THE PROPOSED EXPANSION OF THE VANCOUVER INTERNATIONAL AIRPORT; SOME OCEANOGRAPHIC AND RELATED CONSIDERATIONS

A Report to the
Ecological Sub–Committee of the Airport Planning Committee

by
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ENVIRONMENT CANADA
Fisheries and Marine Service
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I. BACKGROUND

Plans are being prepared by the Ministry of Transport (MOT) for further expansion, during the next several years, of Vancouver International Airport (VIA) on Sea Island. The area primarily involved, as well as the general surroundings, is indicated in Figure 1.

One portion of this planned expansion consists of the construction of a major jet-carrying runway, which is to be located about 5,700 feet north of the present major east-west runway (No. 08 - 26). The total length involved, including the emplacement of the approach lights, would be about 17,000 feet. While a portion of the runway would be laid on Sea Island itself, several concepts already considered involve a greater or lesser degree of intrusion of the runway seaward (westward) of this island, onto the intertidal flat known as Sturgeon Bank.

A few of these general concepts - numbered 1, 2 and 4 - for the location of the proposed new runway are indicated in Figures 2, 3 and 4.

In addition, plans are indicated for the creation of a large service area to be associated with each of the two most westward-thrusting versions of the runway (Concepts 3 and 5 - Figures 3 and 4). These would involve the placement of fill to provide, perhaps in stages, about an additional 1,400 acres of property immediately westward of Sea Island.

The marine area likely to be most intimately affected by the proposed development is, as previously mentioned, composed in great part of Sturgeon Bank. Any complete consideration of the environmental impact of the expansion should include a study of the oceanography of the area, in particular of the Bank itself. The results of such a study would, hopefully, be multi-disciplinary in application - serving not only to refine present knowledge of physical oceanographic conditions per se, but also to provide information useful to other workers (especially those biologically or geologically oriented) in their assessments of possible effects of airport expansion onto the Bank.

It is therefore the object of that portion of the impact study directly involving the Marine Sciences Directorate to:

(a) Describe, as thoroughly as available data permit, the oceanographic conditions on Sturgeon Bank and the immediately-seaward areas;

(b) Utilize the finds from (a) to predict as completely as possible the impact, upon the physical oceanography and closely associated aspects, of the various proposals for runway construction being or likely to be considered.

II. GENERAL DESCRIPTION OF STURGEON BANK

Sturgeon Bank is considered to represent the extensive, primarily intertidal, area of river deposition extending southward from the North Arm Jetty to the Steveston Jetty, and westward to a maximum of about 3 statute miles from the dykes comprising the seaward extremities of Sea and Lulu Islands (Figure 1). The intertidal area of most importance in the present context consists of about 15,000 acres.

The North Arm Jetty, completed in 1935, extends roughly northwestward about 315°T) from western Iona Island. It maintains the Arm across the intertidal area by forming its southern boundary, and is composed basically of stone and dredge spoil from the Arm itself; it remains above water most of the time. The major portion of the Steveston Jetty - which maintains the Main (South) Arm of the Fraser by acting as its northern boundary - extends roughly southwestward (at about 240°T). This jetty, completed in 1932, is made of stone, with a row of piles along much of the seaward portion through which the river flows freely, especially during period of high water level.

The Bank is effectively divided geographically into two parts by the Iona Jetty, a sand-core, rock-faced structure extending about 2½ miles seaward at about 250°T (i.e. just south of west). This relatively recent structure was completed about 1961, a primary objective being the restriction of northerly movement, across the Bank, of effluent discharged by the Greater Vancouver Sewerage and Drainage District's (GVSDD's) treatment plant on Iona Island. The effluent is released into a shallow outfall channel excavated in the Bank just south of the Jetty and paralleling it along its length. In addition, McDonald Slough - a shallow passage between Sea and Iona Islands - was dammed to prevent possible backup of effluent into the North Arm, by way of the Slough, on flooding tides. It may be noted that some authorities, e.g. the now-defunct Lower Mainland Regional Planning Board (1968), have designated Sturgeon Bank as the area lying between the Iona and Steveston Jetties, and the remainder of the Bank between the North Arm and Iona Jetties - comprising about 1200 acres - as a separate entity, sometimes named, simply, "Iona". Subsequent use in this report of such terms as "Iona" or "Iona area" will be based on this definition.

Much of the Fraser Delta, including Sturgeon Bank, can be subdivided into three major environments on the basis of sediment character: salt marsh, main platform and upper foreslope (Luternauer and Murray, 1973). The salt marsh, a flat-to-hummocky area which is about 1/2 mile wide, is located immediately adjacent to the dykes protecting the arable land of the Fraser Delta from the sea; it is vegetated primarily by halophytic growth such as sedge. In the Iona area, however (i.e., north of the Iona Jetty), the salt marsh is generally lacking, much having been buried by sandy fill dredged from the North Arm. The approximate landward limit of a storm-wave action (page III-10) is marked by a zone of driftwood. A steeply-sloping sand beach exists. South of the Iona Jetty, a driftwood zone is also evident, being succeeded to seaward by, successivly, a steep sandy beach and a flatter area of salt marsh. The sediments in the marsh area possess a mean-grain size of less than 0.06mm.*

* The sediment grain-size scale (due to Wentworth) used in this article is based on the metric system (mm), and is therefore most conveniently expressed in that system.

The main platform extends from the edge of the salt marsh to the (geologically designated) most common and distinct first break-in-slope (which is at a depth of about 30 ft. below lowest normal tide - Page III-4). The slope is extremely gentle (generally of the order of 0.1^{o}). The area is featured primarily by minor drainage channels (which are not as well developed as are those on Roberts Bank to the south) and by hydraulic bedforms (ripples generated by current and/or by wave action). A channel presumably associated with the outflow through the old "open" McDonald Slough passage still retains some prominence. Vegetation is extremely sparse. The Bank is mantled almost entirely by pure (over 90% rippled sand of 0.125 to 0.35 mm mean-grain size. A distinctive lobe of uniform, sell sorted medium sand (0.25 - 0.50 mm) extends from the mouth of the Middle Arm to the seaward edge of the platform. The Iona portion of the platform is mantled mainly with medium and fine sand (grain sizes about 0.125 - 0.50 mm).

The upper foreslope extends seaward from, by definition, the first break-in-slope level to a depth of about 300 ft.; it has relatively large slopes (from less than 0.5^{o} to 16^{o}, with an average value of about 1.5^{o} - Murray _et_ _al_., 1972). The shallowest levels of this zone can be strongly affected by such water movements as wave action.

III. FACTORS CONTROLLING THE OCEANOGRAPHY

Three primary forces affect the oceanographic régime of the area in question: tide, wind, and river runoff (primarily that of the Fraser River). The effects of the first two are most readily apparent over the short-term (periods of several hours to a few days). River flow is basically seasonal in effect. Other forces indicated to contribute effects over longer time scales (weekly to yearly), are: differences in mean sea level between the Strait of Georgia and the neighbouring open Pacific Ocean, and density differences set up in maintaining a salt balance. However, the extent of the contributions is at present not well understood. The possibility of quasi-permanent, localized currents being generated by internal waves has recently been suggested (page IV-5). Effects associated with Coriolis and centrifugal forces and with topography can modify water motions already in existence, but cannot themselves initiate movement. For purposes of review, each of the primary forces will be considered briefly in turn.

IIIA. TIDES

In the vicinity of the Fraser River Delta (including Sturgeon Bank) the tides are, as throughout the entire Strait of Georgia, of the mixed type characteristic of the Pacific coast of North America, providing two high and two low waters approximately every 25 hours. The variations in tide due to the moon's declination (angular distance from the equator) predominate over those due to other modes of lunar motion; in fact a diurnal inequality results, which affects the time and height of the tides. This inequality occurs principally in the heights and times of succeeding low waters; it is a maximum one or two days after the moon is at its extreme declination, and a minimum one or two days after the moon is at the equator. The declinational effect is strongest throughout the southern part of the Strait and decreases northward. Because of this strong dependence on the declinational effect, the relationship of the tides to the moon's phase is suppressed. Therefore, tides pass through what are termed "tropic" and "equatorial" sequences in alternate weeks. The former term is associated with tides occurring at or near the maximum declination of the moon, the latter with those occurring when the moon is at or near the equator. The terms perhaps contribute to a better description than do the words "springs" and "neaps", which are otherwise widely utilized. The diurnal inequality is extremely marked in the tropic sequence; tidal ranges are at a maximum.

Typical tidal characteristics for the Strait are summarized in Figure 5. During the week of tropic ranges, there is one large and one small tide each day; the marked diurnal inequality in the low-tide levels is clearly evident. (Abbreviations: LL - lower low water, HH - higher high water, L - low water, H - high water.) The range between an LL and an immediately-succeeding HH is generally greatest in the solsticial periods (June and December), $\sim$ 16 ft., and least at equinoxial times (March and September), $\sim$ 12 ft. During times of equatorial tides, the LL-HH range is usually less than about 9 ft. In the Strait, the effect of seasonal changes in the solar declination may overshadow those resulting from the moon's other motions. The largest tidal ranges of the year occur when both the sun and the moon are simultaneously at maximum declination (north or south of the equator). This situation occurs when the moon is at its maximum declination nearest the solstice in summer or in winter.

In the winter high tides generally prevail during daylight; on summer days, low tides generally occur. The lowest daylight tides will occur in late June near midday when the sun passes directly overhead and a new moon coincides with the maximum lunar declination north of the equator, or a full moon coincides with the maximum lunar declination south of the equator. It may be noted that the lower low waters ("collecting tides" of the intertidal biologist) occur within daylight hours from March to August and are under darkness during the remainder of the year (Waldichuk, 1957).

Throughout the central Strait of Georgia, which includes that portion bounded to the east by Sturgeon Bank, the surface tide floods in a basically north or northwesterly direction and ebbs to the south or southeast. On the eastern (B. C. mainland) side of the Strait, the flood appears generally to be both stronger and of longer duration than does the ebb. On the western (Vancouver Island) side, the ebb predominates.

The tidal flow immediately adjacent to Sturgeon Bank (as well as to the remainder of the Fraser Delta) will presumably be modified by water movement over the Banks (for example, by the easterly component of motion associated with flood tides).

The tidal reference port for the area in the general vicinity of

Sturgeon Bank is Point Atkinson (Caulfeild Cove). However, the tide can be strongly influenced by the Fraser River (especially near the South Arm); Sand Heads, the seaward end of the Steveston Jetty, has been designated a secondary port, and tidal readings there are more indicative of the Fraser's influence than are those at Atkinson. The difference in time between corresponding tidal phases (Sand Heads versus Atkinson) is stated as being at the most about + 18 minutes; the difference between tidal heights at corresponding slack waters is apparently at most about -2.0 feet. The Chart Datum, the reference plane for tidal height, is considered in Canada to be the plane of lowest normal tides. (Chart Datum is, by international agreement, taken to be the plane below which the tide will seldom fall.) Thus, the intertidal portion of Sturgeon Bank is considered to be that exposed at lowest normal tide.

IIIB. WINDS

A complete climatological summary applicable to the Fraser Delta would obviously entail enumeration of the characteristics of many meteorological variables. Some of these variables are perhaps of relevance in other facets of the present impact study (e.g., precipitation with regard to local runoff and to groundwater conditions). However, it is here considered that, for the oceanography-related aspects of the study, the surface wind is the variable of primary importance; discussion will therefore be confined to it.

Surface winds in the Fraser Delta are subject both to stormy "oceanic" and somewhat lesser "continental" influences. Such winds at the Delta are well described at the Atmospheric Environment Service's meteorological station located at the Vancouver International Airport itself (49^{o} 11'N, 123^{o} 10'W). The most noteworthy topographic relief near the Delta involves the 300-ft. cliffs on the Point Grey Peninsula (Vancouver Heights) a few miles north of the airport. The mean-monthly wind speeds (in mph) at the airport for the 19-year period 1953-71 are given in Table I.

TABLE I

Mean-monthly wind speed (mph)

Vancouver International Airport (1953-71)

January	8.0	May	7.3	September	6.8
February	7.7	June	7.2	October	7.3
March	8.3	July	7.1	November	7.8
April	8.4	August	6.6	December	8.2

A windrose for the same period, incorporating frequency and mean speed of wind by direction - for the 8 principal points of the compass (N, NE, E, SE, S, SW, W, NW) - is displayed in Figure 8 (Hoos and Packman, 1974). Figures 9a and 9b provide summaries of mean-monthly data: the former gives wind speeds (equal to the lengths of the corresponding vectors), and the latter the percent frequencies of wind direction.

As for the oceanic influence, it may first be noted that the prevailing surface wind regime on the neighbouring coast of British Columbia is predominantly southeast in winter and northwest in summer. However, it appears that winds in the Strait of Georgia itself do not conform to this simple pattern. Instead, there seems to be, in the southern Strait at least (including that portion bounded by the Fraser Delta), a closed counter-clockwise circulation from October to March (Harris and Rattray, 1954). In spring, winds are predominantly east to southeast throughout the Strait; in summer, they are generally southwest and southeast in the southern part of the Strait, but northwesterly at the northern end.

Although the Strait is protected from the open Pacific Ocean to a significant degree by the mountains of Vancouver Island, gale-force winds do accompany the more intense storms of winter. Movement down the coast of a cold front oriented in a SW-NE direction leads to strong SE winds as the depression with which the front is associated approaches the coast; the wind veers basically to W or NW after the passage of the front. These latter (W, NW) winds are especially marked, particularly in the southern Strait where they are funnelled between the mountain ranges which are present on both sides. The maximum hourly winds recorded at the Airport (over 50 mph) have been from the northwest.

To any oceanic influences must be added the continental effects, if a description of wind - over the western Delta at least - is to be considered accurate. In spite of the presence of the above-noted gale-force winds, the prevailing directions in every month are easterly (E or SE). Apparently, air movements from the south are deflected to a significant degree by the Vancouver Heights, and therefore appear as E, SE as high as several thousand feet above the surface. North winds are rare and light. Calms are of infrequent occurrence.

Land and sea breezes are prominent in summer during fine weather, and can be strongly reinforced by mountain and valley winds in the Fraser Valley itself (Kendrew and Kerr, 1955). The sea breeze sets into the coast about 10 a.m., strengthens until afternoon, and dies away before sunset. It can attain speeds of 10 to 15 mph at its maximum development. The land breeze moving from the east onto the Delta from evening to early morning is lighter, 3-8 mph.

In winter, land breezes due to overnight cooling are sometimes reinforced by a more intense flow of cold arctic air moving down the Fraser Valley. However, due to various topographic features in and about the Delta, such winds seldom affect that portion of the Delta comprising Sea and Iona Islands.

The action of wind on the sea surface can result in several significant effects. The stress of the wind on the surface (the momentum transfer from air to sea) can induce a drift current in the shallower waters. The strength of this current will be determined by several factors, including the strength and duration of the wind. Both theory and observation indicate that, in the presence of a thin light brackish layer overlying stably denser water (a condition obtaining in the vicinity of the Fraser Delta - page IV - 2), much of the current induced by winds of up to moderate speed will be confined to this layer; this effect is in contrast to that for similar wind conditions over homogeneous water, in which case appreciable current can be present over a considerably greater depth interval. Surface speeds of the drift current will, for deep homogeneous water, be of the order of 3% of the wind speed; however, in a "shallow-surface-layer" situation, they can be greater than this. The direction of the surface current is indicated generally to be near to and, in the northern hemisphere, to the right of, that of the generating wind. Such wind-induced motion can either oppose or augment other motions (e.g., those tidally-induced). In the presence of a shore (a solid boundary), an onshore wind of sufficient strength can "pile up" water at the boundary, and thus augment a water level resulting from tidal (or other non-wind) influence. Alternatively, an offshore wind can depress the water level in the vicinity of the boundary. (An important, but often confusing, distinction between the direction of an ocean current and that of a wind should perhaps be re-emphasized here. The direction assigned to an ocean current is that <u>in which</u> the current is moving, whereas that associated with a wind is that <u>from which</u> the wind is blowing (e.g., an easterly current is moving to the east, whereas an easterly wind is blowing from the east).)

In addition, mixing induced by wind results in a tendency to both vertical and horizontal homogeneity in the upper layers of the sea; the stronger such an effect, the more marked the degree of stratification that can be overcome.

On the shallow banks comprising the Fraser Delta, the enhanced mixing due to wind action, together with any turbulence generated by bottom friction, should tend to ensure stirring of fresh and any seawater overlying the delta - and thus aid in moderating horizontal and vertical variability in salinity and temperature.

Another, primarily wind-induced, effect closely related to the presence of the drift current, is that of wave action. It is now believed that most of the momentum transferred into the sea by the wind goes originally into waves, and subsequently - by such mechanisms as breaking of these waves - into the drift current itself. Waves in the Strait of Georgia are limited by the wind strength and by the fetch (the "uninterrupted" stretch of water over which the wind blows); they generally appear to have a maximum trough-to-crest height of the order of 5 feet (achieved primarily during winter storms), with an average height of only about 2 feet. However, waves at the estuary itself may be considerably modified by bottom shoaling and by interaction with runoff and tide. Some of the most vicious waves in the estuary area occur when a northwest wind (having the longest fetch possible with respect to the estuary) opposes an ebb tide in the presence of substantial Fraser River runoff (Hoos and Packman, 1974). Southerly, westerly, and especially northwesterly winds can pile water into the Fraser Delta itself (including Sturgeon Bank) in the form of short-period, sharp-crested chop (Murray *et al.*, 1972).

Waves can provide several potentially important results in the

Sturgeon Bank area. Wave action on the Bank is dependent to some degree upon tidal height. Waves incident at low tide (especially those associated with storms) will expend most of their energy upon breaking on the "outer-flat" and "upper-delta" slope zones (Murray et al., 1972). At higher tides the effect on the delta front will be correspondingly less, and the tidal flat area proper will be subjected to increased wave action. Resultant turbulence and stirring can bring sediments into suspension; the greater the wave action, the larger the size of the material that can thus be affected. Such material can then be redistributed by any significant longitudinal motions present. It has been suggested, on the basis of sediment distribution, that the effect of wave action on Sturgeon Bank can extend to the -30 foot level (with respect to chart datum) (Murray et al., 1972). Wave action may in addition be of some subtle importance to marine life. For example, smaller waves may form sand-ripples on the inter-tidal area; such features, if they remain intact for appreciable periods, may provide havens for benthic organisms (Hoos and Packman, 1974).

III. C.1. FRESHWATER RUNOFF

The freshwater runoff of prime concern to the circulation on, and thus to the study of the biology and the general ecology of, Sturgeon Bank is that of the Fraser River; in fact, about 80% of the runoff into the entire Strait of Georgia is accounted for by the Fraser (Waldichuk, 1957).

The flow characteristics at Hope, B.C. (about 100 miles upstream from the river mouth) are given for 1967, a "typical" year, in Figure 6. The discharge is seen to be strongly seasonal. During the winter (January through March) the flow at Hope is at an annual minimum, values lying generally between about 20,000 and 40,000 cu. ft./sec. In April through June (the freshet period), the flow increases rapidly; the daily rate of increase can be as great as 30,000 cu. ft./sec. The maximum flow occurs in June, values of 200-300,000 cu. ft./sec. being usual; however, outflows of well over 500,000 cu. ft./sec. have been recorded. The flow then declines irregularly to the succeeding winter's minimum.

The Fraser is a prime example of a river with a stored runoff, which feature accounts in great part of the marked annual cycle in the flow rate. The drainage area of the river and its tributaries above Hope is of the order of 90,000 square miles, a large part consisting of typical strongly mountainous B. C. terrain. During the winter, precipitation in the basin is therefore stored as snow and ice on these mountains. With the advent of spring warming, snow- and ice-melt become primarily responsible for the large increases in flow present during the freshet. The flow rate is therefore dependent upon both the intensity and the duration of the heating; occasionally more than one marked peak may occur in the flow during freshet.

III. C.2. SEDIMENT LOAD

The entire drainage area of the Fraser possesses great geological diversity, and includes plutonic, volcanic, metamorphic and sedimentary rock, as well as glacial deposits. There is therefore associated with the outflow a significant transport of sediment; it is believed that a total of the order $25(10^6)$ tons annually reaches the vicinity of New Westminster. There are two primary modes of such transport by moving water: suspended load (considered here to include "wash load") and bed load. There is a seasonality in this transport by the Fraser even more pronounced than that associated with the water flow itself.

The suspended load is distributed throughout the full depth of the river. At Hope, the transport of suspended sediment increases from 1000-3000 tons per day during the low-runoff period to 500,000 - 750,000 tons per day shortly prior to the river's flood crest (Mathews and Murray, 1966). More than $18(10^6)$ tons pass this location each year. The concentrations have been found to range from 15 parts per million (ppm) by volume to 970 ppm. The load averages about 40% sand size, 50% silt and 10% clay (this last finer than about 0.00024 mm); the proportion of sand is greater during freshet than at other times of the year.

Suspended sediment concentrations downstream of Hope follow the same general seasonal pattern, although values can be significantly less because of the decrease in turbulence within the river. At New Westminster, for example, Johnston (1921) found values to range from about 20 ppm in the winter to 200-250 ppm during freshet.

The Fraser River water is more or less turbid throughout the entire year, indicating that the finest particles (silts and clays) are always in suspension. The strong discolouration during the large-runoff period occurs primarily from the presence of fine material originating from scouring of granitic mountainous areas by glaciers. However, a continuous contribution originates both from the wearing away of easily-eroded banks and cliffs of unconsolidated glacial drift and from bank and land-surface erosion on the flood plains of the Fraser Valley (Pretious, 1972).

The turbid Fraser water moves into the Strait of Georgia, and spreads out in a thin layer as a plume overriding the seawater. The speeds associated with the waters of this plume are, therefore, much less than those occurring in the river channel itself. The heavier suspended material will sink out of the surface layer, leaving a successively finer residue in suspension. In addition, another process appears to enhance the degree of sedimentation. As the fresh water moves into the Strait, it entrains (takes up) seawater from below, thus becoming progressively more saline away from the river mouth(s). It appears that a marked surface demarcation between turbid brackish water and the clearer water of Strait-of-Georgia origin occurs at a surface salinity of about $15^{o}/oo$. As an explanation, it is suggested that, in water of salinity between 0 and $15^{o}/oo$, flocculation of the silt fraction is quite marked; in higher salinity waters, only the very fine fraction (e.g., clay, 0.00024 - 0.0039 mm) remains, leaving the water relatively clear (Waldichuk, pers. comm.). (This fraction will itself, of course, eventually precipitate.) Thus a means for visual delineation of the main plume exists; the effect is especially striking from the air during times of large runoff (Fjarlie, 1950; Tabata, 1972) - Figure 7.

The bed load, in contrast to the suspended load, is confined to the deepest portion of the river flow; the concentration of the material decreases upward but is (in the horizontal) everywhere relatively high. The load will in general consist of larger material than that comprising the suspended load - the coarser sand fraction (0.5 to 2.0 mm), as well as (at least at Hope) a significant gravel (2.0 to 256.0 mm) content. Suggested values for the amount reaching New Westminster per year, for example, are large but vary widely.

Bed-load movement downstream of Hope is of little significance during winter (low-runoff) periods. Conversely, during periods of very large discharge, sand ripples or "dunes", having a trough-to-crest height of up to 15 feet and a wave length of 500 feet, have been found to migrate downstream at speeds of about 250 feet/day.

The meeting of fresh and sea water, together with the effect of tide can, because of the formation of a salt-water "wedge", lead to at least a partial separation of suspended and bed loads. The explanation is deferred until the discussion of the circulation on Sturgeon Bank (Section IV B).

IV. CIRCULATION

In this section will be provided a brief discussion of the water circulation on, as well as in the immediate seaward vicinity of, Sturgeon Bank. The following mode of presentation, considered to be a logical one for the present work, will be adopted. First, the basic features of the movement just seaward of the Bank, together with some suggested causes, will be briefly noted. Then a general, essentially qualitative, circulation will be indicated for Sturgeon Bank itself. Finally, because of the possibly significant interaction between the various concepts of airport expansion (Section I) and other man-made features already present in the vicinity, conditions in the vicinity of the proposed runway will be considered in some detail.

IV A. OFFSHORE CIRCULATION

In the "offshore" area under consideration, circulation in the shallower waters will be stressed, as presumably this motion will have the most intimate bearing upon both the contribution to and the modification of water movement on the Bank itself.

The shallow circulation in the Strait of Georgia proper was intermittently studied for several decades prior to the mid-1960's by use of hydrographic casts, drift bottles and current meters. Primarily because of the implications to the study of marine biology, efforts in the vicinity of the Fraser River were emphasized. Deductions from these data have been discussed at some length by Waldichuk (1957) and by Tully and Dodimead (1957); these works should therefore be consulted for general background knowledge of oceanographic conditions within the Strait. One feature revealed by these studies is that outflow from the Fraser River (moving over denser water of essentially oceanic origin below, as already noted (Page III-13)) tends to produce within the Strait, a distinct two-layer vertical structure in density, generated primarily by the variation in salinity. Near the river, a lighter, thin (3-30 ft.) layer of brackish water (to $\sim 10^{o}/oo$) overlies deeper water of much greater salinity (to $\sim 31^{o}/oo$); the characteristic brackishness results from entrainment of seawater into the entrant river water. Both the density (salinity) contrast itself, and the depth interval throughout which it occurs ($\sim 20^{o}/oo$ through $\sim$ 10 ft.), is much more marked in the vicinity of the river mouths (primarily that of the Main Arm). However, tide, wind and diffusive processes ensure extension of the two-layer structure throughout much of the Strait. The structure is, as would be expected, most prominent and widespread during the large-runoff period of the Fraser; it can be slightly emphasized, during this summer interval, by heat (from solar radiation) retained within the upper layer.

The data referred to above include those obtained at the seaward extremities of the Sturgeon Bank-Burrard Inlet area during 1949 and 1950 (Pacific Oceanographic Group, 1951). It may be noted that inferences from these latter data were of prime importance in the decision to locate a GVSDD sewage-treatment plant on Iona Island (Hyde, Oliver and Rawn, 1953). (During this study, a fairly intensive aerial photographic survey of the central Strait of Georgia, including the Fraser Delta, was carried out. Examination of the photographs permitted some useful characteristics of the motion of the water originating in the Fraser River to be determined. A more exhaustive study of this aerial photography has recently been carried out by Tabata (1972)).

Since 1966, somewhat more intensive, although by no means exhaustive, studies have been carried out upon the distribution of the properties and the water-movement characteristics in the vicinity of Sturgeon Bank. Current followers of the crossed-vane variety ("Lagrangian" measurements (Page IV-19)) were utilized, at first, to determine and/or to confirm the basic (surface) current regime. However, as an advance upon previous efforts, current profiling at several locations to a depth of about 160 ft. was carried out (Giovando and Tabata, 1970; Tabata, Giovando and Devlin, 1971; Tabata, Giovando, Stickland and Wong, 1970a,b). From these measurements some basic quantitative characteristics of the circulation near the delta have been obtained.

The data indicate, foremost, that to about 2 mi. offshore of the Bank there can exist, at least between the North Arm and Iona Jetties, a surface-layer flow that is quite persistently northerly in direction, especially during the summer (the large-runoff period of the Fraser River). A high degree of homogeneity in current direction exists within the layer. However, a gradual decrease of speed with depth was found to occur in the layer; in the absence of significant wind effects, values of metered speeds between 0.5 and 1.0 knot were found to be common. Average surface speeds (at 3 ft.) obtained by current followers were in general of the same order, although values as great as 3.5 knots and as small as 0.3 knots were encountered. The waters moved net distances of the order of 11 mi. per 24-hr. day.

The persistent northward flow signifies that ebb-tidal effects can be partially masked (although speeds appeared in general to be somewhat smaller on ebbs than on floods of similar range). There was, in addition, evidence in the data of a zonal component at times; on large floods for example, more easterly motion was present - due perhaps in part to the inundation of Sturgeon Bank by such tides. In summer at least, the northward surface flow is associated with water more silty (light-coloured) than that offshore; this water is thus suggested to be primarily of Fraser River origin. Winds of sufficient strength can, of course, augment or impede the flow according to their direction.

The shallow currents to the west of this northerly "stream" can apparently be extremely irregular, although at times they seem to be related to both the tide and the wind. However, the presence of southerly movement persisting for intervals of at least several days has also recently been noted (Tabata, Giovando and Devlin, 1971).

It may also be remarked that what data are available suggest that, in the area of the northerly flow and at least somewhat to the west, water motion beneath the surface layer can differ markedly both in speed and in direction from that above - at least during the large-runoff period. The currents, to 160 ft. at least, were found to decrease steadily with depth. Values to 0.5 knot were common; however, speeds as small at 0.1 knot and as large at 1.0 knot were occasionally encountered. Directions to 160 ft. were found to be easterly in trend for a few days, but apparently can undergo marked variability; the effect of the tide is in general stronger than is the case near the surface, but can be irregular also.

The concept widely held previously is that, within the shallow waters, a <u>net</u> northerly circulation occurs on the eastern (Mainland) side of the Strait of Georgia. However, the information summarized above suggests that such simplistic interpretations of the circulation within the Strait generally may be extremely unrealistic.

