INTERNATIONAL ASSOCIATION OF HYDRAULIC RESEARCH

SALINITY VARIATIONS, DENSITY CURRENTS, AND SILT TRANSPORT IN THE [illegible]

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SYNOPSIS

Most of the mixing between fresh and salt water in the Saint John River of Eastern Canada is confined to a short reach near the mouth of the estuary due to a natural constriction in the river channel which acts as a salinity barrier and as an impediment to tide propagation. The constriction causes cyclic outflows and inflows of fresh and salt water respectively, creating a highly variable density regime in which the flow is both unsteady in time and non-uniform spatially.

During [illegible] there are two principal flow systems: a two-layer system having [illegible] and large salinity gradients and a single layer unidirectional [illegible] small salinity gradients. The salinity variation in the surface layer may be up to 20°/₀₀. These unsteady mass and velocity fields are difficult to analyze with existing theories, except during Low Water, when the salt water intrusion has the characteristic of an arrested saline wedge. This stage has been examined and good agreement obtained between theory and observations with regard to the interfacial Froude number, the freshet ebb tide discharge during which the salt water is washed away from the mouth of the river, the length of the saline wedge, the critical interfacial velocity and the rate of entrainment from the undiluted saline lower layer into the upper layer.

Colloidal material from the river is carried by the predominantly outward flowing surf[illegible] the mouth of [illegible] where it flocculates, sinks and [illegible] of Fundy. The silt is then subject to the [illegible] of the river from where it [illegible] "Reversing Falls" into the lake-like river system where part of it forms an inverse delta.

SOMMAIRE

Le mélange des eaux salines et douces, pour sa plus grande part, dans l'Estuaire de la rivière Saint John (Canada oriental) est limité à une étendue de 2 ou 3 milles à l'embouchure de l'estuaire, ceci étant dû à un rétrécissement naturel du lit de la rivière qui fonctionne comme une barrière de salinité et un obstacle à la propagation de la marée. Cet étranglement entraîne également la présence de flux et de reflux cycliques d'eau douce et d'eau saline, à l'embouchure de la [illegible] variable [illegible] lequel le [illegible] surface.

Au cour[illegible] systèmes de flot: l'un à deux couches, [illegible] sens opposé et à gradient de salinité élevé, l'autre simple et unidirectionnel, à faible gradient de salinité. Les variations de salinité dans la couche superficielle peuvent aller jusqu'à 20°/₀₀. Cette aire à masse et vélocité instables est difficile à analyser dans le cadre des théories existantes sauf pour les basses eaux, quand l'intrusion d'eau saline se présente sous la forme caractéristique d'un coin de salinité stationnaire. Cette étape a été examinée, et les observations relatives au nombre de Froude, à la décharge de marée d'eau douce au cours de laquelle l'eau saline est refoulée au large de l'embouchure, la longueur du coin de salinité, la vitesse critique interface, et le taux de passage de la couche inférieure saline non diluée, [illegible]

Les mat[illegible] le courant [illegible] elles floculent, précipitent, et se mélangent avec les sables de la Baie de Fundy. La vase est alors soumise au courant de fond qui la ramène en deçà de l'embouchure, d'où elle est entraînee par les "Reversing Falls" dans la partie de la rivière où le système est analogue à celui d'un lac, où, pour une part, elle va former un delta inversé.

Introduction

Saint John Harbour, one of the [illegible] ice-free ports [illegible] located at the mouth of the Saint John River [illegible] along the north shore of the Bay of Fundy, [illegible] a primary [illegible] the harbour, the [illegible] being greatly influenced by the estuarine [illegible]. The nature of this circulation and the mixing pattern were studied by Hachey (1), Trites (2) and from 1958 to 1960 by Neu (3). The results of the latter are briefly discussed and evaluated herein.

Features of the Estuary

Saint John Harbour (Fig. 1) is noted for its large tides, averaging 20.9 feet, and the "Reversing Falls", a [illegible] phenomenon created by a rock ledge in the gorge of the river one and a half miles above the harbour. This gorge connects the lower part of the estuary with a [illegible]-square-mile lake and river system. The narrow channel and rock ridge at the "Falls" act as a restriction to the tide propagation and as a partial barrier against the intruding salt water. The crest of the ridge is located so that water from the harbour can advance into the river system only during the higher tide stages. During the lower stages of the tide, the water from the river, including some of the salt water which intruded at previous higher tide stages, flows outward over the ridge in a foaming waterfall.

