m and the spring tide range 4.9 m.

Oceanography

As with other inlets along the coast, temperature and salinity distributions within Burrard Inlet and Indian Arm vary considerably with season, particularly in the upper portion of the water column. Factors that affect these distributions include conditions in the Strait of Georgia, the amount of local land drainage, the influx of Fraser River water, the tides, and winds.

Throughout most of the year the inlet system has a two-layer structure, with relatively warm, low-salinity water in about the top 5 m overlying colder, more saline water beneath. This configuration is maintained by freshwater discharge from the various rivers, land seepage, and sewer discharge, which together move seaward near the surface with a compensating inflow of saltier water at depth from the Strait of Georgia. The Indian River provides most of the freshwater input to Indian Arm, though as much as 40% can come from Buntzen Lake via the Buntzen Power Plant. Seymour River provides most of the direct freshwater inflow to Vancouver Harbour, and the Capilano River is the main direct source of fresh water into the outer basin. The amount of flow in these rivers is closely tied to local precipitation and tends to be greatest during the rainy season of autumn to winter. Only during a few days each year does the discharge from the north-shore rivers exceed 150 m^3/s (roughly 1% of the discharge rate of the Fraser River) and these are usually periods of flooding associated with heavy rainfall; the record measured discharge for the largest of these rivers, the Capilano, was 408 m^3/s on Nov. 26, 1949. During exceptionally cold winters, however, the precipitation may be held in the snowfields and not released until spring.

The North Arm of the Fraser River and not local rivers is the main source of brackish water in the outer portion of Burrard Inlet. This river water is especially prevalent during the peak runoff period of late spring and summer. The combination of flood currents and the hydraulic head of the river drive a silty layer of fresh water northward along the edge of Point Grey, then eastward along the southern shore of the inlet where it has a murky, green color, a contrast to the darker green of the more salty oceanic water. During certain conditions of wind and tide, Fraser River water can also penetrate into Vancouver Harbour, although in a considerably modified form as a result of tidal mixing at the First Narrows. This brackish layer accounts for the comparatively lower salinities and higher temperatures of the surface waters along the southern shore of the inlet in summer. It also impedes the natural seaward flow of fresh water that enters the inlet system from the indigenous rivers, thereby disrupting the normal estuarine circulation.

Near surface waters are warmest in late July to early August throughout the entire inlet (Fig. 10.34a). Temperatures in the top metre may reach 20°C or more along the southern shore of the outer basin, over the shallow region that extends eastward from the Second Narrows into Port Moody, and over most of Indian Arm. If winds are light in these regions, the surface water temperature will begin to approach air temperature. Unfortunately for swimmers, the thermocline is shallow and water temperatures invariably decrease by 5–10C° within 5 m of the surface. Below 20 m, water temperatures become uniformly cold at around 10°C. The coldest surface water in the inlet during the summer is always in Vancouver Harbour because of the intense tidal mixing within First and Second Narrows. Maximum surface temperatures in this basin are typically less than 15°C, except in sheltered embayments such as Coal Harbour.

In winter, the waters of the inlet system are almost uniformly cold from top to bottom (Fig. 10.34b). Though there is some variation from winter to winter,

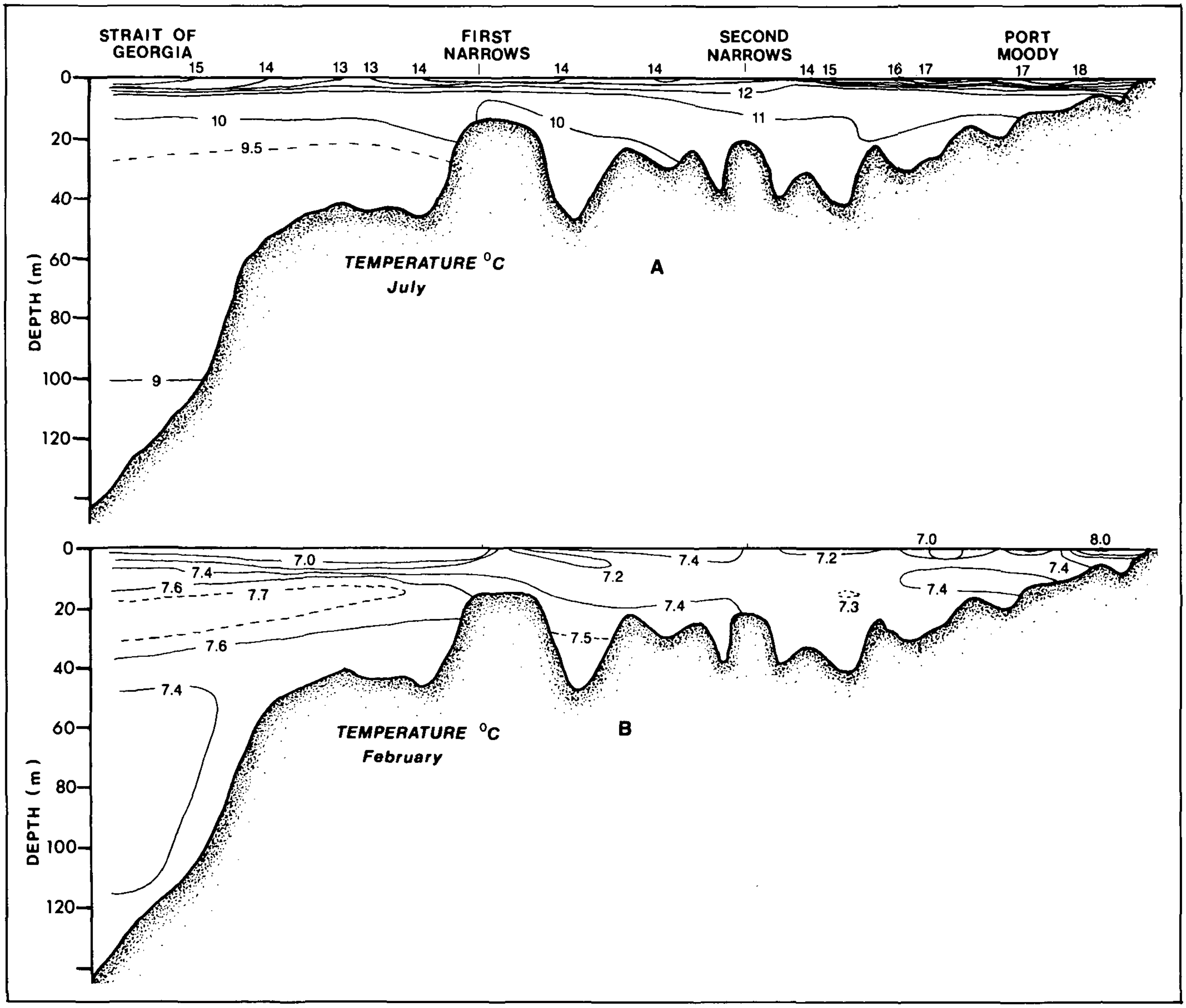


FIG. 10.34. Temperature (°C) distributions in mid-channel sections through Burrard Inlet. (A) July 7–9, 1966; (B) Feb. 15–18, 1962. (Adapted from Anon 1973)

temperatures of between 6–8°C are common, with slightly colder water near the surface due to heat loss to the atmosphere. As at other times of the year, waters within the inner basin of Burrard Inlet exhibit the smallest temperature differences over depth of the entire system.

The Fraser River water in the outer basin creates a complex surface salinity distribution that varies greatly with tide, wind, and runoff conditions. Below 10 m, the salinity distribution becomes more uniform with values of 29–30‰ throughout the year (Fig. 10.35). Lowest surface salinities occur in the summer. The general distribution at this time consists of a tongue of low-salinity water from the Fraser River of 10‰ or less that enters from the vicinity of Point Grey and moves toward the First Narrows (Fig. 10.36). On the average, saltiest water lies over the northern half of the outer basin with maximum values of around 20‰ in the vicinity of Point Atkinson. The presence of relatively high-salinity surface water east of Jericho Beach to False Creek suggests that surface flood currents in the outer basin favor a northeasterly set rather than an easterly set. However, the average distribution in Fig. 10.36 is subject to considerable variation. For example, it is possible to find detached pools or "lenses" of low-salinity water of around 10‰ at about any location in the outer basin. Low-salinity pools can also be prevalent seaward of the mouth of the Capilano River. Typically, these pools persist through only part of the tidal cycle before they are destroyed by tides and winds. In winter, salinities over most of the outer basin are around 25‰ at the surface and increase to about 30‰ below 20 m (Fig. 10.35b).

