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OCEANOGRAPHY AND PREDICTION OF PULP MILL POLLUTION IN ALBERNI INLET

BY

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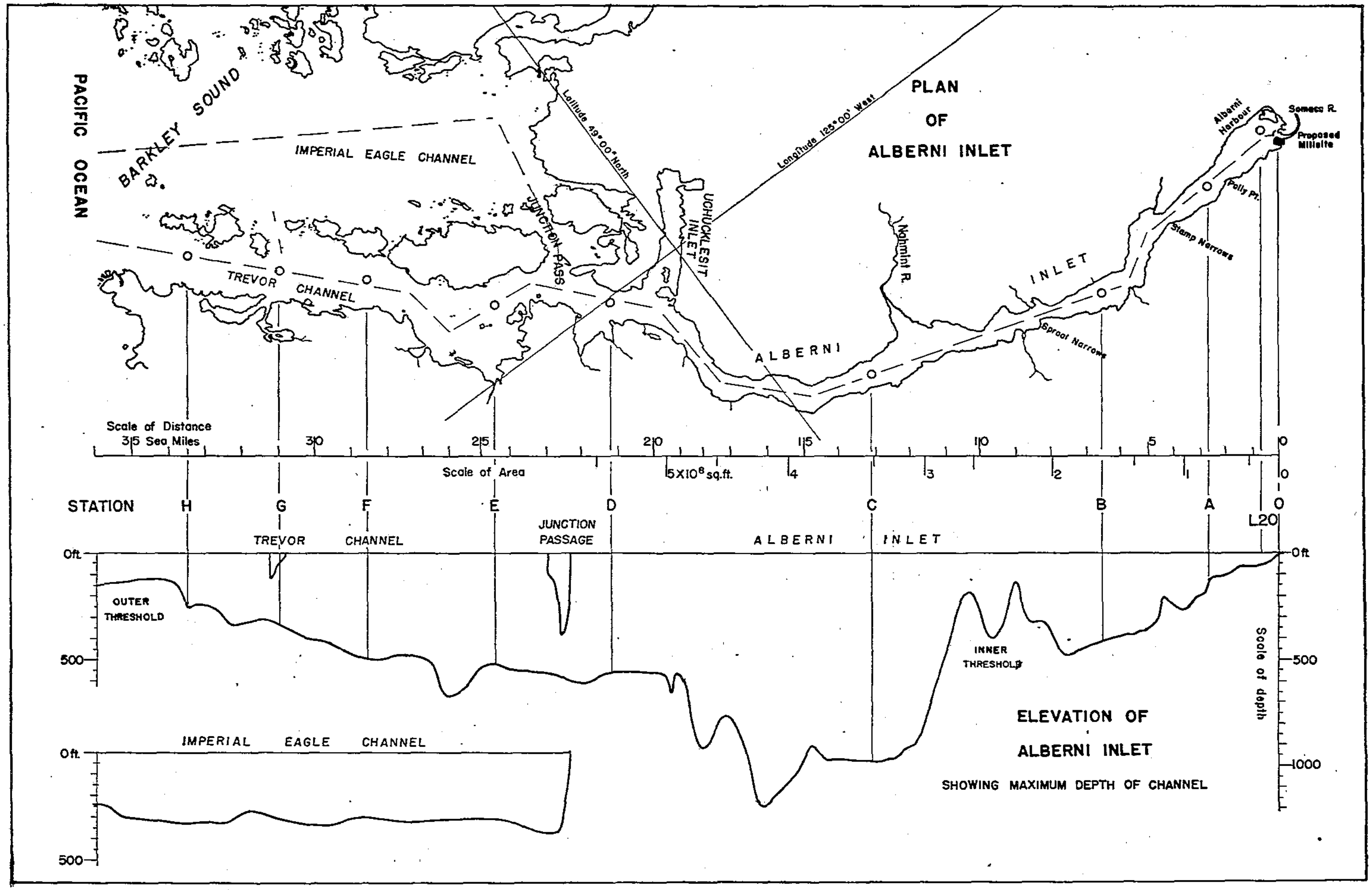
OCEANOGRAPHY AND PREDICTION OF PULP MILL POLLUTION IN ALBERNI INLET



PLAN
OF
ALBERNI INLET
PACIFIC OCEAN
BARKLEY SOUND
IMPERIAL EAGLE CHANNEL
TREVOR CHANNEL
JUNCTION PASS
UCHUCKLESIT INLET
Latitude 49°00' North
Longitude 125°00' West
Nahmint R.
ALBERNI INLET
Sproat Narrows
Stamp Narrows
Polly Pt.
Alberni Harbour
Somass R.
Proposed Millsite
Scale of Distance
35 Sea Miles
30
25
20
15
10
5
0
Scale of Area
5X10^8 sq.ft.
4
3
2
1
0
STATION
H
G
F
E
D
C
B
A
O
L20
TREVOR
CHANNEL
JUNCTION PASSAGE
ALBERNI INLET
0ft.
500
1000
OUTER THRESHOLD
INNER THRESHOLD
Scale of depth
ELEVATION OF
ALBERNI INLET
SHOWING MAXIMUM DEPTH OF CHANNEL
IMPERIAL EAGLE CHANNEL

FIGURE 1.

PART I. OCEANOGRAPHY

This is a quantitative study of the behaviour of fresh water in the sea, in the simple case of the two dimensional system afforded by Alberni inlet.

Generally the oceanographic state varies with time and location, and is usually assessed through tedious and costly surveys which only provide a description of the state after it has passed. However it is assumed that the state at a particular location is a recurrent function of the run-off, wind and tide, and may be related to these factors and eventually predicted, or at least recognized.

It was known from the characteristics of the proposed pulp mill that the sewage could be adjusted to enter the inlet at the same, or a lesser density, than the surface water. Oceanographically, the adjusted mill sewage could be regarded as a fresh water stream, entering at or near the Somass river mouth, and the behaviour of the effluent could be predicted from the existing function of the fresh water.

It is evident that the inlet contains only fresh water from land drainage, and sea water from the ocean. Therefore the fresh water may be regarded as a tracer solution, which may be detected by the degree of dilution of the sea water. The only data required are the geography, tidal function, run-off, wind and observations of the salinity at suitable positions and times, in relation to these factors. Temperature, dissolved oxygen, etc., may be regarded as properties of the mixing waters, or effects of extraneous functions, such as insolation.

It was necessary to determine the behaviour of the fresh water quantitatively, so that the behaviour of the mill effluent could be estimated. It was found that the mechanism in the lower reaches of the inlet was comparatively simple and could be deduced from mid-channel observations of the *chlorinity in situ*, and a few measurements of velocity. In the vicinity of the head, where a much more detailed study was required, it was necessary to amplify the simple chlorinity observations with a hydraulic model study and float experiments.

The Hydrographic and Map Service of Canada has issued Tide Tables (annual), and excellent charts of the area (1932) which satisfied most of the tidal and geographic requirements of this investigation. In addition a tidal station was established at the head of the inlet, and special surveys were undertaken when required. Land drainage data were obtained from records of the Dominion Water Power and Hydrometric Bureau (1947) for the Nahmint and Somass rivers. The Somass is formed by the confluence of the Sproat and Stamp rivers near the head of the inlet. Additional estimates of land drainage were deduced from precipitation into the drainage basin of the inlet, as observed by the Dominion Meteorological Service (Department of Agriculture, 1942).

Presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Washington.

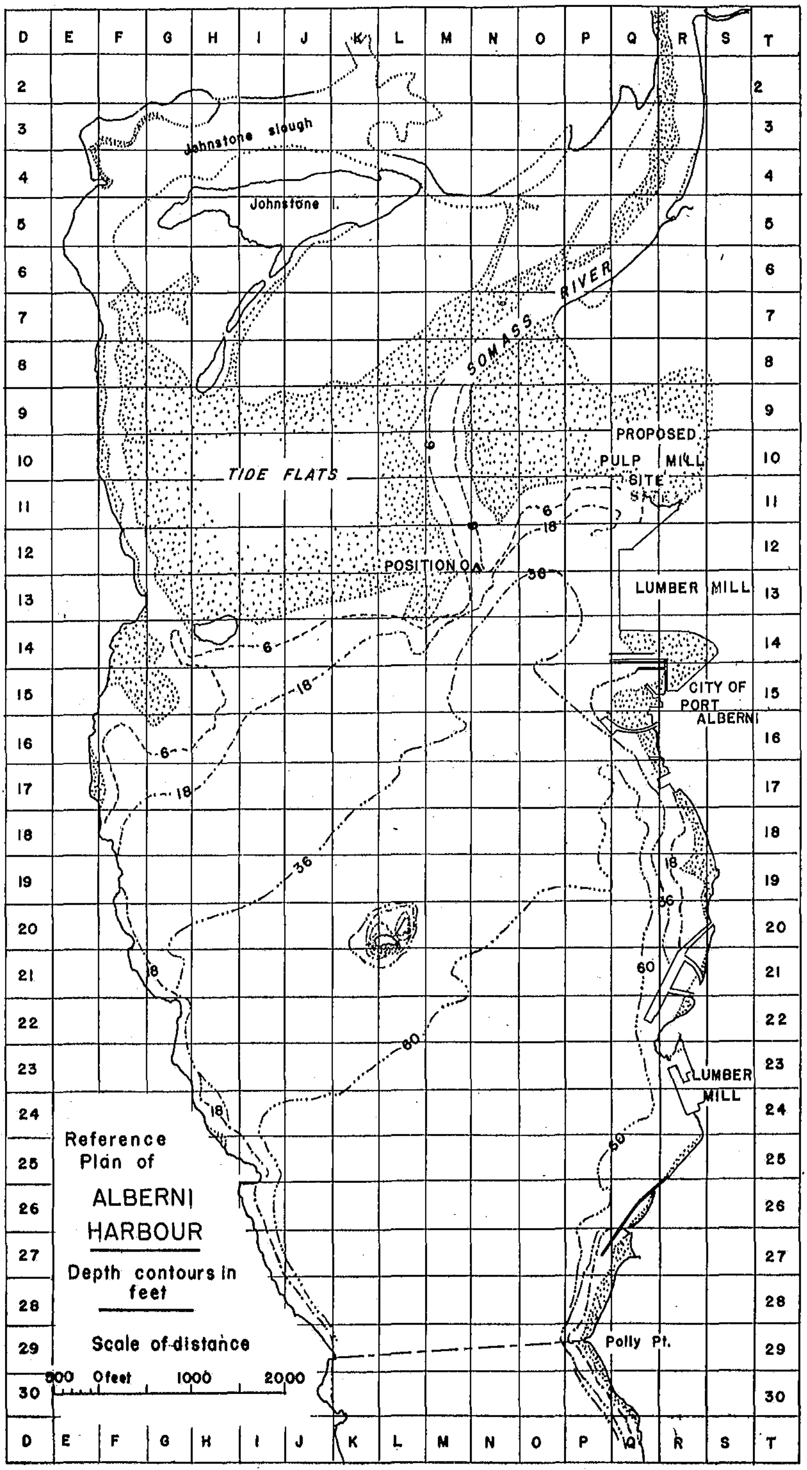

Johnstone slough
Johnstone I.
SOMASS RIVER
TIDE FLATS
PROPOSED PULP MILL SITE
POSITION A
LUMBER MILL
CITY OF PORT ALBERNI
LUMBER MILL
Polly Pt.
Reference Plan of
ALBERNI HARBOUR
Depth contours in feet
Scale of distance
500 0 feet 1000 2000

FIGURE 2.

The properties of the water were observed at suitably located stations and depths to determine their gradients. The methods of observation and the analyses are given in appendix I.

It was proposed to make a survey of the inlet and Alberni harbour in alternate fortnightly periods, but this did not prove feasible. Observations were made at stations L20, A, B, C and D (fig. 1) consecutively to seaward and return, during the six weeks of early summer. Surveys of Alberni harbour were continued through the summer until autumn.

A plan of the estuary region of Alberni harbour (fig. 2) is laid off in 500-foot squares to facilitate reference. It is assumed that any observation is representative of the conditions in its square (e.g. L20, etc.).

Series of hydrographic observations at a number of strategic positions in the area were made as near the time of high tide (or low tide) as possible, and repeated during the following period of low tide (or high tide). However, it was not possible to explore the area with less than 7 stations, and with the vessel available 4 to 5 hours was required for the series. Consequently it was not possible to record the state of the area at any instant, although it was possible to evaluate the average state.

The shores on both sides of Alberni harbour, and the whole of the tidal flats at the head, were occupied by log rafts, and the northwest quarter of the harbour was hazardous for navigation because of the large number of submerged piles. These conditions prevented complete observation of these boundary areas. In the remainder of the area, four complete, and two partial surveys were made. A large number of observations were made at the reference station L20, where an observing float was moored. In addition several series of observations were made to measure tidal variations and particular properties.

In general the data (app. II and III) are assumed to represent the conditions existing in the immediate neighbourhood of the observation, and to recur at the observed stage of the tidal cycle during continuance of the existing tidal range, and rate of run-off. These conditions are not fulfilled exactly, but the changes in these controlling factors are generally slow in comparison with the rate of establishment of isostatic equilibrium, and it may be assumed that the observations represent equilibrium conditions, within the implied limitations.

PHYSICAL OCEANOGRAPHY

Structure

Geography

Alberni inlet is a true fiord, typical of the British Columbia and Alaska coasts (Carter, 1933; Tully, 1937). The principal features are indicated in the outline chart, and mid-channel bottom profile in fig. 1.

From the head to Junction passage the sides are precipitous and rocky. The channel has two mouths. The inner one is Junction passage, which is about 380 feet deep; but circulation is limited by the threshold in Barkley sound at about 280 feet. The outer mouth is through Trevor channel where the threshold is about 120 feet deep and there is also an inner threshold towards the head 138 feet in depth.

The rivers flowing into the inlet are small, the largest being the Somass at the head, and the Nahmint midway down the inlet. Their discharge characteristics are shown in table I.

TABLE I. Discharge limits of the major rivers of Alberni inlet (Somass river is the sum of the discharge of the Stamp and Sproat rivers).

Discharge (cubic feet per second)			
	Average	Maximum	Minimum
Somass..........	3,910	38,400	153
Nahmint.........	739	8,760	33

CHLORINITY

The original data are on file at the Pacific Biological Station, Nanaimo, B.C., and can be obtained on application to the Director.

Fig. 3 illustrates the chlorinity distribution in a typical plan and longitudinal elevation of the inlet, which shows that the waters are vertically and longitudinally stratified. These gradients are similar to the density gradients, and in general the structure recurs on corresponding phases of similar tide cycles while run-off and wind are constant.

Near the head of the inlet (fig. 3 (c)) the characteristic transverse salinity gradient of an estuary permits the stream of river water to be followed. This gradient disappears when the stream comes to occupy the whole width of the channel at the limit of the harbour. By this means the *estuary* is distinguished from the *inlet*. The *mouth* is regarded as the region in the vicinity of Junction passage where Barkley sound water intrudes during the flooding tide.

In the elevation it is possible to recognize a *surface zone*, whose lower boundary is marked by an inflexion in the chlorinity gradient; a *middle zone* between this boundary and the depth of the threshold, where the water is continuous with that in the adjacent sea; and a *deep zone* below the depth of the threshold, where the chlorinity is different from that in the adjacent sea at corresponding depths.

The vertical gradient marks the stability of the system, and degenerates from a discontinuity at the boundary of the upper and middle zones near the head, to an inflected gradient in the lower reaches of the inlet. The longitudinal gradient resulting from this degeneration, represents the dynamic equilibrium between the isostatic forces accelerating movement towards the mouth of the inlet, and the frictional and tidal forces opposing the movement. Evidently the stability expressed in the boundary gradient is everywhere greater than the isostatic forces expressed in the longitudinal gradient.

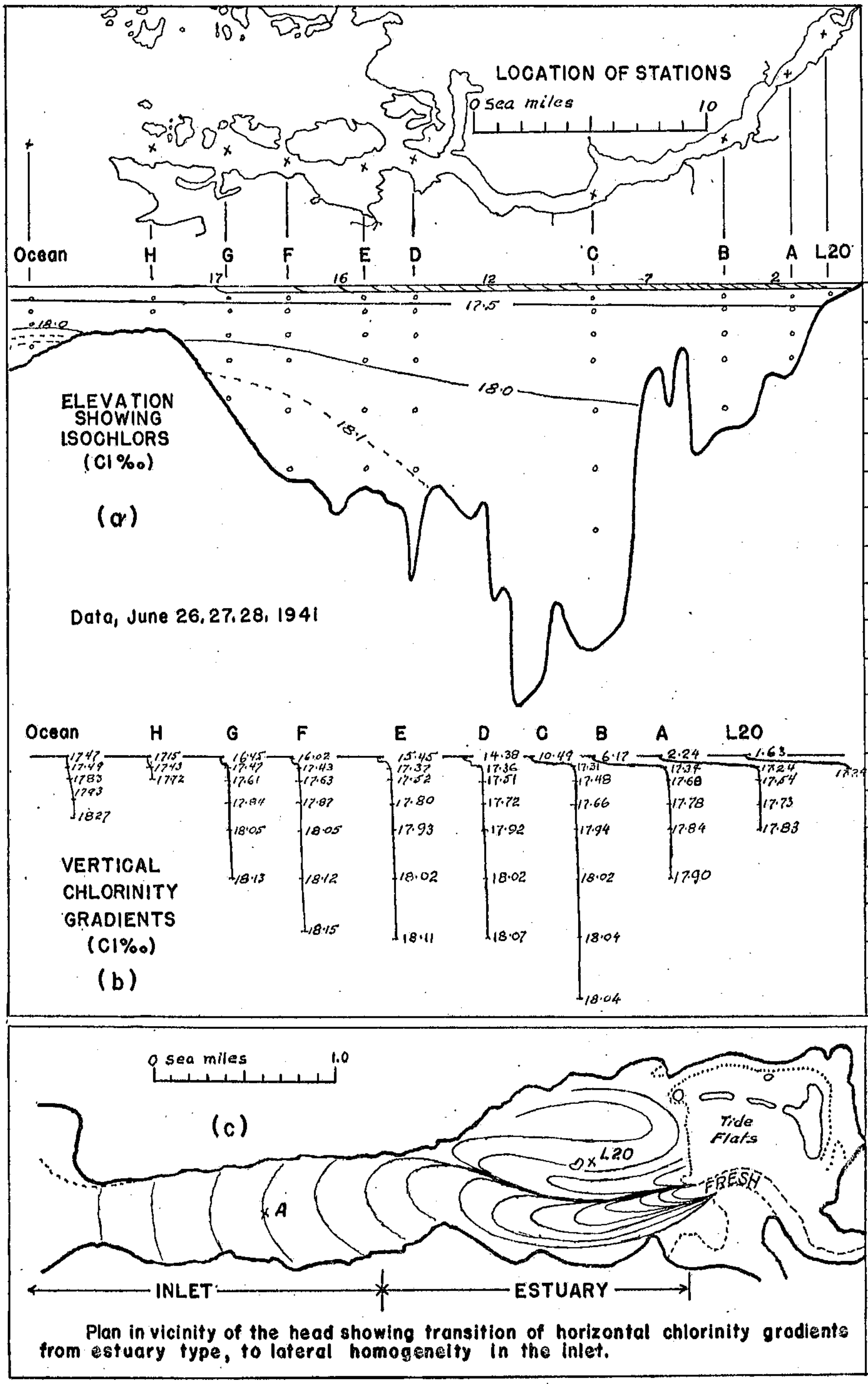


FIGURE 3. Chlorinity of Alberni inlet.

Mechanism of the Upper and Middle Zones

Wind effects may be neglected in the preliminary discussions of mechanism since they are small compared to tide and run-off.

The fresh water that continuously enters the inlet from land drainage mixes with the underlying sea water and forms a brackish *upper zone*, subject to displacement and reversing tidal motion.

Between this layer and the threshold, which acts as a weir, sea water may enter and leave the inlet on the tidal cycle, forming the *middle zone* of circulatory sea water which evidently exchanges water with the upper zone.

Below the level of the threshold, the *deep zone* of sea water is subject only to the frictional transfer of velocity from the middle zone, with which there is evidently a slow exchange of water.

Evidently three mechanisms are involved in the circulatory zones: the seaward movement of fresh water in the upper zone due to its isostatic head, the reciprocal movement in the upper and middle zone due to the hydraulic head of the tide, and the mixing of the two waters.

MIXING

The progressive mixing within and between the upper and middle zone waters (figs. 3 and 4) must be the result of some degree of turbulence. Turbulent flow is usually exemplified in nature by a large number of more or less coherent eddies having random compensatory motion within the fluid. This motion is opposed by friction between the elements (eddy viscosity), resulting in an exchange of fluid between the eddies and their surroundings (mixing).

In a stratified medium, any horizontal movement of the fluid elements inside one stratum is opposed by viscosity alone, but any movement of the elements from one stratum to another is also opposed by isostatic forces which tend to return the element to its own level. From this it would be expected that a stratified flow system would become more homogeneous downstream, and that lateral homogeneity would be more readily attained than vertical homogeneity. This reasoning is confirmed by the observations shown in fig. 3, where it is indicated that lateral homogeneity is attained within a few miles of the head, while vertical homogeneity, even within a single zone is not attained within the length of the inlet.

RUN-OFF

It is reasoned from the principle of isostacy[1] that when fresh water is being supplied continually in one part of the system (at the head) and sea water is supplied in another (adjacent sea) there will be a constant isostatic head inducing a surface seaward flow.

[1]*Isostacy:* The principle of isostacy may be defined as the tendency of a fluid medium to assume the position and structure having the least potential energy. In consequence, the strata in a resting fluid must lie horizontally (normal to the direction of gravity). If the strata are displaced from the horizontal, a difference of potential energy between adjacent points exists, which is termed the "isostatic head", and from which a flow results to compensate the displacement.

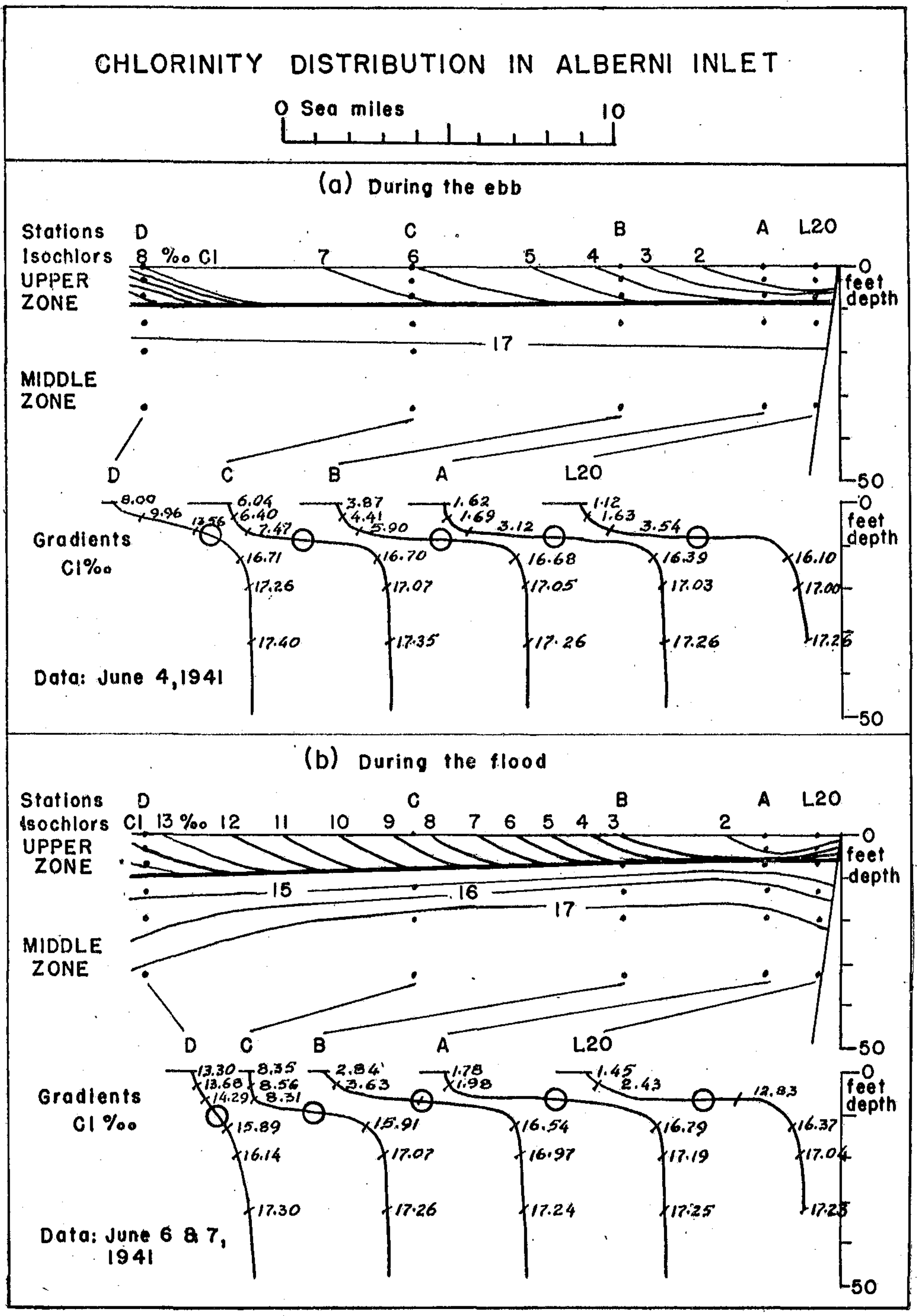

CHLORINITY DISTRIBUTION IN ALBERNI INLET
0 Sea miles 10
(a) During the ebb
Stations D C B A L20
Isochlors 8 ‰ Cl 7 6 5 4 3 2
UPPER ZONE
MIDDLE ZONE
17
0 feet depth 50
D C B A L20
Gradients Cl‰
Data: June 4, 1941
(b) During the flood
Stations D C B A L20
Isochlors Cl 13 ‰ 12 11 10 9 8 7 6 5 4 3 2
UPPER ZONE
MIDDLE ZONE
15
16
17
0 feet depth 50
D C B A L20
Gradients Cl ‰
Data: June 6 & 7, 1941

FIGURE 4.

It is remarked that both the upper and middle zones become more saline to seaward, from which it is reasoned that all the fresh, and at least some of the sea water leaves the inlet through the upper zone, but very little, if any, fresh water leaves through the middle zone. This requires some explanation, since in any process of mixing, the volume of fresh water transferred downward must equal the volume of sea water transferred upward, else the medium would become discontinuous.

In the case of fresh water flowing over a sea water zone, where both move in the same direction but with different velocities, the exchanged water would be carried forward in both zones, which would tend to become more homogeneous downstream. This process is readily observed in passes and narrows, but does not occur in this inlet.

If the sea water (middle) zone is at rest, or moving contrary to the upper zone, both layers will become more dense to seaward. Sea water transferred upward is carried forward to be exchanged again for more dense sea water downstream. Surface water transferred downward will remain at rest, or be carried toward the head of the inlet adjacent to the boundary, and be preferentially subject to further mixing. Also any fresh water accumulating in the middle zone would be isostatically unstable and would tend to join with the upper zone, and a compensatory in-flow of sea water in the middle zone would result.

This is the process occurring in the inlet, where the persistent, accelerating transport in the upper zone, and compensatory movement in the middle zone have been observed. Evidently the fresh water transferred downward is carried toward the head in the middle zone, and returned to the upper zone at an equal rate. The slight longitudinal chlorinity gradient towards the head in the middle zone (fig. 4) probably represents this transfer, in isostatic equilibrium with inflowing sea water.

It may be concluded from this discussion that all fresh water leaves the inlet through the upper zone, and that any accumulation in the middle zone is slight and transitory. Further, the transfer of fresh water through the upper zone must be continuous and the rate equal to the run-off, otherwise the chlorinity gradients (fig. 4) would change with time.

TIDE

During the ebbing tide, sea level falls and the tendency for water to leave the inlet due to the hydraulic head is the same at all levels between the surface and the threshold, but is accelerated in the upper zone by the isostatic flow.

At "low tide" the tidal forces vanish, and the only flow is the seaward transport in the upper zone. As the tide rises the sea water enters the middle zone, since its density is greater than the upper zone, and creates a flood current, which increases with the rate of tidal rise. The slack water associated with low tide occurs when the opposing velocities are equal. Then the upper zone retreats into the inlet, becoming thicker, and fresh water accumulates, all of which increases the isostatic forces until they equal the hydraulic forces of the tide.

This situation is illustrated in the flood tide diagram of fig. 4 where it is shown that the thickness of the upper zone has increased, and the very stable "lower boundary" has become an "end-boundary" at the mouth of the inlet, expressing the equilibrium between the isostatic and tidal forces at this point. This idea can be carried further; the increasing chlorinity gradient to seaward is a series of end-boundaries representing the balance of isostatic and kinetic forces at every point in the inlet.

Eventually the isostatic and tidal forces again attain equality owing to the increase of the former, or to the decrease of the latter, and a second period of slack water associated with high tide occurs. Thereafter the surface ebb movement is resumed, while the flood movement in the middle zone decreases to zero at high tide.

The sea water entering the middle zone during the flood less the run-off, is the volume required to make up the rise. The ebb from both zones consists of the volume required by the fall of the tide, plus the land drainage during this phase.

Then during the steady state the fresh water transferred seaward through any cross-section of the inlet, during a tide cycle, is equal to the run-off above the section, and equal volumes of sea water flood and ebb through the section in a cycle. If these consequences did not obtain, fresh water would accumulate over a series of tidal cycles and the inlet would eventually become fresh; or the upper zone would vanish, if the fresh water were removed faster than it was supplied; or mean sea level would change. Obviously the fact that the fresh and sea waters become considerably mixed in this process, has no effect on the quantities transferred.

It is indicated in the preceding arguments that sea water enters the inlet in the middle zone; during the flood some of it is transferred to the upper zone in the inlet; and sea water escapes from both zones during the ebb tide. It follows that, aside from the fresh water present, the movement of the sea water in the upper zone is predominantly in the ebb direction, while that in the middle zone is predominantly flood, in compensation for the sea water transferred upwards.

Evidently the upper zone is subject to two acceleration forces: the isostatic displacement of fresh water which is constant throughout the length of the inlet, and the transfer of sea water from the middle zone. The latter accumulates in the upper zone as the water progresses seaward, consequently the velocity in the upper zone increases to seaward in direct proportion to the increase of sea water content, and inversely as the cross-section area of the upper zone. This phenomenon is readily observed in any inlet or harbour.

It is immediately evident that energy is required to transfer sea water from the middle zone to the less dense upper zone, and is accomplished by a mechanism of turbulence, which is necessarily a function of velocity. Consequently the energy is not supplied by the isostatic forces, for if it were, the rate of transport would decrease, fresh water would accumulate indefinitely, and the inlet

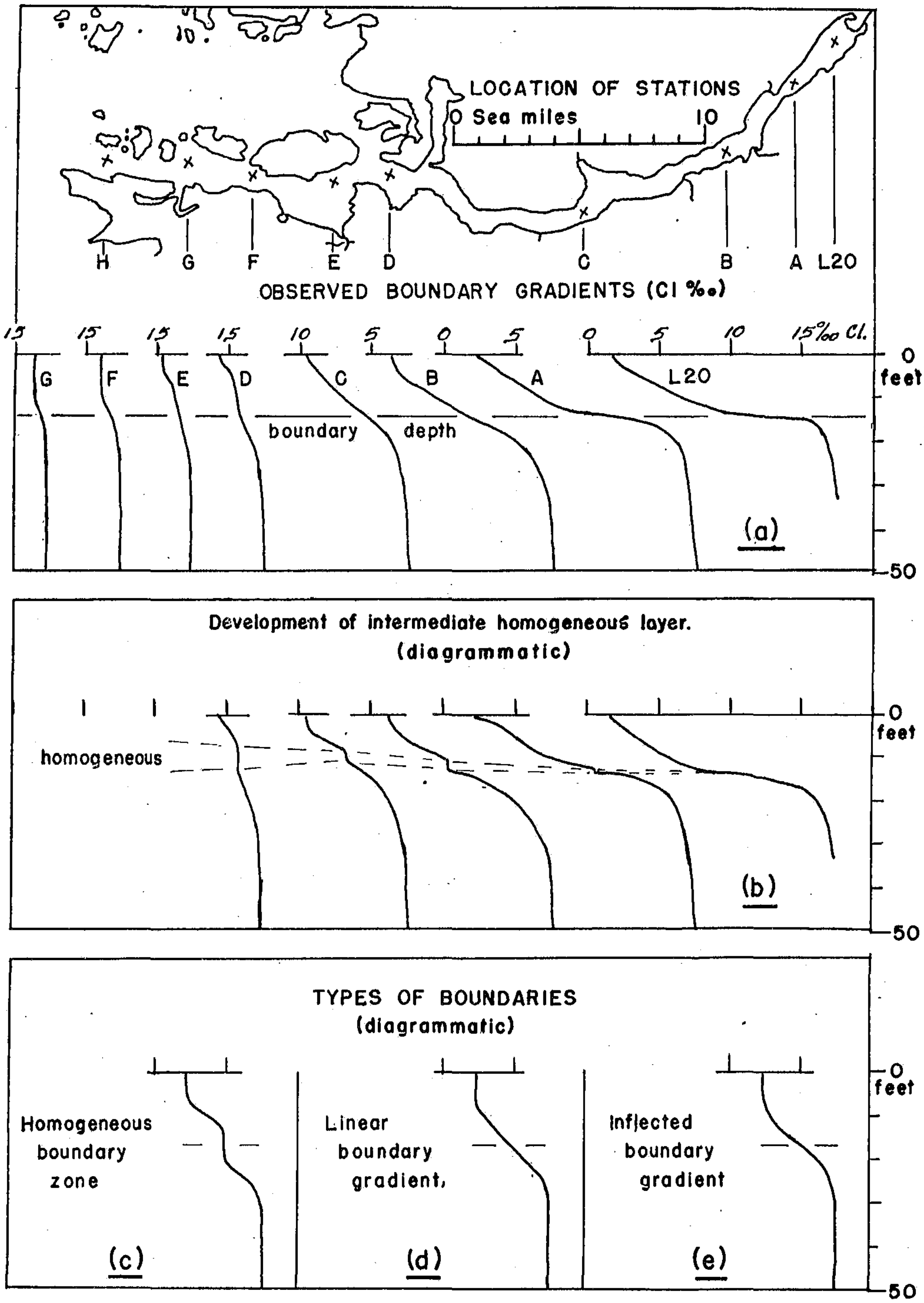


FIGURE 5. Chlorinity gradients in the upper and middle zones of Alberni inlet.

would become fresh. Consequently it must be provided by the tide, at the expense of the rise and fall of sea level in the inlet.

INTERZONE BOUNDARY

A representative series of observed chlorinity-depth gradients are shown in fig. 5(a) where it may be noted that discontinuity marks not only the boundary between the fresh and sea water at the head of the inlet, but also the boundary between upper and middle zone current systems, since the two are distinct at this point. Therefore it is the level of maximum turbulence, since the velocity gradient at the current boundary must be a maximum. Also it is the level of maximum stability, since the density gradient in either zone is less than at this boundary. It is noted that this boundary degenerates into an inflected gradient, which decreases downstream. This decrease of stability must be a measure of the rate of mixing between, and within the zones.

Regardless of the behaviour of the velocity gradient, it is evident that the inflexion in the chlorinity gradient must continue to mark the boundary between the mixed and sea water, from the head to the mouth of the inlet. If the boundary between the upper and middle zone current systems were to depart from the boundary between the two masses, it would be expected that a homogeneous zone would be created above (or below) the primary mass boundary, because of the lesser stability, and would be intermediate in density between this boundary and the surface (or deep water). This is illustrated in the series of gradients in fig. 5(b). From comparison with the observed data shown in fig 5(a) it is evident that no such phenomenon occurs, and it must be concluded that the primary mass boundary remains as the boundary between the upper and middle zone transport systems.

The form of the inflexion describes the relative efficiency of mixing in each of the zones as a function of distance from the boundary. From the fact that water is transferred both up and down across the boundary, and then to the remoter parts of the two zones, it follows that, if the transfer across the boundary were more rapid than its subsequent removal, mixed water would accumulate, and a homogeneous boundary zone would be created as indicated in fig. 5(c). If the rate of transfer from the boundary *equalled* the rate of transfer across the boundary, a linear gradient between the extremes of mixing would be formed as shown in fig. 5(d). Finally, if the transfer from the boundary *exceeded* the transfer across the boundary, the salinity gradient would be expected to decrease with distance from the boundary, which would consequently be marked by a point of inflexion, as shown in fig. 5(e).

From a comparison of the observed data in fig. 5(a) with the diagrammatic type boundaries shown in fig. 5(c), (d) and (e), it is evident that stability decreases more rapidly with distance from the boundary than the degree of turbulence (efficiency of mixing). Towards the mouth of the inlet, the boundary gradient is reduced while the gradient in the remoter parts of the zone is (if anything) slightly increased. Consequently the transfer across the boundary has increased

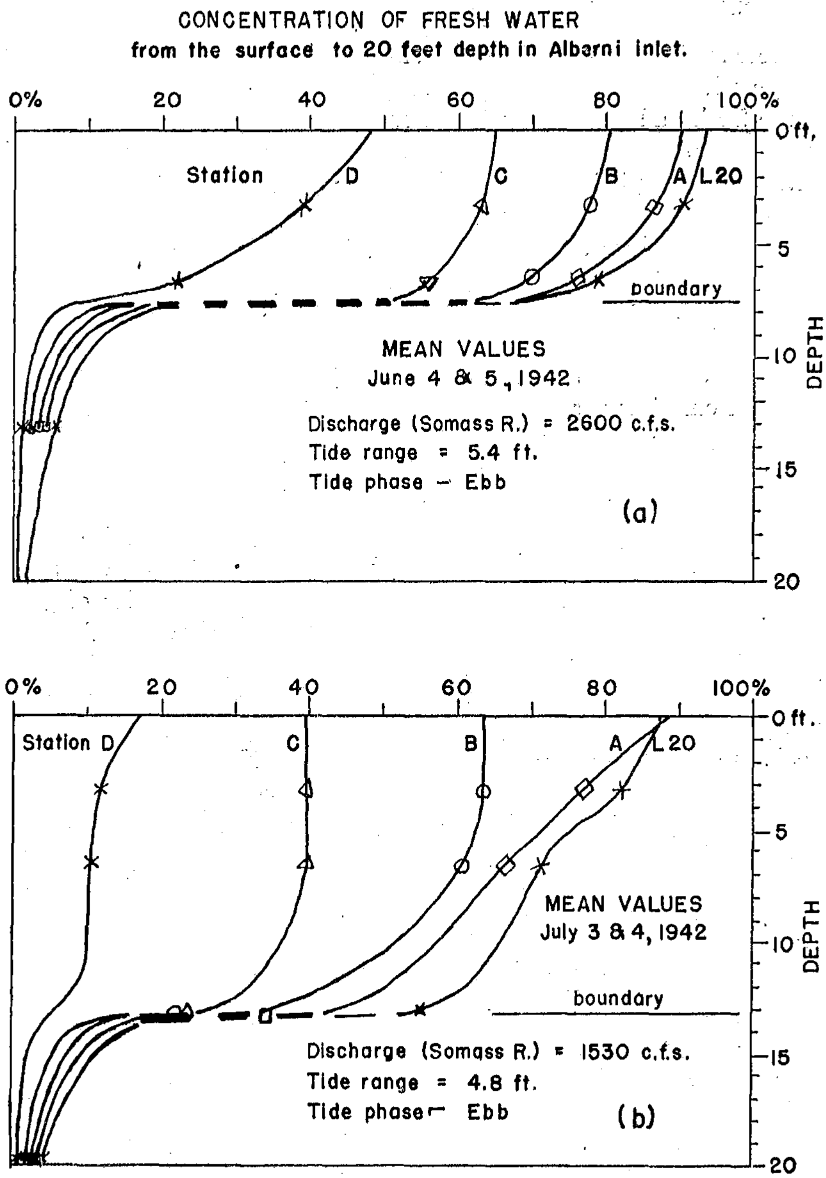

CONCENTRATION OF FRESH WATER
from the surface to 20 feet depth in Alberni Inlet.
0%
20
40
60
80
100%
0 ft.
5
10
15
20
DEPTH
Station
D
C
B
A
L20
boundary
MEAN VALUES
June 4 & 5, 1942
Discharge (Somass R.) = 2600 c.f.s.
Tide range = 5.4 ft.
Tide phase — Ebb
(a)
Station D
MEAN VALUES
July 3 & 4, 1942
Discharge (Somass R.) = 1530 c.f.s.
Tide range = 4.8 ft.
Tide phase — Ebb
(b)

FIGURE 6.

in relation to the transfer away from the boundary, and in the middle reaches of the inlet the gradient approaches the second type (linear gradient). On some occasions (not illustrated) the formation of the small intermediate homogeneous layer has been observed, indicating that the interchange across the boundary exceeds the transfer away from this zone.

The nature of the inflexion at the interzone boundary was deduced to be of the form shown in fig. 6, from the only two complementary series of data observed during the ebb tide. The plotted points represent the mean values of successive observations, and the slope of the curves was sketched to correspond to the differences in these values.

The stations L20 to D were occupied while proceeding seaward during the first day, and while returning the second day, so that station D represents the state near high tide in the first instance and near low tide in the second, and the other stations represent similar converse states. From the observations made it is inferred that the mean values represent the mean state, insofar as the gradients are linear in the vicinity of each point.

Since the thickness of the upper zone would be somewhat different at different stages of the tide, the successive observations at each depth were taken at different positions with respect to the interzone boundary. From this it may be inferred that, if the gradient is small, the difference between successive observations must be small, and if the gradient is large, the differences must be large.

This reasoning is exemplified in table II showing the chlorinity data observed on July 3 and 4, with the successive differences at each depth. Considering the three control stations A, B and C (fig. 1), it is at once evident that the gradient must increase to a maximum in the vicinity of 13 feet, and decrease towards 20 feet in depth. In view of the relative values it was assumed to approach infinity at the point of inflexion. By comparison with similar treatment of other data (June 4 and 5, etc.) where the maximum differences were less, it was concluded that the points of inflexion were at, or very near, the observed depth (13 $\pm$ 1 foot).

Evidently the boundary gradient cannot be less sharply defined at station L20, than at stations A, B, C, etc., since it is closest to the river mouth where the boundary originates. The apparently anomalous constancy of the successive observations results from the oscillation of the interzone boundary about a nodal line in the estuary, which passes through station L20. This phenomenon will be discussed later.

The presence of the maximum chlorinity difference at 3.3 and 6.5 feet in depth at station D follows from the deformation of the zonal boundary near the mouth of the channel at high tide, as explained below.

This reasoning regarding the nature of the gradient in the neighbourhood of the zonal boundary has recently been confirmed by bathythermograph observations of corresponding temperature gradients in several inlets on the British Columbia coast. Therefore, this interpretation is presented with confidence.

TABLE II. Chlorinity data in Alberni inlet, observed on successive days, in converse order, from high to low tide.

Depth (feet)	Station L20			Station C		
	July 3	July 4	Diff.	July 3	July 4	Diff.
	Chlorinity (Cl. °/oo)			Chlorinity (Cl. °/oo)		
0.0	1.15	2.65	1.50	10.53	9.78	0.75
3.3	4.34	3.60	0.74	10.53	10.73	0.20
6.5	5.86	5.78	0.08	10.53	11.11	0.58
13.1	11.30	11.37	0.07	12.40	13.51	1.11
19.7	16.86	16.76	0.10	17.12	16.86	0.26
32.8	17.41	17.32	0.09	17.46	17.48	0.02
	Station A			Station D		
0.0	1.90	2.19	0.29	14.42	13.78	0.64
3.3	3.05	3.00	0.05	15.34	13.81	1.53
6.5	5.04	4.97	0.07	15.64	14.35	1.29
13.1	8.44	6.96	1.48	16.53	15.90	0.63
19.7	16.76	16.51	0.25	17.19	16.95	0.24
32.8	17.35	17.26	0.07	17.53	17.46	0.07
	Station B					
0.0	6.59	6.05	0.54			
3.3	6.61	6.08	0.53			
6.5	7.30	6.49	0.81			
13.1	10.38	14.59	4.21			
19.7	16.95	17.08	0.13			
32.8	17.43	17.41	0.02			

It may be noted in figs. 4 and 5(a) that the inflexion in the chlorinity gradient is continuous and horizontal throughout the length of the inlet during the ebbing tide, and is deformed at the mouth during the flood. Since the stability at this boundary is greater than at any other depth in the system, it is evident that any departure from the horizontal would invoke greater isostatic restoring forces than are involved in the transport movements. Consequently during the ebb movement from high to low water slack, while the upper zone has free access to the sea, the horizontal position of the interzone boundary is maintained by local accelerations. This conclusion is illustrated in fig. 6.

During the flooding tide the deformation of the boundary represents the balance of the isostatic forces due to fresh water, and the kinetic forces of the flooding tide. All stations in fig. 6 were observed during the ebb tide, and so avoided deformation of the boundary at the mouth of the inlet.

FRESH WATER DISTRIBUTION

Because the observed chlorinity distribution represents a steady recurrent state (with constant run-off and similar tide cycles), it is reasoned that the contrary transport of fresh water in the middle zone is a steady proportion, at every point, of that in the upper zone; otherwise there would be local accumulations of fresh water. Then because the same volume of fresh water is transferred through any cross-section in the upper zone in a tidal cycle, the volume of fresh water transferred through any section in the middle zone must also be constant. But the distribution of fresh water between the two zones is dependent on the rate of mixing, which has been shown to be a function of the geography and tide, and these are constant within the limits of similarity of tidal rise. Consequently the ratio of fresh water in the upper zone to that in the middle zone is independent of position, the absolute amount of fresh water present, and rate of transport, and varies only with the tidal range, and so should be virtually constant.

TABLE III. Proportion of the total fresh water present that is contained in the upper zone (Evaluated from the data in fig. 6).

Station	Depth of upper zone (feet)	Proportion of the total fresh water that is contained in the upper zone	Concentration of fresh water in upper zone (by integration)
	June 4 and 5, run-off 2,600 c.f.s., tide range 5.4 ft.		
L20	7.5	0.870	0.865
A	7.5	0.878	0.828
B	7.5	0.881	0.748
C	7.5	0.890	0.605
D	7.5	0.915	0.345
Variation		±0.02	
	July 3 and 4, run-off 1,550 c.f.s., tide range 4.8 ft.		
L20	13.5	0.902	0.659
A	13.5	0.895	0.723
B	13.5	0.915	0.512
C	13.5	0.892	0.370
D	13.5	0.885	0.127
Variation		±0.015	

This conclusion is verified in table III from the same data as in fig. 6, showing that the fresh water contained in the upper zone, is a constant proportion of the total, within ± 2%, regardless of considerable differences of position in the inlet, run-off, concentration of fresh water, and depth of boundary.

MECHANISM OF THE ESTUARY

As remarked by Carter (1933), it is a characteristic of a fiord that the major inflow of land drainage occurs at the head. Further it has been shown by

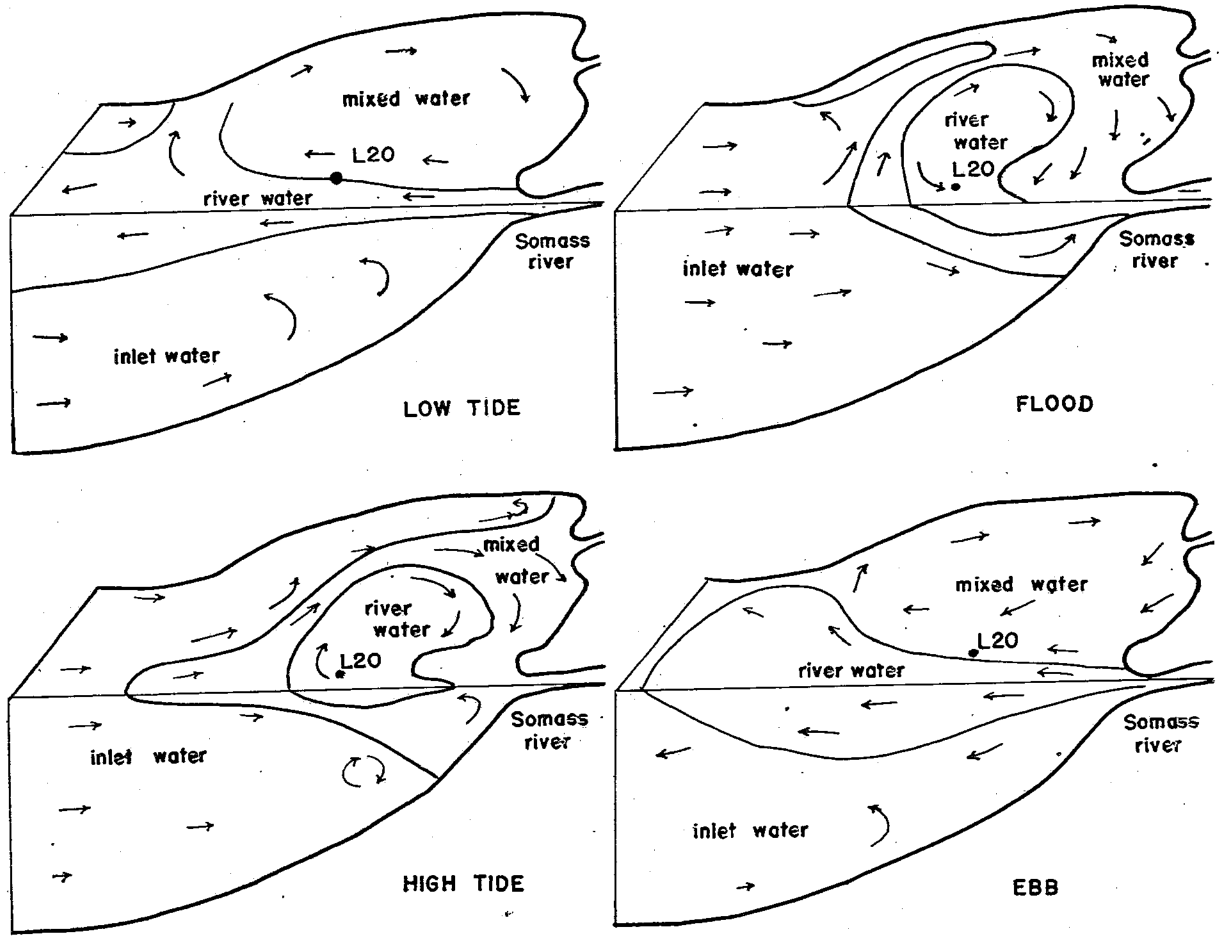


FIGURE 7. Idealized isometric projection of the water masses in Alberni harbour.

Rossby and others (1936) that a stream on entering an open body of water forms a diverging wake stream (estuary) within the resting water until its identity is lost. In an inlet it is evident that the entering stream must diverge until its waters are uniformly distributed across the whole width (fig. 3(c)). After this, mixing may continue with the underlying waters, but there will be no gradient transverse to the direction of flow.

In accordance with local custom it is convenient to designate this estuary region in the vicinity of the head, as Alberni harbour (fig. 2). This avoids confusion with the "head" which properly applies to the point of entry of the river.

TIDE AND RUN-OFF

In the absence of tidal movement, fresh water would enter the head of the inlet from the river forming a "wake stream" on the eastern side, and a tangential eddy on the western side, from which water would be absorbed into the diverging stream (Rossby, 1936; Spilhaus, 1937).

Aside from the properties arising from the wake stream in a particular geographical setting, the tidal mechanism of the harbour is similar to that in the inlet as a whole. Fresh water flows freely through the harbour during the falling tide, but during the rise it is impounded in the area by advancing inlet water, forming an end-boundary which represents the balance between isostatic and tidal forces. The particular mechanism in the presence of tidal movement is illustrated in the idealized isometric projection of the harbour in fig. 7.

The dynamic head of the rising tide, which is approximately uniform across the width of the harbour mouth, opposes the isostatic head of the river stream, which is greatest on the eastern side. The river discharge is impounded in the harbour, where it has little or no motion. The inlet waters intrude on the western side, displacing the waters of the tangential eddy onto the tide flats. During the latter part of the tidal rise, some of the displaced western water enters the river mouth, diverting the river over the tide flats, and isolates a cloud of brackish river water which forms an eddy in the harbour. At this time the upper zone boundary is tilted down towards the head because of the accumulation of fresh water.

The cloud of impounded river water is displaced from the harbour as soon as the tide turns to the ebb, followed by the river stream, and the inter-zone boundary is tilted down towards the harbour mouth. This remarkable sequence of events, from the isolation of the cloud of river water to its complete displacement from the harbour, was observed in the model to occur in less than (the scale representation of) one hour. In view of the five hours required for a hydrographic survey, it is evident that the state could not be captured in nature. It was also observed to be limited to tidal ranges greater than six feet, and river discharges greater than 525 c.f.s. but less than 6,000 c.f.s. The exact limits were not determined.

During the ebb, the river stream is regenerated, and the body of mixed water formed on the tide flats at high tide moves back into the western side of the harbour, forming the tangential eddy again. This water reaches the harbour mouth about the time of low water, only to be met by the advancing inlet waters as the rise commences. Evidently this mixed water can only be displaced from the harbour by transfer into the river stream.

The alternate tilting of the zonal boundary toward the head and mouth of the harbour at high and low tide is demonstrated from the harbour surveys in fig. 8, and the relation of this oscillation to the tide at a position near the mouth of the harbour (M27) is shown in fig. 9(b). This phenomenon is a measure of

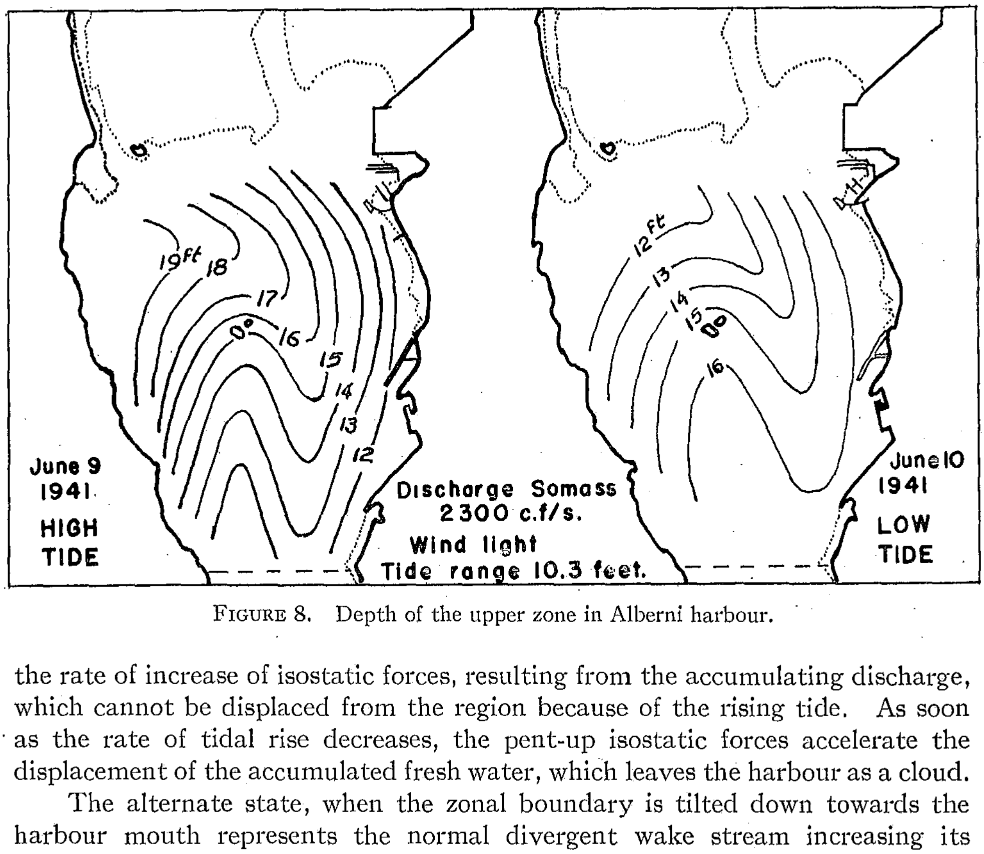


FIGURE 8. Depth of the upper zone in Alberni harbour.

the rate of increase of isostatic forces, resulting from the accumulating discharge, which cannot be displaced from the region because of the rising tide. As soon as the rate of tidal rise decreases, the pent-up isostatic forces accelerate the displacement of the accumulated fresh water, which leaves the harbour as a cloud.

