VIRGIN ISLAND BAYS:

MODELING OF WATER QUALITY AND POLLUTION SUSCEPTIBILITY

Island Resources Foundation St. Thomas, Virgin Islands

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by

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ABSTRACT

A pollution susceptibility model is developed to quantify the flushing action of Virgin Island bays. It provides an estimate of the average concentration that results from a unit rate of discharge under "worst case" conditions of low wind and waves when the tide dominates flushing action. Of the four different types of bays, i.e. (1) open, (2) partly-closed, (3) restricted and (4) closed, the closed bays or salt ponds backed by large watersheds are the most susceptible to pollution. By contrast, the open bays with high ocean exchange are the least susceptible. Of the 23 partly-closed bays, Princess Bay, Vessup Bay, Krum Bay, Cruz Bay, Chocolate Hole and Flamingo Bay are more susceptible than other partly-closed bays. A model of the Mangrove Lagoon and Altona Lagoon is developed to predict the distribution of pollutant concentrations that result from different decay rates and different discharge points. A change in evaporation had little effect on the pollutant distribution in the lagoons. The pollution susceptibility model is useful for coastal planning to evaluate the effect of alterations and development around selected bays and to site regional facilities.

1. Introduction

The Virgin Islands are endowed with more than 100 beautiful bays that are one of the territories' important resources. They provide Virgin Islanders with water for desalinization, with protection for harbors and marinas and with fish, a source of food. Formally, the bays provided a source of construction sand or a place to dump wastes. At the same time the bays are pictorially and esthetically diverse. Together with contiguous beaches and reefs, they are attractive to visitors and thus an essential resource for tourism. Additionally, a vast variety of fish spawn and feed in the bays. Like coral reefs, their well-being is modulated by the energies of waves and currents in the bays. As more people are attracted to the bays, more facilities are needed, i.e. more power, docks, sewage facilities, and pressures for development mount. In turn, the useful environmental values of the bays are threatened. Such threats are often accentuated because bay ecology is sensitive to changes. A small change may produce large effects because the water circulation extends the effects to many parts of the bay.

As a result of rapid and unplanned development in the islands between 1968-73, water shortages and pollution have become major problems continuing to the present. The impact of boat sewage pollution, urban pollution, solid waste disposal, dredge and fill activities and stormwater runoff, are mainly reflected in increased turbidity and nutrient loads. Coral reefs and grass beds have been reduced and productive benthic communities replaced with black anoxic mud. If these impacts continue uncontrolled, more problems will be created.

The task now is to balance the economic needs of an expanding population with the quality and health of the environment. That is, to maintain the bays in their natural or best achievable condition. To meet this objective requires rational planning; alternative management options need to be compared, priorities determined and issues solved. In turn, a scientific basis is needed to assess water quality and to provide a means to manipulate and predict from readily available data.

A major problem facing coastal managers who must act on permits, is the siting of facilities as sewage treatment plants, power stations and marinas. The manager or planner needs to know in advance what the impact of these facilities will have on the bay environment. A critical element to the pollution impact is the concentration of pollutants in the water. For example, water quality depends more on the concentration of suspended material in the water than on the rates of input. In turn, the concentration present depends on the flushing efficiency of the water into which the pollutants are discharged.

Flushing along an open coast is greater than in enclosed bays. However, in siting facilities and in evaluating their pollution impact on the environment, it is necessary to have an objective method to quantify and to compare the relative magnitude of flushing and efficiency in different bays.

2. Objectives

The purpose of this study is to analyze the pollution susceptibility of selected Virgin Island bays as a tool for long-term monitoring and management. Specific questions addressed are: How can one predict the pollution susceptibility of the bays? What types of bays are most susceptible to pollution? What zones of selected bays have a high pollution susceptibility? How do the concentrations of pollutants in selected bays relate to the rates at which they are discharged?

