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EXCHANGE PROCESSES BETWEEN PETPESWICK INLET and CONTINENTAL SHELF WATERS

A Preliminary Report

by

R. H. LOUCKS and H. E. SADLER

AOL REPORT 1971-5

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ABSTRACT

A program of investigation of various inlet types is being carried out by the Coastal Oceanography Section of the Bedford Institute. Petpeswick Inlet has been chosen as representative of one class of inlets. At the request of the Nova Scotia Water Resources Commission, the investigation was widened to include the dispersion of effluent from proposed sewage outfall. The sewer discharge in question is the effluent from a secondary treatment plant serving a county high school with about 800 students. Observations of temperature, salinity and phosphate content were made and experiments with dye dispersion were undertaken in the Upper Bay. The results show the exchange mechanism to vary with the quality parameter in question as well as with location. At Upper Narrows, exchange of dye was mainly diffusive rather than advective. For fresh water exchange the two modes were equally important and for salt exchange, advection was more important. At the Middle Narrows, exchange of fresh water and sea water is diffusive. Average residence or flushing times for fresh water were one-half tidal cycle (12.5 hours/tidal cycle) in the Upper Bay and approximately ten tidal cycles in the Middle Section. The average flushing time through the Upper Bay for dye from the lower layer was approximately two tidal cycles and from the proposed outfall site, approximately four tidal cycles. The interpretation of the dye results with respect to effluent dispersion is discussed in the appendix.

TABLE OF CONTENTS

LIST OF FIGURES

1. OBJECTIVES OF THE INVESTIGATION

The objectives of the investigation are:

(a) To provide a description of the dynamics of the inlet, the forces acting upon it and the resulting exchanges of water and water quality parameters between the inlet and the shelf water (section 4).

(b) To classify the observed exchange of salt (fresh water) within the inlet using the Hansen-Rattray (1966) model and to assess the model's usefulness toward forecasting water motions and exchanges (section 4.1).

(c) To investigate the effects on the inlet of the proposed treated sewage effluent in Upper Bay (Appendix).

2. GENERAL DESCRIPTION

2.1 Description of Petpeswick Inlet

The inlet lies on the eastern shore of Nova Scotia about 20 miles northeast of Halifax. It is about 12 kilometres long and varies in width from about 1.5 kilometres to 50 metres, running almost due north from the entrance. As may be seen in figures 1 and 2, it falls naturally into three sections: the first extends from the open sea to the Middle Narrows; the second, from the Middle Narrows to the Upper Narrows, and the third from the Upper Narrows to the head of the inlet. The three sections will be referred to as the Outer Harbour, the Middle Section and the Upper Bay, respectively.

In general, the depth at low water is small over the whole inlet, rarely exceeding 2 metres except in one area of the Middle Section, south of Smeltzer Island, where depths of about 20 metres are found.

Much of the area of the inlet dries at low water, exposing extensive mud flats, eel-grass beds and a few rock outcrops. A single narrow and tortuous channel leads from East Petpeswick to a point halfway up the Middle Section, the limiting depth at low water being 2 metres. This channel is marked during the non-winter months by small can-buoys and evergreen saplings.

A stream, Little River, enters at the northwest corner of the Upper Bay. This stream is reputed to have remarkably small variation through the year, the level changing only at spring run-off or in unusually prolonged summer drought. During the period of the preliminary experiments, discharge rate has remained relatively constant at about 1 m^3sec^{-1}. Several other small sources enter the inlet but their combined volume is estimated to be less than 10% that of the main stream, which will be referred to as "the river".

The only industry on the inlet is a boat building yard in the Upper Narrows. A small fishing fleet is based on East Petpeswick. There are about 30 houses around the Upper Bay and the Middle Section and another dozen or so in East Petpeswick and around the Outer Harbour. Most of these have septic tanks but there are apparently a few of them which discharge raw sewage directly into the inlet. Near the head of the inlet there is a county high school which has about 800 students. Sewage from the school goes through a secondary treatment plant; it is planned to discharge the effluent from the plant into the Upper Bay. However, for various reasons, the pipeline has not been completed and the effluent from the plant is now entering the inlet with the natural surface drainage from the end of the uncompleted pipe.

The inlet supports a variety of forms of life; besides the extensive beds of eel-grass, bottom growth is wide-spread. Mussels occur on rock outcrops, particularly one in the Upper Narrows. Large numbers of minnows have been seen and there is a local fishery for eels and smelts. A few hair seals have been seen in the Middle Section. There is a varied population of water fowl, and ten herons were counted in a three-mile stretch of the western shore in the Middle Section. There may be potential for oyster culture in the future.

Most of the people living on the shore have boat mooring or jetties, and there is a yacht club in the Middle Section. A small recreation area in the Upper Bay has a protected beach for children's swimming.

2.2 Geomorphology of the Inlet

The Upper Bay (figure 4) is shallow, the mean low-water depth being less than a metre, and it is separated from the Middle Section by four small islands, two of which have causeways connecting them to the shore. (The Fraser's Island causeway is pierced by a culvert.) The remaining outlets, one on each side of Smeltzer Island, are both shallow, the one to the east being almost dry at low water springs. Upper Narrows, to the west of Smeltzer Island, has a channel with a minimum depth of 4 metres, but this does not extend far into Upper Bay. Thus Upper Bay, while not being a basin, has a restricted connection with the rest of the inlet, especially at low water.

The southern half of the Middle Section is largely dry at low water exposing mud flats and eel-grass beds. The northern half of this section does not dry; it contains a relatively deep region with soundings of 20 metres. The deep region forms an isolated basin. This basin has not been fully surveyed, but it extends most of the way across the inlet between Hoar's Island and the yacht club. At the south end of the Middle Section the inlet narrows to about 50 metres. These Middle Narrows are about 1 kilometre long and from 50 to 150 metres wide. Currents are strong in this area and there is intense turbulence.

Immediately below the Middle Narrows (figure 2) the inlet widens to over 1 kilometre with large areas drying at low water. Below the Government Wharf in East Petpeswick the inlet, about 1½ kilometres wide, remains shallow, the bottom being mainly sand. The channel below East Petpeswick remains narrow and shallow, finally merging into the general bottom in about 4 metres of water. The entrance, restricted by Petpeswick Island and the natural sand spit which connects it to the mainland, is about ½ kilometre wide between the Island and South Head.