For the "ribbon" of northward surface flow at the seaward limit of Sturgeon Bank, it appears therefore that tide and wind can generally be considered only as modifying, and not as generating, agents. As for generation, there exists the possibility that the flow can, at least partially, be hydraulically driven. In summer especially, entrant Fraser River water is believed to contribute significantly to the maintenance of a difference in sea level between the mouth and locations some distance away (Waldichuk, 1964). (Both the Main, primarily, and Middle Arms could provide such an effect.) The surface flow resulting from the associated horizontal pressure difference would be subject, among other effects, to Coriolis force (which is proportional to the water speed, and, in the northern hemisphere, results in a deflection to the right of the motion). If this force is of importance, the flow in question would therefore move to the north. Sea-level differences actually observed between the Main Arm and locations several miles away (Waldichuk, 1964) are suggested to be large enough that at least some of the river discharge can contribute to such flow characteristics.

A very recent theory whose results are in good numerical agreement with the primary characteristics (the speed and the lateral extent of the flow) actually observed, has been advanced by Thomson (1974). Internal waves are defined as those occurring between fluid layers of dissimilar densities. Such waves have been known for some time to occur within the Strait of Georgia (e.g., Shand, 1953). It is postulated that the narrow longshore current is generated by the breaking of these internal waves at the frontal slope of the Fraser Delta. The waves themselves are believed generated at each turn of the tide in the passes between Georgia and Juan de Fuca Straits. They have been noted to progress always in a northward direction, and are known to have periods of minutes, heights of about 6 to 30 feet and wave-lengths of the order of 300 feet. Such characteristics as the amplitude can be expected to be most marked at relatively sharp density interfaces, such as those occurring especially off the mouth of the Fraser River.

To quote Thomson: "(the waves propagate) northward in groups having ground speeds of a few cm/sec (*a small fraction of a knot*) for groups moving against an ebb and 25-75 cm/sec (0*.5 to 1.5 knots*) for those moving with a flood. Actual group velocities are typically about 50 cm/sec (*1 knot*) (Gargett, 1970). Distances between the individual groups in the southern straits vary from 2-10 km (*1-6 mi*) depending upon advective effects and upon the number of groups formed at each turn of the tide. The latter varies from 1-4, with larger values associated with the turns to flood. As the groups move north, the initial concentricity of their fronts becomes affected by variations in stratification, advection and topography. Nonetheless, the location and orientation of the Fraser delta shoreline is such that the waves strike it obliquely in a manner conducive to generation of a northward longshore current ... moreover, the groups usually contain ten or more waves, so that the time dependent motions at any locality persist long enough to establish the necessary quasi-stationary state. Constant onshore wave propagation in the absence of significant reflection should therefore establish a continuous flow, while lags of many wave periods between groups should result in an intermittent longshore flow. At present, lack of long period observations in the nearshore region make it impossible to establish which of these features is actually occurring."

The theory predicts that the maximum speeds associated with the longshore current will occur about 1-2 mi off the end of the Iona Jetty. Features such as east-west flow on Sturgeon Bank during large floods or ebbs are considered of importance in determining characteristics of the current. In addition, because of the more marked salinity (density) stratification present during the summer and autumn, any such longshore current should be more characteristic of those times than of the remainder of the year. The times coincide with greatest outflow from the Fraser River, and therefore of greatest northward transport by the current. There will be possibly-associated features such as erosion of the subsurface portions of the delta by breaking internal waves. Such erosion would tend to counteract, to some degree at least, the effect of enhanced sedimentation presumably occurring in summer.

IV B. CIRCULATION ON STURGEON BANK

No general quantitative study of current characteristics (i.e., by current-measuring devices) has as yet been carried out on Sturgeon Bank itself. Some numerical results have been obtained in the vicinity of the Iona Jetty; these are discussed in Section IV C. However, the studies (Fjarlie, 1950) associated with the preparation of the report by Hyde, Oliver and Rawn (1953) involved a qualitative analysis of water-mass movement on Sturgeon Bank during late-freshet conditions (mid-summer). These studies were, admittedly, carried out under conditions somewhat different from those occurring at present (e.g., no Iona Jetty and no causeway across the seaward entrance to McDonald Slough). However, it is suggested that the present circulation on Sturgeon Bank can be basically described by modest modification of the results obtained during this earlier study - primarily by incorporation of the effect both of newer man-made topographic features and of oceanographic characteristics suggested by more recent data.

It may be noted that clarification of the circulation on the Bank in greater detail than that presently available would seem to be an exacting task. Methods holding some promise, such as hydrodynamical-numerical modelling, are at present available; however, the difficulties inherent in both theoretical and experimental aspects associated with any method suggest that a meaningful increase in knowledge is some distance in the future.

As the interaction between tide and Fraser River out-flow is always present, to a greater or lesser degree, and must affect the circulation on Sturgeon Bank, it seems appropriate at first to discuss briefly the basic features generated by this interaction.

An important consequence is the presence of the "salt wedge" already noted (page III-14). The wedge occurs because of the entrance of dense sea water into the river and of the resultant underrunning of the "lighter" river water (Tully and Dodimead, 1957). The term "wedge" is extremely apt, since the boundary between the fresh and the intruding sea water tilts downwards towards the river - to the east in the case of the Fraser; the associated slope, while appreciable in the oceanographic sense, is in actuality extremely small - a few (vertical) yards over a horizontal distance of about 6 mi., i.e., of order 10^{-4}. The sea water intrusion is retarded by frictional effects associated with the opposing seaward river flow. This effect is greatest at the interface itself and decreases with depth; the least effect, and thus the greatest penetration of the salt wedge, occurs at the river bottom.

The generalized behaviour of the wedge and other features of the associated dynamics can be noted (Tully and Dodimead, 1957). On a rising tide, the currents in the fresh water (river) and in the salt water (wedge) are in opposite directions. Speeds associated with the former decrease to seaward, while those of the latter decrease upstream. A convergence (tide rip) forms along the "lateral" line where the opposing flows are effectively equal. Upstream from this convergence the seawater moves eastward (into the river) while the river water moves seaward with a speed equal to the difference of the opposing streams. Seaward of the convergence the flood (upstream) speed exceeds that of the surface (river) water; therefore the surface water moves upstream. Both fresh and seawater therefore accumulate in the estuary on a rising tide. The tide rip forms off the river mouth as the tidal rise commences, and subsequently advances into the river as the rate of tidal rise increases. Subsequent to mid-tide, the rate of tidal rise decreases and the rip retreats seaward. During the rise there need be little or no river outflow; hence the continuing runoff can accumulate in the estuary. Thus the surface flow wanes; however, the deeper flood movement continues until the final stages of the tidal rise. Near the time of high tide the intruding current weakens, and becomes effectively zero at high tide. The boundary surface between the fresh and sea water tends toward the horizontal during this period. Therefore the fresh water accumulated in the estuary during the tidal rise is discharged seaward; the small ebb flow is not sufficient to flush out the sea water. During the long runoff both fresh and sea water are flushed from the estuary.

During any stage of runoff (e.g., the freshet) a tropic (large-range) tidal cycle implies a large intrusion associated with a large tidal rise, a small retreat and intrusion with the succeeding small-range tides (ebb and flood), and a large run-out with the large ebb. During equatorial tides, which have more modest and near-equal ranges, the intrusions and flushings should follow a similar correspondence. Thus there would be a semi-diurnal salinity cycle associated with such tides.

The degree of intrusion of the wedge into the river varies both tidally and seasonally (Johnston, 1921). During freshet, the intrusion apparently rarely reaches beyond the vicinity of Steveston (at the southwest tip of Lulu Island). The seawater-freshwater "surface" convergence is near the mouth of the river at high tide. On the ebb, any convergence will migrate several miles into the Strait. During intermediate river stages, the intrusion can penetrate some distance upriver of Steveston, and the convergence can be well inside the river mouth. During low-runoff conditions, the wedge can reach the Deas Island Tunnel, about 6 mi. upstream of Steveston; some effects (salinity contamination) have been noted as far inland as New Westminster - about 15 mi. upstream (Thomas, 1954).

The river flow is "tidal" as far as about 60 miles upstream from Sand Heads (to the vicinity of Chilliwack) during the low runoff season, but only to about 40 miles upstream (Mission) during freshet (Pretious, 1972).

Fjarlie (1950), studying the North Arm, showed that when the discharge of the Fraser River (as metered at Hope, B. C.) exceeded about 200,000 cu. ft./sec. the meeting place of the tidal and river waters was outside the arm, so that the flow in the river was always seaward. When the discharge was significantly less (between about 120,000 and 75,000 cu. ft./sec.), the tidal currents during the large rise of the tides were greater than the river flow, sea water intruded the arm, the river flow was reversed and there was no outflow during the flood. However, during "half tides" the outflow continued, but varied with the tidal phase. Thus during the periods of average river levels the discharge occurs as a diurnal outflow. Tabata (1956) confirmed these conclusions by indicating that, in the Main Arm, the period of sea-water intrusion varies with the tidal rise and inversely with the runoff, and he proposed similar limits of intrusion.

On large ebbs during freshet, the core of the runoff, especially at the South Arm, can move effectively as a well defined jet several miles into the Strait of Georgia. In the absence of significant winds, the entrant direction (e.g., southwesterly in the case of the Main Arm) can be maintained for appreciable times and distances, thus suggesting a temporary balance between Coriolis and ebb-tidal forces. However, some lateral spreading of the fresh water is inevitable; as a result, there are formed distinct "cloud-like" bodies of fresh or brackish water which float "free" and are subject to the action of currents (or whatever origin) in the vicinity. They are visible during freshet because of their appreciable load of suspended material. A series of these clouds may be present simultaneously (Figure 7). Each cloud will be separated from preceding or subsequent ones by distances moved during the intervening flood-tide interval. The clouds may remain distinct for several tidal cycles; however, whether they move quickly into the Strait of Georgia, or onto portions of the intertidal flat (e.g., Sturgeon Bank) on a flood, they eventually lose their oceanographic identity by mixing with underlying sea water. (During very large rates of flow (say 300,000 cu. ft./sec.) there is a continuous discharge to the Strait - on both ebb and flood. Even under these conditions, however, the discharge will vary to some degree with tide; a chain of connected clouds can result.) The presence of these more-or-less discrete entities could be expected to result in a considerable range of fluctuation in the values of oceanographic properties (especially salinity) within the shallower waters, through various scales of time and/or space.

The salt wedge and the associated tidal dynamics have some interesting consequences to sediment transport in the lower reaches of the Fraser (Mathews and Murray, 1966). During the movement of the wedge into the river mouth, during and immediately following the tidal rise, the bed load (primarily sand - page III-13) can, effectively, be prevented from leaving the river. Alternatively, as the salt wedge withdraws from the river after high tide, the bed load can move out of the river into any southwesterly flow generated by the falling tide (especially by large ebbs) in the Strait of Georgia. However, at least part of the suspended load, of which silt is the primary constituent, will escape continuously from the river during the freshet. This seaward movement will, of course, be more rapid on the ebbs than on the floods. Silt can therefore be carried southward as well as northward. Thus the net effect would be a partial separation of the two primary portions of the sediment load.

The tides have a marked effect on the suspended-sediment concentrations, since the transporting capacity of the river flow is greatest near local low tide (Pretious, 1972). For example, at Port Mann (about 25 miles upstream from the river mouth), the concentration of suspended sediment observed during freshet was found to be about twice as great at the local low tide as at the local high.

The general aspects of water motion on Sturgeon Bank itself can now be considered. Fjarlie (1950) has described, in an essentially qualitative fashion, water-mass movement in the area during late July (i.e., within the immediate post-freshet period for the Fraser). With his results as a basis, it is considered expedient to commence by considering conditions during a tropic tide, in particular at the high water immediately preceding the associated large ebb. The range of this ebb and of the comparable immediately-succeeding flood should provide a measure of the extreme conditions for water movement over the bank during the outflow conditions involved (significant wind effects being considered absent).

As the tide commences to fall, it is believed that several water masses can be identified as residing on Sturgeon Bank (the approximate extent of each being depicted in Figure 10a): brackish water (A) from the Main Arm of the Fraser (see below); fresh water (B), which has spilled over the Steveston Jetty from the Main Arm (the process being presumably abetted by the accumulation of water in the river during the preceding high tide, or "stand" of tide (page IV-9)); fresh water (C), primarily from the Middle Arm, which is assumed to have spread to the north and the south of the arm - in the former instance, it should attain the Iona Jetty (and thus should also include the relatively small fresh-water outflow from the GVSDD outfall on Iona Island (page IV-18)); and brackish water (D) which has originated from the (B) and (C) masses produced during the previous flood tide. (D) should overlie at least the entire Iona portion of the Delta.

All these masses will move generally westward and drain completely from the Bank on the large ebb tide; only fresh water outflowing from the Middle Arm, and essentially confined to its channel across the Bank, and from the sewage channel will be present at low water. The offshore motion should to some degree be accentuated by outflow from the Fraser distributaries involved. At low tide, therefore, the masses lie generally offshore in the deeper water, having effectively become "surface" masses with respect to that water (Figure 10b). All of them, and presumably to a greater degree A and D, which are more seaward than the others, have become more saline by vertical entrainment of underlying sea water.

The masses should move basically in a northerly direction during the ensuing large flood; such motion will be accentuated by any (northerly) longshore current. Further mixing will occur with the underlying water during transit. Thus D, which is now almost two tidal cycles old, and the portion of A just previously on the Bank, might be expected to lie well offshore of the northern portion of the Bank. However, any part(s) of these masses which may intrude into the waters to the immediate west of the longshore-current area (by whatever mechanism) might subsequently move in directions other than northerly (page IV-4). A new D mass, formed presumably in great part by lateral mixing of masses B and C subsequent to high water, will migrate over the Bank, by northeasterly motion, both to the north and the south of the Iona Jetty (Figure 10c, d).

A new B mass will be formed on the rising tide by spillage over the Steveston Jetty. In addition, on an ebbing tide (especially a strong tropic ebb during large runoff) a cloud of fresh water will appear off the Main Arm. The succeeding large flood should move a portion of this cloud onto the Bank; both the northward component of tidal motion and the longshore current (if present), should ensure its northeasterly spreading over much of the outer Bank adjacent to Lulu Island. This will supply a new A mass. (Neither the new A nor B is shown in Figure 10.) On Sturgeon Bank conditions have now passed through a complete (large-ebb-and-flood) tropic cycle. The degree of movement associated with these changes is basically consistent with the observed numerical values of "immediately-offshore" shallow currents (page IV-3).

The Iona Jetty prohibits direct north-south communication on that portion of Sturgeon Bank in its vicinity. A study by Parsons et al. (1973) indicates that some constituents, such as heavy metals, are in general present to a greater degree in the benthic fauna from Sturgeon Bank, including the Iona area, than in those from other areas of the Fraser Delta. They suggest that the primary source of such constituents is the effluent from the Iona outfall (page IV-18). The presence, therefore, of at least a portion of water mass D (containing a contribution from the outfall) throughout the Iona area, as suggested on page IV-13, is consistent with their results. In particular, any large values of heavy-metal content encountered in fauna near the seaward end of the northern face of the Iona Jetty may possibly be related additionally to a localized circulation in that vicinity. Some characteristics of this motion are noted on page IV-27.

Some further comments on the circulation over the Bank can be made. The tidal cycle intervening between two large-range cycles of the type as considered above involves, especially in extreme cases, relatively very small ranges. As a result, therefore, only incomplete removal of the water masses from the Bank should occur during the ebb involved. It appears that when a longshore current is fully developed northerly motion just offshore is of significance even during small tides. Thus at least the most seaward portions of the water masses will undergo the motions already noted as occurring during the larger-range tides. Speeds associated with the longshore current itself can be reduced during ebb vis-à-vis comparably-ranged floods; however, the values associated with large tidal ranges are not necessarily significantly greater than those present during small tides. Water masses C and D should be augmented by further fresh-water input primarily from the Middle Arm during the relatively high stand of water associated with such a small-range tropic tidal cycle.

Portions of water masses C and D may attain the mouth of the North Arm during their sojourn offshore during a flood tide. During the immediate post-freshet period under discussion, there may be, in addition, some penetration of this water into the North Arm; however, the intrusion should be removed on the succeeding ebb.

Other possible combinations of runoff and tidal action may be noted. For equatorial tides, the two cycles associated with each tidal day can at times be of intermediate and quite comparable value. By comparison with tropic-tide conditions, the degree of excursion of water masses over the Bank will therefore be lessened, but the general conditions discussed above should still apply.

During freshet, there will be no tidal reversal of flow in any of the river channels; the movement is seaward at all times. Thus there should be no penetration of water previously resident on Sturgeon Bank into the North Arm during flood tides. There can be horizontal entrainment of such water into the outflow; however, a strong northwestward-directed jet, such as will occur during large outflows, in effect forms a dynamic barrier which will, presumably, in general prevent the penetration of "Sturgeon Bank" water into Burrard Inlet.

During the low-runoff period, waters overlying Sturgeon Bank will generally possess a proportionately greater sea-water content than during the summer. There is a possibility that any movement of water drained throughout an ebb, will, on the succeeding flood, be a more sensitive function of the tides since effect of the longshore current previously discussed may be at an annual minimum (page IV-7); there thus may be a smaller northward transport per tide. However, any masses attaining the mouth of the North Arm will encounter a greatly-weakened (or even non-existent) barrier to northward flow; thus fairly extensive movement of Sturgeon Bank water into Burrard Inlet on the flood is likely. Fluctuations in properties should in general be markedly less than in summer.

High-tide values of both surface salinity and temperature over the Bank have been obtained within the immediate post-freshet period (July, 1973) by Levings and Coustalin, 1974. Salinity on a line north of the Jetty was monitored at such tides throughout about a 30-hour period; values varied from 8.5 to 14.8 $^{o}/oo$ (with a mean of 11.5 $^{o}/oo$) for 23 locations. South of the Jetty, along a line from Sea Island, the range was greater (0.3 to 10.5 $^{o}/oo$) but values were generally less (mean of 5.5 $^{o}/oo$ for 20 stations). The generally-low values represent the basic effect of the relatively large Fraser River outflow in summer; the smaller southerly values probably reflect both the proximity of fresh water from the Middle Arm itself and the shielding effect of the Iona Jetty. The "northerly" temperatures were generally greater also (19.0 to 22.5^{o}C, mean 20.7^{o}C versus 14.5 to 17.2^{o}C, mean 15.8^{o}C). Salinities could generally be expected to be greater, and temperatures less, during winter. Some values obtained in January and February in the immediate southern vicinity of the Iona Jetty will be noted in Section IV C.

The foregoing has neglected the effect of wind. Any movement induced by wind can, as previously noted, augment or diminish currents of other origins according to wind direction. The amount of water on the Bank during a flood tide can be increased or decreased by an onshore or offshore wind; water levels on the downwind areas may, correspondingly, be increased or decreased. In the presence of a strong wind, the vertical mixing between the surface masses and the underlying waters in such conditions will increase the surface salinities with respect to the non-wind case, especially during summer. The generally-greater salinity of the surface waters during the winter will reduce such an effect during that time, although strong winds are more prevalent than during summer.

IV C. THE CIRCULATION IN THE VICINITY OF THE GVSDD SEWAGE-TREATMENT PLANT OUTFALL

1. Information from Current Followers

A major difference between present conditions and those encountered by Fjarlie (1950) - in addition to the presence of the Iona Jetty - is the blockage, by a causeway, of the Fraser River arm now represented by McDonald Slough. There is, therefore, no longer a major contribution from this arm to the water-mass-property regime on Sturgeon Bank. However, there still does exist outflow, primarily of fresh water, originating from the GVSDD sewage treatment plant on Iona Island; under normal conditions, this effluent will have been subjected both to primary treatment and to chlorination. The outfall releasing this flow is located just north of the McDonald Causeway, is about 30 feet in width, and empties from a chlorine contact lagoon; a spillway and a baffle system help to aerate the discharge. Dry-weather flow from the outfall is of the order of 70 cu. ft./sec. or about 35 (10^6) gallons/day; since much of the collecting system serviced by the plant has storm sewers, wet-weather (primarily autumn and winter) flows can be much greater, up to 600 cu. ft./sec. or $300(10^6)$ gallons/day. The outfall flow is thus estimated to be at least two orders of magnitude less than the "pre-causeway" flow moving through McDonald Slough in the large-runoff periods. (It may be noted that if sewage flows to the plant become excessive some sewage is by-passed directly to the outfall without treatment.) The nature of the effluent and the possible deleterious effects associated with its contents suggest the need for a consideration of the local circulation in the vicinity of the outfall in greater detail than would be necessary for Sturgeon Bank as a whole. The results should be useful both to refine insight into present conditions and to aid in the prediction of changes to be associated with any airport expansion.

Two recent field studies have dealt with the properties and/or circulation in the southern vicinity of the Iona Jetty. The two programs were conducted in winter (January-February 1973, and January 1974, respectively), during which time the outflow from the outfall could be expected to be greater than that in summer generally.

Both studies employed current followers for several reasons. The followers provide a Lagrangian form of measurement, in which the actual motions of elements ("parcels") of water are obtained. Such measurements are considered a useful aid for determining the actual fate of effluent issuing from the outfall. In addition, the techniques are, at the present time, much simpler to apply on the Bank than those of the Eulerian method, which however, could, by the use of a sufficient number of current meters, ultimately provide (synoptically) the entire flow field, and its variation in time, within the area in question. The followers provide information primarily on advective (or large-scale diffusive) motions, rather than on smaller-scale turbulence.

1(a). Results from the Study by B. C. Research

The earlier study (B. C. Research, 1973), a multi-faceted effort dealing basically with the dispersion of and effects of outfall effluent on Sturgeon Bank, subsequent to issuance from the GVSDD outfall, primarily considered the local circulation on quite large ebb tides (8-10 ft. range); it noted also, but to a lesser degree, conditions on very small ($\sim$ 1 ft.) floods and on low-slack conditions associated with the "high-water-stand" portion of a near-tropic tide. Water motions at the surface and at a depth of 3 ft. were monitored by free-floating current-followers (drogues): at the surface, by a 4-ft. diameter sheet of plywood with a 2-ft. upright identifying dowel in the centre, and at a depth of 3 ft. by wood-and-styrofoam floats to which were attached 20 in. x 8 in. aluminum vanes crossed at 90^{o} to each other. The drogues were released generally near the outfall, or, more rarely, somewhat to seaward of it; successive positions were located by utilizing a system of markers on the Iona Jetty and on the opposite shore to the south. The survey thus monitored primarily the flow associated with the discharge from the outfall.

During most of this field work, wind speeds, as monitored at the airport, were small (generally less than about 2 mph). However, there occurred a few periods, of the order of 2 hours long, during which speeds ranged up to 10 mph. The high-tide salinities near the outfall and in the southern vicinity of the jetty indicated the presence of a thin ($\sim$ 3 ft. thick) surface layer. Salinities in the layer varied between about 15 and $19^{o}/_{oo}$ on one occasion, with 3-ft. values being of the order of 22 to 24^{o}/oo. At another time, values in general were lower (9-13^{o}/oo in the surface layer, 18 to 20^{o}/oo at 3 ft.). N No overall pattern in distribution existed; however, surface values tended to be slightly lower near the outfall than elsewhere in the area monitored. The temperature range at any time throughout the area appeared to be small; temperature values were generally between about 1.0 to 1.5^{o}C, on one occasion, and between 4.0 and 5.0^{o}C on another. During both periods, values were very slightly colder at the surface. Along the effluent channel, however, the surface water was generally 0.5 to 3.0^{o}C higher than that monitored elsewhere. All these values may be compared with those recorded at some other locations on the Bank in summer (page IV-17).

Both over the sewage channel itself and somewhat to the south, the near-surface motion was, in the presence of very light (<2 mph) winds, found to be persistently seaward and generally parallel to the Iona Jetty along its entire length (Fig. 11, 12 and 13). The stronger winds encountered appeared to be quite effective in modifying the motion, especially that at the very surface (Figures 12, 13). (The design of the current followers, especially those in use at the surface, indicated that they might themselves be quite strongly susceptible to wind action; this fact might lead them to supply somewhat exaggerated indices for motion in the surface layer itself.) Somewhat seaward of the jetty, there appeared to be a northerly movement of surface water on the ebb. In the absence of wind, this might represent a winter manifestation of the nearshore current, although such a current would be expected to be at an annual minimum during the low-runoff period of the Fraser. Hydraulic effects due to Fraser outflow would also be at or near an annual minimum at this time.

The speeds actually recorded varied widely. On the later stages of the

8-ft. ebb (10 January 1973), values as great as 160-200 ft./min. (1.6 to 2.0 knots)* were recorded at the surface; values between 50-80 ft./min. were common. At a depth of about 3 ft., speeds at corresponding times generally were slightly lower. On a larger ebb (∿ 11 ft., 9 February 1973) maximum surface speeds were near 100 ft./min., with values from 30 to 60 ft./min. being generally representative. Any light wind action would have assisted the earlier flow just noted; both the light and strong winds present during the later work would have hindered the outflow as measured. This may indeed be the prime cause of the lesser speeds; neither ebb ranges, nor any difference in flow rates at the outfall (approximately the same on both days), seemed responsible. Speeds encountered during the other periods monitored were generally as follows: for a short time before and after a low slack water intervening between a very large ebb and flood, surface values were very small, 5-20 ft./min. being common; winds were strong (to 10 mph) and northerly or westerly, and tended both to retard westerly flow and to move water against the Iona Jetty. On the first stage of an 8-foot ebb, moderate (3-5 mph) southerly winds had a similar effect; speeds averaged almost 50 ft./min. at the surface, but only somewhat over 20 ft./min. at 3 ft. On a small-range (∿ 1 ft.) flood, surface speeds ranged from 18 to 60 ft./min., averaging about 27 ft./min.

It appears that, occasionally at least, water moved faster over the deeper outfall channel than at corresponding locations on each side.

1(b). Results from the Study by Marine Sciences Directorate (MSD)

The more recent study (MSD, unpublished) conducted almost exactly one year later attempted to monitor water movement in a somewhat more extensive

* 100 ft./min. ≈ 1 knot ≈ 51 cm/sec.

area than that previously considered; that actually examined represented basically the portion of the Bank which would be intimately affected (embayed to a greater or lesser degree) by any presently-considered concept of airport expansion. The study was carried out during those time periods for which horizontal movement might be expected to be relatively limited, and thus the deposition of material contained in the effluent correspondingly more marked: on the small-range floods and the immediately-succeeding slack and near-slack conditions associated with a near-tropic tide.

The surface-current follower used consisted of a stack of three styrofoam seine floats (each approximately 5½" in diameter, and 4" in height) weighted to keep the shallowest float just at the surface; therefore, the integrated current throughout the first foot was measured. The effect of wind upon the movement of the drogue was indicated to be much smaller than that upon the surface follower employed in the previous study. Followers were released by boat, and were tracked by transit from two locations on the Iona Jetty. They were retrieved and repositioned when their motion became uninteresting, or when they moved out of the area of primary consideration. The results of the two days' studies utilizing the drogues are shown in Figures 14 and 15. For ease in viewing, several figures have been allocated to each day's results. That portion of a track travelled during a flood tide is denoted by a dashed line, that on the ebb by a solid line. The two tracking stations, 1200 feet apart, are labelled as A and B. The winds were monitored by a Lambrecht anemometer (Model 1482) located midway between the transit stations, at a height of about 8 ft. above the jetty roadway. The average wind speed and direction present during each hour of a tracking session, as well as for a short time prior to it, are given in Table II. No seawater properties were monitored during the

1974 drogue tracking.

TABLE II

Time Interval (PST)	3 January 1974 Speed (mph)	3 January 1974 Average Direction (Approx.)	4 January 1974 Speed (mph)	4 January 1974 Average Direction (Approx.)
0600 - 0700	2.9	NE	4.2	E
0700 - 0800	3.1	ENE	2.8	E
0800 - 0900	3.0	E	2.2	E
0900 - 1000	4.5	ESE	5.0	ESE
1000 - 1100	3.1	SE	4.2	SE
1100 - 1200	3.1	SE	4.6	SE
1200 - 1300	2.9	ESE	4.3	S
1300 - 1400	0.6	ESE-WNW	3.4	SW
1400 - 1500	2.5	WNW	1.8	WNW

On January 1974 winds during the early part of the session were primarily southeasterly (maximum hourly-average speed about 4-5 mph, average about 3 mph), decreasing and changing to northwesterly during the later stages. Six followers were released on a ∿ 4-ft. flood, about 1 to 2 hours before high-water slack (Figures 14 a, b); four were committed at, or soon after this slack (Figure 14c). Most released in the outfall channel or close to it moved to the northwest more or less strongly, even crossing the channel; such motion was presumably due to the urging of the southeasterly winds occurring. In one instance, seaward movement in the channel prevailed during the flood, although some irregularity, presumably wind-induced also, occurred.

In Figure 14b, water movement to the south of the sewage channel can be seen to be characterized by a "loop" near the time of change from flood to ebb, a condition perhaps primarily responsible for the event. Speeds during the flood were small, being generally about 10-15 feet/min. For 1 to about 3 hours after high water (toward the end of the tracking session) all motions throughout the area were seaward and roughly parallel to the Iona Jetty, consistent in direction with ebb flow. Speeds were generally larger than those just previous, increasing with time and possessing values of the order of 20-40 ft./min. during this period (the initial stages of an ∿ 10 ft. tide). The results were comparable to those occurring at roughly corresponding tidal conditions during the previous study discussed. In the central part of the area, there occurred some northwesterly motion near the end of the session; this appeared unexplainable by wind or by tidal action.