The alternate state, when the zonal boundary is tilted down towards the harbour mouth represents the normal divergent wake stream increasing its dimensions down stream.

In the lower reaches of the inlet, deformations of the zonal boundary can be relieved by local accelerations, and the boundary remains horizontal, although its depth increases due to increase in the zone by the flooding tidal current. This boundary would remain horizontal even if the in-flow of fresh water were much larger, since the isostatic pressures can be relieved both towards the mouth and the head.

Evidently the forces tending to impound the river in the harbour are due to the tide alone, while the isostatic forces tending to maintain the river stream

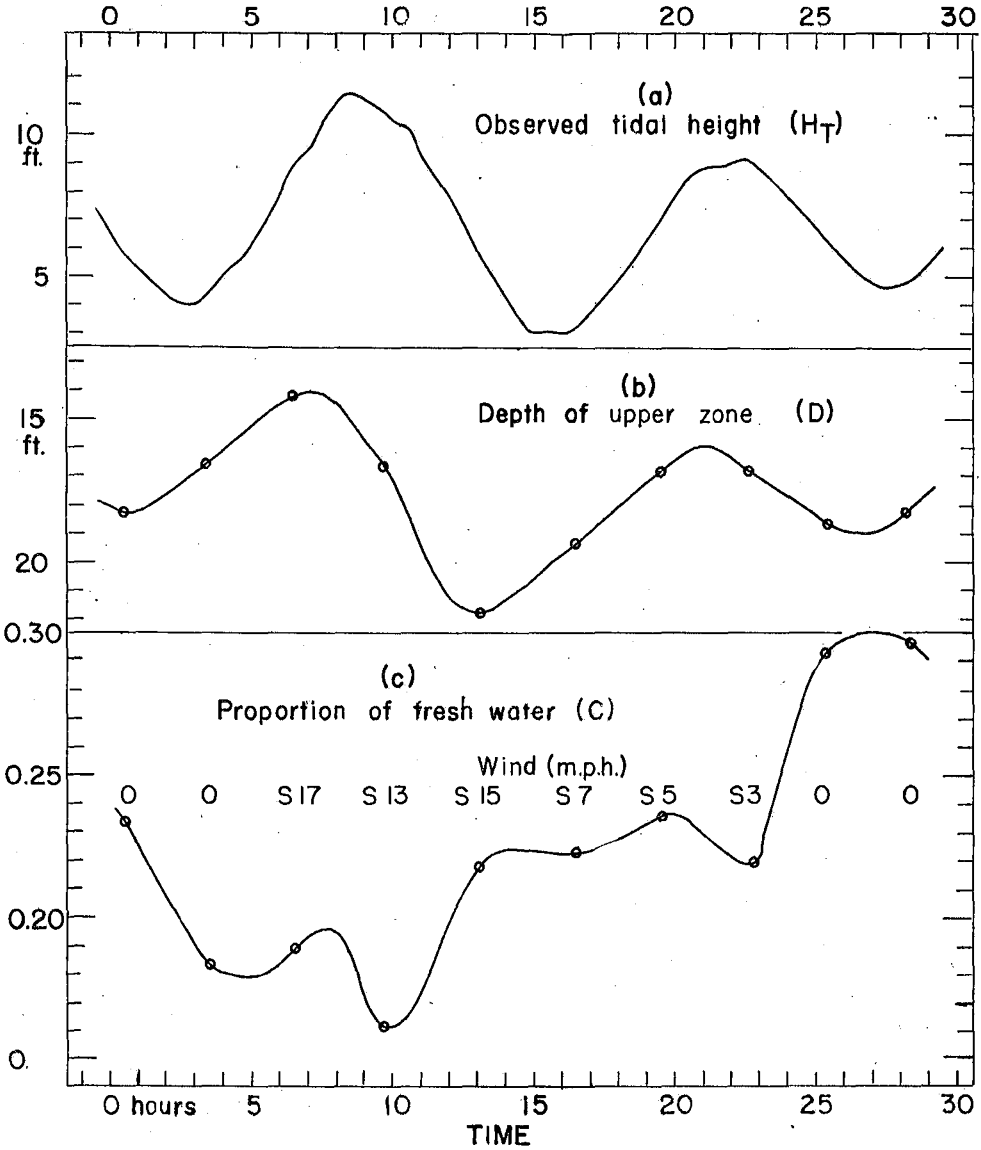


FIGURE 9. Properties of the Upper Zone at Station M27 (fig. 2).

must vary with the discharge. The oceanographic state represents an equilibrium between these, and it would be expected that the process would vary in degree, but be similar in form and sequence between wide ranges of these converse factors.

Some evidence of the surge nature of the displacement of the cloud of impounded river water is shown in fig. 9(c), where it may be noted that the increase in depth of the upper zone commences just before high tide, and is accompanied by an anomalous increase in the proportion of fresh water.

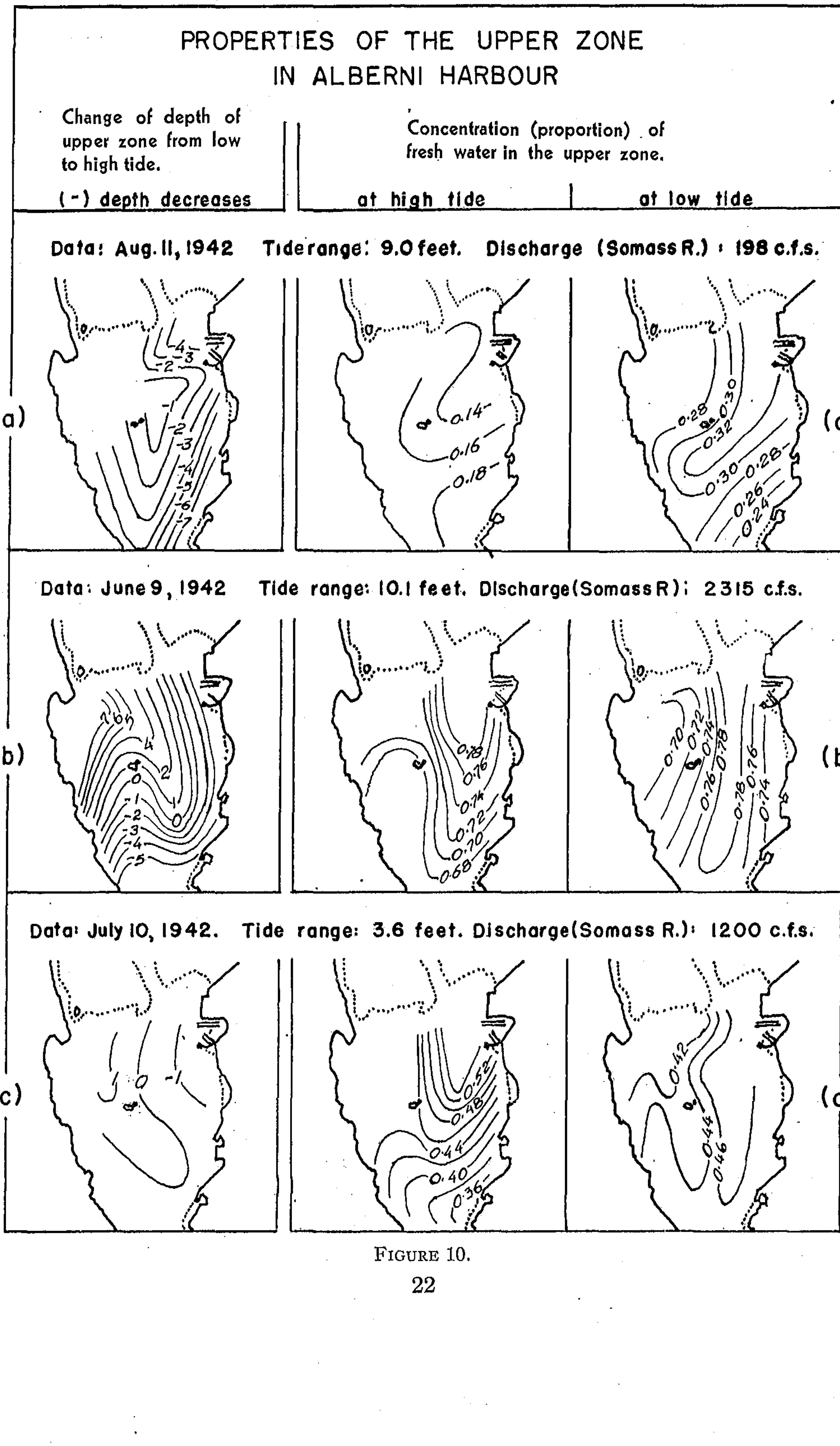

PROPERTIES OF THE UPPER ZONE
IN ALBERNI HARBOUR
Change of depth of upper zone from low to high tide.
(-) depth decreases
Concentration (proportion) of fresh water in the upper zone.
at high tide
at low tide
Data: Aug. 11, 1942 Tide range: 9.0 feet. Discharge (Somass R.): 198 c.f.s.
(a)
Data: June 9, 1942 Tide range: 10.1 feet. Discharge (Somass R): 2315 c.f.s.
(b)
Data: July 10, 1942. Tide range: 3.6 feet. Discharge (Somass R.): 1200 c.f.s.
(c)

FIGURE 10.

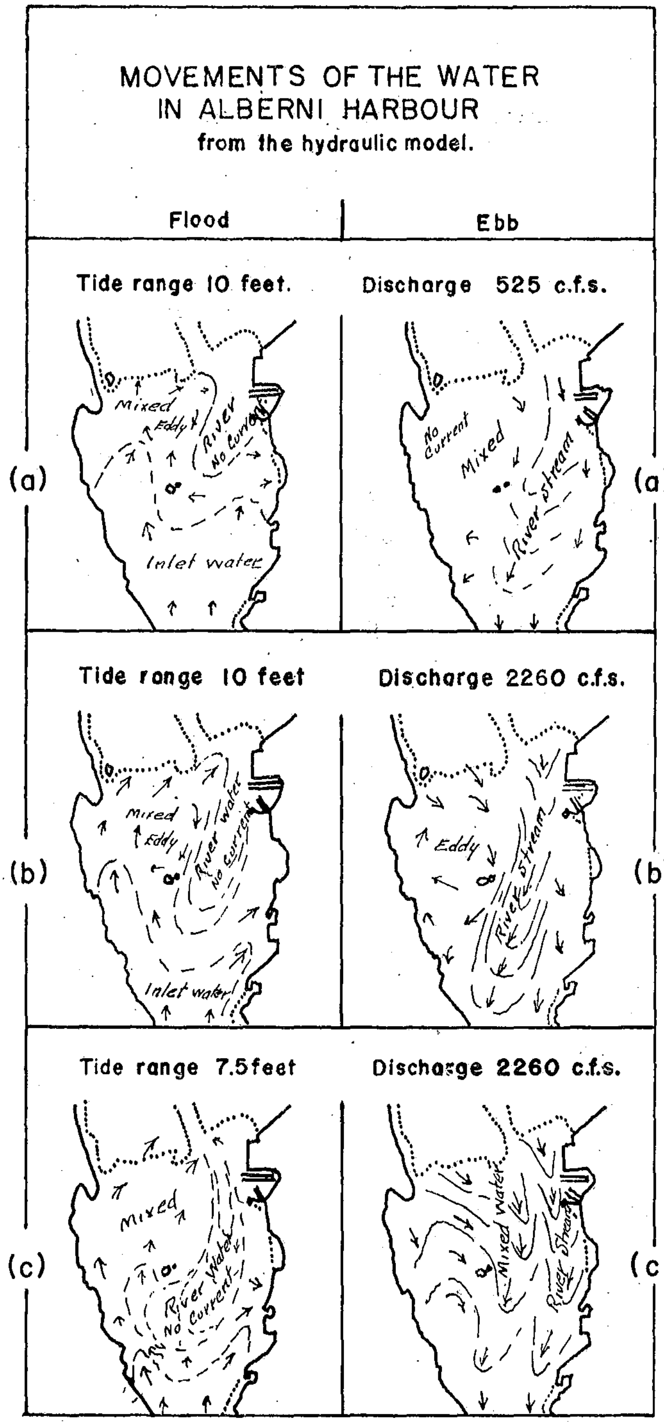

MOVEMENTS OF THE WATER
IN ALBERNI HARBOUR
from the hydraulic model.
Flood
Ebb
Tide range 10 feet.
Discharge 525 c.f.s.
(a)
Mixed
Eddy
River
No Current
Inlet water
No Current
Mixed
River stream
(a)
Tide range 10 feet
Discharge 2260 c.f.s.
(b)
Mixed
Eddy
River water
No current
Inlet water
Eddy
River stream
(b)
Tide range 7.5feet
Discharge 2260 c.f.s.
(c)
Mixed
River water
No current
Mixed water
River Stream
(c)

FIGURE 11.

The lack of symmetry in this fresh water relation is readily explained by the strong contrary wind during the first ebb which opposed the surface flow. As soon as the wind decreased, the impounded fresh water was released with a surge as shown on the second tide.

The distribution of the water at high and low tide extremes are illustrated in the complementary data of the corresponding diagrams (a), (b), and (c) of figs. 10 and 11. Fig. 10 shows the change in the depth of the upper zone between the tidal extremes, and the distribution of fresh water as observed in nature. Fig. 11 shows the currents in the several water masses, as observed in the model. The depth of the upper zone was not observed in the latter experiments.

When the discharge is small the cloud of brackish water impounded in the harbour is small, and large tides displace it almost entirely into the northwest quarter, and onto the tide flats. This is illustrated in fig. 10(a), where it is shown that the whole character of the water in the upper zone is changed from high to low tide, and the change of depth of the boundary indicates that the upper zone retreats bodily towards the tide flats. Under these conditions the river stream is small and the resulting tangential eddy is weak.

At higher discharge the impounded river water remains in the harbour, rather than retreating to the tide flats, indicating an increase in the isostatic forces. This is illustrated in fig. 10(b) which shows that there is a marked increase in depth towards the head with tidal rise (positive values of depth difference) and that the waters impounded toward the head have the same characteristics (proportion of fresh water $C = 0.78$) as those in the river stream at low tide. The corresponding flow diagram (fig. 11(b)) shows that the tangential eddy is well developed during the ebb, and that during the flood the eddy persists, in the part of the mixed water remaining in the harbour, owing to the reaction of the intruding tidal water with the impounded river water. It is also evident in this diagram that the mixed water is about to enter the river mouth, and so isolate the cloud of brackish water in the harbour.

When the tidal range is small (fig. 10(c)), the intrusion of inlet water, and consequent retreat of the mixed water, is also small, and these do not intrude across the river stream to isolate the brackish water in the harbour. As would be expected, the oscillation of the inter-zone boundary is small.

The tangential eddy is well developed during the ebb, but is not apparent on the flood, since the acceleration of the river stream, and reaction between it and the tidal water, are both lacking.

Evidently the position of the lower limit of the harbour, where lateral density gradients vanish, is variable with the volume of land drainage and the phase of the tide. The position of this limit was not determined.

MARGINAL CURRENTS

It will be shown in part II that in the model there was a marginal current along each shore that moved towards the mouth of the harbour on the ebb tide, but did not retreat towards the head during the flood, and was not transferred into the harbour or the river stream. This zone of restricted flow, particularly

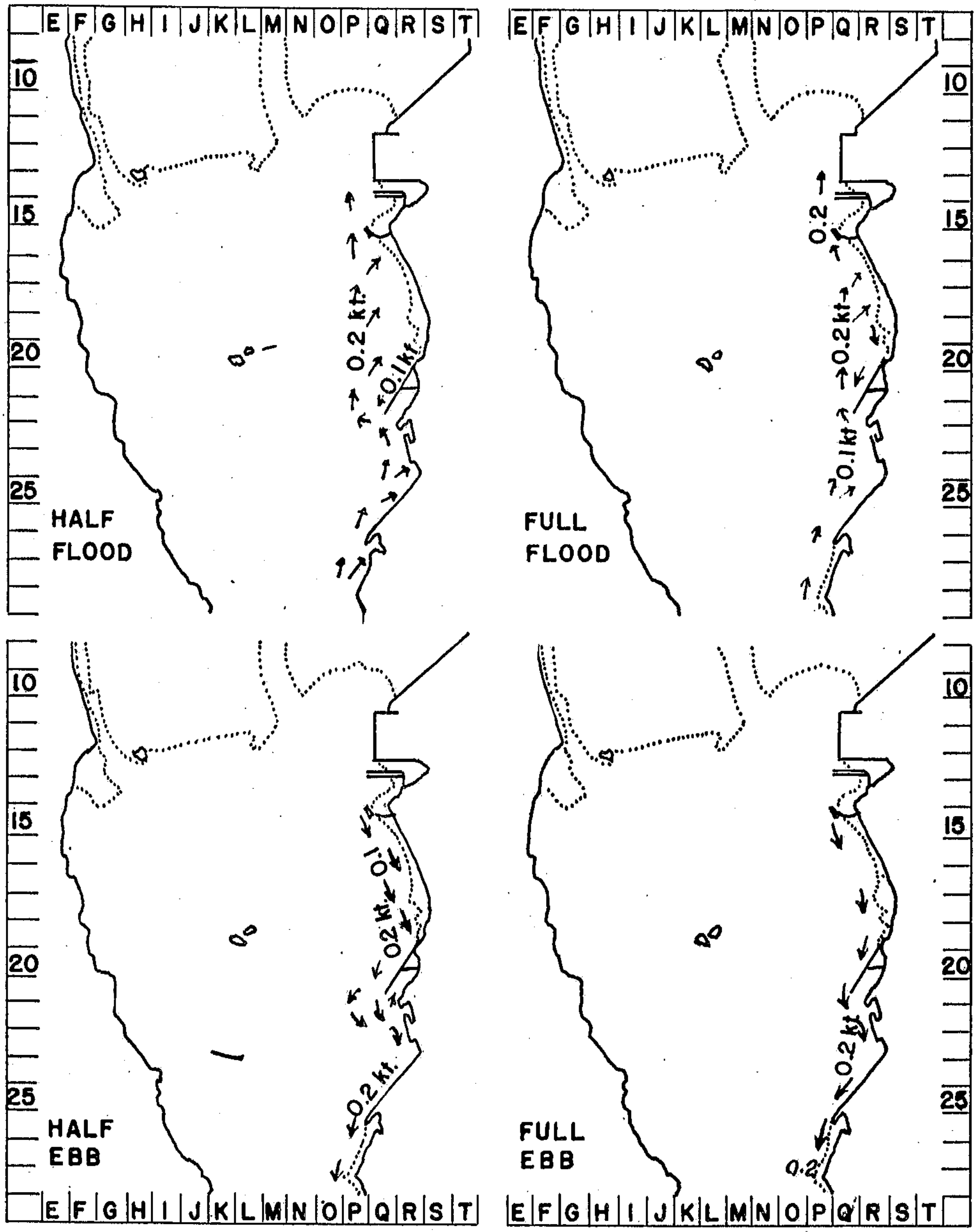


FIGURE 12. Restricted flow along the Eastern shore of Alberni harbour (from float experiments). Data, April 15 to 20, 1942. Somass river discharge ($\bar{Q}$) 3500 c.f.s. Velocity in knots. Marginal divisions represent 500 feet.

along the eastern shore, was of special interest in the disposal of sewage. It occurred in a region of doubtful reliability in the model, and too close inshore for oceanographic observations, so it was observed by a series of float experiments.

The nature of this current at successive tidal stages is shown in fig. 12. During the flood tide there is a slow northward current with a strong tendency to set on shore. This represents the intrusion of inlet water along the shore confirming the evidence in figs. 10 and 11. During the ebb there is a comparatively strong flow along the shore towards the mouth of the harbour.

There was no tendency at any time for the floats to be absorbed into the river stream, or transferred across it to the western side. This observation is in keeping with the conclusions of Rossby and Spilhaus, that a wake stream would tend to react against the eastern shore and swing towards the centre of the harbour. This tendency is indicated in the isometers of fresh water distribution in fig. 11. This contribution to the marginal current from the river stream accounts for its acceleration during the ebb.

LATERAL MIXING

The movement of this marginal water in and out of the harbour was followed in a float experiment as described in part II and illustrated in fig. 13.

The experiment indicates that within the harbour these marginal waters are conserved, but below the harbour they tend to diffuse across the inlet. The number of floats returned to the harbour indicates that of the original water only about 11% returned to the harbour mouth, and only about 4% returned to the starting point. Evidently the remainder represents water that has been transferred beyond reach of the floats and mixed with the inlet water.

This exemplifies the previous conclusions regarding the tidal mixing process. Before being finally displaced from the area, the water moves in and out of the harbour several times (3 to 6) becoming more diffused on each cycle. By the time the centre of longitudinal tidal oscillations has moved out of the harbour the lateral mixing process as shown in fig. 2 is virtually complete.

Evidently the water finally displaced from the harbour in any one tidal cycle is a relatively homogeneous mixture of water from all parts of the region. It is apparent that lateral homogeneity is more closely approximated as the process continues in the lower reaches of the inlet.

VERTICAL MIXING

Examination of the model (part II) showed that no measurable amount of dye was transferred down across the inter-zone boundary within the harbour area. This agrees with the necessary conclusion regarding the state in nature. It has been shown that fresh water enters the harbour in the middle zone, with the contrary flow from the lower reaches of the inlet. If there were a net downward transfer in this region, the fresh water would accumulate, and the harbour would eventually become a fresh water body. Hence it is a necessary conclusion that the net transfer is upward across the boundary in the estuary region.

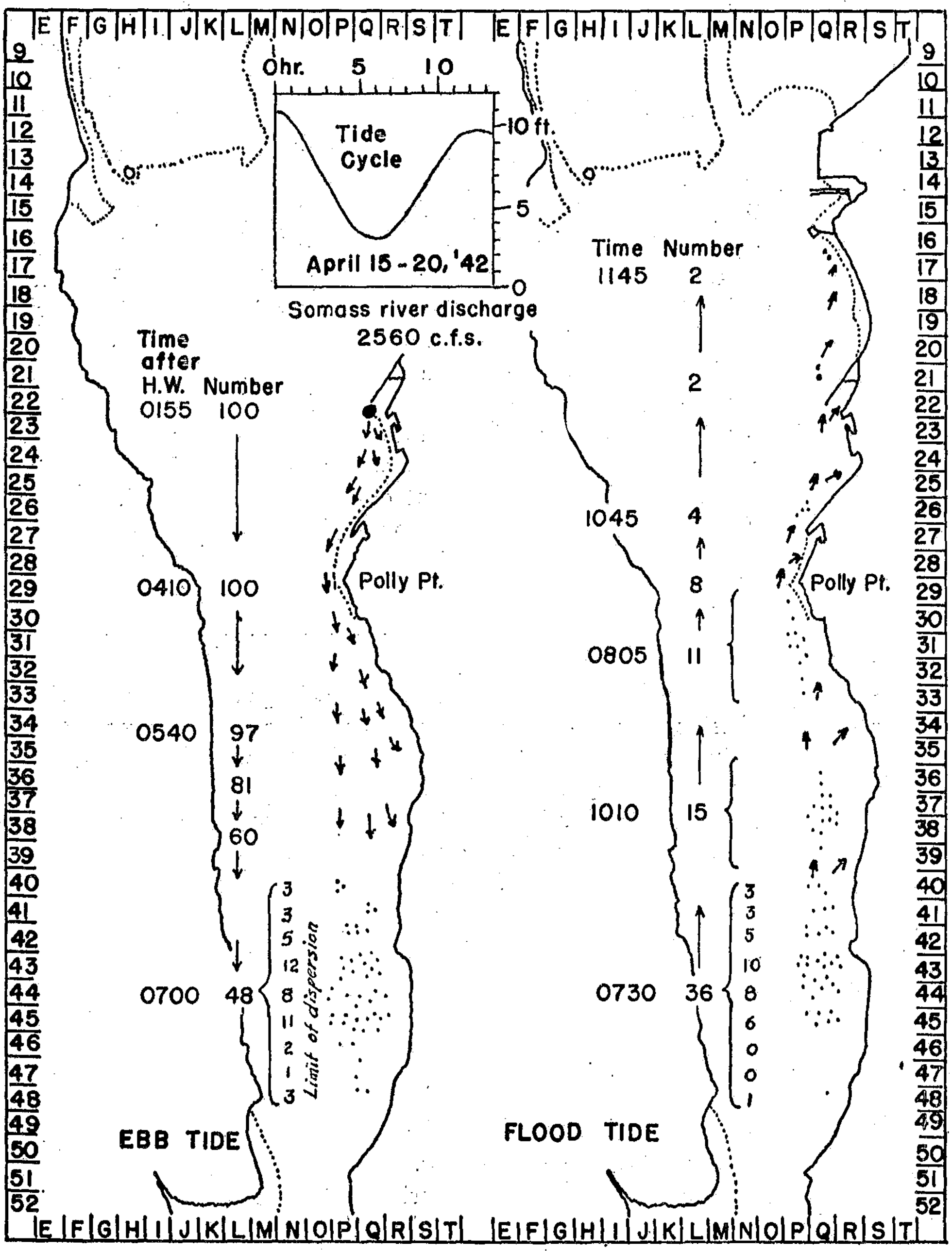


FIGURE 13. Dispersion of floats in one tidal period from the region of restricted flow in Alberni harbour.

Displacement

On the basis of these observations, it is possible to evaluate the seaward movement of fresh water and the degree of mixing en route in terms of the run-off.

Displacement may be defined as the proportion of water in any limited region that is exchanged in a complete tide cycle, without cognizance of the identity of the water involved.

It follows from the discussions of the movement of water through the upper zone that some proportion of the fresh and sea water in any limited region is displaced by like amounts entering the region during a tidal cycle. Evidently the proportion of fresh water displaced is the same as the proportion of sea water displaced, or the proportion of the total amount of water displaced from the region, otherwise one or the other of the components would accumulate.

Displacement may be evaluated from analysis of the fresh water distribution:— Consider an area (A) of the inlet of depth (z) containing a portion ($\bar{C}$) of fresh water, and into which the rate of fresh water flow is (Q) during the time of a tidal cycle (T). Then the displacement of fresh water (r) is the ratio of the volume of fresh water entering the region (Q T) to the volume of fresh water already in the region $A\bar{C}z$; viz.

$$r = \frac{Q\,T}{A\bar{C}z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

This expression is exact and implies absolute knowledge of the factors. The geography and fresh water discharge (run-off) may be observed directly; and the depth of the upper zone and the proportion of fresh water may be determined from suitable chlorinity observations. At this point in the discussion it is sufficient to realize that the relation can be solved within the limitations of the data, although it is necessary to modify the form, and make certain approximations that will be discussed in the following section.

Because of turbulence, no discrete volume of water can maintain its identity for any considerable period of time, but must become mixed with all other water in the same neighbourhood. In view of the oscillatory motion of the tide and its velocity gradients, it is evident that the water leaving any limited region must contain successive proportions of the water that entered during all preceding tidal cycles.

This may be expressed quantitatively from the definition. If the displacement from any region of volume AD (Area x Depth) is a proportion r, the volume entering the region is ADr, and the volume leaving is also ADr. Then in a limited region where the contribution during a tide cycle (T_1) is the volume of new water ADr, the volume of this (T_1) displaced by the end of the next tide cycle (T_2) is $ADr(r) = ADr^2$ and the volume remaining is $ADr(1\text{-}r)$. In the third cycle (T_3) a volume $ADr^2(1\text{-}r)$ of the original (T_1) water is displaced, and $ADr(1\text{-}r)^2$ remains. In the n th cycle (T_n) a volume $ADR^2(1\text{-}r)^{n-2}$ is displaced, and a volume $ADr(1\text{-}r)^{n-1}$ remains.

Now any tidal cycle is the first tide (T_1) with respect to new water entering the interval, the second (T_2) with respect to water entering in the previous tide, and the n th (T_n) with respect to water entering in the n th previous tide. Consequently the volume of the interval is the sum of all the remaining portions from all previous tides

$$AD = \sum_{1}^{\infty} ADr\ (1-r)^{n-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $n = 1, 2, 3, \cdots\cdots \infty$

and the volume displaced contains water of all ages from all previous tides in the proportions associated with n in the series

$$ADr = \sum_{1}^{\infty} r^2\ (1-r)^{n-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $n = 1, 2, 3, \cdots\cdots \infty$.

TRANSPORT

The *transport* (1) is defined as the mean longitudinal progress of a particle, all motions included, in a complete tide cycle, and the *rate of transport* is the mean velocity of progress during this period. The *time of transport* is the time required for the particle to traverse an interval of the inlet (O-A, O-B, etc.).

The idea of transport assumes that the elementary volume of water represented by the particle maintains its identity during its progress down the inlet, while the idea of displacement presumes that the identity is lost.

RELATIONS TO RUN-OFF

From the preceding discussion it may be realized that the factor of displacement defines the dynamic state in the upper zone, and the proportion of fresh water defines the structural state, and they are all related to the run-off. Evidently it is possible to relate the behaviour of fresh water in the inlet to river discharge.

This conclusion is illustrated in figs. 14(a), (b) and (c) from data representing the average state between ebb and flood tide in the harbour, which will be shown to be representative of the inlet as a whole.

On examining the data it was found that the points were considerably more scattered from a simple relation than would be expected from variations of tidal height. Further examination showed that the deviations in one direction were associated with increasing run-off, designated as "freshet divergence". Deviations in the other direction were associated with south winds in excess of 12 miles per hour, which are referred to as "wind divergence". In the presentation of the data the best line drawn through points representing conditions of steady or decreasing discharge, and calm or light winds is regarded as representing a "normal state", and curves embracing the divergent points have been designated accordingly.

The form of the curves are remarkable. Evidently from low to intermediate discharge level (2,600 c.f.s.) the upper zone becomes shallower and fresher, while the displacement increases almost linearly. Above this level the upper zone becomes deeper and more saline.

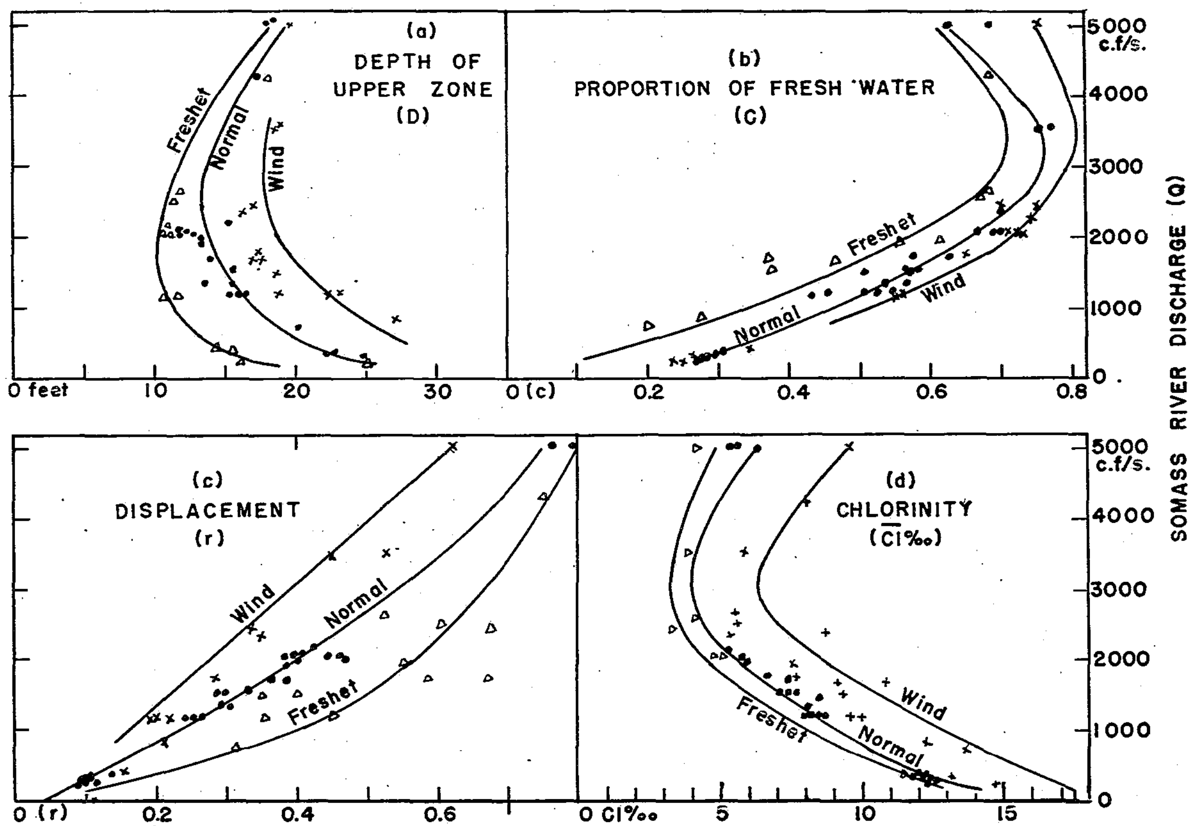


FIGURE 14. Properties of the upper zone in Alberni harbour related to Somass river discharge.
△ Freshet divergence • Normal relation × Wind divergence

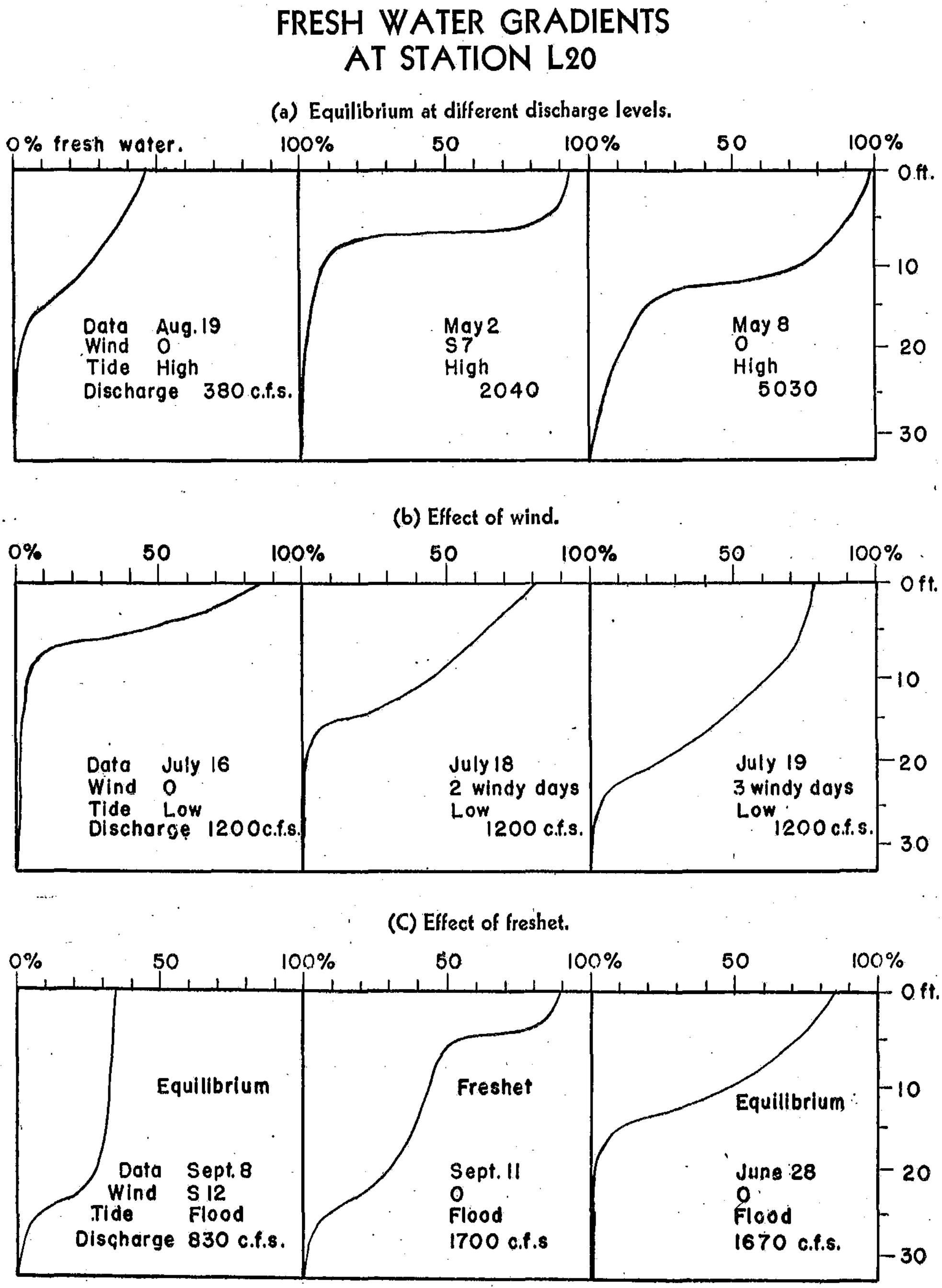

FRESH WATER GRADIENTS
AT STATION L20
(a) Equilibrium at different discharge levels.
0% fresh water.
100%
50
100%
50
100%
0 ft.
10
20
30
Data Aug. 19
Wind 0
Tide High
Discharge 380 c.f.s.
May 2
S 7
High
2040
May 8
0
High
5030
(b) Effect of wind.
0%
50
100%
50
100%
50
100%
0 ft.
10
20
30
Data July 16
Wind 0
Tide Low
Discharge 1200 c.f.s.
July 18
2 windy days
Low
1200 c.f.s.
July 19
3 windy days
Low
1200 c.f.s.
(C) Effect of freshet.
0%
50
100%
50
100%
50
100%
0 ft.
10
20
30
Equilibrium
Data Sept. 8
Wind S 12
Tide Flood
Discharge 830 c.f.s.
Freshet
Sept. 11
0
Flood
1700 c.f.s
Equilibrium
June 28
0
Flood
1670 c.f.s.

FIGURE 15.

These phenomena may be interpreted by recalling the tidal mechanism of the harbour, and referring to the normal fresh water gradients at station L20, associated with low, intermediate and high river discharge (diagram (a) of fig. 15). When the discharge is small, displacement is necessarily small, and the tidal oscillations are relatively large; consequently the harbour waters approach homogeneity as shown in the first gradient. In this case the upper zone is deep and the proportion of fresh water is small.

As the discharge increases the tidal movement of the harbour waters decreases until a balance is reached between the contributions at about 3,000 c.f.s. such that the movement and the consequent turbulence are at a minimum. Further increase of discharge implies that the boundary between intruding inlet water and impounded river water must retreat further seaward. Since this requires increased isostatic forces, it is evident that the depth of the upper zone must increase. This is illustrated in the third gradient associated with a high discharge level. The boundary gradient is not as extreme as in the second case, because there is more movement, and therefore more turbulence associated with the latter state.

WIND EFFECTS

In the presence of strong south winds, which oppose the surface seaward flow, it would be expected that the depth of the upper zone and the proportion of fresh water would be greater than the normal, due to the decreased displacement, as exemplified by the wind divergence. This is illustrated in the sequence of group (b) gradients in fig. 15.

Furthermore it is shown in fig. 14(a) that the effect of wind on the boundary depth is greatest when the depth is least. Its effect on the fresh water proportion (fig. 14(b)) increases with run-off as an expression of the rate of accumulation of river water in the region. The effect on displacement (fig. 14 (c)) increases to a limiting value as the boundary approaches minimum depth with intermediate discharge, and the surface waters become fresh. The limit is reached (at about 4,000 c.f.s.) when the depth of the upper zone becomes great enough to permit displacement below the level of wind influence.

FRESHET EFFECTS

It is apparent that the displacement must increase with run-off, but the evidence in the figures that the depth of the upper zone and the proportion of fresh water decreases, is enlightening.

The phenomenon is readily explained by the freshet forming a surface layer of fresh water, and repeating within the upper zone the function of the upper zone in the inlet as a whole. This is illustrated by the sequence of fresh water gradients observed during the autumn freshet (fig. 15 (c)).

As the surface velocity increases, water is drawn from below into the surface stream, similar to the transfer from the middle to upper zone, so that the chlorinity at this level increases. This change is shown as the transition from the first to the second gradient. If the rise is a true freshet (of short duration), the process ends there, and the original state is slowly re-established. However if the higher discharge continues at a constant level, fresh water accumulates until a new equilibrium is established, as indicated in the third gradient, and the boundary finds a new level.

It is concluded that a freshet has the important effect of flushing the harbour and produces anomalous values of C, and D, since it does not represent equilibrium conditions.

Because there is a tendency for the fluctuations in discharge to be proportional to the discharge, the freshet divergence in the displacement is almost constant up to intermediate discharge levels. Beyond this, the amount of river water accumulated in the harbour is large enough to partially mask the freshet effects.

MEAN CHLORINITY

The mean chlorinity of the upper zone (fig. 14 (d)) is a converse function of the proportion of fresh water (C). It is reproduced here since it is frequently a more useful index of the oceanographic state than the latter function, particularly in the analysis of the properties of the water which are to be discussed later.

DYNAMIC STABILITY

Evidently the chlorinity distribution is not absolutely a recurrent function, since it is subject to distortion by wind and freshet. However it is obvious that the steady state is represented by the normal curves in figs. 14(a), (b) and (c), that the wind divergence represents a state of accumulated fresh water, and that the freshet divergence represents partial depletion. Consideration of the mechanisms of these divergent states shows that the chlorinity distribution returns to the normal when the distorting forces are removed, or if they persist, a new equilibrium is established.

It follows that in general the depth and fresh water content of the upper zone represent the accumulation of fresh water required to provide the isostatic head necessary for the continuous displacement of fresh water at a rate equal to its entry. Evidently this can be attained in a shallow and very fresh zone, or a deeper more saline zone, depending on the divergent forces. However the rate of mixing is primarily a function of the tide, therefore the normal state at any level of run-off is a recurrent function within the limits of constancy of the tidal cycle.

QUANTITATIVE ANALYSES

DISPLACEMENT FACTORS

It has been shown that the determination of the displacement factors and the solution of equation 1 (page 28) provides a quantitative estimate of the behaviour of fresh water in the inlet.

AREA

The area was determined by integration on the hydrographic chart of the region, noting that evaluation of the equation is facilitated by always taking the area (A) to mean the total area of the inlet from the head (position O) to a cross-section at some point to seaward. These are *continuing* intervals, O-A, O-B, etc. This implies that run-off always enters the region with constant composition (100% fresh water) and avoids the complexities involved in consideration of water of variable composition. Then the properties of the *successive* intervals A-B, B-C, etc. are regarded as the differences between the two *continuing* intervals.

The geographic constants of concern to this discussion are shown in table IV.

TABLE IV. Dimensions of the inlet. Position 0, at the mouth of the Somass river (figs. 1 and 2) is designated the head of the inlet, and the origin of all distance measurements.

Consecutive intervals (from one station to the next)					
	Hbr.	0–A	A–B	B–C	C–D
Length (feet)	8,750	15,600	22,380	41,600	49,200
Area (sq. feet) × 10^{-7}	5.85	8.00	8.30	18.50	30.10
Continuing intervals (from the head to the station)					
	Hbr.	0–A	0–B	0–C	0–D
Length (feet)	8,750	15,600	37,980	79,580	128,780
Area (sq. feet) × 10^{-7}	5.85	8.00	16.30	34.80	64.90
Ratio of area	1.0	1.37	2.78	5.95	11.09
	Polly pt.	A	B	C	D
Width (feet)	2,430	3,400	4,250	4,250	7,300

RUN-OFF

Land drainage data (fig. 16) were obtained from records of the Dominion Water Power and Hydrometric Bureau (1947), and consist of daily (noon) observations of the discharge of the Sproat and Stamp rivers, which together form the Somass river.

The time required for the water to move from the point of observation to the head of the inlet was computed from the average current velocity and was observed to be 1.5 days (36 hours) when the discharge was 250 c.f.s. and to decrease proportionately as the discharge increased. Since this value represents nearly the minimum discharge, and the limitations of the data imply that any lag less than this is inconsequential, it is concluded that the observed discharge is representative of the 24-hour day in which it was recorded.

For the solution of the problem, it was necessary to know the run-off into each interval of the inlet. It was assumed that the total run-off into the region

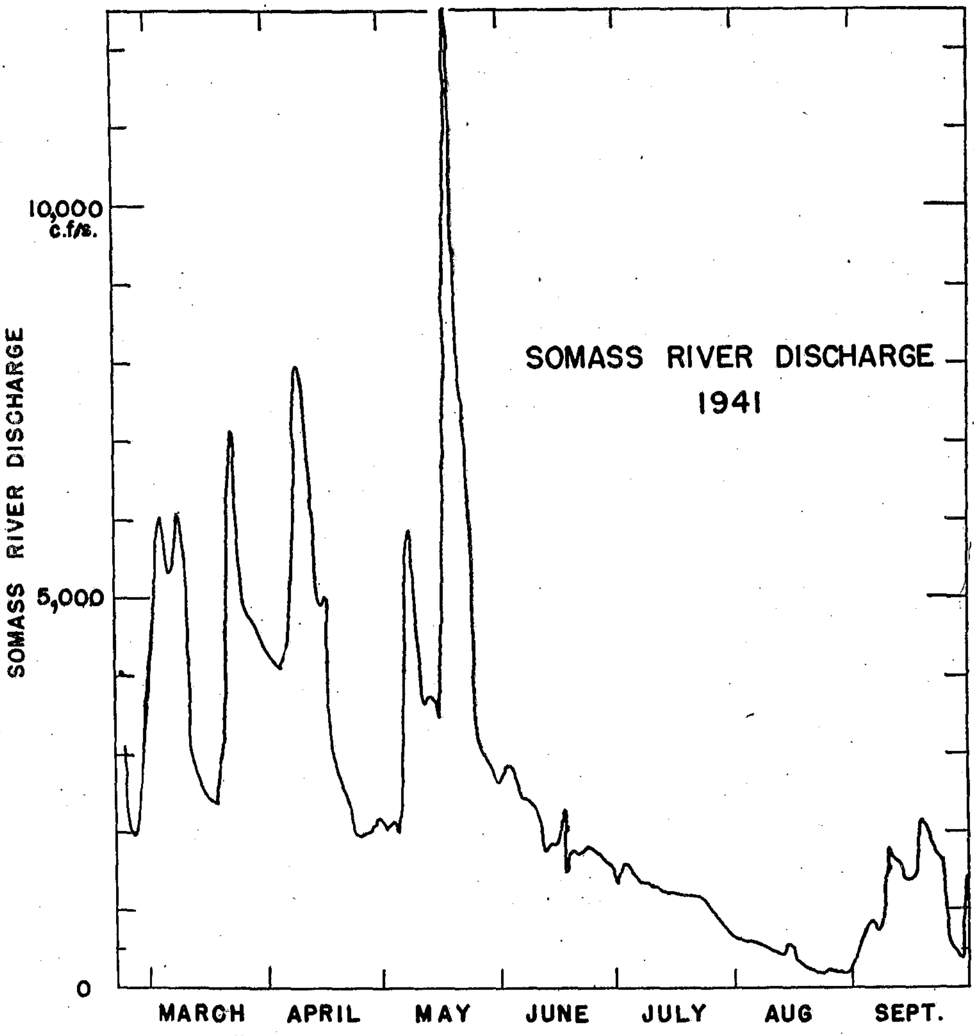


FIGURE 16.

of the head (Alberni harbour) was represented by the Somass river. It was further assumed that the ratio of the drainage into each interval was proportional to the discharge of the Somass river, in the ratio of the total precipitation into the respective drainage areas. This is the best approximation possible under the circumstances. The computed run-off ratios in successive, and continuing intervals of the inlet are shown in table V.

In the equation, Q is taken as the mean rate of discharge during the tidal cycle. As indicated in fig. 16, there is considerable variation in this quantity so that the assumption of a representative value involves some uncertainty.

TABLE V. Computed run-off ratios into the arbitrary intervals in Alberni inlet. Position 0 at the mouth of the Somass river (figs. 1 and 2) is designated the head of the inlet and the origin of all distance measurements.

Consecutive intervals (from one station to the next)					
	Hbr.	0–A	A–B	B–C	C–D
Drainage area (sq. miles)	528	.534	94	169	162
Run-off (sq. mile-inches)	43,260	43,710	7,690	16,570	17,440
Ratio (F)	1.00	1.011	0.176	0.379	0.399
Continuing intervals (from the head to the station)					
	Hbr.	0–A	0–B	0–C	0–D
Drainage area	528	534	628	797	959
Run-off (sq. mile-inches)	43,260	43,710	51,400	67,970	85,410
Ratio (F)	1.00	1.011	1.189	1.570	1.973

However the equation may be written in the form

$$ACz = Q\frac{T}{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where the volume of fresh water contained in the region is the total run-off during T/r tide cycles, and Q is presumed constant. Substituting the mean value for Q, this becomes

$$ACz = \int_0^{T/r} Q.dt \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Then the time, in tidal cycles, required for the accumulated run-off to equal the amount of fresh water present in the region, is numerically equal to the inverse of displacement of fresh water in each tidal cycle, and since the proportion of fresh to sea water is a constant function of the tidal cycle, this value is also the total displacement.

It should be particularly noted that the association of the quantity T/r with the time required for the run-off (Q) to equal the volume of fresh water contained in the chosen interval of the upper zone, is an artifice to evaluate r. As discussed in the section on mechanism, the displaced water contains successive proportions of the water that entered the zone during all preceding tidal cycles.

It will be shown that T/r is the mean time required for the transport of a particle through the interval of the inlet to which the limit applies. This may be freely interpreted as the mean *age* of the water at the time of displacement from the interval (O-A, etc.) and may be expressed in the tidal cycles (T/r) or in days (1.039T/r = T′/r).

DEPTH OF UPPER ZONE

The quantitative study of the distribution, displacement, and transport of fresh water in this system is primarily limited to the upper zone, through which all the fresh water is displaced. Some fresh water is temporarily transferred to the middle zone, but since it is continuously returned, its disposal is automatically considered in any study of the steady state of the upper zone. This implies that the mean depth of the upper zone ($\bar{D}$) is to be substituted for z in equation 5.

Fig. 6 shows the form of the fresh water gradients, which were derived by careful interpretation of selected data. As indicated, the thickness of the boundary between upper and middle zones is of the order of ¼ to 1 foot in thickness, and usually it was not possible to fix its limits precisely, because the sampling bottles were about 1 foot in length, and could not be spaced at less than three-foot intervals on the sounding line. After examination of the remainder of the data, it was concluded that any interpretation other than the assumption of a linear gradient between observed depths, would be an expression of personal opinion.

Since the point of inflexion in the salinity gradient could not be precisely defined, advantage was taken of the conclusion that the fresh water was divided between the upper and middle zones in a constant ratio, and from considerations of the data, was arbitrarily defined as the depth in which 90% of the fresh water occurred. It was evaluated from the limit of integral of the fresh water concentration gradient in the relation

$$0.90 = \frac{\int_o^D cdz}{\int_o^b cdz} \qquad (6)$$

where D is the depth of the upper zone and b is the base depth from which the chlorinity is reckoned. The integrations were made linearly between observed depths.

PROPORTION OF FRESH WATER

The concentration of fresh water (c) at each observed depth was computed from the relation

$$c = 1 - \frac{(Cl)_z}{(Cl)_b} \qquad (7)$$

where Cl_z was the chlorinity (Cl°/₀₀) at depth z, and Cl_b was the base chlorinity, identified as the sea water being mixed into the upper zone. The last term in the equation represents the concentration of sea water, whence the whole expression is the concentration of fresh water present at the point of observation.

The mean concentration of fresh water (C) in any depth interval was evaluated in the usual manner from the relation

$$C = \frac{1}{z}\int_{o}^{z} c dz \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

with the integration made linearly between adjacent observations.

BASE CHLORINITY

The choice of a base chlorinity can be made a matter of some concern. From the arguments advanced in the previous section it should be the chlorinity of the sea water entering the inlet immediately below the level of the inflexion in the chlorinity gradient. This would require an arbitrary choice of base chlorinity within the limits of the entering sea water, which involves an expression of personal opinion.

The difficulty was obviated by observing that there is an isochlor at about 33 feet (10 metres), whose depth and value are constant (± 1 foot, ± 0.1 Cl °/oo) from the head to the mouth (Junction passage). This value may be arbitrarily stipulated as the definition of base chlorinity, implying that it marks the limit of reversible exchange of fresh water.

This assumption is supported by the observation that the value of this isochlor reflects changes in the entering sea water, and that its variation with run-off was not appreciable during the period of four months of observation. Furthermore, in the few examples where it could be observed, this isochlor coincided closely with the inflexion in the chlorinity gradient at the seaward mouth of the inlet. This agrees with the conclusion that all the fresh water leaves the inlet by way of the upper zone.

It may be noted in fig. 2 that the chlorinity below this level decreases from the mouth toward the head of the inlet, indicating that this isochlor is possibly not the absolute boundary of fresh water mixing. However it has been pointed out that in the case of moving water (middle zone) overlying stationary water (deep zone) the lighter water will tend to accumulate in the latter. Therefore this gradient may be attributed to the accumulation of lighter tidal water in the upper part of the deep zone. Evidently it is in isostatic equilibrium with the inflow in the middle zone.

EVALUATION OF DISPLACEMENT

Introducing these conditions into equation 5 the displacement in the upper zone is defined by

$$A\bar{D}\bar{C} = \int_{o}^{T/r} Q.dt \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Recalling the nature of the run-off data, and that these are given in 24-hour (8.64×10^4 seconds) intervals, the evaluation is more nearly represented by the approximation

$$\frac{A\bar{D}\bar{C}}{8.64 \times 10^4} = \sum_{o}^{T(1.039)/r} Q \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

where T = one tidal cycle = 24 hours, 52 minutes = 1.039 days and where the quantity T/r is evaluated in days. Multiplying this by the ratio of a mean solar day to a tidal cycle

$$\left(\frac{24 \text{ hours}}{24 \text{ hours } 52 \text{ minutes}} = \frac{8.64}{8.96} = 0.964 = \frac{1}{1.039}\right),$$

the value of 1/r in the tidal cycles is obtained, from which the displacement may be evaluated.

Where the section of the inlet considered is greater than represented by the discharge of the Somass river alone (e.g. O-A, 0-B, etc.), the equation becomes

$$\frac{A\bar{D}\bar{C}}{F \times (8.64 \times 10^4)} = \sum_{o}^{T\,(1.039)/r} Q \quad \ldots\ldots\ldots\ldots\ldots \quad (10a)$$

where F is the run-off ratio given in table V.

The quantities D and C were readily determined at each station as indicated in these discussions, but the mean states representative of the continuing intervals of the inlet as a whole and of the estuary region, were derived differently, and will be discussed under the applications to these regions.

LIMITS OF ERROR

To some extent, the justification of this approximation of D and C lies in the close agreement of the solution of equation 10 from the "absolute" (for convenience of reference) boundary gradient of fig. 6 and the "approximate" gradient (by linear interpolation). These developments of the data are cited in table VI.

It is notable in both cases, that in spite of the considerable difference in the estimate of the depth of the upper zone, the error in the displacement is small. This follows from the fact that the former is compensated by an opposite error in the estimate of fresh water concentration in the upper zone resulting from the mutual adjustment of these two quantities regardless of the depth taken. That is, the volume of fresh water (ADC) in equation 10 tends to be a constant value determined by the run-off.