East of the First Narrows, there is a gradual decrease in the surface salinity to the head of Indian Arm, regardless of season. Due to the shallowness of the sills separating these inner basins, salinities remain below 30‰. Highest values are attained just inside Vancouver Harbour where density flow from the First Narrows penetrates to

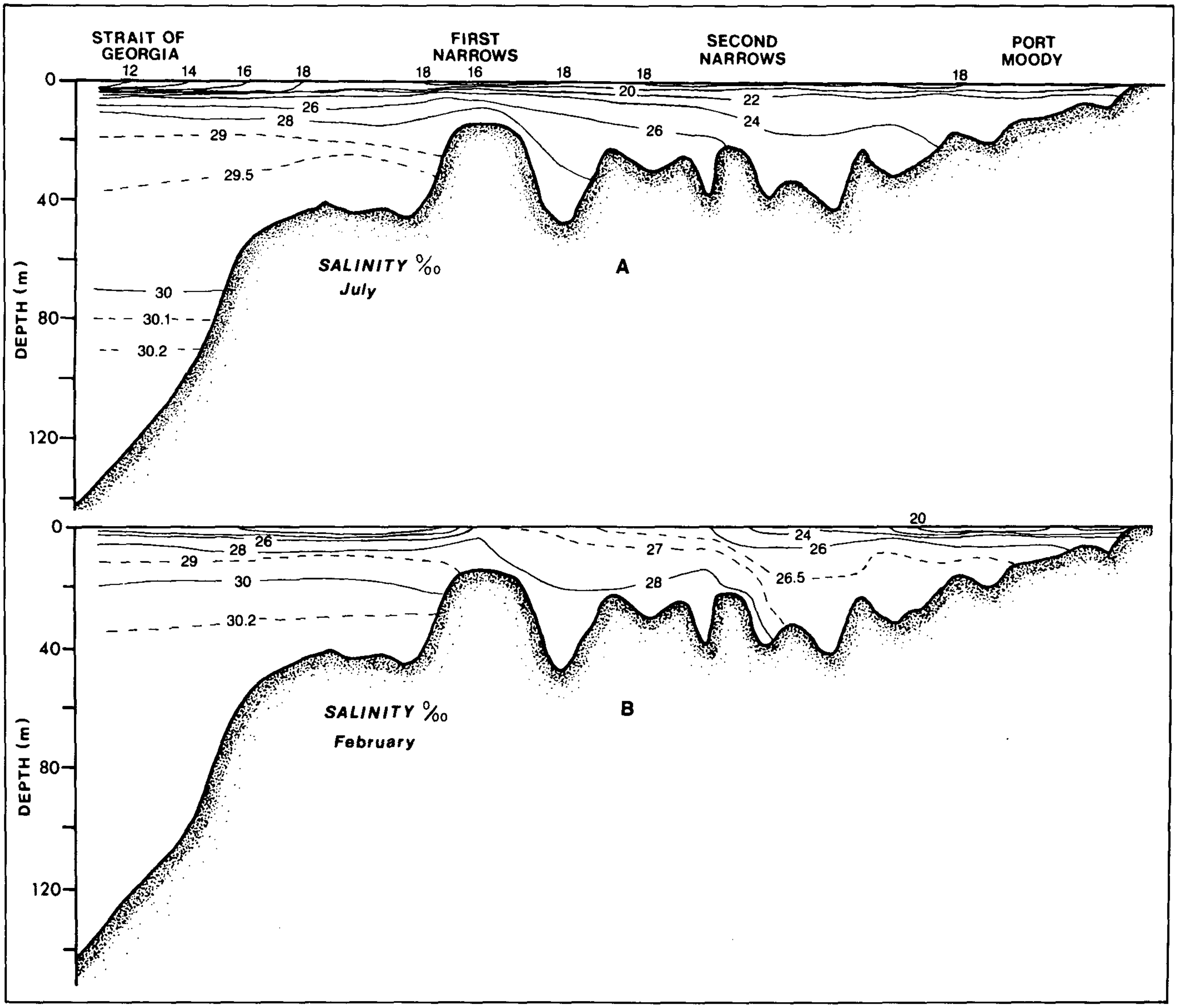


FIG. 10.35. Salinity (‰) distributions in mid-channel sections through Burrard Inlet. (A) July 7–9, 1966; (B) Feb. 15–18, 1962. (Adapted from Anon 1973)

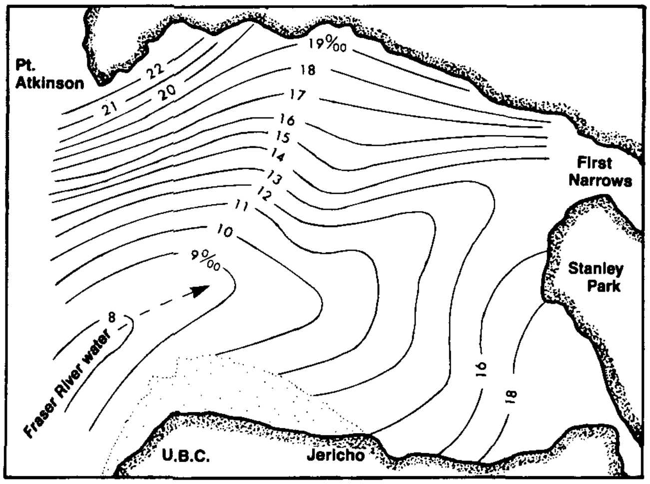


FIG. 10.36. Average surface distribution salinity (‰) in Burrard Inlet during large Fraser River runoff (summer). (From Campbell 1954)

the bottom. Within Indian Arm, surface salinities reach minimum values twice a year: once during summer (July–September) presumably at the time of greatest snow melt; and, again in late winter (January–March) during periods of heavy rainfall. Minimums are around a few parts per thousand at the head of the fiord, and increase to about 10‰ midway along the channel, to about 15‰ at the southern end. Maximum salinities occur in spring and early winter.

Currents

In this section attention will be mostly confined to the flow structure in the outer basin of Burrard Inlet. Those interested in currents in the inner basin are referred to *Vancouver Harbour Tidal Current Atlas 1981*, published by the Canadian Hydrographic Service, which shows the speed and direction of surface tidal streams at hourly stages of the tide. Only a cursory description of the currents in Indian Arm will be presented.

The Burrard Inlet current patterns described below need to be put in perspective. First, they are based on current meter measurements taken over 25 yr ago, when oceanographic technology was in its infancy. Moreover, only two short observational periods of 25 h each were obtained, and these were collected during summer at periods of weak and variable winds. Consequently, the current patterns should be viewed as general representations of the actual flow at various stages of the tide and from which significant departures can be expected.