On 4 January, the monitoring of flow paths was somewhat more intensive, and the data generated on flood tide and slack water greater than was the case for the previous day (Figures 15a,b,c). Average wind speeds were at a maximum (∿ 5 mph) and southeasterly during the earlier part of the tracking period; surface water speeds in general (except very near the end of the period) were appreciably greater than on the day before. The 5 followers released about 2 hours before high-water slack (∿ 3-ft. flood tide) initially indicated general northerly motion in the northern part of the area under consideration; a seaward component at the outfall channel itself was quite marked. The ensuing temporary reversal of flow undergone by two of the followers at about the same time is not readily explainable by wind, and suggested the presence of a counter-clockwise eddy of unknown origin. The progress of water throughout the main body of the area, during the later stages of the flood and about one hour into the succeeding ebb, was generally counter-clockwise; movement was guided by southerly winds and by the landward boundaries toward the vicinity of the outfall channel. Presumably, as a result, the motion somewhat later into the ebb was seaward. Speeds were generally between about 10 and 36 ft./min., with the maximum values occurring during the ebb.

Three followers released throughout the main body of the area about one to two hours into the ebb appeared to confirm the effect of southerly winds of about 4 mph in overcoming the seaward tendency of the surface flow on the ebb. The marked drop in wind speed near the end of the session revealed again the seaward tendency on the ebb. (Figure 15c).

While no monitoring of sea-water properties occurred during the MSD study, meteorological and other conditions suggested the presence of a relatively fresh surface layer throughout the area under consideration. The results obtained (even allowing for the differences between 1973 and 1974 versions of the surface drogues used) appeared to confirm the sensitivity of surface-water movement to the effect of even light winds.

To summarize: under present conditions, shallow-water movement along the entire southern side of the Iona area appears basically to be seaward. This condition is especially marked on large ebbs, but has been found to occur even on small-range tropical flood tides. The effect will perhaps result in part from the seaward thrust of the sewage-effluent outflow. Because of the contribution of rainfall to the discharge, this thrust should in general be more significant during the winter months. In the remaining (and major) portion of the area under consideration, the motion is not always a simple landward (flood-tide) or seaward (ebb-tide) one. The surface waters, perhaps in some contrast to the near-Jetty flow, are sensitive to even very modest winds. For example, such southeasterly winds together, presumably, with the effect of landward boundaries can give rise to a generally counter-clockwise circulation during a tidal sequence involving a small flood and the early stages of the succeeding large ebb. Winds from the west through south should be most effective in influencing the circulation south of the jetty; northerly winds should, because of the sheltering action of the jetty, be of less consequence. Perturbations (e.g., eddies), some of obscure origin, can be embedded in the primary circulation.

The current-follower studies discussed above have also indicated that water attaining the seaward end of the jetty on the ebb can move northward even in winter (e.g., Fig. 16). However, it appears that on some flood tides, especially the larger ones during the summer, a localized micro-circulation can occur near the end of the jetty (Tabata, Giovando and Devlin, 1971). Even on $\sim$ 1-ft. floods, water originating at the southern side of the jetty can be moved in a narrow stream along the northern side for a considerable distance landward; values of at least 2/3 mile have been noted. Very soon after the low-water slack preceding one large ($\sim$ 16-ft.) tide, it was found that water near the end of the jetty initially moved up the sewage channel; a short time ($\sim$ 1 hour) later, this flow reversed and moved around the end of the jetty and along the northern face. A further reversal ensued and the water tracked returned to the end of the jetty. It appears that speeds associated with these flows can obtain values of 50 to 100 ft./min. (0.5 to 1.0 knot). These restricted flows do not apparently bear any obvious relationship to the more persistent non-tidal characteristics of the immediately-offshore movement (e.g., the northerly longshore current). Winds were not monitored in the immediate area, but values in the general vicinity do not apparently aid in an explanation. Thus the cause(s), and therefore other features such as times and durations of occurrence, of this motion remain obscure. There exists the possibility of a downstream eddy being formed at the end of the jetty during both flood and ebb tides. Such a feature, that associated with a flood tide presumably, may contribute, in some degree, to the principal characteristics of the observed effect.

2. Information from Tracers (Dye)

(a) Introduction

The solid current followers previously described provide, essentially, knowledge concerning advective aspects of water movement in the area involved. A further method for elucidating the circulation involves the monitoring of changes in the concentration of substances dissolved or suspended in the water body in question. Such measurements could, in theory at least, supply information not only upon motions generated by advection but also upon those engendered by turbulent diffusion of a wide range of scales. Such materials (tracers) can be introduced into the water by natural processes or by man himself; variations in their concentrations may be noted visually, or recorded by photographic or other instruments. For example, aerial photography of the distribution of a natural tracer (suspended material from the Fraser River) has aided in the determination of water-mass movement on Sturgeon Bank and in the vicinity of the Fraser Delta generally (Tabata, 1972). However, such large sources of tracer material are generally beyond man's control as to location, and intensity and time of release. In the present study, aerial photography of the progress of a tracer introduced by man (a fluorescent dye dissolved in the water) has been carried out on a very modest scale both in time and in space in an attempt to provide further information on at least one aspect of the circulation considered significant in the vicinity of the treatment-plant outfall.

(b) Background

Artificially produced and introduced tracers were first utilized in an attempt to determine liquid-flow characteristics late in the last century. At the present time such techniques employing organic fluorescent dyes (which dissolve readily in fresh- and in seawater) or radioactive isotopes are being increasingly utilized. In particular, the use of dyes has become relatively prominent because of the design of the modern stable, portable fluorometer that has made tracing practical and efficient; concentrations as small as those of order 10^{-11} can be determined by this means. Dyes have been employed at surface and/or subsurface in both instantaneous and continuous (space and/or time) source modes in attempts to subject to experiment the various theories of diffusion that have been put forward. For a general background of efforts in theory and in experimentation one can consult, for example, the work of Krauel (1972).

A fluorescent material is a colored substance which, upon absorbing light, instantly emits uncollimated (unfocused) light of a longer wavelength. Materials which absorb in the green or yellow and fluoresce in the red are relatively rare in nature. However, the most commonly used man-made fluorescent tracers are of this type; as a result there will in general be little competing (and unwanted) background fluorescence during their use.

The two fluorescent dyes at present most often used in marine studies are Rhodamine B and Rhodamine WT, the latter a refinement of B. Other dyes employed are pontacyl brilliant pink and fluorescein, the latter emitting in the green. All these dyes are considered harmless to human and marine life under normal experimental conditions, Rhodamine B, in particular, to concentrations at least as great as 100 millilitres/litre. They dissolve readily in seawater and remain in solution for relatively long periods of time. In particular, both Rhodamines are characterized by good color contrast with the sea and thus should permit useful color photography and/or detailed visual observations for at least several hours after introduction of the dye. The photochemical decay rate of the Rhodamines (and of pontacyl pink) in sunlight is negligible in comparison to the reduction in concentration that would usually be expected from water movement. Thus the effectiveness of fluorometry, and even aerial photography, is limited primarily by dilution, and these dyes may thus be considered a conservative quantity persisting for hours or even days. By contrast, the effect of sunlight on fluorescein is so great as to render it useless except for nocturnal work or for waters at depths unaffected by daylight.

Rhodamine B does possess one disadvantage which might under some circumstances prove significant, a relatively high propensity for adsorption onto inorganic or organic water-borne particles, leading to the possibility of serious errors should field work be carried out in very turbid or productive marine environments (e.g., the Fraser River plume in summer). Rhodamine WT suffers little from this defect. However, the period during which the present tracing was undertaken (late February and late March) is one of near minimum Fraser

River runoff and thus of inorganically-caused turbidity. Also, organic production would be at an annual minimum in the area at this time. It was therefore considered that neither factor would significantly reduce the value of any Rhodamines employed in the present area of interest. This conclusion was exremely attractive, as these dyes were found generally to be cheapest (in order: B and WT) of the four noted above, and in addition they were by far the most readily available locally. They were therefore employed in the present work.

(c) The Present Study

In theory, the acknowledged complexity of oceanic (especially nearshore) circulation, in particular of the smaller-scale components, might be expected to favor in many instances the use of tracers such as dyes. In the present case, the lack of suitable and readily available equipment for work on Sturgeon Bank, as well as other logistical difficulties, prevented the use of the fluorometric method. However, as previously noted, it was believed that aerial-photographic tracking of dye might be feasible and useful, especially within a modest area. The immediate vicinity of the Iona outfall was selected to be studied on a small (2-3 ft.) flood and the earlier stages of the subsequent ebb, occurring during a fairly high stand of water level ($\sim$ 10 ft.). The primary object would be to provide some detail on the nature of any "backing-up" and/or retention of the effluent indicated to occur during present conditions. The data obtained would be complementary with respect to both method and time; (e.g., tidal stage) to those obtained in the same area by B. C. Research (1973), and thus useful for suggesting major changes likely to occur in the circulation as a result of geographical alterations introduced by airport expansion. The visual detection limit of dye under good natural lighting conditions is believed to be a few tens of parts per billion. Therefore the results of such field work would be basically qualitative, and possess perhaps two orders of magnitude less sensitivity than those from fluorometry.

(d) Results

Because of unfavorable logistical and meteorological conditions, field experiments were limited to three days (22 February, 19 and 20 March 1974). The dye was purchased in 55-pound batches in plastic carboys, each batch containing between 5 and 6 gallons of dye as a 40% solution in acetic acid. This original solution is somewhat denser ($\sim$ 1.04) than any seawater to be encountered in the Strait of Georgia. The dye was released at the Iona outfall itself; strong mixing with the effluent in the discharge system would presumably reduce the density of the dye solution to near that of fresh water. Releases of dye were carried out somewhat before the low-water slack preceding the small flood tide, so that photography could commence at the slack. Photography was carried out at a height of 6000 (± about 200) ft. from a Cessna 180 aircraft specially equipped to carry a Vinten Military Reconnaissance camera equipped with a lens of 3 in focal length. True Color Direct-Positive Kodak No. 2448 film was employed, at f/2.8 or 3.5 with a UV Filter, at 1/1000 sec. (Kodak No. 2443 Infra-red Modified False-Color film was also utilized at (f/2.0, with Wratten No. 12 yellow filter at 1/1000 sec.) simultaneously with the other on the first day of observations.) It, however, proved of little value, providing generally poor contrast between dye and background, and its use was consequently abandoned. Photography was carried out about every 15 minutes for as long as 7 hours. Calm, clear weather would, obviously, have been preferred for the experiments. Visibility was generally good, especially during the final two days; however, hourly surface wind speeds throughout each flight - as recorded at the Vancouver

Airport - were usually appreciable ($\geq$ 4 mph) and generally westerly (W, WNW, WSW, SW) in direction.

Discussion of the results of the dye tracking will be confined to those of 20 March. It is assumed that essentially all dye is retained within the patch visible to the aerial photography. This day's findings, it may be noted, appeared to be essentially representative of those obtained from all of the tracking sessions. Winds were SW to WSW, at 6 to 9 mph. Tidal conditions occurring are depicted in Fig. 17. Initially (at low-water slack, 1000 hours), the tidal flat in the vicinity was indicated from the ground to be clear of seawater to about ½ mile west of the outfall. At slack water, about 10 gallons of Rhodamine B solution were released at the outfall at the rate of about 4 gals/min. The rate of effluent outflow from the plant was about 230 cu. ft./sec.

The display of all photographs obtained during the day's flight has not been attempted here. However, in Figs. 18 (a), (b) and (c), are provided black-and-white representations of 12 of the frames which are believed to indicate the primary changes in dye distribution encountered throughout the tracking session. The time for each of these frames is given. The spatial scale in each picture is about 1/3 mi. to the inch.

Frames 1, 2 and 3 were taken at 15-minute intervals, commencing 15 minutes after the dye release. It is seen that the effluent flow is indeed confined to the channel, the progress of the dye indicating a surface speed of about 0.3 knots (30 ft./min.). Frame 4, taken at 1115, indicates that the incoming tide has encountered the flow of dyed effluent. Frames 5 through 9 have been taken at one-hour intervals, commencing at 1215 - No. 8 at 1515, almost exactly at the time of high water ($\sim$ 12 ft.) slack. During the interval roughly between

1115 and 1415 the dyed fluid has essentially been contained; little general seaward movement is evident, except over the outfall channel itself. The fluid has diffused laterally, primarily southward, but also as far north as the adjoining land boundary permits. The effect of retention is believed due basically to the tidal flow, which would be augmented by any landward water motion resulting from the westerly winds present at the time. It may be noted that the progress of the undyed effluent issuing forth subsequent to the introduction of the dye can be followed within the dye patch on the color photos. After an initial period of jetting to seaward, this effluent too is apparently mixed with, and thus retained within, the dyed fluid. The general lack of seaward motion persisted throughout the remainder of the flood tide. Observations of Frames 4 (1115) and 6 (1315) indicate that the landward speed of seawater in general, was under these conditions, of the order of 0.3 knot, consistent with the "halting" of the sewage-channel outflow.

However, even in the initial stages of the succeeding ($\sim$ 6 ft.) ebb (Frame 9), a substantial draining movement of all water in the vicinity, including the previously contained dyed effluent occurred. Frames 10, 11 and 12 were taken at the same time (1700), about 2 hours into the ebb. The three pictures are needed to indicate fairly completely both the seaward displacement and the further dilution of the dye. These pictures have not been made into a mosaic; however, sufficient overlap and distinguishing features, both on land (e.g., the protuberance on the north side of the Iona Jetty about ½ mile (1½ in.) seaward of Iona Island) and in the dye patch itself, are present to provide some quantitive measures of at least the westward movement. The speed involved was again about 1/3 knot (30 ft./min.) near the jetty.

The numerical values obtained are reasonably consistent with those found, under generally similar conditions, by means of current followers. The retention of effluent within the general vicinity of the outfall is seen to occur for at least a few hours, even during the non-extreme values of tide and of water levels occurring during the present dye experiments. The attendant possibility of further deposition of material from the effluent so restrained therefore bears consideration.

It is again emphasized that the use of the dye-tracking technique in the present instance has, because of various unavoidable factors, been very limited both in scope and in degree of sophistication. However, it is suggested that more refined and extensive application of the technique might be explored with profit in studies similar in nature to the present one.

V. DISCUSSION

V A. OCEANOGRAPHIC AND RELATED EFFECTS ASSOCIATED WITH THE VARIOUS AIRPORT-EXPANSION CONCEPTS

From the information supplied in preceding sections (and, to some degree, from even casual but intelligent observation) it becomes apparent that numerous marine-oriented effects could occur on Sturgeon Bank as direct or indirect results of actions (filling, dredging, etc.) associated with any expansion of the airport onto the bank.

One major category of effects involves possible gross changes in the characteristics of water movement and properties on the bank, as well as the temporary or permanent disruption of appreciable portions of both the intertidal and salt-marsh segments of the bank. Another, more site-specific group, although obviously related to the preceding one to some degree, is concerned with any impairment of the efficiency in the present system of effluent disposal from the GVSDD's Iona Island sewage-treatment plant.

Some qualitative remarks upon the general consequences believed likely to ensue are provided. These are followed by a summary of significant changes likely to be associated with the individual expansion concepts; mention is made of some possible means for ameliorating the resultant conditions should these indeed be proven to be of major ecological concern. A brief discussion dealing with sites proposed for a B. C. Ferry terminal on northern Sturgeon Bank is also given.

V A. 1. GENERAL EFFECTS

Obviously, water circulation will be eliminated throughout that portion of the Bank covered with fill during the implementation of any of the five concepts proposed for airport expansion. As for the unfilled remainder of the Bank, it appears unlikely that, for water speed, the primary statistical characteristics (e.g., averages and ranges over time and space) would be much different than those typical of the present time. Numerical data on the circulation over the Bank, with the exception of the vicinity of the effluent outfall, (Section IV) are non-existent; however, information obtained to seaward of the Bank suggests that currents unaffected by wind would generally possess speeds less than 1 knot at all depths. The direction of horizontal movement will in general be altered at the seaward limit of any fill, during flood tides at least. At such times, this movement at any point on the fill-water boundary must be parallel to that boundary; the direction will usually be different from that occurring at present during corresponding flood-tidal stages. Winds of sufficient strength will, of course, influence both speed and direction of the motion. In addition, the outflow from the various arms of the Fraser River (a source of fresh water to the water-mass régime on the Bank) will be basically unaffected by any expansion. Therefore the statistics characterizing the variability in both time and space of the primary physical and chemical properties of water overlying the Bank (e.g., temperature, salinity, dissolved oxygen content and the amount and nature of suspended material) should also remain essentially unaltered after any placement of fill. It thus appears that the actual gross physical- (and even chemical-) oceanographic changes associated with any airport expansion presently contemplated can, in the most general sense, be considered minimal throughout the unfilled portion of the Bank. There exists the possibility of some disruption of the area over various time scales by dredging associated with the new construction; this is considered on page V-4).

It is here considered that the most marked general environmental disruption on the Bank would result from the permanent loss of both intertidal and salt-marsh areas by the placement of fill. Any ramifications entailed by this disappearance can, admittedly, best be discussed in the context(s) (e.g., biological) most intimately concerned. Nevertheless, it appears germane to note briefly a few of the more important and general possible consequences, in order to emphasize further the major role played by water (its circulation and physical/chemical properties) in the various aspects of marine conditions on the Bank. The loss can result in the breakdown of possibly important portions of the estuarial food web. For example, any growth of mud algae or of marsh flora can contribute detrital matter, to the sediment, which can eventually be utilized to at least some degree by the diverse benthic fauna. When water overlies the Bank, many of these benthic species can become planktonic, and thus available to any fish population within the area (e.g., juvenile salmonids). Thus both potential food as well as a portion of the associated "grazing area" can be irretrievably lost to such a population.

One possibility for providing plant growth on the face of any fill extending onto the Bank, in order to compensate for that lost by destruction of salt-marsh area, can be noted. The core of the fill will presumably be armored with rock fragments, generally of considerable size (rip-rap). Algae can flourish upon such a substrate. However, several factors would seem to militate against a corresponding general growth of marsh plants there: the lack of sediment, the near-perpendicularity of the facing, and the fact that the location would be exposed to a greater period of submergence (the more so the more seaward the limit of the area considered) and also therefore to more prolonged periods of wave activity. Thus the marsh is apparently irretrievably lost, with no compensatory growth possible, unless means are found to manufacture areas conducive to such growth.

Areas used for feeding and loafing by both migratory and resident wildfowl populations can also be adversely affected.

The method chosen for disposal of effluent from Iona Island was presumably predicated at least partly on the assumption that dilution and dispersion (as well as further deposition, oxidation, and any lethal effect of seawater and sunlight on disease microorganisms) would be enhanced by processes of both advection and diffusion throughout an appreciable portion of the area of Sturgeon Bank. If the present means of disposal is not radically altered, the presence of fill, would, among other problems, remove parts of the Bank having value in this regard. It may be noted that, although effluent from the Iona Island treatment plant is associated with a relatively small flow volumetrically (page IV-19), changes in the distribution could be of permanent significance, aesthetically and even medically, if not oceanographically, throughout a considerable area. Such possible effects will be discussed more fully in some later portions of this section.

Dredging will be necessary to obtain material for the core of any fill area. This process can involve unwholesome effects upon the local environment additional to those associated with the placement of fill. Cost alone would demand that such dredged spoil be obtained from areas as nearby as possible. For example, the bank on the northern side of the North Arm opposite the jetty, and an area of Sturgeon Bank seaward of the mouth of the Middle Arm, are both apparently now considered to contain suitable material in satisfactory proximity to the expansion site. The effect of removal of material from the former location is considered to be of little significance to any marine aspect of the area under investigation here. Provision of material from Sturgeon Bank, on the other hand, might entail serious consequences, some possessing a time scale of at least a year. For example, removal of surface sediment would destroy possible benthic habitat, temporarily at least. Dredging could supply other effects such as chemical interaction of overlying waters with the newly-exposed sediment; the degree and duration would depend largely upon the amount and the nature of the exposed material. Re-establishment of any benthic colonies, both as to speed and degree, would depend presumably upon such factors, as well as perhaps upon the speed and the nature of any remantling of the dredged area by further sedimentation. (This could, in the case of the Fraser Delta, require from one to two years - e.g., C. Levings, pers. comm.)

Apparently the fill necessary to implement the two least-extensive runway concepts could be supplied from the North Arm. The most westward-reaching runway, as well as the service areas being considered, would demand dredging on Sturgeon Bank as well, apparently to a maximum depth of a few tens of feet throughout a considerable area.

Both dredging and filling will result in an increase in the turbidity of any adjacent waters. The effects could be significant over an area much larger than that actually occupied by fill or exposed by dredging. The consequences to aquatic clarity would be at a minimum for the relatively turbid waters present on the Bank during the freshet of the Fraser River, and at a maximum during winter or early spring. The introduction of a marked increase in turbidity into otherwise relatively-clear water present at such crucial times (and locations) as feeding periods (and grazing areas) for juvenile and larval fish might lead to significant alteration in the feeding habits of, and predation against, such populations. Whether such changes are of sufficient importance to necessitate a ban against construction during such times is left to the biologists to decide. Turbidity may remain for periods of the order of days after the cessation of dredging or filling. It appears that if the "dyke-and-fill" method were employed, any such effects would be minimized. However, a possible problem might result even from this technique because of the release of waste water accompanying the dyked spoil, especially during non-freshet times. Because of the fluid volumes involved in the dredging, the rate of such release will be considerable, of the order of a few tens of cu. ft./sec., a not insignificant fraction of the minimum rate of flow from the sewage outfall at Iona Island (page IV-19). The effect of a localized discharge of the fine fraction (suspended in the waste water) into the sea or directly onto the bank itself, and its implications to such features as benthic fauna, might bear examination.

A further possible source of suspended material in the nearshore vicinity of Sturgeon Bank has been noted (B. C. Wildlife Federation, pers. comm.). It is estimated that of the order of 10% of the spoil routinely dredged from the lower reaches of the Fraser River is disposed of in deep water just off the mouth of the South (Main) Arm. The finer material remaining in suspension for a considerable time after such dumping and being moved by currents, especially those at the near surface, is suggested as creating a possible marine-environmental hazard. Any such problem would become more acute if spoil were negligently disposed of in shallower water overlying the delta slope. Again, it would appear likely that any effect would be insignificant during the freshet season, but might be of marginal importance during periods of minimal runoff from the Fraser River.

V A. 2. EFFECTS ASSOCIATED WITH THE INDIVIDUAL CONCEPTS

It is almost *a priori* true that the diurnal inequality associated with the astronomical-tide regime in the Strait of Georgia is not basically conducive to efficient removal of the effluent from the vicinity of the Iona Island plant. The dredged outfall channel now in use apparently was considered at the time of the plant's construction to be a compromise to supply as favorable a system for neutralization as possible without excessive cost. However, only at very low tides is the primary removal function of the channel at all well fulfilled. The possible further deterioration of a system that is not extremely efficient even at present would therefore demand a careful examination of changes likely to occur, since construction involved in any proposed Vancouver Airport expansion would be primarily within the near-vicinity of the present sewage outfall-channel system. It is here assumed that the present location of the outfall cannot, or will not, be altered.

In particular, the northern boundaries of the various lengths of new runway considered in expansion concepts 1, 2 and 4 (Figs. 2, 3 and 4) are seen to be associated with some degree of embayment of an area immediately adjacent to the outfall. Thus a study of the possible consequences to marine-environmental conditions within this particular area would appear to constitute an especially important feature of any impact assessment.

(a) Concept 1 (Figure 2)

This scheme involves a relatively short ($\sim$ 1/3 mi.) intrusion of fill for the new runway proper onto Sturgeon Bank. About 70 acres (about 0.1 sq.

mi.) of present intertidal flat, as well as about 1/3 mi. of the western shoreline of Sea Island and its associated marsh fauna and flora, will be permanently lost. The net interference with the general present circulation in the vicinity of the treatment-plant outfall (Section IV C.) should be minimal; the degree of embayment is not great. There should, similarly, be little effect upon the more seaward portions of the flat available for the dilution and dispersal of the effluent. In the southern part of the enclosed area, the juncture of the northern boundary of the runway and Sea Island would form a small pocket, whose presence might result in a back eddy being formed at high water levels (e.g., the latter stages of large floods, especially those associated with tropic-tidal conditions). Under present disposal practices, this could entail the enhanced deposition of suspended organic and/or inorganic material contained in effluent which could at such times be temporarily retained within the area. Any resulting effect upon marine life of further deposition, even over an extended period, can be assumed small, as the area is considered to be already severely degraded, both biologically and chemically (B. C. Research, 1973); however, aesthetic disadvantages (e.g., odor) might further intensify. Such a condition could be alleviated if necessary by streamlining of the corner with extra fill. It is re-emphasized that borrow material presently indicated to be available from the North Arm should suffice to provide the fill for this concept; further concomitant disturbance of Sturgeon Bank by dredging could therefore be avoided. Navigational aids (approach lights) at the western end of such a runway would of necessity extend seaward about an additional one-third of a mile. If the lights were mounted on an impermeable structure (causeway), the area in the vicinity of the outfall would be somewhat further enclosed. An additional, but very small, amount of bank would be permanently lost by filling. More important, a second and more seaward, pocket would be formed; this should be streamlined also, since it could otherwise result both in an extension of, and intensified deposition throughout, the presently degraded area. If the landing lights, etc. were located upon open, piling-type structures, any such effects would be effectively nullified - provided that the piling units could be located not too close together. Any "corners" associated with the southern side of any of the proposed runway(s) and/or service areas(s) would not, it is here believed, result in any significant adverse effects.

(b) Concept 2 (Figure 3)

This concept involves shifting the proposed runway of Concept 1 to the west, with a resultant extension of the runway proper about 3/4 mi. farther onto Sturgeon Bank than that of the previous concept; the total length on the Bank would be somewhat over one mile. There would be an overall loss of about 235 acres (about 1/3 sq. mi.) of intertidal flat, but no loss of salt marsh further to that for Concept 1. An area somewhat greater than 1/2 sq. mi. would be very nearly enclosed.

A relatively narrow opening, apparently about 700 to 800 feet in width, would be formed between the seaward end of the runway extension and the Iona Jetty. Tidally-induced flows through this constriction should be considerably greater than those occurring in the area during corresponding stages at present. Extrapolation from recent field data (Section IV) suggests that depth-mean speeds, at least those associated with tropic tides, could attain maximum values of up to a few knots. Crude geometrical calculations supply still-appreciable, but somewhat more modest, values. The seaward movement of the effluent should augment tidal speeds within the constriction during the ebb and reduce them during the flood; the effect should be most prominent generally in winter, at which time effluent-discharge strengths are at an annual maximum. Any water movement due to westerly winds would, conversely, tend to augment speeds on the flood and reduce them during the ebb.

The presence of the gap could therefore lead, primarily during tropic-tide floods and stands of high water associated with very small, immediately-succeeding ebb and flood, to much enhanced back-up and/or retention of effluent within the embayment created. The deposition, at least of effluent-borne suspended matter, could be aggravated throughout much of the enclosure at such times. The presently degraded area thus could be increased in extent and the rate of undesirable mantling at the bottom increased, both effects being much more marked than those associated with Concept 1.

Further possibly adverse effects might result from the formation of the embayment. The mean grain size of the surficial sediments on Sturgeon Bank is generally in the 0.125 to 0.250 mm range (fine sand). It appears from previous studies (e.g., Hjulström, 1939) that water having speeds of the order of 1 knot can both erode and transport granitic material in the complete sand-size range (0.06 to 2.0 mm), as well as that appreciably smaller and larger. In an apparent paradox, sand of about 0.5 mm size can be eroded at speeds smaller than is the case for either coarser or finer material. One-knot bottom speeds would perhaps not be difficult to attain within the constriction, at least during tropic tides. Therefore there could exist a capability, appreciably more so than at present, for currents to bring about significant, if intermittent, scouring within the area. The erosion and movement of material could lead to some modification, e.g., deepening of the sewage channel within the gap should the channel itself be retained after any construction associated with airport expansion. It may be noted that the channel has, from its construction in 1961 to the present, apparently undergone no significant change in configuration (Luternauer, in: Hoos and Packman, 1974); this fact suggests that a dynamic (quasi) equilibrium has persisted between the sediments and physical processes resulting from such agents as wave and current action. Thus the stability of the bottom near, or perhaps even underlying, such structures as the Iona Jetty or the runway expansion could be compromised to some degree. It would be suspected that an equilibrium within the gap might eventually be reached upon sufficient deepening of the channel, barring such events as slumping into the channel.

At least some of the eroded material moved into the embayment during a flood tide could settle there. The ability of wave action to rework this material, or any other organic or inorganic bottom deposits within the area, would be severely restricted because of the sheltering associated with the various man-made boundaries of the embayment.