It would be expected that the error in the estimate of depth would increase from zero, when the boundary was midway between observed depths, to a positive maximum when the boundary was adjacent to the upper observation, and would approach a negative maximum toward the lower observed depth. The estimate of concentration of fresh water and of displacement varies in the opposite sense. In the case cited, the boundary was adjacent to the upper observed depth (6.6 ± 0.5, and 13.1 ± 0.5 feet); wherefore it was concluded that these differences represented the maximum probable error, and were within the limit of error of the integration of run-off.

Attention is drawn to the remarkable constancy of the depth of the boundary in each series of approximated depths (D ± 0.6 feet). This verifies the deductions regarding the fresh water gradient, and the constancy of the ratio of its distribution between the upper and middle zones. Evidently the absolute

Table VI. The "absolute" and "approximate" methods of interpretation of the depth of the upper zone (D) and the concentration of fresh water (C) contained therein. *Absolute method:* The fresh water gradient is accurately interpreted from suitable data (fig. 6) and the values determined by direct examination of the curve. *Approximate method:* The depth of the upper zone (D) is defined as the depth containing 90% of the fresh water occurring above base level (33 feet) and all values are determined by linear interpolation or integration between observed points. Arbitrary values of depth of upper zone are underlined.

Interval of inlet	Procedure	Depth of upper zone (D) (feet)	*Calculated values* Proportion of fresh water (C)	*Calculated values* Age (1.039T/r) (days)	Displacement (r)
Data Mean values of July 4 and 5, 1941			Tide range 5.4 feet, run-off 2600 c.f.s.		
0–A	Absolute	*7.55*	0.865	2.24	0.242
	Approx.	10.43	0.671	2.62	0.198
	Difference	+ 2.88	−0.19	+0.38	—0.04
0–B	Absolute	*7.55*	0.826	3.26	0.160
	Approx.	10.30	0.624	4.08	0.128
	Difference	+ 2.75	−0.184	+0.82	−0.03
0–C	Absolute	*7.55*	0.745	5.31	0.098
	Approx.	11.55	0.576	6.11	0.085
	Difference	+ 4.0	−0.167	+0.80	−0.013
0–D	Absolute	*7.55*	0.621	6.20	0.084
	Approx.	11.77	0.482	7.71	0.068
	Difference	+ 4.22	−0.139	+1.51	−0.016
Data Mean values of June 3 and 4, 1941			Tide range 4.8 feet, run-off 1550 c.f.s.		
0–A	Absolute	*13.45*	0.691	5.55	0.094
	Approx.	16.34	0.569	5.30	0.097
	Difference	+ 3.89	−0.122	− 0.25	−0.003
0–B	Absolute	*13.45*	0.655	8.81	0.059
	Approx.	15.77	0.568	8.83	0.059
	Difference	+ 2.32	−0.087	+ 0.02	0.00
0–C	Absolute	*13.45*	0.541	11.45	0.045
	Approx.	15.56	0.483	11.51	0.041
	Difference	+ 2.11	− 0.58	+ 0.06	−0.004
0–D	Absolute	*13.45*	0.405	12.25	0.042
	Approx.	16.66	0.351	12.77	0.040
	Difference	+ 3.21	−0.054	+ 0.52	−0.002

gradient bears a constant relation to the approximated gradient, whence the depth of the "absolute" boundary must be constant, and the defining ratio of fresh water in the two zones must mark corresponding points on the absolute and approximated gradients within these limits.

It is concluded that the error in the estimated depth is a constant proportion, depending on the proximity of the absolute boundary to the mid-point between observed depths, and the accuracy of the assumed value of the defining proportion of fresh water in the upper zone. Consequently the procedure is justified, and an overall probable error in the depth of the upper zone of 50% of the depth between adjacent observations, in the concentration of fresh water in the upper zone of 25%, and in the displacement and dependent quantities of 20%, is accepted.

TRANSPORT

This idea was introduced as the mean progress of a particle (distance gained in one tidal cycle) independent of turbulence and tidal oscillation. Then the mean value in the upper zone may be determined at the downstream limit of an interval (A, B, C, etc.) as the volume of water displaced in one tidal cycle, divided by the area of the cross-section:

$$\text{Transport} = \frac{ADr}{DW} = \frac{A}{W} r \quad \text{.............} \quad (11)$$

where W is the width of the cross-section. Then the rate of transport (v) is

$$v = \frac{L}{T} = \frac{Ar}{WT} \quad \text{.....................} \quad (12)$$

The use of this relation is facilitated, by expressing the velocity in terms of the average width of the inlet (W) by setting $W = A/L$ where L is the length of the interval; then the mean values become

$$\bar{L} = Lr \quad \text{....................} \quad (11a)$$

and

$$v = \frac{Lr}{T} \quad \text{......................} \quad (12a)$$

Evidently $\bar{L}$ is associated with the integral of the area of the inlet above the point of observation, since it represents the length in a channel of average width. For the convenience of these and later computations the relation of $\bar{L}$ to distance from the head and area of the inlet, is shown in fig. 17. Then the velocity through any cross-section of the upper zone would be the product of the mean velocity ($\bar{V}$) with the ratio of the mean width of the inlet to the cross section. The geographical data required for these manipulations are given in table IV.

It is at once evident that the water displaced from any region of lateral homogeneity is that contained in the distance corresponding to $\bar{L}$ above the limit of the interval (i.e. A, B, C, etc.).

It follows from these discussions that the "time of transport" is the average time required for the transport of a particle through the interval, and may be

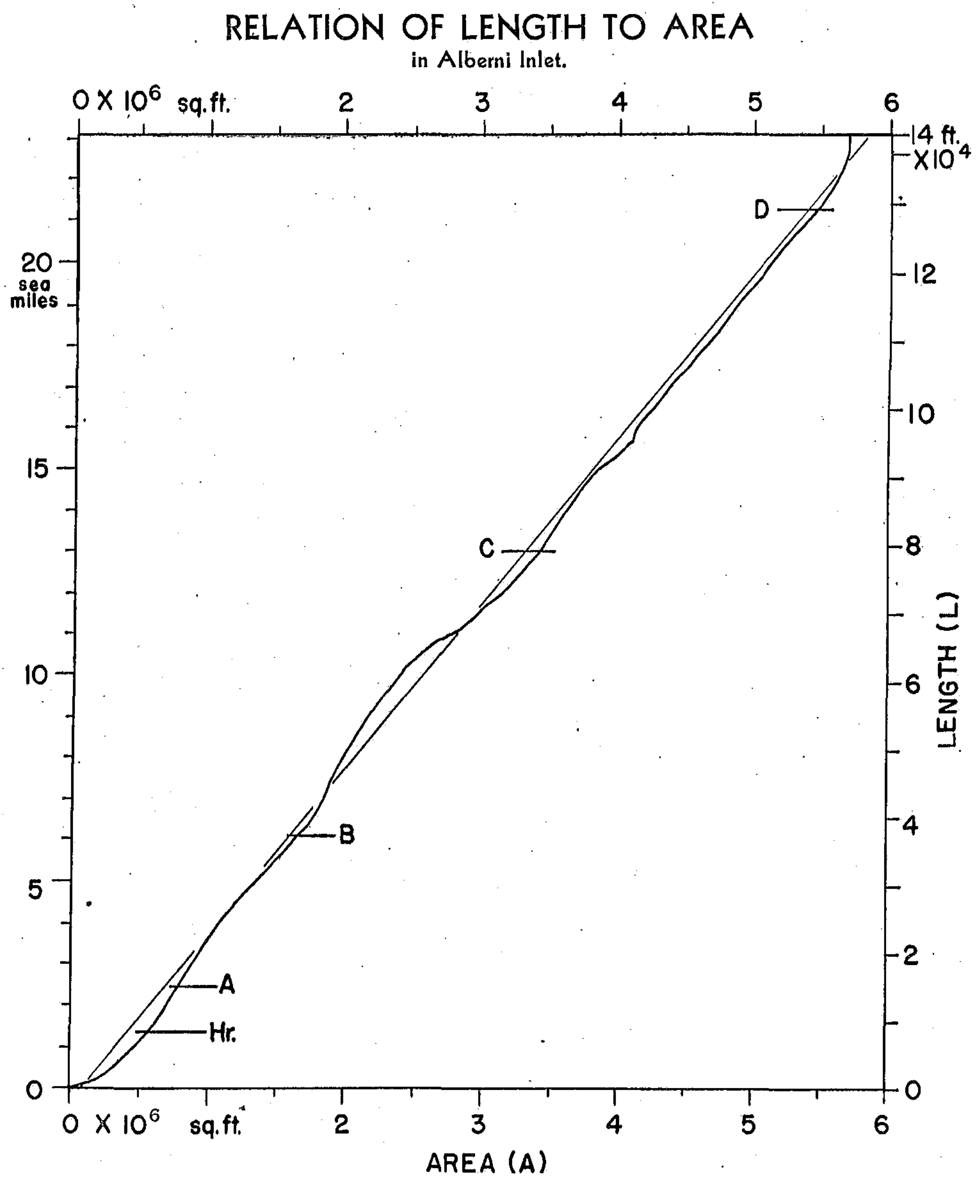


FIGURE 17.

expressed as

$$\frac{L}{V} = \frac{LT}{Lr} = \frac{T}{r} \qquad (13)$$

which is the quantity already derived as the limit of the discharge integral in equation 10.

Lacking suitable data for the analysis of this function, the displaced waters are assumed to be a proportional mixture of all ages, as indicated in equation 3.

Application to the Estuary

GEOGRAPHY

Because of the tide flats at the head (fig. 2), the area of Alberni harbour varies considerably with tidal height, although the width may be assumed to be constant because of the steep sides. The volume of the harbour, to the arbitrary limit at Polly point, is shown as a function of sea level in fig. 18.

RUN-OFF

The Somass river discharge (fig. 16) represents at least 98.5% of the land drainage into the harbour; consequently all other sources can be neglected.

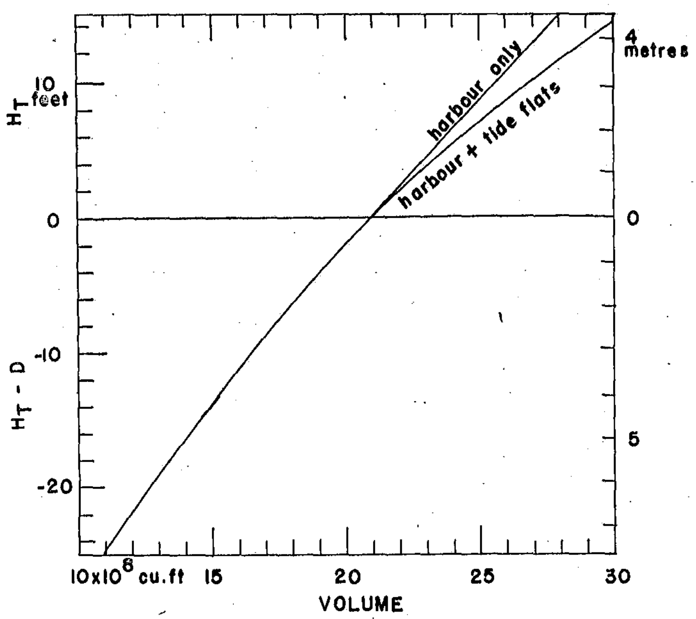


FIGURE 18. Relation of the volume of Alberni harbour to the tidal height.

METEOROLOGY

There are only two wind directions. One wind from the north (down the inlet) is usually of small velocity (less than 10 miles per hour) and of little consequence. The other wind is from the south (up the inlet) and frequently attains velocities of 20 to 25 miles per hour during the late summer, when it regularly endures from noon till sundown. At such times it has considerable effect on oceanographical conditions in the upper zone.

MEAN DEPTH OF THE UPPER ZONE

In order to compute the displacement and transport from the harbour as a whole, it is necessary to determine representative values of the depth of the upper zone (D) and the proportion of fresh water ($\bar{C}$).

It has been shown that the depth of the boundary oscillates with an amplitude depending on the tidal range, and about a nodal line whose depth depends on

TABLE VII. Depth of upper zone (D) in Alberni harbour in feet.

Date	June 9, 1941	June 10, 1941	
Mean Tide Range 7.7 ft.			
Station	*Flood*	*Ebb*	*Difference*
P15	11.30	15.48	4.18
Q19	12.01	15.12	3.11
P27	10.68	15.32	4.64
L24	11.74	14.81	3.07
L20	15.00	14.10	*−0.90*
M17	15.90	11.86	−4.04
K17	15.92	10.98	−4.94
H23	17.90	11.00	−6.90
Date	June 17, 1941	July 16, 1941	
Mean Tide Range 3.5 ft.			
Station	*Flood*	*Ebb*	*Difference*
015	10.76	11.80	1.04
P23	10.58	10.87	0.29
027	10.58	10.58	0.00
J27	9.60	10.47	0.87
I20	10.30	10.19	−0.11
L17	10.58	10.61	0.03
L20	10.69	10.02	*0.67*
Date	Aug. 27, 1941	Aug. 28, 1941	
Mean Tide Range 6.6 ft.			
Station	*Flood*	*Ebb*	*Difference*
P25	13.73	19.99	6.26
L28	14.68	17.28	2.60
P20	14.50	16.57	2.07
I24	13.30	16.82	3.52
P16	15.20	16.20	1.00
N14	12.15	15.78	3.63
L20	14.99	16.39	*1.40*

the run-off, but whose position appears to be fairly constant, at least where it passes through or very close to station L20. This is indicated by the data of boundary depth corresponding to fig. 10, given in table VII, which shows that the change at this station is the minimum in the harbour area. The conclusion is further supported by the data in table VIII, which shows that over a long series of observations, including a considerable range of discharge, the depth of the upper zone was constant within small limits on consecutive high and low tides. The one anomalous observation is readily explained by the extreme wind conditions.

TABLE VIII. Depth of upper zone at station L20.

Date 1941	Run-off (Q) (c.f.s.)	Depth of Upper Zone (D) (feet)		Diff.	% Diff.
		(H.W.)	(L.W.)		
April 23	2,070	12.10	12.72	0.62	5.2
24	1,970	13.12	12.22	−0.90	− 6.7
May 2	2,040	11.75	11.89	0.14	1.1
3	2,070	11.64	11.89	0.25	2.0
8	5,030	17.80	18.79	0.99	5.3
9	4,270	17.43	18.03	0.60	4.0
15	3,580	18.79	18.94	−0.15	− 1.0
16	5,040	18.48	18.94	0.46	1.6
June 9/10	2,270	16.15	15.18	−0.97	− 6.1
July 17/16	1,190	11.51	10.80	−0.71	6.3
18	1,195	15.40	16.00	0.60	3.8
19	1,195	18.90	23.08*	4.18	22.2*
Aug. 19/18	395	15.66	14.32	−1.34	− 8.6
22	330	25.78	24.90	−0.88	− 3.3
27/26	225	16.08	17.62	1.54	8.7

*Presumed to be in error because strong south wind at low water.

It is concluded that the depth of the upper zone at station L20 is the mean value in the harbour.

MEAN CONCENTRATION OF FRESH WATER

The mean concentration of fresh water in the upper zone, observed at the several stations, during three high and low waters surveys (corresponding to fig. 11) is given in table IX, where it may be noted that the value at station L20 is very close to the mean value at high and low water.

The significant difference between the high and low water values is explained by referring to the previous discussion of the water impounded over the tide flats. Since these were not observed, it was assumed that they were similar to those near the head at low water. Including this quantity in the mean high tide values in the area, the values at station L20 were found to agree within small limits, independent of tidal range, wind and run-off as shown in table X. The agreement of the low tide values is no less remarkable, as summarized in the second part of the table. Evidently the average of high and low tide values will show similar agreement.

Finally all data showing the proportion of fresh water in the upper zone at station L20, at neighbouring high and low tides is given in table XI, where it is shown that, except at the time of very low river discharge, the two values

TABLE IX. Proportion of fresh water (c) in the upper zone (C) of Alberni harbour.

Station	June 9, 1941 (H.W.)	June 10, 1941 (L.W.)	Diff.	Mean
P15	0.779	0.769	−0.010	0.744
Q19	0.752	0.735	−0.017	0.744
P27	0.682	0.768	0.086	0.725
L24	0.691	0.773	0.082	0.733
L20	*0.692*	*0.738*	*0.046*	*0.715*
M17	0.791	0.725	−0.066	0.758
K17	0.765	0.709	−0.056	0.737
H23	0.681	0.692	0.011	0.687
Mean (8)	0.717			
Mean H.W. (Est.)	0.720 with tide	flats		
(Mean—L20)	0.025 (3.6%)	0.008 (0.1%)		
	July 17, 1941	July 16, 1941		
O15	0.544	0.416	−0.128	0.480
P21	0.442	0.450	0.006	0.447
O27	0.360	0.447	0.087	0.403
J27	0.434	0.445	0.011	0.440
I20	0.443	0.438	−0.005	0.441
L17	0.447	0.455	0.008	0.451
L20	*0.458*	*0.435*	*−0.023*	*0.447*
Mean (7)	0.447	0.441	0.006	0.443
Mean H.W. (Est.)	0.446 with tide	flats		
(Mean—L20)	0.011 (0.2%)	0.06 (1.3%)		
	Aug. 27, 1941	Aug. 26, 1941		
P25	0.191	0.237	0.046	0.214
L28	0.174	0.284	0.110	0.229
P20	0.154	0.303	0.159	0.234
I24	0.165	0.319	0.154	0.242
P16	0.133	0.324	0.191	0.229
N14	0.154	0.302	0.148	0.228
L20	*0.158*	*0.291*	*0.133*	*0.224*
Mean (7)	0.161	0.294	0.105	0.242
Mean H.W. (Est.)	0.189 with tide	flats		
(Mean—L20)	0.003 (1.9%)	0.003 (1.0%)		

correspond within the limits of error. This anomaly has been explained by the complete change of the character of the water under these conditions (cf. fig. 10(a)).

It may be concluded from this discussion that the proportion of fresh water in the upper zone at station L20 is the mean value in the harbour at any time, and that the mean of the values observed at high and low water represents the mean values in the area during a tidal cycle.

DATA

For convenience in handling the large numbers of data, the computations

TABLE X. Proportion of fresh water (c) in the upper zone in Alberni harbour. Comparison of observed values (c) at Station L20, to mean of observed values ($\bar{C}$) at all other stations.

Date (1941)	River discharge (c.f.s.)	Tide range (feet)	Wind dir. vel. (m.p.h.)	C (L20)	$\bar{C}$	Diff.	% Diff.
			High tide				
May 16	5,040	7.1	S. 16	0.750	0.755	0.005	0.6
June 9	2,345	9.6	S. 22	0.692	0.720	0.028	3.9
July 8	1,360	9.6	– 0	0.536	0.549	0.013	2.4
July 17	1,195	6.8	– 0	0.458	0.446	−0.012	−2.7
Aug. 19	382	8.0	– 0	0.305	0.324	0.019	5.9
Aug. 27	215	9.5	– 0	0.158	0.161	0.003	1.9
Sept. 8	830	9.1	S. 12	0.277	0.272	−0.005	−1.8
			Low tide				
May 15	3,590	7.8	S. 12	0.656	0.696	0.040	5.8
June 10	2,200	12.5	– 0	0.738	0.739	0.001	0.0
July 16	1,189	9.9	N. 1	0.435	0.471	0.036	7.6
Aug. 26	238	8.8	N. 2	0.291	0.294	0.003	1.0

TABLE XI. Proportion of fresh water (c) in upper zone at station L20, at consecutive high and low tides.

Date 1941	River discharge (c.f.s.)	Proportion of fresh water (C at L20)		Difference	% Difference (referred to low tide value)
		High tide	*Low tide*		
April 23	2,080	0.690	0.700	0.010	1.4
May 2	2,040	0.665	0.704	0.039	5.5
3	2,070	0.727	0.723	−0.004	−0.6
8	5,020	0.626	0.681	0.055	8.1
9	4,300	0.555	0.530	−0.025	−4.7
15/16	4,300	0.750	0.756	0.006	0.8
June 9/10	2,300	0.692	0.738	0.046	6.2
July 17/16	1,190	0.458	0.435	−0.023	−5.3
18	1,190	0.510	0.554	0.044	7.9
19	1,195	0.525	0.545	0.020	3.7
Aug. 19/18	382	0.305	0.345	0.040	11.6
22	330	0.245	0.291	0.046	15.8
27/26	225	0.158	0.291	0.133	45.7

TABLE XII. Oceanographic characteristics in the upper zone of Alberni harbour, computed from the observations at station L20.

Date 1941	Run-off (Q Somass) (c.f.s.)	Wind		Tide		Depth of upper zone (D) (feet)	Volume of upper zone (AD) (cu. ft. $\times 10^{-8}$)	Proportion of fresh water (C)	Volume of fresh water in upper zone (ADC) (cu. ft. $\times 10^{-8}$)	Age T(1.039)/r (days)	Displacement (r)	Anomaly
		Dir.	Vel. (m.p.h.)	Phase	Height (feet)							
April 23	2,080	—	0	F	8.6	12.10	6.78	0.690	4.67	2.60	0.398	Normal
23	2,050	N	1	LW	3.2	12.72	5.90	0.700	4.13	2.33	0.444	Normal
24	1,975	—	0	HW	8.8	13.12	7.50	0.614	4.60	2.69	0.386	Normal
24	1,962	—	0	LW	3.3	12.22	5.70	0.557	3.18	1.88	0.552	Normal
May 2	2,034	—	0	LW	3.1	11.89	5.55	0.704	3.90	2.22	0.466	Normal
2	2,040	S	7	HW	9.0	11.75	6.75	0.665	4.49	2.55	0.406	Normal
3	2,070	S	7	LW	3.2	11.89	5.55	0.723	4.01	2.24	0.462	Normal
3	2,065	W	10	HW	9.0	11.64	6.65	0.727	4.84	2.71	0.382	Normal
8	5,030	—	0	HW	9.6	17.80	9.40	0.626	5.89	1.36	0.764	Normal
8	5,020	S	7	LW	3.0	18.79	8.25	0.681	5.62	1.30	0.798	Normal
9	4,310	—	0	HW	9.8	17.43	7.45	0.680	5.06	1.38	0.752	Freshet
9	4,220	N	5	LW	2.9	18.03	7.95	0.530	4.21	1.16	0.896	Freshet
15	3,570	S	22	LW	2.2	18.79	8.10	0.756	6.13	1.96	0.528	Wind
15	3,590	S	12	E	7.1	18.94	9.25	0.775	7.16	2.31	0.448	Wind
16	5,040	S	16	HW	9.7	18.48	9.70	0.750	7.27	1.67	0.622	Wind
June 4	2,650	—	0	HW	8.2	11.91	6.60	0.683	4.51	1.97	0.526	Freshet
5	2,530	—	0	LW	3.9	11.49	5.45	0.672	3.66	1.68	0.618	Freshet
6	2,405	—	0	F	6.4	10.98	6.44	0.495	3.18	1.53	0.678	Freshet
7	2,430	S	20	E	7.8	17.00	8.65	0.750	6.49	3.10	0.336	Wind
9	2,345	S	22	HW	9.6	16.15	8.75	0.692	6.05	2.99	0.348	Wind
10	2,200	—	0	LW	−0.7	15.18	6.25	0.738	4.61	2.43	0.426	Normal
23	1,786	—	0	F	5.6	6.50	3.65	0.650	2.37	1.54	0.674	Normal
25	1,757	S	15	E	8.0	17.33	8.80	0.625	5.50	3.62	0.286	Wind
26	1,719	—	0	LW	1.4	17.08	7.20	0.578	4.22	2.84	0.364	Normal
28	1,670	—	0	F	6.4	17.31	8.40	0.465	3.90	2.72	0.382	Normal
30	1,550	S	3	LW	1.9	18.82	8.05	0.586	4.72	3.53	0.294	Normal
July 1	1,492	S	23	F	7.7	17.29	8.75	0.505	4.42	2.96	0.350	Wind
3	1,528	N	1	F	7.0	15.68	7.90	0.569	4.49	3.40	0.304	Normal
4	1,535	S	10	LW	4.3	15.70	7.35	0.566	4.16	3.14	0.330	Normal
8	1,360	—	0	HW	9.6	13.61	7.65	0.536	4.10	3.49	0.296	Normal
16	1,189	N	1	LW	4.9	10.80	5.40	0.435	2.35	2.29	0.452	Freshet
17	1,195	—	0	F	6.8	11.51	6.65	0.458	3.05	2.95	0.352	Freshet
18	1,193	N	1	HW	7.6	15.42	7.95	0.510	4.05	3.93	0.264	Normal
18	1,198	S	6	LW	5.4	16.00	7.65	0.554	4.24	4.10	0.252	Normal
19	1,198	S	7	F	6.3	16.81	8.20	0.546	4.48	4.34	0.240	Normal
19	1,192	S	10	HW	7.7	18.90	9.40	0.523	4.91	4.77	0.218	Wind
19	1,195	S	11	E	6.4	22.16	10.35	0.545	5.65	5.48	0.190	Wind
19	1,200	S	22	LW	5.6	23.08	10.40	0.545	5.67	5.49	0.198	Wind
Aug. 18	405	S	16	LW	4.7	14.32	6.80	0.345	2.34	6.73	0.154	Wind
19	382	—	0	HW	8.0	15.66	8.15	0.305	2.48	7.53	0.138	Normal
21	358	S	5	F	8.1	22.08	10.75	0.293	3.15	10.20	0.102	Normal
22	335	—	0	LW	1.9	24.90	10.25	0.291	2.98	10.31	0.098	Normal
22	336	N	4	F	7.4	22.80	10.80	0.278	3.00	10.36	0.098	Normal
22	329	S	18	HW	8.9	25.78	12.35	0.245	3.03	9.71	0.106	Wind
22	333	S	17	E	4.4	25.02	10.80	0.268	2.90	10.07	0.104	Wind
26	238	N	2	LW	4.3	17.62	8.10	0.291	2.36	11.43	0.090	Normal
27	215	—	0	HW	9.5	16.08	8.70	0.158	1.38	8.89	0.116	Normal
Sept. 4	290	S	12	F	3.7	25.00	10.65	0.267	2.84	11.36	0.092	Freshet
5	735	S	13	HW	10.4	20.64	10.80	0.198	2.14	3.37	0.310	Freshet
8	830	S	12	HW	9.1	27.14	12.85	0.277	3.56	4.96	0.208	Wind
11	1,700	—	0	F	5.9	14.02	7.00	0.371	2.60	1.77	0.586	Freshet
14	1,500	N	2	F	5.7	18.87	8.90	0.378	3.36	2.60	0.400	Freshet

TABLE XIII. Observed oceanographic characteristics in the upper zone at each station in Alberni inlet.

Station	Date (1941) Time	Wind Dir.	Vel. (m.p.h.)	Tide Phase	height (feet)	Tidal data Time	height (feet)	Depth of upper zone (D) (feet)	Proportion of fresh water (c)
	May 28							Discharge (Somass R.) 2840 c.f.s.	
A	1110	N	14	F	5.8	0757	1.7	12.4	0.729
B	1412	N	6	HW	9.9	1423	10.0	15.2	0.624
C	1600	SW	17	E	9.3	1953	5.3	17.2	0.471
D	1818	SW	3	E	6.5			11.7	0.249
	Σ(7:05)							Mean(14.1)	
	May 30							Discharge (Somass R.) 2640 c.f.s.	
A	1934	—	0	E	5.8	0910	1.9	10.6	0.499
B	1740	N	5	E	8.0	1539	9.8	8.2	0.530
C	1520	N	9	HW	9.8	2120	5.4	10.1	0.354
D	1302	W	8	F	7.4			12.6	0.175
	Σ(6:32)							Mean(10.4)	
	June 4							Discharge (Somass R.) 2568 c.f.s.	
L20	0750	—	0	HW	9.1	0745	9.1	11.9	0.683
A	8837	N	8	HW	8.9	1334	3.7	11.7	0.686
B	0949	NE	10	E	7.3			11.7	0.568
C	1131	N	6	E	5.1			12.3	0.485
D	1450	SW	8	F	4.5			11.6	0.247
	Σ(7:00)							Mean(11.8)	
	June 5							Discharge (Somass R.) 2428 c.f.s.	
L20	1535	—	0	LW	4.3	0857	9.4	11.5	0.672
A	1450	S	4	LW	4.0	1432	3.9	6.8	0.649
B	1337	S	6	E	4.2			11.0	0.529
C	1100	—	0	E	7.5			11.2	0.500
D	0848	NE	5	HW	8.9			12.0	0.271
	Σ(6:48)							Mean(10.5)	
	June 6							Discharge (Somass R.) 2396 c.f.s.	
L20	0709	—	0	F	6.7	0338	2.4	11.0	0.495
A	8800	NW	2	F	8.0	1000	9.8	10.5	0.549
B	0921	—	0	HW	9.5	1533	4.1	11.8	0.479
C	1105	SE	26	HW	9.2			11.6	0.540
D	1214	S	6	E	6.1			6.3	0.277
	Σ(6:05)							Mean(10.2)	
	June 7							Discharge (Somass R.) 2418 c.f.s.	
L20	1243	S	20	E	8.7	0435	1.5	17.0	0.750
A	1150	S	25	E	9.9	1057	10.3	16.7	0.661
B	1045	S	20	HW	10.3	1630	4.2	12.3	0.549
C	0850	S	20	F	8.5			12.2	0.400
D	0700	S	14	F	4.8			21.7	0.121
	Σ(5:43)							Mean(13.0)	

TABLE XIII—*Continued*

Station	Date (1941) Time	Wind Dir.	Vel. (m.p.h.)	Tide Phase	height (feet)	Tidal data Time	height (feet)	Depth of upper zone (D) (feet)	Proportion of fresh water (c)
	June 23							Discharge (Somass R.) 1790 c.f.s.	
L20	0906	—	0	F	6.3	0550	2.2	6.5	0.650
A	1019	NW	6	F	8.0	1216	9.6	6.5	0.584
B	1134	S	1	F	9.4	1736	5.6	10.2	0.386
C	1345	S	21	E	8.8			9.1	0.304
D	1630	SW	12	LW	5.9			11.4	0.155
	Σ(7:24)							Mean (8.7)	
	June 25							Discharge (Somass R.) 1717 c.f.s.	
L20	1521	S	15	E	8.6	0704	1.6	17.4	0.625
A	1447	S	22	E	9.4	1327	10.0	17.0	0.479
B	1107	S	9	HW	10.0	1859	5.3	16.1	0.374
C	1025	S	14	F	6.4			24.5°	0.130
D	0740	—	0	F	2.0			8.6	0.062
	Σ(7:39)							Mean(16.7)	
	June 26							Discharge (Somass R.) 1695 c.f.s.	
L20	0712	—	0	LW	1.5	0739	1.4	17.1	0.578
A	0809	NW	6	LW	1.7	1402	10.2	16.8	0.530
B	0921	S	1	F	3.1			19.4	0.427
C	1131	S	21	F	7.3			18.6	0.232
D	1400	SW	12	HW	10.2			20.6	0.088
	Σ(6:48)							Mean(18.5)	
	June 28							Discharge (Somass R.) 1638 c.f.s.	
L20	1226	S	15	F	6.7	0851	1.6	17.3	0.465
A	1137	S	22	F	5.2	1515	10.4	18.3	0.580
B	1014	S	9	F	2.6	2106	4.8	24.7	0.367
C	0806	S	14	LW	1.8			23.8	0.202
D	0550	—	0	E	5.5			15.0	0.083
	Σ(6:36)							Mean(19.8)	
	June 30							Discharge (Somass R.) 1335 c.f.s.	
L20	0954	—	0	LW	2.5	1015	2.5	18.8	0.586
A	1043	—	0	LW	2.6	1642	10.5	18.0	0.591
B	1202	—	0	F	4.1			23.5	0.411
C	1415	S	18	F	7.8			18.1	0.231
D	1638	S	9	HW	10.5			16.1	0.084
	Σ(6:44)							Mean(18.9)	
	July 1							Discharge (Somass R.) 1540 c.f.s.	
L20	1516	—	0	F	8.4			17.3	0.505
A	1420	—	0	F	7.0	0441	9.6	16.8	0.585
B	1222	S	13	F	4.0	1104	3.1	17.1	0.459
C	1015	S	8	E	3.3	1737	10.6	16.4	0.298
D	0735	—	0	E	6.7			17.3	0.108
	Σ(7:41)							Mean(17.0)	

TABLE XIII—*Continued*

Station	Date (1941) Time	Wind Dir.	Vel. (m.p.h.)	Tide Phase	height (feet)	Tidal data Time	height (feet)	Depth of upper zone (D) (feet)	Proportion of fresh water (c)
	July 3							Discharge (Somass R.) 1508 c.f.s.	
L20	0507	S	10	F	7.0			15.6	0.569
A	0600	SW	7	F	8.4	0109	3.6	16.6	0.621
B	0715	S	15	HW	9.0	0722	8.9	16.3	0.486
C	0902	S	21	E	7.5	1300	4.1	16.4	0.325
D	1130	SW	11	E	4.7			16.5	0.088
	Σ(6:23)							Mean(16.3)	
	July 4							Discharge (Somass R.) 1478 c.f.s.	
L20	1449	S	10	LW	4.7			15.7	0.566
A	1359	S	18	LW	4.5	0840	9.1	17.1	0.638
B	1208	S	15	E	5.7	1403	4.5	13.0	0.520
C	1002	S	2	E	8.4			16.5	0.296
D	0800	N	4	F	9.0			17.2	0.137
	Σ(6:49)							Mean(15.9)	
	Aug. 21							Discharge (Somass R.) 217 c.f.s.	
L20	0958	S	5	F	7.3	0529	2.1	22.1	0.293
A	1021	S	3	F	9.1	1153	10.2	23.2	0.268
B	1254	S	28	HW	9.7	1731	4.6	20.6	0.222
								Mean(22.0)	
	Oct. 31, 1939							Discharge (Somass R.) 2650 c.f.s.	
A	1800	S	3	E	5.2			11.3	0.495
B	1700	S	4	E	7.5	0754	5.4	9.4	0.197
C	1400	S	5	HW	8.8	1350	12.0	8.4	0.184
D	0915	N	3	F	6.2	2042	2.0	13.6	0.156
	Nov. 1, 1939							Discharge (Somass R.) 2550 c.f.s.	
A	1000	—	0	F	6.4			11.3	0.302
B	1110	N	2	F	8.2	0835	5.6	11.8	0.311
C	1430	—	0	HW	10.6	1429	11.6	10.4	0.195
D	1500	W	1	E	8.7			13.3	0.227

which follow directly from equation 10, were arranged in tabular form and are shown with examples in appendix IV.

The displacement factors and associated quantities computed from the data at station L20 are shown in table XII.

APPLICATION TO THE INLET

As has been explained, the requirements of observation in the inlet were only met on two occasions (June 4 and 5, and July 3 and 4). Otherwise every series contains more than one tidal phase; hence the mean state cannot be evaluated from consecutive series of observations. Because of this, and because the inlet survey was only continued for six weeks, it was decided to evaluate the mean properties in each continuing interval, in each series, and attempt to relate the state observed in the inlet, to that in the estuary (harbour).

OBSERVED DATA

The displacement factors and associated data as observed at each station are shown in table XIII.

The representative values of the factors in each continuing interval were computed as the integral mean of the values at each station, e.g.

$$\overline{D} = \frac{1}{A}\int_0^A (D)\, dA \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where A is the area of the inlet from the head (O) to the seaward limit of the interval (station A, B, C, D).

The mean values of the factors, displacement and the transport functions in each continuing interval are shown in table XIV. The tabular method of computing these quantities is illustrated in appendix II.

TABLE XIV. Mean oceanographic characteristics in continuing intervals of the upper zone in Alberni inlet.

Date (1941) Interval	Mean discharge Somass river ($\overline{Q}$) (c.f.s.)	Depth of upper zone ($\overline{D}$) (feet)	Proportion of fresh water ($\overline{C}$)	Volume of upper zone ($A\overline{DC}$) (cu. ft. $\times 10^{-8}$)	Displacement (r)	Age T (1.039)/r (days)	Transport (l) (feet)	Velocity (v) (ft./sec.)
May 28								
0–A	1,960	12.4	0.731	7.28	0.244	4.25	3,810	0.0425
0–B	2,020	13.1	0.702	15.05	0.144	7.22	5,460	0.0610
0–C	2,240	14.7	0.612	31.40	0.100	10.36	7,960	0.0889
0–D	2,350	14.6	0.497	47.10	0.088	11.72	11,310	0.126
May 30								
0–A	2,720	11.6	0.498	4.22	0.584	1.77	9,100	0.102
0–B	2,820	10.0	0.506	8.25	0.364	2.85	13,800	0.154
0–C	2,900	9.8	0.476	15.85	0.258	4.02	20,500	0.230
0–D	2,960	10.4	0.370	24.90	0.210	4.93	27,100	0.302
June 4								
Harbour	2,650	11.9	0.683	4.51	0.526	1.83	4,600	0.0514
0–A	2,800	11.9	0.681	6.50	0.390	2.65	6,090	0.0680
0–B	2,740	11.8	0.654	12.60	0.232	4.446	8,810	0.0983
0–C	2,740	11.9	0.586	24.28	0.158	6.52	12,600	0.141
0–D	2,780	11.9	0.485	37.48	0.130	7.95	16,780	0.187
June 5								
Harbour	2,530	11.5	0.672	3.66	0.536	1.93	4,690	0.0523
0–A	2,680	11.5	0.661	6.06	0.400	2.59	6,245	0.0696
0–B	2,740	10.2	0.630	10.41	0.280	3.70	10,620	0.119
0–C	2,720	10.7	0.566	21.00	0.182	5.70	14,500	0.162
0–D	2,710	11.1	0.479	34.50	0.140	7.46	18,050	0.202

TABLE XIV—*Continued*

Date (1941) Interval	Mean discharge Somass river ($\bar{Q}$) (c.f.s.)	Depth of upper zone ($\bar{D}$) (feet)	Proportion of fresh water ($\bar{C}$)	Volume of upper zone ($A\bar{D}\bar{C}$) (cu. ft. $\times 10^{-8}$)	Displacement (r)	Age $\frac{T(1.039)}{r}$ (days)	Tranport (l) (feet)	Velocity (v) (ft./sec.)
June 6								
Harbour	2,405	11.0	0.495	3.18	0.678	1.53	5,930	0.066
0–A	3,100	10.9	0.496	4.34	0.648	1.60	10,110	0.113
0–B	2,610	11.0	0.505	9.10	0.300	3.40	11,400	0.127
0–C	2,680	11.4	0.509	20.20	0.186	5.56	14,800	0.165
0–D	2,680	10.3	0.468	31.20	0.152	6.80	19,600	0.218
June 7								
Harbour	2,430	17.0	0.750	6.49	0.344	3.01	3,010	0.0336
0–A	2,560	17.0	0.751	10.20	0.228	4.55	3,560	0.0397
0–B	2,640	15.7	0.681	17.48	0.160	6.46	6,080	0.0679
0–C	2,640	13.9	0.585	28.22	0.134	7.73	10,680	0.119
0–D	2,650	15.3	0.419	41.50	0.112	9.18	14,450	0.161
June 23								
Harbour	1,786	6.5	0.650	2.37	0.630	3.17	5,500	0.0613
0–A	1,760	6.5	0.463	2.40	0.664	3.01	10,360	0.116
0–B	1,731	7.4	0.505	6.11	0.306	6.56	11,610	0.130
0–C	1,715	8.6	0.410	12.25	0.196	10.18	15,600	0.174
0–D	1,735	9.4	0.318	19.30	0.160	12.60	20,600	0.230
June 25								
Harbour	1,757	17.4	0.625	5.50	0.310	3.34	2,710	0.0302
0–A	1,761	17.3	0.626	8.68	0.184	5.63	2,870	0.0320
0–B	1,610	17.0	0.528	14.55	0.118	8.82	4,490	0.0501
0–C	1,805	18.7	0.369	24.00	0.104	9.94	8,280	0.0924
0–D	1,755	17.7	0.251	28.80	0.108	9.61	13,920	0.155
June 26								
Harbour	1,719	17.1	0.578	4.22	0.322	3.21	2,820	0.0315
0–A	1,573	17.1	0.580	7.90	0.181	5.74	2,820	0.0315
0–B	1,725	17.6	0.527	15.10	0.116	8.72	4,400	0.0491
0–C	1,775	18.3	0.419	26.70	0.092	11.00	7,320	0.0818
0–D	1,780	19.0	0.294	36.20	0.085	11.90	10,950	0.122
June 28								
Harbour	1,670	17.3	0.465	3.90	0.374	2.72	3,270	0.0365
0–A	1,680	17.3	0.465	6.43	0.233	4.36	3,640	0.0406
0–B	1,720	19.4	0.470	14.90	0.120	8.42	4,560	0.0510
0–C	1,695	22.0	0.362	27.60	0.085	12.00	6,760	0.0755
0–D	1,715	20.8	0.267	36.00	0.079	12.30	10,200	0.114
June 30								
Harbour	1,550	18.8	0.586	4.72	0.264	3.78	2,310	0.0258
0–A	1,615	18.2	0.586	8.82	0.163	6.24	2,540	0.0284
0–B	1,670	19.8	0.544	17.50	0.100	10.21	3,800	0.0424
0–C	1,680	20.3	0.423	29.90	0.077	13.13	6,140	0.0685
0–D	1,680	18.9	0.311	38.00	0.076	13.29	9,800	0.110

TABLE XIV—*Continued*

Date (1941) Interval	Mean discharge Somass river ($\bar{Q}$) (c.f.s.)	Depth of upper zone ($\bar{D}$) (feet)	Proportion of fresh water ($\bar{C}$)	Volume of upper zone ($A\bar{D}\bar{C}$) (cu. ft. $\times 10^{-8}$)	Displacement (r)	Age $\frac{T(1.039)}{r}$ (days)	Transport (1) (feet)	Velocity (v) (ft./sec.)
July 1								
Harbour	1,492	17.3	0.505	4.42	0.312	3.25	2,730	0.0305
0–A	1,590	17.3	0.505	6.99	0.202	5.03	3,150	0.0352
0–B	1,655	17.1	0.515	14.35	0.120	8.44	4,560	0.0510
0–C	1,680	16.9	0.443	26.10	0.089	11.46	7,090	0.0790
0–D	1,680	16.9	0.332	36.40	0.080	12.70	10,300	0.115
July 3, 1941								
Harbour	1,528	15.7	0.569	4.49	0.294	3.42	2,570	0.0287
0–A	1,555	15.7	0.569	7.13	0.193	5.26	3,050	0.0340
0–B	1,620	16.1	0.561	14.70	0.115	8.84	4,370	0.0488
0–C	1,660	16.2	0.478	27.00	0.085	11.98	6,760	0.0755
0–D	1,660	16.3	0.352	37.20	0.081	12.51	10,420	0.116
July 4, 1941								
Harbour	1,535	15.7	0.566	4.16	0.302	3.37	2,640	0.0295
0–A	1,530	15.6	0.568	7.13	0.190	5.33	2,960	0.0331
0–B	1,590	15.4	0.574	14.40	0.115	8.81	4,370	0.0488
0–C	1,700	15.0	0.487	25.50	0.092	11.05	7,320	0.0819
0–D	1,641	15.9	0.354	36.50	0.078	13.02	10,050	0.112
August 21, 1941								
Harbour	358	22.1	0.293	3.15	0.103	9.88	900	0.0101
0–A	408	22.1	0.294	5.19	0.070	14.53	1,090	0.0122
0–B	463	22.0	0.269	9.64	0.050	20.21	1,900	0.0212
October 31, 1939								
0–A	3,120	11.3	0.496	4.48	0.617	1.64	9,650	0.108
0–B	3,140	10.8	0.424	7.47	0.438	2.32	16,650	0.186
0–C	3,145	9.8	0.311	10.60	0.408	2.49	32,500	0.364
0–D	3,150	10.4	0.242	16.25	0.335	3.02	43,100	0.482
November 1, 1939								
0–A	2,940	11.6	0.363	3.36	0.780	1.30	12,200	0.136
0–B	3,020	11.5	0.334	6.28	0.500	2.03	19,000	0.212
0–C	3,070	11.3	0.292	11.47	0.368	2.75	29,300	0.328
0–D	3,180	11.5	0.254	18.90	0.290	3.50	37,300	0.417

RELATION BETWEEN INLET AND ESTUARY DATA

A good many of the primary arguments and deductions regarding the mechanism of the inlet have been predicated on the constancy of the depth of the upper zone, and the dependence of the rate of mixing on the tidal velocity, for which no individual examples could be given. Because it was definitely attempted to make observations in the consecutive series of stations in the inlet on complementary phases of the tide, and because the error in measurement of the depth of the upper zone was a function of the distance of the inter-zone

TABLE XV. Ratio of displacement factors at each station in Alberni inlet.

	L20	A	B	C	D
Depth of upper zone (*D*)					
Ratio	1.0	1.0	1.0	1.0	1.0
Fiducial limit (90%)		±0.04	±0.14	±0.14	±0.08
Constancy (feet)		±0.4	±1.4	±0.8	±1.1
Proportion of fresh water (*C*)					
Ratio	1.0	0.95	0.82	0.59	0.30
Fiducial limit (90%)		±0.10	±0.14	±0.15	±0.13

boundary from the mid-point of adjacent observation, the probability of these errors being positive or negative is about equal, and they should tend to vanish in consideration of the mean state from all the data, but any persistent function would remain.

Accordingly, the ratio of the displacement factors at each station to those at station L20 (which represents the estuary) in each series was calculated. The mean values with the fiducial limits of 90% reliability are shown in table XV.

TABLE XVI. Computation of sea water transferred to the upper zone per unit time.

	Hbr.	A	B	C	D
Ratio of fresh water at each station (table XIV)	1.0	0.98	0.82	0.59	0.30
Ratio of elemental volumes of fresh plus sea water to fresh water	1.0	1.02	1.22	1.70	3.34
		0–A	A–B	B–C	C–D
Sea water gained in each successive interval		0.02	0.20	0.48	1.64
Ratio of transport time in each interval ($\Delta T/r$, table XVII)	1.0	0.41	0.97	0.85	0.33
Sea water gained per unit time in each interval	0	0.08	0.21	0.41	0.54
Computation of the ratio of tidal velocities					
		0–A	0–B	0–C	0–D
Ratio of inlet area continuing intervals (table IV)	1.0	1.37	2.78	5.95	11.09
		A–B	A–B	B–C	C–D
Ratio of average width of consecutive invals (table IV)	1.0	0.719	0.555	0.664	0.916
Ratio of average tidal velocity in consecutive intervals	1.0	1.91	5.01	8.96	12.1
Transport velocity					
Ratio of average transport velocities in consecutive intervals (table XVII)	1.0	1.3	1.6	2.4	3.7

The depth of the upper zone is shown to be constant within the interval of sampling (± 1.5 feet), which confirms the earlier deduction that any inequalities in this level must be compensated by local accelerations in excess of transport velocity.

The decreasing proportion of fresh water towards the mouth of the inlet was deduced to be the result of the rate of mixing due to the tide alone. If this is the case, the rate of mixing should increase towards the mouth of the inlet, in proportion to the increase in tidal velocity.

The rate of mixing is most conveniently indicated by the volume of sea water added to the upper zone per unit of time, during the transit of the unit volume through each successive interval of the inlet (A-B, B-C, etc.). The

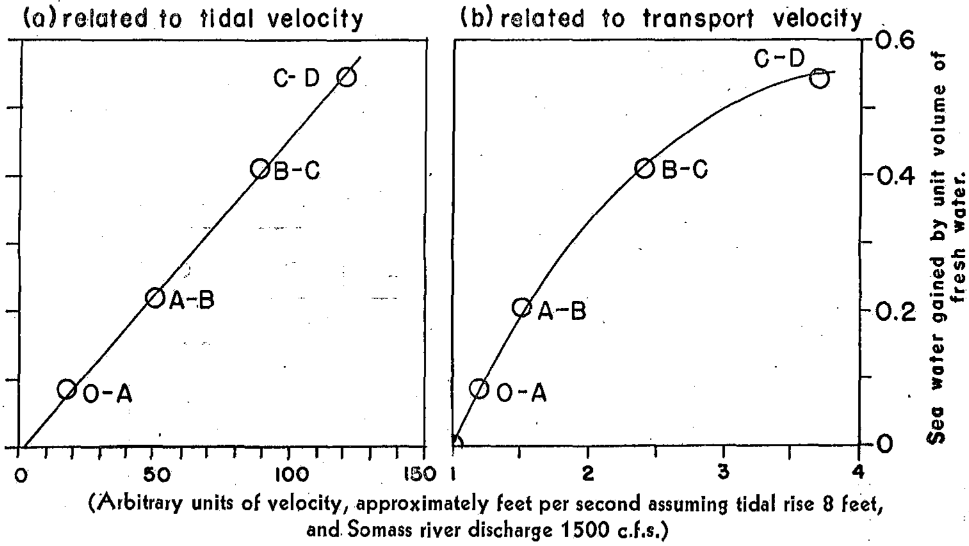


FIGURE 19. Sea water gained by unit volume of fresh water per unit time in each successive interval of Alberni inlet, (see table XVI)

ratio of the tidal velocities in each section is the ratio of the volume required for unit tidal rise in the continuing interval (O-A, O-B) divided by the ratio of the average width of the successive sections. These computations are shown in table XVI.

The relation between these quantities is linear (fig. 19(a)), which confirms the earlier deduction that mixing is a tidal function. The relation of mixing to the transport velocity in each interval is also shown (fig. 19(b)) and indicates that the downstream increase in velocity is greater than the increase in the rate of mixing. Further, if this relation were significant, the relation to tidal velocity would not be linear.

The relation to tidal velocity also confirms the deduction that the vertical chlorinity gradient is in equilibrium with the velocity gradient; for, if the cycle of tidal velocity gradient (fig. 4) varied significantly in relation to the depth of the upper zone, the points would be scattered randomly.

The ratios between the displacement and transport functions in the continuing and consecutive intervals of the upper zone were determined as shown in table XVII, with fiducial limits of 90% reliability.

TABLE XVII. Ratio of properties in intervals of the upper zone.

Ratios in continuing intervals.

	Hbr.	0–A	0–B	0–C	0–D
Depth of upper zone (D)					
Ratio	1.00	1.00	1.00	1.00	1.00
Fiducial limit (90%)		±0.00	±0.03	±0.07	±0.06
Constancy (90%) (feet)		±0.1	±0.3	±0.4	±0.8
Proportion of fresh water (C)					
Ratio	1.00	0.98	0.94	0.75	0.58
Fiducial limit (90%)		±0.04	±0.03	±0.07	±0.05
Displacement (r)					
Ratio	1.00	0.71	0.42	0.31	0.28
Fiducial limit (90%)		±0.08	±0.03	±0.03	±0.04
Transport velocity at seaward limit					
Ratio	1.0	1.3	1.8	2.9	4.4
Fiducial limit (90%)		±0.2	±0.1	±0.3	±0.5
Transport time	1.00	1.41	2.38	3.23	3.56

Ratios in consecutive intervals

	Hbr.	0–A	A–B	B–C	C–D
Displacement (r)	1.00	0.71	0.83	0.59	0.60
Mean transport velocity	1.0	1.3	1.6	2.4	3.7
Transport time	1.00	1.41	0.97	0.85	0.33

PREDICTION OF THE PHYSICAL STATE

It is now possible to recognize the oceanographic state in any part of the upper zone from knowledge of the discharge of the Somass river and of the wind conditions.

The relations of the mean depth of the upper zone, the concentration of fresh water and the displacement from Alberni harbour as a whole to the discharge of the Somass river are shown in figs. 14(a), (b) and (c), and the relations of these factors and the transport functions at the stations and in the continuing, and consecutive intervals of the inlet are given in tables XV and XVII. The

TABLE XVIII. Properties of the water at station L20 (mean values in the upper zone).

Date (1941)	Discharge ($\overline{Q}$) (Somass r.) (c.f.s.)	Wind Dir.	Wind Vel. (m.p.h.)	Tide Phase	Tide Height (feet)	Mean temp. ($\overline{T}$°C.)	Chlorinity ($\overline{Cl}$. °/₀₀)	Dissolved oxygen Concentration (p.p.m.)	Dissolved oxygen Solubility (p.p.m.)	Dissolved oxygen Saturation (%)
April 23	2,080	—	0	F	8.6	13.51	5.30	10.11	9.91	102
23	2,050	N	1	LW	3.2	13.52	5.12	9.92	9.92	100
24	1,975	—	0	HW	8.8	13.71	5.85	9.98	9.80	102
24	1,962	—	0	LW	3.3	13.27	7.55	9.18	9.72	95
May 2	2,034	—	0	LW	3.1	12.68	5.11	10.29	10.12	101
2	2,040	S	7	HW	9.0	12.72	5.77	9.59	10.04	95
3	2,070	S	7	LW	3.2	12.91	4.78	10.06	10.10	100
3	2,065	W	10	HW	9.0	13.32	4.71	9.91	10.01	99
8	5,030	—	0	HW	9.6	11.92	6.41	10.13	10.14	100
8	5,020	S	7	LW	3.0	12.13	5.46	10.45	10.19	103
9	4,310	—	0	HW	9.8	12.52	5.49	10.03	10.11	99
9	4,220	N	5	LW	2.9	12.40	8.06	10.06	9.85	102
15	3,570	S	22	LW	2.2	13.53	5.83	10.03	9.85	102
15	3,590	S	12	E	7.1	13.41	3.79	9.50	10.10	94
16	5,040	S	16	HW	9.7	13.04	4.21	9.81	10.13	97
June 4	2,650	—	0	HW	8.2	15.07	5.47	9.27	9.58	97
5	2,530	—	0	LW	3.9	15.16	5.64	9.28	9.61	97
6	2,405	—	0	F	6.4	14.17	8.71	8.98	9.43	95
7	2,430	S	20	E	7.8	15.02	4.29	9.51	9.60	99
9	2,345	S	22	HW	9.6	14.70	5.29	9.24	9.67	96
10	2,200	—	0	HW	−0.7	15.11	4.50	9.23	9.66	96
23	1,786	—	0	F	5.6	14.81	6.13	6.22	9.50	65
25	1,757	S	15	E	8.0	14.37	6.49	8.79	9.61	91
26	1,719	—	0	LW	1.4	16.98	7.28	8.71	9.05	96
28	1,670	—	0	F	6.4	16.90	9.22	9.19	8.88	103
30	1,550	S	3	LW	1.9	17.46	7.06	8.88	9.00	99
July 1	1,492	S	23	F	7.7	17.35	8.40	8.94	8.88	101
3	1,528	N	1	F	7.0	16.12	7.51	8.89	9.17	97
4	1,535	S	10	LW	4.3	18.22	7.54	8.84	8.80	100
8	1,360	—	0	HW	9.6	18.00	8.08	8.66	8.80	99
16	1,189	N	1	LW	4.9	19.22	9.95	8.45	8.43	100
17	1,195	—	0	F	6.8	20.35	9.55	8.37	8.28	101
18	1,193	N	1	HW	7.6	20.87	8.65	8.10	8.28	98
18	1,198	S	.6	LW	5.4	20.63	8.19	8.37	9.36	100
19	1,198	S	7	F	6.3	22.06	7.96	8.10	8.16	99
19	1,192	S	10	HW	7.7	21.90	8.26	7.98	8.15	98
19	1,195	S	11	E	6.4	23.97	7.94	8.00	7.88	101
19	1,200	S	22	LW	5.6	21.65	8.26	8.01	8.19	98

TABLE XVIII—*Continued*

Date (1941)	Discharge ($\bar{Q}$) (Somass r.) (c.f.s.)	Wind Dir.	Wind Vel. (m.p.h.)	Tide Phase	Tide Height (feet)	Mean temp. ($\bar{T}$°C.)	Chlorinity ($\bar{Cl}$. °/₀₀)	Dissolved oxygen Concentration (p.p.m.)	Dissolved oxygen Solubility (p.p.m.)	Dissolved oxygen Saturation (%)
Aug. 18	405	S	16	LW	4.7	20.01	11.45	8.89	8.17	109
19	382	—	0	HW	8.0	19.48	12.28	8.10	8.18	99
21	358	S	5	F	8.1	17.71	12.31	7.62	8.45	90
22	335	—	0	LW	1.9	19.20	11.70	7.42	8.27	90
22	329	S	18	HW	8.9	18.70	13.11	7.45	8.22	91
22	333	S	17	E	4.4	19.32	12.10	7.95	8.21	97
26	238	N	2	LW	4.3	17.52	12.31	7.04	8.48	83
27	215	—	0	HW	9.5	15.50	14.73	6.74	8.59	79
Sept. 4	290	S	12	F	3.7	15.90	12.58	7.81	8.72	90
5	735	S	13	HW	10.4	14.86	13.65	7.31	8.80	83
8	830	S	12	HW	9.1	16.62	12.28	8.26	8.65	96
11	1,700	—	0	F	5.9	14.81	10.87	8.00	9.07	88
14	1,500	N	2	F	5.7	15.29	9.28	8.51	9.15	93

deviations to be expected in the presence of strong south winds and freshets are shown in the figures. The tidal cycle of the estuary has been quantitatively demonstrated, and that in the inlet has been shown to be a simple function of it.