On a large flood, the northward flowing tidal streams in the Strait of Georgia turn into Burrard Inlet with a northeasterly set in the vicinity of Point Grey (Fig. 10.37a). During the time these measurements were taken there was an accompanying southeasterly set off Point Atkinson where flood streams entered the inlet from Queen Charlotte Channel. Because of the constricted nature of this channel, the latter feature may indeed typify the flow at large floods, though normally a more westerly set off Point Atkinson is expected. Over most of the inlet, the surface currents are then directed toward the First Narrows, and attain maximum speeds of around 25–50 cm/s. Modifications of this simple picture are subsequently brought about through the influence of winds and shoreline geometry. Westerly winds, for example, would be expected to augment the flood streams in the top few metres of water by approximately 3% of the wind speed and to turn them more to an easterly set; by the same token, easterly winds would reduce the flood and cause it to set more toward the northeast. The wide shoal areas on the southern shore and the protrusion of Point Atkinson into the inlet result in downstream backeddies. East of Spanish Bank, a weak nearshore counterflow of 10–20 cm/s was found in the earlier study, although westerly winds would presumably reverse this tidal flow, particularly in summer when brackish Fraser River water overlies most of the south shore. The flood into False Creek is accelerated, but even under the Burrard Street Bridge it is typically less than 50 cm/s. Funneling of the flood streams through the First Narrows leads to a strong flow into Vancouver Harbour at speeds to 300 cm/s (6 kn) during spring tides. The flow decelerates as it fans out to the east of Brockton Point, though speeds are sufficient to set up well-defined backeddies in the lee of prominences in the harbor.

During small floods, the flow pattern is similar to that of a large flood except that midchannel currents are weaker and tend to broaden more within the inlet (Fig. 10.37b). In addition, there is a more pronounced northerly set of the tidal streams at the Strait of Georgia entrance to the inlet, and the counterclockwise eddy between Sandy Cove and Point Atkinson extends westward to join the northerly set into Howe Sound. Wind drift currents can be expected to play a dominant role in determining the overall flow structure on small floods during periods of moderate to strong winds.

Surface currents on a large ebb are illustrated in Fig. 10.37c. The most pronounced feature is the strong, narrow current, which can often extend from the First Narrows to Point Atkinson. The core of the flow at such times is offshore, except near Reardon Point and the Narrows, and has maximum velocities of around 100 cm/s. Along most of its path the flow broadens generally, but narrows again off Point Atkinson, where it merges with the southerly flow from Howe Sound. On other occasions, the narrow current appears to be deflected toward mid-channel rather than to hug the northern shore, although why it should do so is not yet understood. Obviously further work in this area is needed before a complete understanding of the flow behavior is achieved.

Because of Stanley Park, an extensive anticlockwise gyre is set up over much of English Bay on the ebb resulting in weak and variable currents along the adjoining recreational beaches. The flow pattern near the southern shore is further complicated by the ebb from False Creek directed westward along Jericho Beach and Spanish Bank. The continued northerly set off Point Grey on the ebb is due to the hydraulic head of the North Arm of the Fraser River, which continues to drive surface waters toward the north. Needless to say, winds will modify the entire flow pattern depending on direction, strength, and duration.

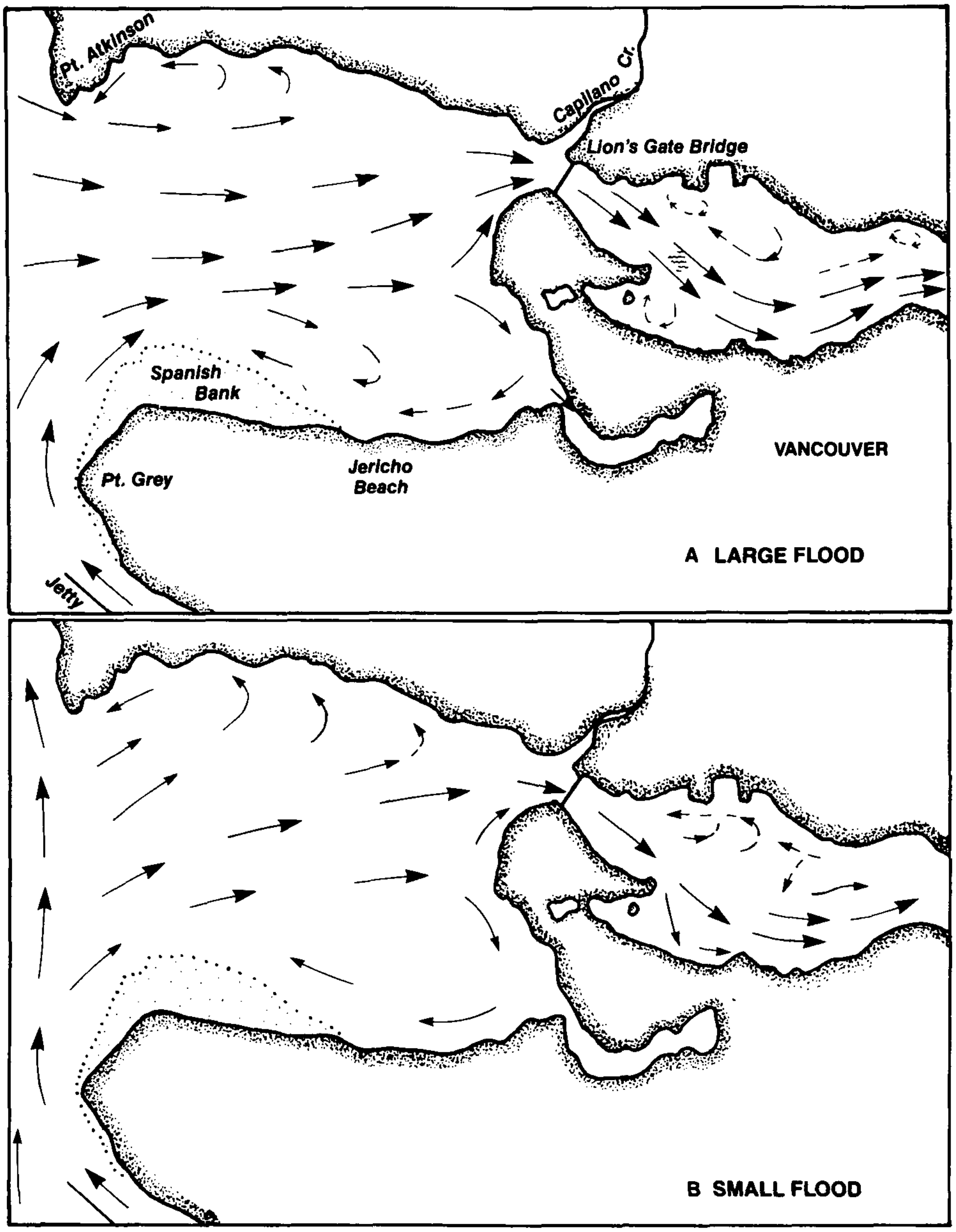


FIG. 10.37. Tidal currents in Burrard Inlet; (A) large flood, (B) small flood, (C) large ebb, (D) small ebb. Larger arrows, 25–50 cm/s (0.5–1.0 kn); small arrows, less than 25 cm/s (except First Narrows where flow is generally over 50 cm/s). (Adapted from Campbell 1954)

During small ebbs, the northshore jet is weaker and less well established so the counterclockwise eddy does not form over the eastern portion of the inlet. However, ebb streams still tend to be directed northward along the beaches of Stanley Park (Fig. 10.37d).

Waves

The limited fetch within Burrard Inlet makes it impossible for local winds to generate waves of any appreciable significance. As a consequence, the comparatively large seas sometimes found at the entrance to the inlet originate with strong winds in the Strait of Georgia. Low swell-like waves propagate into the inlet following the passage of frontal systems, but these rapidly diminish in strength along the axis of the channel. Within Vancouver Harbour, boat-generated waves are probably as important as wind waves when it comes to disturbing the shoreline.

Despite the small wave heights, vigorous rips occur in regions of strong tidal flow. During westerly winds, rips dangerous to small boats often form in the vicinity of Point Atkinson and seaward of the First Narrows on the ebb. The latter may be further increased by the outflow from the Capilano River. Noteworthy rips are also formed over Burnaby Shoal in Vancouver Harbour on larger floods.