2.3 The Dynamic Forces Acting on the Inlet

2.3.1 Tidal Forces

The tides in the inlet are semi-diurnal; the maximum range is about 2 metres at the head of the inlet. More accurate tidal data will be available when the tidal records now being obtained have been analyzed. Since the inlet is shallow and has a large area of drying banks, the tidal prism is a large fraction (60%) of the total volume at high-water, and tidal flushing is obviously an important factor in the exchanges taking place in the inlet. Accurate values for the volumes of the tidal prism and the low-water volume are not available in the absence of a recent detailed survey.

2.3.2 River Flow

The measurements of river discharge were carried out by Mr. Peter Hiltz, Water Survey of Canada. The rate of discharge of the river is sensitive to small changes in level. The mean value for the period 25 October to 21 November was 0.855 ± 0.008 m^3/sec or $(3.85 \pm 0.04) \times 10^4$ m^3 per 12.5 hour tide cycle.

The standard deviation of the flow on any particular day in this period was ± 0.4 m^3/tidal cycle.

The mean discharge during one tidal cycle, $3.9 \times 10^4 m^3$, is only about 10% of the volume of the tidal prism in the Upper Bay; nonetheless, the effects of freshwater inflow are particularly noticeable in this area.

2.3.3 Wind Effects

No attempt has yet been made to measure the effects of wind on the circulation in the inlet. It is hoped that a statistical analysis of wind records now in progress will be useful in this respect.

3. METHODS AND RESULTS

3.1 Preliminary Observations

3.1.1. It was immediately realized that there is no existing chart on a sufficiently large scale to reveal the geomorphology and permit the planning of sampling locations. It was clearly impossible to carry out a full survey of the inlet with the manpower and time available, and the initial planning was done using a sketch survey of the Upper Basin based on points fixed by horizontal sextant angle. Later a series of five air photographs taken in 1961 was obtained which covered the whole of the inlet on a scale of approximately 15,800:1, a scale which is still a little too small for convenience. The charts in figures 1 and 2 were drawn from these photographs.

A series of soundings was made by Bedford Institute hydrographers under Mr. R.C. Lewis using a portable echo sounder from a small boat to obtain a series of cross-sections at a number of points down the inlet. Using available charts and soundings the low water volume in the Upper Bay was estimated to be $2.5 \times 10^5 m^3$ and the intertidal volume, to be $5.4 \times 10^5 m^3$.

3.1.2 A pressure gauge tidal station was established at the southeast corner of Park Jetty and a survey party from BI levelled this into three survey markers set in nearby rocks. A direct comparison with chart datum at Halifax awaits an analysis of a 15-day tidal record.

3.1.3 The river discharge measurements are described above.

3.1.4 A recording station for wind, temperature and rainfall was also placed on the end of Park Jetty but instrumental malfunctions have reduced the amount of useful data obtained.

3.1.5 The sewage from the high school passes through a secondary treatment plant (10,000 gallons per day capacity); the effluent is chlorinated. The flow rate was checked at peak periods and was estimated to be 1 litre per second. Since the outflow is essentially zero outside school hours, the average outflow was estimated to be about 0.25 litres per second or 5000 gallons per day. The effluent at present is added to the normal surface drainage from the end of the uncompleted pipeline. Most of this surface drainage enters the inlet via a small culvert under the road near the old clam factory. The proposed outfall will extend to a point about 10 metres out from the south end of this culvert (figure 4a).

3.2 Evaluation of Dilution Flushing Capability

3.2.1 Salinity Measurements (for tracing of freshwater over Upper Bay and Middle Section)

Both temperature and salinity were measured using a Hamon Temperature-Salinity Bridge Model 602. Measurements were made on water skimmed from the surface and at a number of depths to the bottom. The Upper Bay station locations are shown in figure 4a. The salinity profiles for these stations are shown in figure 5 for 16 November 1970. The longitudinal salinity (or freshwater) distribution through the whole inlet is shown in figure 3. In addition, a time series of current, temperature and salinity measurements was carried over a tidal cycle at two locations in the Upper Narrows in order to classify the salt exchange mechanisms there (Hansen and Rattray, 1966).

3.2.2 "Simultaneous One-Shot" Injection of Dye (throughout Upper Bay)

It was hypothesized that the bottom layer might exchange relatively slowly leading to long residence time and build-up of pollutants. To test this an experiment was carried out using dye in the bottom layers. Initially, a survey for background fluorescence was carried out. The levels found were less than 0.5 ppb except in one case where the level was 2 ppb; we suspect that some oil from the outboard motor contaminated this sample. The threshold significant concentration was taken to be 1 ppb.

Ten separate slugs of 1 litre each of undiluted dye were injected on the bottom in each of ten stations using a weighted hose on 25 November 1970. The positions of these stations are shown in figure 4b. They are scattered over the whole area of the Upper Bay, including the side coves. The dye was all released within 30 minutes during high-water slack and was sufficient to provide an average concentration of 10 ppb. At the next two periods of high-water slack, samples were taken at the surface and near the bottom and their dye content measured. The results are shown in Table 1.

TABLE 1

Distribution of Dye Concentration in Upper Bay

Station No.	Dye Concentration (ppb) After 1 tidal cycle bottom	 After 1 tidal cycle surface	 After 2 tidal cycles bottom	 After 2 tidal cycles surface
1	1.8	6.2	2.4	2.5
2	1.4	4.1	1.3	1.3
3	3.9	4.2	1.5	1.5
4	6.0	4.1	4.3	2.2
5	4.1	4.5	2.6	2.3
6	3.4	4.0	3.3	1.3
7	4.7	4.6	1.5	2.2
8	9.8	4.2	1.1	1.8
9	3.3	2.4	1.2	1.3
10	2.1	2.6	1.6	1.7
Mean	4.1	4.1	2.1	1.8

3.2.3 Continuous Injection Dye Tracer Study (for proposed outfall site)

It was decided that the experiment with continuous dye injection should simulate as nearly as possible the actual conditions to be expected when the sewage outlet is installed. To accomplish this the dye was mixed with fresh water and led by means of a weighted hose to the position of the sewage outfall, about 10 metres from the roadway. The fresh water was obtained by damming a ditch, which discharged into the inlet, and using a small electric pump to give a flow of 4 litres per minute. Below the pump a T-junction was inserted and Rhodamine B dye diluted 10:1 was dripped into the output from a 15-litre container at a rate of 40 drops per minute. Thus the dye concentration released was

$$\frac{\dfrac{40\text{ drops dye}}{\text{min}} \times \dfrac{1}{10} \times \dfrac{1\text{ ml}}{20\text{ drops}}}{4 \times 10^{3}\,\dfrac{\text{ml water}}{\text{min}}} = \frac{0.2\text{ ml dye}}{4 \times 10^{3}\text{ ml water}} = 5 \times 10^{-5}\,\frac{\text{dye}}{\text{water}}$$

$$= 50{,}000\text{ ppb dye.}$$

The steady (with minor readjustments every three hours) discharge of dye was maintained for 80 hours between 14 November and 17 November 1970. At various times during this period water samples were taken and analyzed for dye concentration using a Turner Model 111 fluorometer. The results are shown in figures 6a to 6h.