PROPERTIES OF THE WATER

TEMPERATURE

The original data are on file at the Pacific Biological Station, Nanaimo, B.C. and can be obtained on application to the Director. The mean values in the upper zone are given in tables XVIII and XIX.

Daily observations of the sea water temperature were made during the latter half of the rising tide occurring in daylight hours, at 3 feet depth, at the proposed mill site near the mouth of the Somass river (fig. 2). These data (fig. 20) are characteristic of bays along the British Columbia coast and show that the temperature in the upper zone is primarily a seasonal function.

A series of typical temperature gradients at the various stations are shown in fig. 21. In these it is remarked that the inflexion in the temperature gradient always coincides with that in the salinity gradient, which is to be expected from the mechanism at this boundary. It is to be noted that there is a tendency for the temperature to increase slightly with depth at the head station (station L20) indicating that in general the fresh run-off waters which lie on the surface are colder than the inlet water. This phenomenon vanishes downstream as the waters become mixed. The maximum temperatures occur between stations A and B, and decrease from there to the mouth of the inlet. Evidently the rate of insolation exceeds the cooling effect of mixing with middle zone waters to this point, but to seaward the waters are mixed more rapidly than

TABLE XIX. Properties of the water in Alberni inlet (mean values in the upper zone).

Date (1941) Station	Wind		Tide		Mean temp. ($\overline{T}$°C.)	Chlorinity ($\overline{Cl}$. °/₀₀)	Dissolved oxygen		
	Dir.	Vel. (m.p.h.)	Phase	Height (feet)			Concentration (p.p.m.)	Solubility (p.p.m.)	Saturation (%)
May 28						Discharge (Somass R.) 2840 c.f.s.			
A	N	14	F	5.8	15.00	4.70	9.78	9.67	101
B	N	6	HW	9.9	14.71	6.53	9.63	9.55	101
C	SW	17	E	9.3	14.38	9.12	9.66	9.34	102
D	SW	13	E	6.5	14.80	12.95	9.83	8.87	111
May 30						Discharge (Somass R.) 2640 c.f.s.			
A	—	0	E	5.8	14.21	8.69	9.69	9.42	119
B	N	5	E	8.0	14.65	8.15	9.67	9.40	103
C	N	9	HW	9.8	14.40	11.20	9.70	9.11	107
D	W	8	F	7.4	13.63	14.30	10.62	8.95	119
June 4						Discharge (Somass R.) 2568 c.f.s.			
L20	—	0	HW	9.1	15.07	5.47	9.27	9.58	97
A	N	8	HW	8.9	15.21	5.42	9.19	9.55	96
B	NE	10	E	7.3	14.71	7.46	9.60	9.45	102
C	N	6	E	5.1	14.90	8.90	9.58	9.26	103
D	SW	8	F	4.5	15.41	12.99	10.32	8.76	118
June 5						Discharge (Somass R.) 2428 c.f.s.			
L20	—	0	LW	4.3	15.16	5.64	9.28	9.61	97
A	S	4	LW	4.0	15.90	6.04	9.62	9.36	103
B	S	6	E	4.2	15.15	8.10	9.54	9.30	103
C	—	0	E	7.5	15.30	8.60	9.76	9.21	106
D	NE	5	HW	8.9	14.79	12.51	9.98	8.93	112
June 6						Discharge (Somass R.) 2396 c.f.s.			
L20	—	0	F	6.7	14.17	8.71	8.98	9.43	95
A	NW	2	F	8.0	14.40	7.78	9.52	9.48	101
B	—	0	HW	9.5	14.38	9.00	9.06	9.35	97
C	SE	26	HW	9.2	14.82	7.94	9.57	9.38	102
D	S	6	E	6.1	14.65	12.48	10.11	8.95	113
June 7						Discharge (Somass R.) 2418 c.f.s.			
L20	S	20	E	8.7	15.02	4.29	9.51	9.60	99
A	S	25	E	9.9	14.87	5.82	9.18	9.59	96
B	S	20	HW	10.3	14.78	7.75	9.53	9.41	101
C	S	20	F	8.5	14.33	10.30	8.68	9.21	94
D	S	14	F	4.8	14.30	15.10	9.35	9.75	96

TABLE XIX—*Continued*

Date (1941) Station	Wind		Tide		Mean temp. ($\bar{T}$°C.)	Chlorinity ($\bar{Cl}$.°/₀₀)	Dissolved oxygen		
	Dir.	Vel. (m.p.h.)	Phase	Height (feet)			Concentration (p.p.m.)	Solubility (p.p.m.)	Saturation (%)
June 23						Discharge (Somass R.) 1790 c.f.s.			
L20	—	0	F	6.3	14.81	6.13	6.22	9.50	66
A	NW	6	F	8.0	14.76	7.29	8.58	9.46	91
B	S	1	F	9.4	14.40	10.72	8.79	9.16	96
C	S	21	E	8.8	14.13	12.20	9.54	9.06	105
D	SW	12	LW	5.9	13.78	14.80	10.17	8.88	114
June 25						Discharge (Somass R.) 1717 c.f.s.			
L20	S	15	E	8.6	14.37	6.49	8.79	9.61	91
A	S	22	E	9.4	15.40	9.02	9.01	9.15	98
B	S	9	HW	10.0	14.78	10.83	9.49	9.08	105
C	S	14	F	6.4	13.90	15.07	9.74	8.83	110
D	—	0	F	2.0	13.35	16.22	9.96	8.90	112
June 26						Discharge (Somass R.) 1695 c.f.s.			
L20	—	0	LW	1.5	16.98	7.28	8.71	9.05	96
A	NW	6	LW	1.7	15.60	8.11	9.05	9.21	98
B	S	1	F	3.1	15.13	9.88	9.37	9.11	103
C	S	21	F	7.3	14.73	13.26	9.66	8.86	109
D	SW	12	HW	10.2	14.70	15.72	9.75	8.63	113
June 28						Discharge (Somass R.) 1638 c.f.s.			
L20	S	15	F	6.7	16.90	9.22	9.19	8.88	103
A	S	22	F	5.2	17.00	7.25	9.12	9.05	101
B	S	9	F	2.6	15.78	10.91	9.59	8.91	108
C	S	14	LW	1.8	15.27	13.28	9.37	8.76	107
D	—	0	E	5.5	15.50	15.82	9.77	8.48	115
June 30						Discharge (Somass R.) 1335 c.f.s.			
L20	—	0	LW	2.5	17.46	7.06	8.88	9.00	99
A	—	0	LW	2.6	17.58	6.97	8.95	8.98	99
B	—	0	F	4.1	16.70	10.21	9.19	8.82	104
C	S	18	F	7.8	16.30	13.11	9.24	8.61	107
D	S	9	HW	10.5	15.40	15.62	9.62	8.51	113
July 1						Discharge (Somass R.) 1540 c.f.s.			
L20	—	0	F	8.4	17.35	8.40	8.94	8.88	101
A	—	0	F	7.0	17.89	7.19	9.05	8.91	101
B	S	13	F	4.0	17.18	9.36	9.19	8.82	104
C	S	8	E	3.3	16.65	12.16	9.47	8.65	109
D	—	0	E	6.7	15.27	15.42	9.22	8.55	108

TABLE XIX—*Continued*

Date / Station	Wind Dir.	Wind Vel. (m.p.h.)	Tide Phase	Tide Height (feet)	Mean temp. ($\bar{T}$°C.)	Chlorinity ($\bar{Cl}$. ‰)	Dissolved oxygen Concentration (p.p.m.)	Dissolved oxygen Solubility (p.p.m.)	Dissolved oxygen Saturation (%)
July 3, 1941						Discharge (Somass R.) 1508 c.f.s.			
L20	S	10	F	7.0	16.12	7.51	8.89	9.17	97
A	SW	7	F	8.4	16.33	6.61	9.10	9.21	99
B	S	15	HW	9.0	17.51	8.95	9.22	8.80	105
C	S	25	E	7.5	16.98	11.76	9.09	8.64	105
D	SW	11	E	4.7	16.98	15.89	9.83	8.24	119
July 4, 1941						Discharge (Somass R.) 1478 c.f.s.			
L20	S	10	LW	4.7	18.22	7.54	8.84	8.80	100
A	S	18	LW	4.5	18.81	6.29	8.83	8.82	100
B	S	15	E	5.7	17.39	8.34	9.03	8.88	102
C	S	2	E	8.4	16.81	12.21	9.15	8.61	106
D	N	4	F	9.0	16.40	14.99	9.49	8.41	113
Aug. 21, 1941						Discharge (Somass R.) 217 c.f.s.			
L20	S	5	F	7.3	17.71	12.31	7.62	8.45	90
A	S	3	F	9.1	18.81	12.73	7.75	8.23	94
B	S	28	HW	9.7	18.25	13.71	7.95	8.24	97
Oct. 31, 1939						Discharge (Somass R.) 2650 c.f.s.			
1	S	3	E	5.3	11.10	8.82	6.85	10.05	68
2	S	4	E	7.5	10.52	14.02	5.87	9.56	61
3	SE	5	E	10.8	11.67	14.80	6.65	9.25	72
4	W	2	HW	11.8	10.40	13.70	7.24	9.64	75
8	N	3	F	6.2	10.30	14.73	7.88	9.53	83
Nov. 1, 1939						Discharge (Somass R.) 2550 c.f.s.			
1	—	0	F	6.4	10.89	12.20	5.83	9.70	60
2	N	2	F	8.2	10.46	12.02	6.74	9.80	69
3	—	0	F	10.9	10.59	13.18	7.25	9.65	75
4	S	2	E	10.4	10.51	14.97	7.63	9.46	81
8	W	1	E	8.7	10.42	13.50	8.09	9.65	84

they are warmed. This is confirmed by the tendency of the upper zone to attain constant temperature in the lower reaches of the inlet.

As shown by the data in fig. 21 the temperature in the middle zone (30 to 200 feet) is continuous with that in the open ocean as would be expected.

Dissolved Oxygen

The original data are on file at the Pacific Biological Station, Nanaimo, B.C. and can be obtained on application to the Director. The mean values in the upper zone are given in tables XVIII and XIX.

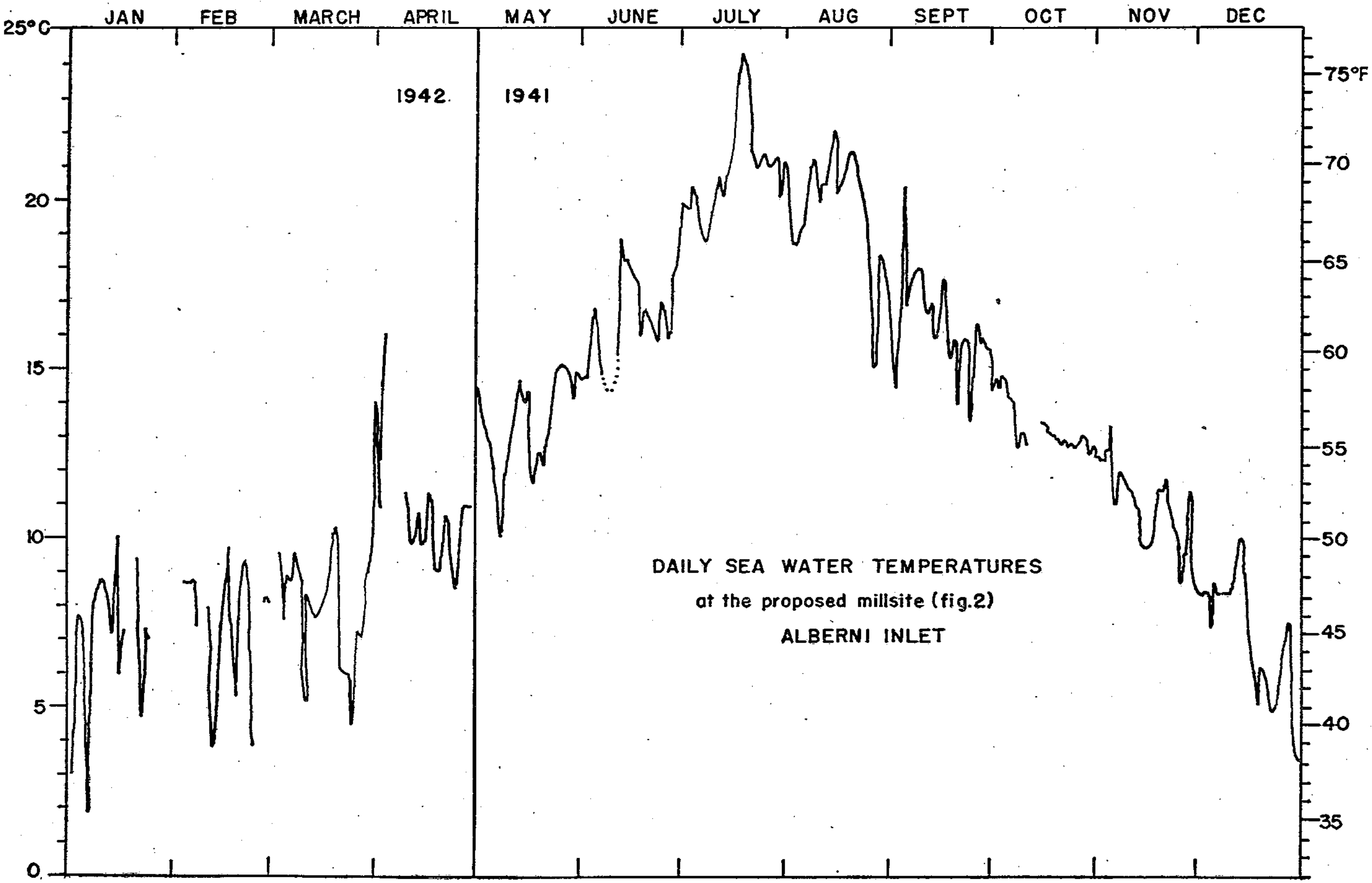

JAN FEB MARCH APRIL MAY JUNE JULY AUG SEPT OCT NOV DEC
25°C
20
15
10
5
0
75°F
70
65
60
55
50
45
40
35
1942.
1941
DAILY SEA WATER TEMPERATURES
at the proposed millsite (fig.2)
ALBERNI INLET

FIGURE 20.

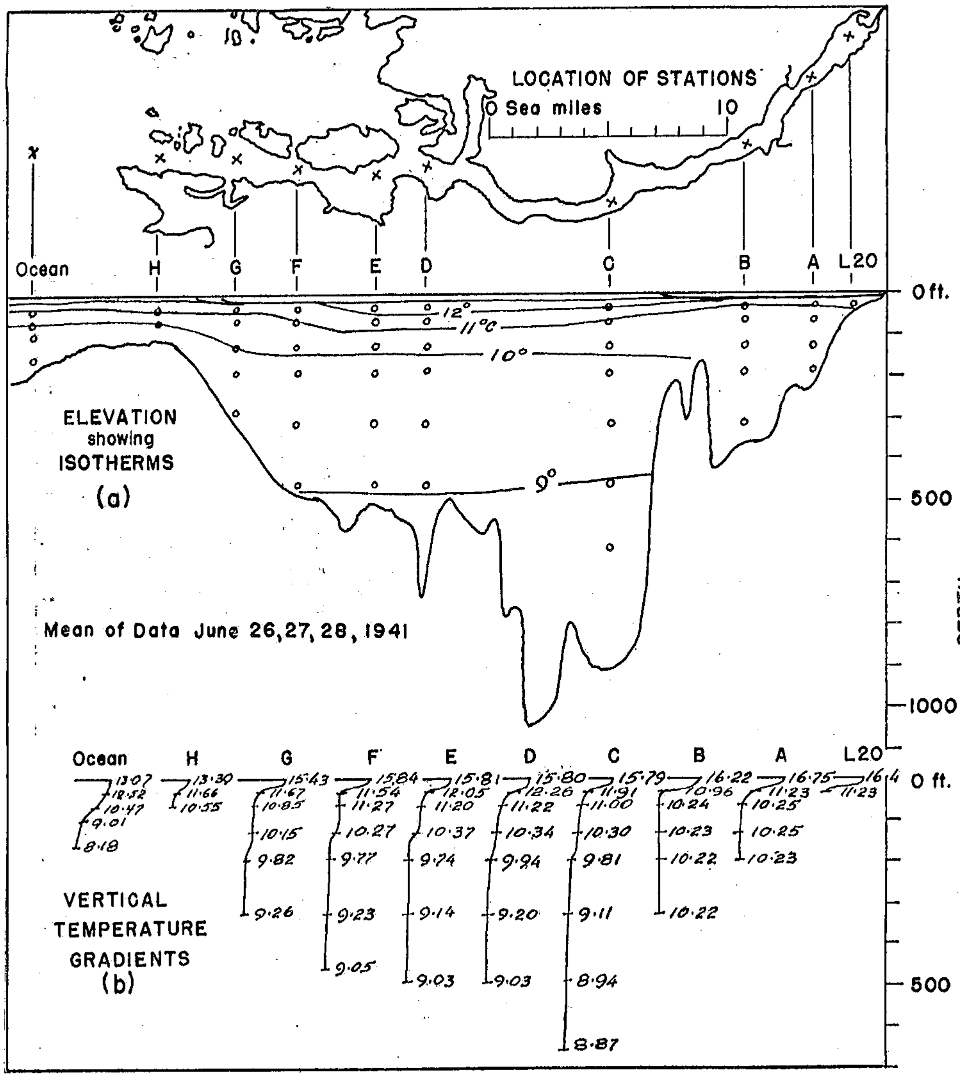


FIGURE 21. Temperature distribution in Alberni inlet.

The concentration of dissolved oxygen may be represented by the concentration present (parts per million) or by the degree of saturation. The former value has significance in physical considerations, while the latter is the more informative biological index, since it provides a measure of availability to marine organisms, and includes the effects of temperature and salinity. Both quantities are reported, and the typical gradients at the observed stations are shown in fig. 22(b).

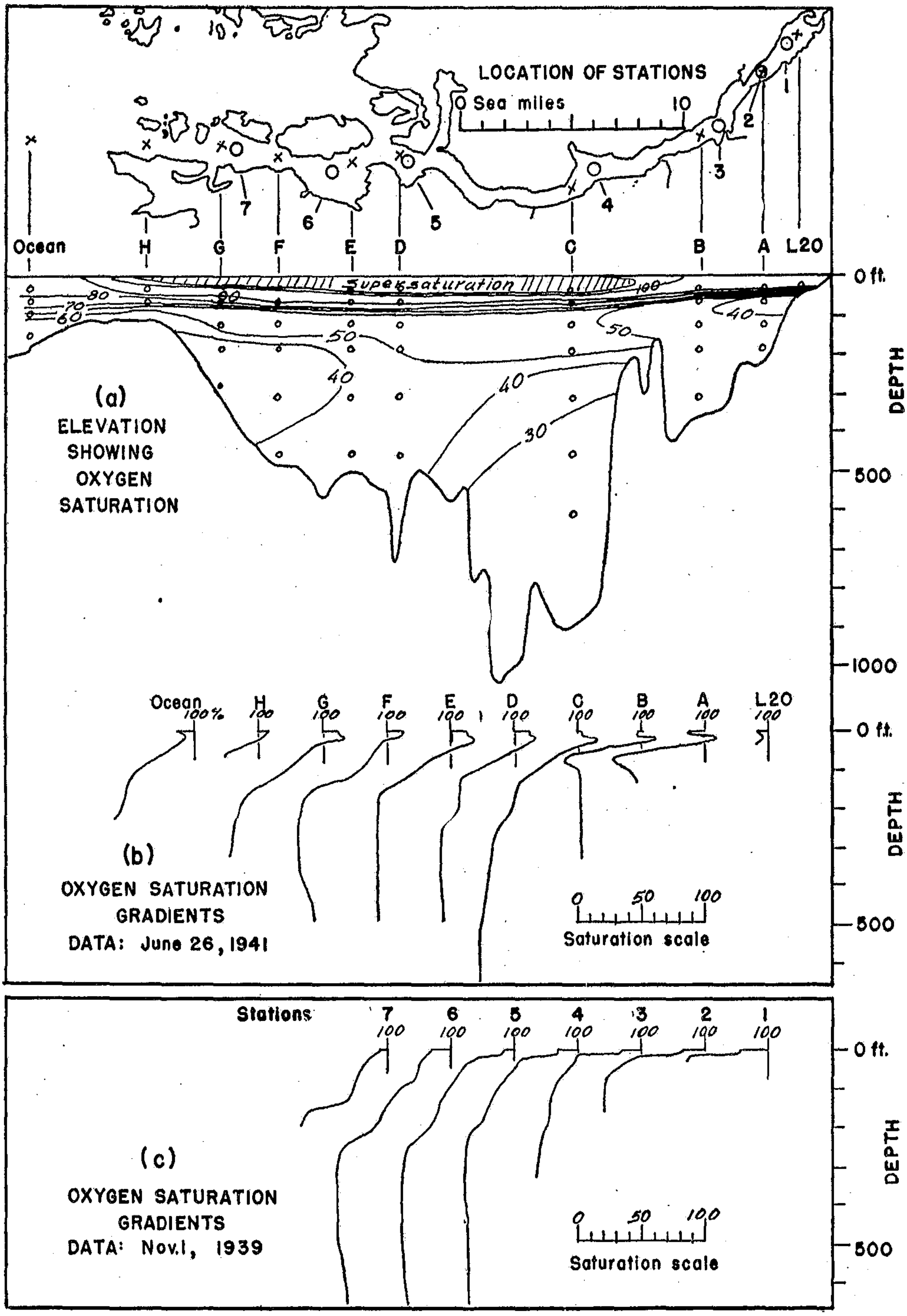


FIGURE 22. Observations of Dissolved Oxygen in Alberni inlet.

In the upper zone, the oxygen concentration increases with depth from saturation at the surface to a maximum at, or just below, the boundary. Immediately below the maximum there is an inflexion in the gradient marking the lower limit of oxygen enrichment. This maximum increases from about 90% saturation at the head to 120% at Junction passage (station D) and then decreases seaward through Trevor channel.

It is at once evident that the supersaturation must be attributed to photosynthetic action of phytoplankton. This has been investigated by many authors, notably Clarke and Ostler (1934), Gran and Thompson (1930) and Harvey (1932-1938).

It is suggested that the sea water entering the inlet carries spores of most of the phytoplankton species from the ocean. These bloom in the inlet as they encounter their specific optimum chlorinity and temperature conditions. This would result in concurrent, stratified blooms of a number of species. This point was not investigated, but the rank growth that was casually noted indicates some such process must occur.

Because of regular wind agitation, the oxygen concentration at the surface would tend to remain about 100% regardless of sub-surface variation, and the fact that wind action is restricted to the upper zone by the stability of the boundary accounts for the depth of the oxygen maximum in, or immediately below, the boundary.

The absolute values show a tendency for the oxygen concentration in the upper zone to decrease with time, although the degree of saturation remains constant. It is suggested that the state represented in fig. 22 (a) and (b) is an equilibrium between the rate of supersaturation by phytoplankton and release by wind agitation. As a result, the oxygen concentration follows the saturation values determined by temperature and chlorinity.

In the middle zone at the seaward end of the inlet (stations E, F, G, H) the oxygen concentration is continuous with that in the adjacent sea from 30 to about 120 feet in depth.

At stations B and A, there is a distinct oxygen minimum between 60 and 85 feet in depth, which is not associated with the depletion in the deep zone. This minimum persisted throughout the series of observations, and is attributed to the oxygen demand of dead phytoplankton from the superior zones, which sink into, and are carried towards the head in the middle zone. Being more dense than the upper zone water, they are rejected in the mixing process at the boundary and accumulate in the middle zone near the head of the inlet. In consequence the middle zone water would be enriched with carbon dioxide, phosphates, silicates, etc., and would be returned to the upper zone to fertilize it for further plankton growth.

From these considerations it is concluded that the oxygen distribution observed in the upper 50 to 100 feet of the inlet is largely a result of the rank growth of phytoplankton occurring during the summer. Aside from the fact that the phytoplankton is a dependable cause of supersaturation in the upper zone its contribution to the observed states cannot be calculated.

One series of observations was made on October 31 and November 1, 1939, (fig. 22c), which illustrate a condition that existed during the autumn freshet. Here the oxygen content of the upper zone increases from 68% at the head to 83% at Junction passage, indicating aeration of the oxygen-deficient waters in their seaward transport. The middle-zone water enters the inlet at about 70% saturation, and decreases to about 35% at the head. This deficiency is explained by the oxygen demand of humus and debris washed into the inlet by the freshets which occurred at this time, and represents an example of natural pollution.

THE BASE STATE

The *base state* of dissolved oxygen is defined as the concentration resulting from the contribution of land drainage and sea water to the upper zone. This represents the basic condition associated with the mechanism of displacement.

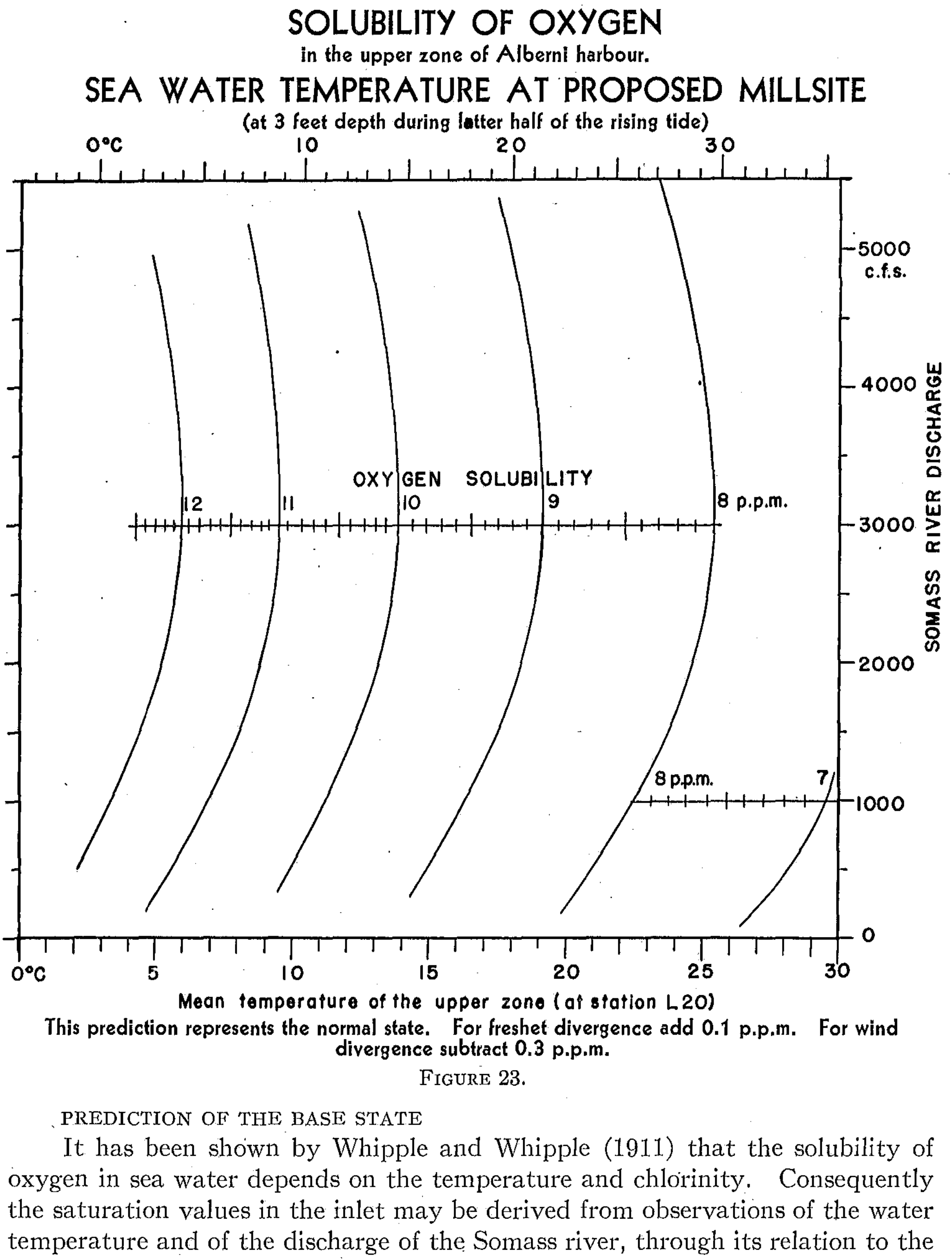
Added to this is the *aeration effect,* due to strong winds in the inlet, which always tend to maintain the surface oxygen concentration at 100% saturation. The base state is masked by enrichment from phytoplankton in the 1941 series of data, and by an oxygen demand in the 1939 series; consequently its properties must be deduced.

In general the run-off water may be assumed to be 100% saturated, since drainage into the inlet is from shallow, turbulent, mountain streams, which rise in lakes, or directly from surface drainage.

The oxygen content of the sea water entering the middle zone varies seasonally with the properties in the adjacent sea. During the period of this survey, northwesterly winds prevailed along the ocean coast resulting in the upwelling of deep ocean waters (Tully, 1942) which are deficient in oxygen. In the winter when surface ocean water accumulates along the coast under the influence of the prevailing southwesterly winds, the oxygen concentration exceeds 90% to depths well below the threshold level. Therefore it would be expected that the oxygen content of the water entering the inlet would be a seasonal function varying from a minimum (in the summer during the prevalence of westerly winds along the ocean coast) of the order of 70% of saturation, to a maximum during the seasons of variable or southwesterly winds, when it would be 90% to 95%, so that the average oxygen content in the upper zone would be as shown in table XX. The oxygen content of the upper zone would vary from saturation at the surface to this value at the inter-zone boundary.

TABLE XX. Estimated base state of dissolved oxygen in the middle zone of Alberni inlet.

Dates	Trade winds	Oxygen saturation
June 15 to September 15	Northwest	85% ± 5%
October 15 to May 15	Southwest	95% ± 5%



This prediction represents the normal state. For freshet divergence add 0.1 p.p.m. For wind divergence subtract 0.3 p.p.m.

FIGURE 23.

PREDICTION OF THE BASE STATE

It has been shown by Whipple and Whipple (1911) that the solubility of oxygen in sea water depends on the temperature and chlorinity. Consequently the saturation values in the inlet may be derived from observations of the water temperature and of the discharge of the Somass river, through its relation to the chlorinity (fig. 14(d)). Both of these are readily observable quantities and provide a convenient index of the normal state of dissolved oxygen. From these data the oxygen solubility referred to the mean temperature in the upper zone ($\overline{T}$) was calculated (fig. 23). This was related to the temperature (T′) observed daily at the proposed mill site by

$$\bar{T} (\pm 1.0°C) = 2.8 + 0.76T' \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

which scale is shown across the top of the curve in fig. 23. Any other reference point could be established in a similar manner.

The fiducial limit of 90% reliability of this correlation is ±1.0°C which implies a limit of accuracy in the estimate of solubility of 0.2 at 8.0 p.p.m. to 0.3 at 12.0 p.p.m. as indicated by the comparison of the scales in the figure. This variation amounts to 2.5% which is within the limits of error of the discharge data.

The ratio of the observed oxygen solubility at the successive stations (A, B, C, D) in the inlet to that in the harbour (L20) are shown in table XXI, with the fiducial limits of 90% reliability. These indicate that the solubility decreases 5% in the length of the inlet to Junction passage. This is within the limits of error of the prediction, and may be disregarded in most cases.

TABLE XXI. Ratio of oxygen solubility in Alberni inlet to that in Alberni harbour.

Station	Harbour	A	B	C	D
Ratio	1.00	1.00	0.99	0.96	0.95
Reliability (90%)		±0.01	±0.01	±0.01	±0.01

To predict the base oxygen content (without plankton supply) anywhere in the upper zone of the inlet it is only necessary to know the prevailing coastal wind, the Somass river discharge and the water temperature at a reference point, such as the proposed mill site. From the last two items, the solubility of oxygen in the upper zone of the harbour is determined in fig. 23, and the normal oxygen content is 85% to 95% depending on the prevailing coastal wind, as shown in table XX. The oxygen content would then increase more or less uniformly to seaward to reach the saturation value, which is a proportion of that in the harbour, as shown in table XXI.

The probable error of this estimate is determined by the oxygen content of sea water entering the middle zone, in which a fluctuation of ±10% may be expected. It should also be noted that a secondary effect of phytoplankton enrichment, or oxygen demand of debris will frequently mask this base state, as has been discussed.

OXYGEN DEMAND

It has been remarked that in the presence of phytoplankton enrichment in the upper zone, there is a corresponding oxygen demand in the middle zone due to death and rotting of the organisms. Even in the absence of this demand there must be some demand from the sewage of the city of Port Alberni, and from the waste of the logging operations in the area.

An effort was made to determine the oxygen demand (O.D.) *in situ* by a method approximating Clarke and Ostler's (1934) estimation of plankton activity. The oxygen content of 3 samples from each of three depths (0, 13 and 26 feet) was determined when fresh, and after being stored in sealed bottles at their respective depths, at station L20, for 120 hours, so that the natural light and temperature conditions were simulated as closely as possible. The 5-day natural O.D., determined as the mean difference of the groups of 3 samples, is shown in table XXII.

TABLE XXII. Five day natural oxygen demand in Alberni harbour. DO (fresh sample)—DO (after 120 hrs.) = 5 day natural N.O.D. (p.p.m.)

Date	Depth	Position	Position	Position	Position
1941	(feet)	N.O.D. (p.p.m.)	N.O.D. (p.p.m.)	N.O.D. (p.p.m.)	N.O.D. (p.p.m.)
				L20	
June 11	0			0.53	
	6.5			0.56	
	13			1.65	
	19.5			0.27	
			P14	L20	G20
June 16	0		—	0.16	0.57
	13		0.63	0.29	1.07
	26		1.02	2.59	0.33
				L20	
June 19	0			0.26	
	13			0.31	
	26			−0.49	
		016	P14	L20	G21
July 9	0	0.39	0.41	0.45	0.43
	13	−0.21	−0.05	0.15	−0.06
	26	−0.05	−0.03	0.0	−2.13
			N16	L20	G21
July 15	0		0.28	0.0	−0.04
	13		0.02	−0.09	−0.14
	26		−2.03	−0.98	−2.05
			P16	L20	F20
Aug. 20	0		1.00	1.45	0.81
	13		0.81	0.74	1.10
	26		0.43	0.29	1.18
				L20	
Sept. 3	0			0.73	
	13			0.74	
	26			0.14	

In general the O.D. is positive, as would be expected. The occasional negative value is probably due to sporadic development of phytoplankton, similar to that discussed by Clarke and Ostler. This conclusion is supported by the examination of several samples at intervals during the time of storage, as shown in table XXIII. This illustrates the process of an increasing concentration of dissolved oxygen, presumably due to continuation of the plankton bloom, followed by a drop in the values due to the death and decay of the organisms. The occasional negative value in table XXII probably signifies a delayed, or secondary bloom of the same or different species, which could be caused by changes in light or temperature, or enrichment of the stored sample from decay of the first bloom. Such a process is indicated in the first sample in table XXII.

TABLE XXIII. Rate of natural oxygen demand in Alberni harbour (station L20). DO (fresh sample)—DO (after t hours) = (t hours) natural N.O.D. (p.p.m.).

Date (1941)	Depth (feet)	Time (t) hours			
		6	24	48	120
		Natural oxygen demand (p.p.m.)			
June 16	13	+0.22	−0.05	+0.09	−0.29
	26	+0.50	+1.44	−0.04	−2.59
June 19	26	+0.13		+0.05	+0.49

These experiments confirm the supposition of an oxygen demand originating in phytoplankton. Because opportunity and facilities were lacking, the point was not investigated further, nor is it considered particularly significant in the over-all picture. As has been remarked, there is a sublayer of oxygen deficiency associated with oxygen enrichment by phytoplankton which would be expected from the mechanism of the system. Aside from this, the oxygen demand in the upper zone appears to be negligible.

Hydrogen Ion Concentration (pH)

The original data are on file as for temperature and dissolved oxygen.

The pH observed in Alberni harbour (station L20) is shown in table XXIV. In general, the values increase to a maximum about the depth of the boundary and appear to be associated with the plankton development (Gran and Thompson, 1930); otherwise there is no apparent correlation. The rise in pH with oxygen supersaturation is usually associated with the removal of carbon dioxide, therefore, the drop in pH in the zone of oxygen depletion (fig. 22) would indicate its regeneration in this zone.

TABLE XXIV. Hydrogen ion concentration (pH) in the upper zone of Alberni harbour.

Date (1941)	Depth (feet)					
	0 pH	3 pH	6.5 pH	13 pH	19.5 pH	33 pH
April 23	8.1	8.4	8.3	8.1	8.05	7.7
24	8.2	8.15	8.15	8.15	8.00	7.8
May 2	8.11	8.0	7.9	8.3	8.2	8.0
June 4	7.6	7.7	8.1	8.2	8.15	7.9
5	7.7	7.9	8.1	8.2	8.2	8.1
6	7.7	7.9	8.3	8.3	8.2	8.1
9	7.7	7.7	7.9	8.1	8.3	8.1
10	7.5	7.7	7.7	8.1	8.3	—
23	7.5	7.7	8.1	7.9	7.7	7.7
25	7.7	7.85	8.0	8.1	8.2	8.1
26		7.7	7.9	8.2	8.1	—
28	7.7	7.9	8.2	8.2	8.3	8.1
30	7.5	7.9	8.0	8.1	8.3	8.1
July 1	7.7	7.9	8.1	8.1	8.3	8.2
3	8.1	8.2	8.2	8.1	7.9	7.7
4	7.85	7.9	8.1	8.2	8.2	8.15
8	7.6	8.0	8.2	8.2	8.2	7.9
16	7.7	8.1	8.2	8.15	8.1	7.8
17	7.85	8.1	8.15	8.2	8.1	7.7
18	7.9	7.95	8.1	8.1	8.2	7.7
	7.7	7.95	8.1	8.2	8.2	7.8
19	7.7	7.9	8.1	8.1	8.2	8.1
	7.9	8.0	8.1	8.1	8.15	8.1
	7.9	7.9	7.9	8.15	8.15	8.2
	7.9	7.9	7.95	8.1	8.2	8.1
Aug. 19	8.2	8.3	8.4	8.3	8.1	7.9
21	8.2	8.3	8.3	8.3	8.2	8.1
22	8.3	8.3	8.3	8.3	8.2	8.1
26	8.1	8.2	8.3	8.1	8.1	8.0
27	8.2	8.3	8.1	8.1	8.0	8.0
Sept. 4	8.1	8.2	8.3	8.3	8.3	8.1
5	8.1	8.2	8.3	8.3	8.2	8.2
8	8.2		8.3	8.2	8.2	8.1
11	7.9		8.2	8.1	8.0	8.0
14	7.7	7.8	8.2	8.2	8.1	8.0

THE DEEP ZONE

As remarked by Carter (1933), it is a characteristic of a fiord that there be one or more deep basins separated from each other and from the adjacent sea by well defined thresholds, resulting in the isolation and stagnation of the deep water. In many cases there is no exchange of water over a period of years so that the dissolved oxygen vanishes, and hydrogen sulphide and nitrites become apparent.

In Alberni inlet there is a small *inner* deep zone near the head and a large *outer* deep zone occupying the central part of the inlet. The chlorinity of these waters is shown in fig. 2, the temperature in fig. 21 and the oxygen distribution in fig. 22.

In general the temperature in the outer deep zone is higher than that in the adjacent sea, and the inner deep waters are even warmer. This agrees with the usual experience, but the decreasing chlorinity toward the head and the presence of appreciable oxygen concentrations are contrary to previous instances (Carter, 1933; Tully, 1937).

The situation may be explained by noting that one mouth of the inlet (Trevor channel) opens directly into the ocean, and by recalling that deep ocean water upwells along this coast owing to the northwest trade winds from mid-June to mid-September. During this time cold (8-9°C.) saline (18.1 to 18.3‰ Cl.) ocean water approaches the surface and enters the inlet in the lower part of the middle zone. On the occasions when it is more dense, it shifts some part of the deep-zone water into the middle zone, effecting a change of water in the deep zone at least once a year. From the disposition of the isochlors in fig. 2, it is evident that the process was occurring during the observations.

During the winter, when there is no upwelling of deep ocean water along the coast, the deep zone of the inlet is completely isolated, which is illustrated by the data of November, 1939 (fig. 22), in which the oxygen deficiency in the deep water is much more marked than in these summer examples. No doubt this decrease in oxygen is due to the demand from debris brought down by the autumn freshets, as discussed earlier. Recalling that oxygen concentrations in the adjacent sea are high (about 90% saturation) at this time, it is evident that there is no exchange of water.

Under these circumstances it would be expected that the deep-zone waters would reach a limiting density in some year of extreme upwelling and would thereafter be permanent. However, there is some oscillation and internal circulation owing to frictional transfer from the middle zone. It was remarked in the discussion of mechanism that, in the case of water moving over a resting body of water, there would be an exchange between the two zones. Consequently during the winter there would be a slow exchange of water between the middle and deep zones so that the density of the latter would become less; then with the advent of summer the conditions for direct displacement by upwelling ocean water would be restored.

Unfortunately the opportunity did not offer for the complete investigation of this hypothesis, which can only be offered as the most reasonable explanation of the observed situation.

CONCLUSIONS

Alberni inlet is a fiord whose geography and oceanography are typical of the inlets along the British Columbia and Alaska coasts.

There are three principal layers in the oceanographic structure of the water mass. The upper zone contains mixed fresh and sea water, and becomes progressively more saline from the head of the inlet to the mouth. This layer is clearly defined by an inflexion in the salinity-depth gradient, below which there is a middle zone containing circulatory sea water, whose salinity does not vary markedly within the length of the inlet. This zone is limited by the threshold, which acts as a weir, protecting the deep zone waters from all but frictional transfer of mass and velocity.

Sea water enters the middle zone during the flood tide and some is transferred to the upper zone by turbulence resulting from tidal velocity. During the ebb tide sea water leaves the inlet in both the upper and middle zones. The current in the middle zone is predominantly towards the head.

Fresh water entering the upper zone from land drainage remains in the zone and moves persistently seaward owing to isostatic head. The depth of this zone is constant in the length of the inlet owing to isostatic equilibrium, and the velocity accelerates downstream in proportion to the amount of sea water added from the middle zone.

In the immediate vicinity of each inflowing river there is a wake stream of fresh water as the outflow diverges to the width of the inlet. This results in lateral salinity gradients in the vicinity of the river estuary. The particular properties of this region are discussed in detail.

During a tidal cycle a proportion of the mixed fresh and sea water in any limited region of the upper zone is displaced by similar amounts of fresh and sea water, from land drainage and the middle zone respectively. This proportion may be defined as the ratio of the volume of land drainage during the tidal cycle to the volume of fresh water present in the region, and may be evaluated from a knowledge of land drainage, and of the composition and limits of the upper zone.

Displacement and its factors are functions of the rate of land drainage, modified by contrary winds which retard the seaward flow and freshets which accelerate this movement.

During the summer the temperature distribution closely follows the salinity structure, with minor modifications due to insolation, but in the winter the system becomes isothermal while the characteristic salinity distribution persists. The relation of mean temperature in the upper zone to values observed at one point is shown.

In the surface zone the concentration of dissolved oxygen approaches saturation at all times, being slightly greater in the summer owing to plankton enrichment, and less in the winter owing to the lower oxygen content of middle-zone sea water. In the middle zone, the normal oxygen content of the sea water is of the order of 60% to 70% saturation during the summer and is further reduced by the oxygen demand of dead plankton sinking from the upper zone. In the winter the oxygen concentration increases to 80% to 90% of saturation. The relation of mean oxygen concentration in the upper zone to that observed at one point, is shown.

The hydrogen ion concentration in the upper zone is shown to vary between pH 6.8 and 8.5, and to be a function of plankton activity, and of seasonal variations in the character of the contributory water.

PART II. MODEL STUDIES OF ALBERNI HARBOUR

It will be shown (part III) that the density of the sewage can be adjusted by dilution with fresh water so that it will remain in the upper zone (surface layer of mixed fresh and sea water). A study of the oceanography of Alberni inlet (Part I) has shown that it will be displaced seaward in this zone at a rate depending on the river discharge. Below Alberni harbour the distribution will be laterally uniform, and vertically similar to the fresh water gradient. However the harbour region is an estuary, where the circulation is dominated by the wake stream of the Somass river, and although the average conditions can be estimated, the course and displacement from any particular sewer outlet can not be predicted from the oceanographic observations alone.

Rather than attempt to examine all possible sewer sites by tracing dye solutions in the harbour, or by float experiments, it was decided to examine the situation in a hydraulic model, (App. III) and then check the most promising possibilities in nature.

Current Systems

Before discussing the peculiarities of the flow from each sewer site, it is advantageous to appreciate the general current system in the harbour. This was independently deduced from an oceanographic survey in the region (part I) and found to agree with the observations in the model.

From this it is recognized that the displacement of water from the harbour is less than the average on the western side, which is therefore *a region of accumulation.* The displacement is greater than average in the river stream, which may be regarded as a *region of displacement.* It was observed that there is some exchange between these regions, but in general their designation is descriptive. In addition, it was observed that there was a *marginal current* along the eastern and western shores in which the ebb movement was dominant, and which did not dissipate within the Harbour.

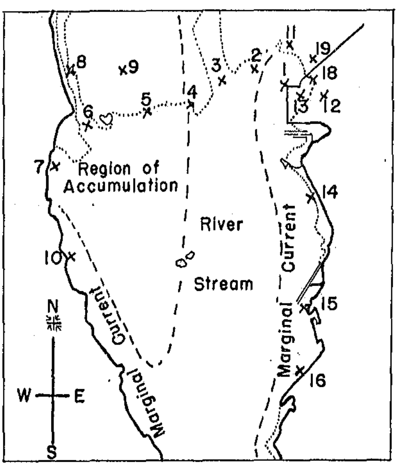


FIGURE 24. Sewer sites investigated in the model of Alberni harbour.

Data

Observations of the progress of the simulated effluent were made in the model to determine its probable distribution in the harbour, the location of accumulation, and to find any peculiarities of flow which might aid in the reduction of the anticipated pollution (Part III).

An index to the model experiments is given in table XXV, and the sewer sites examined are shown in fig. 24.

TABLE XXV. Index to Model Experiments.

Position	Tide range	Wind Force	Wind Direction	River discharge (Q)	Experiment no.
1	7.5	0		2,260	1
		light	S		11
		strong	S		12
2	7.5	0		2,260	2, 23
		light	S		21
		strong	S		22
	10.0	0			54
	"	strong	N		55
3	7.5	0		2,260	3
4	7.5	0		2,260	4
5	7.5	0		2,260	5
	"	light	N	"	15
	"	"	S	"	16
6	7.5	0		2,260	6
7	7.5	0		2,260	7
	"	light	S	"	17
	"	strong	S	"	18
8	7.5	0		2,260	8
	6.0	0		525	77
	"	strong	S	"	78
	"	"	N	"	79
	"	0		4,000	80
	"	strong	N	"	81
	"	"	S	"	82
	9.3	0		4,000	92
	"	strong	N	"	92a
	"	"	S	"	93
	"	0		6,900	97
	"	strong	S	"	98
	"	"	N	"	99
	6.2	"	N	"	104
	"	0		"	105
	"	strong	S	"	106
9	7.5	0		2,260	9
	"	light	S	"	19
	"	strong	S	"	20

TABLE XXV—*Continued*

Position	Tide range	Wind Force	Wind Direction	River discharge (Q)	Experiment no.
	10.0	0	S	2,260	49
18	"	strong	N	"	50
	"	"		"	51
	"	0	N	9,330	57, 69
	"	strong	S	"	58
	"	"		"	68
	"	0	S	525	70
	"	strong			70
19	10.0	0		2,260	56
19D	"	0		525	71
20D	6.0	0		525	73
	"	strong	S	"	74
	"	"	N	"	75
20	"	0		4,000	85
	"	strong	S	"	86
	"	"	N	"	87
20B	9.3	0		4,000	88
	"	strong	N	"	89
	"	"	N	"	90
	"	"	S	"	91
20	"	0		6,900	94
	"	strong	N	"	100
	6.2	0		"	101
20D	"	strong	N	"	103
20	"	"	S	"	107

P.S. 20D signifies dyke around position.
20B signifies boom around position.

Although the behaviour of the tracer solution differed in some details between each sewer, it was found that it could be broadly classified in three main categories on the basis of the harbour regions: (1) Region of accumulation in the northwest quarter (sites 6, 7, 8, 9, 10); (2) River stream, in the vicinity of the river mouth (sites 2, 3, 4, 18D, 19D, 20D); (3) Marginal current along the eastern shore (sites 11, 12, 13, 14, 15, 16, 18, 19).

REGION OF ACCUMULATION

Johnstone slough (fig. 2) is the region of extreme accumulation, and it was considered possible that some areation would occur if the mill sewage were disposed there (Part I). The model representation of the slough was not

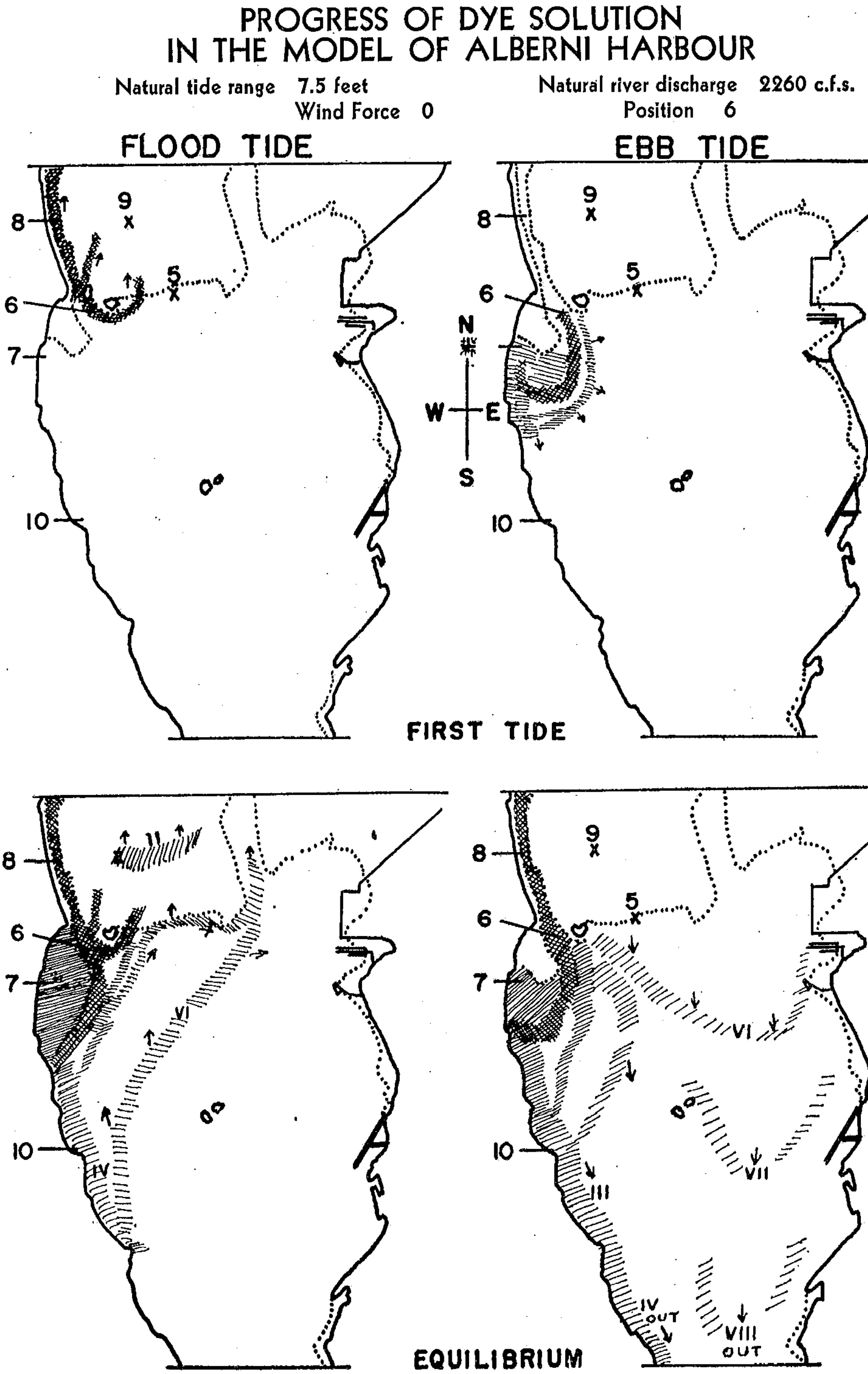

PROGRESS OF DYE SOLUTION
IN THE MODEL OF ALBERNI HARBOUR
Natural tide range 7.5 feet
Wind Force 0
Natural river discharge 2260 c.f.s.
Position 6
FLOOD TIDE
EBB TIDE
FIRST TIDE
EQUILIBRIUM
N
S
W
E
VI
IV
III
VII
IV OUT
VIII OUT

FIGURE 25.

considered reliable, but it is evident that once equilibrium was established, the rate of discharge into the harbour would be equal to the mill discharge. It was observed in nature that most of the exchange occurred through the channel in the northwest corner of the harbour, and near high tide some exchange was effected across the tide flats. The course of these discharges in the harbour was examined by setting the dye source at sites 6, 7, 8, 9 and 10.

The data are summarized in terms of the observations from site 6 (fig. 25). The first two diagrams (Flood and Ebb) show the progress of the dye from the source in one tidal phase. The second pair of diagrams show the motion of the dye fronts after equilibrium was established. The numerals on the dye fronts refer to their age, e.g. I is the discharge from the previous period, II is from the second previous, etc.

During the flood, dye from the source moved toward Johnstone slough and over the tide flats. During the ebb, it moved into the northwest corner of the harbour and accumulated in an eddy. Equilibrium was attained in about 8 tidal periods. This did not appear to vary appreciably between 550 c.f.s. and 4,000 c.f.s. discharge, but decreased to 3 tides at 9,000 c.f.s.

From the point of accumulation, most of the dye of age IV and older progressed seaward along the western shore during the ebb, and was displaced on the sixth ebb. During small tides there was no tendency for this marginal current to retreat into the harbour during the flood. On large tides (10 feet range) the slow flood retreat was offset by an increased ebb velocity. This current was not affected by river discharge, so that in general the rate displacement by this route was constant.

During the flood, part of the accumulated dye was dispersed across the northern end of the harbour, onto the tide flats and towards the river mouth. Part of this moved into the western side and towards the harbour entrance on the ebb, where it encountered the flooding waters from the inlet before it was displaced. This portion was only displaced by lateral mixing into the river stream. As a result, more than 10 ebb tides were required to reach equilibrium accumulation in the western half of the harbour. The remainder of this eastern-moving dye entered the river mouth, and some reached the eastern shore during the latter half of the flooding tide. The river cleared during the first of the following ebb, and the dye was displaced from the harbour in the same, or the following tide.