Eroded sediment would be transported to seaward of the gap on ebb tides. Such material would be deposited at distances varying with the strength of outflow. It could possibly form, primarily in summer, during prolonged periods of insignificant wave activity, a temporary bar in the channel or vicinity. However, it is believed that eventually such material would be reworked and distributed throughout the expanse of, or offshore of, the Bank itself. The possibility of formation of such a bar should be much lessened during the generally more violent conditions occurring in winter.

Construction of a solid navigational causeway at the end of the runway would compound the problems already noted. The constriction formed by this causeway and the Iona Jetty would be even narrower (apparently by about a factor of 2) than the more inshore one. The speeds of flow within this gap would therefore be greater than in the previous case. All comments about such features as erosion and effluent retention would remain basically applicable.

In this concept, the causeway extends into the outfall channel itself. If the open channel were to be deemed worthy of retention, it should be kept free of intrusion by the causeway. Probably, some of the coarsest material eroded during flood tides might settle out and remain on the northern side of the causeway. However, the finer material would probably move as before into the main portion of the modified embayment. On ebb tides material could be moved westward from the more seaward constriction a somewhat greater distance than during corresponding conditions in the absence of the causeway, before undergoing such effects as reworking.

The additional complications resulting from the presence of the causeway itself could be avoided by placing the navigational aids concerned on well spaced pilings. Thus this form of emplacement could be even more advantageous than in the case of Concept 1.

(c) Mitigation by Action Upon the Effluent Itself

It might be pertinent at this juncture to note briefly a few possible major methods for ameliorating, to some degree at least, general adverse affects resulting from implementation of the various concepts for expansion; the emphasis would be upon conditions indicated to result from Concept 2, but Concepts 1, 3, 4 and 5 (the last three to be discussed later) would also, hopefully, receive some benefit. The methods, which involve action upon the effluent itself, could result in lessened deposition from the effluent as well as in generally improved water quality, at least in the vicinity of the present outfall. It is strongly urged that the utility of these methods (as well as of any potentially useful combinations or variations that might come to light) be thoroughly scrutinized in all aspects, including cost-benefit considerations.

The most effective process, and the one presumably the least disruptive to the entire marine area now affected by the effluent, would appear to be secondary treatment of sewage on Iona Island itself. This treatment would result effectively in removal of all suspended material from the effluent, and thus should lessen markedly the degradation of the area in the vicinity of the present outfall. It would not significantly reduce the amount of nutrients or, perhaps more importantly, of heavy metals in the effluent; such removal must be accomplished by other means, e.g., by tertiary treatment and by control-at-source, respectively. Secondary and any succeeding treatments would result in a marked lessening of environmental degradation even in the absence of any airport expansion as presently contemplated. The expenses associated with capital (and even with operating) costs could be large, but the degree of relief that could be afforded from the problems just considered appears to entitle the general method to very favorable consideration.

If such treatment(s) cannot be provided, some other, probably less satisfactory alternatives can be suggested. It may be noted that these all provide, basically, modification in the routing of the present effluent. One would entail the provision of a closed conduit (rather than the present open channel) for seaward transportation of the effluent. In the specific case of Concept 2, it should be extended somewhat to seaward of the runway, or of the navigational-aid causeway, if constructed. Resulting headlosses could be overcome by construction of a conduit of sufficient size and/or by provision of pumping facilities; cost and other factors would play a part in determining which means was the more efficient. This scheme would afford the undiluted effluent immediate and less restricted access to at least the more seaward areas of the Bank. It should therefore lessen, to a significant degree, deposition in the inshore zone most strongly affected at present. There would, obviously, be the likelihood of enhanced deposition on the outer portions of Sturgeon Bank, but the effect would occur further from shore, and in a more open area than is the case for present accumulation. The resulting circulation, minus effluent outflow, within the embayment (although restricted) would become basically a more cleansing one than at present, although some retention of effluent within the embayment might still temporarily occur at high water levels, with or without accompanying strong westerly winds.

It might be queried why (ignoring here any considerations of cost) a closed conduit parallel to the Iona Jetty should not be extended more to seaward, or even as far westward on Sturgeon Bank as possible. The prime cautionary factor involved would be the introduction of more concentrated, or even undiluted, effluent into the waters at the end of the Iona Jetty. Such effluent would therefore immediately be strong subject to that action of tides and of whatever northerly longshore flow is present. There would, of course, be at least some subsequent dilution of the effluent by both horizontal and vertical mixing associated with the various motions. During flood tides there could result, at any time of the year, a movement into Iona, and the potential beach areas there of an amount of effluent greater than that entering during corresponding conditions at present; increased deposition of organic and/or of heavy-metallic material could ensue. As for the effect of any northward surface flow, this will depend generally to a great degree upon the time of year. During the freshet of the Fraser River water containing the effluent might remain light enough, despite mixing, to attain the North Arm while still at the surface. It should then, on all tides, be directed basically northwest, in the initial stages at least, by mixing into the jet associated with the outflow from the arm. Should the effluent have become sufficiently dense, it may underrun the fresh-water outflow from the arm and for a short period at least travel almost independent of it. During the immediate post-freshet period, there may, on flood tides at least, be movement of effluent to some degree both into the North Arm and into Burrard Inlet (and onto Spanish Bank). Thus during the time of yearly maximum recreational value of the Bank deleterious material again additional to that involved under present conditions may be deposited in the areas noted. In the winter (low-runoff period), enhanced movement into these areas during flood tides is much more probable than at other times of the year. However, during this period (one, incidentally, of generally low value for water-contact recreation) increased mixing, and therefore dilution of effluent, will occur; for example, effluent will be distributed throughout a greater depth interval than in summer because of a weakening of the near-surface vertical stratification, due both to a reduced fresh-water content and to generally stronger winds.

Meaningful determination of the effect of any effluent re-routing upon the aesthetic and medical integrity of waterfrontage in the vicinity (other than that near the present outfall) would appear at least to demand a sound knowledge both of the local circulation involved and of the present impact of such factors as deposition upon the areas in question.

It may be noted that if the effluent possessed enough entrant momentum upon issuance from the conduit, significant diffusion across any northerly longshore shears and into the more offshore and aesthetically and medically less sensitive waters could perhaps be developed. This would tend to lessen any adverse transport by the northerly flow. However, whether such momentum could be supplied at a cost rational within present circumstances remains to be determined.

In the light of such possible behaviour of the effluent, further refinements for enclosed transport can be suggested. The conduit could be extended, from the embayed area, across Sturgeon Bank in a basically southwesterly direction. Even the attainment of the western end of the channel associated with the Middle Arm could be considered; useful additional seaward thrust could be obtained, especially during the large run-off period. Even if transferred into any northerly longshore movement in the area, the effluent would undergo dilution and dispersion through a greater distance and period of time before reaching any sensitive areas to the north of the Iona Jetty. Such refinement should be useful, in the absence of secondary treatment, for any of the five concepts of expansion so far advanced. Should dredging for fill on Sturgeon Bank in the vicinity of the Middle Arm become necessary, both the orientation and length of any such conduit extension would be subject to review. Any disruption of the bottom subsequent to that due to the installation of the conduit itself should be minimal.

The possibility of discharging the effluent to the Strait of Georgia at depth can also be given brief comment. This method could involve the extension of a closed conduit westward onto the upper foreslope of Sturgeon Bank.

The rationale of course is that the effluent would be rendered innocuous by dilution and dispersion resulting from both horizontal and vertical motion, and by the various purification processes in a submerged field. It would in theory therefore neither attain nor otherwise influence disruptively the near surface waters. Several basic conditions should ideally obtain if this objective is to be realized: among them, strong stratification should occur somewhere within the water column, the discharge should be at sufficient depth beneath this stratification, and the horizontal motion at depth should be favourable. To elaborate briefly on these aspects; there is a marked near-surface stratification in the area in question, especially during the summer (page IV-2). The effluent itself is primarily fresh water; upon discharge at some depth beneath the surface layer, mixing with the denser ambient sea water would occur at the outlet (diffuser) and, generally, during subsequent buoyancy-induced upward movement. The effluent-seawater mixture might thus attain a density greater than that of the waters within the brackish surface layer. If the point of discharge is deep enough, the vertical motion could be sufficiently arrested so that intrusion of the mixture into the surface layer would not occur at all - a desirable condition. However, should the motion of the mixture be great enough at the depth (interval) of stratification, effluent and deep water could attain the surface - most spectacularly as a "boil". Although the mixture might because of density considerations sink again to deep-water level (providing that combination with surface water was not excessive), at least part of the desired advantage of deep discharge would be lost. In addition, it is suggested that, for periods of up to a few days at least, deeper-water motion (e.g., that at 30-100 ft) a short distance west of Sturgeon Bank in the area under discussion can be slow and easterly (Tabata, Giovando and Devlin, 1971). Therefore the corresponding motion at or near the very edge of the

Bank must be northerly or southerly. If such motion were small, there might thus be some temporary accumulations of effluent, and therefore an increased possibility of the significant introduction of effluent into the near-shore surface waters, presumed undesirable, especially for the case of northerly shallow-water motion. This action could be enhanced during winter because of the attendant general decrease in stratification within the water column; the problem, however, should not be as aesthetically (or medically) objectionable as in summer. A suitable depth for the discharge of effluent could presumably be estimated by any of several empirical techniques well known at present.

The feasibility of this means of effluent removal and neutralization would appear to depend primarily upon a thorough knowledge of the geological characteristics of the upper foreslope upon which the submarine outfall would be placed. For example, the front of the Fraser River Delta is not static; in particular, a general westward advance of that portion of the front between the Iona Jetty and the Middle Arm has apparently occurred recently, at least from October 1968 to April 1972 (Luternauer and Murray, 1973); minor deposition and erosion apparently occurred during the succeeding four months. The effects of present and possible future changes in the bathymetry of the foreslope would appear to demand careful consideration. Such crucial aspects as outfall construction itself, as well as subsequent performance if construction were to be deemed feasible, are involved.

Each of the various versions of a closed system for effluent conduction could entail considerable initial and operation expenses. An open channel, similar in nature to the present one but directed southwesterly from the embayed area, would be an even less costly possibility for some degree of mitigation. It would even, at low water levels at least, avert to some degree any unfavorable interaction arising from proximity of effluent to the service areas proposed in Concepts 3 and 5 (see pages V-22 to 23), and would permit natural treatment of the effluent in a less confined area than is the case for the more seaward portion of the present channel. However, it would suffer from any general deficiencies characterizing the present channel. In addition, there might be difficulties in maintaining the integrity of the channel, because of factors such as transport of sand (especially during freshet) by the flow of the Middle Arm, and a greater degree of wave action than occurs for the present channel.

Another suggestion would involve imparting an added momentum to the seaward flow in the present sewage channel. No alterations would be made to the channel itself. The method would hopefully aid, to some degree at least, in neutralizing the effect both of shoreward water movement and of confinement in the vicinity of the outfall. This should also enhance the horizontal mixing, and thus flushing of any embayment created. Such added momentum could be most simply obtained by providing a westerly outflow from McDonald Slough; this would involve breaching the present McDonald causeway. A dyke to guide outflow from the Slough into the channel might prove useful. The addition of an outflow up to several times greater than that provided by the effluent discharge alone appears possible. Such added thrust could, in this case also, promote diffusion through any longshore current into more distant waters. The condition of the effluent reaching the end of the Jetty would be more favorable (more diluted) than would be for the case of a conduit extended into the area.

The increased seaward flow would, according to its strength, weaken, or even negate, the flood-tidal flow through the constriction. Thus deposition of scoured material within the embayment would be lessened with respect to the no-diversion conditions or rendered non-existent. However, the scouring by flow in the seaward direction could be strong, and less intermittent than previously. The tendency for deposition of any heavier material in the vicinity of the gap would be much reduced.

It would appear necessary that the engineering involved permit some flexibility in (as well as the complete stoppage of) the flow of the diverted water. The stoppage would prevent any backflow of water, and of contained effluent, into the Slough and beyond - should any extremely unpropitious circumstances tend to result in such a reversal.

(d) Concept 4 (Figure 4)

Consideration of the remaining three concepts proposed can be briefly provided.

Concept 4 involves the extension of the runway about 2 mi onto Sturgeon Bank. The runway will in this case intersect the Iona Jetty, thereby completely isolating from the open Strait of Georgia the area adjacent to the outfall. About another 250 acres of filled area additional to that involved in Concept 2 would be required for the runway proper, providing a total loss of intertidal flat of somewhat under 1 sq mi. This construction would make essential the enclosed movement of the effluent from the outfall to at least the seaward edge of the runway. The totally enclosed portion of the Bank might best be quickly remantled, at least thinly, since the bottom deposits already accumulated would otherwise probably provide an aesthetic nuisance for a considerable period after isolation. Ground water should be prevented from entering the area in quantity. Some consideration should be given to the final utilization of the enclosure, e.g., as a completely filled area or as a fresh-water lagoon created by diversion of water from McDonald Slough.

Maintenance of the seaward end of the jetty would necessitate easy access by land being ensured. The intrusion of the runway onto the Iona area of the Bank would tend to restrict shoreward water motion along the northern face of the jetty. A pocket would be formed if the necessary approach lights were placed on a causeway. Undiluted and undispersed effluent moving through a closed conduit, as noted on page V-14, would be discharged much nearer the end of the jetty than is the case at present. This effluent, if it moved to the northern face of the jetty, might, in conjunction with the pocket just noted, provide an increased deposition of undesirable matter at the seaward end of that face. Enclosed conduction of the effluent southwest across Sturgeon Bank (page V-16) would presumably alleviate this problem to a great degree. However, in any case, the approach lights should be placed upon pilings and the pocket streamlined by fill. These measures will be of some value in reducing the effect of the effluent should closed conduction not be feasible; they should also aid in reducing any effect of the seaward end of the runway upon the general circulation in the Iona area. This runway could be constructed entirely with North Arm spoil.

The two remaining concepts (3 and 5, Figs. 3 and 4) involve the addition of appreciable service areas to the south of the runways for Concepts 2 and 4 respectively. The total area of fill involved would be of the order of 1500 acres. The primary effect would, as previously noted, be to the Bank south of the Iona Jetty; they would not in general add further to any problems associated with embayment. However, their presence might still entail some consequences to effluent disperal, and can be considered in logical extension to those of the associated runway areas. Dredging from areas other than, or additional to, the North Arm (presumably Sturgeon Bank) would be necessary to satisfy the need for borrow material, with the possible, previously-noted consequences involved.

(e) Concept 3 (Figure 3)

This scheme involves the addition of a large-sized service area adjoining the south side of the runway of Concept 2. Several debits would therefore be incurred: effectively the entire length (∿1-3/4 mi) of the present seaward face of Sea Island, together with the associated marsh flora, would be lost; the fill would cover an area possibly acting at present in one or more of the following desirable capacities - a habitat for benthic organisms, a feeding ground for fish, and a zone for the dilution, dispersion and purification of effluent.

(f) Concept 5 (Figure 4)

A loss of a further large area (giving a total of about 2-1/2 sq mi) of possible benthic habitat would be lost. No salt-marsh areas additional to those erased by implementation of Concept 4 would be affected. In the absence of secondary treatment, this concept would presumably be best accompanied both by streamlining of the pocket formed to the north of the jetty and by construction of a closed conduit at least to the seaward edge of the newly filled area.

Conditions resulting from both concepts (especially 5) would presumably be improved by conduction of effluent away from the jetty in a southwesterly direction. Again, a conduit closed along the entire length would appear to be the most useful.

The southerly limits of the service areas associated with Concepts 3 and 5 (especially the latter) would presumably provide a much greater degree of westerly "training" of Middle Arm flow than does any presently being supplied by the causeway which extends about 1/2 mi across Sturgeon Bank from the southwestern shore of Sea Island (Figure 1). Such an effect for this causeway already has been suggested on the basis of the distribution of benthic organisms in the vicinity (Levings and Coustalin, 1974).

V B. GEOLOGICAL EFFECTS ON BEACHES OF THE IONA AREA AND OF SPANISH BANK

A matter worthy of some consideration in the present context is the geological effect, in the sense of any change in the sediment supply, of the proposed airport expansion upon any present or potential recreational beach lands nearby to the north, i.e., those of the northern Iona area (page II-2) and Spanish Bank, the latter being the tidal flat fronting the northwest portion of the Point Grey peninsula. The probable influences of effluent from Iona Island have already been considered, with respect to the various concepts, in Section V A.2. The effect of the removal of material from potential borrow sites, especially those in the North Arm, is not considered here.

The most recent pertinent information on the Iona area is provided by Luternauer (in: Hoos and Packman, 1974). The north and south boundaries - the North Arm and Iona Jetties respectively - "... have effectively prevented dispersal of sediment from the north or south into the (area). Some sand size sediment may migrate around the end of the outfall channel and be 'bulldozed' shoreward by waves and currents. However, unless the outfall channel is appreciably self-scouring, the fact that the outfall channel has not had to be dredged since its original excavation in 1961 may indicate that there is not significant northward dispersal of sand along this segment of the Sturgeon Bank tidal flats." Also, Luternauer suggests that even the finer fraction of suspended material which may be introduced by water-mass intrusions, particularly during the Fraser freshet, apparently does not remain there for a long period.

All fill associated with expansion onto Sturgeon Bank would be placed on the southern side of the Iona Jetty. Any alterations to present movement of sediment not directly related to the Iona Island effluent into or out of the Iona area by such fill is here considered, upon the basis of present knowledge, to be generally negligible.

Spanish Bank is about 3-1/2 mi long and somewhat greater than 1/2 mi in maximum width. A recent study (Waslenchuk, 1973) indicates that the stability of the most seaward third of this tidal flat is heavily dependent upon sediment supplied from the North Arm of the Fraser; the more inshore area is probably maintained to a significant degree by material from the adjoining University-area cliffs. Any fill relevant to airport expansion now under consideration should have no significant effect upon the present flow, and thus upon the sediment supply, from the North Arm. Thus any expansion should have no bearing upon the geological maintenance of Spanish Bank in the context of present conditions.

V C. OCEANOGRAPHIC AND RELATED EFFECTS ASSOCIATED WITH TERMINALS ON NORTHERN STURGEON BANK PROPOSED BY THE B. C. FERRIES

Another development being at present (1974) actively considered for the Fraser Delta is the construction of an additional mainland terminal for the B. C. Ferries. At least four sites on Sturgeon Bank were originally under review, but more recently two appear to have become most strongly favored by the B. C. Government organization most intimately involved (Department of Highways), at least from an engineering viewpoint: the seaward end of the Iona Jetty (Fig. 19), and the southern side of the North Arm Jetty, somewhat east of the seaward end (Fig. 20). These two latterly-noted facilities are not, of course, directly related to any proposed airport expansion itself, but would be located within the general area under study in this report. It would therefore appear appropriate to provide at least some preliminary comments upon possible environmental impact of the proposed terminals, in both the absence and the presence of airport expansion.

Considering first the terminal suggested for the Iona Jetty area (Fig. 19), construction would involve an extension of this Jetty about one mile almost due west, to the -20-foot contour with respect to lowest normal tides. Thus this extension would be located entirely on the main platform, very near the first break-in-slope (page II-3). The seaward end of the extension would consist of a dock and a short north-south breakwater; an area inshore of the breakwater would be dredged to -23 feet to permit berthing of the ferries. The present jetty would be widened to accommodate the automotive traffic generated.

The construction and dredging involved, would, of course, result in some changes in the vicinity (e.g., increased turbidity); however, these should be on a scale very modest (both in space and in time) even compared to any introduced by the various airport expansion concepts already discussed, and would primarily occur appreciably more to seaward. Again, it appears that the dyke-and-fill method of construction would minimize whatever such effects were generated. There exists the possibility of disruption of a small area of habitat for any benthic forms present. The general locality, it may be noted, could be geologically more unstable than the adjacent expanse of inter-tidal area. There apparently exists a crab resource of commercial significance in the area involved (Levings and Coustalin, 1974).

The proposed terminal will extend an appreciable distance onto a permanently inundated portion of the Bank; some potentially deleterious effects resulting from interaction between the structure and primary-treated effluent from the Iona outfall can be recognized. The open outfall channel now in use would at times tend to guide effluent almost directly into the terminal area. This action would be especially marked during large ebb tides and/or the succeeding intervals of low water. Any effluent attaining the area on a flooding tide would have presumably undergone some degree of dilution and of dispersion. Such introduction of effluent (especially in more concentrated form) into the area, and the possible accumulation, is here suggested to represent a basically undesirable condition. The water movement on the permanently inundated portion of Sturgeon Bank traversed by the proposed approach structure can be quite complex, being influenced by, among other factors, both wave- and tide-induced turbulence; however, there exists the possibility that effluent reaching the terminal area on the south side of the jetty could be further confined there by, for example, the most inshore portion of any northerly longshore current (page IV-5). A closely related feature is the possibility of entrapment of northward-moving suspended sediment by the terminal, particularly within the ferry-berthing area, especially during the Fraser River freshet. However, the determination of the actual importance of such an effect must await the results of further studies. Furthermore, the presently degraded area in the vicinity of the present outfall could provide a very marked aesthetic nuisance (odor) to ferry automotive traffic, especially at low tides. Thus, even in the absence of any airport expansion, the construction of a ferry terminal at Iona would probably demand curtailment of the deposition of effluent-borne material, at least as presently permitted, in the vicinity of the outfall. It is suggested that the provision of secondary treatment at the Iona plant would nullify much of this adverse effect of the effluent. If such treatment could not be made available, a closed-conduit system for effluent transport away from the immediate vicinity of the Iona Jetty (say to the southwest, as previously discussed - page V-16) should be of value as at least a partial solution to any accumulation of effluent near the terminal.

With either of these methods (especially the former) the aesthetic nuisance of the deposits already laid down in the degraded area would in time disappear. However, especially in the case of embayment associated with airport expansion, the problem could more quickly be solved, for example, by the filling or, alternatively, a modest remantling of the degraded area.

As for the other ameliorating possibilities previously suggested in the absence of secondary treatment, (pages V-13, V-18 to 19), a conduit parallel to the jetty and extending only as far seaward for example as the limits of embayment associated with Concept 2 might better be avoided, as might any diversion of water from McDonald Slough. The former action could, especially during low tidal stages, guide concentrations of effluent greater than those at present into the terminal area via the remaining portion of the open channel. The latter scheme would provide more seaward thrust to fluid travelling the length of the channel; however, the direction involved, even though the effluent would presumably undergo more dilution and dispersion than in the case just discussed, could still provide unacceptable concentrations at the terminal. Enclosing the entire length of the present channel would obviously be unacceptable.

It may be remarked that the simultaneous presence of an operating Iona ferry terminal as now proposed and an intercepting runway as in Concept 4 would appear to be impossible.

The terminal suggested for the North Arm (Fig. 20) involves a land area generally similar in size, orientation and other characteristics to that proposed for Iona, located on the southern side of the North Arm Jetty, about 1/2 mile inshore of the seaward end. Any ecological disruption resulting from construction should be transitory and small. No significant effect upon effluent removal should occur because of the presence of this terminal, and little resultant change should occur in the general circulation within the Iona area. Any entrapment of water-borne sediment by this terminal area should be not greater than would be the case for a terminal at the Iona Jetty (and would possibly be appreciably less). In the absence of secondary treatment at the Iona plant, it would appear that the terminal at the North Arm should be the more acceptable from a strictly environmental and aesthetic point of view, perhaps with the exception of visual aspects with respect to the northern bank of the North Arm. However, if secondary treatment were provided, much of this advantage would be nullified.

There exists the possibility that further variations to the general concepts of airport expansion discussed here may yet be brought forward for consideration. However, unless some extremely radical proposals, such as relocation of the entire airport, are to be entertained, the general remarks provided in this section should certainly retain some validity. Changes introduced into any localized situation, such as that characteristic of the Iona Island outfall area, could probably be readily incorporated into the discussion already provided.

A number of additional developments have been proposed for the Fraser River Estuary, e.g., the B. C. Ferries terminal already noted, and a marina suggested by B. C. Packers for the mouth of the Middle Arm of the Fraser. The latter project would apparently entail the construction of another jetty westward across the entire width of Sturgeon Bank. It is here believed that the Fraser Delta/Estuary represents an ecological entity. These various proposals for development should not, in this philosophy, be considered in isolation; both they, and their possible interaction, should be regarded within the context of overall usage of the estuary.

VI. CONCLUSIONS

1. Each of the five concepts of expansion presently being contemplated for Vancouver International Airport will entail placement of fill on Sturgeon Bank, and therefore the permanent loss of at least some portion of the intertidal and salt-marsh areas of the Fraser Estuary.

2. Several general environmental effects may occur because of this loss. Various links in the estuarial food web may be disrupted by loss of salt marsh and of intertidal habitat. Areas of possible value to the preservation of wildfowl in the general area will be lost. There will be a reduction in the area of Sturgeon Bank available for ameliorating any deleterious effects of effluent presently issuing from the GVSDD's sewage-treatment plant on Iona Island.

3. There appears to be little hope for establishing compensatory marsh-flora growth on the seaward face of any filled area.

4. Subsequent to the placement of the fill, the direction of horizontal water movement at any point on the boundary of the fill must, on the flood tide, be parallel to that boundary; in these circumstances the direction at any such point will in general be different from that occurring at the corresponding tidal level in the present case. Water movement over the main uncovered portion of the Bank should continue to be generally easterly (or northeasterly) on the flood tide, and westerly (or southwesterly) on the ebb. Speeds under 1 knot should be common at all depths. Wind, as well as runoff from the Fraser River, will modify this basic flow both in speed and in direction.

5. A narrow (1-2 mile wide) northerly surface current appears to persist just seaward of Sturgeon Bank. Speeds of 0.5 to 1.0 knot are most common. During the freshet of the Fraser River, the outflow from the North Arm can act as a dynamic barrier, tending to prevent water (and thus any effluent) in this current from entering either the arm itself or western Burrard Inlet. In contrast, at other times, primarily during the low-runoff period, direct movement into these two areas is likely, especially on flood tides. These physical features and conditions should not be altered significantly by any airport expansion.

6. Sediment useful for airport expansion exists on the bed of certain stretches of the lower Fraser River; a much larger amount is present on Sturgeon Bank. The removal of material from the lower Fraser should have little effect upon marine conditions in the general area under consideration. However, dredging on Sturgeon Bank could result in injurious effects to the benthic habitat which may persist for a considerable time.

7. Both dredging and filling will result in some decrease of water clarity (increase in turbidity) over considerable areas. This decrease would be at a minimum, relative to ambient conditions, during the freshet of the Fraser River and at a maximum during winter. Large relative increases in turbidity could be of significance if introduced, for example, during crucial times of fish species' life cycle such as spawning or feeding within waters overlying the Bank. The enhanced turbidity due to dredging or filling may persist for days after the cessation of the operation.

8. While the dyke-and-fill method appears to be the least environmentally-injurious for placement of fill, the discharge of fine material suspended in the wastewater, either into the sea or onto the Bank itself,

may be locally significant.

9. Throughout the southern vicinity of the Iona Jetty, water overlying the Bank can, at least during calms or very light winds, be characterized by a thin brackish (salinity-originated) surface layer in winter. Over the GVSDD sewage outfall channel immediately to the south of the Jetty and along its entire length, water movement within this layer is seaward on ebb tides; maximum values of well over 1 knot are attained during tides of large range. Corresponding speeds beneath the layer are also seaward, but generally smaller in value. Seaward flow can apparently also occur, even during small flood tides, over the more-landward portions of the channel at least; the effect is presumably due in great part to the fresh-water effluent outflow, which is generally at an annual maximum in winter. During large floods the flow is presumably landward.

Away from the channel, surface-layer motion appears to be generally a complex function of tide, wind, bottom topography and the land-sea boundary. Wind speeds as small as 3 mph (especially those from the southwest quadrant) although not strong enough to destroy the surface layer, can significantly influence motion within it. Indeed, motion at all depths can be more complicated than that near the jetty. The motions throughout the area in question will be those most affected by any airport expansion presently proposed.

10. Airport expansion Concept 1 involves a relatively short ($\sim$ 1/3 mile) intrusion of runway fill into Sturgeon Bank, with an accompanying loss of about 70 acres of inter-tidal flat and about 1/3 mile of the western shoreline of Sea Island. The interference with the present water circulation should be small; the degree of embayment effected partly by the Iona Jetty and the

intrusion of fill is not great. The small pocket formed near the southeast corner of the embayment might result in the formation at times of a back eddy, with consequent enhanced deposition of suspended material from any effluent* thus temporarily confined. The area that would receive such deposition is believed to be severely degraded biologically; nevertheless, the pocket should be erased by the addition of fill. A solid causeway for the emplacement of navigational aids should be avoided, as it would accentuate the embayment and thus could result in degradation of an area somewhat greater than at present. The aids might alternatively be placed on pilings spaced as far apart as possible. Fill obtained from the North Arm of the Fraser should suffice to provide the runway of this concept.

11. Concept 2 involves a runway proper extending about 3/4 mile onto the Bank. A loss of about 235 acres of flat, but of the same amount of salt marsh as for Concept 1, would occur. The degree of embayment is great; the resultant, aggravated back-up and/or retention of effluent especially on flood tides and at high water levels, could increase deposition throughout the entire area enclosed. Tidally-induced current speeds at the narrow entrance to the embayment could apparently attain values of a few knots. Such strong currents could promote marked scouring at the entrance and thus perhaps significantly alter "bottom" conditions in the vicinity, e.g., the depth of the present outfall channel. An impermeable causeway for navigational aids should be avoided in this concept also. Spoil from the North Arm should be sufficient for construction of this runway.