The relationship, during a tide cycle, between the water levels above and below the "Falls" and between the inflowing and outflowing water, for a discharge of 2[illegible],000 c.f.s. from the river system are shown in Figures 2 and 3. The computed discharge over the "Falls" for a river discharge of 2[illegible],000 c.f.s. varies from a maximum of about 110,000 c.f.s. inward to a maximum of about 100,000 c.f.s. outward; the volumes of discharge being in the ratio of about 1 to [illegible]. The salinity of the inflowing water varies from [illegible]°/oo to 20°/oo and that of the outflowing water from 3°/oo to 7°/oo.

Thus, in the Saint John River estuary, almost undiluted fresh water is brought to the vicinity of the mouth of the river where it is released with large cyclic variations in discharge to meet the undiluted salt water in the harbour and mouth of the river, where most of the mixing occurs. Salt water advances upstream periodically, under influence of the tide, and cuts off the fresh water supply.

Salinity Distribution and Current [illegible]

Observations of salinity and current velocity along the estuary during a tide cycle with a river discharge of [illegible],000 c.f.s. are plotted on Fig. 8. No measurements were made at or near the "Reversing Falls", due to the turbulent flow. The 30°/oo isohaline is chosen as the boundary between the diluted and undiluted sea water.

Vertical and longitudinal salinity gradients indicate that the harbour area can generally be classified as "partially mixed". The mixing takes place in a wedge-shaped upper layer whose thickness, depending on the tide stages, varies from 20 feet to 30 feet at the mouth of the river and from 40 to the full depth of 70 feet in the harbour. Below the mixing layer there is, except

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(1) Hachey, H.B. Hydrographic [illegible] of the Waters of Saint John Harbour. J. Fish. Res. Bd. Can., [illegible], 1939.

(2) Trites, R.W. An Oceanographical and Biological Reconnaissance of Kennebecasis Bay and the Saint John River Estuary. J. Fish. Res. Bd. Can., 17 (3), 1960.

(3) Neu, H.A. Hydrographic Survey of Saint John Harbour, N.B. National Research Council of Canada, Mech. Eng. Report MH-97, Ottawa, June 1960.

[illegible] a very short period, a layer of undiluted sea water whose thickness and [illegible] length increases and decreases with the tide stages. It is apparent that this layer provides the [illegible] for mixing and [illegible] of the water for the total volume of the [illegible]. The variations in salinity at the mouth of the harbour are shown [illegible] maximum salinity at the surface occurs one-quarter of a tide cycle before High Water (H.W.) and minimum salinity one-quarter of a tide cycle after H.W. At these respective stages maximum and minimum vertical salinity gradients occur, the former tending to more stratified and the latter to more mixed condition.

In response to these different mass fields and to the tidal currents, two basic flow systems prevail during a tide cycle, a two-layer system with oppositely moving layers, lasting approximately half the tide cycle, and a single layer system which changes its direction, during the remaining time. The two-layer system occurs with the large and the single layer system with the small [illegible] longitudinal salinity gradient. The two-layer system forms shortly before Low Water (L.W.) and exists between 3/4 Rising Tide (3/4 R.T.) and [illegible] The thickness of the layer flowing inward increases as the tide rises, in a similar manner to the undiluted salt water layer at the bed, until the entire body of water flows upstream to the "Falls" and into the lake and river system. Between 1/4 Falling Tide (1/4 F.T.) and 1/2 F.T. the flow reverses, carrying ahead of it, well mixed, more saline water which had been injected previously into the river system from the harbour. Tidal currents predominate when the single layer system occurs, the velocity profiles showing little evidence of densimetric flow. As the outflow proceeds, the water becomes less saline and [illegible] fresh, thus providing the conditions for the formation of a new two-layer [illegible]. Evidently, the density regime during the course of a tide cycle is [illegible] variable and the flow [illegible] is unsteady and non-uniform [illegible].

[illegible] quasi [illegible] which seems to exist for a short time is during the period at [illegible], when the intruding salt water balances the fresh water outflow of about 100,000 c.f.s. During this short period the salt water intrusion can be classified as "arrested" with moderate tidal current.

Farmer and Morgan (4) have given theoretical solutions to this type of salt water intrusion. They have shown that the interfacial Froude number, defined by

$$\frac{\bar{u}^2}{\frac{\Delta\rho}{\rho} g h} \qquad (1)$$

[illegible] at the [illegible] main equation [illegible] is the velocity of the [illegible] density difference between the upper and lower layers, and ρ the density of the lower layer. It was found that this relationship holds at the mouth of the river for all stages of two-layer flow.