During low river discharge (525 c.f.s.) the tendency for dispersion toward the river mouth was limited to the western side of the harbour, and much the greatest displacement occurred in the western marginal current. During high river discharge (4,000 c.f.s.) most of the dye dispersed towards the river, and was displaced on the third to fifth tide after entering the harbour.

Increase of tidal range, from 6 to 10 feet, increased the dispersion, particularly on the western side, but did not increase the displacement. Strong south winds increased dispersion, so that an appreciable concentration appeared in the whole area. This wind did not noticeably affect the western marginal flow.

Aside from some movement across the tide flats during the flood tide, the behaviour of discharge from site 8 was similar. From site 9, dispersion into the mid-harbour and the river stream was favoured at the expense of accumulation in the northwest corner and the western marginal current. Moving the dye outlet to sites 7 and 10 eliminated dispersion except at very high river discharge, and the dye was wholly confined to the western shore.

These observations showed that if the pulp mill sewage were wasted into Johnstone slough, or the northwest quarter of the harbour, it would accumulate to a high concentration in that corner. Normally the greater amount of sewage would form a seaward migration stream along the western shore. Dispersion would occur across the northern end of the harbour and the tide flats during the flood tides, and would tend to increase with river discharge. During the ebb the dispersed sewage that did not reach the river would accumulate on the western side, and would only be displaced by subsequent absorption into the river stream. The part that reached the river would be displaced during the same or the following tide.

During lowest river discharge the river stream and the eastern side of the harbour would be almost free of effluent, and at higher discharge, the concentration would not be noticeable because of the rapid displacement. Increase of tidal range would increase the dispersion, and strong south winds would also retard the displacement.

Referring to the discussion of pollution (Part III) it will be apparent that this disposal would aggravate the pollution, since the sewage would remain in the harbour for a considerable time, and reduce the oxygen concentration below the tolerable limit.

The River Stream

The estimate of general pollution was predicated on the discharge of the mill sewage at or near the mouth of the Somass river on the assumption that its distribution and displacement would be similar to that of the fresh water from the source (Part I). This alternative is demonstrated in fig. 26, which illustrates the dispersal of dye from site 2, the proposed site of the mill sewer.

During the first half of the flooding tide, the dye moved along the eastern side of the river stream into the harbour, but on the strength of the flood the direction of flow was reversed to enter the river and the tide flats. The dye left in the harbour moved east to the foreshore. When the tide turned to the ebb, some of the latter dye moved seaward in the river stream, and the rest moved along the shore in the eastern marginal current. The portion in the river was extruded, and along with the discharge during the ebb, was carried towards the harbour entrance, and most of it was displaced in the same tide. The part on the tide flats moved into the middle of the harbour towards the western side, where it tended to accumulate, as discussed in the previous section.

It was also remarked that there was considerable accumulation of dye in a cyclonic eddy in the small bay in the northwest corner of the harbour, which was usually displaced into the river stream during the following ebb.

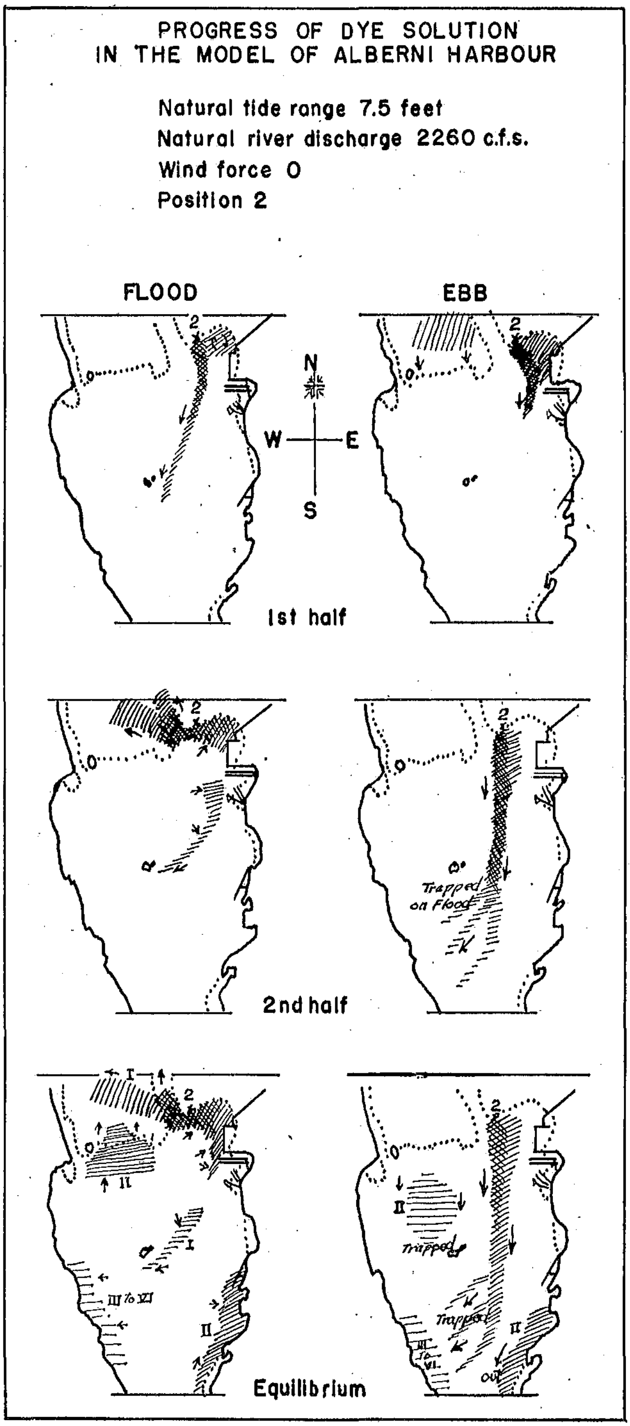

PROGRESS OF DYE SOLUTION
IN THE MODEL OF ALBERNI HARBOUR
Natural tide range 7.5 feet
Natural river discharge 2260 c.f.s.
Wind force 0
Position 2
FLOOD
EBB
N
W
E
S
1st half
2nd half
Trapped on Flood
Equilibrium
Trapped
Out

FIGURE 26.

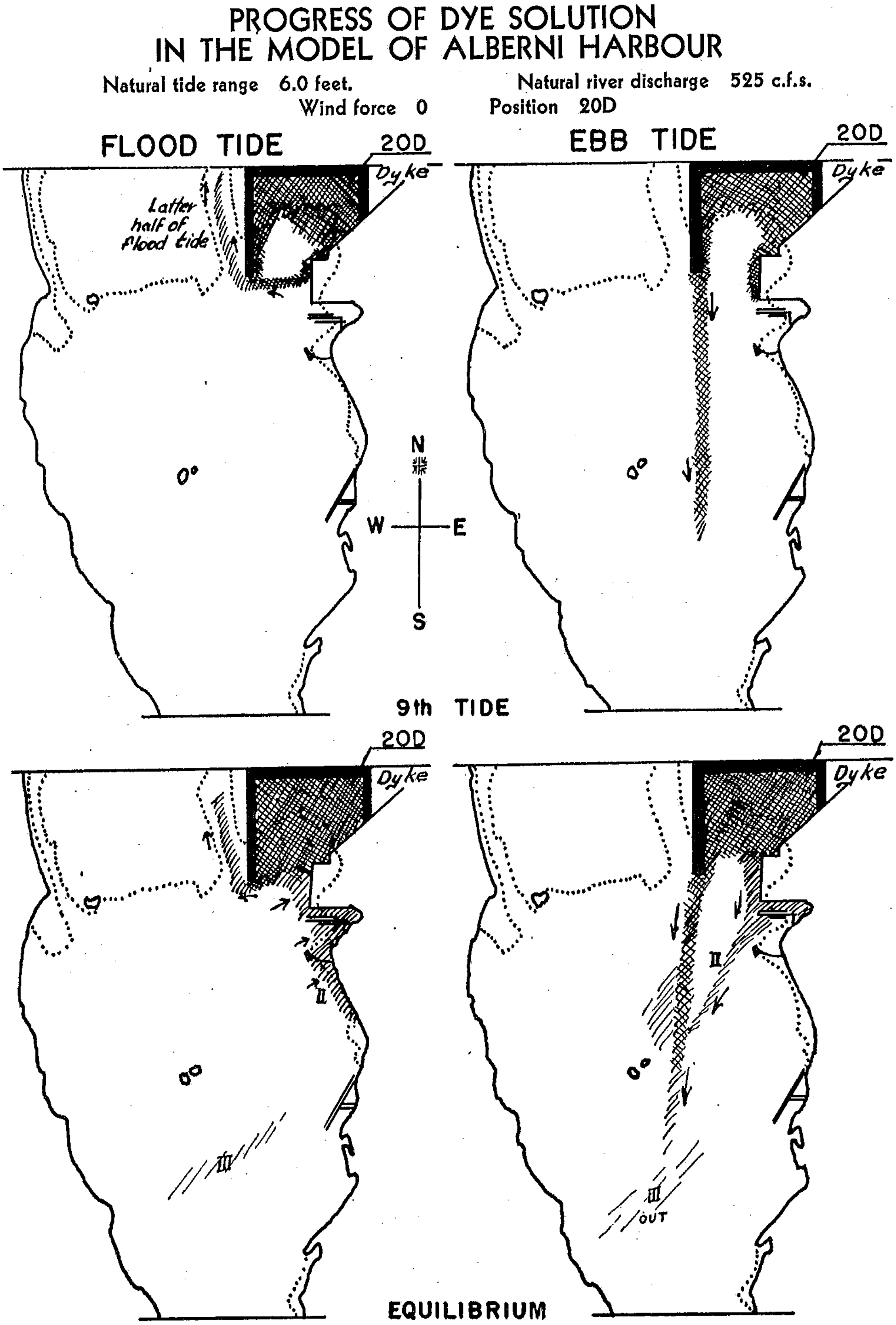

PROGRESS OF DYE SOLUTION
IN THE MODEL OF ALBERNI HARBOUR
Natural tide range 6.0 feet.
Natural river discharge 525 c.f.s.
Wind force 0
Position 20D
FLOOD TIDE
EBB TIDE
20D
Dyke
Latter half of flood tide
N
W
E
S
9th TIDE
II
III
OUT
EQUILIBRIUM

FIGURE 27.

At equilibrium, there was evidence of dye throughout the whole area with streams of greater concentration associated with the mill sewer, and the isolated clouds of one and two tidal periods age. The one cloud along the eastern shore was displaced on the second tide by the eastern marginal current, and exhibited no tendency to further dispersion into the river stream or harbour. The cloud from the tide flats oscillated on the western side of the harbour, part being re-absorbed into the river stream, and part moving over to the western marginal current. This concentration did not increase after the fifth or sixth tide.

Increase of tidal range increased the dispersion and distance of oscillation, without altering the general phenomena. Strong south winds also increased dispersion, but retarded displacement so that the overall concentration increased.

At low river discharge (525 c.f.s.) the dye moved about half the length of the harbour during the ebb, and required at least two tidal periods for displacement to begin. In this case the equilibrium concentration was noticeably higher than in the case just discussed, and the western mid-harbour cloud was mixed to homogeneity before it was displaced. At high discharge levels (9,330 c.f.s.) most of the dye was displaced in one tide cycle. The remaining clouds of dye represented the effluent discharged during the last part of the ebb tide, and were displaced or dispersed in the following period.

EFFECT OF A POND

It was proposed that if a dyke be placed around the small northeast bay it would retain the effluent during the flood, and prevent it from reaching the western side of the harbour from the tide flats. The possibility was examined as shown in fig. 27.

Six to eight tides were required to fill the pond. Then there was no discharge during the first part of the flood, but during the latter part a stream of dye intruded the river. This showed no tendency to cross the tide flats, and was expelled during the first of the ebb. During the whole ebb tide, dye was discharged into the river stream from the outer corner of the pond. At lowest river flow (525 c.f.s.) it extended 2/3 the length of the harbour in one tide, and was displaced on the third tide, similar to the ebb movement from site 2.

The only accumulation in the harbour was the residual dye trapped during the last part of the ebb. Comparison of this situation with that shown in fig. 25, indicates that the presence of the dyke did prevent contamination of the western side of the harbour by the accumulation on the tide flats. At this low river level equilibrium was reached in about 20 tidal periods, and a heavy concentration of dye appeared along the eastern foreshore in the upper part of the harbour, but most of this tended to clear during the ebb.

At higher discharge (4,000 c.f.s.) the restricting influence of the dyke was less apparent, because the remnant of dye from the last part of the ebb circulated around the harbour during the flood. However, this was displaced on the next tide, and did not indicate accumulation.

The dyke had the general effect of regulating the discharge so that the only region of accumulation was within the dyke and along the waterfront of

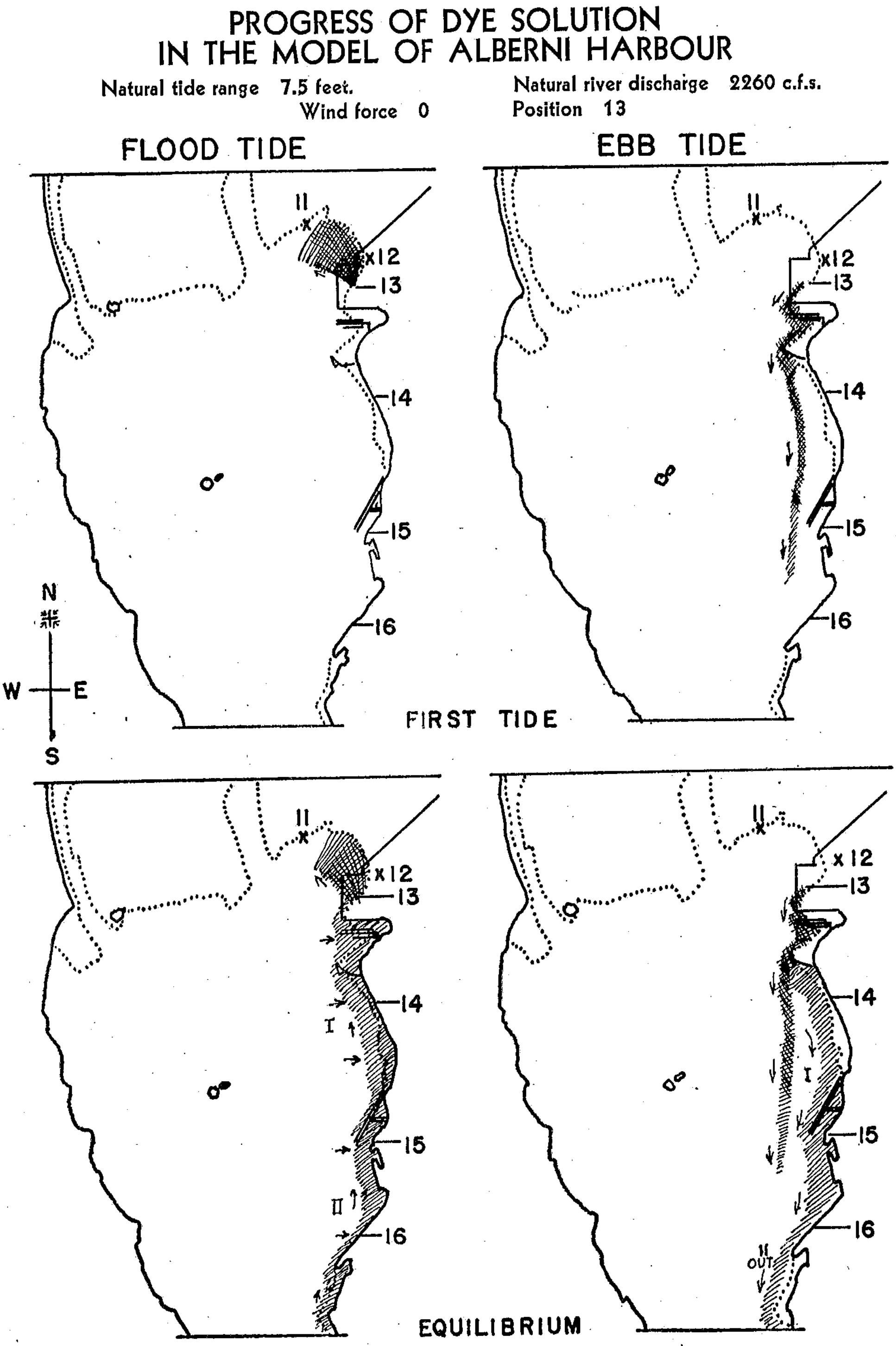

PROGRESS OF DYE SOLUTION
IN THE MODEL OF ALBERNI HARBOUR
Natural tide range 7.5 feet.
Wind force 0
Natural river discharge 2260 c.f.s.
Position 13
FLOOD TIDE
EBB TIDE
FIRST TIDE
EQUILIBRIUM
N
W
E
S
11
x12
13
14
15
16
I
II
OUT

FIGURE 28.

the city of Port Alberni. The dye entered the river stream during the ebb, attained dilution, and was displaced in three tides or less.

The Eastern Marginal Current

It was remarked that as the sewer site was withdrawn into the small north-east bay, or placed at any point to seaward along the foreshore, the dye was increasingly restricted to the eastern marginal current. This tendency was examined from sites 11, 12, 13, 14, 15 and 16, and the results are summarized in fig. 28, showing the sequence from site 13.

During the flood, the dye accumulated in the small bay, showing no tendency to enter the river or the tide flats area. During the ebb this accumulation, and the discharge from the sewer, moved seaward parallel to the eastern shore in a stream of high concentration, reaching about 2/3 the length of the harbour in one ebb tide. It was remarked that the ebb movement began before high tide (from about ¾ high) and persisted after low tide (to about ¼ high). During the flood period, the dye moved onto the foreshore where it remained with little or no longitudinal movement. When the tide turned, the ebb movement was resumed and the dye was displaced.

At the medium river level (2,260 c.f.s.) there was no tendency for the dye to be transferred to any other part of the harbour. At very high river discharge (9,330 c.f.s.) there was a slight tendency to invade the river during the flood, and some dye was drawn into the river stream in the harbour during the ebb and circulated on the western side during one tidal period. This is of no consequence since pollution could not occur from the transitory presence of the effluent at such a river level (Part III).

During a strong south wind, at the medium river level (2,260 c.f.s.) it was observed that some of the dye entered the river stream near the sewer outlet, during the flood tide. This retreated to the foreshore during the following ebb, and was not dispersed afterwards. There was no tendency for wind dispersion from the marginal current in the lower harbour. The rate of seaward progress was retarded by this wind, and in the upper part of the harbour the accumulated dye retreated slightly (less than 1,000 feet in nature) during the flood.

With increased tidal range (10 feet), a small amount of dye invaded the river during the latter part of the flood, and some dispersion into the river stream occurred in the vicinity of Port Alberni. Both of these were suppressed on the ebb.

The Marginal Current in Nature

Evidently utilization of this marginal current to transport the pulp mill effluent out of the harbour would leave most of the region clear of pollution, and ensure its suitability for schooling fish (Part III). However, realizing that this representation was at the boundary of the model where its reliability was questionable, it was necessary to examine the possibility in nature.

Between 50 and 100 floats, each having a large vane suspended three or four feet below the surface, were released at a number of positions and their progress observed. A considerable proportion of the floats became entangled or lost in

PROGRESS OF FLOATS IN ALBERNI HARBOUR

in calm weather

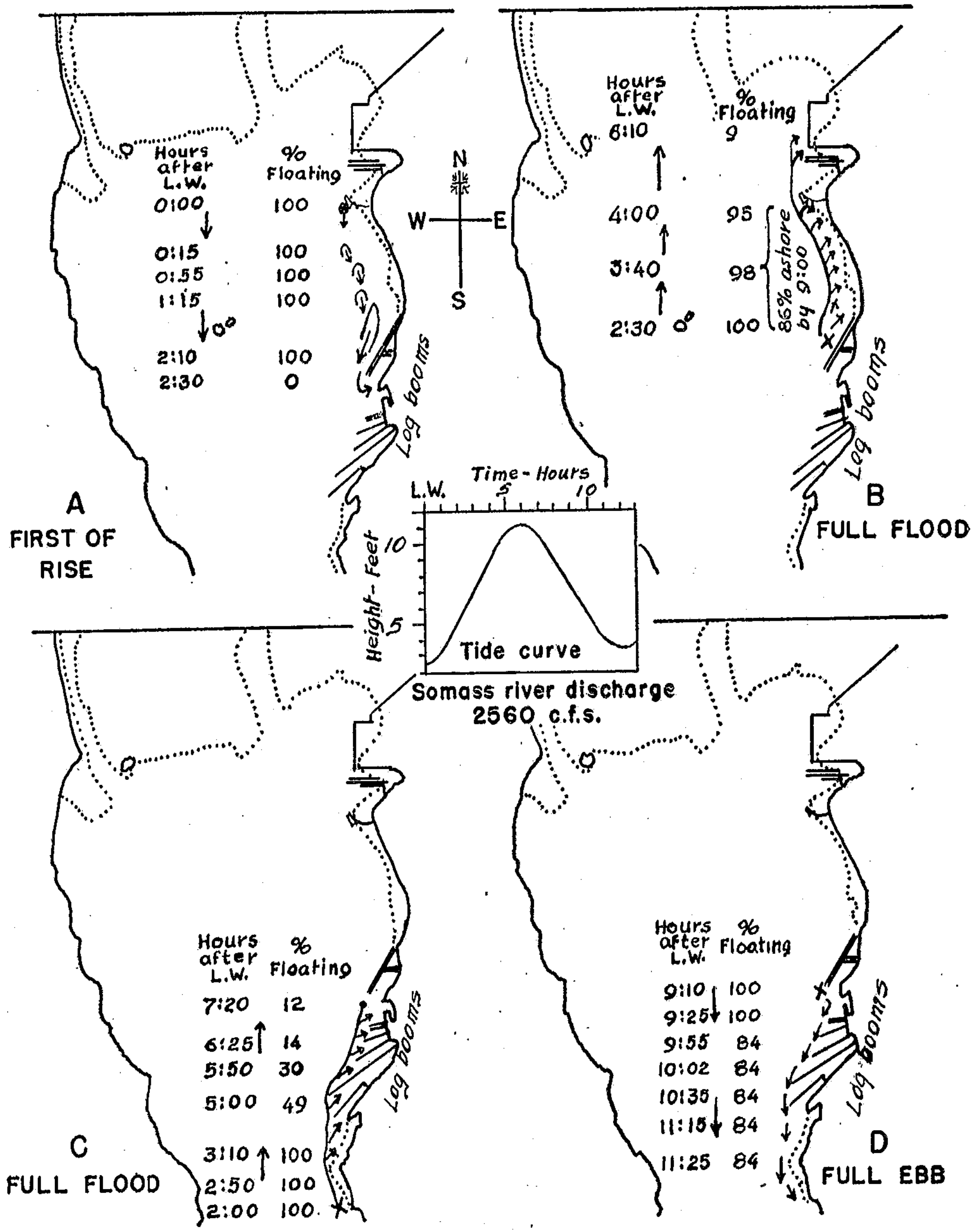


FIGURE 29.

the log rafts along the shore, so that it was necessary to release them at successive positions, and compound the observations into a continuous description.

The detail of a series is given in fig. 29 showing the stages in the marginal current cycle from one low tide to the next. Diagram A shows that the ebb movement continued for 2 hours and 10 minutes (02:10) after low water, during which time the floats showed no tendency to move into the river stream or go ashore. At this time the tide turned and the floats went ashore within 20 minutes (02:30).

Diagram B shows the movement of another group of floats set out at this time just north of the wharf (Q21). These moved north about 1,000 feet and then the majority (91%) stopped along the foreshore. By the end of the flood movement 86% had gone ashore. The remaining 9% migrated north parallel to the shore and were found floating at high tide. It is probable that these floats would have returned along the shore during the ebb. During the same flood, a group of floats were set out at the harbour entrance as shown in diagram C to examine the probability of dispersion. As shown, they moved in the flood direction, going ashore along the route. During the following ebb movement, which began just before high tide, the floats moved freely toward the harbour entrance, which they reached at half tide.

These data are analysed in fig. 12 which shows the directional arrows and approximate velocities of successive tidal stages.

In all these experiments exhaustive search was made for stray floats in the river stream but none were ever found. From this it is concluded that the lost floats were entangled in the log booms that lined the foreshore. This was confirmed in a number of instances when floats were eventually found inside booms, evidently having been dragged there by the sub-surface currents.

It may also be remarked, that because of the log booms it was necessary to set the floats at some distance offshore, where they were exposed to the flood tide movement. The situation observed in the model (fig. 28) indicated that the greatest proportion of the effluent would be under the booms and wharfs, and consequently protected from the flood tide, and wind effects.

WIND EFFECTS

Fortunately it was possible to confirm the model predictions of the effects of strong south winds. The course and survival of floats released during the flood and ebb tide movements under these conditions are shown in diagrams A and B of fig. 30, and the observed form of the wave fronts and direction of spume drift are shown in diagram C. It is indicated that the flood movement was no greater than in the absence of wind (fig. 29) but the ebb movement was restrained. Most of the floats went ashore before leaving the harbour, showing that this marginal current was more conservative under these adverse conditions.

It is probable that in the vicinity of the marginal current, the wind current is strictly limited to the surface, and the tidal current persists at a few feet depth.

PROGRESS OF FLOATS IN ALBERNI HARBOUR

during strong South winds

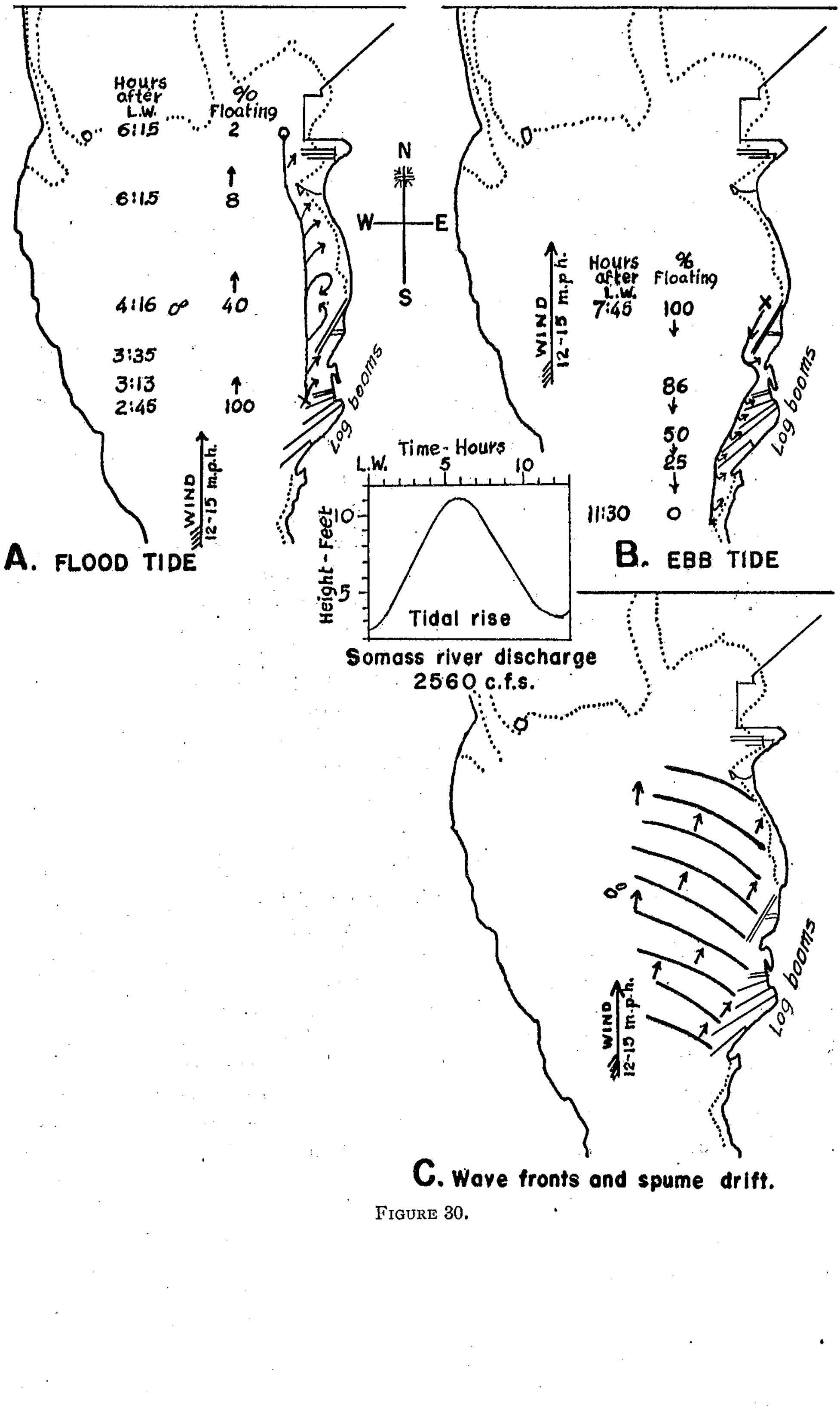


FIGURE 30.

DISPLACEMENT

In order to follow the movement of this marginal water in and out of the harbour, 100 floats were set out at high tide at a point midway from head to mouth of the harbour, and followed through the tide cycle. The progress is shown in fig. 13. The floats remained in a compact group, during the ebb, as far as Polly point, but below the harbour there was a tendency towards diffusion across the inlet, which vanished completely on the flood, when all floats were set close inshore. The experiment indicates that within the harbour these marginal waters are conserved, but below the harbour they tend to diffuse across the inlet.

The number of floats returned to the harbour indicates that of the original water only 11% returned to the harbour mouth, and only about 4% returned to the starting point. Evidently the remainder represents water that has been transferred beyond reach of the floats, and mixed with the inlet water. This exemplifies the tidal mixing process. The water moves in and out of the harbour several times (3 to 6) becoming more diffused on each cycle. By the time it is finally displaced, the lateral mixing is virtually complete (Part I).

These observations confirmed the predications of the model, that there is a marginal current along the eastern foreshore in which the seaward movement during the ebb tide is considerably greater than the contrary movement during the flood; that there is no tendency for this water to disperse into the river stream or the harbour during either the flood or ebb tides; and that there is no dispersal during strong south winds. This warranty of reliability at the boundary of the model is adequate assurance of its reliability in the other parts, where the river stream and accumulation were studied.

CONCLUSION

There are arguments for and against disposal of the pulp mill effluent in any of the three regions of the harbour. Disposal in the northwest region of accumulation may be discarded at once, because the final concentration of mill sewage would be greater than from any other sewer site. Consequently the pollution could never reach a minimum value.

Disposal into the river stream, from a sewer at site 2, would be followed by the calculated state of average pollution (Part III) which the model shows would probably be greatest on the western side of the harbour, and least in the river stream. This disposal has the advantage that maximum dilution is quickly obtained, and there would be no visible accumulation in any part of the harbour. This would be of particular advantage along the city foreshore, which is occupied by industries, wharves, and a public swimming beach.

The state of partial pollution on the western side of the harbour would be considerably alleviated by a pond of the form shown in fig. 27, which would have the effect of regulating the sewage discharge to obtain maximum displacement, at the expense of accumulation in the small bay adjacent to the mill site. (This might be considered an advantage since the sewage would probably kill the teredos in this log pond.) The transitory intrusion of sewage into the river during the latter part of the flooding tide is not significant since the concentration and the oxygen demand would be less than the critical values (Part III).

Disposal of the mill effluent in the eastern marginal current, either near the proposed mill site, or further seaward along the shore, appears to be the most suitable alternative from the fisheries standpoint. This would leave most of the harbour clear of effluent and suitable for schooling fish. However the public nuisance value would be a maximum, because there would be a visible concentration of sewage along the city foreshore. This could be alleviated, at considerable expense, by piping the sewage to an outlet below the city (between sites 14 and 15).

Either of these alternatives appears acceptable subject to the limits of mill operation discussed (Part III), but it is probable that release into the river stream from site 2, preferably from a pond, would be the most practical from all considerations.

This hydraulic model was built in 1940, and was a new departure in that it attempted to show the nature of stratified flow. It was studied as a means of estimating the probable pollution in Alberni harbour. The criticism of the reliability was so extreme that the study was abandoned, and a hydrographic investigation of the inlet was undertaken in the following year (Part I). As has been shown, that study and the series of float observations confirmed the model predictions in every important respect. The two valid criticisms were that the model should have included the whole inlet, and that it should have been built to a larger scale. Such a model would have been built, if the pollution problem (Part III) had not been solved from the hydrographic observations. However this point may be established by comparison of this study with the other, that the model approach provides much the more informative description of the water movements, is considerably cheaper and quicker, and is to be preferred in the study of any suitable region.

PART III. PREDICTION OF PULP MILL POLLUTION

The Pollutant

THE PULPING PROCESS

Sulphite pulp is manufactured by cooking resinous wood chips with a mixture of limestone and sulphurous acid under pressure in a large retort. During the period of digestion, the chemicals dissolve the lignin, which binds the wood fibres together, and any sugars or other substances in the wood, leaving only the cellulose unaffected. After the digestion, the waste sulphite liquor is drained off (blown off) and the remaining pulp is washed with clean water until all traces of digester liquor have been removed.

The "blow-pit liquor" (digester liquor) as first discharged, has a fairly constant composition (11-12% solids) depending on the wood being digested and the grade of chemicals being used. Its dilution with wash water is considerable and variable; consequently calculations are usually based on the solid content, which represents 50% of the weight of the wood taken for digestion, or on the volume of the blow-pit liquor. This liquor is not reclaimable, and at present must be disposed of as a waste product. The effluent from a pulp mill is the waste sulphite liquor, the wash, and other mill waters combined, and contains about 0.1% of the pulp fibres, which are lost in the process.

SITE AND CHARACTER OF MILL

The site of the proposed mill is on the east side of Alberni harbour, near the mouth of the Somass river (fig. 1).

The characteristics of production of the mill are stated to be as shown in table XXVI.

PROPERTIES OF WASTE LIQUOR

Analyses of waste sulphite liquor show considerable variation in different areas and mills. Benson (1937) discusses the composition of typical liquors from mills in Washington State as shown in table XXVII, which may be taken as representative of this general area. As may be judged from these analyses, waste sulphite liquor is essentially a solution of calcium salts of sulphurous and sulphuric acids, and sulphur-containing complexes of sugars, alcohols, and organic acids.

Benson and Partansky (1936) showed that most of these substances are present in the reduced state, and are quite stable to air oxidation in the concentrated liquor. When sufficiently diluted, the organic constituents are fermented aerobically to carbon dioxide and water, in both fresh and sea water mediums. They also showed that the immediate oxygen demand is chiefly due to the fermentation of the sugars, and the long term demand to the lignin.

Eriksen and Townsend (1940) working with sea-water dilutions at 20° C., showed that the blow-pit liquor (11.5% of solids) is quite stable at concentrations

TABLE XXVI. Production characteristics of the proposed pulp mill.

Rate of production (tons of pulp per day)	135
Waste sulphite liquor (digester liquor) (gallons U.S. per day)	308,000
(cu. ft. per day)	41,200
Mean rate of discharge (c.f.s.)	0.477
Density of digester liquor	1.048
% solids in solution	11-12
Wash water (gallons U.S. per day)	5,650,000
(cu. ft. per day)	755,000
Miscellaneous water from the mill (gallons U.S. per day)	1,500,000
(cu. ft. per day)	200,200
Total volume of sulphite sewage (digester liquor + wash water) (gallons U.S. per day)	5,958,000
(cu. ft. per day)	784,000
Steady rate of discharge (c.f.s.)	9.1
% concentration of digester liquor in sewage (solids)	0.61
Density of sewage (Townsend) (equivalent to sea water of 1.7°/₀₀Cl)	1.0062

TABLE XXVII. Analyses of waste sulphite liquor (Benson, 1936).

	Sample 1	Sample 2
	parts per thousand	
Total solids	109.5	138.7
Residue on ignition (as sulphates)	15.72	26.75
Total volatile acids	5.46	6.41
Formic acid	0.84	1.19
Acetic acid	4.62	5.22
Calcium (CaO)	6.71	9.47
Total sulphur (S)	10.98	11.68
sulphate (SO_3)	1.30	2.35
Free SO_2	5.42	1.45
Loosely combined SO_2	6.10	5.83
Sulphone sulphur (S)	9.47	14.18
Permanganate oxygen demand	102.2	125.0
Methyl alcohol	1.12	0.72
Ethyl alcohol	0.16	0.23
Acetone	0.15	0.10
Furfural	0.23	0.24
Lignin	56.4	69.6
Total sugars	20.64	20.47
Pentoses	2.74	3.37
Hexoses	17.4	17.1

of 10,000 p.p.m., but the rate of oxidation increases with dilution. At concentrations of 50 to 500 p.p.m., about 50% of the oxygen demand is satisfied in the first three days. The oxidation of the lignins is a slow process, requiring 90 to 140 days under normal circumstances. These authors conclude that the aerobic fermentation of sulphite liquor requires about 1,000 pounds of oxygen for each ton of pulp produced.

Because of the general similarity of the sea water (temperature and chlorinity) in Alberni inlet to that studied by Eriksen and Townsend in Grays harbor (Washington State, U.S.A.), their conclusions have been adopted as the standard reference in this investigation. These data are shown in table XXVIII and do not differ materially from other data in the literature.

TABLE XXVIII. Integral B.O.D. of waste sulphite liquor (11.5% solids) (blow-pit liquor) at a concentration of 100 p.p.m. and 25°C, in sea water, 9.57 Cl°/₀₀. (Adapted from Eriksen and Townsend, 1940).

Hours	*Time* Tidal periods (n = T/r)	B.O.D. (p.p.m.)
20	0.805	0.83
51	2.05	1.54
120	4.83	2.59
184	7.41	3.23
240	9.66	3.63
312	12.58	4.00
355	14.30	4.15
480	19.31	4.45

Benson and Partansky (1936) showed that waste sulphite liquor fermented anaerobically in the presence of bacteria contained in sea-bottom and freshwater muds. The process, which is similar to that in domestic sewage, occurs in two stages. In the first stage carbon dioxide, butyric acid, and similar products are developed, and in the second stage the process yields methane, hydrogen, hydrogen sulphide, and a biochemically stable liquid.

Townsend (1940), commenting on the process in sea water, pointed out that some of the products (butyric acid) were offensive, and some (unnamed) were distinctly poisonous to fish.

NATURE OF PULP MILL POLLUTION

The pollution effects of pulp mill effluent may be attributed to high oxygen demand, high acidity, direct toxic effects, or the presence of pulp fibres.

The fibre contained in the liquor consists of pure cellulose which settles to the bottom of the water and oxidizes so slowly that it is usually regarded as inert. Hopkins *et al.* (1931) regard the resulting matte as being deleterious in the neighbourhood of spawning grounds of anadromous fish, because it interferes with their spawning and feeding. Other bottom forms such as oysters and clams are likely to be smothered.

Sulphur dioxide and sulphurous acid are noxious at high concentrations, largely on account of their acidity. The effect is rather involved, since both the sea water and the waste sulphite liquor exhibit buffer effects. Benson and Benson (1932) and Ericksen and Townsend (1940) discuss the point, and show that at concentrations of 100 p.p.m. or less, of sulphite liquor, the effect on sea water is small (less than 0.2 pH), is extremely variable, and is largely due to the carbon dioxide released by the fermentation.

The inorganic calcium salts, and the sulphates are readily precipitated in most sea waters and are consequently removed from consideration, as shown by Benson and Benson's analyses (1932) of the sulphate-chlorinity ratios in the Puget sound areas.

The direct toxic effect of the organic constituents is more obscure. Townsend (private communication) showed that in the presence of 1,000 p.p.m. of fresh blow-pit liquor (11.5% of solids) in fresh water of normal oxygen content (8-9 p.p.m.), coho salmon (*Oncorhynchus kisutch*) lived satisfactorily, but their growth rate was about 10% less than that of the controls, which were not exposed to pollution. Townsend and Earnest (1939) showed that at oxygen concentrations of less than 2.0 p.p.m., no fish survived contact with 1,000 p.p.m. of sulphite liquor. This supersedes Nightingale's qualitative observations (1938) that under these conditions no deleterious effect could be noted. Townsend further observed that in this concentration of waste sulphite liquor, mortality became apparent when the dissolved oxygen content of the water was reduced below 5 p.p.m. He concludes that the presence of this pollution reduces the fish's utilization of dissolved oxygen.

Townsend (private communication) showed with gradient tank experiments that coho salmon fingerlings, in the absence of an oxygen gradient, do not avoid concentrations of blow-pit liquor less than 1,000 p.p.m., but that they are very sensitive to variations in oxygen concentration. He concludes that avoidance of the polluted areas in nature may be associated with the resulting oxygen gradient, rather than with the sulphite liquor directly.

It appears that the products of aerobic fermentation are on the whole innocuous at great dilutions, but that there is a deleterious effect from the fresh liquor, and the products of anaerobic fermentation. This conforms with the general view that the greatest detrimental effect of waste sulphite liquor is its high oxygen demand, and at great dilutions all other effects are inconsequential.

LIMITS OF TOLERANCE

Eriksen and Townsend (1940) have suggested the following criteria for limits of tolerance, based on their studies of Gray's harbor, Washington State, U.S.A.: (*a*) The concentration of the digester liquor should not exceed 100 p.p.m., (*b*) The alteration of the acidity of the water should not exceed 0.2 pH., (*c*) The dissolved oxygen content of the water should not be less than 5.0 p.p.m.

These criteria do not all indicate the same state of pollution, but it is considered that no circulating water system may become over-polluted if the concentration of the digester liquor does not exceed 100 p.p.m. In fresh water the limiting alteration of pH may be reached at a concentration of 25 to 50 p.p.m., while in sea water of high salinity it might not occur until the concentration became 100 to 200 p.p.m. However, neither the sulphite liquor concentration nor the alteration of pH are susceptible to critical measurement at these levels. The residual oxygen concentration, and the oxygen demand, remain as the only universal chemical indicators of the state of the system, which can be used in all instances. The sulphite liquor concentration and the alteration of pH may be utilized as corroboratory evidence, and to indicate the trend in the system.

Under quite normal conditions in sea-water systems the concentration of dissolved oxygen is frequently less than the proposed critical limit. Table XXIX shows a few examples of much lower concentrations, observed on the fishing banks in the open ocean in the approaches to Barkley sound (fig. 1). Besides large populations of bottom fishes, salmon were present on the banks during these observations.

It is suggested that the degree of saturation (proportion of solubility) is a better biological index of the oxygen state than the concentration, since it expresses the availability to the fish, and includes the variations with temperature and salinity.

Townsend's conclusion is based on his own experiments and on the observations of Ellis (1937) in fresh water, at 9 to 12° C. where 5.0 p.p.m. corresponds

TABLE XXIX. Examples of low oxygen concentrations observed in the open sea, in the approaches to Barkley sound.

Date	Position				Depth	Dissolved oxygen	
June 1937	Latitude		Longitude		(feet)	Conc. (p.p.m.)	Saturation (%)
16	48°	38.0′	125°	37.7′	98	5.5	59
					159	4.5	47
					246	3.0	31
21	48°	35.5′	125°	24.0′	98	4.4	46
					159	4.2	44
					246	3.3	34
23	48°	27.5′	125°	44.5′	98	5.4	56
					159	3.8	39
					246	2.5	28
24	48°	36.7′	125°	06.5′	98	2.1	24
					159	1.4	15
					280	1.0	11

to 40 to 50% saturation. From this it is concluded that 40% saturation with dissolved oxygen represents a reasonable limit of tolerance in a sea-water fishery.

POLLUTION RECORDS

It may be reasoned that, if the pulp mill sewage enters a stratified body of water at a low density, so that it is stable at or near the surface, only the upper waters would be polluted, and a suitable habitat should exist for the fish underneath the polluted zone.

Stratification does not exist in the presence of turbulent currents, such as occur in rivers, passes, or narrows, because the waters are mixed to homogeneity by the currents. Stratification does occur in lakes during the summer, due to thermal stability, but vanishes with the temperature gradient in the winter. It also exists in non-turbulent seaways (bays, harbours, inlets) in the summer owing to thermal stability, and in other seasons owing to salinity stability resulting from land drainage. In the last cases some degree of stratification is always present, wherefore the pollution and the consequent mortality should be limited. The point was examined in a number of instances of sulphite liquor pollution in the presence and absence of salinity stability (table XXX). The data indicate that where salinity stability is present, mortality among fish is neglible, but where this is absent, the mortality is serious.

TABLE XXX. Fish mortality related to salinity stability.

Location	Type of system	Fish	Mortality Sessile organisms	Plankton	Authority
Salinity stability present					
Port Alice (Quatsino sound)	inlet	none			Hutchinson & Lucas, 1927
Ocean falls (Dean channel)	inlet	none			No complaints
Powell river (Georgia strait)	seaway	none			No complaints
Woodfibre (Howe sound)	inlet	none			No complaints
Everett harbor (Washington state)	bay	negligible	considerable	considerable	Townsend *et al.* 1941
Shelton (Oakland bay, Washington State)	bay		considerable	increased bloom	Hopkins, Galtsoff *et al*, 1931
Salinity stability absent					
Gray's harbor (Washington state)	bay	serious	serious	serious	Eriksen and Townsend, 1940

Evidently the fish naturally avoid the polluted zones, when an alternative unpolluted zone is within their cognizance, as observed by Townsend in the gradient tank experiments cited above. High mortality occurs among the sessile forms because they normally inhabit the inter-tidal zone, and are exposed to the polluted surface water from which they cannot escape. In the absence of salinity stability the whole water system becomes polluted at some time during the season, and when this is greater than the tolerance, mortality results.

THE FISHERY

The fishery of Alberni inlet includes large, well-established runs of sockeye, coho, chum, and spring salmon and of steelhead trout into the Somass river. Herring spawn in Uchucklesit inlet (fig. 1), but have not been reported above this point in Alberni inlet. In common with most British Columbia fiords (Carter, 1933), Alberni inlet is remarkably unproductive, compared with the adjacent ocean and Barkley sound.

THE DEGREE OF POLLUTION

APPROACH

On the basis of the physical properties, two methods of disposal are possible.

The concentrated blow-pit liquor of density 1.048 could be released at the bottom near the lower end of Alberni harbour, and would find its way with very little diffusion into the deep zone north of Sproat Narrows (fig. 1) where presumably it would accumulate. The remaining mill sewage, consisting of wash water containing about 10% of the waste sulphite liquor, and all the waste fibre, would enter the upper zone where it would not reach a concentration of limiting tolerance.

This solution was rejected at once because anaerobic fermentation would occur, releasing noxious and gaseous products which would diffuse into the deep zone. Then (Part I) the deep waters would be annually displaced into the middle and upper zone, which would lead to irregular and uncontrolled instances of extreme pollution. These would be disastrous to the fish in the inlet, because the whole body of water would be polluted.

Alternatively, if the blow-pit liquor were mixed with all other mill water and allowed to enter the inlet at the minimum density, (which corresponds in density to sea-water of chlorinity 1.7°/₀₀, table XXVI), it would be stable in the surface waters in any part of the inlet. Consequently its behaviour would be virtually the same as the present flow of fresh water from the Somass river. In this case the pollution would be limited to the upper zone by the "salinity stability" of the system, and the limit of downward mixing would be of the order of 33 feet. The effluent would be diluted quickly and removed continuously from the inlet, and the state of pollution would always be under control by limiting the operation of the mill. At the anticipated dilutions (100 to 200 p.p.m.) all pollution factors except the biochemical oxygen demand would become inconsequential.

In either case the waste pulp fibre would enter the inlet and sink to the bottom. It has been shown (Part I) that dead plankton from the upper zone sinks into the middle zone and that these particles are not returned to the upper zone in the mixing process. It may be reasoned that this simulates the behaviour of the waste fibres, and that these would eventually collect on the bottom between the head and Sproat Narrows (fig. 1). Since there are no bottom-spawning fish, or any bottom forms of any account, in the part of the inlet likely to be affected, it is concluded that the deleterious effects of the accumulation of pulp fibre on the bottom may be disregarded.

Therefore the specific problem is to define the limits and conditions of operation of the proposed mill, so that the limits of tolerance of salmonoid fishes to the oxygen demand of waste sulphite liquor shall not be exceeded at any time, in any part of Alberni inlet. Further, these limits should be stated in terms of readily observable factors so that the operation of the mill may be controlled when necessary.

THEORY OF POLLUTION

Regardless of the form of pollution there must be some level of tolerance, determined by the environment, the form of life affected, and the nature of the pollutant. This implies that there are degrees of pollution within the limit of tolerance, and this degree may be expressed as

$$P = \frac{\text{Pollution effects}}{\text{Limit of tolerance}} \quad \ldots\ldots\ldots\ldots (16)$$

where the effects and the limits are expressed in comparable terms. This equation allows an exact definition of a tolerable degree of pollution as any state in which "P" is less than one.

In the present case the pollution effect is the oxygen demand (B.O.D.) of the waste sulphite liquor. The limiting tolerable state occurs when the residual oxygen concentration is reduced to 40% of the oxygen solubility. That is the total tolerable demand is 0.6 of the solubility, and the definition may be written

$$P = \frac{\text{B.O.D.}}{0.6\ (\text{DO})} \quad \ldots\ldots\ldots\ldots (17)$$

which represents the degree of pollution, derived from a state of oxygen saturation in a closed system (e.g. a tank).

It has been shown (Part I) that a proportion (r) of the water in any limited region of the inlet was displaced seaward in each diurnal tide cycle, by an equal amount of fresh and sea water entering the region. This may be recognized in the equation by comparing the specific oxygen demand [BOD] in one tide cycle to the oxygen supply (at saturation) in the same period, (DO)r, wherefore the definition is made specific for a limited region, connected to an infinite region, by

$$P = \frac{[\text{BOD}]}{0.6\ (\text{DO})r} \quad \ldots\ldots\ldots\ldots (18)$$

DISSOLVED OXYGEN

It has been established (Part I and fig. 23) that the solubility of dissolved Oxygen in the upper zone of Alberni harbour and of the inlet could be estimated in terms of (1) the discharge of the Somass river, and (2) the mean temperature of the upper zone. It was also shown that the "base concentration" arising from the contribution of the run-off, and middle zone water, would be a proportion (85% to 100%) of this value, depending on the season. The oxygen supplied by phyto-plankton blooms, and wind aeration, was imponderable. On the basis of that study it may be assumed that dissolved oxygen content will always be 90% of saturation.

This value implies that 10% of the oxygen solubility (DO) is not available, whence equation 18 is made specific for Alberni inlet in the form:

$$P = \frac{[BOD]}{0.5\ (DO)r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

During the autumn freshets the dissolved oxygen concentration frequently falls below this value, due to the oxygen demand from organic debris. However it will be shown that the value of displacement at this time is so large, that the deficiency is not significant.

Oxygen Demand

The Biochemical Oxygen Demand has been examined by several workers from whose work the tables compiled by Eriksen and Townsend (1940) (table XXVIII and fig. 31(a)) estimated by the methods of the American Public Health Association (1936) have been selected as the most representative of the proposed mill.

It has been shown that the volume of water in any limited region of the inlet is made up of successive portions of water that entered the region during all previous tide cycles. Then in this region, where the displacement is r, and the total concentration of waste sulphite liquor is N, the liquor entering region in the last tide cycle is Nr. There is also a concentration Nr(1-r) remaining from the previous tide cycle, $Nr(1-r)^2$ from the second previous, and $Nr(1-r)^n$ from the n^{th} previous cycle. Then the total concentration of waste sulphite liquor may be expressed by

$$N = \sum_{1}^{\infty} Nr(1-r)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

where $\qquad n = 1, 2, 3 \cdots \infty$ tide cycles.

The [BOD] due to the most recent portion of waste sulphite liquor is Nr(0.350) p.p.m. during the tide cycle (cf. fig. 31a). Similarly the demand due to the portion that is n periods old is

$$Nr(1-r)^n(\Delta BOD)_n;$$

whence the [BOD] due to the concentration N of waste sulphite liquor is

$$[BOD] = \sum_{1}^{\infty} Nr[0.350 + (1-r)^n(\Delta BOD)_n] \quad \ldots\ldots\ldots\ldots \quad (21)$$

where $n = 1, 2, 3 \cdots \infty$ tide cycles

and where the value of $(\Delta BOD)_n$ is the differential of the cumulative values in n tidal periods (fig. 31(b)). From this curve the equation was evaluated for successive values of n (fig. (31b)).

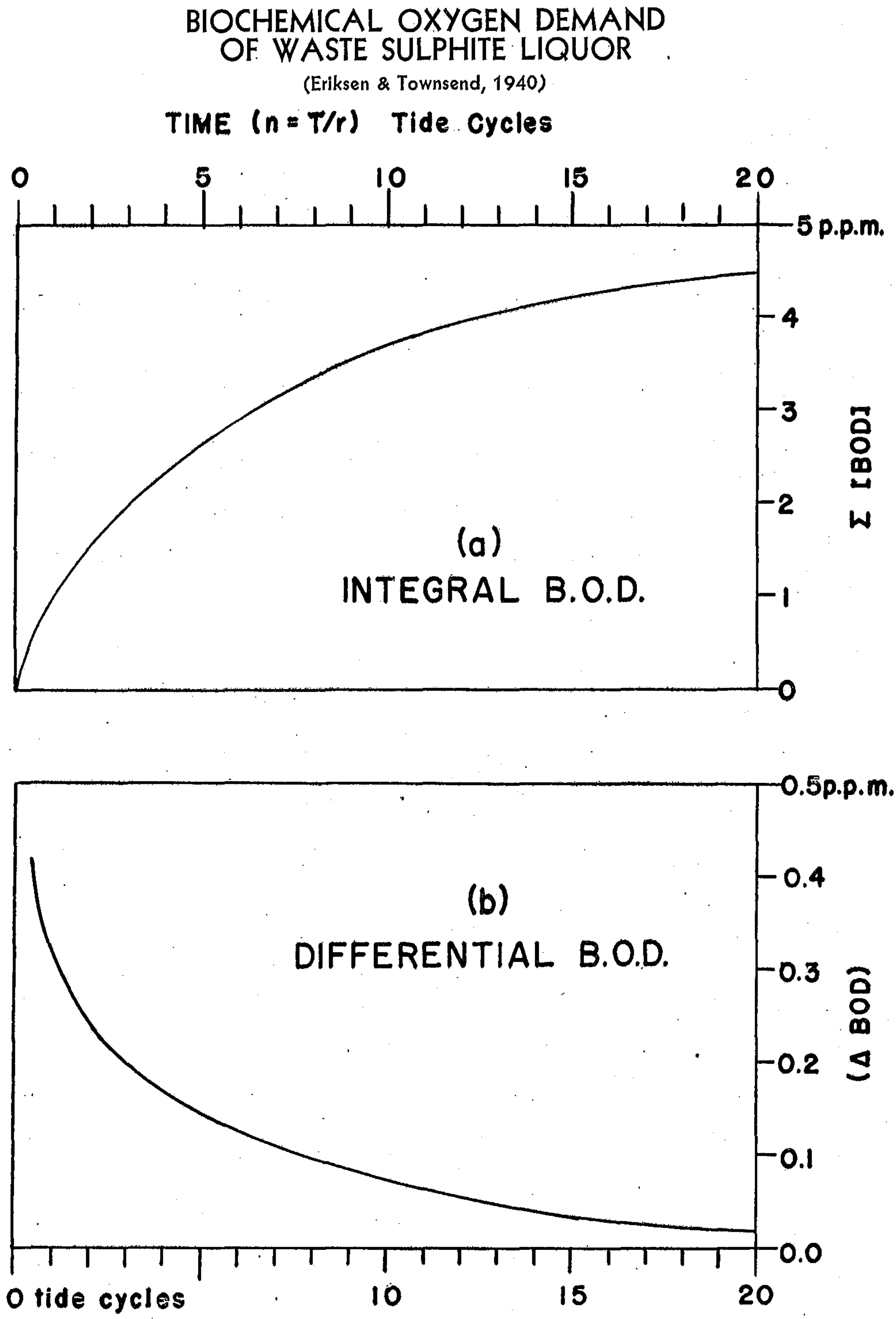

BIOCHEMICAL OXYGEN DEMAND
OF WASTE SULPHITE LIQUOR
(Eriksen & Townsend, 1940)
TIME (n = T/r) Tide Cycles
0
5
10
15
20
5 p.p.m.
4
3
2
1
0
Σ [BOD]
(a)
INTEGRAL B.O.D.
0.5p.p.m.
0.4
0.3
0.2
0.1
0.0
(Δ BOD)
(b)
DIFFERENTIAL B.O.D.
0 tide cycles
10
15
20

FIGURE 31.