Slick bands associated with the up-inlet propagation of internal gravity waves that originate in the Strait of Georgia are common in the outer basin in summer. As

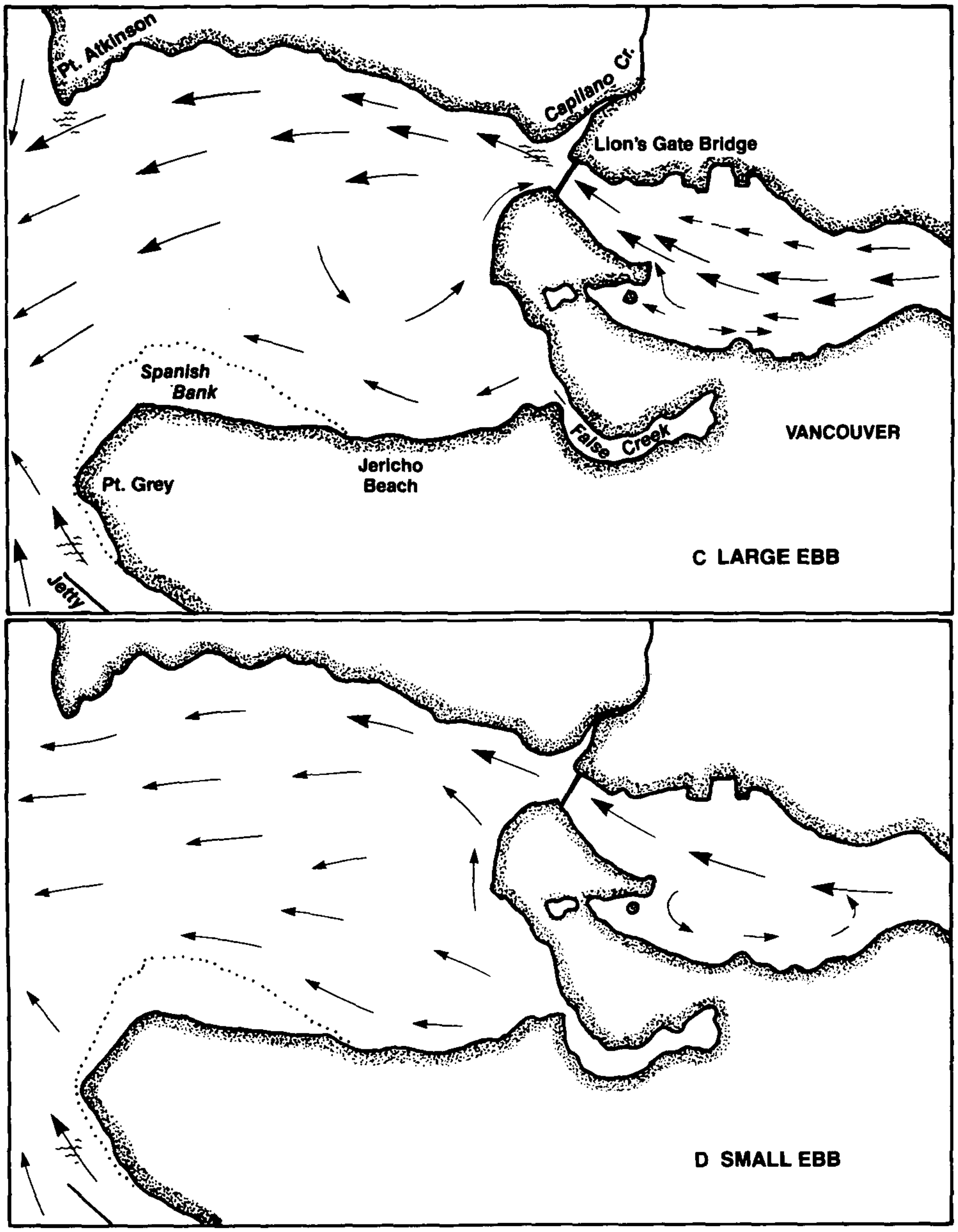


FIG. 10.37. Tidal currents in Burrard Inlet; (A) large flood, (B) small flood, (C) large ebb, (D) small ebb. Larger arrows, 25–50 cm/s (0.5–1.0 kn); small arrows, less than 25 cm/s (except First Narrows where flow is generally over 50 cm/s). (Adapted from Campbell 1954)

with surface waves, the energy of these waves is dissipated by breaking on the shores, a process that goes unnoticed by human eyes.

Indian Arm Circulation

In common with most west coast fiords, the basic circulation in Indian Arm consists of a surface outflow of brackish water driven by freshwater accumulation in the basin, with a compensating inflow of salty water at depth. Superimposed on this structure are the ebb and flood of the tidal currents and the wind-driven currents at 3% of the wind speed. At any particular time, therefore, the speed and direction of the surface waters to a depth of about 5 m depend on the amount of river discharge (which determines the strength of the seaward outflow), the range and stage of the tide, and the wind strength and direction. Maximum tidal streams at the shallow southern end of the fiord vary in velocity from 25 cm/s for a 2-m tide to 50 cm/s for a 4-m tide, but are considerably weaker within the main basin itself. As a consequence, the surface outflow in Indian Arm is only completely stemmed by the flood near the mouth of the inlet during periods of low runoff. Over the bulk of the fiord, the surface currents are almost always southward, but of variable strength, weakest for a flood and/or southerly winds and strongest for an ebb and/or northerly winds. Immediately beneath the outflowing brackish layer an intruding jet is formed at the southern end on the flood, which penetrates part way up-inlet before mixing with the surrounding water.

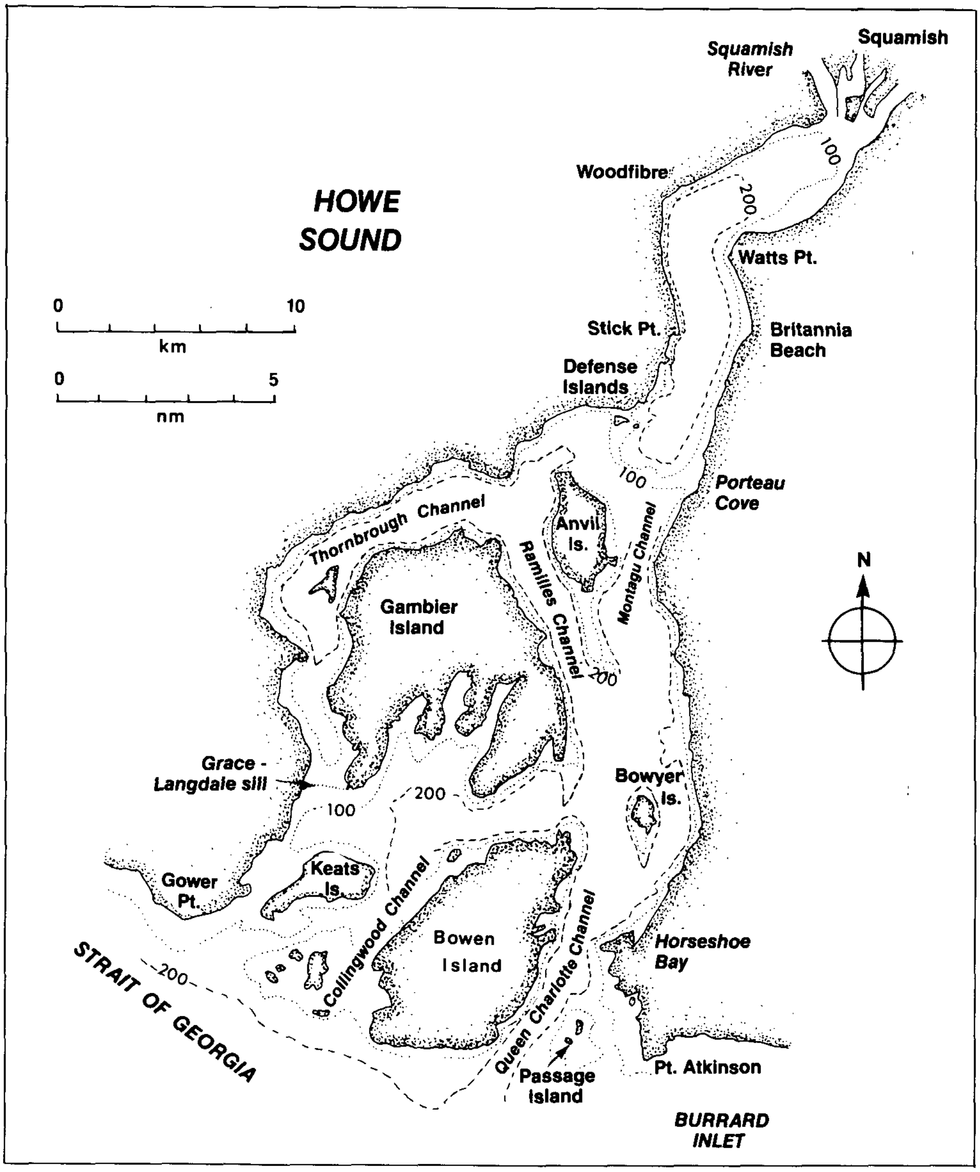


FIG. 10.38. Howe Sound. (Depths in metres.)