3.3 Other Observations

A number of determinations of the dissolved oxygen level were made on samples from both the Upper Bay and the Middle Section. Results indicate anoxic conditions in the deep area of the Middle Section (figure 3) and a time series of profile readings has been initiated to determine the extent and the duration of these conditions.

A full tidal cycle series of samples will be obtained to permit the determination of a number of biological factors and nutrient abundances. Nutrient samples will also be obtained in the Upper Bay.

4. INTERPRETATION: Evaluation of Dilution/Flushing Capability

4.1 Salinity Measurements (for tracing of fresh water over Upper Bay and Middle Section) (figures 3 and 5)

The salinity profiles for the Upper Bay (figure 5 [typical high water case]) show a thin surface layer of low-salinity water near the river mouth which becomes progressively diluted with sea water downstream. This layer has a depth of 15 cm and fresh water content of approximately 50% averaged over the Upper Bay. Thus the volume of river water retained is estimated to be 0.5 x 0.15 m x 0.5 km x 0.5 km or 2×10^4 m^3. This is approximately one-half the volume discharged by the river in one tidal cycle. Therefore the weighted average residence time for fresh water in the Upper Bay is gauged to be approximately half a tidal cycle or seven hours.

The volume of fresh water retained in the Middle Section is estimated from figure 3 and from similar results of other surveys to be 3×10^5 m^3. Therefore the average residence or flushing time for fresh water in migration through the Middle Section is gauged to be approximately ten tidal cycles.

The results of the time series measurements in the Upper Narrows permit classification of the inlet according to Hansen and Rattray (1966). The parameters involved in this classification process are:

(i) the top to bottom salinity increment,
(ii) the cross-sectional average salinity,
(iii) the average surface current,
(iv) the velocity of river discharge averaged over the cross-sectional area.

The classification for the Upper Narrows (both sides of Smeltzer Island is Hansen and Rattray's type 3b where salt exchange is mainly advective and fresh water exchange is approximately equally partitioned between advection and diffusion. This is supported by the fact that the fresh water fraction in the Upper Narrows exhibits regular variation through the tidal cycle. (In advection, exchange is more or less continuous in two layers while in diffusion exchange is pulsed at tidal frequency.)

It may be inferred that in the Middle Narrows the Hansen-Rattray classification is 1a and the exchange is diffusive for both salt and fresh water. (Petpeswick Inlet offers a unique opportunity to trace the progression of dominant exchange mechanisms from the river to the sea through narrows using the Hansen-Rattray model; the model has proved useful in making the present interpretations for both fresh water and dye and may lead to further insights.)

On a separate topic, the salinity-temperature measurements in November 1970 revealed that the water in the deepest basin of the Middle Section had relatively high density; dissolved oxygen measurements showed this water to be depleted below 12 metres and virtually anoxic from 16 to 24 metres (Fig. 5). Thus this water was confirmed as isolated and stagnant. Exchange would be expected to occur intermittently although it is not yet possible to predict the probable frequency of replenishment; however, measurements in late January 1971 showed negligible density gradient and plentiful dissolved oxygen indicating that replenishment had occurred.

4.2 Single Injection of Dye (throughout the lower layer of Upper Bay)

Dye was injected at the equivalent of 10 ppb and was reduced yy flushing to 4 ppb after one tidal cycle and to 2 ppb after two tidal cycles (Table 1). During the first tidal cycle, the dye was dispersed throughout upper and lower layers. This supports the suggestion that sea water advection with entrainment is operating. The dye concentrations indicate the replacement fraction per tidal cycle to be one-half and suggest that the tidal prism water becomes well mixed with Upper Bay water. The average residence time of dye in the Upper Bay is inferred to be two tidal cycles. The dominant flushing mechanism is tidal diffusion acting upon the longitudinal gradient in dye concentration.

4.3 Continuous Injection Dye Tracer Study (for proposed outfall site)

The qualitative interpretation of figures 6a to 6h is given in Table 2.

TABLE 2

Interpretation of the Dye Distribution
Found during the Continuous Injection Tracer Study

Figure	Time of Survey	Dye Dispersion	Interpretation
6a	15 November morning high water	No significant concentrations of dye were detected.	Dye concentration will not yet have built up to equilibrium.
6b	15 November afternoon low water	Small dye concentrations were observed.	It is inferred that dilution/flushing is extensive.
6c	16 November morning high water	Small dye concentrations were observed.	It is inferred that dilution/flushing is extensive.
6d	16 November afternoon low water	Small dye concentrations were observed.	The above inference is supported; however, some slight accumulation is indicated in the cove east of Fraser's Island.
6e	17 November morning high water	Small dye concentrations were observed.	The above inference is supported; however, some slight accumulation is indicated in the cove east of Fraser's Island.
6f	17 November afternoon low water	Significant dye concentrations were observed along the leeward shore.	The wind was observed to move water containing high concentrations of dye out of the cove, where it was being released, and along the leeward shore.
	Dye injection stopped at midnight.		
6g	18 November morning rising tide	Concentrations within 100 m of the source were reduced compared to those of fig. 6d; concentrations away from the source were similar to those of fig. 6d and 6c.	The wind continued to move dyed water along the leeward shore although dye injection had been stopped at midnight.
6h	18 November afternoon ebbing tide	Concentrations within 200 m of the source were reduced compared to those of fig. 6e; concentrations away from the source were similar to those of 6c, d and e.	The normal tide and river dilution/flushing processes caused reduction of concentrations near the previous source and maintained in low concentrations in those areas still in quasi-equilibrium.