The fresh water discharge at which the salt water is washed away completely from the mouth of the river can then be calculated from the modified equation:

$$\sqrt{\frac{\Delta\rho}{\rho} g H} \qquad (2)$$

[illegible] the harbour entrance channel [illegible] H the [illegible] feet wide and 50 feet [illegible] for [illegible] is 240,000 c.f.s. [illegible] with [illegible] the extrapolation of observations on Fig. 3, which indicates that during a discharge over the "Falls" of 235,000 c.f.s., resulting from a river

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(4) Farmer, H.G. and G.W. Morgan. The Salt Wedge. Proc. Third Conf. Coastal Eng., pp. 54-64, 1953.

discharge of 165.000 c.f.s., all the salt water is flushed out of the harbour. This, [illegible] shortly afterward, and during most of [illegible] water [illegible]

Keulegan [illegible] arrested [illegible]

$$L_0 = 6 \left\{\frac{V_\Delta H}{\nu}\right\} \left\{\frac{2V_r}{V_\Delta}\right\} .H \qquad (3)$$

In this equation V_Δ is the velocity of the saline front, referred to as the densimetric [illegible]

$$[illegible]$$

V_r is [illegible] viscosity of [illegible] water. The term

$$R_e = V_\Delta \frac{H}{\nu} \qquad (5)$$

is the densimetric Reynolds number, whose order of magnitude must be 10^7 for equation (3) to apply.

At L.W., [illegible] outflow over the [illegible] the lower part of the harbour of 40 feet [illegible] 3.2 ft./sec. V_r = 3.5 ft/sec and [illegible] Introducing [illegible] equation (3), [illegible] number equals [illegible] 10^7 [illegible] 5,000 feet. [illegible] nated wedge length [illegible] verify this length.

The thickness of the salinity wedge at the river mouth as derived from the equation

$$h = \left[1 - 0.63 \left\{ \frac{2V}{\text{[illegible]}} \right\}^{2/\text{[illegible]}} \right] \text{[illegible]} \qquad (6)$$

is more [illegible] compare in the absence of [illegible] thickness [illegible] of [illegible] depth [illegible] in [illegible] approximate agreement with [illegible]

The critical velocity at which mixing starts between the two layers can, according to Keulegan (5), be obtained from the equation:

$$U_c = 7.3 \left\{\nu g \frac{\Delta\rho}{\rho}\right\}^{1/3} \qquad (7)$$

This yields U_c = 0.1 ft/sec in the [illegible]. The upward velocity across the interface is given by:

$$U_n = 2.12 \times 10^{\text{[illegible]}} \text{[illegible]} \qquad \text{[illegible]}$$

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(5) Keulegan, G.H. The Mechanism of an Arrested Saline Wedge. In Estuary and Coastline Hydrodynamics, Eng. Soc. Monographes, McGraw-Hill Bk. Comp., In., 1966.

in which U is the velocity in the upper layer, and Q_m the rate of entrainment, is [illegible] from the equation

$$Q_m = U_m \cdot L_0 \cdot B$$

For a value of U = 2.2 ft/sec and a channel width B = 1,200 feet, U_m becomes 0.000425 ft/sec and Q_m is 7,700 c.f.s. This seems to agree quite well with the observed upstream transport in the lower layer of 7,000 c.f.s. at the mouth of the river.

The agreement which has been obtained between analytical results by applying the arrested saline wedge theory, and field observations, indicates that during L.W., the character of the intrusion, for a short time, approaches the wedge type two-layer flow with entrainment. During the remaining tide period, conditions are too unsteady to be analyzed with existing theories.

SILT PROBLEM

The sediment in the estuary is composed of sand and fine colloidal material; the former being supplied by littoral transport along the coast of the Bay of Fundy and the latter by the river. The colloidal material is carried into the bay at the mouth of the river by the outward flowing fresh water layer, where it flocculates on contact with salt water and sinks. The water in the forebay, though exposed to clockwise and anticlockwise circulations generated by the large offshore tidal currents in the Bay of Fundy, is also subject to densimetric two-layer flows initiated by the fresh water of the river. As shown in Fig. 7, the net flow in most of the forebay is inward near the bed and outward at the surface. Flocculated material mixed with sand is transported to the mouth of the river by the inward flowing bottom currents, where an [illegible] continues [illegible] and transports it over the "Reversing Falls" and into the [illegible]. Part of this silt will be carried back during spring freshets, but the remainder is used to form an inverse delta in the lake system.

Captions to Illustrations

Fig. 1. [illegible] Estuary.
[illegible]

Fig. 2. [illegible]
[illegible]

Fig. 3. Discharge at "Reversing Falls".
Décharge aux "Reversing Falls".

Fig. 4. [illegible]
[illegible] de fond.