12. Several alternatives and variations for easing adverse effects of the embayment associated with Concepts 1 and 2 (especially the latter),

* issuing from the GVSDD outfall as presently located.

as well as any of the present effects of the effluent regarded as undesirable, can be suggested for careful scrutiny. The most effective, as well as the least disruptive to the environemnt, is probably the provision of secondary treatment of sewage at the Iona Island treatment plant. If this cannot be supplied one might consider transport of the effluent as presently treated out of the embayment by a closed conduit, rather than via the present open channel; an extension of the conduit southwestward to or near the edge of the Bank might be of additional value. Alternatively, imparting both a greater seaward momentum to flow in the present open channel and a concomitant more-vigorous flushing of the outfall area, by the introduction of flow from McDonald Slough into the present effluent outfall area could also be considered. The feasibility and the advantage of effluent discharge at depth to the Strait of Georgia may be difficult to ascertain.

13. Concept 4 involves the construction of a runway about 2 miles onto the Bank. This will intersect the Iona Jetty, and thus isolate the present effluent outfall from the open sea. About 500 acres of intertidal area would be lost. Closed-conduit transport of effluent at least out of the enclosed area is therefore mandatory. Spoil obtainable from the North Arm would be insufficient to complete this effort.

14. Concepts 3 and 5 deal with the additions of large service areas adjoining to the south of, Concepts 2 and 4 respectively. A total of about 1500 acres of intertidal flat would be involved in both cases. No further degree of embayment in the vicinity of the outfall would be involved. The entire western shore (marsh) of Sea Island ($\sim$ 3/4 mile long) would be effectively destroyed. Sediment from Sturgeon Bank would be necessary to complete either concept.

15. It is suggested that any placement of fill associated with airport expansion would have no significant effect upon the present supply of sediment to any beach areas (present or potential) within the Iona or Spanish Bank areas. Therefore, for these areas, the degree of natural maintenance of the beaches, as occurring at present, should remain unaltered by this action.

16. Two locations for a new mainland ferry terminal are now (1974) receiving favorable consideration by the B.C. Department of Highways: one at the seaward end of the Iona Jetty, another somewhat inshore of the seaward end of the North Arm Jetty. Any physical-oceanographic effects of filling and dredging associated with the construction of either of these terminals, such as induced turbidity, would appear to be very modest with respect to both time and space. In addition, these effects would occur more to seaward than would the similar ones involved in any airport expansion. The construction of either terminal would permanently remove small areas of benthic habitat. The construction of a terminal at the Iona Jetty might permanently disrupt a crab fishery of some commercial significance.

17. The present sewage outfall channel would tend, especially on ebb tides and low waters, to guide effluent almost directly into the vicinity of the terminal proposed for Iona. Such introduction of effluent (and any possible resultant accumulation) should be avoided; the provision of at least secondary treatment of sewage at the Iona Island plant would therefore be of great value in this case, even in the absence of any airport expansion. The benefit of such treatment would, of course, be accentuated for the simultaneous presence of a ferry terminal at the Iona Jetty and an expansion of the airport.

18. In the absence of secondary treatment, apparently the only useful mitigation of any such unwelcome effects would be the conduction of the effluent by closed conduit away from the Iona Jetty area, e.g., to the southwest. Other methods of possible value for the case of airport expansion alone would appear to be of little use.

19. For both terminals, but probably especially for one at the Iona Jetty, there exists the possibility of entrapment of some northward-moving suspended sediment; this would occur primarily at the south side, in particular within the ferry-berthing area.

20. The terminal proposed for the North Arm is much more free of objections involving the presence or transport of effluent than is the more southerly one. If secondary treatment is not provided, a North Arm terminal would appear to be preferable from the point of view of ecological and/or aesthetic conditions on Sturgeon Bank to one at the Iona Jetty. However, if secondary treatment were supplied, any such advantage would disappear.

VII. INADEQUACIES IN KNOWLEDGE RELEVANT TO THE ENVIRONMENTAL IMPACT ASSESSMENT

That portion of the impact assessment carried out by the Marine Sciences Directorate has suggested inadequacies in several possibly significant aspects of the study. These voids, which may demand more than cursory examination, are listed below. Sections and/or pages, in the MSD report, relevant to each aspect are noted in parentheses; no particular order of importance is suggested.

1. Greater detail of the circulation and properties of water overlying Sturgeon Bank and the area just offshore: more refined knowledge than exists at present would be useful in biological and geological considerations, as well as providing a more complete basis upon which to evaluate the various alternatives for ameliorating conditions resulting from effluent discharge from the treatment plant on Iona Island (Section IV A, B, C).

2. The alternatives noted in (1) which include secondary treatment and/or re-routing of effluent: these should be thoroughly examined in every aspect, including that of cost-benefit. Information from (1) should be of value in this regard, as would a thorough knowledge of the present effects of the effluent upon such areas as those containing recreational facilities, present or potential. Each concept for airport expansion should be considered individually and also in conjunction with the B. C. Ferries terminal proposed for the seaward end of the Iona Jetty. (Pages V-24-28).

3. The possible erosion and the subsequent effects within and near the constriction formed by the Iona Jetty and the runway construction associated with Concepts 2 and 4. (Pages V-10,11).

4. The characteristics of subsurface sediments that would be exposed by dredging on Sturgeon Bank: this aspect would involve the possible degree of toxicity as it would relate to:

(a) The effect of the exposed sediment upon the quality of the overlying water and upon marine life in the general area.

(b) The use of the sediment for fill. (Pages V-6,7).

5. The effect upon marine life of water turbidity generated by dredging and filling: this would include the case of a decrease in water clarity resulting from the presence of suspended fines in wastewater associated with the dyke-and-fill method of runway construction. The low-runoff period of the Fraser would be the one of most significance in this regard. (Pages V- 5).

6. The effect upon water quality and turbidity, and thus upon indigenous marine life of the release of dredge spoil off the main mouth of the Fraser River, especially during low run-off periods. (Page V-6).

7. The rates of recolonization of benthic fauna known to inhabit areas of Sturgeon Bank that could be dredged and/or be adversely affected by wastewater fines. (Page V-5).

8. The feasibility of replacement of marsh flora to replace any loss due to airport expansion: success in this regard could also involve general enhancement of such growth within the Fraser Estuary if considered to be of sufficient value to the food web. (Pages V- 3).

9. The necessity of considering the Fraser Estuary/Delta as an ecological unit: this would demand an examination of the possible interactions

between, as well as the individual effects of, the various developments proposed for the Estuary/Delta, rather than merely an examination of each project (i.e., VIA expansion) in isolation. (Pages V-28,29).

VIII. ACKNOWLEDGEMENTS

The author wishes to acknowledge the invaluable efforts of Dr. S. Pond and of Messrs. E. Black, D. Fissel, H. Heckl and B. Stewart in obtaining data on the circulation in the Iona outfall area (January, 1974) and in constructing the current followers used. Thanks are due Messrs. D. L. McKay, D. Devlin and S. Vernon of the Greater Vancouver Sewerage and Drainage District for their provision of ground facilities for the dye-tracking experiments, and to Mr. D. Budlong of that organization for his assistance in the field. B. C. Packers Ltd. kindly donated the seine floats used in the construction of the current followers employed in January 1974. Ms. L. M. Hoos and Mr. G. A. Packman provided reference material of great value to the report. The aerial photography was carried out by Mr. Parker G. Williams of Integrated Resources Photography Ltd. Ms. Lesley Manning provided the formal drafting.

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FIGURES

X. LIST OF FIGURES

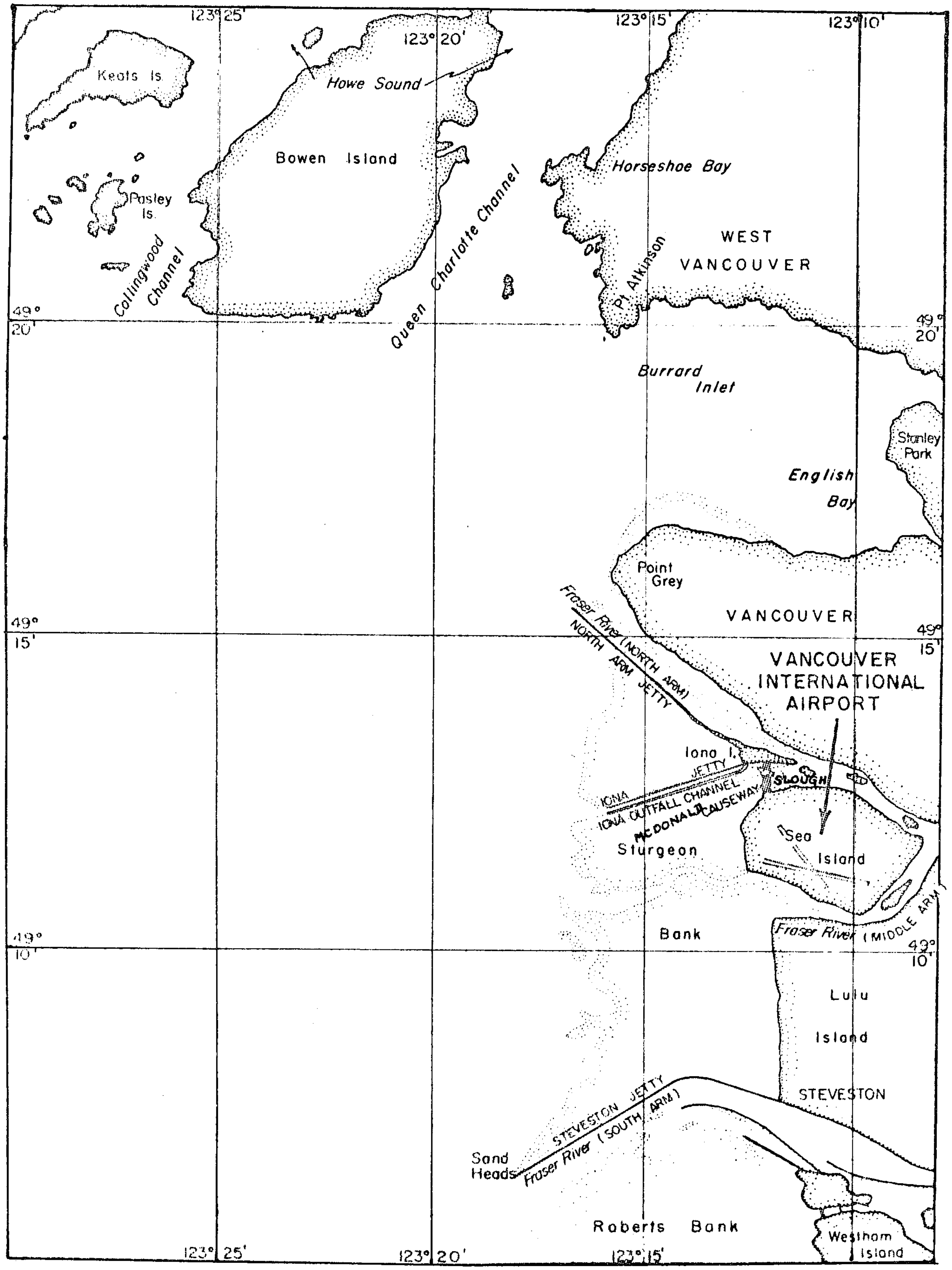

123° 25'
123° 20'
123° 15'
123° 10'
Keats Is.
Howe Sound
Bowen Island
Horseshoe Bay
Pasley Is.
Collingwood Channel
Queen Charlotte Channel
Pt. Atkinson
WEST VANCOUVER
49° 20'
Burrard Inlet
Stanley Park
English Bay
Point Grey
VANCOUVER
49° 15'
Fraser River (NORTH ARM)
NORTH ARM JETTY
VANCOUVER INTERNATIONAL AIRPORT
Iona I.
JETTY
IONA
IONA OUTFALL CHANNEL
McDONALD CAUSEWAY
SLOUGH
Sea Island
Sturgeon
Bank
49° 10'
Fraser River (MIDDLE ARM)
Lulu Island
STEVESTON
STEVESTON JETTY
Fraser River (SOUTH ARM)
Sand Heads
Roberts Bank
Westham Island

Figure 1

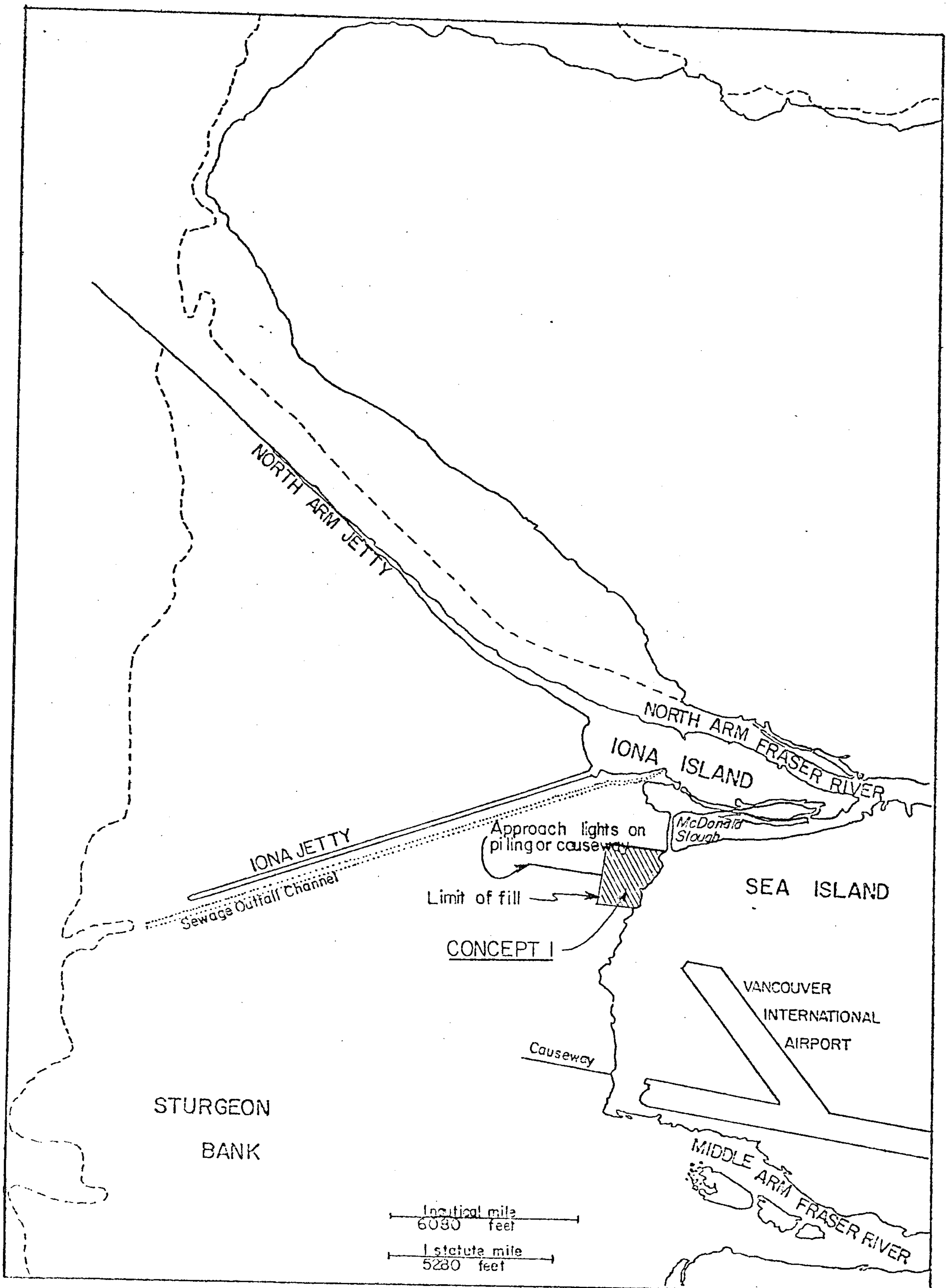

NORTH ARM JETTY
NORTH ARM FRASER RIVER
IONA ISLAND
McDonald Slough
Approach lights on piling or causeway
IONA JETTY
Sewage Outfall Channel
Limit of fill
CONCEPT I
SEA ISLAND
VANCOUVER INTERNATIONAL AIRPORT
Causeway
STURGEON BANK
MIDDLE ARM FRASER RIVER
1 nautical mile
6080 feet
1 statute mile
5280 feet

Figure 2

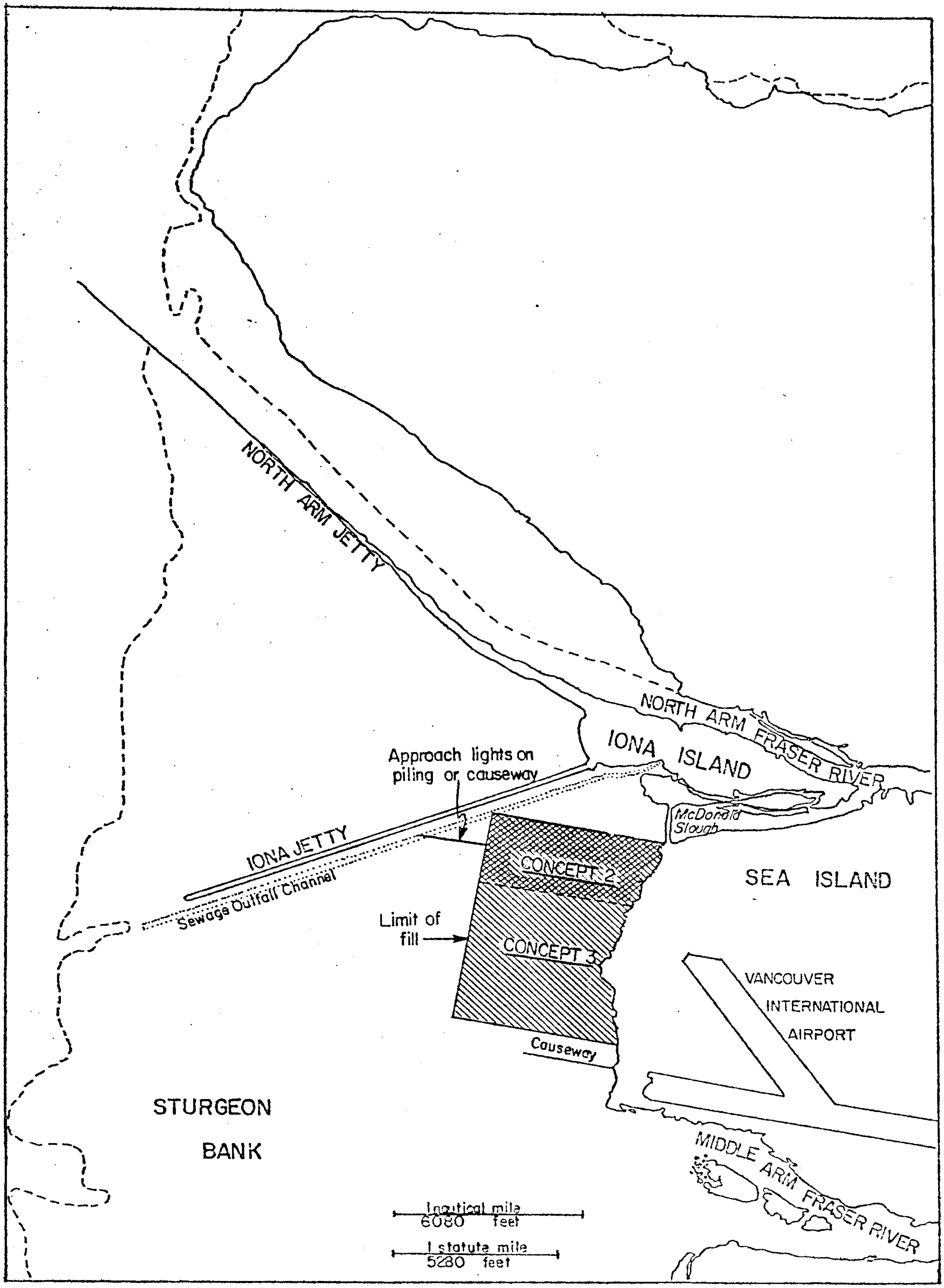
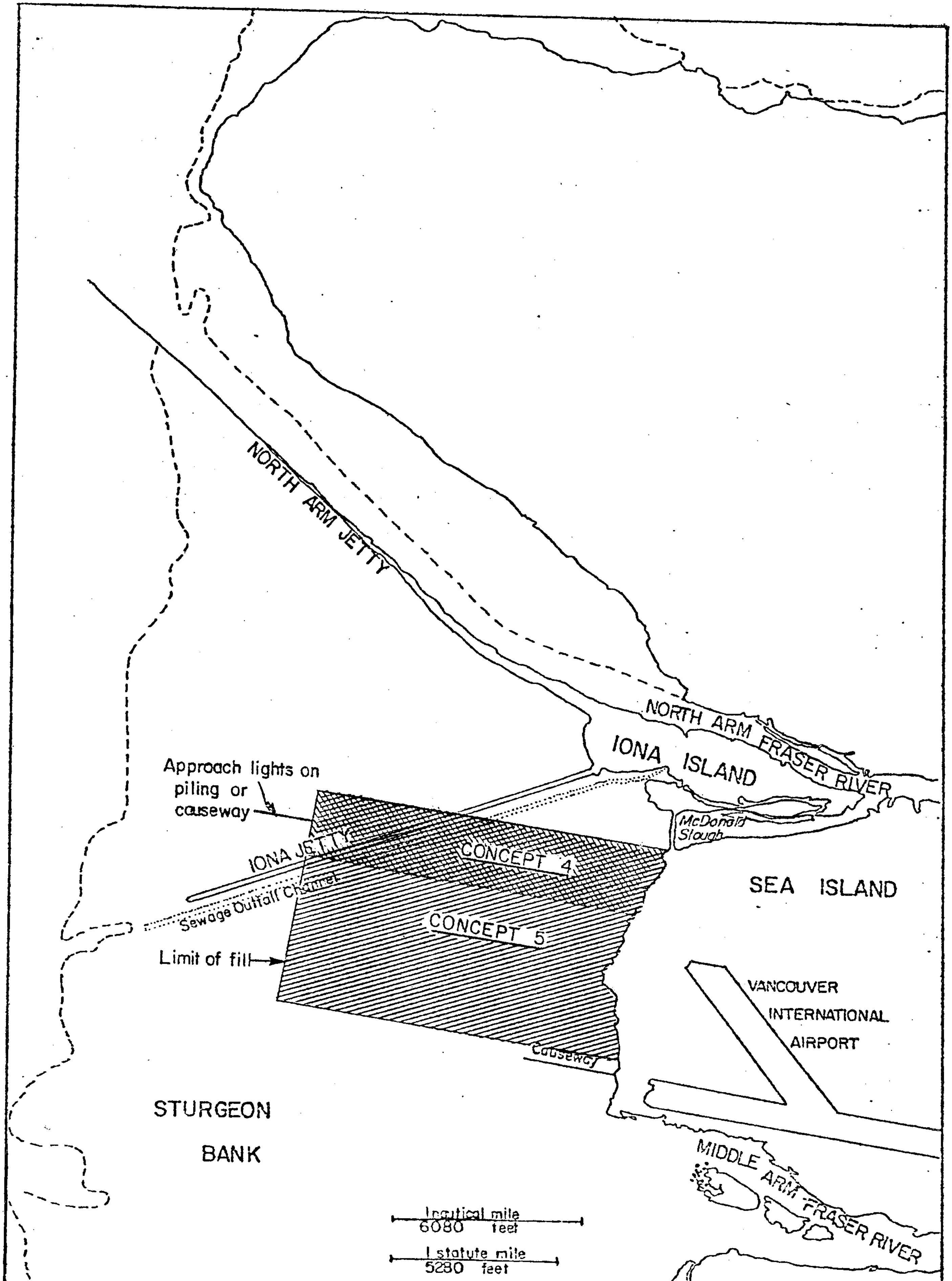
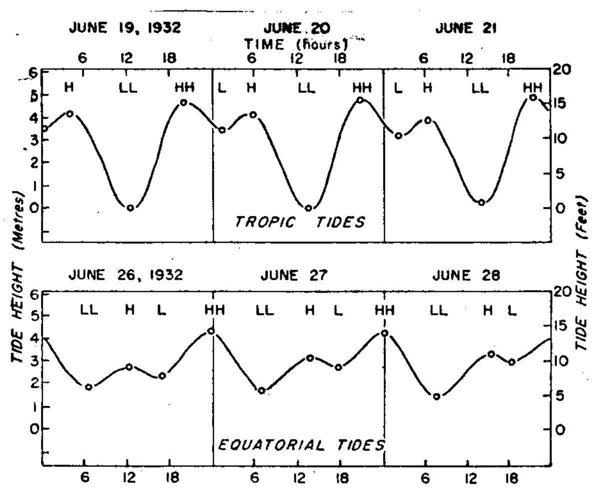

NORTH ARM JETTY
NORTH ARM FRASER RIVER
IONA ISLAND
Approach lights on
piling or causeway
McDonald
Slough
IONA JETTY
Sewage Outfall Channel
CONCEPT 2
SEA ISLAND
Limit of
fill
CONCEPT 3
VANCOUVER
INTERNATIONAL
AIRPORT
Causeway
STURGEON
BANK
MIDDLE ARM FRASER RIVER
1 nautical mile
6080 feet
1 statute mile
5280 feet

Figure 3



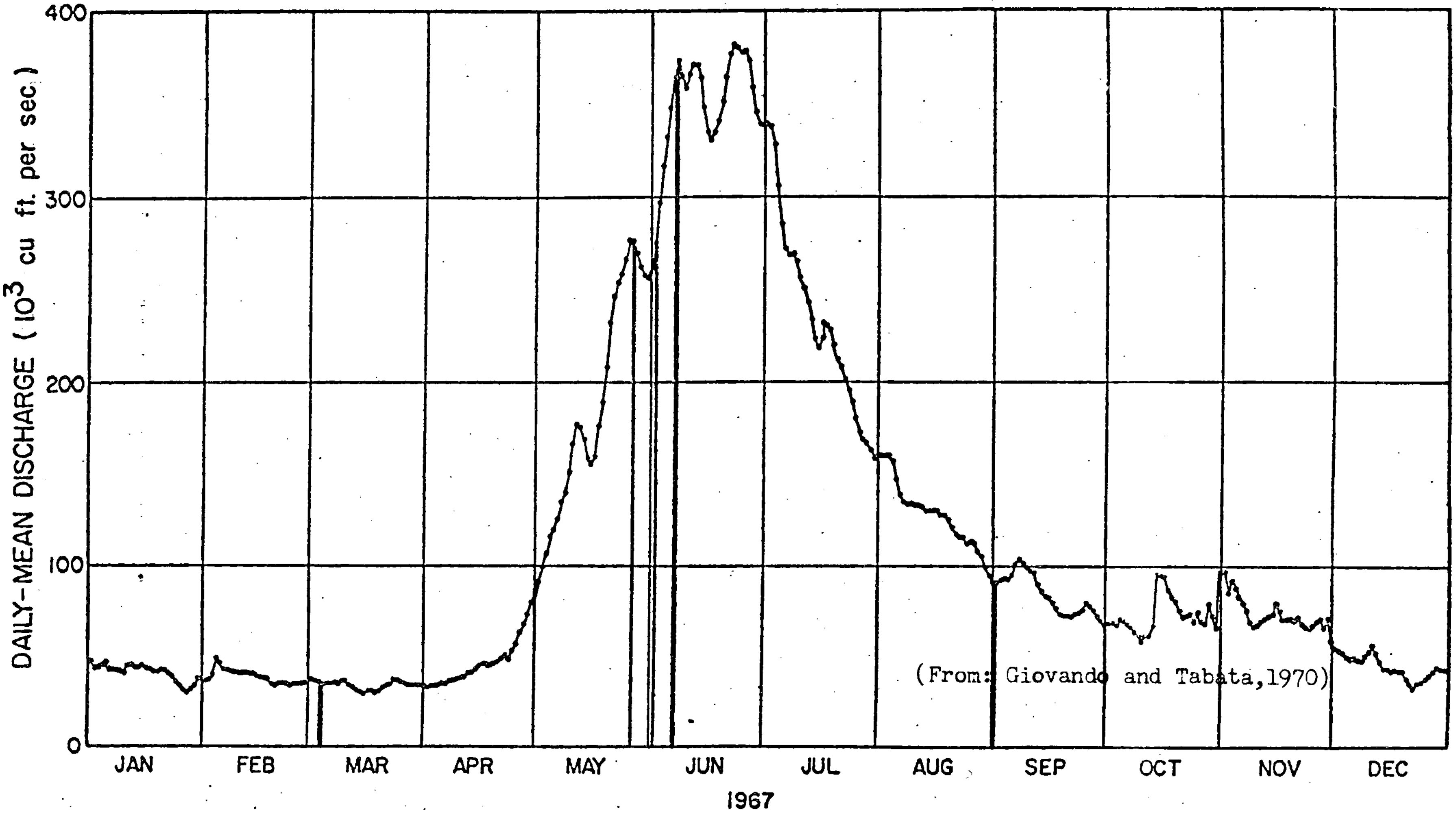
NORTH ARM JETTY
NORTH ARM FRASER RIVER
IONA ISLAND
Approach lights on
piling or
causeway
McDonald
Slough
IONA JETTY
CONCEPT 4
SEA ISLAND
Sewage Outfall Channel
CONCEPT 5
Limit of fill
VANCOUVER
INTERNATIONAL
AIRPORT
Causeway
STURGEON
BANK
MIDDLE ARM FRASER RIVER
I nautical mile
6080 feet
I statute mile
5280 feet