It can be seen from figures 6a to 6h that the dye entered both upper and lower layers. It is estimated from dye concentrations observed to persist that the average flushing time through a quadrant of 100 metre radius from the point of discharge is two tidal cycles and through the Upper Bay, three tidal cycles.

5. CONCLUSIONS

(a) The river water migrates through the Upper Bay in approximately one-half tidal cycle and through the Middle Section in approximately ten tidal cycles.

(b) The exchange through the Middle Narrows is diffusive for salt and fresh water.

(c) The exchange through the Upper Narrows is mainly advective for salt, both advective and diffusive for fresh water, and diffusive for dye injected in the lower layer. The flushing time from the Upper Bay for dye in the lower layer is approximately two tidal cycles.

(d) The flushing from the Upper Bay of dye injected continuously at the proposed outfall site is estimated to require approximately three tidal cycles.

6. ACKNOWLEDGEMENTS

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APPENDIX

PERSPECTIVES ON WASTE DISCHARGE INTO NATURAL WATERS

Introduction

This section describes a systematic approach, such as may be practicable in the near future, for evaluating a specific waste discharge situation. The essence of the approach is contained in a flow chart below. Definitions of terms, elaboration of intricacies and identification of information which is required but unavailable is given for each section of the flow chart. The Petpeswick Inlet situation is discussed as an illustrative example.

Suggested flow chart for evaluating a waste-discharge situation:

(a) Formulate water resource management plan including specifications for the stressed zones.

(b) Choose from a national "library" of water quality criteria (in sets according to water use) a set of water quality standards commensurate with the water resource management plan.

(c) Using these standards and data on the concentrations of the critical constituents in the effluent and in the receiving waters, calculate the dilution factor required. (This dilution contour will form the boundary of the stressed zone.)

(d) Taking into account both the required dilution factor and the rate of effluent discharge, use the results of dye dispersion studies of critical constituent monitoring to determine the location and extent of the stressed zone.

(e) Compare the actual stressed zone with that prescribed in the water resource management plan with respect to size, location and capacity for the future. If the actual zone exceeds the prescribed limits, the limits may be adjusted, the concentration of the critical constituent may be reduced by further treatment or the dilution/flushing may be somehow enhanced.

Discussion of Flow Chart - Section by Section

(a) A water resource management plan would describe the uses envisaged for the resource. These uses would probably exert stress on the receiving water body. Stress is defined in the following exerpt from The National Estuarine Pollution Study (U.S.A.) (1970):

> A stress (on an estuary) is a process which drains available energy. Stress can be either direct as in the case of harvesting finfish or shellfish from the system, or indirect as happens when increased turbidities shade out light or when some substance such as phenol is added to the aquatic system, either causing mortality or demanding special adaptive work on the part of the surviving organisms to sustain life. Energy drains on existing organisms may also occur when excesses of nutrients added to the system deplete the available oxygen necessary for respiration.

The acceptable limits for the significantly stressed zone could be prescribed in the management plan. These limits might best be cast in probablistic terms. For example, an acceptable situation might be one where the stressed zone is 99% certain to be confined to within 1 kilometre of the outfall for at least 160 of the 168 hours in each week.

(b) A national "library" of water quality criteria appropriate to the spectrum of water uses is being compiled under the Canada Water Act. Also the report of the U.S. Committee on Water Quality Criteria (1968) is a valuable reference. However, criteria for oceanic and estuarine environments are not well established in general.

(c) Dilution factors for all potentially critical constituents should be estimated so that the largest dilution factor derived is sufficiently stringent. The stressed zone is taken to be that region within which the dilution required for safe dispersion has not been achieved. Even with these precautions there are complications which can arise when dependence is placed upon dilution/flushing. It seems that when slight stress is applied to an ecosystem, its stability may be decreased and its productivity increased with the result that conditions may come to favour one opportunistic species which will then bloom in mass proportions. Thus algal blooms such as "red tides" could occur near the perimeter of a stressed zone. In addition, the possibility that a critical constituent could be rendered more noxious naturally through reconcentration must be considered.

(d) and (e) These sections are elucidated in the example below.

Example - An Attempt to Relate the Above Perspectives to the Petpeswick Inlet Situation

This discussion will follow the outline of the flow chart.

(a) The Petpeswick Inlet water resource is presently used for swimming, boating and fishing. The long range plans for this water resource may or may not be clearly formulated at this time. It is not known how large a stressed zone (resulting from discharge of secondary-treated sewage effluent) could be tolerated.

(b) A criterion for primary contact recreation (Water Quality Criteria, 1968) which is possibly relevant is that fecal coliforms be fewer than 200/100 millilitres (log mean). In addition, a guide, rather than a criterion, might be that the enteric virus density should be as low as that commonly found in surface waters - 0.1 to 1 virus unit per 100 millilitres (Clarke *et al.*, 1964, quoted in Shuval 1969).

A second criterion might be that outside the stressed zone oxygen depletion, due to consumption by decaying plant material whose growth was stimulated initially by the nutrients in the effluent, should be less than 2 mg/l. This would preserve an oxygen concentration of at least 4 mg/l in accordance with the recommendation in *Water Quality Criteria*.

(c) If the above criteria are taken as standards defining the boundary of the stressed zone then we may calculate the dilution required for the effluent at this boundary. However, in addition to these standards data are required on the concentrations of these critical constituents in the effluent and the receiving waters. Since fecal coliforms should be eliminated from the effluent by chlorination, dilution on this account should not be required. With respect to virus, data are incomplete. However, if we assume that the receiving waters are free of virus, and that the effluent contains 50 virus units per 100 millilitres (this is allowing tenfold reduction due to treatment (Shuval and *Water Quality Criteria*), then the required dilution to achieve 0.1 virus units per 100 millilitres is 500-fold. With respect to oxygen depletion, the source concentration of secondary oxygen demand is calculated to be 2500 mg O_2/l. This calculation involves the total measured phosphorus concentration of the effluent (0.5 mg at/l) multiplied by the oxygen demand per unit phosphorus (276 mg at O_2/mg at P ; Ketchum, 1969). (This is a generous estimate since nitrogen is likely to be limiting (Riley, 1967).) Division by the standard decrement for the receiving water (2 mg/l) yields a dilution factor of 1200. However, this cannot be related to the stressed zone without further discussion because of a complication (*cf.* section d below).