In any considerable interval of the inlet (O-A, O-B, etc. cf. fig. 1) it is reasonable to assume that the effluent discharge from the mill requires some time to be *transported* from the mill sewer to the lower limit of the interval, where displacement occurs. It also assumed that during this time it becomes uniformly distributed throughout the interval (Part I).

Then the total B.O.D. in one tidal period is this cumulative B.O.D. from 0 to n, where n is the time in tidal periods required for transport of the waste sulphite liquor from the mill sewer to the lower limit of the interval in the inlet, plus the portion of equation 19 from n to infinity which represents the displacement process.

OXYGEN DEMAND OF WASTE SULPHITE LIQUOR

during one tidal cycle in a region of displacement (r).

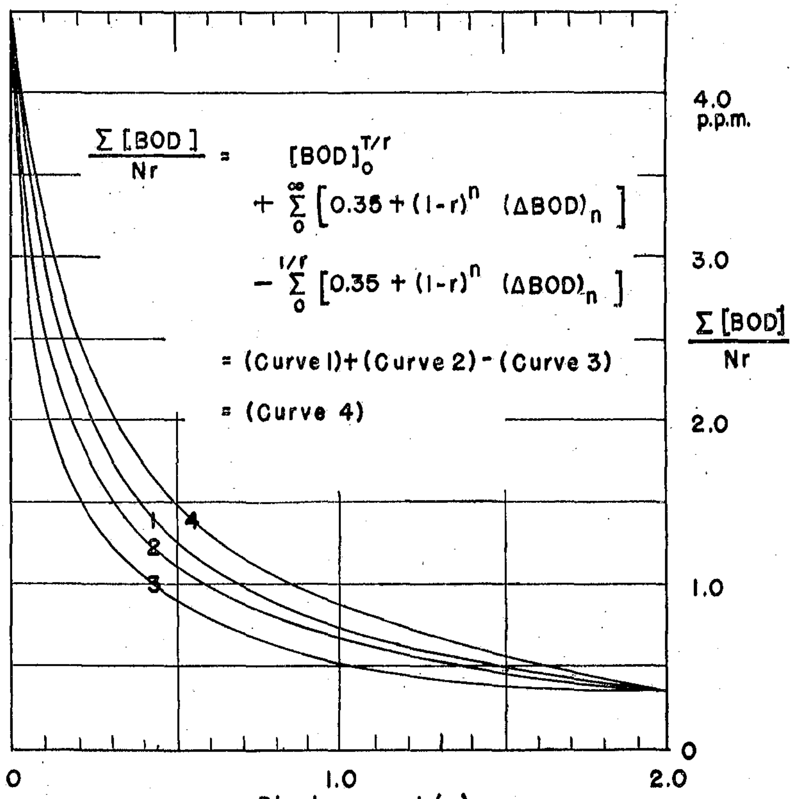


FIGURE 32.

The cumulative [BOD] of one cycle's discharge of waste sulphite liquor during the following n tidal periods is given in fig. 31(a). Then because the region through which the waste sulphite liquor is being transported before displacement occurs, contains the discharge of n periods, the above value is also the [BOD] in the n^{th} tidal cycle, of the total discharge during the previous n cycles. This value may be expressed as:

$$Nr[BOD]_1^n$$

The manipulation of these quantities may be simplified by realizing that the time of transport (n) through the interval, is the time required for the displacement of a volume equal to the volume of the upper zone, i.e. where AD = (area) × (depth) = (volume),

$$n = T \frac{AD}{ADr} = \frac{T}{r} \text{ tide cycles} \qquad (22)$$

where T = 24 hrs. 52 minutes = 1 tide cycle.

Collecting these quantities, the total [BOD] in a continuing interval of the inlet is defined by

$$\frac{\Sigma[BOD]}{Nr} = [BOD]_0^{T/r} + \sum_1^{\infty} [0.350 + (1\text{-}r)^n (\Delta BOD)_n] - \sum_1^{T/r} [0.350 + (1\text{-}r)^n (\Delta BOD)^n] \qquad (23)$$

where n = 1, 2, 3 ······ ∞ tide cycles.

The terms of this expression are shown in curves 1, 2, 3 and 4 of fig. 32.

This derivation defines the cumulative B.O.D. of all the waste sulphite liquor contained in the region of the inlet specified by the displacement (r) and the concentration (N). In effect it is the demand accomplished in the water at the time of its displacement from the region, and therefore describes the state at the downstream limit of the interval.

TABLE XXXI. Characteristics of Alberni inlet (from Part I).

	Harbour	*Continuing Intervals*			
		O-A	O-B	O-C	O-D
			Values		
Area (sq. ft. × 10^{-7})	5.85	8.00	16.30	34.80	64.90
Length (feet)	8,750	15,600	22,380	41,600	49,200
			Ratios		
Run-off (F)	1.0	1.011	1.189	1.570	1.973
Displacement (r)	1.0	0.71	0.42	0.31	0.28
Proportion of fresh water (C)	1.0	0.98	0.94	0.75	0.58
Concentration of W.S.L.	1.0	0.96	0.79	0.48	0.29

	Harbour	*Successive intervals*			
		O-A	A-B	B-C	C-D
Displacement (r)	1.0	0.71	0.83	0.59	0.66

The value of the above equation may be introduced into the numerator and denominator of the equation so that the degree of pollution in Alberni inlet is expressed by

$$P = \frac{[BOD]}{Nr} \times \frac{N}{0.5(DO)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

DISPLACEMENT

The displacement (r) from Alberni harbour under normal oceanographic conditions, and the maximum divergences due to strong south winds and freshets were determined in the oceanographic investigations (fig. 14c). The ratios of displacement from the continuing intervals (Hr., O-A, O-B, etc.) to the function in the harbour was also established, and are shown in table XXXI, along with other quantities required in these calculations.

CONCENTRATION OF WASTE SULPHITE LIQUOR (W.S.L.)

It is assumed that the concentration of waste sulphite liquor in the fresh water contained in the inlet, is in the proportion of the discharge of the liquor (Q_E) to run-off (Q) into the region of the inlet being considered. Then where

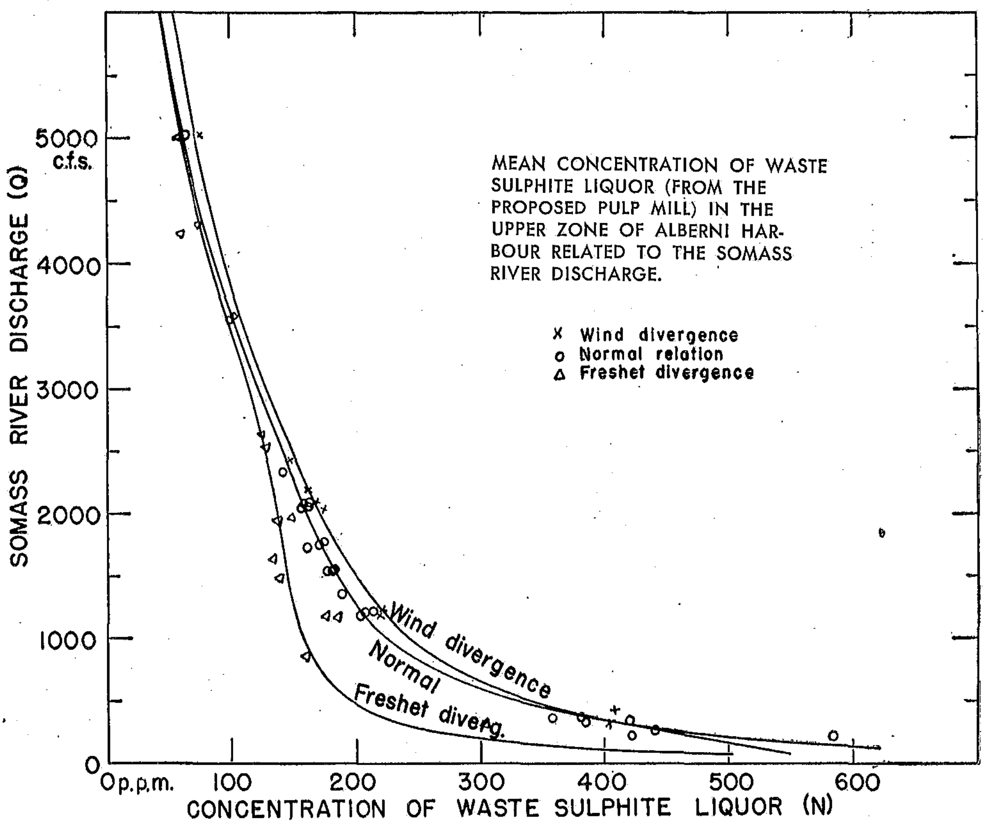


FIGURE 33.

(C) is the proportion of fresh water in the upper zone of the region, the mean concentration of waste sulphite liquor (N) is

$$N = \frac{Q_E C}{Q} \times 10^6 = \frac{C}{Q} 4.77 \times 10^5 \text{ p.p.m.} \qquad (25)$$

where Q_E is evaluated in table XXVI.

If the mill sewer is in, or near the mouth of the Somass river, the concentration of the effluent may be assumed to vary similarily to the distribution of fresh water in the inlet (Part I). The average concentration of the waste sulphite liquor in the upper zone of Alberni harbour (fig. 33) in successive intervals (O-A, O-B, etc.) is proportional to the concentration of Somass river water, whence ratio $N = \frac{\text{ratio } C}{F}$, where ratio C is the ratio of the fresh water content in each interval, and F is the ratio of run-off (i.e. additional fresh water) in successive intervals. These values are shown in table XXXI.

CALCULATED POLLUTION

The situation was explored (fig. 34) by solving equation 24 from the data cited, to show the pollution accomplished in Alberni harbour during normal oceanographic conditions, and the limiting divergences due to strong south winds, and freshet, in relation to the temperature.

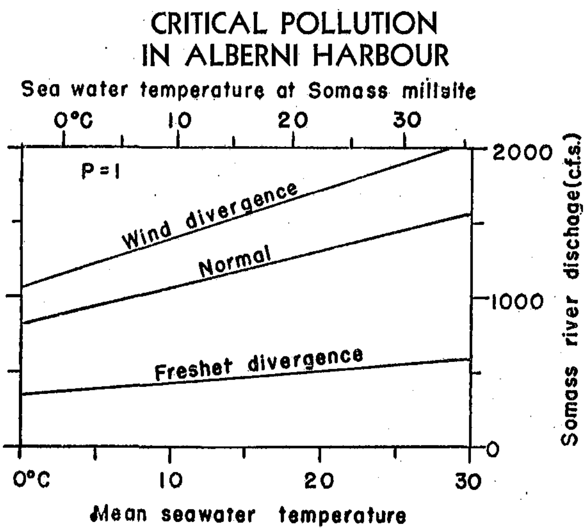


FIGURE 34.

It is evident at once that the limiting pollution will be defined by the normal state, or wind divergence, and, as will be discussed, the freshet divergence need not be considered further. On comparing the incidence of pollution in the remaining curves to the temperature and run-off data (Part I), it was found that critical values of run-off occurred in August when the average temperature in the upper zone was between 18 and 19° and exceeded 20° C. on one occasion (for three days). From this it was concluded that 20° C. was representative of the most unfavourable conditions. Then the distribution of pollution at the limits of the successive intervals in the inlet (i.e. at Polly point, stations A, B, C, D) was calculated, and is shown in fig. 35. This computation was made by applying the ratios given in table XXXI to the values of displacement, and concentration of waste sulphite liquor in the harbour, by the procedure already established. The increase of oxygen content, and decrease of solubility towards

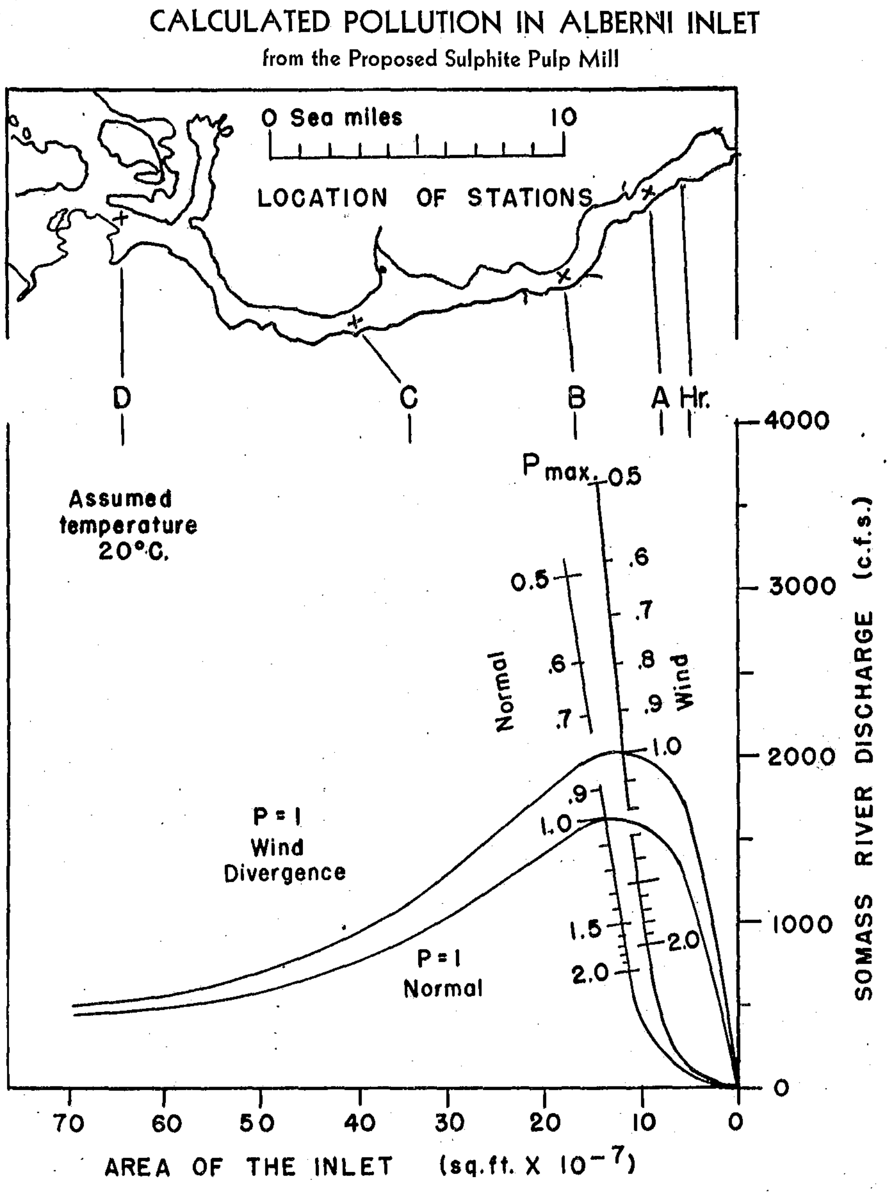


FIGURE 35.

the mouth of the inlet were neglected, since they did not affect the maximum values of pollution (P_{max}).

The data are plotted as a function of the area of the inlet, on the assumption that this represents the volume of the upper zone, since it has been established (Part I) that the depth of this zone was normally constant at any given value of run-off.

This figure (35) represents the calculated solution of the problem, since it brackets the equilibrium state of pollution in any part of the inlet between two levels of Somass river discharge. It assumes that the waste sulphite liquor is mixed with all mill sewage, and enters the inlet at sea level near the mouth of the Somass river. No account has been taken of the alleviating effects of wind aeration, or photosynthetic enrichment of the oxygen supply by phytoplankton.

DISCUSSION

Pollution in Alberni Inlet

It has been established (Part I) that the Somass river water followed a particular course through Alberni harbour, but to seaward the lateral distribution of fresh water became uniform. From this it is concluded that the pulp mill sewage would also follow a particular course in the harbour, but beyond this, its concentration would be a general function of the distance of seaward transport. In this sense the solution of the problem is general in the inlet, but particular in the harbour.

LONGITUDINAL DISTRIBUTION

The outstanding feature of the distribution of pollution is the occurrence of a maximum, indicating that the oxygen demand increases with distance to seaward more rapidly than the oxygen supply, to a limit at the point of maximum pollution (P_{max}) between stations A and B, beyond which the increase in the oxygen supply is the greater.

The form of these curves is in entire agreement with the observations of Eriksen and Townsend (1940) in Gray's harbour where the residual oxygen content of the water decreased to seaward from the mill site to a minimum, beyond which it was regenerated to approximately normal values at the harbour mouth. The predication of this behaviour in the present analysis confirms the reliability of the reasoning.

The excess oxygen residue (over 40% saturation) to seaward of the maximum could be utilized by releasing the effluent in diminishing proportions throughout the length of the inlet. However, from an engineering standpoint it would be just as easy to pipe the waste sulphite liquor to the lower reaches, which solution of the problem was previously discarded as being impractical.

VERTICAL DISTRIBUTION

It is assumed that the vertical distribution of the mill effluent would be essentially the same as the distribution of fresh water from the Somass river, and on this assumption a quantitative differentiation of the concentration of waste sulphite liquor could be made. However the age of the effluent in each stratum could not be evaluated, therefore the gradient of pollution could not be predicted. It might be reasoned qualitatively that the oxygen demand will decrease with depth, in the same ratio as the fresh water and the effluent concentration, which are similar to the gradient of dissolved oxygen in the base state, and the velocity gradient. Considering all these factors it is probable that the resulting pollution gradient would be less than the gradient of waste sulphite liquor.

Whether or not this supposition is correct is immaterial to the definition of the state of pollution, because if one part of the zone is over-polluted, there will be another part correspondingly under-polluted as long as $P_{max} = 1$. Townsend has shown that in short distances, such as the depth of the upper zone (5 to 30 feet) the fish follow the oxygen gradient and so avoid the most polluted part of the zone.

RELATION TO ABNORMAL CONDITIONS

The normal state has been defined (Part I) by the occurrence of steady or decreasing run-off and no south winds in excess of 10 miles per hour. Wind divergence from the normal implies greater winds, and freshet divergence designates the state occurring during increasing river discharge. With wind divergence the pollution exceeds the normal (fig. 34) owing to the restriction of displacement. It has been shown (Part I) that a freshet "flushes" the upper zone, from which it would be expected that the pollution would be less than normal, as predicted by the calculations. It has been remarked that these divergent states are transitory periods between equilibria represented by the normal state.

Wind deviation is a limiting factor because during the summer, when the river discharge is at, or below, the critical levels, strong south winds occur regularly for about eight hours each day, from noon till sundown. During the night, and the following morning the normal state is re-established. This cycle of conditions was observed during the oceanograhic investigations, but does not appear in the meteorological observations which were made at some distance from the inlet.

WIND AERATION

Regardless of whether the upper zone as a whole is supersaturated or deficient in dissolved oxygen, it approaches saturation at the surface, and towards the mouth of the inlet (Part I). This effect is attributed to wind. From examination of data representing a state of partial pollution due to debris carried in the autumn freshet it has been shown that saturation of the upper zone is not accomplished in the whole length of the inlet, probably because of the continuing oxygen demand. This indicates that oxygenation from wind aeration would not be a considerable factor in the region of maximum pollution, above station B (fig. 1).

The efficiency of oxygenation increases with oxygen deficiency; consequently the most efficient aeration would be expected in the region of maximum pollution, where it would be an alleviating factor.

PHYTO-PLANKTON ACTIVITY

The occurrence of supersaturation with dissolved oxygen at the boundary of the upper zone (15 to 40 feet) during the summer has been remarked (Part I), and it has been pointed out that in the absence of pollution this has been a dependable, but not a calculable, source of oxygen. It would be due to phytoplankton activity.

Unless there are poisonous substances in the waste sulphite liquor, it may be reasoned that its presence would promote the growth of phyto-plankton, since the fermentation process is the converse of photosynthesis. This theory finds some support in the fact that Hopkins *et al.* (1931) observed an abnormally large growth of the chain diatom *Melosira borreri* in the sulphite-liquor-polluted waters of Oakland bay (Washington State, U.S.A.). This evidence is contradicted in principle by Eriksen and Townsend (1940) who observed that the abundance of phyto-plankton in Gray's harbour was low compared to nearby seaways, but they could not determine whether this was due to the pollution, or the greater fluctuations of oceanographic conditions in that harbour. There may be some basis for the belief, but there is not sufficient assurance that plankton activity is a dependable source of oxygen supply in the presence of pollution.

RELATION TO TEMPERATURE

The relation of pollution to average temperature in the upper zone of Alberni harbour and to temperature at the proposed mill site (fig. 55) is evidently complicated by the variation of oxygen solubility with river discharge (which determines the chlorinity and salinity of the water) and with temperature as shown in fig. 2. The significance cannot be established, since the base state of dissolved oxygen on which it was predicted was not observed. It is probable that the relation is of the correct order, in the sense that the incidence of pollution would be associated with a lower level of Somass river discharge in the winter than in the summer. However, in the presence of short term fluctuations of temperature, the concentrations of dissolved oxygen would probably remain fairly constant. In consequence the relation has only been used as a guide to the state most representative of the period of probable pollution, with the knowledge that the concentration of dissolved oxygen will not be less than the value indicated.

RELATION TO pH

The alteration of the pH of sea water by waste sulphite liquor was studied experimentally in fresh water by Benson and Benson (1932), and in sea water by Eriksen and Townsend (1940). Combining the values cited by both authors, the relation between the change of pH (Δ pH) and the concentration of waste sulphite liquor, and chlorinity was computed. This was expressed in terms of the discharge of the Somass river from the relations cited (Part I), and is shown in fig. 36.

It is indicated that the limiting tolerable reduction of 0.2 pH, mentioned in Townsend's criteria, would occur when the discharge of the Somass river was about 1,000 c.f.s., which is a considerably lower discharge level than the calculated occurrence of $P_{max} = 1$.

The maximum alteration of pH (ΔpH $= 0.5$) does not appear to be a critical factor in itself, for as already shown (Part I), the normal seasonal variation, and the variation from top to bottom of the upper zone in the summer, exceeds this amount.

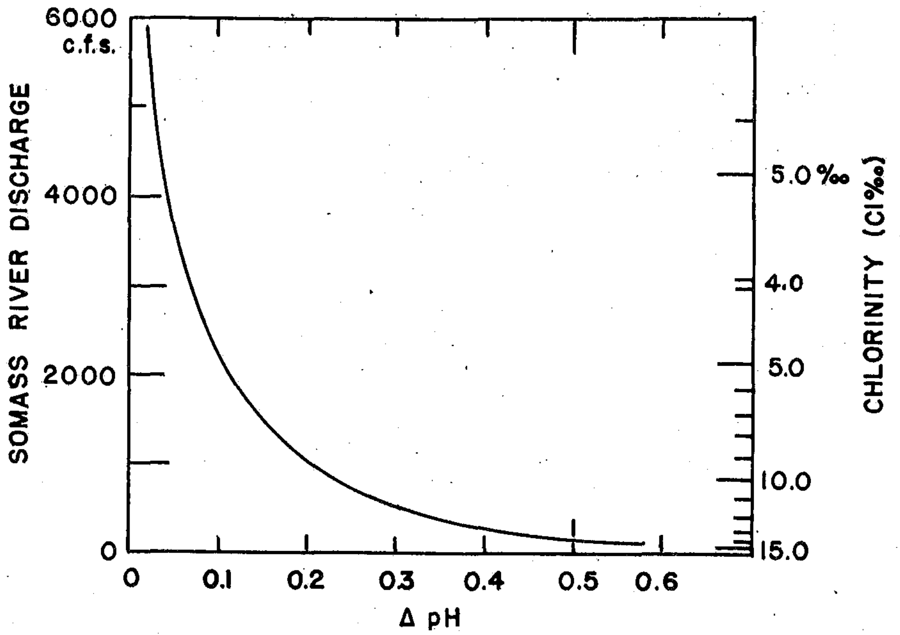


FIGURE 36. Estimated change in pH (ΔpH) in Alberni harbour due to sulphite liquor concentration from the proposed 135 ton pulp mill, related to Somass river discharge, and mean chlorinity of the upper zone.

THE CRITICAL STATE

Townsend showed that fish would avoid a region of oxygen deficiency in the presence of an alternate region of sufficiency. Consequently it would be reasoned that the pollution maximum in the inlet would constitute a barrier to migration, assuming the fish would remain in the less polluted waters in the lower reaches of the inlet. Contrary to this, it has been observed (Tully, unpublished) that the adult salmon continue their spawning migration into polluted areas. Townsend also observed, that both the spawning and the seaward migration occurred through the over-polluted region in Gray's harbour, resulting in the death of the fish. It may be concluded that the presence of the pollution maximum would not alter the migratory habits of the salmon and trout in the inlet.

Evidently the fish cannot realize that a more suitable habitat exists beyond the maximum pollution, and so accelerate their migration through the limited region. Consequently the pollution must not exceed values likely to be deleterious to the fish that remain in the region for a considerable time. This condition has been established in the definition of critical pollution (equation 26).

Recalling the probable vertical distribution of the pollutant, it is evident that in the presence of excessive pollution at or near the surface, there would be less than the calculated pollution below this, near the boundary of the upper zone, and little or no pollution in the middle zone, which would provide an alternate migration route for the fish. This conclusion is confirmed by the absence of mortality in the presence of salinity stability (table XXX).

There are several alleviating factors, such as the probability of wind aeration, and of phyto-plankton enrichment of the oxygen supply. Further, the computations were based on the minimum (base) oxygen supply (assumed 90% saturation rather than 100%) and temperature (assumed 20°C. rather than the average value of 16° to 18°C.). However there is no justification for assuming more optimistic conditions, until the state resulting from operation of the proposed mill can be assessed.

Considering all these factors, it is concluded that the limit of tolerable pollution ($P_{max} = 1$) from the proposed mill, operating under the assumed conditions, will be reached when the discharge of the Somass river is between 1,600 and 2,000 c.f.s., the former limit applying to a condition of prolonged strong south winds, and the latter to the average state. In view of the transitory nature of the wind divergence it is concluded that the critical discharge level is about 1,800 c.f.s., above which no intolerable degree of pollution is expected.

Pollution in Alberni harbour

Aside from maintaining a "tolerable limit" of pollution in the inlet as a whole, the behaviour of the mill sewage in Alberni harbour (fig. 2) is probably the most important consideration from the standpoint of the fishery. Both the adult and fingerling salmon form schools and remain in the area for some time, probably utilizing the considerable salinity gradient in their transition between fresh and sea-water environments. There is no commercial fishery, but there is a considerable sport fishery in the area. In addition, the city of Port Alberni is on the eastern side of the harbour, where the waterfront is occupied by lumber mills, log booms, and wharves for deep sea and local shipping, and a public swimming beach. For this reason some thought should be given to possible nuisance effects of the pulp mill sewage.

The oceanographic mechanism of Alberni harbour has been discussed in the oceanographic section, where it has been shown that during the ebb tide the river stream flows through the harbour on the eastern side, diverging downstream to occupy almost the whole width of the inlet, at or just below, Polly point. The western side of the harbour is occupied by mixed inlet and river water, which is only displaced from the region by being drawn into the river stream. During the flood tide inlet water enters the harbour, opposing the outflow of river water, which accumulates as a cloud. At the same time the mixed water on the western side is displaced onto the tide flats at the head. Boundary currents were observed along both eastern and western shores, in which the flood movement was very weak while the ebb movement was comparatively strong, and the water was conserved near the shore.

From this it may be recognized that the western, and in particular the northwestern part, of the harbour is a region of accumulation, where seaward displacement of the water is a minimum. The river stream is a region of displacement, and along both shores there is a region of restricted flow. There are arguments for and against wasting the effluent in any one of these regions, and the problem has been given considerable study, both in the field, and in a hydraulic model of the area (Part II).

The general solution is predicated on the steady disposal of the sewage at or near the mouth of the Somass river. From this point the distribution of waste sulphite liquor can be assumed to be proportional to the distribution of fresh water, that is, the concentration would be greatest in the river stream, and would attain laterally uniform distribution immediately seaward of the harbour entrance (vicinity of station A). Considerable effluent would be returned during the flood tides, and at equilibrium the harbour would contain waste sulphite liquor of all ages, but the degree of pollution would not be uniform because the maximum oxygen supply is in the river stream. The river itself would not be polluted since any effluent that might intrude on the flood tide, would be completely displaced during the first part of the ensuing ebb.

The pulp fibre that did not accumulate in the immediate vicinity of the sewer, would be carried in the river stream, and probably deposited to seaward of the middle of the harbour in relatively deep water.

From this sewer site the effluent would attain its maximum dilution in the shortest time; the river stream would be under-polluted while the pollution on the western side would approximate P_{max} or be over-polluted. The nuisance value would be at a minimum since no visible concentration of the sewage or pulp accumulation would appear along the city foreshore.

The region of extreme accumulation is in Johnstone slough (fig. 2) where, if the whole effluent of the concentrated blow-pit liquor were discharged, the slough would be almost full before equilibrium exchange with the harbour was established. Then the effluent would enter the northwest quarter of the harbour, which is also a region of accumulation, and there would be further delay in dilution and displacement.

The probability of satisfying a significant proportion of the oxygen demand of the concentrated waste sulphite liquor by aeration in Johnstone slough may be discounted. The experience of ponding in Oakland bay region (Washington State, U.S.A.) (Eriksen and Townsend, 1940) indicates that at the high concentrations that would be experienced, the liquor is stable to oxidation over long periods.

It is evident that at equilibrium the displacement from the slough into the harbour would equal the rate of discharge from the mill; consequently the only effect would be to delay entry of the effluent into the harbour, and this would not differ materially from wasting it directly in the northwest quarter. In either case the displacement would be less than the calculated average; consequently the peak of pollution would occur further upstream, probably within the harbour, and because of the accumulation, the concentration of waste sulphite liquor would be high on the western side, and would be present in all parts of the area.

The restricted flow along the eastern shore was particularly examined in the model, and later confirmed by float experiments cited in the oceanographic section. It has been shown that the effluent from a sewer located on the shore immediately south of the city of Port Alberni (reference squares 16 to 19 in fig. 2) would accumulate along the shore during the flood, and most of it would be displaced from the harbour during the first ebb tide after its discharge. There would be no tendency for diffusion into, or across the river stream, within the harbour, although lateral diffusion would be accomplished at or below station A. It was also noted that light winds had no effect on this current, and that strong south winds tended to conserve the water along the shore.

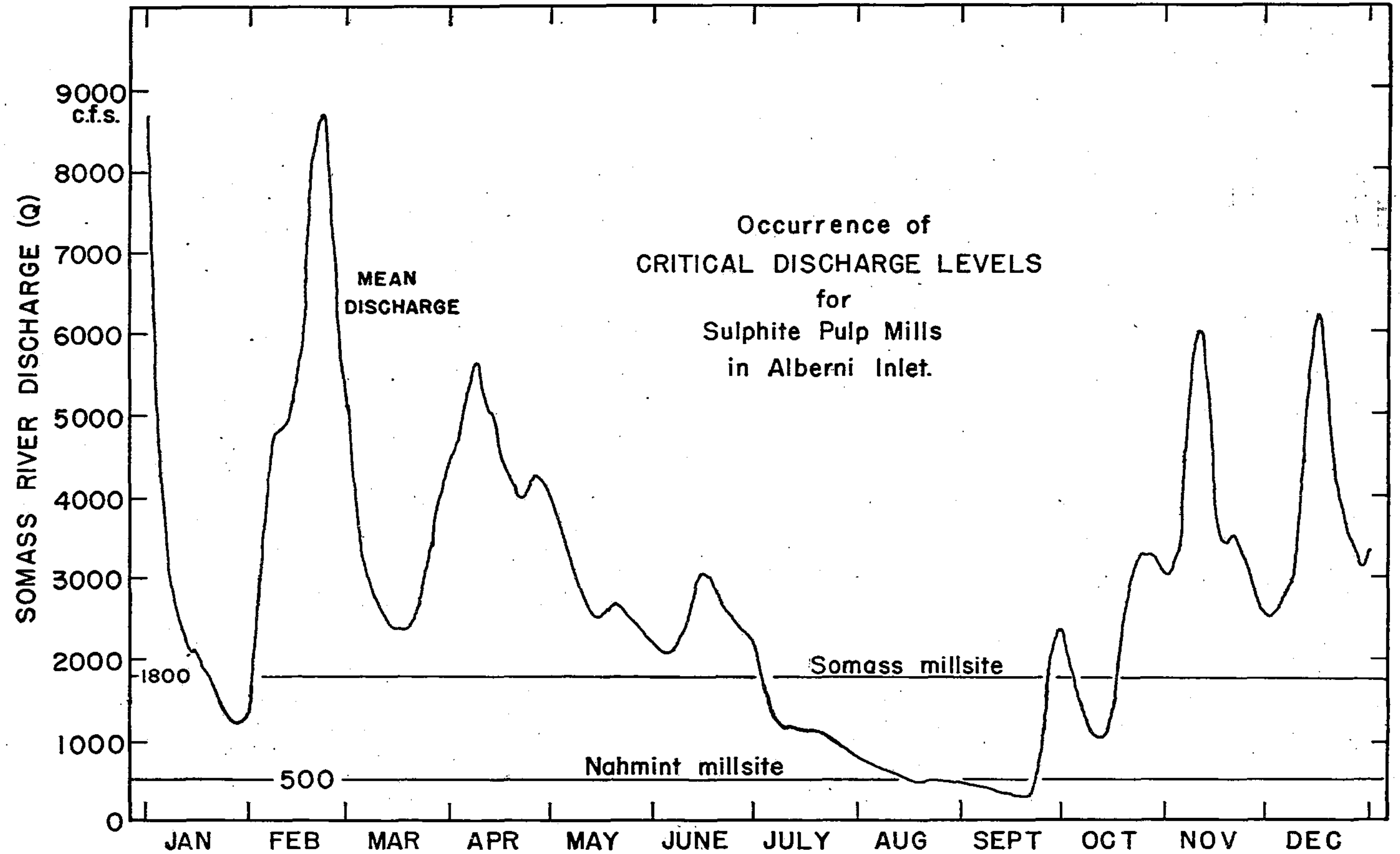
Although the experiment was disappointing from a quantitative point of view, a rough estimate of the displacement was possible from one series of observations. One hundred floats were released, at the middle of the ebb tide, at position Q19 (fig. 2). All were displaced from the harbour during the remaining part of the ebb. Of the number remaining afloat, 24% returned to the harbour, and 15% returned north of the original release. Combining this with the previous experiments, it would appear that, if the sewer mouth were placed on the shore between positions Q16 and Q22, about 89% of the effluent accumulated in the neighbourhood during the flood would move out of the harbour during the ebb, and of this about 24%, or about 19% of the total, would be returned during the flood. From this release, the displacement would be of the order of 61% (0.6) under normal conditions. (The observations of extreme drift were made in the absence of wind.)

In this case, most of the effluent would be displaced from the harbour in one rather than three to five tides, and only about 10% would be transferred to the river stream during the tidal oscillations. Then the general state of pollution would be expected to be about 10% of that calculated in the general solution. In the interval above station A it is anticipated that 90% of the effluent would be restricted to about 30% of the area, in which the pollution would be about three times as great as estimated. The remainder of the area would be correspondingly under-polluted, which would be advantageous to the schooling fish.

The general effect of the introduction of the sewage into this region of restricted flow would be to release it into the general circulation system at intervals down the inlet, rather than at one point as assumed in the general solution. It appeared from the observations, that diffusion across the inlet might become general at Stamp point, or thereabouts. This would tend to depress the peak of maximum pollution by shifting some of the demand down the inlet, and utilizing some of the excess oxygen supply below Stamp narrows. Then the critical pollution would occur at somewhat lower values than predicted in fig. 56. The location and magnitude of the peak of the pollution in this instance is a particular solution of the problem, depending on the specific location of the outlet of the mill sewer.

Contrary to this means of disposal, it may be pointed out that the effluent and waste fibre would accumulate along the foreshore and create a public nuisance. Further it would require about one mile of 40-inch sewer along the industrial waterfront, which would involve considerable expense.

Disposal of the whole effluent at or near the mouth of the Somass river



Occurrence of
CRITICAL DISCHARGE LEVELS
for
Sulphite Pulp Mills
in Alberni Inlet.
MEAN
DISCHARGE
SOMASS RIVER DISCHARGE (Q)
9000
c.f.s.
8000
7000
6000
5000
4000
3000
2000
1800
1000
500
0
Somass millsite
Nahmint millsite
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC

FIGURE 37.

appears to be the next most acceptable alternative. The limiting tolerable state of pollution may occur at slightly higher levels of river discharge than the above plan. However it has been estimated and provision can be made for control of the mill operation.

The possibility of wasting the whole of the concentrated effluent in Johnstone slough or tide flats should not be considered, as this would result in accumulation of waste sulphite liquor on the western side of the harbour and probably bring the peak of pollution into the harbour area.

Limits of Production

THE PROPOSED MILL

It has been shown that the degree of pollution from the proposed sulphite pulp mill (135 tons per day) is a function of the Somass river discharge, modified by temperature. Consequently if the tolerable degree of pollution is not to be exceeded, the mill must cease operation during periods when the discharge of the Somass river is less than the critical value (1,800 c.f.s.) or reduce its production within limits defined by the discharge.

The consequence of the first option is shown in fig. 37, which illustrates the mean discharge of the Somass river during 13 years, with a line marking the critical level.

The second option may be estimated from the fact that the concentration of waste sulphite liquor, and consequently the degree of pollution, is a linear function of the rate of mill production. Then the rate associated with $P_{max} = 1$ is defined by

$$\frac{1}{P_{max}} = \frac{\text{(Rate of production, tons/day)}}{135} \quad \ldots\ldots\ldots\ldots\ldots (26)$$

where P_{max} is the calculated maximum pollution associated with any level of Somass river discharge (fig. 35). This relation for the proposed mill is shown in fig. 38.

AN ALTERNATIVE MILL SITE

The general solution shown in fig. 35 presumes the mill sewer will discharge at or near the mouth of the Somass river, which defines the location of P_{max}. It was suggested that the mill might be located at the mouth of the Nahmint river (fig. 1) with the hope that the maximum pollution might be reduced, and displaced to seaward of Junction passage.

The conclusion of fig. 35 was transferred to the Nahmint river mill site, by realizing that the depth of the upper zone was constant at any level of run-off (Part I) and setting P_{max} at a point downstream such that the displacement from the interval (Nahmint to P''_{max}) equaled the displacement from the interval (Somass to P'_{max}) at that level of Somass river discharge. This condition is defined by

$$r_0 \times R_n = r_0 \times R_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

where r_0 is the displacement from the harbour at any discharge level of the

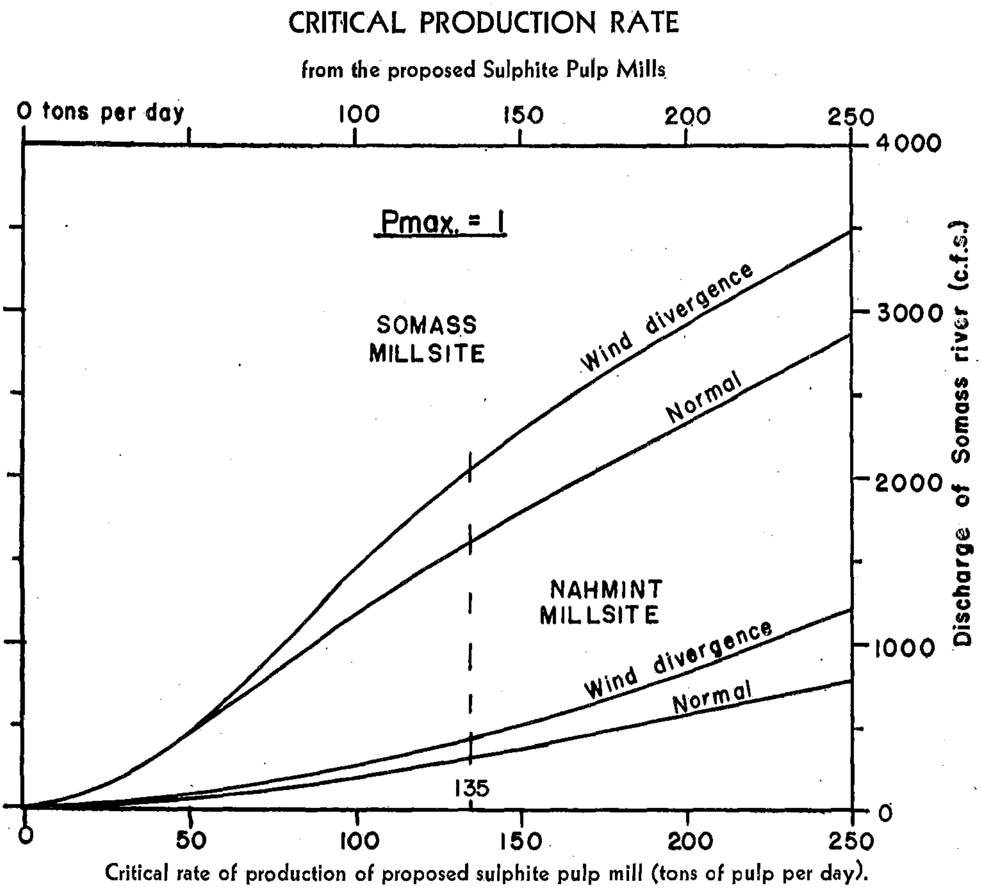


FIGURE 38.

Somass river, R_n is the differential displacement ratio in the interval (Nahmint to P''_{max}), and R_s the ratio for Somass to P'_{max}.

The values of R_s from the head of the inlet to P'_{max} were obtained from a plot of the displacement ratios as functions of area (table XXXI). A similar graph of the differential displacement from the Nahmint to station D served to define A_n. The position of P''_{max} was located by integration on a suitable chart of the area, and is shown in fig. 39.

From the condition that the displacement from the two regions is the same, it follows that the oxygen demand is the same (fig. 32) and it has been assumed that the oxygen concentration was constant. Therefore the relative degree of pollution is expressed by the relative concentration, which is the ratio of the volumes of upper zone water displaced through the cross-sections at the two positions of P_{max}.

$$\frac{P_n}{P_s} = \frac{r_o \times R_s \times A_s}{r_o \times R_n \times A_n},$$

OCCURRENCE OF MAXIMUM POLLUTION IN ALBERNI INLET

from the Proposed Sulphite Pulp Mills

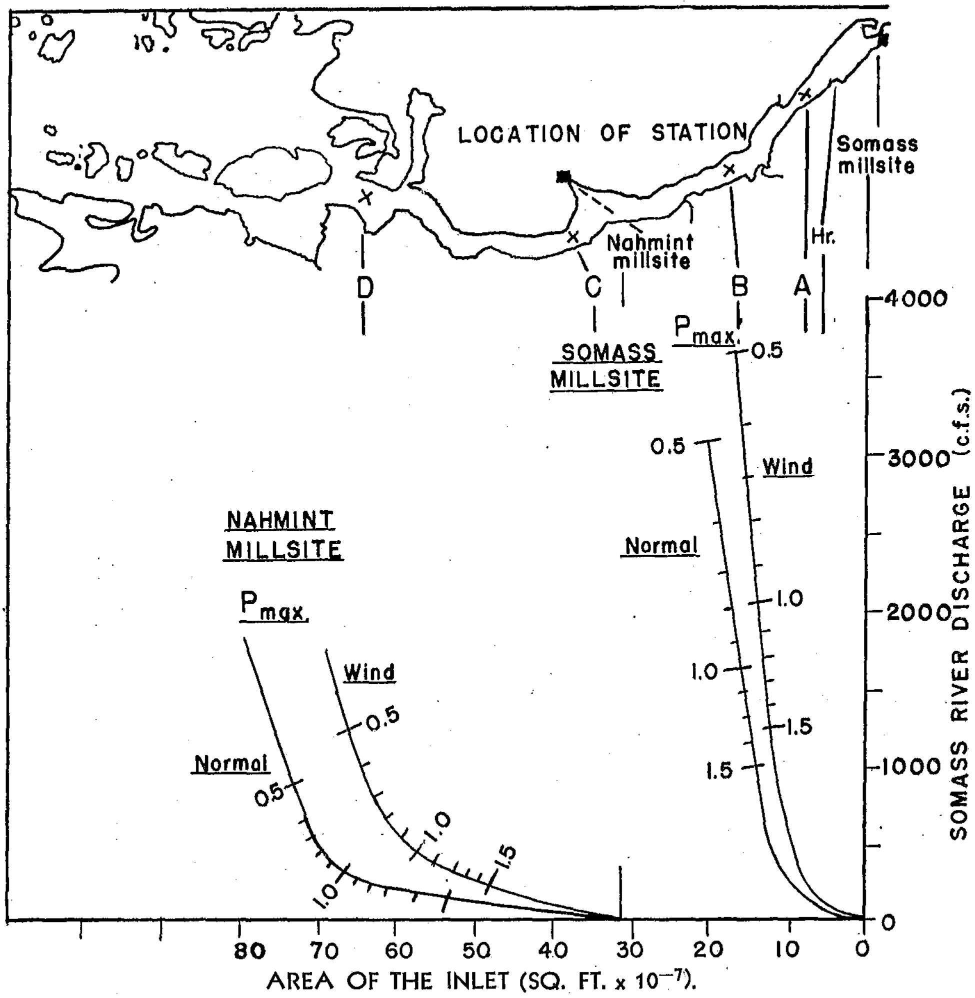


FIGURE 39.

but $R_s = R_n$, wherefore

$$P_n = \frac{A_s}{A_n} \times P_s \quad \text{.........................} (28)$$

in which P_n and P_s are the degree of pollution at P_{max} associated with the Nahmint and Somass mill sites respectively. A scale of P''_{max} was derived from values at several levels of discharge.

From this mill site critical pollution would be incident between Somass river discharge levels of 350 to 450 c.f.s. and would occur in the vicinity of Uchucklesit inlet (fig. 1). The incidence of critical pollution in this region from the Somass mill site is shown in fig. 35 to occur between 550 and 650 c.f.s. That is, the degree of pollution in the lower inlet would not be significantly alleviated by the change of mill site, although the upper reaches would be free of pollution, and the tolerance of the mill operation would be greatly increased as shown in fig. 38.

AN ALTERNATIVE MILL

It has been established that the polluting factor (B.O.D.) is proportional to the solids dissolved in the waste sulphite liquor (Eriksen and Townsend, 1940) and in the derivation of the equation (25) it was shown that pollution arising from any other mill (P_x) with a similar effluent, and at the same site, may be expressed as a proportion of the values shown here (P_0) in the form:

$$P_x = P_0 \times \frac{(\text{proportion of solids})_x}{(\text{proportion of solids})_0} \times \frac{(\text{rate of production})_x}{(\text{rate of production})_0} \quad \ldots\ldots (29)$$

For example, an alternative sulphate mill was proposed, having the production characteristics shown in table XXXII. Comparing these with the reference values in the above equation,

$$\text{Pollution from 150-ton sulphate mill} = 1 \times \frac{21.6}{11.5} \times \frac{4400}{41200} \doteq 0.20.$$

TABLE XXXII. Production characteristics of proposed sulphate pulp mill.

	Sulphite pulp mill (table XXVI)	Sulphate pulp mill
Total production (tons of bleached pulp per day).....	135	150
Digester liquor discharged into mill sewer (cu. ft. per day)........	41,200	4,400
% total digester liquor wasted........	100	10
Concentration (% solids in solution)........	11.5	21.6
Total water discharge (cu. ft. per day)........	784,000	1,090,000

That is, at the river level of critical pollution from the proposed sulphite mill (1,800 c.f.s.) the pollution from the 150-ton sulphate mill would be P = 0.2. For more general application of the data, the ratio of the polluting factors may be solved in equation 29 in the form:

$$\text{Pollution from a 150-ton sulphate mill} = \frac{21.6}{11.5} \times \frac{4400}{41200} \times 135$$

$$= 27.1$$

= pollution from a sulphite mill producing 27.1 tons per day.

Then consulting fig. 38, it may be seen that the critical discharge level of the Somass river is about 160 c.f.s. Referring to fig. 37, it may be noted that this level does not occur every year, and when it does, it only lasts a few days. From the standpoint of pollution this would provide one of the most acceptable alternatives.

SEWER DESIGN

It cannot be emphasized too strongly that the restriction of the effluent to the upper zone of the inlet is a critical factor in these deductions. Therefore the density of the mill sewage must be controlled at the lowest possible level (table XXVI). This condition implies that mixing tanks are required in the sewage disposal line, and that the blow-pit liquor be mixed to homogeneity with *all* wash water from the mill before discharge into the inlet. The effluent must enter the inlet at the surface, with a minimum of turbulence, and no vertical component in the flow. This implies that the sewer mouth should be located above sea level on a gently sloping beach, or a floating outlet should be provided.

The conclusions that have been drawn are predicated on a steady discharge of the sewage, but it may be found advantageous to institute controlled discharge at certain tidal phases, in order to take advantage of local displacement functions.

It is reasonable to assume that a certain amount of experimental work will be required to determine the most efficient form, and position, of the outlet, and the capacity and design of the mixing tanks, but the original design should be adequate to comply with the primary requirements.

Alternative Solutions to the Problem

The discussion has been concerned with the disposal of the whole effluent in Alberni inlet as required by the problem. However there are other approaches based on the stabilization, destruction, or utilization of the waste sulphite liquor. Although the majority of these do not concern the discussion directly, there are some that are within the bounds of practicability and should be considered as alleviating factors, if not alternative solutions.

OXIDATION

Considerable research has been done in an effort to stabilize waste sulphite liquor and so reduce or eliminate its pollution potential. Obviously any means of supplying oxygen to the waste sulphite liquor from some source other than Alberni inlet waters would alleviate the demand on the system and increase the limiting rate of production.

Methods of simple ponding at ordinary temperatures (50° to 65°F.; 10° to 15°C.) of the concentrated liquor have been relatively ineffective as shown by the ponding of blow-pit liquor in old lake beds in the Oakland bay region. For this process to be successful the waste sulphite liquor would need to be diluted from its concentration of 795 to 1,085 p.p.m. in the mill sewage (table XXVI) to 50 to 100 p.p.m., which would require all the upper zone water in Alberni harbour. This is impractical both because of the size of the ponds, and the fact that the diluting water would be drawn from Alberni inlet system which would not reduce the overall demand.

It has been noted by O'Dell and Greenlaw (1934) that the efficiency of the process increases greatly with temperature. Presumably working with blow-pit liquor (11.5% solids) they showed that 79% of the B.O.D. may be satisfied by simple ponding for 10 hours at 50°C. (122°F.). Further examination showed that the efficiency could be increased by raising the temperature so that an 85% reduction of B.O.D. could be obtained in 2 hours at 90°C. (194°F.). It is possible that a practical means of alleviating the demand during low run-off levels could be devised on this basis.

Aside from this, most oxidation processes are cumbersome and expensive. Usually the treatments prescribe precipitation of inorganic sulphite with hydroxides or limestone ($CaCO_3$) and subsequent oxidation of the organic constituents with varying degrees of mechanical aeration, combined with control of temperature and concentration.

ANAEROBIOSIS

Benson and Partansky (1936) proposed anaerobic fermentation of the waste sulphite liquor at a concentration of 300,000 p.p.m. as a means of reducing the B.O.D. before discharge into natural water ways. It has been noted that Townsend objected to the products in a natural fish-way. Benson and Partansky noted the nuisance value of the process due to generation of hydrogen sulphide, and butyric acid. They suggested removal of the sulphites by lime precipitation at the boiling point, and subsequent removal of butyric acid by distillation, or solvent treatment. They also indicated that further research might mitigate the generation of these products.

CONTROL OF RIVER DISCHARGE

If the discharge of the Somass river were controlled so that it was always greater than the critical value, the peak of pollution from the Port Alberni mill site would never attain the critical value ($P = 1.0$).

It may be argued that the development of pollution in the inlet has been studied on the basis of proportionally increasing run-off down the inlet. This may be compensated by noticing that the peaks of pollution always occur above station B, and the ratio of run-off in the section O-B to the Somass river discharge is 1.189:1 (table XXXI). Then, if clearance of pollution depended on the Somass river alone, the critical discharge (Q) would be

$$Q = 1.189 \times 1800 = 2140 \text{ c.f.s.}$$

An examination of the discharge data in fig. 58 indicates that there is a considerable period in March and April when the run-off is greatly in excess of that required to alleviate pollution. If sufficient water could be stored and released in July, August, and September to maintain the discharge above the critical level, then the mill could discharge its whole effluent into the inlet continuously.

A cursory examination shows that the necessary water could be stored by raising the level of Sproat lake or Great Central lake, which contribute to the Somass river, about 18 feet. It is not within the province of this investigation to examine this suggestion further, but obviously the possibility merits some engineering examination.

EFFLUENT STORAGE

Conversely to the above argument, the state of excessive pollution could be alleviated by storing the blow-pit liquor through the period of low river discharge, and releasing it during periods of excessive run-off. This option would be tantamount to altering the rate of production of the mill in accordance with the curve of limiting production (fig. 38).

A cursory examination shows that the required storage could be found in about two feet above sea level in Johnstone slough, across the Somass river from the present mill site (fig. 2).

In further consideration of this option it would be necessary to provide dykes around the area selected for storage, to provide for adequate dilution (1:20) of the stored blow-pit liquor before its release, and to select a suitable point for discharge of the resulting whole effluent. Then the rate of discharge should be controlled within the limits of production as shown in fig. 38.

BURNING

In some mills the digester liquor is partially evaporated, and the concentrate utilized in specially adapted furnaces as an auxiliary heat source.

DUMPING

When the run-off is less than the critical value at Gray's harbour, the digester liquor from the mill is taken out to sea in barges, and dumped.

INDUSTRIAL UTILIZATION

There are several recent developments in the utilization of waste sulphite liquor, notably in the field of plastics and binders. Most of this work is protected by patents and industrial secrecy, and is not readily available.

CONCLUSION

On the basis of these discussions it is concluded that an intolerable state of pollution will result due to disposal of the whole effluent from the proposed 135-ton sulphite pulp mill in Alberni inlet, when the discharge from the Somass river is less than 1,800 c.f.s.

This assumes that the blow-pit liquor is thoroughly mixed with all mill water, and the resulting homogeneous sewage is discharged at sea level near the mouth of the Somass river, or at some point to seaward along the eastern shore of Alberni harbour.

It is possible that certain imponderables such as aeration by the wind, or oxygen enrichment by phyto-plankton, may significantly reduce the critical run-off level. However it does not appear likely that these, or the utilization of any oceanographic properties of the inlet, would sufficiently reduce the probability of excessive pollution at lower run-off levels, to allow continuous operation of the mill.

If the mill sewer were situated at the Nahmint river, the critical discharge level of the Somass river would be reduced to 450 c.f.s. This would allow operation during a much longer season, but even in this case there is a probability of excessive pollution in the late summer.

If the concentrated blow-pit liquor were discharged on the bottom of the harbour, or in the depths of the inlet, it would probably accumulate unnoticed for some time. Eventually it would diffuse or circulate into overlying water and cause catastrophic pollution which could not be controlled. Consequently this is not a solution of the problem.