Howe Sound

Situated immediately north of Burrard Inlet, Howe Sound is an estuarine-type body of water that cuts 43 km northward into the Coast Mountains to the mouth of the Squamish River (Fig. 10.38). Topographically, it can be subdivided into two separate basins. The island-strewn outer basin is a true "sound," which narrows from 20 km at the entrance between Point Atkinson and Gower Point to about 3.5 km at the Defense Islands, 26 km inland. From this point, the sound gives way to a narrow fiord-like inner basin with steep precipitous cliffs, a large river at its head, and a sill at its entrance (Pl. 2).

Though most visitors to Howe Sound are impressed by its rugged countenance and beauty, the first white men to enter the area were not overly enthusiastic about what they saw. Captain George Vancouver's remarks in June 1792 were anything but flattering:

> "Quitting Point Atkinson and proceeding up the Sound . . . we made a rapid progress, by the assistance of a fresh southerly gale, attended with dark gloomy weather that greatly added to the dreary prospect of the surrounding country. The low fertile shores we had been accustomed to see, though lately with some interruption, here no longer existed: their place was now occupied by the base of the stupendous snowy barrier, thinly wooded and rising from the sea abruptly to the clouds; from whose frigid summit, the dissolving snow in foaming torrents rushed down the sides and chasms of its rugged surface, exhibiting altogether a sublime, though gloomy spectacle, which animated nature seemed to have deserted . . ."

For many people today, the "gloomy spectacle" that Vancouver so poetically described is equated to the thick grayish smoke from the Woodfibre pulp mill which, when atmospheric conditions are right, covers much of the Sound with a shroud of unpleasant chemical air.

Bathymetry

Howe Sound began as a river valley that was subsequently gouged and reformed by powerful glacial excavations. At their peak, the ice sheets filled the valley to the present 1950-m level, and when they retreated left behind thick layers of sediment that now overlie the bedrock of the channel. Two major sills were formed as a result. The inner sill extends across the mouth of the fiordlike northern basin between Porteau Cove and the Defense Islands, rises to within 35 m of the water surface, and is thought to be a terminal moraine marking the maximum advance of a recent glacial period. It partially blocks the northward movement of deep oceanic water, and thereby encourages a stagnation of the bottom waters within the inner basin. The comparative shallowness of this area, and the fact that the Squamish Highway descends to sea level at this point, makes it a favorite haunt of scuba divers.

The outer sill lies across the southern end of Howe Sound and consists of glaciomarine deposits that accumulated where the seaward advancing ice sheet from the Sound met the pack ice of the Strait of Georgia. At one time it acted as a barrier to deepwater exchange with the Strait but was later breached by faults. Within Queen Charlotte Channel, erosion by tidal currents has further deepened the breach to the extent there is now a free exchange of water between the Strait and the outer basin of the Sound. Minimum depths over the remaining portion of the sill are around 60 m and average slopes are approximately 1 in 7. A smaller sill (the Grace-Langdale sill) with minimum depths of 30 m extends from the southern tip of Gambier Island to the mainland coast. Depths within the inner basin average 275 m; those in the outer basin average about 240 m. Both basins are flat-bottomed by coastal standards with midchannel reliefs of only a few metres. The bathymetry is appreciably more rugged near the islands and mainland shores where it mirrors the rocky nature of the mountainous terrain. There is also a fairly steep bottom slope seaward of the Squamish River delta; by some estimates, the river sediments are advancing the delta front as much as 7 m/yr.

Winds

Estuarine-type regions like Howe Sound are strongly influenced by winds which, in addition to their direct effect on surface currents, play an indirect role in modifying the oceanographic structure of the deeper waters. This is especially true of the fiordlike inner basin of the Sound where tidal effects appear to be relegated to secondary importance. In Howe Sound as a whole, moderate-to-strong winds are linked with frontal systems associated with Pacific disturbances, arctic outflow, and locally generated sea breezes.

From October to March, frontal disturbances that move across southern British Columbia are commonly preceded by gale-force southeasterly winds that are funneled into strong up-channel winds in Howe Sound. This effect is most pronounced in the northern sector of the Sound where the air is more confined by the local terrain. With the approach of a front, winds can shift from light to storm intensity within a matter of hours, and on one occasion were clocked at average speeds of 25 m/s (50 kn) with gusts to 40 m/s (80 kn) at the head of the Sound. In winter, southerly winds in excess of 7.5 m/s (15 kn) occur approximately 30% of the time and commonly reach speeds of 15 m/s (30 kn) with gusts to 20 m/s (40 kn).

Strong down-channel Squamishes are also fairly common in Howe Sound during the cold winter months. As in other coastal inlets, Squamishes are formed when cold, dense arctic air sitting over the interior of the province surges seaward along river valleys in the manner of a density current. Events of this kind are often triggered by the passage of a low-pressure system down the outer coast and though they tend to occur less frequently than southerly winds, they are generally more persistent once initiated. What few data are available concerning Squamishes in Howe Sound indicate they may persist for 3–5 days and occur on the average about 5–6 days during December and January. Wind speeds frequently reach 15 m/s (30 kn) with gusts of up to 30 m/s (60 kn).

From May through August, the wind pattern in Howe Sound is dominated half the time by a vigorous sea-breeze effect associated with the differential heating of the land and water (see Chapter 2). These diurnal winds tend to be somewhat stronger than their counterparts over much of the Strait of Georgia because of the confined nature of the local terrain, and are most prevalent during clear sunny weather. At such times, the land breeze blows from the north with light winds between midnight and about 9 A.M. With the onset of daytime heating, the winds shift to southerly or southwesterly and by afternoon the sea breeze commonly attains speeds of 10 m/s with gusts to 15 m/s (in one case, gusts of 20 m/s were recorded at Squamish during an intense sea breeze of 15 m/s). The winds die off after sunset and revert to light northerly near midnight. This cyclic summer pattern can, of course, be modified by larger scale atmospheric conditions, such as the passage of weak fronts or a strongly westerly flow of air from the Pacific, and should not be thought to prevail without exception.

Tides

The mixed, predominantly semidiurnal tides in Howe Sound differ little from those in Burrard Inlet, and for most practical purposes Point Atkinson serves as an excellent reference port for both areas. At Squamish, for example, the mean range of 3.2 m and the large tide range of 4.9 m differ by only a few centimetres from the corresponding values of 3.3 m and 4.9 m, respectively, at Point Atkinson. Moreover, the times of high and low water at the head of Howe Sound are usually only a few minutes behind those at Point Atkinson, though this delay can be increased somewhat by Squamish winds. Conversely, southerly winds associated with passing frontal systems will cause the tides to occur a few minutes sooner than predicted and to have slightly greater heights.

Oceanography

Distributions of salinity and temperature in the Sound are similar to other estuarine environments affected by river runoff, winds, air temperatures, and tides. Typically, a relatively low-salinity surface layer 5–10 m thick overrides a much deeper layer of appreciably higher salinity, where conditions are nearly constant throughout the year.