(d) (i) Virus

In order to determine the location and extent of the stressed zone we must first express the results of dye dispersion studies in terms of dilution factor. Since the concentrated dye was released at a rate of 0.25 ml/min and is being used to simulate the discharge of treated effluent at an average rate of 15 litres per minute (5000 gallons per day), the dye concentration before dilution is 17,000 ppb. The actual dye concentrations corresponding to various dilution factors for discharge rates of both 5000 and 10,000 gallons per day are listed in Table I . For given effluent discharge rate and dilution factor standard, one may find from the table the corresponding threshold dye concentration. Then by referring to figures 6a to 6h, which show the observed dye concentrations through the Upper Bay, one can estimate the location of the dilution factor standard contour, or stressed zone boundary.

TABLE I

Relationship Between Dilution Factor and Dye Concentration for Two Discharge Rates

$$\frac{0.25\ \text{ml/min}}{15\text{x}10^3\ \text{ml/min}} = 1.7 \text{ x } 10^{-5}$$

$$= 17\ 000\ \text{ppb}$$

Dye concentration	Treated effluent dilution factor Discharge rate of 5000 gal/day	Discharge rate of 10 000 gal/day
3400 ppb	5	2.5
1700 ppb	10	5
340 ppb	50	25
170 ppb	100	50
34 ppb	500	250
17 ppb	1000	500
3.4 ppb	5000	2500

Referring to figures 6a to 6h, in particular to the region with concentration greater than 34 ppb (500-fold dilution of 5000 gal/day), it can be seen that this region surrounds the outfall and extends outward for a distance varying approximately between 20 and 100 metres. If the rate of discharge were increased fivefold, the critical dye concentration would be 7 ppb, and the coves around the Upper Bay would likely be affected.

The average time required for 500-fold dilution of effluent from the proposed outfall site may be estimated as the volume of the affected zone, say $\frac{\pi}{4} \text{ x } (100)^2 \text{ x } 2 = \frac{6}{4} \text{ x } 10^4\ \text{m}^3$, divided by the exchange rate, $500 \text{ x } 0.25 \text{ x } 10^{-3}\ \text{m}^3/\text{sec} = 0.1\ \text{m}^3/\text{sec}$ which yields 10^5 sec or 2 tidal cycles.

Since the dye from the proposed outfall site requires more time for flushing than does river water, one might consider discharging the effluent through a diffuser just above the salt wedge in the river mouth. There are perhaps disadvantages in this but initial dilution of 1000-fold could be achieved with consequent reduction of the stressed zone and the effluent would be dispersed in the fresh water which is a major driving force for flushing in the Upper Bay.

(ii) Oxygen Depletion

The zone stressed by oxygen depletion could have been estimated as was done for virus were it not for the fact that the oxygen consumption develops some time after release of nutrients and that the nutrients are continually regenerated from the biomass and recycled. This cycling time is a key parameter in the analysis. Phosphorus may be regenerated within minutes (Rigler, 1956 and 1964, in Hutchinson, 1969); however, nitrogen may be the more important limiting factor in coastal zones (Riley, 1967) and seems to be regenerated relatively slowly (Riley). Carpenter *et al.* (1969) find the regeneration time in Chesapeake Bay to be one to four days. To be conservative let us take the cycling time as one tidal cycle (12.5 hours) *i.e.* during each tidal cycle the nutrients in a parcel of water stimulate the growth of a new crop of plant material with its subsequent oxygen consumption. We shall also neglect the accumulation of dissolved oxygen from photosynthesis. The approach will be to divide the region near the head of the inlet into segments such that the residence time of the effluent in each segment is one tidal cycle. It is taken that in each segment during each tidal cycle the local oxygen demand is equivalent to that triggered by the nutrients in the effluent discharged per tidal cycle. Moreover, it is held that oxygenated water mixes and exchanges toward the head of the inlet at approximately the same rate as depleted water migrates seaward—the system is mainly diffusive. Then the resultant oxygen depletion is estimated by accumulating the depletions per unit volume from the sea inward to the point of effluent discharge and return; however, the progression seaward into segments of increasing volume involves dilution as well as accumulation. The results are presented in Table II and described below.

The total oxygen demand per tidal cycle was estimated as the product of the oxygen demand per litre (2.5 g/l) and the effluent discharge rate (10,000 gal/day or 2 x 10^4l/tide cycle). The segment exchange rates were determined from the survey results for (continuous) dye and fresh water; the technique amounts to mapping out successive volumes containing the amount of dye or river water discharged per tidal cycle. Segment #1 is within a 40 metre radius of the proposed outfall site. Segment #2 is between #1 and a 100 metre radius of the site. Segment #3 is that occupied by river water up to one tidal cycle after discharge; it extends from #2 through the Upper Bay and into the Middle Section. Segments #4 and #5 are in order seaward from #3 in the Middle Section. The discrete oxygen depletion is the local demand per unit volume. The cumulative depletion involves the progression, first landward and then seaward, with dilution limiting accumulation of depletion. The segments (#1 and #2) where depletion exceeds 2 mg/l are predicted to become stressed. Discharge into the river would minimize the stressed zone; the influx and dilution dominate the depletion. It does not seem likely that the waters of the basin (segment 4) would be significantly de-oxygenated by the present effluent discharge.

TABLE II

Estimation of Oxygen Depletion Through Petpeswick Inlet due to Discharge of $5x10^4$ g Oxygen Demand per Tidal Cycle

Segment		Oxygen Depletion/Unit Volume - TC		
		Clam Factory		River
No.	Inlet Water Exchange Rate (m^3/tidal cycle)	Discrete mg DO/l	Cumulative mg DO/l	Cumulative mg DO/l
5	5×10^6	0.01	0.01	0.01
4	5×10^5	0.10	0.11	0.11
3	1×10^5	0.5	0.61	0.61
2	1×10^4	5	5.61	-
1	1×10^3	50	$\boxed{55.6}$	-
2	1×10^4	5	$\boxed{10}$	-
3	1×10^5	0.5	1.5	-
4	5×10^5	0.1	0.4	0.2
5	5×10^6	0.01	0.05	0.03

(e) The next step (which has not been taken yet in the case of Petpeswick Inlet) is to compare the predicted stressed zone with that prescribed in a water resource management plan with respect to size, location and capacity for the future.