Fig. 5. Bed Salinity-Discharge Relation [illegible]
Relation Salinité-Décharge au fond, pour la Station C à marée basse.

Fig. 6. Bed Salinity with Changing River Discharge of Station C.
[illegible] au fond, avec des changements de décharge de rivière.

Fig. 7. [illegible] Velocity
Vélocités [illegible] de fond et de surface.

Fig. 8. Salinity and Velocity Distribution during a Tide Cycle.
Distribution des Salinités et des vélocités au cours d'un cycle de marée.

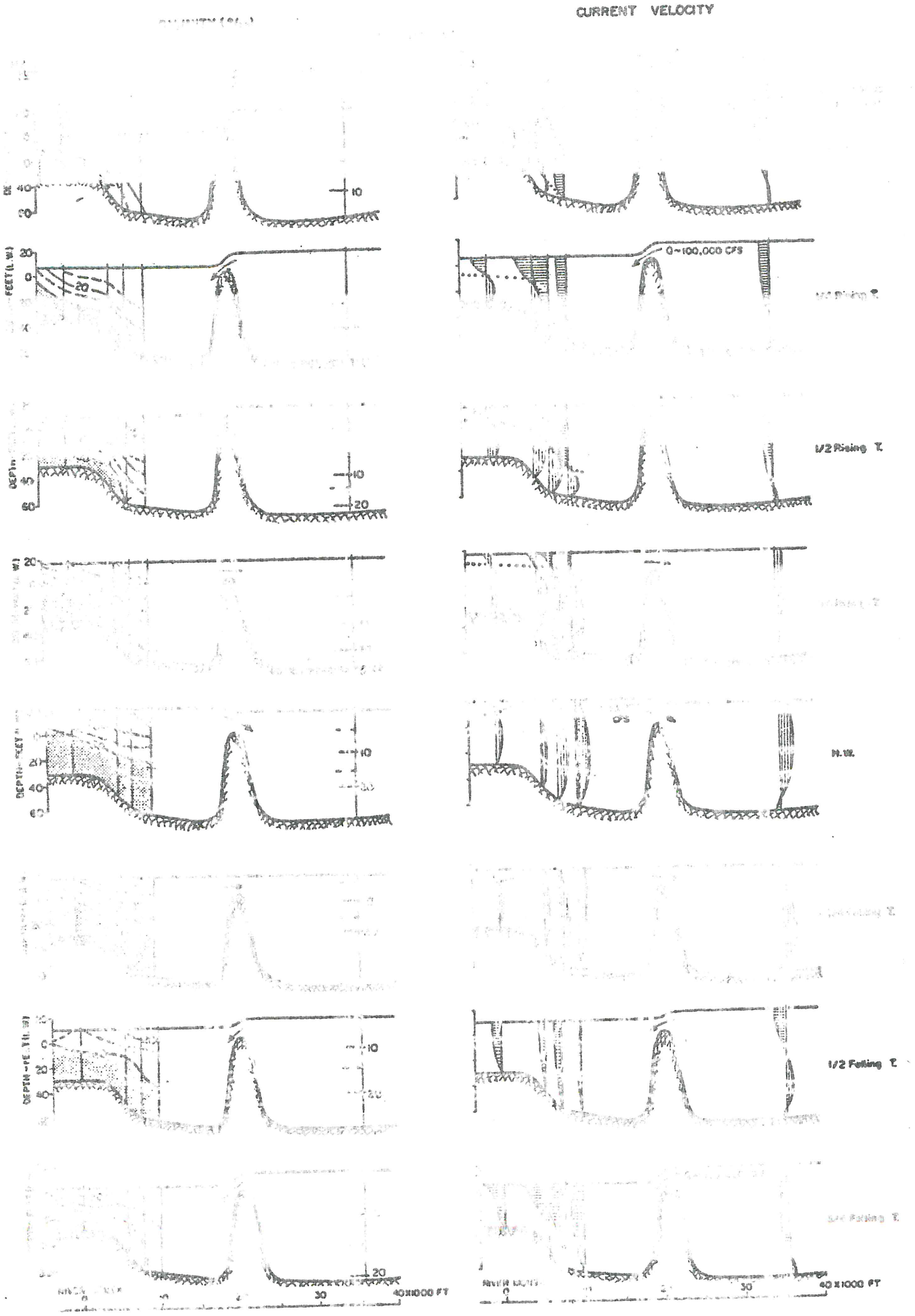
CURRENT VELOCITY
FEET (L.W.)
DEPTH-FEET
20
0
20
40
60
10
20
0~100,000 CFS
1/2 Rising T.
H.W.
1/2 Falling T.
30
40 X 1000 FT

Fig. 8.