Figure 4



JUNE 19, 1932
JUNE 20
JUNE 21
TIME (hours)
TIDE HEIGHT (Metres)
TIDE HEIGHT (Feet)
TROPIC TIDES
JUNE 26, 1932
JUNE 27
JUNE 28
EQUATORIAL TIDES
H
LL
HH
L

Figure 5

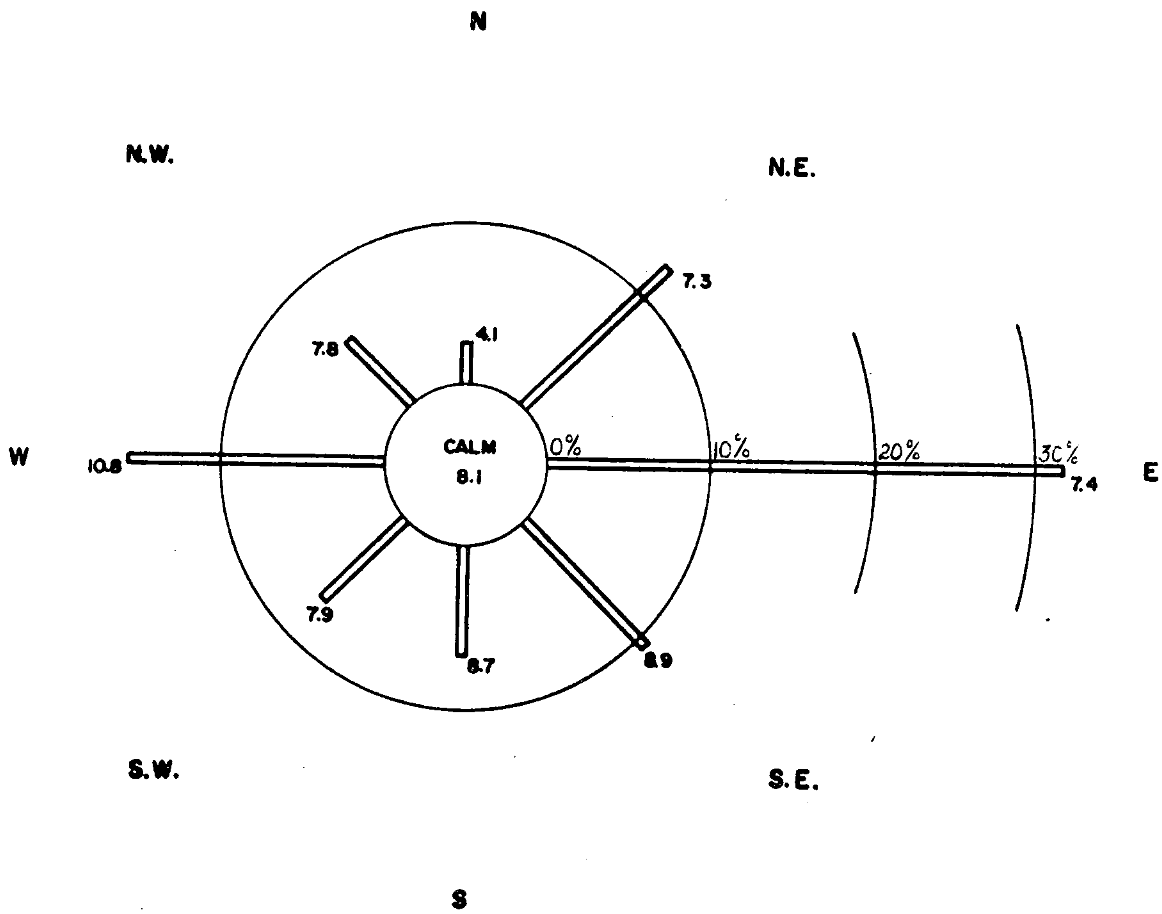


DAILY-MEAN DISCHARGE (10^3 cu ft. per sec.)
400
300
200
100
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1967
(From: Giovando and Tabata, 1970)

Figure 6


BOUNDARY BAY
GALIANO I.
FRASER R.
POINT GREY
B.C. Government Air Photograph
BC 1056-85

Figure 7



Mean Wind Speed by Direction: (Miles per Hour)
Percentage Frequency of Wind by Direction: (I Inch = I0 Percent)

Figure 8
WIND ROSE, VANCOUVER INTERNATIONAL AIRPORT (1953-1971)
(From: Hoos and Packman, 1974)

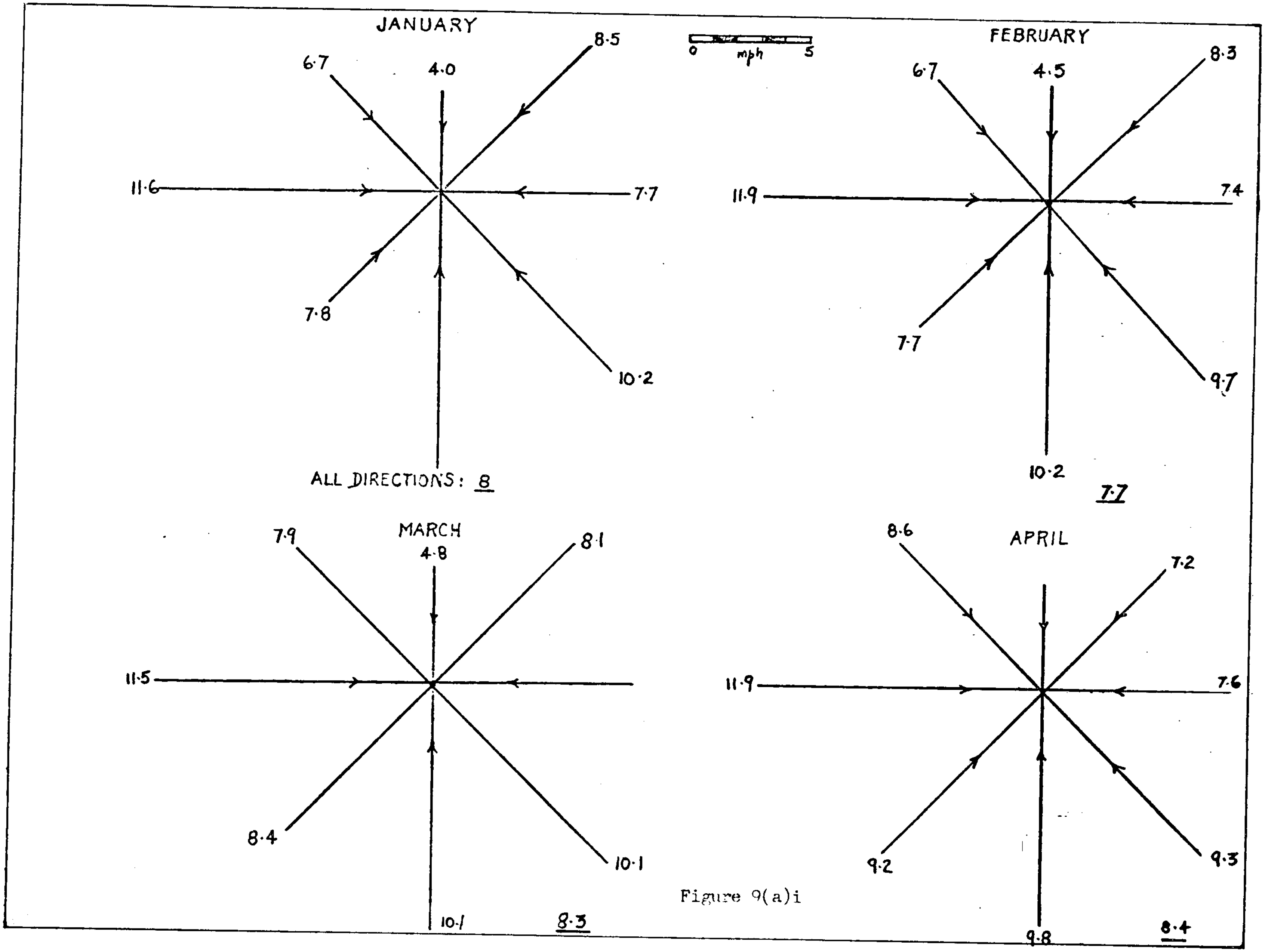

JANUARY
0 mph 5
FEBRUARY
6·7
4·0
8·5
11·6
7·7
7·8
10·2
ALL DIRECTIONS: 8
6·7
4·5
8·3
11·9
7·4
7·7
9·7
10·2
7·7
MARCH
7·9
4·8
8·1
11·5
8·4
10·1
10·1
8·3
APRIL
8·6
7·2
11·9
7·6
9·2
9·3
9·8
8·4

Figure 9(a)i

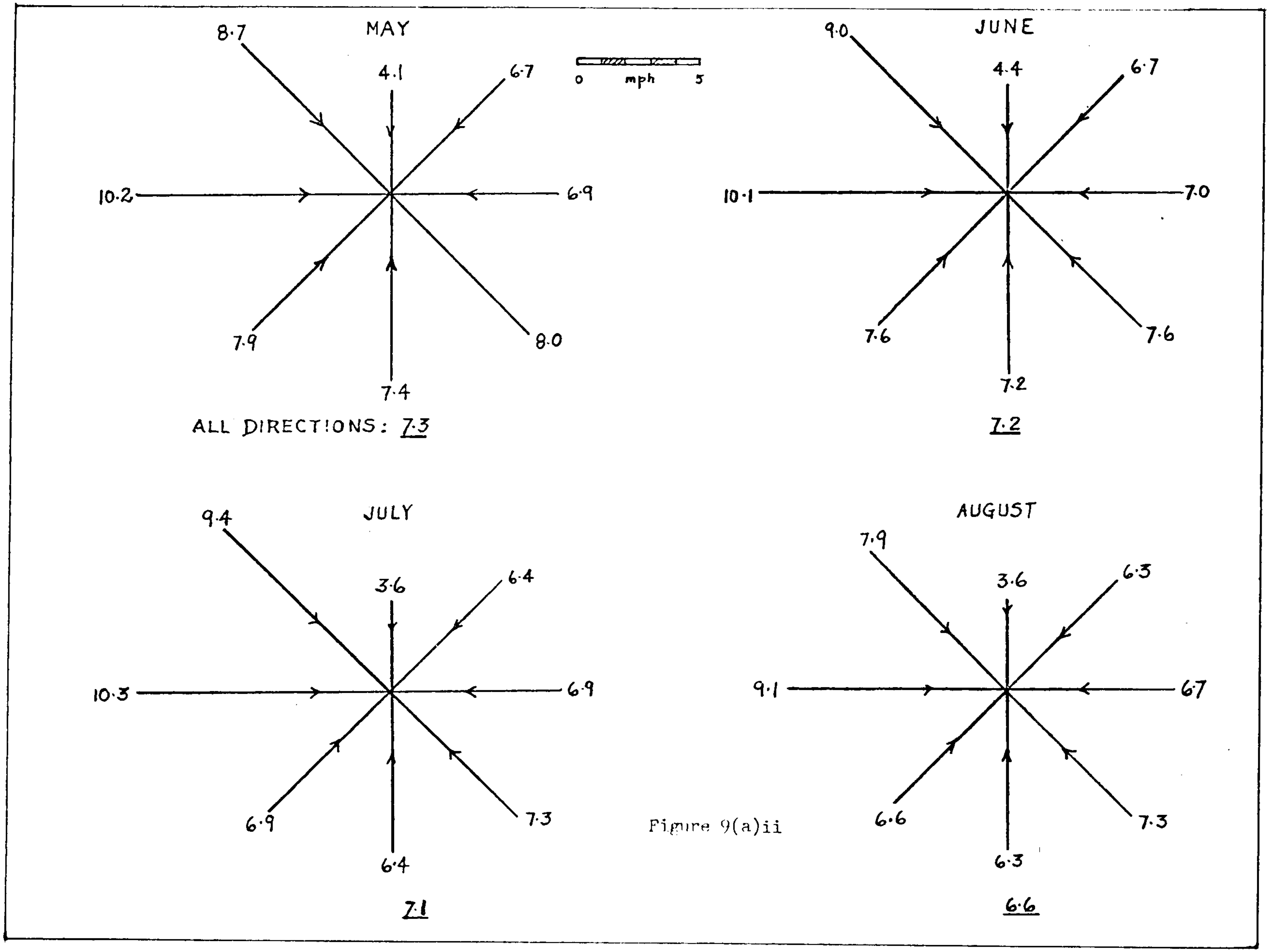

MAY
8·7
4·1
6·7
10·2
6·9
7·9
7·4
8·0
0 mph 5
ALL DIRECTIONS: 7·3
JUNE
9·0
4·4
6·7
10·1
7·0
7·6
7·2
7·6
7·2
JULY
9·4
3·6
6·4
10·3
6·9
6·9
6·4
7·3
7·1
AUGUST
7·9
3·6
6·3
9·1
6·7
6·6
6·3
7·3
6·6

Figure 9(a)ii

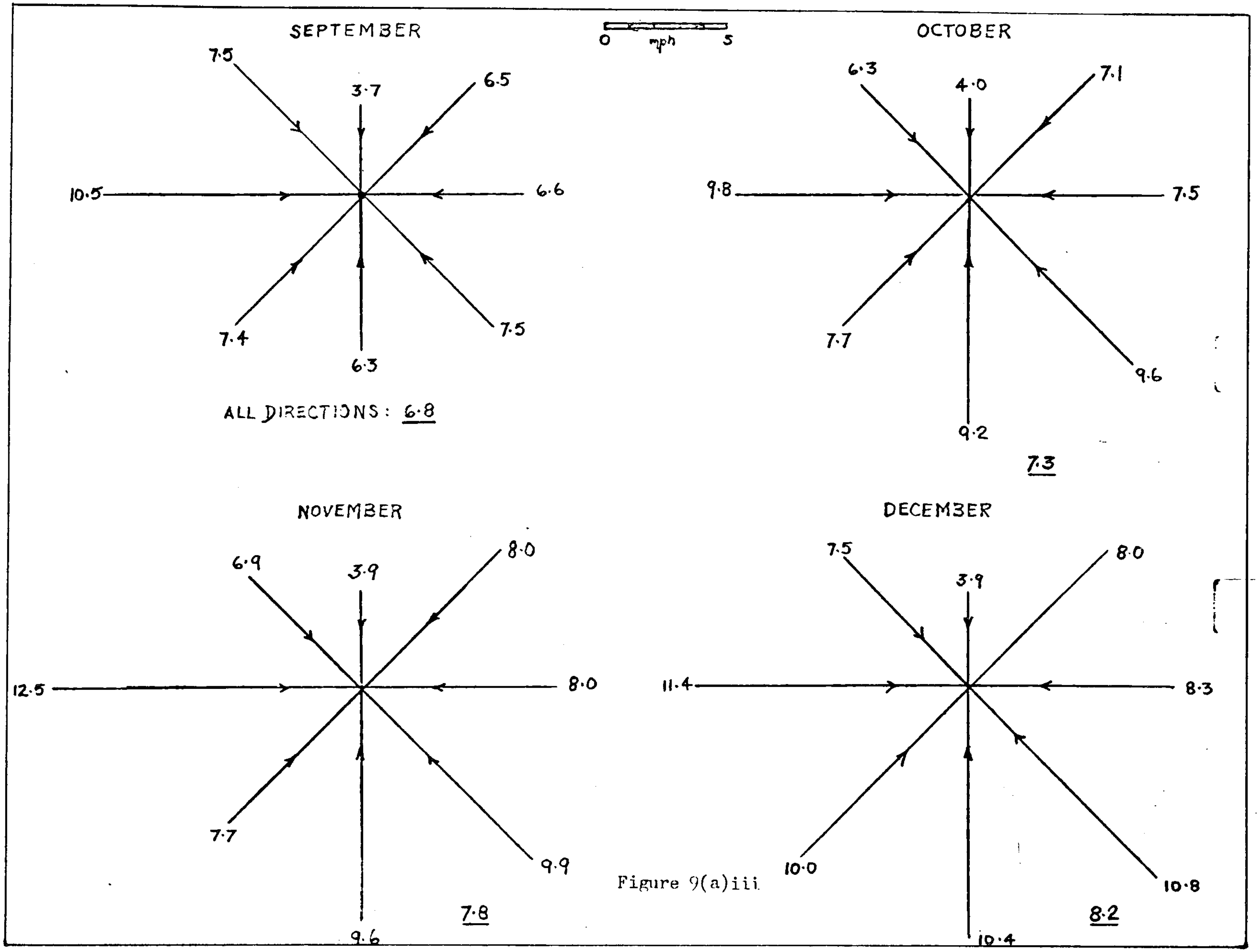


Figure 9(a)iii

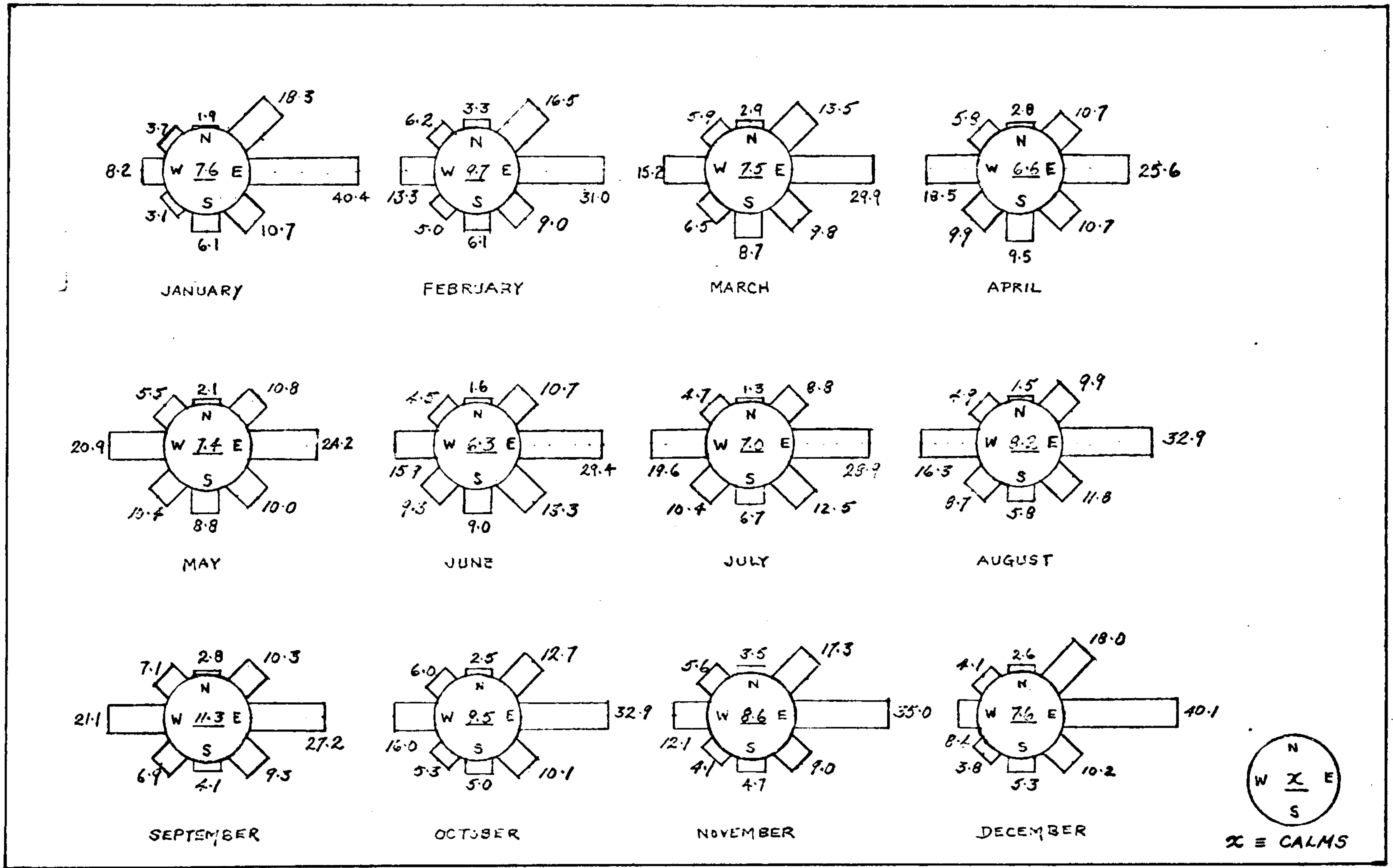

JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
x ≡ CALMS

Figure 9(b)

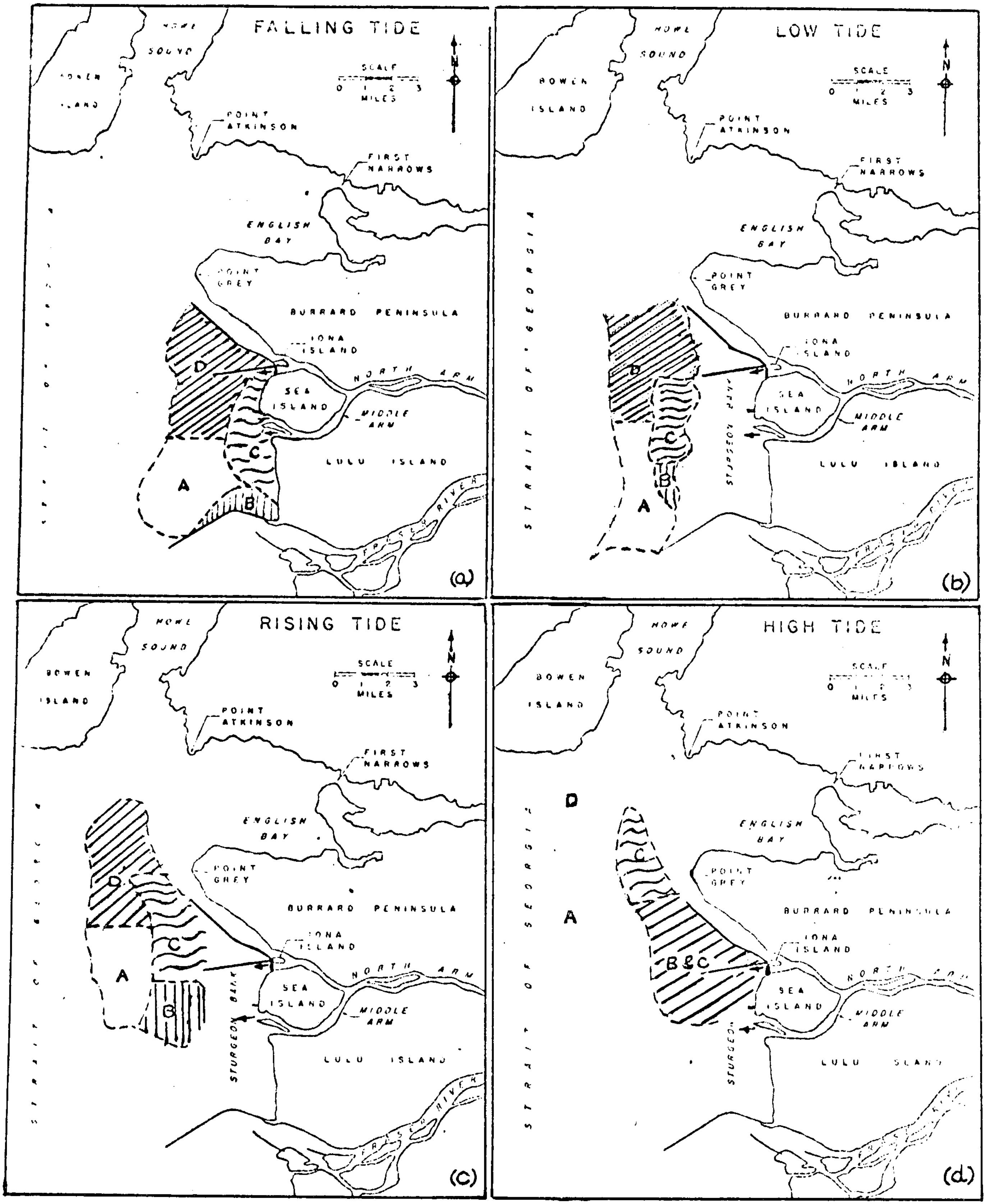

FALLING TIDE
LOW TIDE
RISING TIDE
HIGH TIDE
HOWE SOUND
BOWEN ISLAND
POINT ATKINSON
FIRST NARROWS
ENGLISH BAY
POINT GREY
BURRARD PENINSULA
IONA ISLAND
SEA ISLAND
NORTH ARM
MIDDLE ARM
LULU ISLAND
FRASER RIVER
STURGEON BANK
STRAIT OF GEORGIA
SCALE
0 1 2 3
MILES
N
A
B
C
D
B&C
(a)
(b)
(c)
(d)