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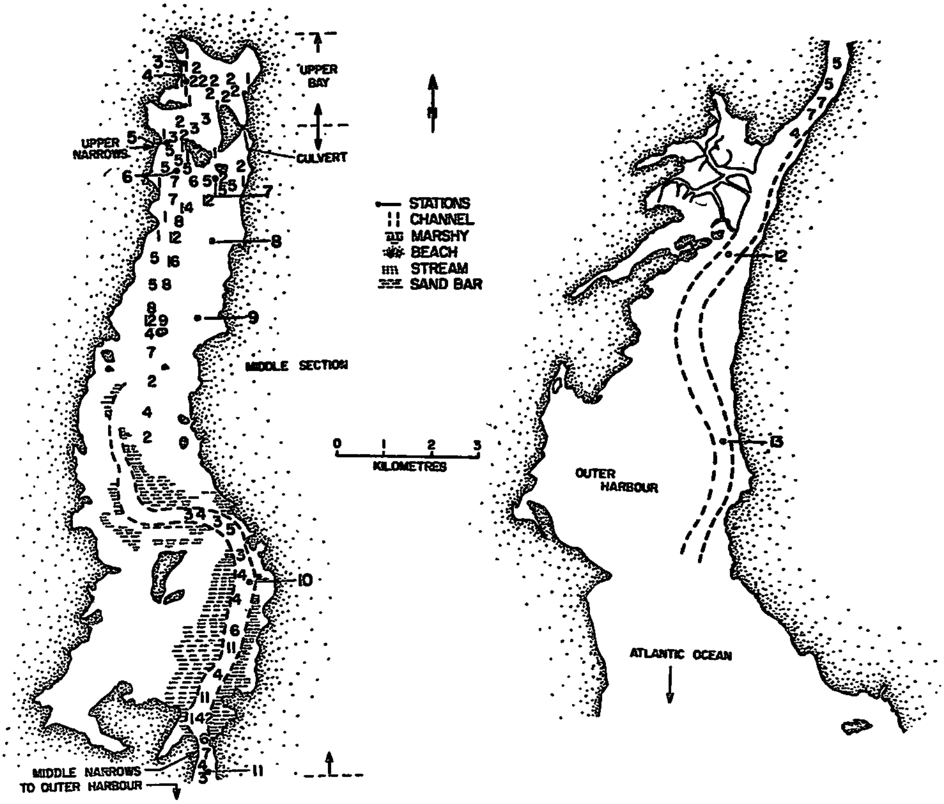
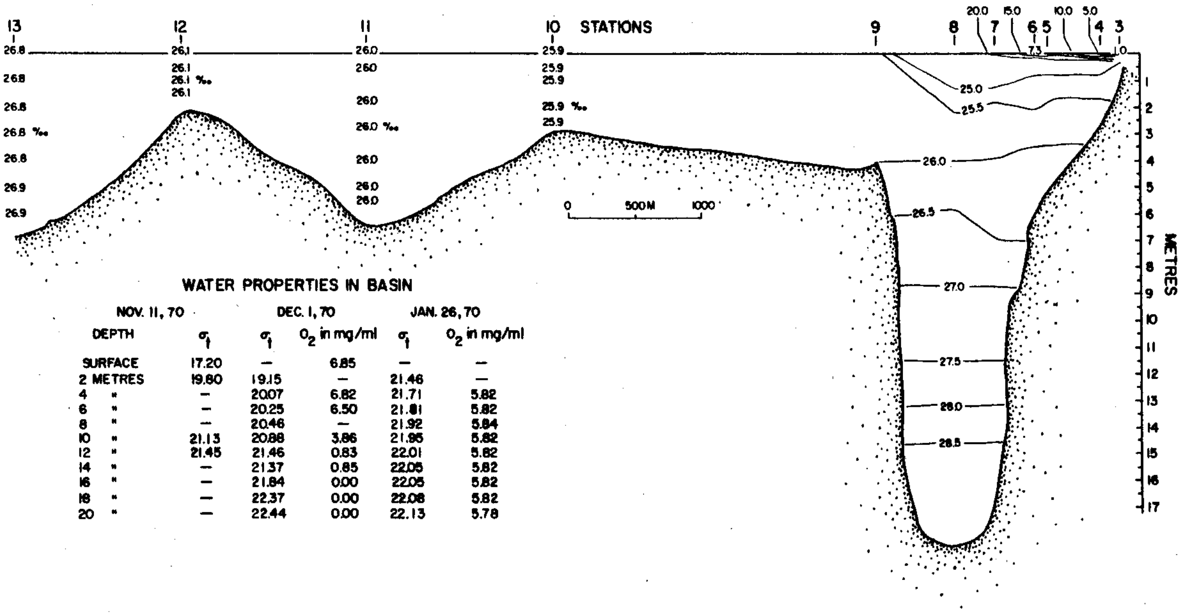
NOTE ADDED IN PROOF:

Mr. R.E. Drinnan, Marine Ecology Laboratory, Dartmouth, Nova Scotia, has pointed out that, with respect to oxygen depletion through addition of nutrients and decay of plant material, the stressed zone is perhaps only potentially stressed; oxygen depletion would be reduced by the grazing activities of both planktonic and benthic filter feeders; copepods, bivalve molluscs, etc.; the latter being especially important in an area with a high rate of water exchange.



Figures 1 and 2

Plan view of Petpeswick Inlet from the head to the Middle Narrows (Fig. 1) to the mouth (Fig. 2) with soundings and station positions relevant to Figure 3.



WATER PROPERTIES IN BASIN

	NOV. 11, 70	DEC. 1, 70		JAN. 26, 70	
DEPTH	σ_t	σ_t	O_2 in mg/ml	σ_t	O_2 in mg/ml
SURFACE	17.20	—	6.85	—	—
2 METRES	19.80	19.15	—	21.46	—
4 "	—	20.07	6.82	21.71	5.82
6 "	—	20.25	6.50	21.81	5.82
8 "	—	20.46	—	21.92	5.84
10 "	21.13	20.88	3.86	21.95	5.82
12 "	21.45	21.46	0.83	22.01	5.82
14 "	—	21.37	0.85	22.05	5.82
16 "	—	21.84	0.00	22.05	5.82
18 "	—	22.37	0.00	22.08	5.82
20 "	—	22.44	0.00	22.13	5.78

Figure 3. Longitudinal Salinity Distribution of Nov. 11, 1970, with Density and Dissolved Oxygen Data for the Basin.