Fresh water to Howe Sound is supplied mainly by the Squamish River which, together with its two major tributaries, the Cheakamus and Mamquam rivers, drains an area of about 3700 km^2, making the Squamish one of the larger rivers of the province. Essentially fed by snow melt, the Squamish River system reaches a maximum discharge rate of around 760 m^3/s in early summer and a minimum discharge rate about 1/10 of this value in late winter. Abnormally large discharges up to 2100 m^3/s have occured in the fall of certain years, due to sudden thaws and heavy rainfall, and have combined with high tides and winds to cause damaging flash floods over the Squamish delta. (The town of Squamish has been inundated with nearly 1½ m of water about once every 16 yr since its founding, and to a somewhat lesser degree about every 7 yr, a problem which hopefully has been alleviated by the construction of a retaining dyke along the river bank.) Accompanying the pronounced summer-to-winter variation in the river discharge is a corresponding seasonal variation in the temperature, salinity, and currents within the surface waters of the Sound.

As the river runoff progresses seaward it entrains saltier oceanic water from below, which results in a discernible down-channel increase in salinity in the upper 10 m of the water column. By the time the brackish layer has reached the outer basin, values are commonly around 15‰ in summer with somewhat higher values in winter, when runoff is lower. There is a further downstream increase in salinity to the mouth of the Sound, where values become comparable to those in the Strait of Georgia. Below 50 m or so, the salinity ranges between 29 and 31‰ throughout the year, with slightly higher values in the outer basin compared to the inner basin, due to the blocking effect of the sill at the entrance to the inner basin. Fortunately for marine organisms that reside below sill-depth in the inner basin, nature provides an approximately biannual refreshening of the deeper waters by an overflow of more oxygen-rich water from the outer basin. Indications are that such overflow events are triggered by a combination of strong Squamish winds and abnormally high river discharge, produced by a heavy rainfall or sudden thaw at higher elevations. Though these events may only last a few days, they are essential to the renewal of the water in the inner basin.

Levings and McDaniel (1980) have shown that, whenever such events are delayed too long, the resulting low oxygen levels lead to widespread depletion of numerous species of benthic organisms. The absence of a major bottom-water inflow in 1977 resulted in the temporary annihilation of shellfish stocks over much of the inner basin.

In the mainstream of Howe Sound, water temperatures in summer remain persistently cool, the only substantial warming occurs in the protected coves of the island-strewn outer basin. It appears that the surface brackish layer formed by the snow-fed Squamish River, whose temperatures hover around 10°C, has little opportunity to warm during its seaward journey to the Strait of Georgia. In winter, it is common for surface temperatures in Howe Sound to drop to 5°C. Below the upper freshet layer, temperatures are consistently around 8–10°C throughout the year, with only minor modifications in the outer basin brought about by incursions of warmer water from the Strait.

Circulation

In contrast to many areas of the coast, currents in Howe Sound have been fairly well documented, especially in the inner basin where effects of the Squamish River are most widely felt. Some excellent work in this regard was conducted by J. Buckley from May to July 1973. Buckley determined the nature of the surface flow by deploying radar trackable drogues and further supplemented his findings with data collected from strings of moored current meters.

Basically, Howe Sound has an estuarine-type circulation structure primarily driven by the freshwater discharge from the Squamish River system. There is a net seaward flow of brackish water in a relatively shallow-surface layer of around 10 m, together with a slow inward drift at depth, which compensates for the loss of salt water to the surface layer (Chapter 2). Observations suggest that currents in the top 3 m are uniform with depth so a ship's keel will lie within a slab of water that moves at the same velocity. However, the simple estuarine flow is modified appreciably by the action of the wind and, to a lesser extent, tides. In addition, there is an ever-present, cross-channel variation in the strength of the seaward surface current in the inner basin, and often a reversal in direction from one side to the other. The strength of the surface current will also vary with season, is weakest during the winter months when runoff is relatively low, and greatest in summer when runoff is high.

The most visible feature of the surface layer is the silty, chalky looking water that originates from the Squamish River and flows seaward along the length of the Sound mixing and widening as it goes (Pl. 2). In many instances, the demarcation between the silt-laden brackish water and the greenish colored salty water of the Sound also marks a distinct change in the currents. At other times the currents are identical on either side of the "line," ruling it out as a reliable indicator of a change in the flow. Although the position of the core of silty water shifts from day to day following shifts in the prevailing winds, and its strength varies with the amount of river runoff, a general picture of the surface currents in Howe Sound is now beginning to emerge. In Fig. 10.39, the core of the river "jet" enters the Sound along the retaining dyke on the Squamish delta at about 50 cm/s. From there it progresses southward until it contacts the shore north of Watts Point, where it is deflected across-channel in the direction of Woodfibre. To the north of the main flow there is a large clockwise backeddy with nearshore up-channel speeds of about 20 cm/s to the vicinity of the river mouth. The core of the brackish layer then turns southward off Woodfibre, often hugging the coastline until "Stick Point" (a local name not on the hydrographic charts) where it separates from the shore to flow down center-channel. (Along the opposite shore there is a weak return flow northward to the vicinity of Watts Point.) By the time the remnant of

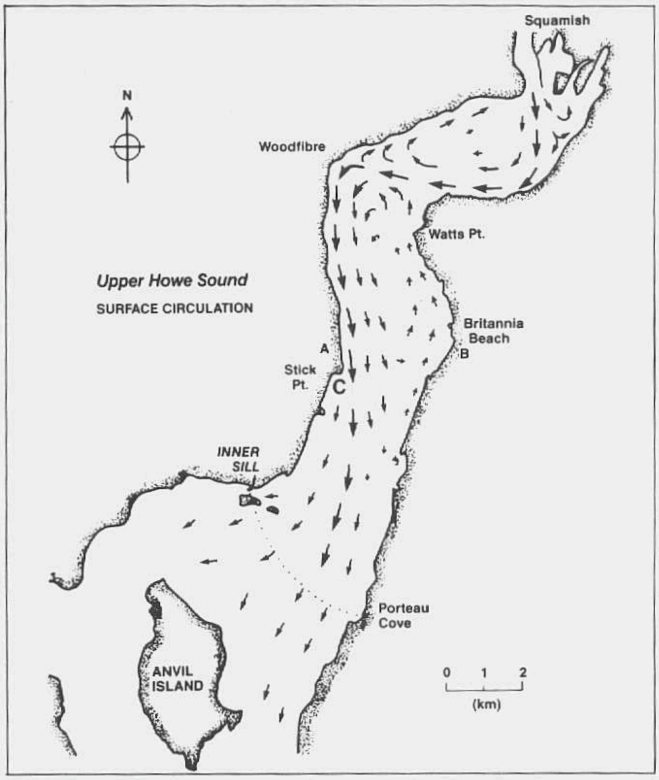


FIG. 10.39. General surface current pattern for upper Howe Sound deduced from surface drogue studies. Arrow size proportional to speed and persistence of flow. (For currents in cross-section between A and B, see Fig. 10.40.) (From Buckley 1977)

the core has reached the sill that divides the two major basins of Howe Sound, its strength has waned and the flow is everywhere seaward, provided there are no strong up-channel winds. Generally speaking, surface currents in the fiordlike inner basin have a strong down-channel component within the core of brackish outflow hugging the shoreline, and a moderately strong up-channel component on the opposite shoreline. Available data further indicates that, under normal circumstances, the down-channel flow along the western side is strongest at the surface, whereas the up-channel current on the east side reaches a maximum at a depth of a few metres (Fig. 10.40).

The abrupt change in the nature of the currents near Stick Point provides a practical example of the effect of the flow regime on marine traffic in the Sound. Tugboat operators pulling booms or barges up-channel usually work the western shore to take advantage of the weak currents and backeddies, but once they round the point they often become "stuck." Under such conditions it may be more expedient for the operator to head toward mid-channel rather than continue to stem the core of the narrow outflow-jet north of this point.