Figure 10

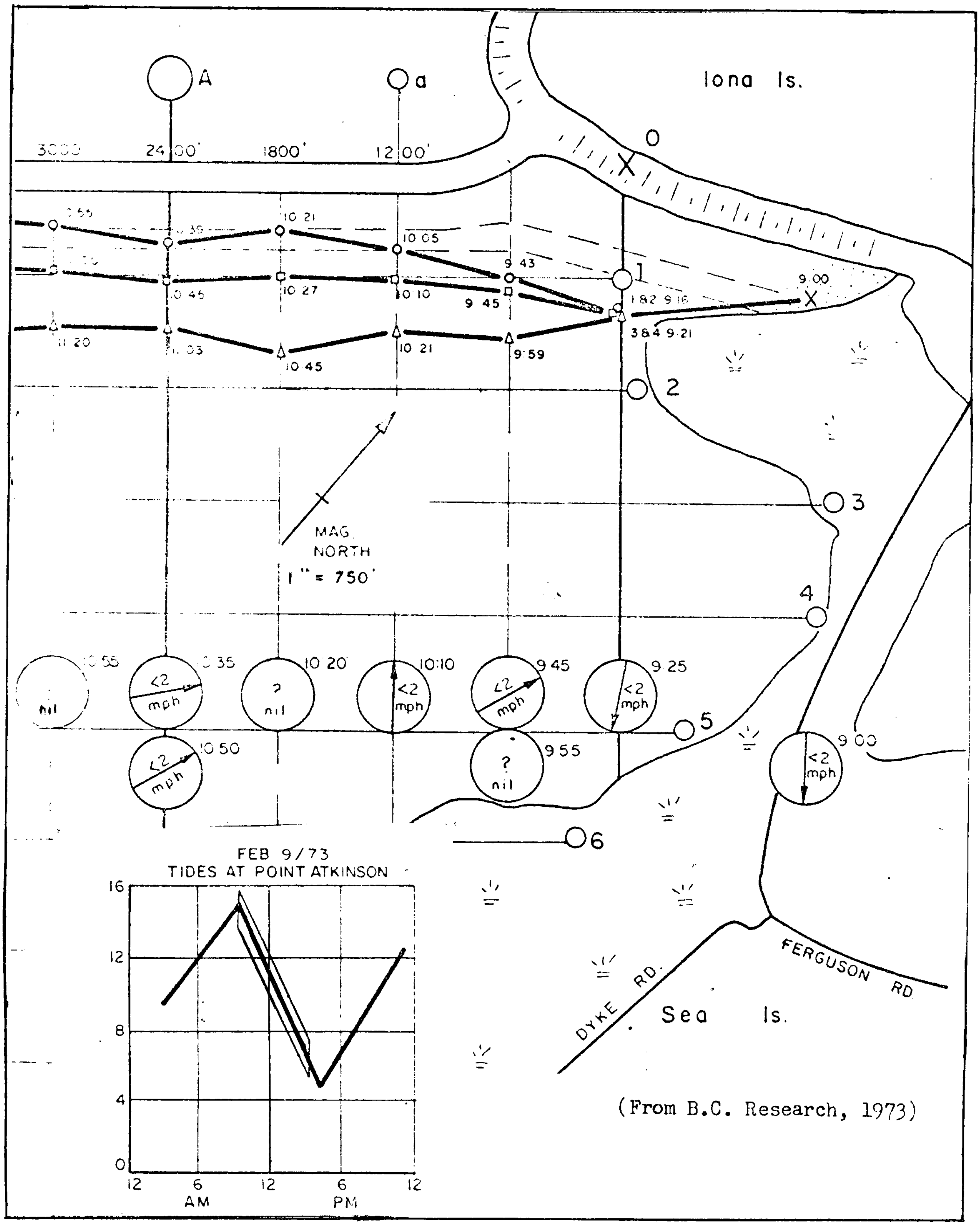
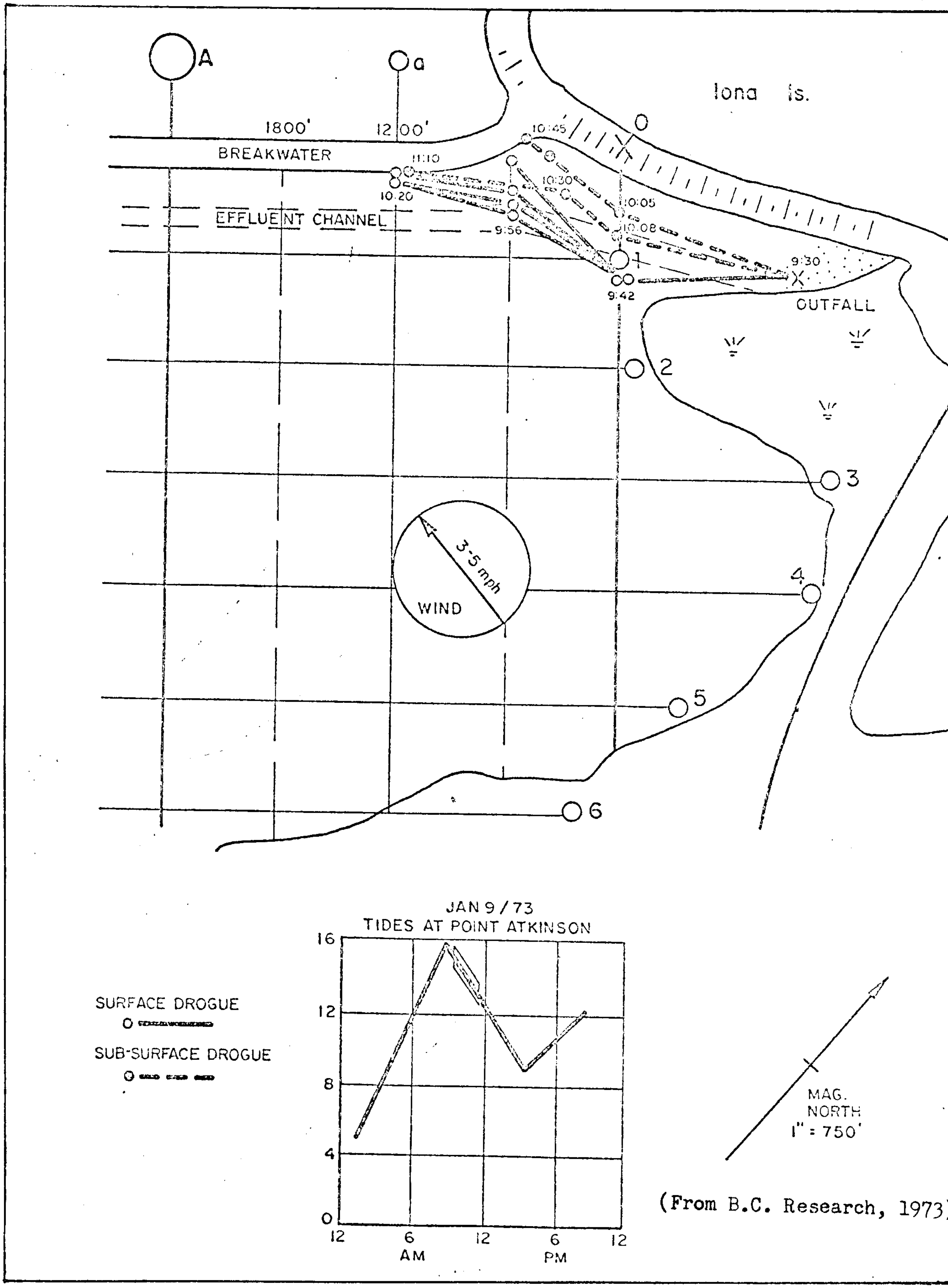
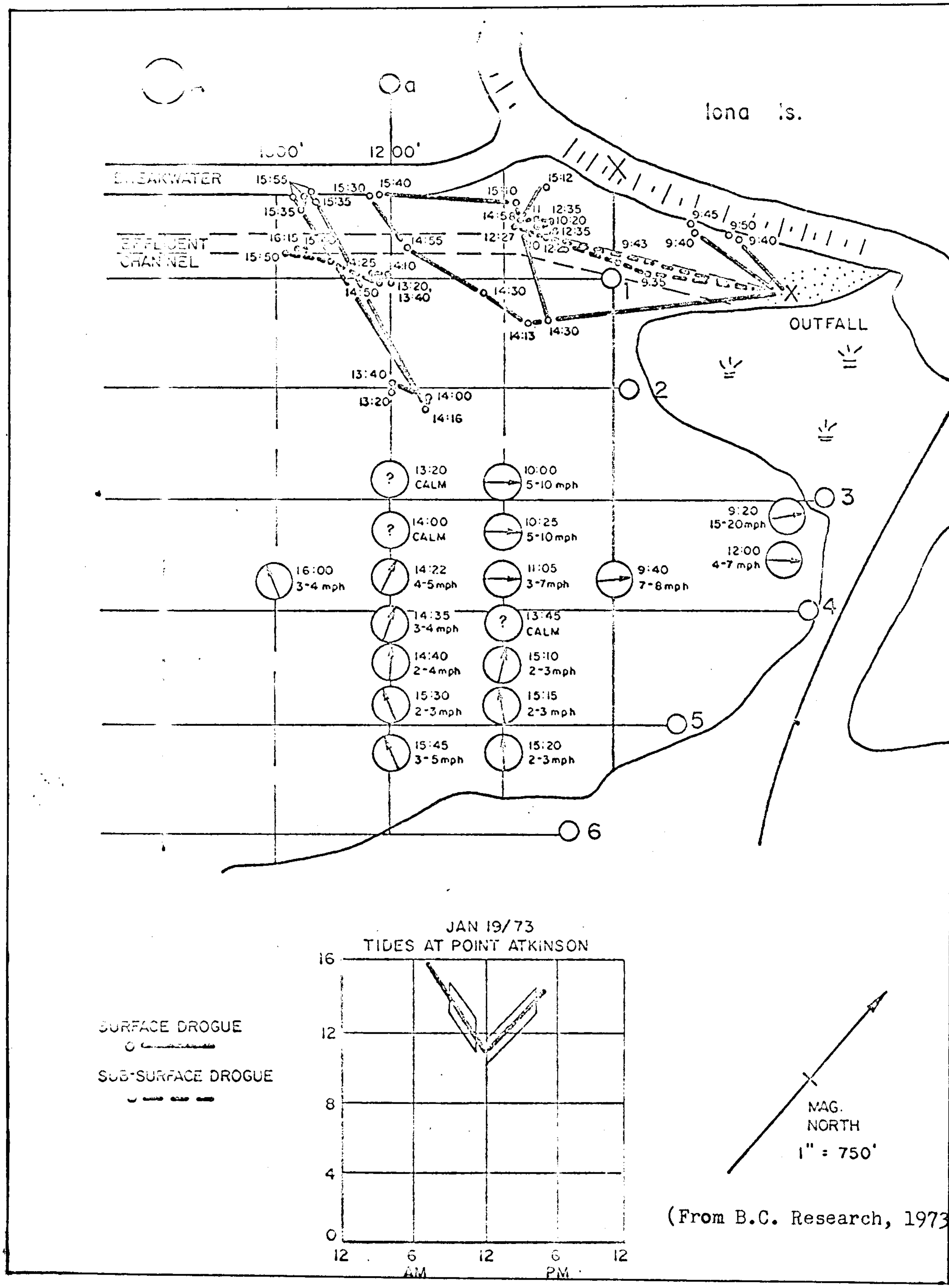

Iona Is.
A
a
24 00'
1800'
12 00'
0
1
2
3
4
5
6
MAG. NORTH
1" = 750'
<2 mph
nil
Sea Is.
DYKE RD.
FERGUSON RD.
FEB 9/73
TIDES AT POINT ATKINSON
AM
PM
(From B.C. Research, 1973)

Figure 11



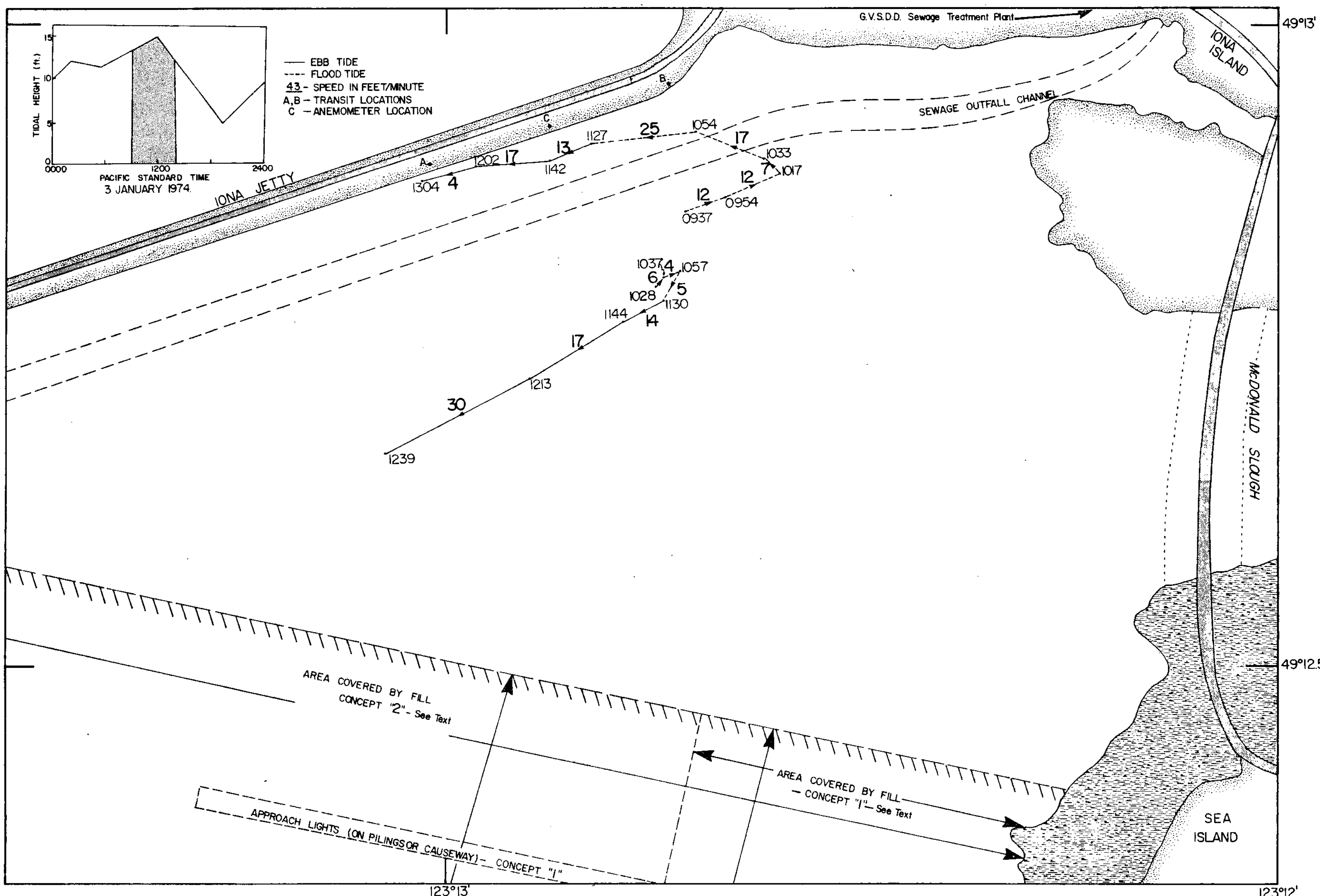
(From B.C. Research, 1973)

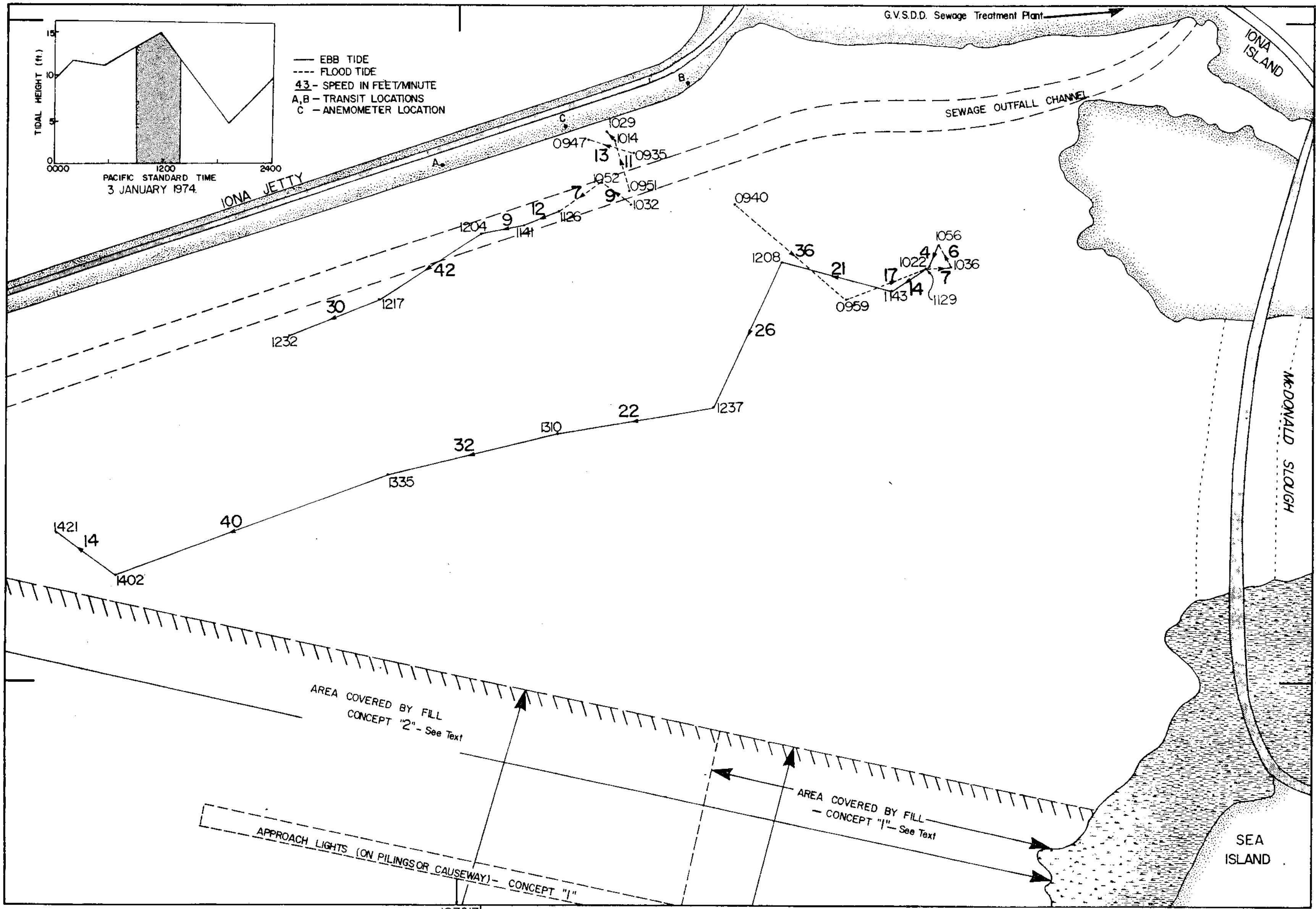
Figure 12



Iona Is.
12 00'
BREAKWATER
EFFLUENT CHANNEL
OUTFALL
13:20 CALM
14:00 CALM
14:22 4-5 mph
14:35 3-4 mph
14:40 2-4 mph
15:30 2-3 mph
15:45 3-5 mph
10:00 5-10 mph
10:25 5-10 mph
11:05 3-7mph
13:45 CALM
15:10 2-3mph
15:15 2-3 mph
15:20 2-3mph
16:00 3-4 mph
9:40 7-8mph
9:20 15-20mph
12:00 4-7 mph
JAN 19/73
TIDES AT POINT ATKINSON
AM
PM
SURFACE DROGUE
SUB-SURFACE DROGUE
MAG. NORTH
1" = 750'
(From B.C. Research, 1973)

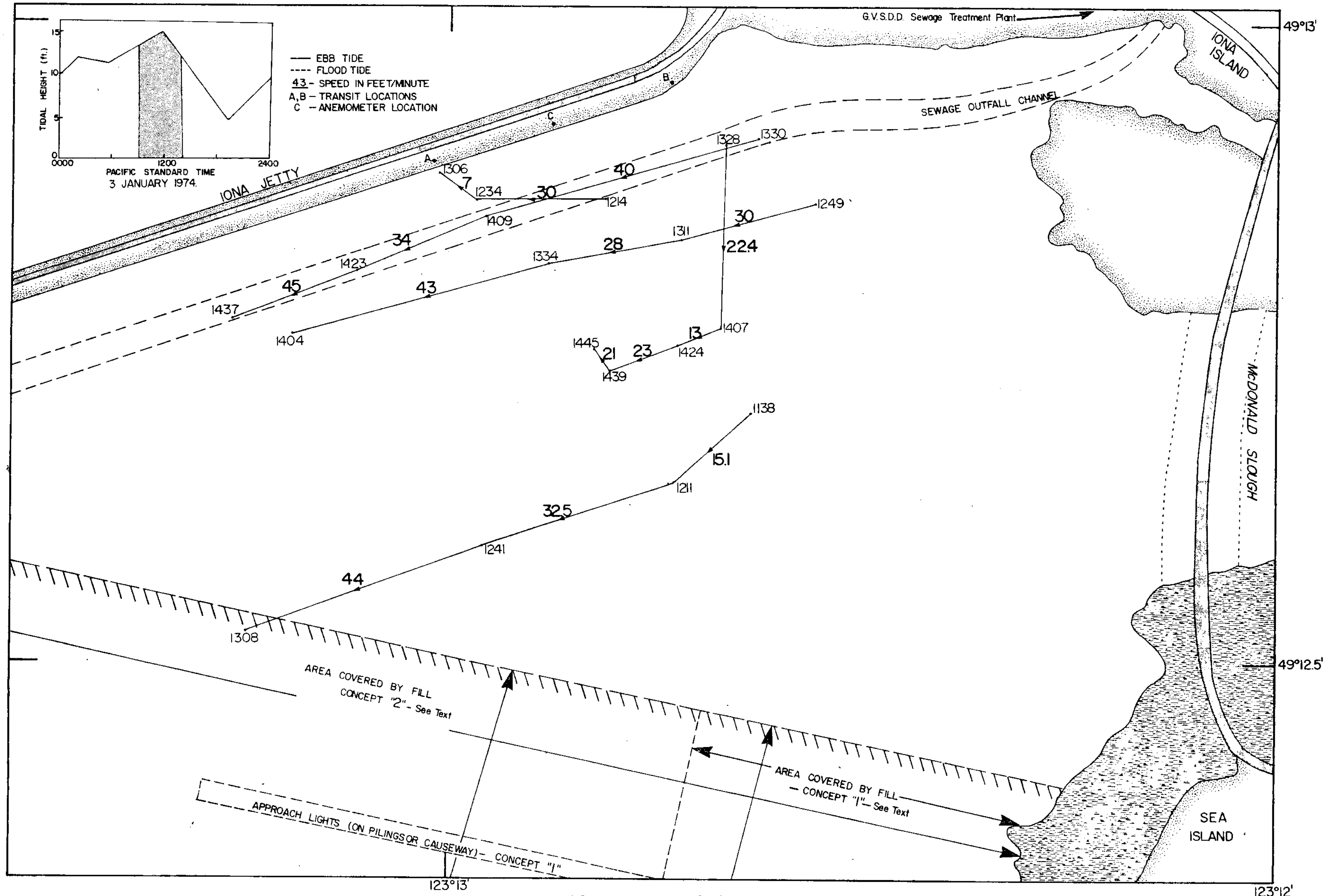
Figure 13


G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
SEWAGE OUTFALL CHANNEL
IONA JETTY
McDONALD SLOUGH
SEA ISLAND
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
3 JANUARY 1974.
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
AREA COVERED BY FILL
CONCEPT "2" - See Text
AREA COVERED BY FILL
- CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'
Figure 14(a)



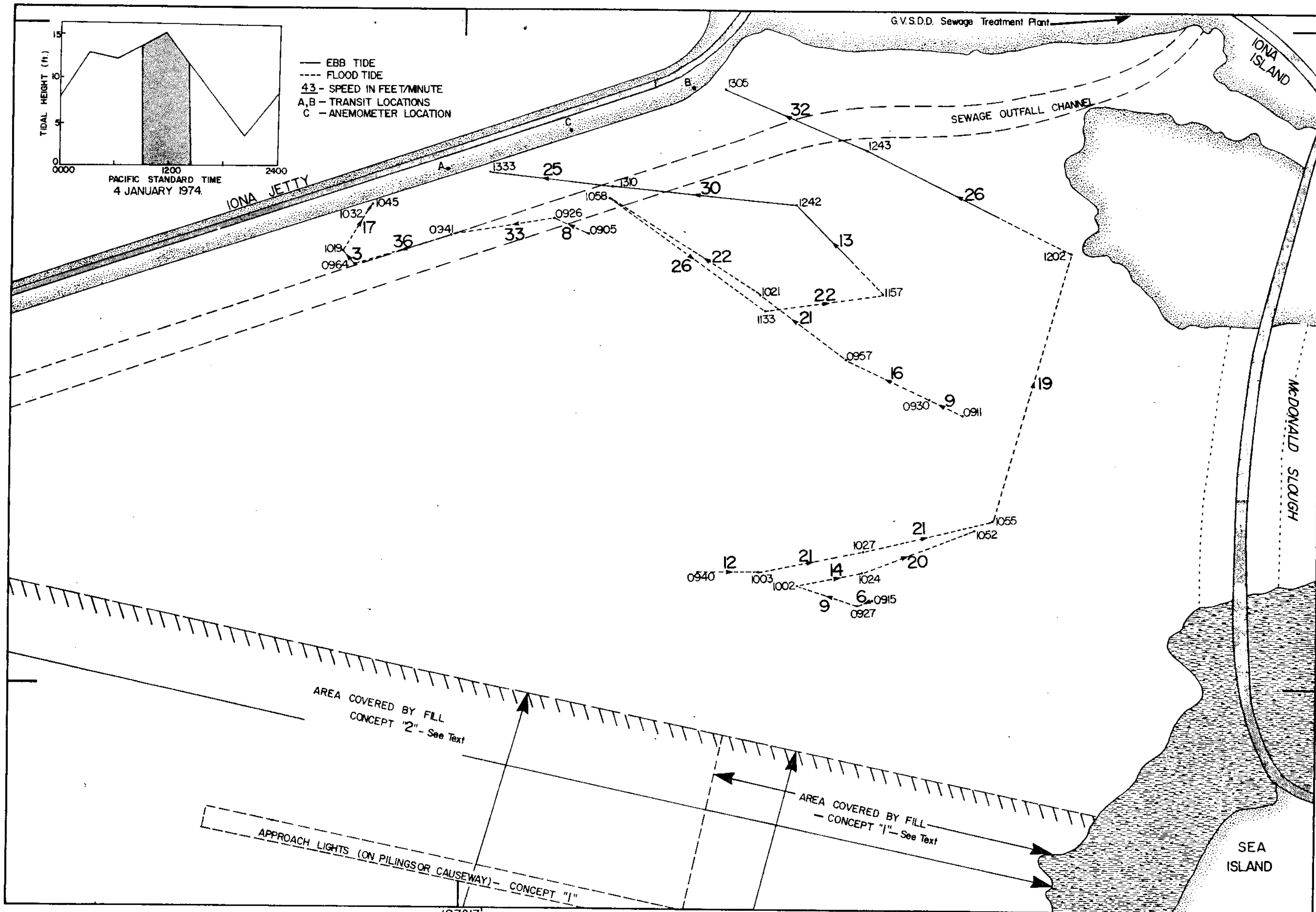
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
3 JANUARY 1974.
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
IONA JETTY
SEWAGE OUTFALL CHANNEL
McDONALD SLOUGH
SEA ISLAND
AREA COVERED BY FILL CONCEPT "2" - See Text
AREA COVERED BY FILL - CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'

Figure 14(b)



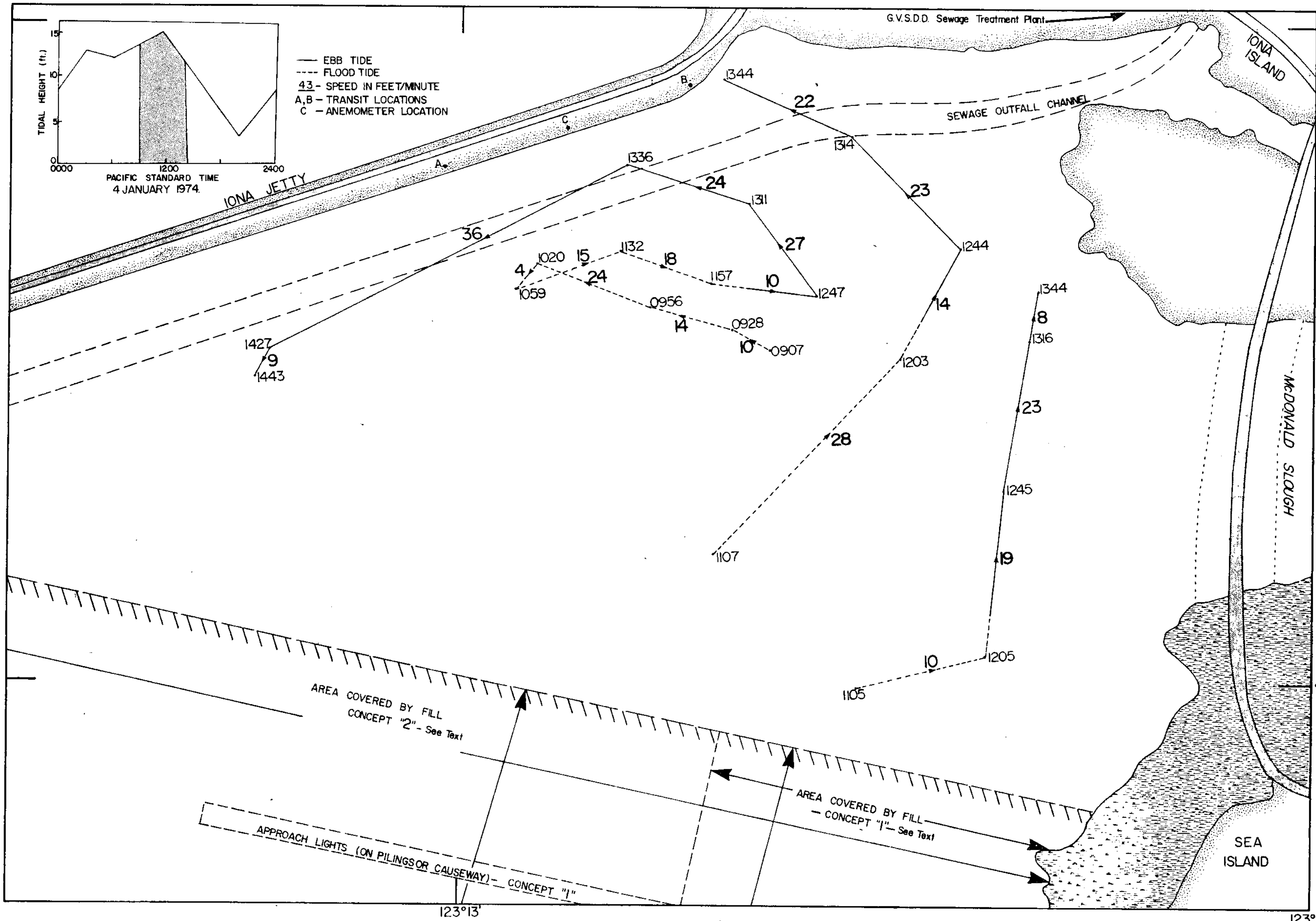
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
3 JANUARY 1974.
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
IONA JETTY
G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
SEWAGE OUTFALL CHANNEL
McDONALD SLOUGH
SEA ISLAND
AREA COVERED BY FILL CONCEPT "2" - See Text
AREA COVERED BY FILL - CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'

Figure 14(c)