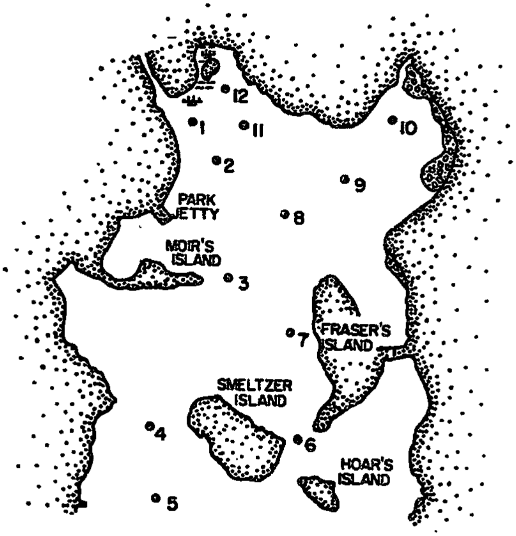


Figure 4a. Plan view of Upper Bay showing location of Salinity Stations relevant to Figure 5.

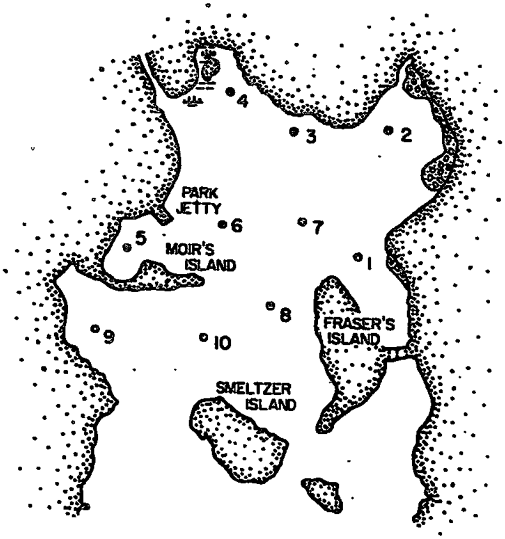


Figure 4b. Plan view of Upper Bay showing locations of "One-Shot" Injections on Nov. 25, 1970.

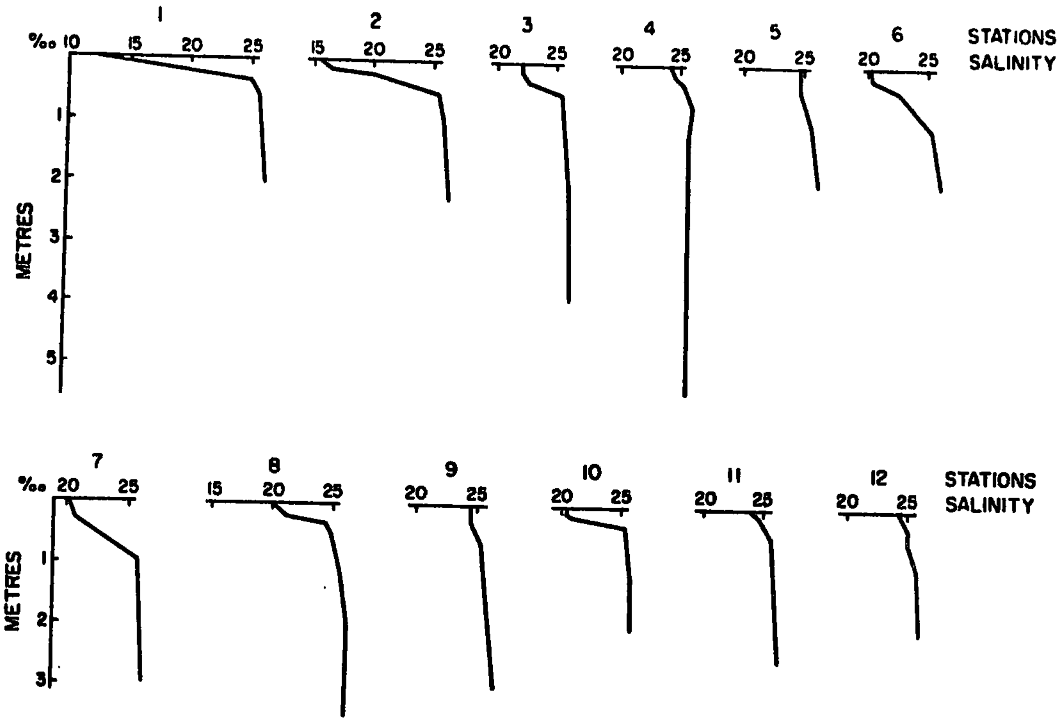
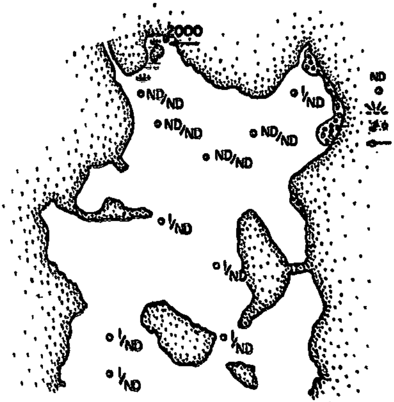
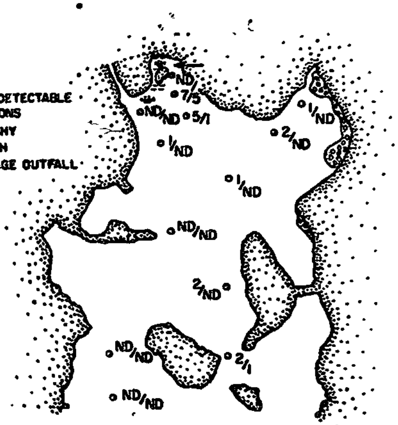


Figure 5. Salinity Profile in Upper Bay during Morning High Water, Nov. 16, 1970

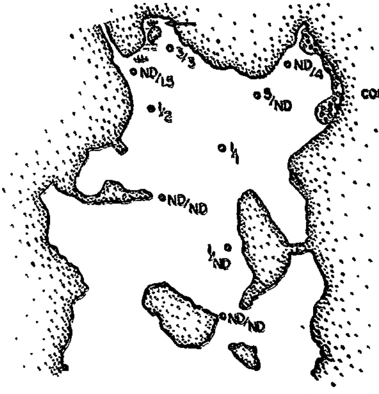


ND NON DETECTABLE
○ STATIONS
MARSHY
BEACH
SEWAGE OUTFALL

6a) Dye Concentrations (from continuous injection), during morning high water, Nov. 15/70