The presence or accumulation of pulp fibre in the anticipated amounts is not considered deleterious since there are no anadromous fish or sessile bottom forms in the part of the inlet likely to be affected.

This research was limited to defining the limits of tolerance of this seaway to pulp mill pollution, which object has been accomplished. However because the tolerable limit is less than the pollution potential of the proposed mill some of the possibilities of reducing the potential by other means have been considered.

In the case of the sulphite mill, the problem may be solved by storing the blow-pit liquor at a dilution of about 1:4 (250,000 p.p.m.) during the period of low river discharge, followed by controlled release at high river level, after dilution to 1:20 (50,000 p.p.m.). Fermentation which would reduce its pollution potential could be expected in the stored liquor. Free release of effluent would be permissible during the greater part of the year, obviating the necessity of excessive storage capacity.

Alternatively water could be stored in one of the lakes supplying the Somass river, and the discharge controlled so as to always be in excess of 2,140 c.f.s., which would compensate for the lesser run-off from other parts of the Alberni inlet system.

The possibilities of aerobic and anaerobic fermentation have been examined and found to be impractical because of the excessive storage required, or because of the noxious products. The possibilities of chemical neutralization, burning, and industrial utilization do not appear to provide a practical solution to the problem at the present stage of research.

Possibily the most satisfactory solution to the problem would be found in changing the characteristics of the mill. A 150-ton sulphate would have the same pollution potential as a 27-ton sulphite mill. This would be tolerable at the proposed mill site while the Somass river discharge is in excess of 160 c.f.s., which would allow almost continuous operation.

GLOSSARY OF SYMBOLS AND ABBREVIATIONS

A	Area of any region. Area of any interval in Alberni inlet between the head (position O) and a seaward position (station A, B, etc.).
b	Depth of base chlorinity (33 feet at station L20).
B.O.D.	Biochemical oxygen demand.
c	Concentration of fresh water in unit volume of inlet water at a specified position, depth and time.
C	Concentration of fresh water in the upper zone at any position (station A, B, etc.) expressed as the proportion of fresh water in a column of unit area.
$\overline{C}$	Mean concentration of fresh water in the upper zone, in any interval of the inlet, expressed as the proportion present in the total volume of the region.
c.f.s.	Cubic feet per second (refers to discharge of a river).
Cl_b	Base chlorinity. Chlorinity (Cl $^{\circ}/_{oo}$) of the sea water below the influence of fresh water, at the boundary between the upper and middle zones. Accepted as the chlorinity at 33 feet depth at station L20.
Cl_z	Chlorinity (Cl $^{\circ}/_{oo}$) at a specified position, depth and time.
d_1	Density of pure water at temperature (T_1°C).
d_2	Density of pure water at the temperature (T_2°C).
D.O.	Dissolved oxygen concentration.
d_t	Density of sea water sample at T°C.
D	Depth of the inflexion in the chlorinity gradient. Depth of the upper zone at any position.
$\overline{D}$	Mean depth of the upper zone in any interval of the inlet (O-A, O-B, etc.).
F	Factor expressing the ratio of run-off in any continuing interval of Alberni inlet (O-A, etc.) to the discharge of the Somass river (Q) into Alberni harbour.
H_T	Tidal height above low water datum, (fig. 22).
l	Litres.
L	Length of any interval in Alberni inlet (O-A, or A-B, etc.).
ml.	Millitres.
m.p.h.	Statute miles per hour.
n	Any number, 1, 2, 3, etc.
N.O.D.	Natural oxygen demand.
$^{\circ}/_{oo}$	Parts per thousand by weight.
p.p.m.	Parts per million (usually signifies by weight).
Q	Mean rate of discharge of the Somass river (c.f.s.) during a day. The index of run-off into the inlet.
$\overline{Q}$	The mean rate of discharge of the Somass river during the time (T(1.039)/r) required for this discharge to provide a volume of water equal to the fresh water contained in the upper zone of any interval (O-A, etc.) of the inlet.
r	Displacement. The proportion of the water in any limited region (e.g. upper zone in interval O-A) that leaves the region in one tide cycle (T). This volume is replaced by a like amount of new water.
t	Time, the general term.
T	Time of one tidal cycle, 24 hours 52 minutes, or 1.039 days.
T°C	Temperature in degrees centigrade.

v	Velocity, rate of transport of a particle in the inlet.
W	Width of the inlet at a specified position.
z	General symbol for depth, reckoned positive (+) downwards.
[BOD]	Specific Biochemical oxygen demand in one tide cycle (T) due to the concentration (N) of waste sulphite liquor in a specified sample of sea water.
(DO)	Solubility of oxygen in a specified sample of sea water (temperature and chlorinity defined)
N	Concentration of waste sulphite liquor from the proposed sulphite pulp mill in any region of the inlet.
P	The degree of pollution, defined by equations 1, 2, 3, 4 and 9 in "Prediction of pulp mill pollution."
P_{max}	The maximum degree of pollution existing in the inlet at any one level of discharge of the Somass river. Implies the position in the inlet.
P'_{max}	The maximum degree of pollution as above, referred to the proposed sulphite pulp mill at the Somass river mill site.
P''_{max}	The maximum degree of pollution as above, referred to the proposed sulphite pulp mill at the Nahmint river mill site.
P_n, P_s	The degree of pollution associated with P''_{max} and P'_{max}, above.
P_o, P_x	The degree of pollution associated with a sulphite pulp mill whose rate of production is (o, x) tons of pulp per day. P_o refers to the proposed mill production of 135 tons per day.
Q_E	The mean rate of discharge of waste sulphite liquor from the proposed sulphite pulp mill (0.477 c.f.s.).
R, R_n, R_s	Ratio of the displacement from any interval of Alberni harbour. R_n signifies the displacement ratio in the interval from the Nahmint river to P''_{max} associated with the Nahmint mill site. R_s signifies the ratio in the interval from the Somass mill site to P_{max}.
r_0	Displacement from the region of Alberni harbour.
X, X_1, X_2 etc.	General symbol for position (e.g. X = Stn. A, B, etc.).

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APPENDIX I

METHODS OF OBSERVATION AND ANALYSES

Oceanographic Equipment

The oceanographic observations were made from the C.G.M.S., A. P. Knight, a semi-diesel motor cruiser of 35 tons displacement. This vessel could not be manoeuvred at slow speeds, so it was necessary to anchor for every observation. In addition to the usual ship's equipment and accommodation, there was a gasoline winch for the sounding line, and a small chemical laboratory, enabling completion of all analyses on board.

Samples were taken with Ekman deep-sea reversing water-sampling bottles, placed on a galvanized steel sounding line, which was measured over a standard metre-wheel (Thompson and Robinson, 1931).

Sampling Procedure

Since the depth at each station was known, no sounding was necessary. The six Ekman bottles were placed on the line at definite intervals, lowered until all were in position, and allowed to remain for five minutes, when the messenger was dropped. The time was recorded, and the bottles raised. The six deepest samples were usually lifted first. A complete series of samples was termed a "haul."

From each Ekman bottle one sample (about 400 ml.) was drawn, for the estimation of chlorinity and pH, into a brown glass beer bottle (Hutchinson and Lucas, 1929). A second sample was then drawn into a glass-stoppered bottle for oxygen analyses. Care was taken to avoid aeration. The analyses were commenced immediately after the haul was completed.

From previous work (Hutchinson and Lucas, 1929), it was found that change in the concentration of the various constituents of sea water is more rapid near the surface than in the deep water. Hence the depths from which the samples were drawn were chosen to include, surface, 1, 2, 4, 6, 10, 20, 30, 50, 100, 150, and 200 metres, or as many of these as the depth of the water at any station permitted. The metre-wheel was standardized before the investigation and found to be correct.

The length of the Ekman bottles was about 1/3 of a metre and they could not be operated in series at less than one metre intervals on the line. These were the controlling factors in measurement of depth and in estimation of the gradients. Closer measurement would have been desirable.

Temperature

The thermometers were manufactured by Richter and Weise, Berlin, and were especially designed for use with the Ekman deep-sea reversing bottle. They were standardized by the III Reich, and were satisfactory for all the work encountered.

The temperature was read immediately after the Ekman bottle was removed from the line, and recorded at once, the usual precautions being taken to avoid parallax errors. It was found that the use of a watchmaker's lens facilitated accurate interpolation on the thermometer scale.

Readings on the auxiliary thermometers were taken, and the correction of the "observed temperature" to temperature *in situ* was made according to the graphical method of Tully (1937).

It is considered that the error from all sources in the temperature determination did not exceed 0.03°C.

CHLORINITY

Chlorinity was determined by the Mohr (1856) titration of a 10 ml. sample of sea water with silver nitrate, standardized against purified sodium chloride (Thompson, 1928). Constancy of the silver nitrate was assured by frequent comparison with standardized sea water.

REAGENTS

A primary standard was prepared from recrystallized sodium chloride as outlined by Thompson (1928).

About 29 to 31 gm. of NaCl were made up to one litre at 20°C., corresponding to a chlorosity of 17.5 to 18.8 Cl/litre.

A standard silver nitrate solution was prepared whose titre at 20°C. expressed the chlorosity of the standard. The weight of silver nitrate required is,

$$\text{Weight of } AgNO_3 \text{ per litre} = \frac{(\text{wt. of NaCl/litre}) \times (\text{vol. of sample})}{(\text{theoretical titre}) \times 0.34407} \quad \ldots\ldots (30)$$

where the theoretical titre is determined by

$$\text{Titre at T°C.} = \frac{0.6066 \times (\text{wt. of NaCl/litre}) \times d_1}{(\text{volume of sample ml.}) \times d_2} \quad \ldots\ldots (31)$$

where d_1 is the density of pure water at the desired temperature (t°C.), and d_2 is the density of pure water at the temperature of the titration. When the required titre is 20°C., d_1 becomes 0.99820. The error resulting from taking d_2 as the density of pure water, rather than that of the standard solution, does not exceed 0.006 ml. which is within the usual limits of error of the determination.

The stock solution was made up approximately by weight, and adjusted by addition of distilled water, or pure silver nitrate, until the titre was within ± 0.1 ml. of the theoretical value.

To compensate for the final difference a "solution correction" was applied. The limits of the volume of silver nitrate solution to which each correction applied were determined from

$$\frac{(\text{Actual titre})}{2n + 1} = \tfrac{1}{2} \text{ correction interval} \quad \ldots\ldots (32)$$

where n is the correction in units of 0.01 ml. of silver nitrate solution.

Example: A standard solution of NaCl of concentration 18.65 gm. Cl/1 is being used to standardize an unknown solution of silver nitrate. Upon titration the observed titre is 18.60 gm./litre (including burette corrections). Therefore the amount of the solution correction is + 0.05. Substituting in formula (4) the interval 3.40 ml. is obtained. By using this information a table of corrections is made.

Limits		*Correction*
From (ml.)	To (ml.)	(ml.)
0.00	3.40	± 0.00
3.41	6.81	+ 0.01
6.82	10.22	+ 0.02
10.23	13.63	+ 0.03
13.64	17.04	+ 0.04
17.05	20.45	+ 0.05

A secondary standard was prepared by filtering a large sample of sea-water taken from a depth greater than 150 metres, and preserving it with one small crystal of phenol to prevent bacterial growth. This sea water was compared with the standard silver nitrate at the time it was compared with the primary standard.

The indicator was the filtrate from a saturated solution of K_2CrO_4 from which halide impurities were removed by shaking with sufficient silver nitrate to form a permanent red precipitate.

PROCEDURE

Ten ml. of the sea water sample were accurately pipetted into a 125 ml. Erlenmeyer flask, diluted with about 30 ml. of distilled water, and one drop of indicator solution added. Silver nitrate was added from a Squibb type burette while the flask was gently shaken. On the appearance of the red chromate precipitate, the flask was stoppered and shaken violently to break up any curds which might occlude sea salt. This process was repeated until the end-point tint was permanent. The titre was noted, and burette and solution corrections applied to obtain the chlorosity (Cl/litre at t°C.).

The chlorinity (Cl °/₀₀) was obtained from the chlorosity by the graphical method of Carter and Tully (1937). This transformation requires knowledge of the temperature of the silver nitrate and sea water solutions, to the nearest 1½°C., which were observed at frequent intervals during the analyses.

Every sample was re-titrated after a lapse of time (a few hours) to check within ± 0.01 Cl. °/₀₀.

Dissolved Oxygen

Dissolved oxygen was estimated by Winkler's method (cf. Jacobsen and Knudsen, 1921).

REAGENTS

Reagent 1

Prepared by making up 400 gm. of C.P. manganous chloride ($MnCl_2.4H_2O$) or 450 gm. of manganous sulphate ($MnSO_4.4H_2O$) to one litre in distilled water.

There is some objection to the use of the chloride because of frequent iron impurity; however it was found on analysis that the sample in use contained 0.001% Fe, an amount which was negligible.

Reagent 2

Prepared by making up 420 gm. of sodium hydroxide and 100 gm. of potassium iodide to one litre in distilled water.

Reagent 3

Approximately 10 normal sulphuric acid.

Reagent 4

Approximately 0.01 normal sodium thiosulphate.

This solution was prepared by making up 2.5 gm. of the technical salt ($Na_2S_2O_3.5H_2O$) to one litre in distilled water. Three drops of carbon disulphide were added as a preservative, and the reagent stored for a month before standardizing against re-sublimed iodine. With this procedure, the normality remained constant over a period of several months.

Reagent 5

Approximately 0.4% starch solution (Platner, 1944).

Approximately 75 ml. of a 20% solution of NaOH was added to a suspension of 2 gm. potato starch in 300 ml. of water until it became thick, syrupy, and almost clear. It was allowed to stand for about one hour to ensure complete action by the alkali, and then made slightly acid to litmus with approximately 30 ml. of 35% hydrochloric acid. One ml. of glacial acetic acid was then added as a preservative.

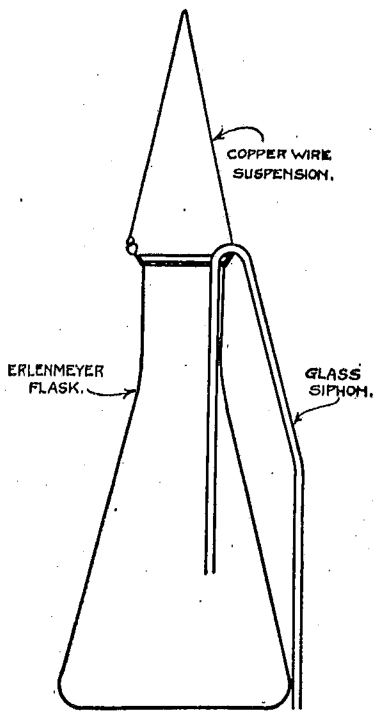

FIGURE 40. Measuring and titration flask used in the dissolved oxygen determination.

APPARATUS

The titration was carried out with a Squibb type automatic burette. It was found advisable to pump the air used for the pressure through a trap filled with sodium hydroxide, in order to prevent excess carbon dioxide coming in contact with the solution, and disturbing its normality.

The measurement of a standard volume was performed in an Erlenmeyer flask freely suspended from a hook, by wires to the neck, and fitted with a removable glass siphon (fig. 40). The action of such a siphon is quite uniform in effecting the removal of all liquid in excess of a determinable volume, if care is exercised to insure that the siphon always hangs in the same position. This appliance has the advantage of not being affected by the rolling of the boat, since the free suspension insures the parallelism of the surface of the liquid to the bottom of the flask during siphoning. If the siphon is constructed of tubing of moderately small bore (3 mm.) and is carefully removed from the flask after use, it will prime itself when introduced into the next sample.

The flask was calibrated from the average weight of distilled water that remained in it after siphoning. This volume was constant within 0.3 ml. Since the volume of the oxygen sample bottles was quite close to 350 ml. and the measuring flask retained approximately one-half the volume, the diluting effect of reagents 1 and 2 was compensated by deducting 1 ml. from the calibration volume. The maximum error due to this procedure was of the order of 0.07%.

PROCEDURE

Within 10 minutes of the collection of the samples, 1 ml. of reagent 1, and then 1 ml. of reagent 2 were added from a dropping pipette to the water in each oxygen-sample bottle. This operation must be completed quickly. The contents were thoroughly mixed by holding the bottle by the neck and rolling the wrist. After the precipitate had been allowed to settle for about 20 minutes, 1 ml. of reagent 3 was added, and the contents again mixed. The resulting iodine solution was transferred into the measuring flask, and the excess over the standard volume siphoned off. The remainder was titrated in the flask with reagents 4 and 5, the burette reading being recorded to the nearest 0.05 ml. Any dark brown residue evident at the beginning, dissolved during the titration.

ERROR

The total errors involved in the determination of the dissolved-oxygen content of a sample of normal sea water are estimated not to exceed 2%.

It is realized that there is a correction to be applied, embodying the deviation of titration temperature of the sample and the thiosulphate from the temperature of standardization of the titration flask and the thiosulphate, similar to that in the chlorinity determination. However an analytical error of 1% exceeds the greatest error accruing from the above deviation.

CALCULATIONS

Oxygen may be expressed as milligrams of the dissolved gas per kilogram of sea water according to the formula:

$$\text{mg. } O_2 \text{ per litre} = \frac{8000 \times (\text{titre}) \times (\text{Normality})}{(\text{ml. sample}) \times d_t} \quad \ldots\ldots\ldots\ldots\ldots (33)$$

where d_t is the density of the sea water sample. In general practice the density correction is omitted since it is usually within the required limits of error of the determination ($d_t = 1.02 \pm 0.01$).

It was recommended at the Fifth Pacific Science Congress that the concentration of dissolved constituents of sea water, including oxygen, be expressed as milligram-atoms (Mg.A) per kilo of sea water (Carter *et al.*, 1934). For this purpose the above values may be divided by 16, evaluated from

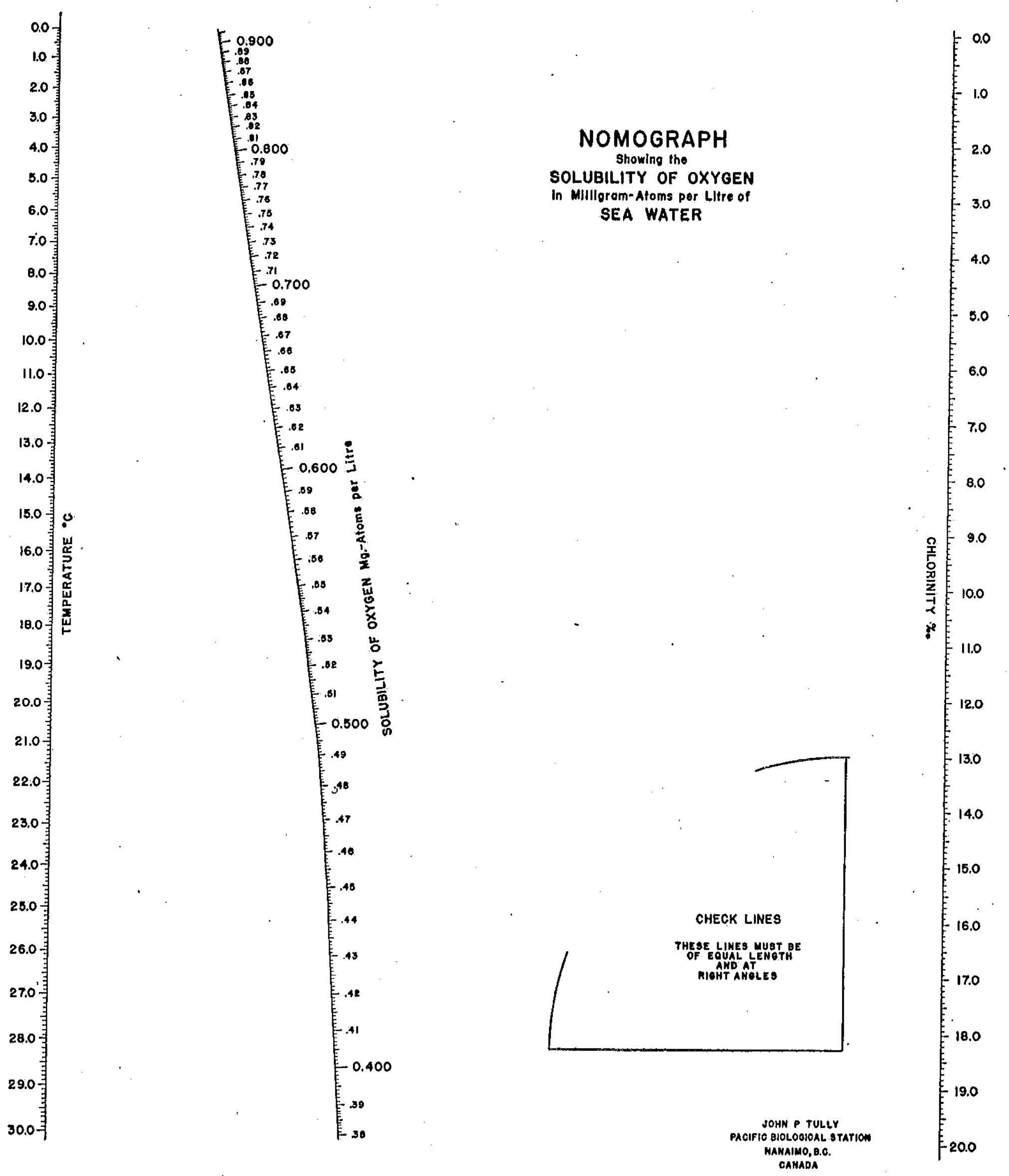
NOMOGRAPH
Showing the
SOLUBILITY OF OXYGEN
In Milligram-Atoms per Litre of
SEA WATER
TEMPERATURE °C
SOLUBILITY OF OXYGEN Mg-Atoms per Litre
CHLORINITY ‰
0.900
0.800
0.700
0.600
0.500
0.400
CHECK LINES
THESE LINES MUST BE
OF EQUAL LENGTH
AND AT
RIGHT ANGLES
JOHN P TULLY
PACIFIC BIOLOGICAL STATION
NANAIMO, B.C.
CANADA

FIGURE 41.

$$\text{Mg.A of } O_2 \text{ per litre} = \frac{500 \times (\text{vol. titre}) \times (\text{Normality})}{(\text{vol. sample}) \times d_t} \quad \ldots\ldots\ldots\ldots (34)$$

or converted from one set of units to the other by the graphical method of Tully (1938).

The concentration of dissolved oxygen in either of these units is widely used in oceanographic practice. For biological purposes the degree of saturation is frequently a more useful index since it expresses the availability to marine organisms, and includes the temperature and salinity effects.

This is expressed as % of saturation in

$$\% \text{ saturation with oxygen} = \frac{(\text{obs. conc. } O_2) \times 100}{(\text{solubility of oxygen})}$$

where the solubility of oxygen in sea water is obtained from the tables of Whipple and Whipple (1911). For convenience of computations these tables have been arranged in the form of a nomograph (fig. 41) from which the solubility of oxygen may be read directly in terms of the sea water temperature and chlorinity.

Hydrogen Ion Concentration (pH)

The hydrogen ion concentration (pH) was estimated entirely by colorimetric means. In practice, a LaMotte block comparator with cresol red standards was used. It was not considered advisable to estimate values closer than pH 0.05, the consistent accuracy of a set of standards probably being in the neighbourhood of pH 0.1. The pH was presented without a salinity or temperature correction (Ramage and Miller, 1925; Buch, 1929).

Oxygen Demand

Two samples of the water to be tested were drawn in a similar manner to the samples for dissolved oxygen analyses. One sample was analysed immediately for dissolved oxygen as already described. The other was sealed and stored at station L20 (fig. 2) at the depth of sampling, for 120 hours. It was then analysed for dissolved oxygen.

The difference in oxygen content between the two samples was attributed to biological and other processes as discussed in the text. The procedure closely approximates the method of Clarke and Ostler (1934) for the estimation of plankton activity.

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APPENDIX II

METHODS OF COMPUTATION

For convenience of handling large numbers of data, most of the computations were arranged in tabular form.

Observed Data

An example of the tabulation of data from one observation of station L20 is given in Table XXXIII and the criteria are given in the subsequent explanation.

Table XXXIII.

(1) Station L20 ± 0. (2) Date—June 6, 1941. (3) Wind S 5.
(4) Tide height + 6.4 feet. (5) Rate of change + 1.22 ft. per hour.
(6) Run-off 2396 c.f.s. (7) $\overline{Q}$ = 2405 c.f.s.

(8) Time	(9) Depth metres	(10) T°C.	(11) Cl. ‰	(12) σ_{st}	Dissolved Oxygen (13) Conc. p.p.m.	Dissolved Oxygen (14) % saturation	(15) pH
0709	0	15.02	1.45	1.24	9.60	96.0	7.7
	1	15.61	2.43	2.52	9.04	97.0	7.9
	2	13.48	12.83	17.49	8.99	99.5	8.3
	4	12.16	16.37	22.68	8.29	92.1	8.3
	6	11.66	17.04	23.71	8.63	95.7	8.2
	10	11.13	17.23	24.06	7.10	78.3	8.1

Explanation of Table XXXIII

(1) *Station* number corresponding to the position shown in figure 1. (+ 0.0) signifies the error of the position occupied in sea miles towards the head of the inlet. (−) indicates the error to seaward. In the case of Harbour surveys the number indicates the position corresponding to the cross references in figure 2 of the text.
(2) *Date* of observation.
(3) *Wind* direction (from which it blows) and velocity in miles per hour.
(4) *Tide height* (feet above low water datum) at the time of observation determined from a control station in Alberni harbour.
(5) *Rate of change* of tidal height in feet per hour. Positive (+) when tide is rising, and negative (−) when falling.
(6) *Run-off*, the rate of discharge (cubic feet per second) into the area repre-

sented by the station, on the day of observation. At station L20 and A this is the discharge of the Somass river. At any other station it represents the run-off into the section above the station, as determined by the run-off ratio of Table V.

(7) *Q*, the mean rate of runoff (c.f./5) into the area represented by the station, during the time T(1.039)/r as determined from equation 10.

(8) *Time*, Pacific standard time, to the nearest minute, of the collection of the water sample.

(9) *Depth* in metres at which the water sample was taken.

(10) Temperature in degrees centigrade of the water sample *in situ*.
(N.B.) Thermometers were graduated in degrees centigrade.

(11) *Chlorinity* in parts per thousand (Cl o/oo) as determined on the water sample. (Appendix I).

(12) σ *at* = (density *in situ* − 1) 1000 (Appendix I).

(13) *(DO) (p.p.m.)* Dissolved oxygen concentration in parts per million (Appendix I).

(14) *(DO) % saturation.* The degree of saturation of the water with dissolved oxygen (Appendix I).

(15) *pH.* The *hydrogen ion concentration* of the water determined colorimetrically with Cresol Red, not corrected for salt error (Appendix I).

DEPTH OF UPPER ZONE (D)

The procedure of the interpolation of D is demonstrated in Table XXXIV.

TABLE XXXIV. Procedure for depth of upper zone (D).

Station L20, Date June 6, 1941										
(1) Depth (m.)	(2) Cl. °/oo	(3) Sea water (%)	(4) Fresh water (%)	(5) Fresh (mean %)	(6) Depth interval (m.)	(7) Fresh (rel. vol.)	(8) Fresh (Σ vol.)	(9) Total F.W. (%)	(10) D (m.)	(10) D (ft.)
0	1.45	8.4	91.6				0	0		
				88.8	1	88.8				
1	2.43	14.1	85.9				88.8	48.4		
				55.8	1	55.8				
2	12.83	74.4	25.6				144.6	78.8		
				15.3	2	30.6			3.34	10.98
4	16.37	95.0	5.0				175.2	95.5		
				3.05	2	6.1				
6	17.04	98.9	1.1				181.3	98.9		
				0.65	4	2.3				
10	17.33	100.0	0				183.5	100.0		

Explanation of Table XXXIV

Column 1. Depth of the original observation in metres.

2. Cl $^0/_{00}$ from original observation (cf. Table XXXIII).

3. % inlet water $= \dfrac{\text{Cl (obs)}}{\text{Cl (10m)}} \times 100$, (cf. equation 7).

4. 100 − % inlet water = % fresh water (cf. equation 7).

5. Mean % fresh water between adjacent observations.

6. Successive depth interval, successive intervals expressed in metres, from column 1.

7. Product, column 5 × column 6. Depth interval × % fresh water = Volume fresh water in 100 square units by 1 unit deep.

8. Successive sums of column 7, i.e. Total volume of fresh water in 100 square units by depth z.

9. % fresh water in column of depth z =

$$\frac{\text{Volume of fresh water in depth z} \times 100}{\text{Volume of fresh water in base depth}}$$

e.g.

$$\frac{88.8 \times 100}{183.5} = 48.4\%$$

10. D = depth in metres in which 90% of fresh water occurs, and is determined by linear interpolation.

PROPORTION OF FRESH WATER (C)

The proportion of fresh water in the upper zone may be determined from the summation of fresh water given in column 8 of table XXXIV, as

$$C = \frac{(0.90) \times \text{Volume of fresh water in base depth}}{\text{D} \times \text{area of the column}} = \frac{0.90 \times 183.5}{3.34 \times 100} = 0.495.$$

EVALUATION OF DISPLACEMENT FACTORS IN ALBERNI HARBOUR

The evaluation of these quantities required somewhat different treatment in the regions of the head and the inlet as discussed in the text.

The volume (AD) of the upper zone in cubic feet was computed from the curve of volume of the Harbour, figure 18 (text).

$$\left(\begin{array}{c}\text{Volume of harbour at}\\ \text{tidal height H}\end{array}\right) - \left(\begin{array}{c}\text{Volume of harbour at depth of}\\ \text{upper zone H} - \text{D}\end{array}\right) = \text{Volume (AD)}$$

where H is the observed tidal height at the time of observation, e.g.

$H = 4.6$, $D = 10.96$, $H - D = -6.4$

From figure 18

$(23.6 - 17.8) \times 10^8 = 5.8 \times 10^8$ cu. ft. = AD

Then the displacement is evaluated from equation 10 as demonstrated in Table XXXV.

TABLE XXXV. Evaluation of displacement (r) from Alberni harbour (June 6, 1941).

$$(1) \quad \frac{\overline{ADC}}{8.64 \times 10^4} = \sum_{o}^{T(1.039)/r} Q = 3680$$

(2) Date (1941)	(3) Q (c.f.s.)	(4) ΣQ (c.f.s.)	(5) $\sum_{o}^{T(1.039)/r} Q$ (c.f.s.)	(6) Days
June 6	2396	2396	3680	1
5	2418	4814		0.53
				1.53

(7) T/r = 1.53 x 0.964 = 1.47

(8) r = 0.678

Explanation of Table XXXV

Line 1. Modified form of equation 10 in which it is required to determine the value of the limit T(1.039)/r in days.

Column 2. Date of observed discharge values.

3. Observed daily discharge (cubic feet per second).

4. ΣQ, successive sums of discharge in column 2.

5. Value of the summation to which limits are to apply, from line 1.

6. Process of interpolation, i.e. 3680 represents 1.53 days discharge which is T(1.039)/r in days.

Line 7. Transformation of column 6 to T/r in tidal periods, from the ratio of mean solar to tidal day (0.964).

8. Determination of r as the inverse of line 7.

EVALUATION OF DISPLACEMENT FACTORS IN CONTINUING INTERVALS OF THE INLET (table XXXVI)

Process A—Determination of mean values of displacement factors between successive stations.

Mean depth of upper zone (D).

Line 1. Depth of boundary (feet) computed from the data at each station, as shown in table XXXIV.

2. Sums of adjacent values.

3. Mean depth of upper zone between stations, line 2 divided by 2. The value at station L20 is presumed to be representative of the section O-A, hence no mean is taken.

TABLE XXXVI. Determination of displacement factors in continuing intervals (0-A, 0-B, etc.) of Alberni inlet, data of June 6, 1941. See text for explanation.

Process A—Mean sectional values

	Stations				
	Hbr. (L20)	A	B	C	D
1. D (feet)	11.0	10.5	11.8	11.6	6.3
2. Sum			21.3	23.4	17.9
3. Mean ($\bar{D}$) ($\overline{X_1X_2}$) (feet)	11.0	11.0	10.7	11.7	9.0
4. A ($X_2 - X_1$) (sq. ft. $\times 10^{-7}$)	5.85	8.0	8.3	18.5	30.1
5. A$\bar{D}$ ($X_2 - X_1$) (cu. ft. $\times 10^{-8}$)	6.44	8.80	8.89	21.6	27.1
6. C	0.495	0.549	0.479	0.540	0.277
7. Sum			1.028	1.019	8.17
8. Mean ($\bar{C}$) (X_2X_1)	0.495	0.495	0.514	0.510	0.409
9. A$\overline{DC}$($X_2 - X_1$)(cu. ft.$\times 10^{-8}$)	3.18	4.35	4.61	11.00	11.10

Process B—Integral values

	Intervals				
	Harbour	0-A	0-B	0-C	0-D
10. A$\bar{D}$ (cu. ft. $\times 10^{-8}$)	6.44	8.80	17.69	39.3	66.4
11. A$\overline{DC}$ (cu. ft. $\times 10^{-8}$)	3.18	4.35	8.96	19.96	31.06
12. $\bar{C}$	0.495	0.494	0.507	0.508	0.468

Process C—Determination of displacement

	Intervals				
	Harbour	0-A	0-B	0-C	0-D
13. F $\times$ 8.64 $\times 10^4$ ($\times 10^{-4}$)	8.64	8.75	10.28	13.58	17.08
14. A$\overline{DC}$/F$\times$8.64$\times 10^4$	3,680	5,650	8,730	14,710	18,210
15. Age $T(1.039)/r$ (days)	1.41	1.60	3.46	5.69	6.83
16. T/r (tidal cycles)	1.36	1.54	3.34	5.38	6.58
17. Displacement (r)	0.738	0.648	0.300	0.186	0.153

Process D—Representative discharge

18. $\bar{Q}$ (Somass) (c.f.s.)	2405	3100	2610	2680	2680

Mean volume of the upper zone (ADC).

4. Area of each interval of the inlet, from table IV.
5. Volume of upper zone in each section of the inlet Line 3 multiplied by line 4.

Mean proportion of fresh water (C).

6. $\underline{C}$, proportion of fresh water in the upper zone at each station, computed from the data as demonstrated in item (c) above.
7. Sums of adjacent values in line 6.
8. Mean value of C between stations, line 7 divided by 2.
9. ADC, volume of fresh water (cubic feet) in intervals between stations. Line 8 multiplied by line 5.

Process B—Determination of integral values of AD, ADC, and integral mean values of C.

Line 10. $\overline{AD}$, Total volume of upper zone cubic feet in the integral section O-X. Successive sums of line 5.

11. $A\overline{DC}$, Total volume (cubic feet) of fresh water in the integral section O-X. Successive sums of line 9.

12. $\overline{C}$, Mean value of C in the integral section O-X. Line 11 divided by line 10.

Process C—Determination of displacement.

Line 13. Evaluation of F $\left(\frac{8.64}{V} \times 10^4\right)$ in equation 10(a) where F is the run-off ratio from table V (text).

14. Evaluation of the integral of Somass river discharge (c.f.s.) as in equation 10(a). Line 11 divided by line 13.

15. Interpolated value of the limit T(1.039)/r in equation 10, performed as demonstrated in table XXXV.

16. l/r in tide cycles, line 15 multiplied by the factor 0.964 relating mean solar to tidal day.

17. Displacement (r) determined as the inverse of line 16.

Process D—Representative discharge.

Line 18. Representative discharge of the Somass river (c.f.s.) through the section determined according to equation (10(a)), by dividing line 14 by line 15.

DISSOLVED OXYGEN

Computation of the mean concentration of dissolved oxygen (p.p.m.) in the upper zone is demonstrated in table XXXVII.

Explanation of Table XXXVII

Line 1. Station and date, the same date as Table XXXIII.

2. Depth of upper zone (metres) from Table XXXIV.

TABLE XXXVII. Mean concentration of dissolved oxygen in the upper zone.

(1) Station L20. Date, June 6, 1941.
(2) Depth of upper zone = 3.34 m.

(3) Depth (m.)	(4) DO (p.p.m.)	(5) Mean	(6) Interval (m.)	(7) Product
0	9.60			
		9.32	1	9.32
1	9.04			
		9.02	1	9.02
2	8.99			
		8.74	1.34	11.70
3.34	8.49			
			(8) Sum	30.04
4	8.29			
			(9) Mean	9.08 p.p.m.

Column 5. *Depth* of observation (metres).
4. Observed *concentration* of dissolved oxygen.
5. *Mean* of adjacent values in column 4, using interpolated value at depth of the upper zone (3.34 metres).
6. *Interval* between successive depths to the depth of the upper zone (from column 3).
7. *Product* of corresponding values in columns 5 and 6. The oxygen content of the column of unit area, between observations.

Line 8. *Sum* of column 8. The oxygen content of a column of unit area, of depth of the upper zone.
9. *Mean.* Line 8 divided by the depth of the upper zone. The mean concentration of dissolved oxygen (p.p.m.) in the upper zone.

MEAN CHLORINITY

The mean chlorinity in the upper zone was evaluated similarly to the dissolved oxygen as given above.

MEAN TEMPERATURE

The mean temperature in the upper zone was evaluated similarly to the dissolved oxygen.

APPENDIX III

A HYDRAULIC MODEL OF ALBERNI HARBOUR

It has been shown (Part I) that river discharge, tide, and salinity of the entering sea water are the only variables of consequence, that wind can be regarded as a distorting factor, and that the velocity and salinity distribution are dependent variables. In the model the independent variables have been reproduced to scale, and similarity with the prototype established by comparing the vertical salinity gradient with that observed in nature.

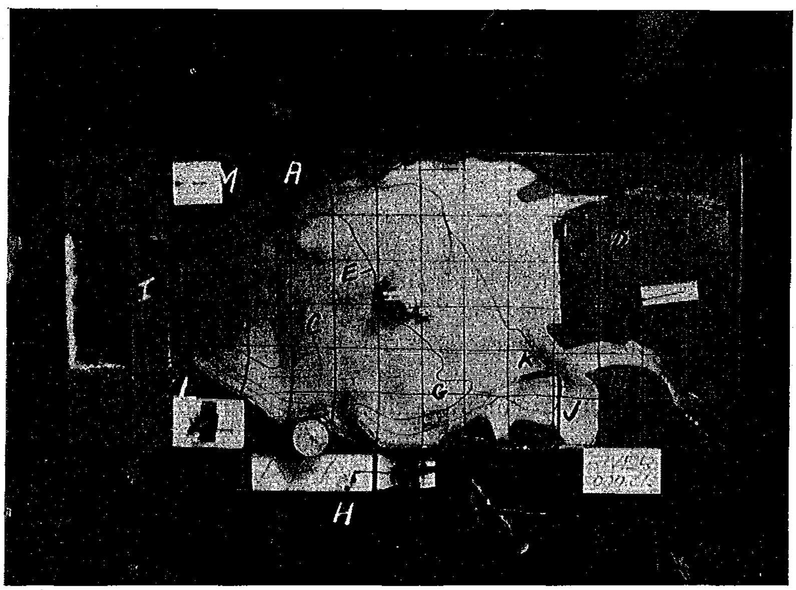

FIGURE 42.

Plan of the model showing arrangement of instruments.

A Land above high tide (khaki)
B Intertidal zone (yellow)
C Sea bottom (blue)
D 1000 ft. squares (red)
E 30 ft. contours (red)
F River system
G Tide gauge
H Tide recorder
I Solenoid core
J Dye solution feed
K, Trace made by dye
L Wind gauge
M Wind vane

Fig. 42 shows a photographic plan of the model with the parts named that are of interest to the observer. Fig. 43 is a diagrammatic elevation, showing the essential features of the mechanics, and fig. 44 shows the assembly as it appeared in operation.

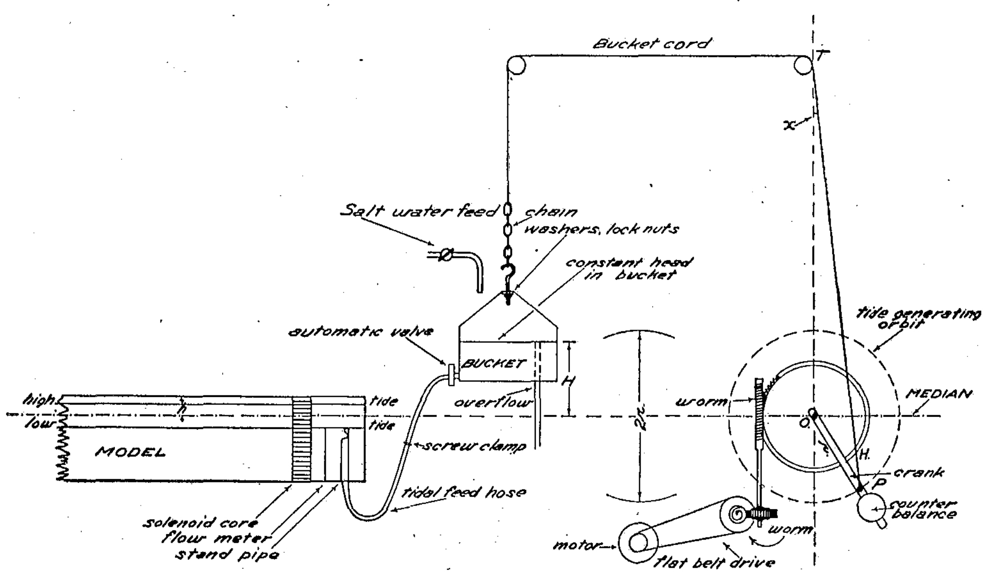

FIGURE 43. Diagrammatic elevation of model assembly.

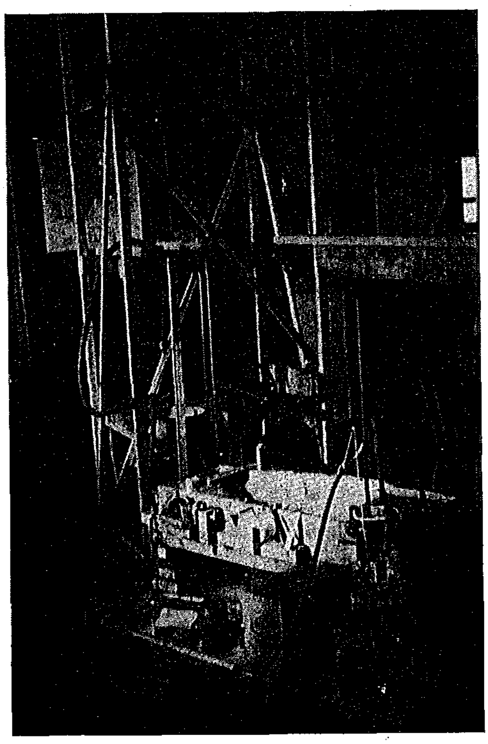

FIGURE 44. Photograph of complete model assembly.

The model form has a distorted scale (different horizontal and vertical scales). A continuous flow of fresh water simulates the Somass river discharge. Sea water has been alternately supplied from, and discharged into, a rising and falling bucket, which simulates the tidal movements. Constant winds have been generated by a fan arrangement. The mill effluent has been simulated by dye solutions of appropriate density, whose progress and intensity have been recorded by sketched notes, or motion pictures.

MODEL CONSTRUCTION

Model Form

THEORY

The form of hydraulic models has received considerable attention in the literature of hydraulic engineering, where it has been shown by O'Brien and Hickox (1938) that the preliminary criterion of similarity between a model and the prototype is shown by the Reynolds number. The Reynolds number may also be used as a measure of the degree of turbulence, and in areas which are wide in comparison to their depth it may be written

$$N_R = \frac{VZ\rho}{\nu} \quad \text{(35)}$$

where V = velocity, Z = depth, ρ = density of the medium, and ν = kinematic viscosity. If these values are all represented in absolute units, turbulence occurs at any value greater than 500.

For general calculations in a model where water is used as a medium it may be assumed that the density = 1 and viscosity = 0.01, then

$$N_R = 100\ VZ \quad \text{(36)}$$

and, if the minimum velocity at which it is required that turbulence should occur in the model is known, the required depth of the model may be calculated.

The same authors show that in models of open channel flow, where it may be assumed that the flow is horizontal, and where water of a similar character to that in nature is used in the model, if the ratio of distance (b_x) and depth (b_z) are fixed, then all other dimensions are fixed from the relation

$$b_v^2 = b_z \quad \text{(37)}$$

which follows directly from the fundamental relation of hydraulics:

$$V^2 = kh + c \quad \text{(38)}$$

where V is the velocity of flow, h is hydraulic head, and k and c are constants.

If it is required that turbulence should occur in the model at a simulation of the velocity V_N in a depth of water Z_N, then the required depth of the model may be calculated from the second and third of the above equations, as follows:

$$\begin{aligned} N_R &= 100\ (V_N b_z^{1/2})\ (D_N b_z) > 500 \\ &= 100\ V_N Z_N b_z^{3/2} > 500, \end{aligned}$$

whence

$$b_z > \frac{(5)^{2/3}}{V_N Z_N} = \frac{2.922}{V_N Z_N} \quad \text{(39)}$$

In order to have turbulence develop at the representation of the velocity at which it occurs in nature, it would be necessary to build a full-scale model. Consequently it is necessary to choose a limit at which it is desired to have turbulence occur and thus fix the depth scale of the model at the most suitable dimension for the purpose.

Owing to the presence of a large area of tide flats in Alberni harbour (fig. 2) and the reciprocal nature of the tidal currents, the values of both V_N and Z_N in the last equation must vanish for a time during each tide cycle. Consequently in the application of these theories to tidal estuaries it is impossible to make a model on a reasonable scale in which the criteria for continuous turbulence could be attained.

It was found that, if the dimensions of the model were so adjusted that turbulence occurred at the representation of a velocity of 0.2 knots in 90 feet of water in nature, then the presence of turbulence in the model indicated the time and location of the maximum current velocity.

Substituting these values in equation 39,

$$b_z > \frac{1}{311}$$

and a convenient value of this order was found to be

$$b_z = \frac{1}{288} = \frac{\frac{1}{4}\text{ inch}}{1\text{ fathom}}.$$

In order that the volume of water required to operate the tidal and river system might be within the limits of the amount available, it was necessary to use a distorted scale model. This was permissible, since the circulation was wholly horizontal, as was found in the study of the density distribution in nature.

Convenient values of the defining ratios were found to be:

Distance	(b_x)			$= 1/4308$
Depth	(b_z)			$= 1/288$
Velocity	(b_v)	$=$	$(b_z^{1/2})$	$= 1/16.97$
Discharge	(b_q)	$=$	$(b_x b_z^{3/2})$	$= 1/2.11 > 10^7$
Time	(b_t)	$=$	$(b_x b_z^{-1/2})$	$= 1/254.2$
Volume	(b_{vol})	$=$	$(b_x^2 b_z)$	$= 1/5.35 > 10^9$
Density	(b_ρ)	$=$		$= 1.00$
Viscosity	(b_γ)			$= 1.00$
Reynold's number		$=$	(b_{N_R})	
		$=$	$(100\ b_z^{3/2})$	$= 1/48.9$

CONSTRUCTION

From a layout plan of the area, the detail of the boundaries was modelled in Plaster of Paris over a roughly shaped wooden form, contained in a galvanized iron tank. The position of the bottom was indicated by the height of nails, set in the wooden base. Slots were moulded to contain the flow assembly, and the model was water-proofed with repeated coats of resin in alcohol, and was finished with amyl acetate paint (Duco), pale blue below low tide level, canary yellow in the intertidal zone, and khaki around the shore line.

To facilitate observations, 1,000 foot squares were projected onto the model, and contours at 30, 60 and 90 feet depth below mean tidal level were marked. This construction, although unorthodox, was found to be sufficient for the purpose in this small scale model, which operated continuously for about 300 hours.

THE TIDE MACHINE

The tide was generated by a machine, in which a crank was rotated at a uniform rate consistent with the model scale of the tidal period, and the vertical component of this motion was transferred by a cord to a bucket, which provided an oscillation head for the tidal action. The bucket was connected to the model by an automatic valve and a hose. When the bucket was above the median, the water flowed to the model, creating a flood tide, and when it was below the median, the flow was reversed, creating an ebb tide. The amplitude of the tide was controlled by a screw clamp on the rubber hose. The automatic valve could be adjusted to divert any portion of the ebbing water to waste, and an automatic salt water feed system replaced it with the desired amount of new water.

TIDAL FUNCTION

The height H of the tide is a compound harmonic function of the angles of the moon and sun with the local meridian, and consequently of the time (t) of the form

$$H = A \cos (at + \alpha) + B \cos (bt + \beta) + \text{etc.} \qquad (40)$$

where A, B, etc. express the amplitude or semi-range of the tide, a, b, etc. express the relation of time, and α, β, etc. express the lag of the tidal impulse with regard to the controlling celestial body.

It is indicated in fig. 43 that the tide machine was an approximation of the cosine function, since it was the mechanical translation of the vertical component of uniform circular motion of the point P on the crank. In the construction it was necessary that the cord from the crank to the bucket should pass over a fixed pulley (T), and as a consequence the derived component (H) differed from the ideal by a small amount which became infinitesimal when the length OT was made large as compared to OP.

Then assuming constant level of the water in the bucket and model, the difference in height between the two

$$(\Delta h) \text{ is } \Delta h = k_1 \cos \theta \qquad (41)$$

and the discharge (Q) between the model and the bucket is of the form

$$Q = k_2\sqrt{\Delta h} + c = k_3\sqrt{\cos \theta} + c \qquad (42)$$

If the intertidal zone of the model were rectangular, the tidal rise would be the quadrature of the desired cosine curve, but as it was irregular, it was possible to approximate the theoretical form of the curve so closely that no discrepancy was apparent.

In models involving a mixed type of tide it is usually sufficient to represent the simple procession from spring tides, through the neaps to springs, without considering the exact tidal phenomena for a particular day. This may be simulated on the tide machine by two components as shown in the first equation, one expressing the function of the moon and the other the sun, represented by cranks whose time of revolution is in the ratio of a semi-lunar day (12.42 hours) to a semi-solar day (12.00 hours) and whose lengths OP are in the ratio of the component forces, which are respectively M_2 (moon) and S_1 (sun).

Assuming that the minimum tidal range observed in the area of the model represents the moon and sun acting in opposition, and the maximum range represents a state of apposition,

$$\frac{M_2}{S_1} = \frac{(\text{maximum} + \text{minimum})}{(\text{maximum} - \text{minimum})} \quad \ldots\ldots\ldots\ldots\ldots\ldots (43)$$

which is a sufficient approximation.

The rate of rotation of the cranks must be adjusted in the time ratio, and

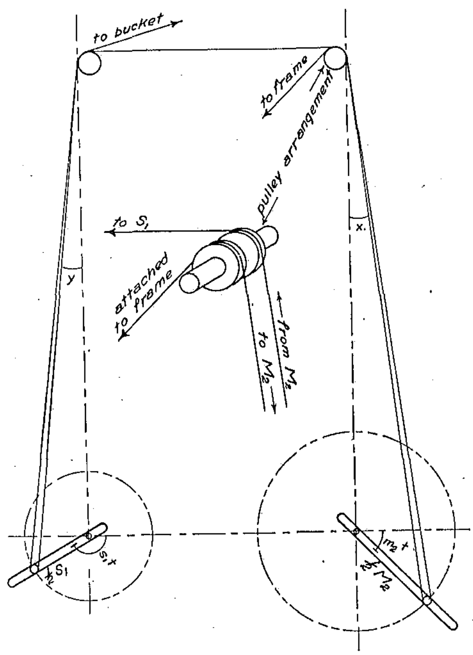

FIGURE 45. Assembly of a compound tide machine.

the lengths of the cranks in the force ratio, and the motion compounded on a single cord by the arrangement shown in fig. 45.

CONSTRUCTION

In the model the crank was driven by a constant speed motor geared down in the ratio 5,050:1. The crank carried a counter weight between O and P (fig. 43) which could be adjusted to balance the weight of the bucket. A flexible steel wire was led from the crank, over suitably placed guide pulleys to the bucket, which was supported by a bridle. Connection between the wire and

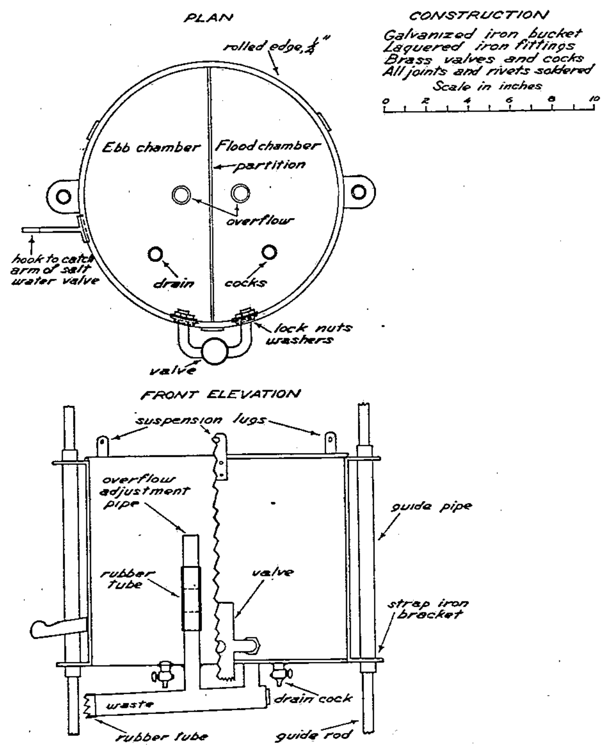

FIGURE 46. The tidal bucket.

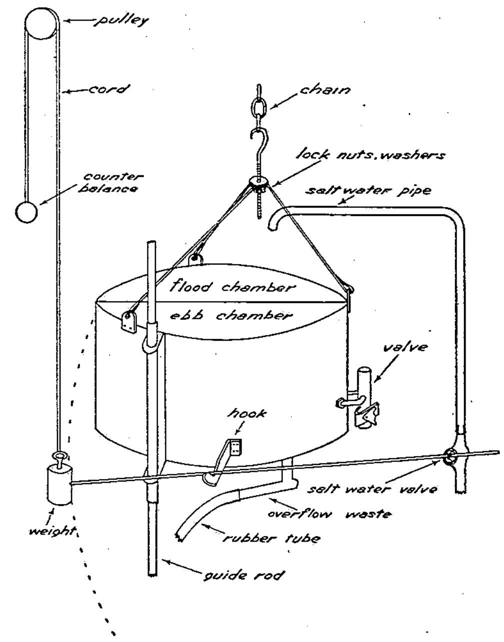

FIGURE 47. Salt water supply system.

the bridle was made with a swivel and a threaded shank hook as shown in fig. 29. The bucket was guided by vertical rods fitting inside guide pipes on each side as shown in figs. 46 and 47.

The range of the bucket could be set by adjusting the position of P (fig. 43) (which was on a sliding clamp) on the crank, and the centre of the range, or median level could be adjusted by the threaded hook at the bucket.

Applying the scale ratio for the time of a semi-lunar day, the time for each revolution was

$$(12.42 \text{ hours})\ b_t = \frac{745.2}{254.2} \text{minutes} = 175.2 \text{ seconds} = 0.342 \text{ r.p.m.},$$

and for the solar day

$$(12.00 \text{ hours})\ b_t = \frac{720}{254.2} \text{ minutes} = 170 \text{ seconds} = 0.356 \text{ r.p.m.}$$

This machinery was mounted in a suitable frame in which the height OT (fig. 43) was made as great as possible.

The Tidal Water Supply

As in nature part of the water that leaves the area during the last of the ebb is returned on the first of the following flood (Part I), it was necessary to simulate this function if the salinity gradient was to be simulated.

From a mechanical standpoint it was necessary to have a constant level of water in the bucket so that the head would vary as the derived component of the crank rotation. This condition could not be accomplished if there was a simple reciprocal flow between the model and the bucket, since the ebbing waters would be diluted by fresh water from the river system, which would progressively alter the state in the bucket and the character of the flooding waters.