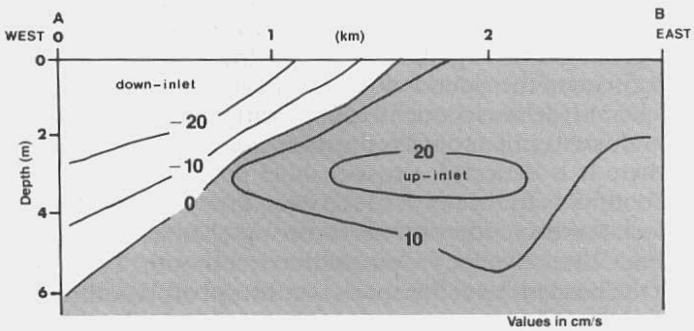


FIG. 10.40. Along-inlet velocity structure in top 6 m of Howe Sound (cm/s), deduced from 3-h averaged drogue motions Sept. 6, 1973. Positive values, up-inlet (landward); negative values down-inlet (seaward). See Fig. 10.39 for locations of A and B. (From Buckley 1977)

Winds over the inner basin lead to considerable modification of the generalized flow pattern in Fig. 10.39. In the region between Watts Point and Stick Point, for example, the onset of a fresh-to-strong southerly blow will cause the currents associated with the seaward flowing jet to slow down or stop, whereas from about mid-channel to the opposite shore it will induce up-channel currents with speeds to 50 cm/s (Fig. 10.41). At times, southerly winds in this area may be enough to reverse the flow of the jet, especially during periods of comparatively low runoff. (Except near the northern end of the basin, tidal currents appear to have only a secondary influence compared to winds, and for the most part can be disregarded.) However, there comes a point when, after several hours, a southerly wind loses its ability to counter the down-inlet flow of the surface jet and the currents again begin to speed up, sometimes accompanied by a shift of the core toward mid-channel. This is presumably due to the fact that while the wind is retarding the natural seaward tendency of the brackish layer, a head of water is built up that eventually overcomes the force exerted by the wind, and allows down-inlet currents to regain speeds of 25–50 cm/s. Away from the main core, on the other hand, winds continue to drive the surface layer inland with greatest speeds roughly 1 km from the eastern shore. Between Watts Point and the river delta, the wind and tide have equal influence, though neither is strong enough to appreciably alter the flow regime. In this area, the time of maximum down-inlet velocity closely coincides with the time of high water at Squamish; the core of the jet may be shifted slightly northward by strong southerly winds. Reversals in flow induced by southerly winds at the seaward end of the inner basin occur almost uniformly across the width of the channel with only slightly stronger currents over the eastern half (Fig. 10.42). Up-channel velocities are typically 25 cm/s a few hours after the onset of southerly winds that exceed 15 m/s, though again the build-up of brackish water within the basin can lead to a down-channel set near the western side prior to any slackening of the winds.

Once the strength of the southerly winds begins to fall below about 10 m/s, the circulation in the inner basin returns to its usual pattern shown in Fig. 10.39. Northerly winds such as Squamishes will, of course, augment the velocities of the surface flow in this pattern with the result that surface currents will be everywhere seaward except in the lee of prominences where small backeddies will be formed. Down-channel speeds associated with the core of the jet can be expected to reach 100 cm/s while in other areas maximum speeds of around 50 cm/s will pertain. Finally, under most wind conditions the direct effect of the wind is confined to the top few metres, and even when

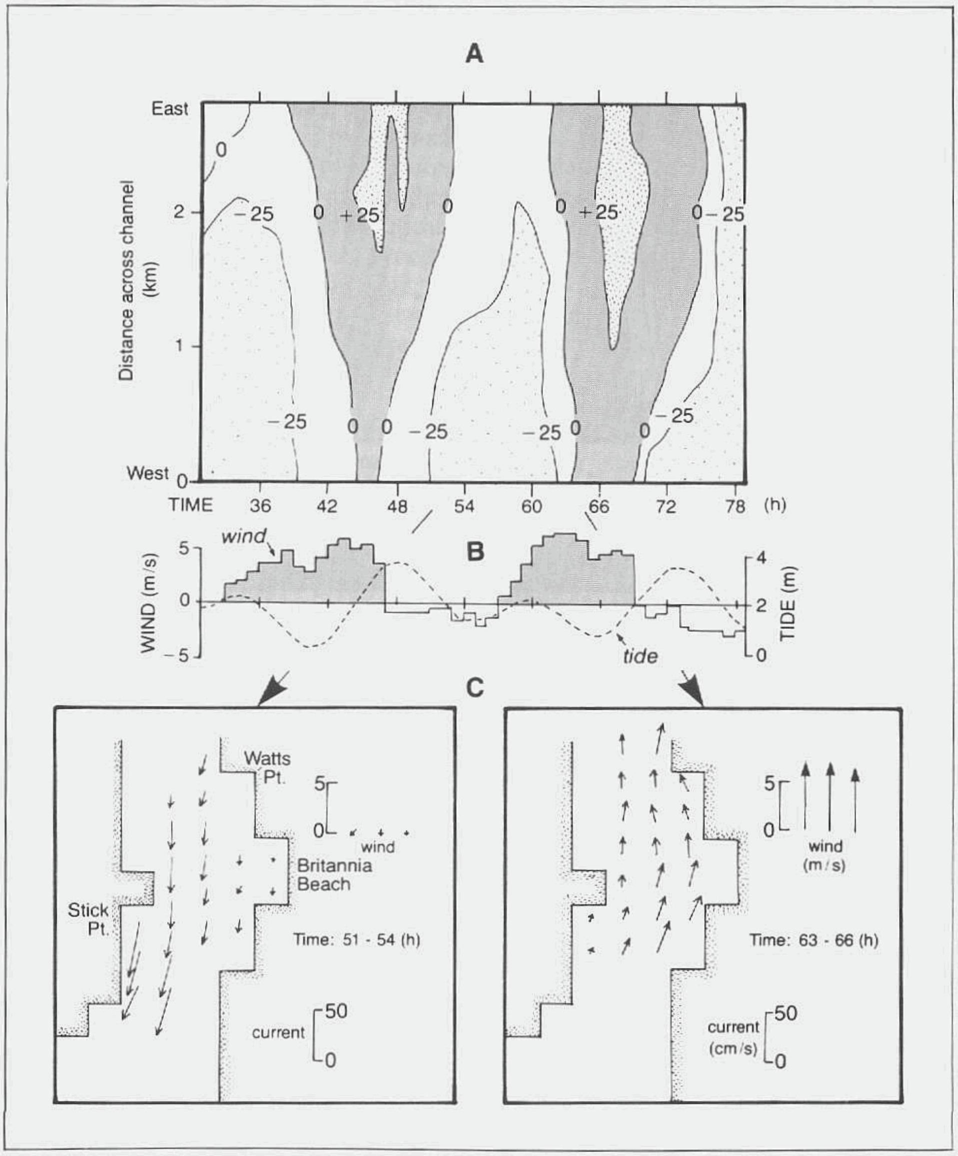


FIG. 10.41. Effect of winds on surface currents in central region upper Howe Sound, May 9–11, 1973. (A) Variation in speed (cm/s) and direction of along-inlet surface current over 48 h between A and B in Fig. 10.39. Positive values indicate up-inlet currents, negative values down-inlet currents. At 72 h for example, flow is down-inlet on west side at over 25 cm/s, but up-inlet on east side at 0–25 cm/s. (B) Wind speed (m/s) and tide height (m) correspond to the times in (A). Positive values (shaded), up-inlet (northward) winds; negative values, down-inlet (southward) winds. At 72 h winds light from north, tide high. (C) Surface current vectors in plan view. Flow averaged over 3 h and surface area of 0.5 nm on side for each of two different time intervals. Compare with (A), (B). Length of current arrows in cm/s, when compared to lower scale; wind speed scale, m/s; and wind vectors shown for each of 3 h over which flow is averaged. (Adapted from Buckley 1977)

the surface outflow has been reversed there is often a persistent seaward current between 5 and 10 m. At greater depths the flow is slowly up-channel to within a few kilometres of the river mouth.