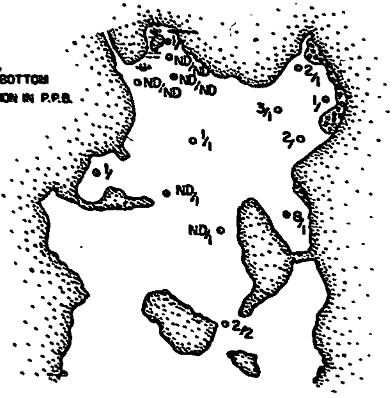


6b) Dye Concentrations (from continuous injection), during morning high water, Nov. 16/70

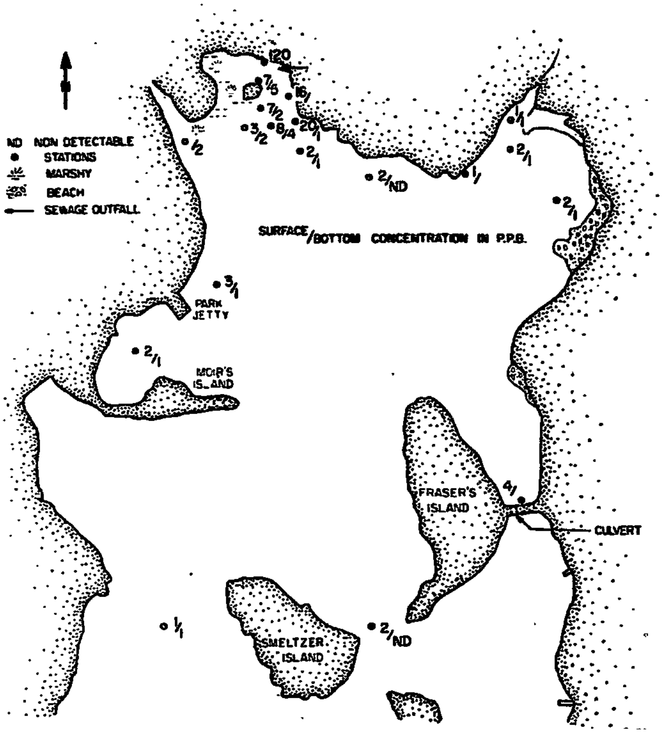


SURFACE/BOTTOM CONCENTRATION IN P.P.B.

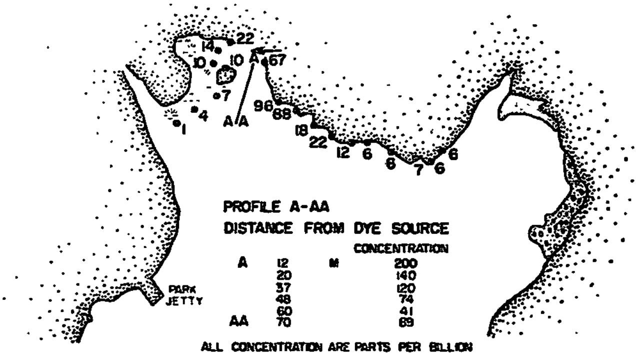
6c) Dye Concentrations (from continuous injection), during afternoon low water, Nov. 15/70



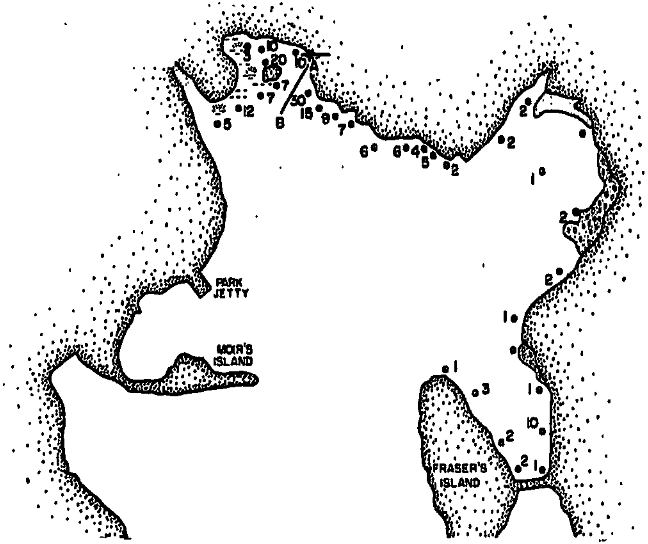
6d) Dye Concentrations (from continuous injection), during afternoon low water, Nov. 16/70



6e) Dye Concentrations (from continuous injection), during Morning High Water. Nov. 17, 1970



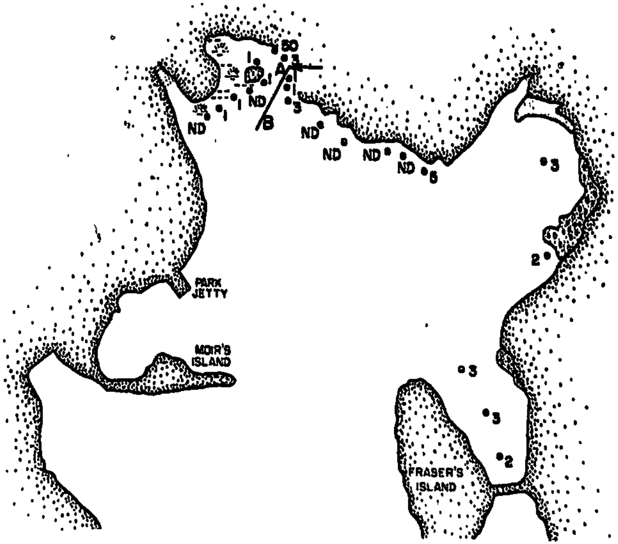
6f) Dye Concentrations (from continuous injection), during Afternoon Low Water. Nov. 17, 1970



6g) Dye Concentrations (from continuous injection), during Morning Rising Tide, Nov. 18, 1970

PROFILE A-B

Distance from A		Concentration	
A	M.	5	P.P.B.
6		15	
12		10	
18		20	
24		9	
31		12	
37		10	
(B) 43		5	



6h) Dye Concentrations (from continuous injection), during Afternoon Ebbing Tide Nov. 18, 1970

PROFILE A-B

Distance from A		Concentration	
3	M.	21.6	P.P.B.
7		2.4	
14		1.2	
21		2.3	
35		ND	
43		ND	