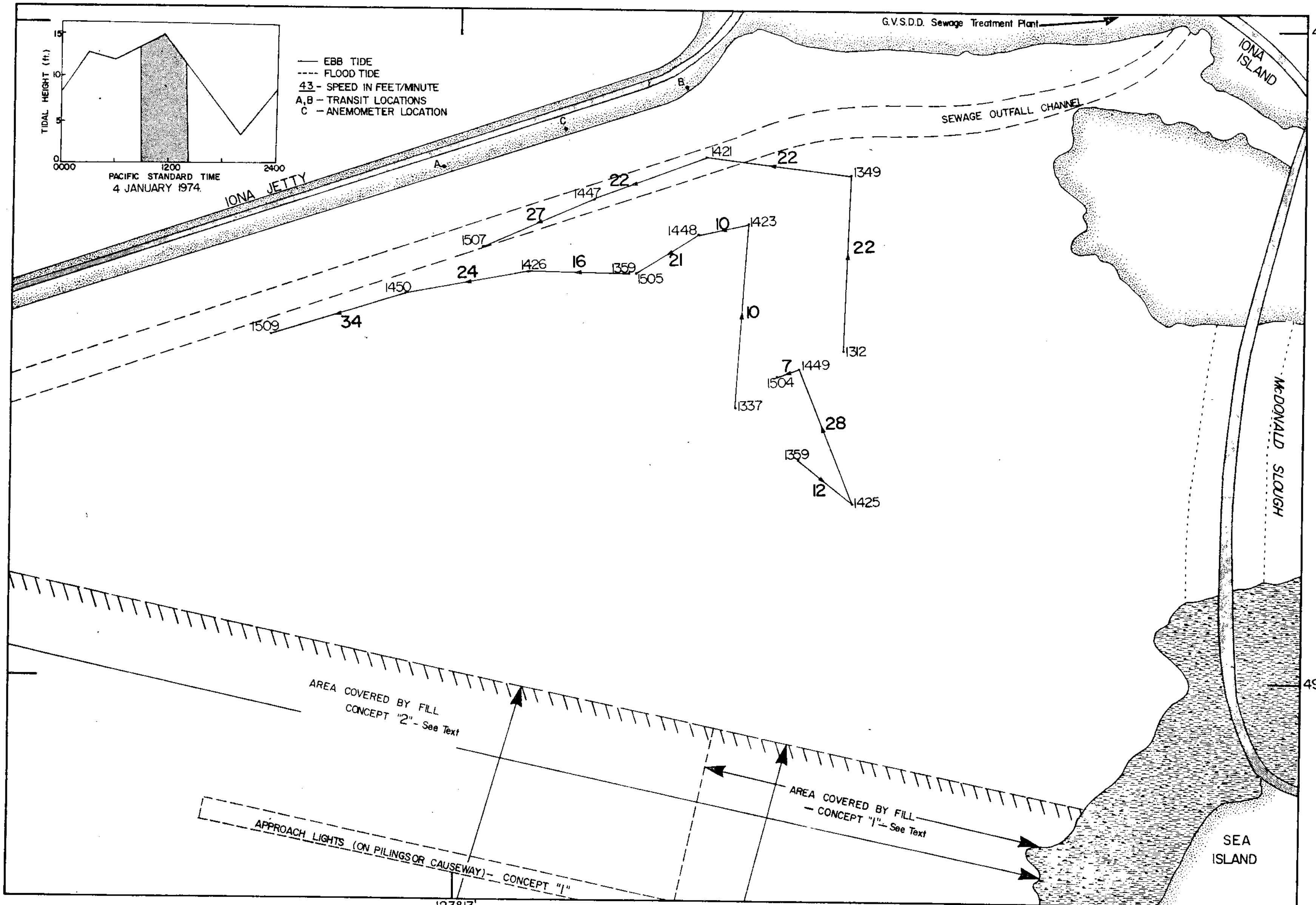
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
4 JANUARY 1974
IONA JETTY
G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
SEWAGE OUTFALL CHANNEL
McDONALD SLOUGH
SEA ISLAND
AREA COVERED BY FILL
CONCEPT "2" - See Text
AREA COVERED BY FILL
- CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'

Figure 15(a)



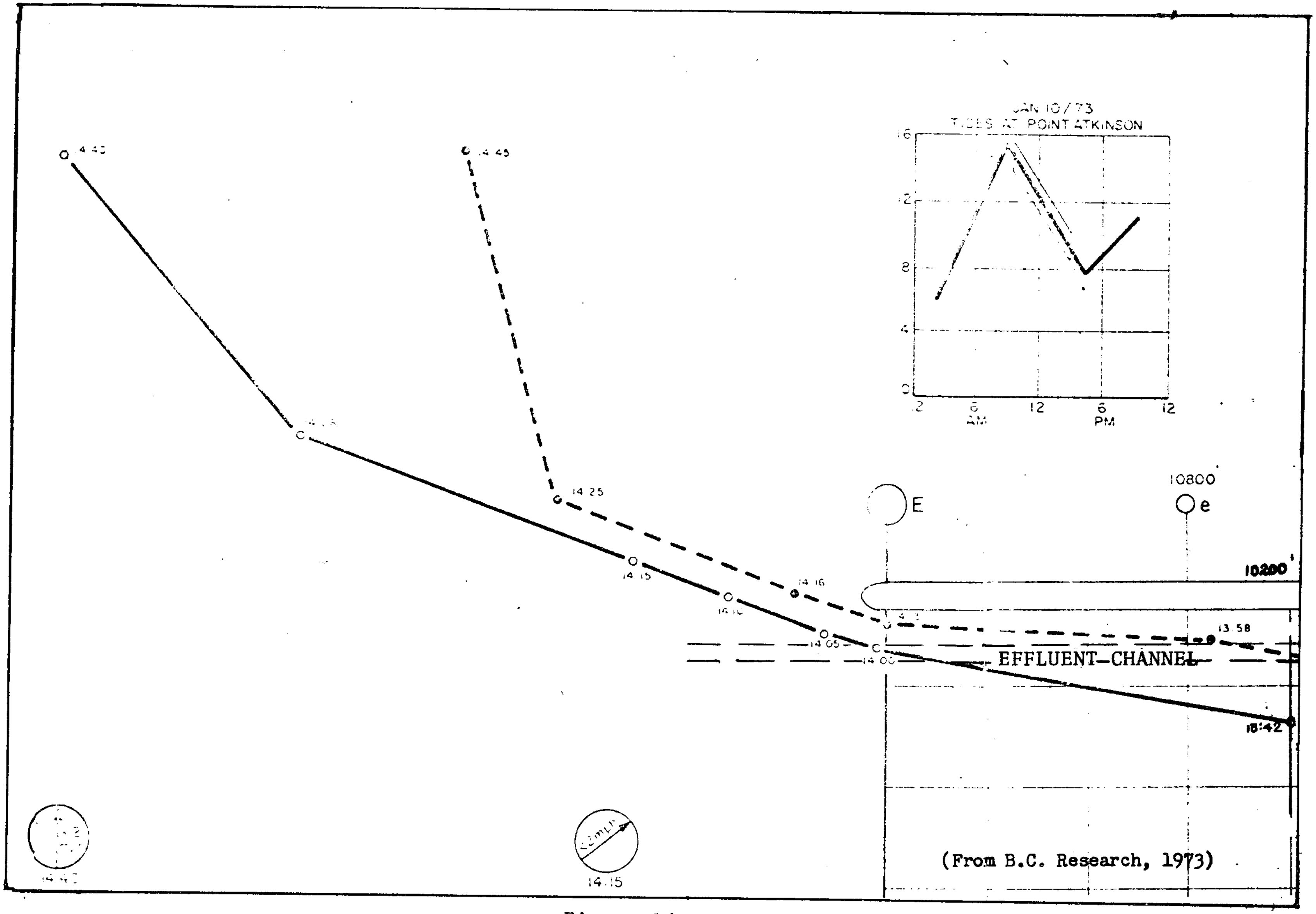
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
4 JANUARY 1974.
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
IONA JETTY
G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
SEWAGE OUTFALL CHANNEL
McDONALD SLOUGH
SEA ISLAND
AREA COVERED BY FILL CONCEPT "2" - See Text
AREA COVERED BY FILL - CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'

Figure 15(b)



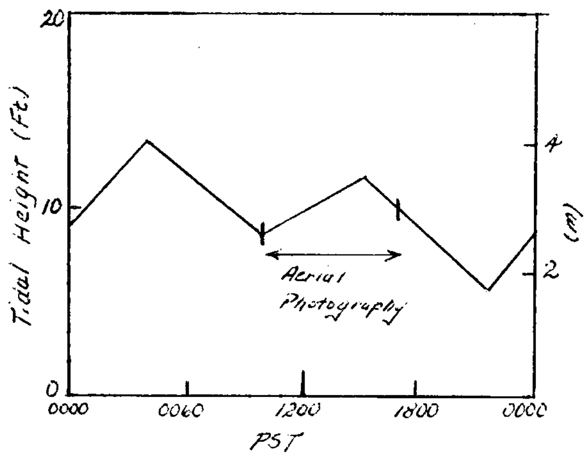
TIDAL HEIGHT (ft.)
PACIFIC STANDARD TIME
4 JANUARY 1974
EBB TIDE
FLOOD TIDE
43 - SPEED IN FEET/MINUTE
A,B - TRANSIT LOCATIONS
C - ANEMOMETER LOCATION
IONA JETTY
G.V.S.D.D. Sewage Treatment Plant
IONA ISLAND
SEWAGE OUTFALL CHANNEL
McDONALD SLOUGH
SEA ISLAND
AREA COVERED BY FILL CONCEPT "2" - See Text
AREA COVERED BY FILL - CONCEPT "1" - See Text
APPROACH LIGHTS (ON PILINGS OR CAUSEWAY) - CONCEPT "1"
49°13'
49°12.5'
123°13'
123°12'

Figure 15(c)



JAN 10/73
TIDES AT POINT ATKINSON
16
12
8
4
0
12
6
AM
12
6
PM
12
14:45
14:25
14:16
14:15
14:10
14:05
14:00
13:58
13:42
10800
E
e
10200
EFFLUENT–CHANNEL
14:15
(From B.C. Research, 1973)

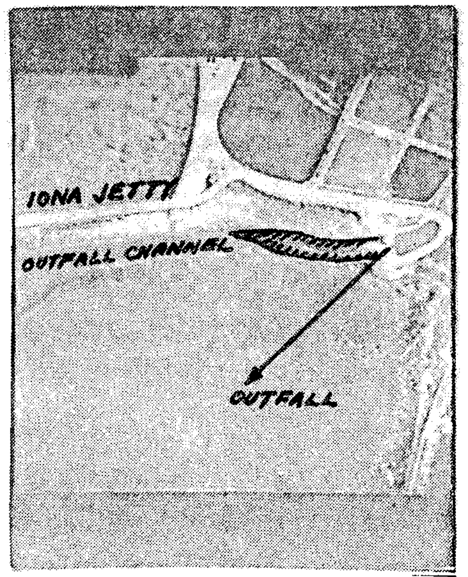
Figure 16



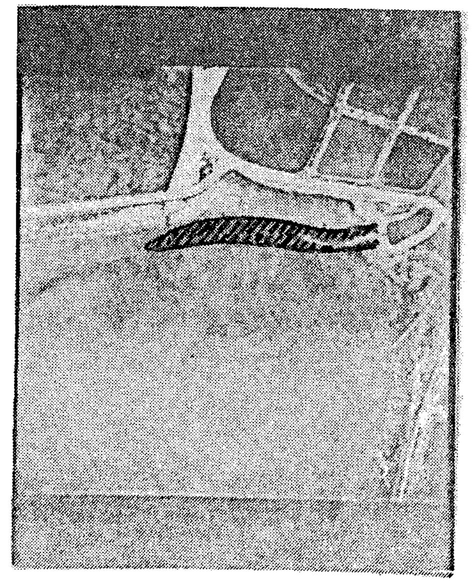
20 MARCH, 1974

POINT ATKINSON

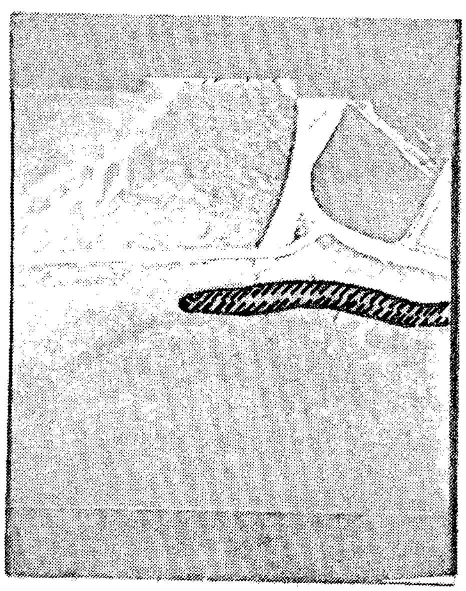
Figure 17

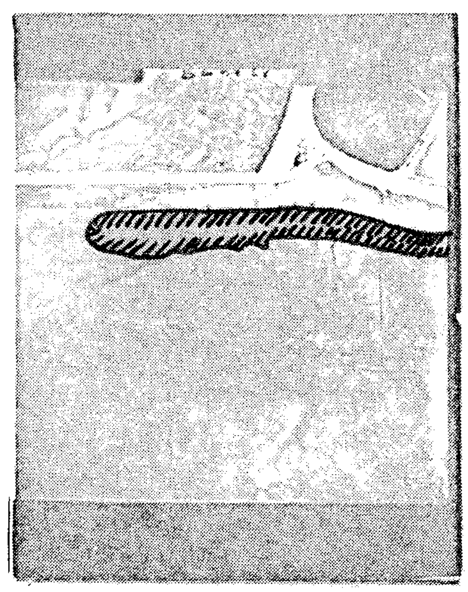


Frame 1 - 1015



Frame 2 - 1030





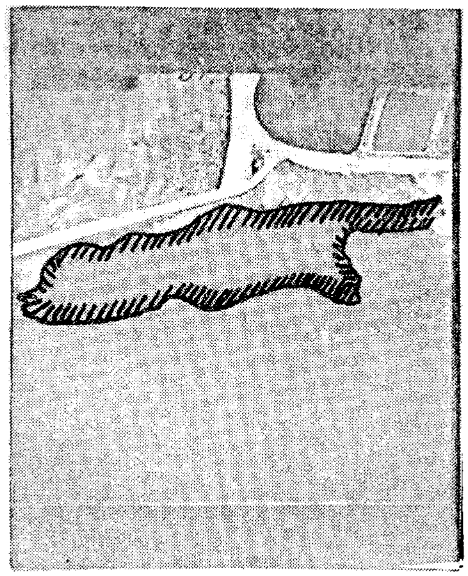
The Extent of the Dye Patch is indicated by:

Frame 3 - 1045

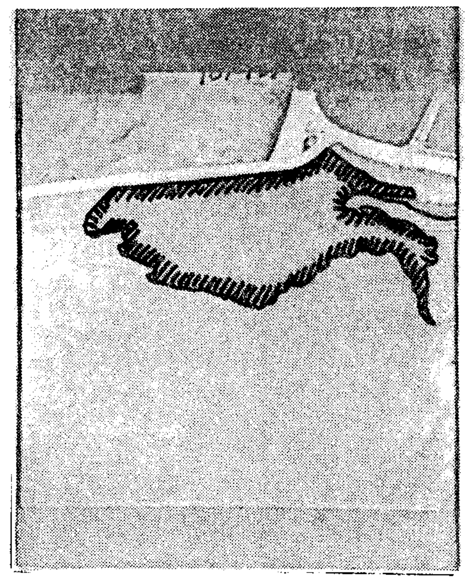
Frame 4 - 1115

20 March, 1974

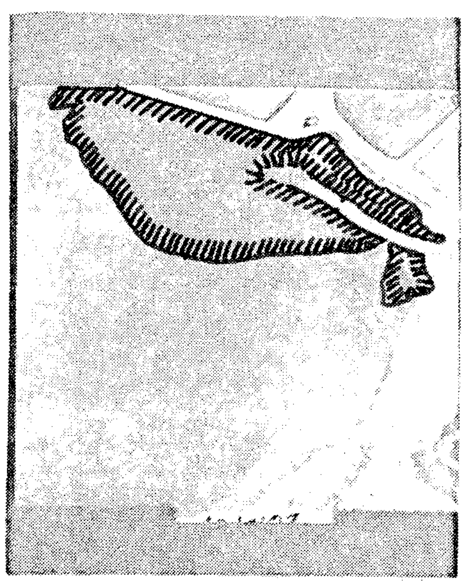
Figure 18(a)



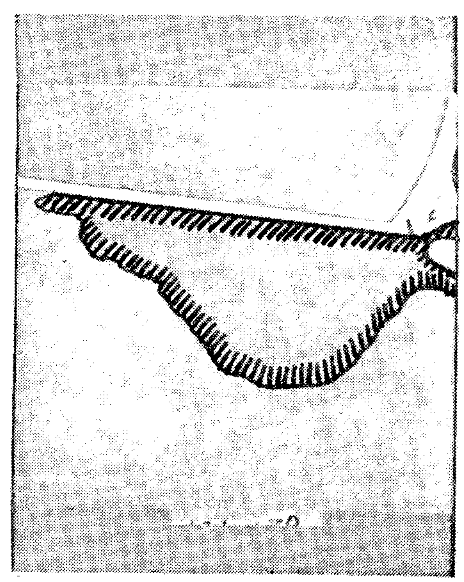
Frame 5 - 1215



Frame 6 - 1315



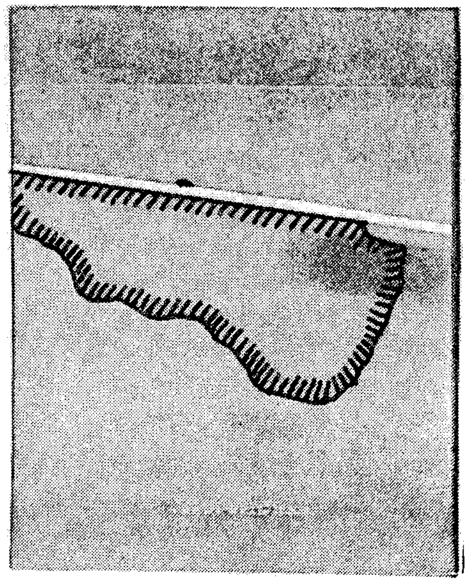
Frame 7 - 1415



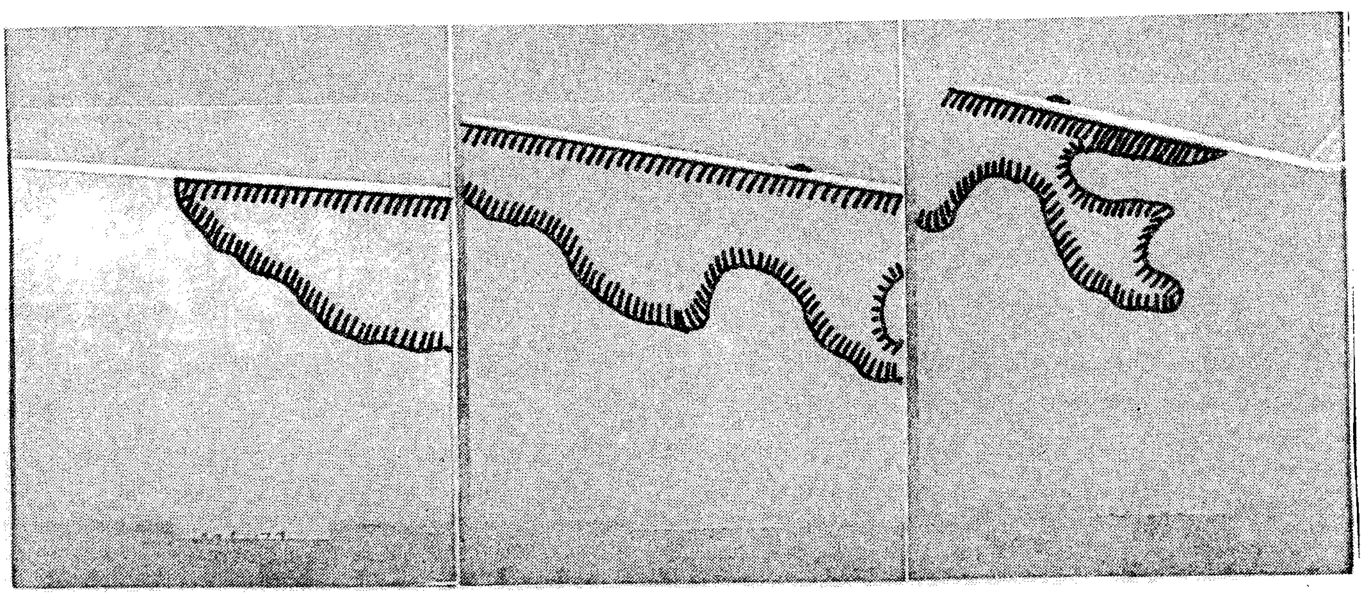
Frame 8 - 1515

20 March, 1974

Figure 18(b)



Frame 9 - 1615



Frame 10 - 1700 Frame 11 - 1700 Frame 12 - 1700

20 March, 1974

Figure 18(c)

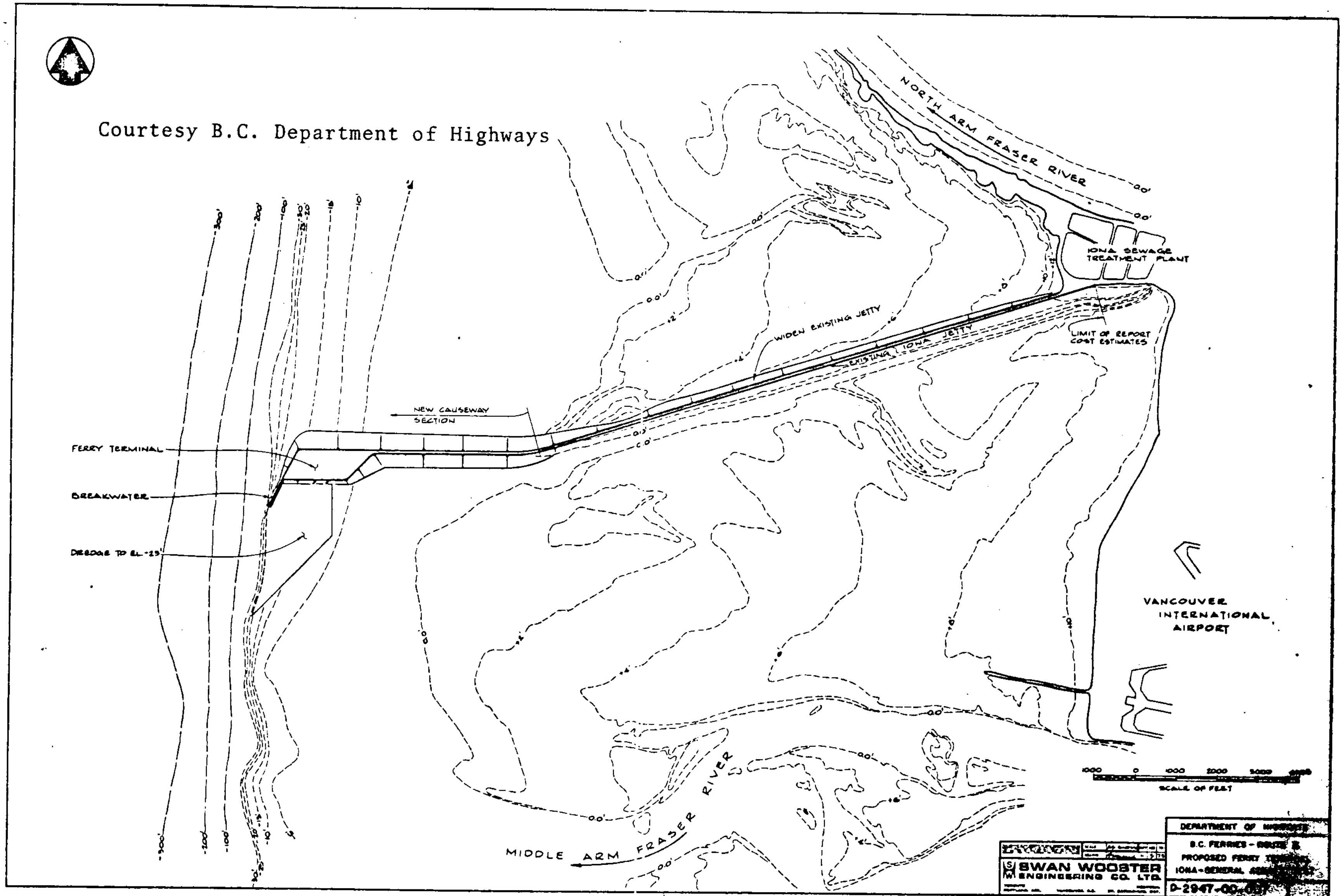

Courtesy B.C. Department of Highways
NORTH ARM FRASER RIVER
IONA SEWAGE TREATMENT PLANT
WIDEN EXISTING JETTY
EXISTING IONA JETTY
LIMIT OF REPORT COST ESTIMATES
NEW CAUSEWAY SECTION
FERRY TERMINAL
BREAKWATER
DREDGE TO EL-25'
VANCOUVER INTERNATIONAL AIRPORT
MIDDLE ARM FRASER RIVER
SCALE OF FEET
SWAN WOOSTER ENGINEERING CO. LTD.
PROPOSED FERRY TERMINAL

Figure 19

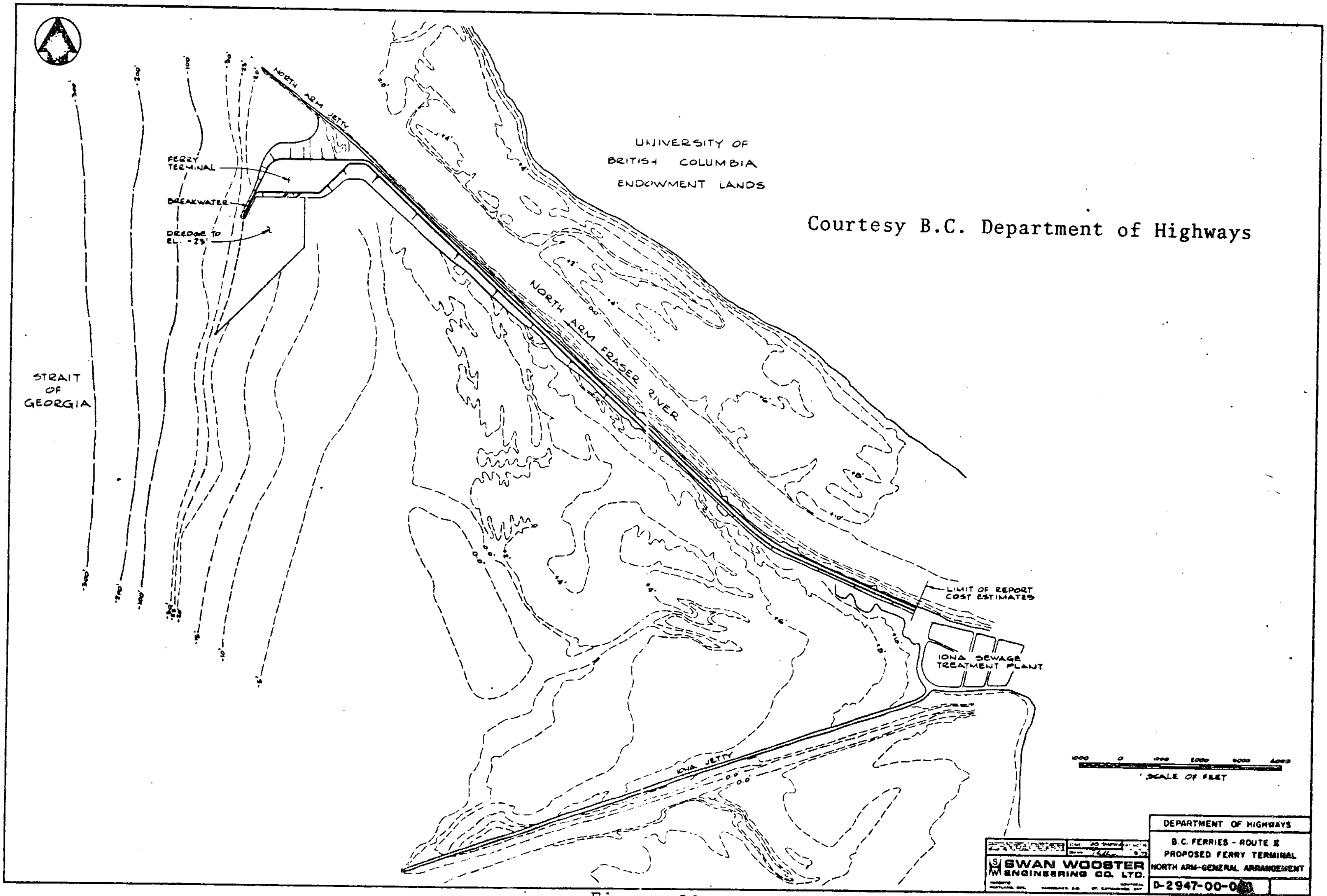

UNIVERSITY OF
BRITISH COLUMBIA
ENDOWMENT LANDS
Courtesy B.C. Department of Highways
NORTH ARM JETTY
FERRY TERMINAL
BREAKWATER
DREDGE TO EL. -25'
NORTH ARM FRASER RIVER
STRAIT OF GEORGIA
LIMIT OF REPORT COST ESTIMATES
IONA SEWAGE TREATMENT PLANT
IONA JETTY
SCALE OF FEET
DEPARTMENT OF HIGHWAYS
B.C. FERRIES - ROUTE II
PROPOSED FERRY TERMINAL
NORTH ARM-GENERAL ARRANGEMENT
SWAN WOOSTER
ENGINEERING CO. LTD.
D-2947-00-0

Figure 20