The required system was established by dividing the bucket into two symmetrical chambers, one to supply sea water during the flood tide, and the other to receive mixed water during the ebb. The first had an automatic salt water supply, and both chambers had adequate overflow systems, which served to maintain equal constant levels and to preserve the symmetry of flow between the flood and ebb movements. An automatic valve was fitted which connected one chamber to the tidal hose of the model during the flood, and the other during the ebb flow. The change from one to the other was activated by a trigger, which was controlled by the movement of the bucket.

TIDAL BUCKET

As indicated in fig. 46, the bucket consisted of a round flat-bottomed tank, having a watertight partition through the centre. The overflow pipes were of larger diameter (¾ inch) than the valve fittings (½ inch) and were led into a common waste pipe which had a still larger diameter (one inch). This common waste pipe consisted of a flexible hose which led to a convenient sewer. The height of the overflow inside the bucket could be adjusted by a rubber fitting. Drain cocks were provided in each chamber so that the bucket might be emptied when not in use.

Three strap iron lugs, equally spaced, were riveted to the top edge of the bucket to provide for suspension. Strap iron brackets were riveted to opposite sides of the bucket to carry the guide pipes which fitted over the guide rods.

The salt water supply, as shown in fig. 47, was brought to a valve from which it was carried by a pipe so that the flow was directed into the flood chamber of the bucket. One end of a bar was attached to the bolt of the valve and the other end carried a lead weight which was connected by a string over a pulley to a small counter weight. The bar was free to move in an arc in the vertical plane close to the range of the bucket, from which a hook projected far enough to catch the bar.

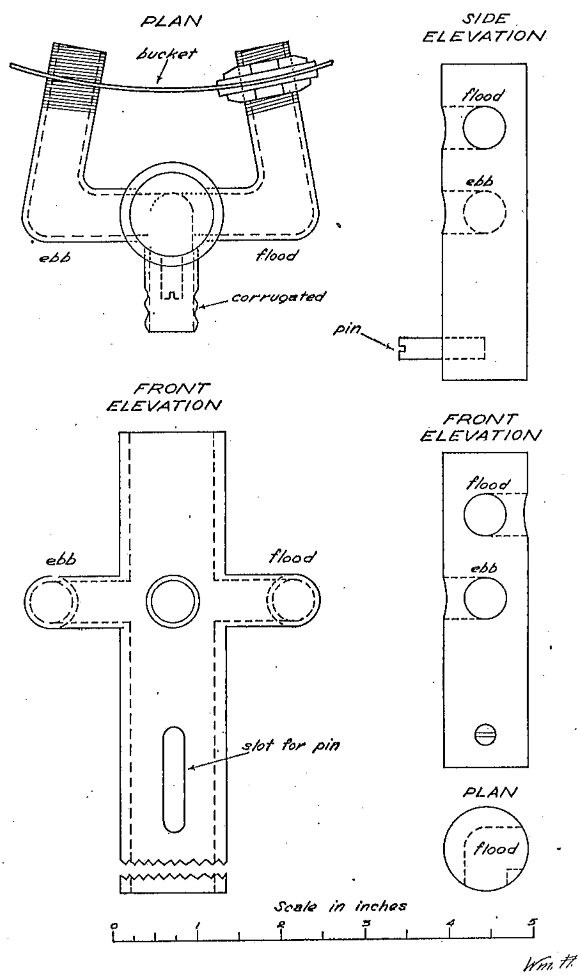

FIGURE 48. Tidal flow control valve.

The system was so adjusted, that as the bucket rose above the median of the model, the hook caught and raised the bar, opening the valve, which allowed salt water to flow into the flood chamber. The weight on the free end of the bar held it in contact with the hook, so that it descended with the bucket, closing the valve when it reached the median. The length of the string was adjusted so that the counter weight caught in the pulley when the valve was closed, and prevented further descent of the bar. When the bucket rose again it picked up the bar at this point.

This arrangement was more suitable than continuous flow because it reduced the demand on the salt water supply, and prevented overloading the overflow system.

The tidal flow control valve, as shown in fig. 48, consisted of a bolt and sleeve. The bolt was a solid brass cylinder in which there was two holes (½ inch in diameter) forming right angle elbows, the upper turning to the right and the lower to the left. The bolt was machined to fit a brass sleeve with between four and six thousandths of an inch clearance, and was practically watertight.

The sleeve had three taps at right angles to each other in the same horizontal plane, one facing to the front, one to the left, and one to the right, into which pipes of ½ inch inside diameter were fitted. The one facing forward was corrugated to form a fitting for the flexible rubber hose in the model. Those facing to the side were fitted with elbows and short pipes having male threads so that they could be fitted into holes in the front of the bucket, the right to the flood chamber and the left to the ebb, and secured with lock nuts and washers.

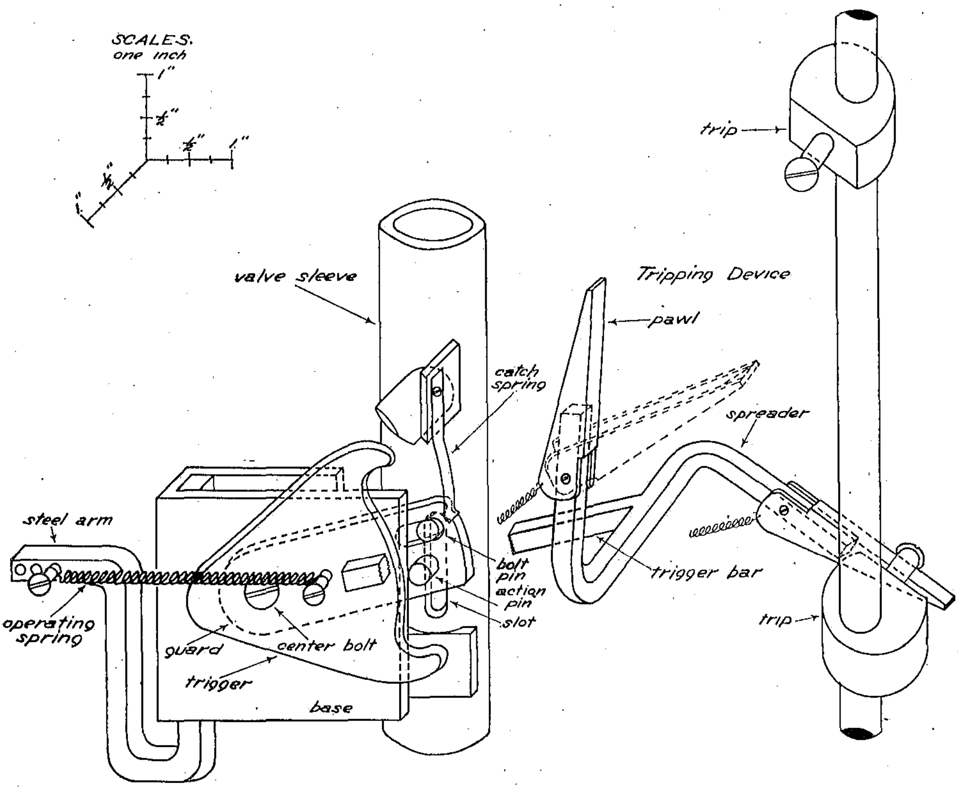

FIGURE 49. Trigger action of the tidal flow control valve.

A pin was fitted to the front of the bolt and projected through a slot in the case. This pin served as a bracket by which the bolt could be raised or lowered, and the slot served as a guide and limited the motion.

The action was such that when the bolt was "up" there was a clear passage from the model to the ebb chamber, and when it was "down" the passage was from the flood chamber to the model.

The upper part of the valve sleeve was made about one inch longer than necessary to accommodate the bolt in the "up" position so that it could be lubricated by occasionally filling this upper space with fresh water.

The trigger action was similar in principle to the shutter action in a box camera. It consisted of four parts as shown in fig. 49, a base which carried the moving parts, a guard which served to support the valve in the "up" position, a trigger which imparted the motion to the mechanism, and an arrangement of trips which actuated the trigger at the desired position.

The base consisted of a flat plate fastened by one edge to the front of the valve sleeve, and had a hole drilled to accommodate a centre bolt, about which the moving parts operated. A steel arm extended outward from the edge of the base plate opposite to the valve to carry the operating spring. Holes were drilled and tapped at intervals along the arm so that a screw could be made to hold this spring at any one of several tensions.

The guard was a flat piece of metal, having a centre hole and a slot which was large enough to fit loosely over the bolt pin, and of sufficient length to allow the pin to move through its range as determined by the length of the slot in the valve sleeve. An action pin was set in the face of this guard so that it could be engaged by the trigger, and a notch was cut in the free end so that it would be held by a catch spring when the bolt was in the "up" position.

The trigger was a flat piece of metal shaped as shown, having a centre hole, and a bar extending across the front of the valve. The bar carried a spreader at right angles to the plane of the trigger plate, and the spreader carried two arms set at an angle of 45° to the bar and at right angles to each other, in the plane of the trigger plate. Each arm carried a pawl on the free end, the one on the down-pointing arm lifted to an upward pressure (caught to a downwards pressure) and the one on the up-pointing arm worked oppositely. These pawls were designed to be caught by trips fastened to a vertical rod as shown.

The action was assembled by laying the guard over the base plate, with the valve bolt pin through the guard slot, and the centre bolt through the centre hole. The trigger was laid over this, and the centre bolt secured with lock nuts and washers, allowing free action. A strong spring (about 10 lbs.) was extended from the screw on the spring arm of the base to the spring pin on the face of the trigger.

In the "up" position the bolt was held by the catch spring in the notch of the guard, and the passage through the valve was open from the model to the ebb chamber. As the bucket rose, the pawl on the down-pointing arm (horizontal at this time) caught in the trip, as illustrated in fig. 30, and detained the trigger arm until the line of the spring passed over the centre. Then the spring caused the trigger to snap downwards, freeing the guard from the catch spring and allowing the bolt to fall into the "down" position. This opened the passage through the valve from the flood chamber to the model and closed the ebb chamber. The trip pin on the other side of the trip rod was passed by the pawl on the up-pointing arm during this operation. While "down" the bolt retained its position by its own weight. As the bucket descended the up-pointing pawl (now horizontal) caught the second trip pin, which detained the trigger arm until the spring passed over the centre, when the spring caused the trigger to snap upwards, raising the guard, which in turn raised the bolt, and the catch spring engaged the notch in the guard, holding the bolt in the "up" position.

In operation, when the bucket was above the median of the model, water flowed from the flood chamber to the model, while the level of the water in the chamber was maintained by the salt water feed and overflow system. As the bucket descended to the high tide level of the model, the trigger action moved the valve so that it made connection with the ebb chamber, and while the bucket was below this level water flowed from the model to the ebb chamber, in which the level was maintained by the overflow. Since it was desired to return some of the ebb water to the model the trigger action was adjusted to make the transfer from the ebb to the flood chamber after the flood movement had started, that is, after the bucket had risen above the low tide level of the model a distance (H°) sufficient to return the required amount of ebb water to the model.

The proportion of water required to be replaced on each tide could be calculated from the expression for the volume of flow:

(Height of tidal rise) × (Area of tidal zone in nature)
× (Mean chlorinity of this volume)
= (Volume of river flow during the tidal rise)
+ (Volume of tidal water entering the area)
× (Mean chlorinity of flood waters in tidal interval)

All of these factors except the volume of tidal water entering the area may be observed in nature, then

$$\frac{\text{(Volume of tidal water entering the area)} \times 100}{\text{(Volume of tidal zone in the area)}}$$

= % of new water required on each tide to maintain the mean chlorinity, and

100 − % of new water = % water returned on each tide.

In an area where mixed tides prevail, it is evident that this value can only be calculated for the mean tidal rise.

The volume of water to be replaced in the model must be contained in the connecting hose and the bucket. Then if the constants of the equation of flow, k and c in

$$Q = \frac{vol}{time} = k\sqrt{h} + c$$

between the model and the bucket have been determined, the height ($h°$) of the second trip, above the low tide level of the model, may be determined approximately from the equation

$$\text{Vol} = [k\sqrt{r \sin k_1 t}\,]_o^t = c,$$

where t may be determined by substitution, then

$$h° = \sqrt{r \sin k_1 t} + c.$$

The position of this second trip could also be determined by a series of approximations, first setting the trip and observing the chlorinity gradient after equilibrium had been established in the model, and again altering the trip, until the chlorinity gradient observed in the model agreed with that observed in nature.

It was found advisable to calculate the position of the trip, and to check this by observation of the chlorinity, making further alterations if necessary.

The constant c in the above equation of flow represents a distance in the rise of the bucket above the tidal level of the model, in which there is not sufficient head to cause flow. Allowance must be made in all settings for this height.

The setting of the trips for the trigger action and the observation of the range of the bucket was greatly facilitated by fitting a vertical scale on the tide machine so that a pointer attached to the bucket indicated its position at all times. The median and the high and low tide levels could be permanently marked on the scale.

Once these trips were set they remained constant through all subsequent operations of the model, because the alterations in the range of the bucket automatically compensated for the changes in the rate of displacement.

The range of the bucket was held constant (2r, fig. 43) and was of sufficient length to operate the automatic valve when the centre of the bucket range was set some distance below the median of the model to compensate for the river flow. On the present model it was found convenient to set the radius of the semi-lunar tide-generating crank at about 13 inches and to set the level of the model in relation to the tide machine so that the centre of the resulting range could be at least 6 inches below the median.

CONNECTING HOSE

The connection between the model and the bucket was made through ordinary chemical rubber hose of slightly greater diameter than the various valve passages (½ inch). The rate of flow between the bucket and the model, and consequently the magnitude of the tidal impulse could be controlled by

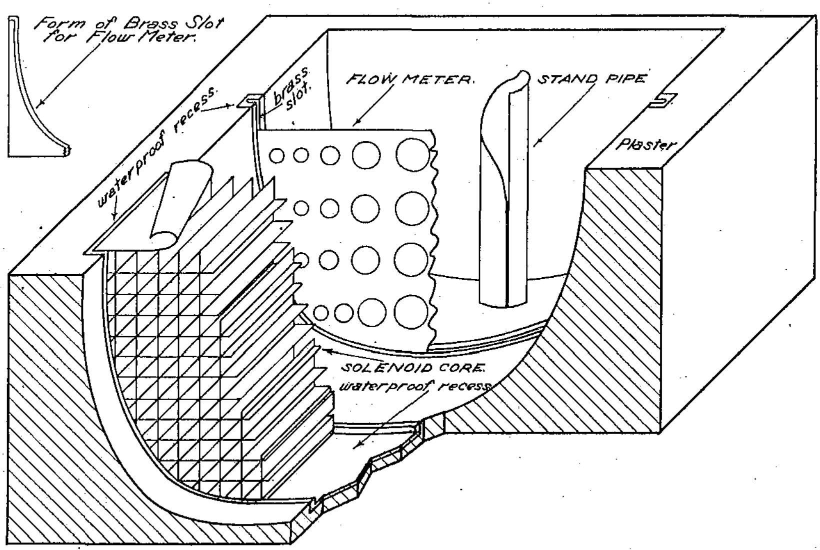

FIGURE 50. Installation of the flow assembly.

the range (2r) of the bucket, or the cross-section area of the connecting hose. In order to reduce the number of adjustments to a minimum, the range of the tide was controlled by a screw clamp on the connecting hose. In order to ensure symmetry in the reciprocal flow, the hose was made as short as possible, and the clamp was set in the middle of its length.

THE FLOW ASSEMBLY

In order to obtain a representative distribution of velocity and order of turbulence at the entrance to the model, the flow was controlled by the assembly illustrated in fig. 50. The vertical velocity gradient was determined by a stand-pipe, which was slotted vertically in such a manner that a predetermined proportion of water left the model at each depth. The lateral distribution of flow was controlled by a flow meter having several horizontal series of holes whose area was proportional to the velocity front at each point. The order of turbulence in the flooding waters was controlled by a solenoid core of suitable dimensions.

The tide machine and the flow assembly represented the ocean and the length of the inlet from the sea to the area was represented by the model.

STAND-PIPE

The vertical velocity gradient during the flood tide was indirectly controlled by the stand pipe; since the flood waters were more dense than those on the surface; they sank and circulated in the depths (fig. 51) displacing surface water, and creating the horizontal salinity gradient. The amount of sinking and the vertical velocity gradient on this phase were determined by the depth of brackish water, which was a resultant of the magnitude of the river flow. The vertical velocity gradient on the ebb tide was completely controlled by the

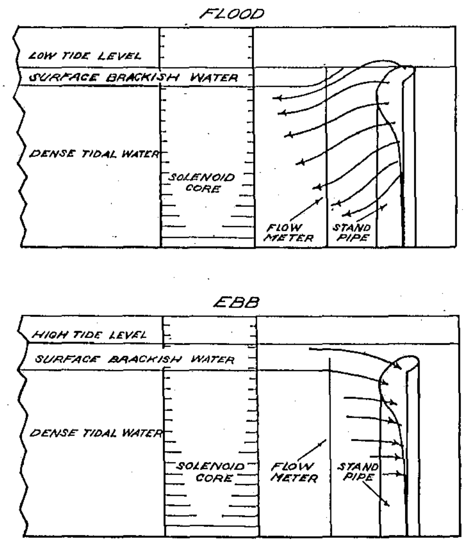

FIGURE 51. Diagrammatic elevation of the flow assembly.

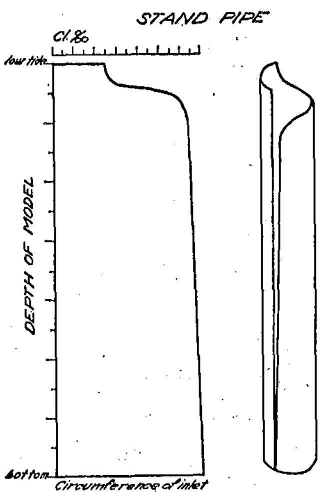

FIGURE 52. Construction of stand-pipe which controls the salinity gradient.

stand-pipe, and the maximum velocity occurred at the surface and decreased rapidly with depth as shown.

As has been shown (Part I) the chlorinity gradient defines the zones of circulation in a system of this type, and consequently provides a graphical means of determining the form of the opening in the stand pipe from data observed in nature.

The pipe was fashioned from a flat oblong piece of metal (fig. 52) whose length was equal to the depth of the model from low tide level to the bottom at the entrance of the tidal feed connection, and of width equal to the inside circumference of this fitting. The width was taken to represent the chlorinity from zero to the maximum occurring in nature at this position. Then the chlorinity was plotted against depth, and the points joined by a smooth line as shown. The excess metal was cut away and the remaining piece rolled into a pipe which fitted neatly into the tidal feed connection, so that the pipe was vertical and the slot faced directly towards the model.

Obviously it was necessary to change the stand-pipe to suit each type of condition being studied.

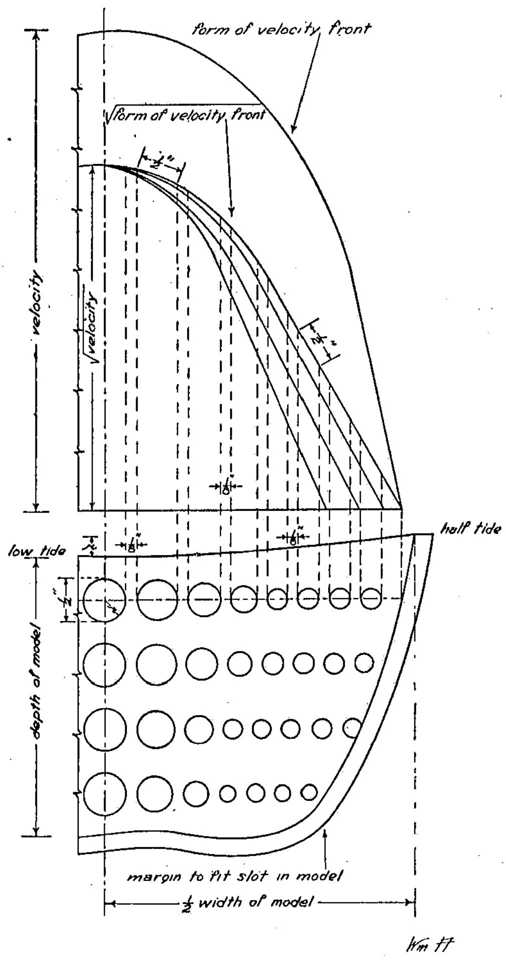

FIGURE 53. Construction of the flow meter which controls the velocity gradient.

FLOW METER

The horizontal velocity front in an inlet of this nature resembles the arc of a parabola, and in order to obtain such a velocity front a flow meter (fig. 53) was designed. It consisted of a flat piece of metal set into the cross-section of the model (fig. 50) and had several series of holes of appropriate size and spacing to form the required velocity front.

From the equation of flow (equation 38) the velocity of flow (V) is directly proportional to the volume of flow (Q) and is proportional to the area, hence to the square of the diameter (d) of the holes in the flow meter

$$V = k_1Q = k_2d^2,$$

and

$$\sqrt{V} = k\,d \quad \text{......................(44)}$$

hence if the diameter of the holes varies as the square root of the velocity of the current, the desired front across the inlet may be obtained.

Referring to fig. 53, the form of the square root of the velocity front from the centre of the stream to one side was plotted to the scale of the model, and the form of one-half of the cross-section of the inlet, which was equivalent to one-half the flow meter, was drawn beneath it. The top edge of this latter was marked in a curve which was an inverse proportion of the square root curve shown above, from low tide level at the centre to half tide level at the side. A series of horizontal lines was drawn across the flow meter at one-inch intervals from the mean tide level to the bottom edge of the cross-section. These indicated the lines of the centres of the holes which were spaced 1/8 inch apart horizontally. The diameter of the centre hole in each line was arbitrarily set at ½ inch. One-eighth inch was stepped off from the edge of this, along the first horizontal line to the edge of the next hole. This last point was projected up to the square root curve, and ½ inch was stepped off on the curve and projected down to the line. This projection represented the diameter of the hole to be drilled in the plate. The procedure was then repeated for each subsequent hole to the edge of the plate. A second square root curve was then drawn, of diameter equal to the width of the model at the depth of the second row of holes, but having the same height of crest as the first curve, and the graphical determination of the size of holes was carried out as before.

The holes were drilled with the standard drill nearest in size to the theoretical diameter of the holes, and a margin was allowed all around the meter to fit into the slot prepared in the model (fig. 50).

TURBULENCE CONTROL

The flow from the stand-pipe developed considerable turbulence when passing through the flow meter, and in order to reduce this to stream flow at the entrance to the model, or to turbulence of the same order as that in the inlet, a solenoid core (fig. 50) was interposed in the cross-section of the inlet. The action of this core in reducing the turbulence is apparent from a consideration of the Reynold's number of the form

$$N_R = \frac{R\,V\rho}{\gamma}$$

where R is the hydraulic radius, and turbulence develops at a value of 2,000. By interposition of a core of solenoids of small hydraulic radius the value of the Reynold's number may be reduced below that necessary for turbulence.

A satisfactory solenoid was adapted from the radiator core of an automobile. It was made of copper and the holes were about ¼ inch square, and smooth and streamlined inside. A section was cut about ½ inch larger than the cross-section of the model at the point of installation, and a copper strip was soldered around its edge so that the water tubes were sealed. The core was fitted into a slot prepared in the model as previously described.

The distance between the units in this system were set arbitrarily, as there appeared to be no simple relation between them. In the present model the distance from the stand-pipe to the flow meter (1½ inches) was about one-sixth of the width of the channel, and from the flow meter to the solenoid core (3 inches) was about twice this distance.

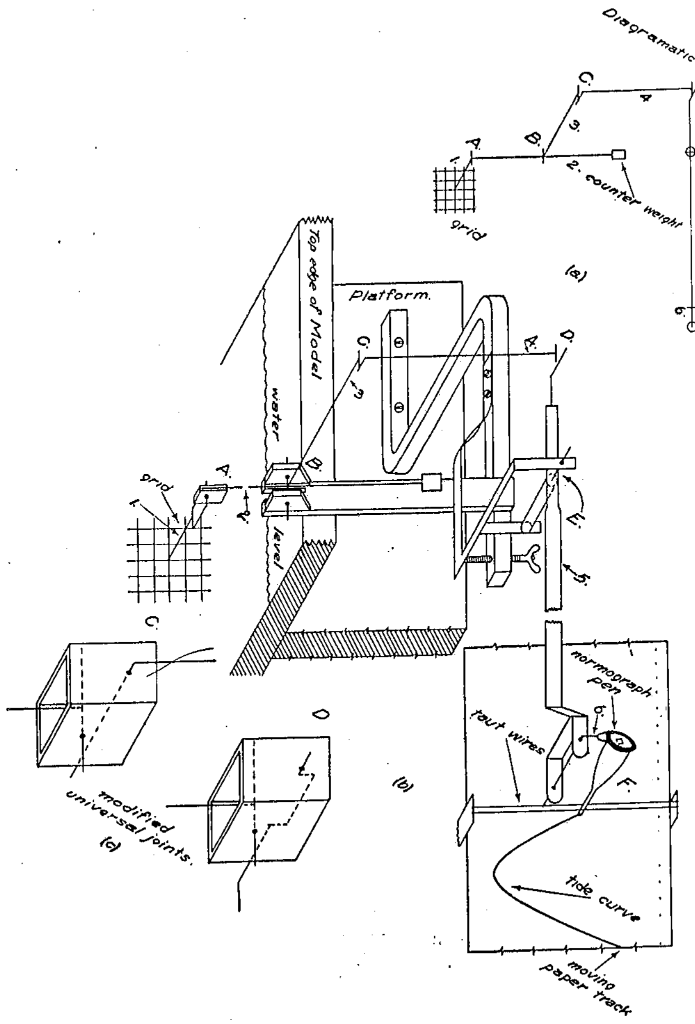

FIGURE 54. Construction of the lever system of the tide gauge. (See text for details.)

RECORDING TIDE GAUGE

The rise and fall of the tide was recorded by transferring the vertical component of the movement of a floating wire screen, through a system of levers to the horizontal plane, where a tracing was made on a moving paper track, on which time was indicated simultaneously by a series of dots.

The assembly is shown in fig. 54(a). The float consisted of a wire grid, made of fine non-rusting wire about 1 inch square and of 3/16 inch mesh, which was held on the water by surface tension, and was found to be the most suitable form of float. This grid was soldered to lever 1, the length of which was adjusted to the distance between the surface of the water and the top of the model. Lever 1 was joined by a pivot at A to lever 2 which was pivoted in the centre at B and had a counter weight, to balance the grid, attached to the end remote from A. The length of lever 3 was equal to the distance between A and B, and it was soldered at right angles to lever 2 at B. C and D were modified universal joints (fig. 54(b)), and were joined by lever 4, whose length was adjusted to the relative positions of the pen and the grid. Lever 5 provided the magnification of the tidal movement, and was pivoted one-quarter of its length from D at E. Pivot E was made so that it could be moved by a small set screw (fig. 54(c)), so that the position of the pen on the paper track could be adjusted. A "Normograph" pen was soldered to lever 6, which was pivoted at F (fig. 54(d)). The pen moved across the paper in a track provided by two taut wires, spaced to allow free movement of the pen.

The two pivots B and E were fixed to a wooden frame (fig. 54(e)) and the counter weight was adjusted so that the grid rested lightly on the surface of the water. All levers except 5, which was made from a strip of spring brass, were made from stiff non-rusting wire, and all bearings, pivots and joints were obtained from clock-works.

The principle of this lever system may be discussed with reference to the diagrammatic representation in fig. 55. During the tidal rise the screen moved from position P to P′, transmitting this motion through the indicated levers, so that the pen moved from G to G′.

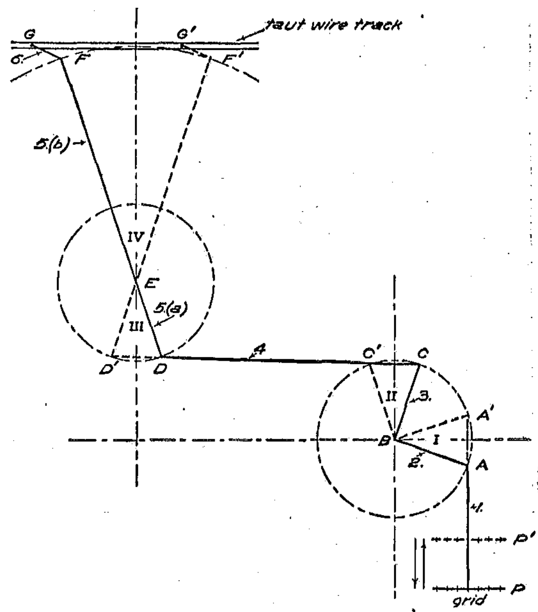

FIGURE 55. Diagrammatic representation of the lever system of the tide gauge.

If BC = DE and the arcs CC′ and DD′ of circles B and E are located orthagonally, and angle ABC is a right angle, then arc AA′ = arc CC′ = arc DD′, since the triangles I and IV are similar, and FF′ is directly proportional to AA′. If lever 6 is made equal to lever 1 and the wire track for the pen is orthagonal and tangent to the arc FF′, then the pen G repeats on a magnified scale the approximate motion of P. If lever 5(b) is made three times the length of 5(a), the error of the approximation becomes less than the thickness of the line of the tracing.

It is most important to note in the construction, that each of the levers should move in similar arcs, and that these should be located orthagonally.

The movements of the pen were traced (fig. 56) on a moving paper track of adding-machine tape, which was led from the main roll, over a metal table, to a receiving roller, on which it was wound at constant speed. In order that the paper should move at a sufficiently slow constant rate, it was necessary to introduce a gear-reduction system and to turn the receiving roller by friction on its upper surface. A clock-work movement was adopted for this purpose. The regulator wheel was removed and a pulley substituted for the escapement gear. (A strip of brass soldered around the escapement gear formed a very

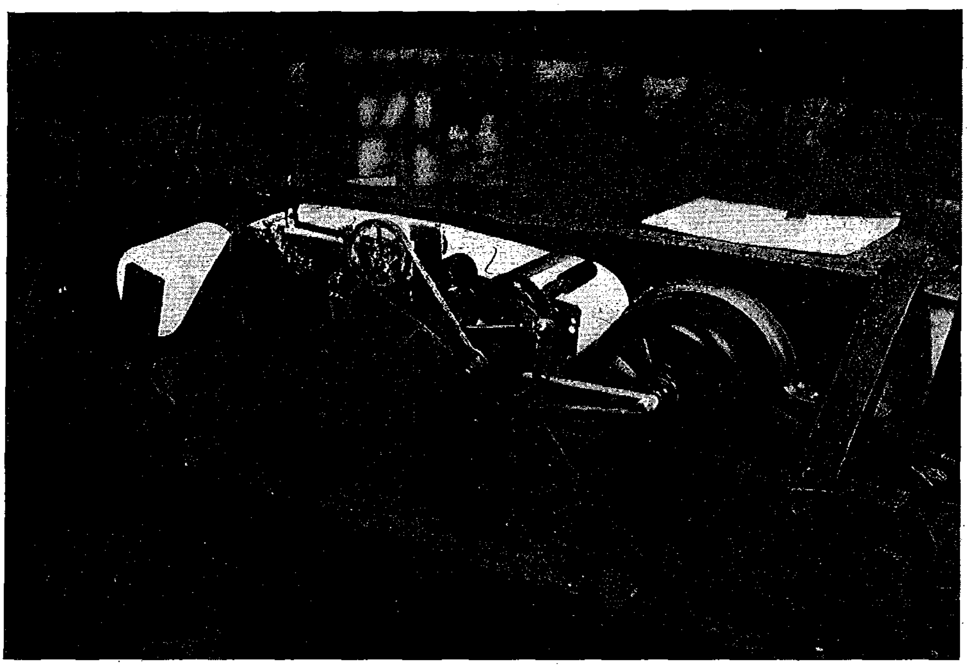

FIGURE 56. Photograph showing the arrangement of the recording time gauge.

serviceable pulley). The main spring was removed, and an extension, covered by a piece of rubber tubing, was fitted to the axle of the mainspring gear. The whole assembly was mounted on a pivot at one corner of the frame, so that the extension of the mainspring gear axle rested on the upper surface of the receiving roller, which it drove by friction. The drive was made more positive by weighting the clock frame so that it bore heavily on the roller. With this pivot arrangement the increasing size of the roll did not affect the speed of the paper across the table.

The escapement wheel pulley was driven by a rubber band belt from the axle of a constant speed motor. The fact that the belt would stretch compensated for the variation in distance between the motor and the gear system, caused by the increasing thickness of the roller.

The speed of the paper could be regulated by adjusting the diameter of the friction drive on the receiving roller, or by wrapping the pulley or the axle of the motor with adhesive tape.

To indicate time, a series of dots at regular intervals were marked on the paper track, by the device shown in fig. 57. This consisted of a lever, made from a strip of spring brass and pivoted in the centre, carrying a "Normograph" pen at one end and engaged by the teeth of a small gear at the other end. The gear was mounted with a pulley, which was driven by a rubber band from the minute hand axle of the clock movement. As the gear rotated the teeth engaged and disengaged with the end of the lever, and so lifted and dropped the pen to make a series of dots.

The time between the dots was regulated by adjusting the diameter of the minute hand axle, or the size of the pulley in relation to the number of teeth

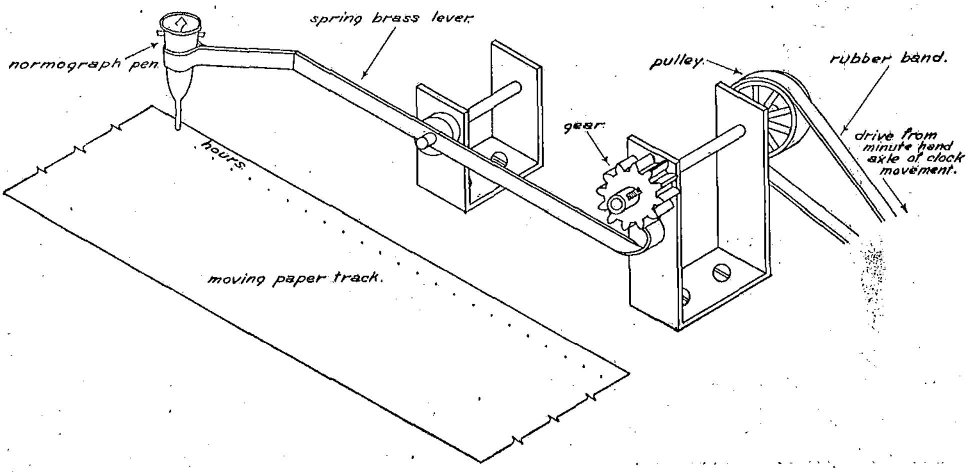

FIGURE 57. Timing device on the tide gauge.

in the small gear. In the present model the device was adjusted to make a dot every 14.2 seconds, that is, the distance between the dots represented one hour of time in nature.

The assembly of the time and tide recorder is shown in fig. 56 where it is indicated that the assembly was mounted as a single unit so that it could be fastened to the side of the model at any convenient position.

THE RIVER SYSTEM

The river flow was supplied from a constant head feed system which discharged into a cup sunk in the model (fig. 58). One side of the cup was cut away to conform with the cross-section of the river bed at that point, and the overflow from the cup constituted the river discharge.

The constant head was supplied from a tank having a fixed level overflow as shown. The tank was connected by a hose to a tube which was directed into the river well, but care was taken that it did not contact the surface. Fresh water was allowed to run into the tank at a slightly greater rate than was required to supply the river flow, and the excess was carried away by the overflow. The apparatus was assembled on a chemical clamp stand so that the discharge could be standardized outside of the model, by measuring the volume of flow per unit time, and then be put in position without disturbing the settings. The rate of discharge could be adjusted by altering the height of the tank above the discharge pipe, or by a screw clamp on the hose.

WIND SYSTEM

It has been shown by Rossby and Montgomery (1935) that under the influence of steady wind the surface water transport is a constant function of the wind velocity. It follows that the velocity of the wind over the model should be a velocity scale (b_v) representation of that in nature, provided that this force is great enough to overcome the inertia of the water mass. However, the inertia follows the scale of volume ($b_x^2 b_z$), which introduces the effect of the distortion of the model scale. From this it is apparent that a true representation of the wind effects could only be made on a natural scale model. In a distorted model it is only possible to represent the effects of a steady wind after equilibrium between the wind force and the transport has been attained, and the effects of a variable wind cannot be simulated satisfactorily.

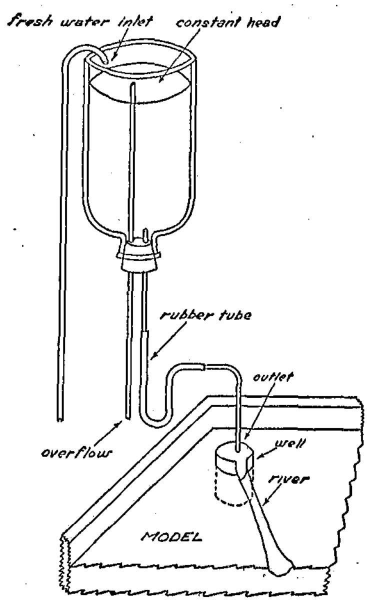

FIGURE 58. Diagram of the fresh water supply system for the river discharge.

In the present model no representation of winds less than 15 miles per hour were obtained, since the scale magnitude of this force was the minimum required to overcome the inertia of the system. It was found that the best simulation of the wind effects was obtained by introducing a large wind force over the model, until noticeable effects were obtained, and the inertia of the system was overcome, and then reducing the wind to scale dimensions, and allowing the system to assume equilibrium.

The wind over the model was generated by an electric fan, blowing through a tunnel of the form of a frustrum of a right quadrilateral cone (fig. 59(a)). The fan was mounted at the small end of the tunnel, which was a square of the same diameter as the fan. The large end of the tunnel was one and a half times as wide as the model and the same depth as the small end of the tunnel. A cardboard solenoid core (partitions from a case of bottles) was fitted into the large end, and two metal vanes were set vertically inside the tunnel near the fan. The velocity front was adjusted by altering the positions of the vanes until the force of the wind was the same across the whole width of the model, as indicated by a number of silk streamers, hung from a transverse bar between the tunnel and the model. The tunnel was set at a small angle pointing down on the model, as it was found that when it was level there was an upwards eddy formed at the leading edge of the model, which effectively shielded the surface of the water from wind effects.

The direction of the wind was shown by a number of wind arrows (fig. 59(b)). A small arrow was cut from photographic film, and a longitudinal wedge of film was glued at right angles to the plane of the arrow, with the large end at the head of the arrow. A small brass sleeve was glued vertically at the point of balance, and an upright pin fastened to a broad base, fitted loosely into this sleeve, and served as a bearing. When this miniature wind vane was viewed from above the arrow flew with the wind.

The force of the wind was indicated by an inertia gauge (fig. 59(c)). The vane was a piece of film about 1 inch square, and had a ½-inch hole in the centre. It was glued to a fine wire, which was fastened to a cross wire. This was free to swing in a bent brass support having V bearings. The wind caused the vane to tilt and the force could be judged from the angle of the vane with the vertical. This angle could be observed from above on a scale placed below the vane, one piece of metal, which was bent in the arc of a circle.

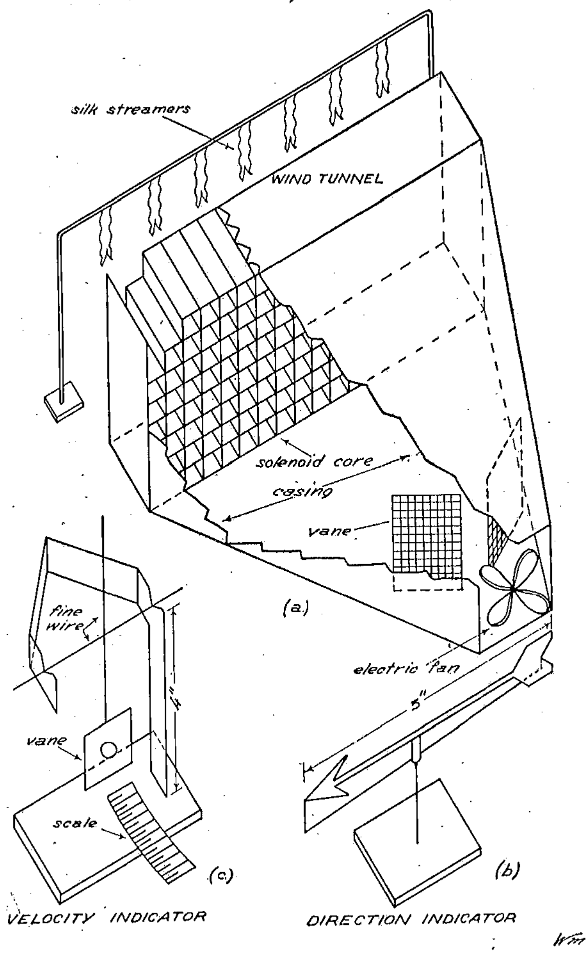

FIGURE 59. Construction of (a) the wind tunnel, (b) wind vane, and (c) wind gauge.

These simple wind gauges were standardized by comparison with an anemometer, and were sensitive to the winds employed over the model.

OPERATION OF THE MODEL

ADJUSTMENT

In nature the tide rises to a fixed height regardless of the amount of river flow, from which it follows that

(Volume of flood tide water) = (Volume of inter-tidal zone)
− (Volume of river discharge during the flood tide period)

and

(Volume of ebb tide water) = (Volume of inter-tidal zone)
+ (Volume of river discharge during the ebb tide period).

By setting the centre of the vertical range of the bucket at some distance below the median tide level of the model, the extra volume of water contributed by the river could be balanced by the increased ebb and decreased flood volume, which corresponds to the system as it occurs in nature (Part I).

In the operation of the model a fixed river flow was set up, then the tidal bucket was stopped at its extreme height, and the model allowed to fill from both souces. When the water reached the half-tide level, the tide machine and the tide recorder were started. If the tide gained in the model (i.e. if each successive tide was higher than the last) the centre of the range of the bucket was lowered by means of the screw and chain connection between the cord and the bucket. If the tide was losing, the centre of the bucket range was raised till a point of balance was found at which the tidal oscillations were constant. The range of the tide in the model was then observed on a vertical scale set in the model, and if necessary the tide was adjusted to the desired range by means of the screw clamp on the connecting hose. If this latter alteration was large, a further slight adjustment of the bucket range was necessary.

Chlorinity of Tidal Water

It is not necessary that the chlorinity (which has the same significance as salinity, Part I) of the feed water into the tidal system should be of the same density as that in nature. The slope of the chlorinity gradient would be very nearly the same in the model and prototype, provided there was sufficient range of chlorinity available in the water systems of the model. Consequently any sea water feed system could be used in which the chlorinity was greater than the range of chlorinity in the area in nature.

This may be illustrated by an example. The range of chlorinity in the area in nature at a certain point was from 5.70 Cl°/₀₀ at the surface to 17.30 at the bottom. The range in the model was observed to be from 4.35 to 13.10°/₀₀. Thus, applying the ratio of the bottom values as a factor to that observed at the surface,

$$\frac{17.30}{13.10} \times 4.35 = 5.75^{\circ}/_{\circ\circ}$$

it was found that the gradient in the model was a constant function of that in nature, within the limits of error of observation.

The chlorinity gradient in the model was determined from the chlorinity of small samples, taken at depth intervals which were scale representations of those at which the observations were made in nature. It was necessary that the samples be small compared to the volume of the model, so that the effect of the loss of water due to the sampling would be negligible.

The samples were taken with the apparatus shown in fig. 60, which consisted of a series of fine glass tubes, each with a tip bent at right angles to the vertical, and the assembly was clamped between cross-bars as shown. The apparatus was supported in the model by cross-bars which did not interfere with the flow. The lengths of the tips were adjusted so that they were in a straight vertical line and suitably spaced. A 5 ml. transfer pipette was connected by small rubber tubing to the upper end of each glass tube, and a short piece of rubber tubing and a clamp were fitted to the upper end of the pipette.

In the sampling process, the apparatus was set over the model so that the tips were at the required depth, when the tide was at the level it would occupy when the samples were to be taken. The row of vertical tubes was set longitudinally with the current so that the apparatus would create as little disturbance as possible. One operator was assigned to each pipette, and at a signal each drew a sample from the model. It was necessary to draw about twice the volume of the pipette, because the tubes became filled with water to the level of the model when the apparatus was set up. When sufficient water was drawn for the sample, the clip was placed on the rubber tubing at the top of the pipette, which was disconnected from the sampling tube, and the measured sample transferred to a titration flash and the chlorinity determined by the Mohr method (Part I).

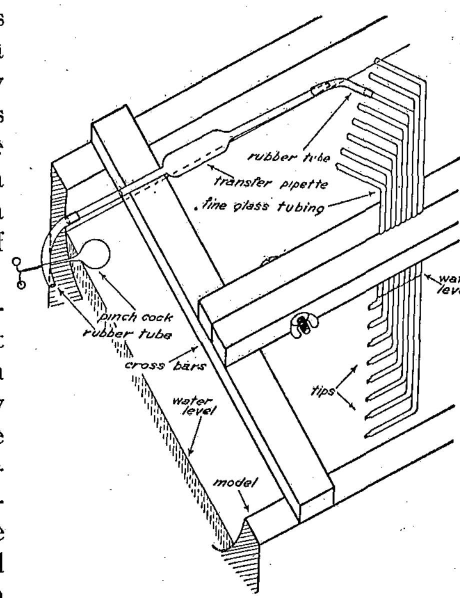

FIGURE 60. Water sampling apparatus.

It had been suggested that a multiple suction head be made, into which all the pipettes should fit, but it was found that it was necessary to have individual control over each pipette, and this could not be accomplished easily with such a device.

The depth from which the sample was drawn could not be fixed more accurately than 1/8 inch, which represented 3 feet in nature, and the time required to draw the sample was from 20 to 30 seconds, which represented 8 to 12 minutes in nature. Of these, the depth error was most significant and could introduce more than 5% error in the value of the chlorinity. Such large errors could be partially eliminated by making several series of observations, until at least two were found to coincide within the desired limits.

TRACING THE FLOW

In order to trace the flow, a solution of dye was allowed to discharge from a constant head feed system (fig. 61). A long glass tube was connected by rubber tubing to a stopcock which served as a control valve. This was connected by rubber tubing to a funnel, which was supported in a vertical position. A bottle of dye solution was inverted in the funnel, and served to maintain a constant head within small limits. An adjustable tip was set in the long glass tube and sealed with heavy grease as shown. The whole apparatus was mounted as a unit on a chemical clamp stand so that the rate of flow could be standardized outside of the model, and set up at any position desired. The rate of flow could be finely adjusted by altering the setting of the control value or the height of the funnel above the delivery tube. A suitable rate of discharge was found to be 1 milliliter in from 80 to 100 seconds, and was so small that its effect on the circulation system in the model was negligible.

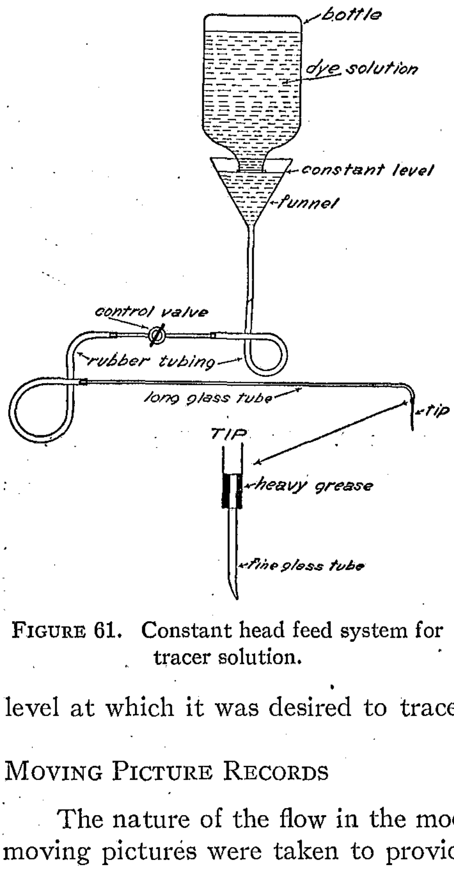

FIGURE 61. Constant head feed system for tracer solution.

It was found that a water solution of the bacteriological stains, methylene blue or gentian violet, containing 0.3 gm. of the dry stain per litre, was the most suitable for visual observation, while a similar solution of cochineal was the most suitable for photographic observation. It was necessary to avoid the use of alcohol as a solvent, since the reaction of the alcohol with water resembled extreme turbulence.

The depth at which the dye solution circulated was determined by its density, which was adjusted by the addition of an amount of salt to the solution equal to the observed salinity of the depth level at which it was desired to trace the current.

MOVING PICTURE RECORDS

The nature of the flow in the model was indicated by the dye solution, and moving pictures were taken to provide a permanent record of the action.

A moving picture camera was set vertically over the model on a suitable system of supports and the height of the camera was adjusted so that the picture included only the area of the model and the recording instruments along one side (fig. 42). Sufficient lighting was provided so that the aperture of the camera could be set at f8 to insure sharp delineation. The pictures were taken with a hand-cranked camera operated by remote control through a system of pulleys and a belt drive. This was preferable to a spring-cranked camera because the frequency of the pictures could be altered as desired.

In studying the pictures a general view of the action could be obtained by cinema projection in the usual manner, but for detailed study it was more convenient to place the film between microscope slides and project the individual pictures through a low-power camera lucida of the Spencer Lens Co. "Promar" type.

Using this modification it was only necessary to take pictures at the rate of about one per second, which was equivalent to a complete observation every four and half minutes in nature.

As shown in fig. 42 each picture contained a record of the tidal height and phase, shown on the tide graph. Time was indicated by a watch laid face upwards on the model, and the rate of discharge of the river was indicated by a label. Direction of the wind was indicated by the arrows, and the force by the wind gauges. The nature of the flow was indicated by the distribution of the dye, distance was indicated by the squares marked on the model, and depth by the contours. The velocity of flow could be computed from the distance moved by the dye, and the difference in time between successive frames. Thus the pictures contained a complete record of the immediate condition of the experiment.

Reliability

A model of a complex dynamic system such as that described is necessarily a series of approximations whose cumulative effect may be shown arbitrarily to represent the prototype.

In sea-water systems where the flow is multi-directional, it is impossible to use the customary test of model accuracy,

$$b_v^2 = b_z,$$

and the only alternative is to compare the distribution of a conserved property such as chlorinity in the two systems.

As previously indicated (Part I), the distribution of chlorinity in the system is an expression of the energy distribution, modified by the boundary conditions. In the model, all the boundary conditions and energy factors except resultant velocity were represented to scale. Consequently if the chlorinity gradient in the model agreed with that in nature, it follows that the energy distribution in the former was a correct scale representation of that in nature, which could only occur if the above relation were true.

This reasoning is more particularly applicable to the exchange of water between the source of supply and the model. From the chlorinity data in nature it is possible to make an approximate calculation of the total amount of water exchanged on an average tide, but since the amount of vertical mixing is unknown it is quite impossible to calculate the proportion of water exchanged at any level. If the density gradient maintained in the model agrees with that in nature then it follows that the exchange of water between the model and the source of supply on each tide is a correct representation at all depths of the corresponding exchange in the prototype. The model may then be regarded as a device to differentiate the exchange between definite small limits, the size of which is determined by the limits of error.

In fig. 62 a comparison is shown between the chlorinity gradient observed in nature under known conditions of tide, river discharge, and wind, and that obtained in the model under the same conditions simulated to scale. The model data were treated proportionately as described above.

There was considerably less mixing of the fresh and salt water in the model than in nature. This may be attributed to the reduction of turbulence in the model, which follows from the reduced scale, and the fact that the eddies in the model are probably spherical, rather than ellipsoid as would be required by the distorted scale.

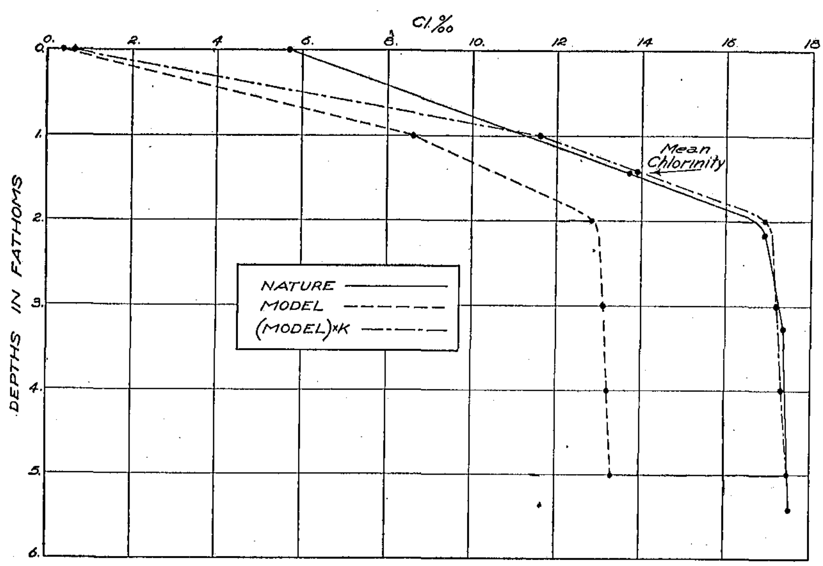

FIGURE 62. Comparison of the chlorinity gradient observed in nature and in the model.

However the position of the boundary between fresh and salt water, and the depth and value of the mean chlorinity were reproduced, within the limits of the sampling error, which indicates that the displacement of water, and the relative velocity distribution were correctly represented.

In an area of this type there are many possibilities for the observation of peculiarities of flow under specific conditions, which may be used for comparison. In this case it was observed that the salt water advanced up the river during the flood tide. The time and extent of this intrusion in the model was found to correspond favourably with the natural conditions. During high river flow an anti-cyclonic eddy persisted in the area regardless of the wind direction. Probably the most significant warranty of the reliability was the float experiments undertaken in nature, which completely verified the model representation of marginal currents in the harbour. These data will be reviewed in a later section.

LIMITATIONS

This model was constructed to determine the probable distribution of the proposed effluent in the harbour area, and while it remains in that area the model representation may be considered reasonably reliable as indicated by the criteria. However in nature, some of the upper-zone harbour water moves southward out of the model area during the ebb tide and returns during the flood. In the model all ebbing waters were mixed completely and returned as a homogeneous mass to the middle and upper zones; consequently the model gives no representation of the phenomenon of displacement in the lower harbour, but this does not vitiate its value as a means of exploring the circulation systems which are completely within the area.

GLOSSARY OF SYMBOLS

N_R	Reynolds number defined by equation 35.
ρ	Density of the medium.
ν	Kinematic viscosity.
b	Ratio of a dimension in the model to that in nature, e.g. b_z is the ratio of depth.
x	Horizontal distance.
h	Hydraulic head.
k, k_1, etc.	Constants of flow.
c	Hydraulic head required for incidence of flow.
V_N, Z_N, etc.	Velocity, depth, etc. in nature.
H	Tidal height.
t	Time (general term).
A, B, etc.	Constants of tidal amplitude.
a, b, etc.	Constants of tidal time.
α, β, etc.	Constants expressing lag of the tidal impulse with regard to the controlling celestial body.
Δ^h	Difference between water level in the tidal bucket and the model.
Θ	Position of the tidal bucket in terms of the rotation of the crank in the tide machine.
Q	Rate of discharge from tidal bucket, river, etc.
M_2	Factor expressing the moon's effect on tidal amplitude.
S_1	Factor expressing the sun's effect on tidal amplitude.
r.p.m.	Revolutions per minute.
H°	Height of second trip on tide machine above low tide level in the model.
r	Radius of crank on tide machine.
d	Diameter of holes in flow meter.
R	Hydraulic radius.

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