Relatively little is known about the general circulation in the island-strewn outer basin of Howe Sound, though, based on the geometry of the region, surface currents can be expected to be weaker, more variable, and to have considerably more eddylike structure than those in the confined inner basin. Tidal currents play a greater role in this region but their presence will be partially masked by strong winds. Because the tide is delayed by only a few minutes throughout the Sound, maximum floods occur midway through a rising tide, and maximum ebbs, midway through a falling tide. During relatively light to moderate airs, tidal streams attain speeds of around 25 cm/s in the comparatively unobstructed eastern channels with somewhat greater speeds in the narrower passages between the islands and in the vicinity of points of land. Southerly winds in excess of 5 m/s will lead to stronger surface flood currents and weaker ebb currents which, on occasion, may be reversed to up-channel flows. However, northerly winds will accelerate the ebb and decelerate the flood. During the summer months, the added effect of the brackish outflow is to strengthen the ebb and weaken the flood.

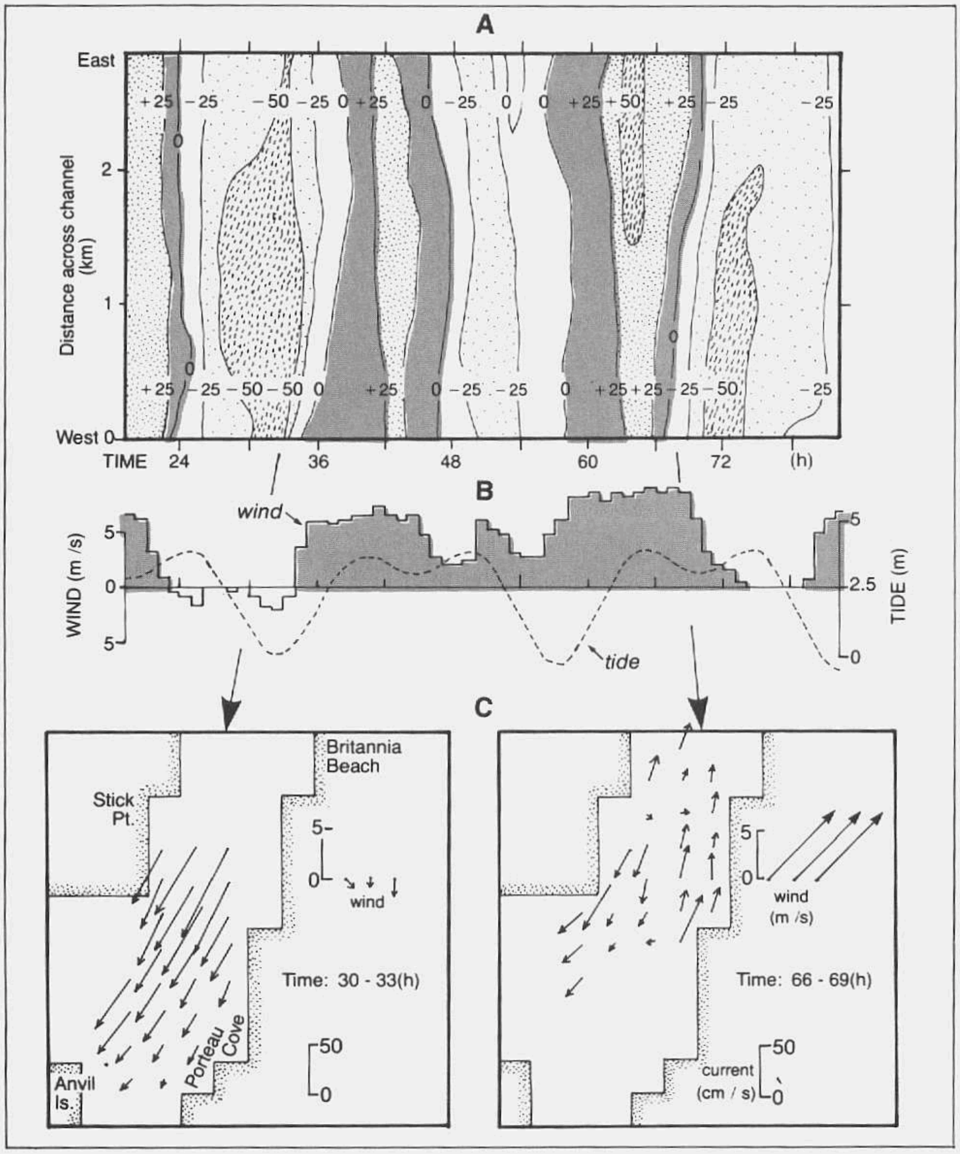


FIG. 10.42. Effect of winds on surface currents at southern end upper Howe Sound, June 27–29, 1973. (A) Variation in speed (cm/s) and direction of along-inlet surface current over 48 h in cross-channel section north of Anvil Island. (B) Wind speed (m/s) and tide elevation (m) at times of current observations. Except for few hours, winds were up-inlet (positive). (C) Plan view of average surface current vectors for two, 3-h periods selected from observational period of (A). Rectangular shoreline consistent with fact that drogue measurements averaged over 0.5-nm grid array. (Adapted from Buckley 1977)

A hydrographic chart might suggest that the silt-laden surface layer that moves seaward from the inner basin would always prefer to enter the outer portion of the Sound via Montagu Channel (Fig. 10.38). Though this is prabably true in general, the few available aerial and current observations suggest there are numerous instances when the opposite occurs. Plate 2, for example, clearly shows that the main core of the brackish jet impinges on Anvil Island, then turns abruptly westward to follow the shoreline into Ramilles and Thornbrough Channels in the "lee" of the island. Nevertheless, a considerable portion of the silty water progresses into Montagu Channel, at least partially supporting the thesis of a surface outflow along the eastern side. Perhaps at the time of the photograph the southerly winds were mainly responsible for forcing the core to the west of Anvil Island, whereas during northerlies or weaker southerlies the brackish layer would more readily flow through Montagu Channel. Logic then dictates that the seaward outflow would continue on a preferred path to the Strait of Georgia via Queen Charlotte Channel. However, it seems that the head of water associated with the North Arm of the Fraser tends to drive brackish Fraser River water northward into this Channel, and forces the brackish Squamish River water to deflect through Collingwood Channel over most of a tidal cycle. Thus, a boater traveling into Queen Charlotte Channel during calmer summer weather will have the advantage of an up-channel set about as far as Bowyer Island (except during the times around maximum ebb) but will subsequently begin to buck a down-channel set north of the island.

Although detailed information concerning the outer basin is scanty, and probably will remain so for some time yet, the very nature of the convoluted shoreline assures a complex circulation pattern. Backeddies, for instance, undoubtedly prevail downstream of the smaller islands and in the lee of points of land that project into the main channels where nearshore counterflows will be produced, but in the larger embayments such as along the southern end of Gambier Island, currents will be insignificant. Confused and variable currents are also to be expected where the flows from different channels converge, for example north or south of Anvil Island where, depending on the stage of the tide, water moving through Ramilles Channel contacts that moving through Montagu Channel.

Waves

Strong winds can come up suddenly in Howe Sound and, despite the comparatively short fetches, can soon generate short, steep, choppy seas that are particularly hazardous to small craft. Greatest wave heights of 1.5 m are generally produced over the longer fetches available to southerly winds that blow inland from the Strait of Georgia, though waves to 2.5 m have been reported during storm-forced Squamishes. Swell-like waves that originate in the Strait can also penetrate a short distance into the Sound before being dispersed by the topography. Smallest waves at any given time will be found within the sheltered areas between the numerous islands in the outer basin and largest waves will be generated along the exposed eastern channels leading into the northern basin. Especially vigorous seas can be expected to form over the main core of the seaward flowing river jet in the inner basin, following the onset of a southerly gale.

Squamish winds often create an expanse of turbulent breaking waves adjacent to the outside entrance of the Sound. Wave heights diminish rapidly away from the outer islands as the arctic air fans out to the south; nevertheless, the effect is disconcerting to a boater who approaches the region from otherwise flat calm conditions in the Strait. At other times the presence of Squamish winds is not felt until the boater is well within Queen Charlotte Channel.