3. Status of Information

The water quality and pollution problems of Virgin Island bays have mainly been studied by direct field observations and water sampling. Concentrations of dissolved oxygen and suspended solids, besides temperature, salinity, pH and turbidity indicate the condition of bay water at the time of sampling. Results of monthly and weekly monitoring are given in water quality inventory reports of the Division of Natural Resources Management, Department of Conservation and Cultural Affairs, while results of site studies over the past 10 years are published in more than 20 water pollution reports of the Caribbean Research Institute and the Island

Resources Foundation. Special pollution studies include those of Jacobsen (1951) in selected problem harbors; Candelas (1971) and the Federal Water Pollution Control Administration (1967) in St. Thomas harbor. Surveys of the National Ocean Survey in 1924-1926 and in 1972-1975 provide good bathymetric coverage of many bays along the open coast. Although NOS has occupied more than 10 stations for measurements of tidal height for short periods, current measurements are scarce. In support of NASA-ERTS experiments to determine the utility of space imagery, Colburn _et al_. (1973) measured currents and certain water quality characteristics in St. Thomas Harbor. Since bay waters have short "memories", monitoring and field observations provide data that reflect those processes and inputs active at the time of sampling or during the previous few days or weeks. However, when such data is accumulated over several years, it provides historical "benchmarks" against which new or present-day impacts can be assessed.

In contrast to the available information on the short-term indicators of water quality and pollution, almost nothing is known about long-term predictive indicators that take into account the inputs of pollutants, their flux through the bay and rate of removal. The numerical analyses presented in this report is an initial step toward this end. It is one of several important steps in decision-making processes.

4. Modeling Rationale

Pollutants introduced into a lagoon or coastal embayment are diluted by the receiving water due to turbulent mixing. They are commonly flushed out of the estuary or coastal embayment by the following mechanisms:

(1) displacement by freshwater runoff from the drainage basin,

(2) flushing by tidal currents,

(3) gravitational circulation resulting from a density gradient,

(4) wind and wave induced circulations.

The relative contributions from each of the mechanisms to the pollutant flushing vary not only from water body to water body but also from time to time. In general, the most persistent and steady mechanism over the long-term is tidal flushing.

The magnitude of density gradient in an estuary or coastal bay decreases with relative magnitude of freshwater discharge to tidal flow. When the freshwater runoff is small, not only the net seaward displacement is small but also the gravitational circulation is reduced. The drainage basins of Virgin Island bays are small and, for long periods freshwater runoff into the bays is minimal. Therefore, the first and the third flushing mechanisms are relatively insignificant for Virgin Island bays except for short periods of flood and runoff.

Although the circulation driven by the wind or induced by waves during refraction and breaking dominates flushing of Virgin Island bays, these intermittent mechanisms cannot be counted on for water quality planning and management. Instead, only a model based on tidal flushing which tends to be conservative, is suitable. The tide is the dominate flushing mechanism in protected bays and in restricted lagoons like the Mangrove Lagoon and Altona Lagoon. It is an important mechanism during periods of low wind and waves that create "worst case" flushing conditions for pollution.

A. Tidal Prism Concept

The tidal prism of a bay is the volume of water between the plane of low water and the plane of high water; that is, the intertidal volume. It is derived from the difference between the water volume at high tide and at low tide. In an estuary, part of the volume is contributed by river inflow, and in part by water entering through the seaward entrance on the flood tide. In most Virgin Island bays, river inflow is so small most of the time that the tidal prism consists wholly of seawater brought in by the flood tide. This intertidal volume of water serves to dilute pollutants and eventually flush them out of the bay.

B. Study Approaches

For the purpose of this report the tidal prism concept is applied in different ways:

1. To determine the gross pollution susceptibility or relative response of different bays to a unit discharge. Three types of bays are treated:

   a. Open coastal bay
   b. Partly-closed bay
   c. Closed bay or salt pond

2. To determine the flushing rate and detailed pollution susceptibility or specific response for a range of tidal heights and evaporation conditions in restricted lagoons:

   a. The Mangrove Lagoon, St. Thomas
   b. Altona Lagoon, St. Croix

C. Pollution Susceptibility - Defined

Pollution susceptibility, or unit response, is a simple quantitative measure of the flushing efficiency of a coastal bay (Weyl, 1976). It indicates the concentration distribution of a pollutant that would result from a unit discharge rate. A high pollution susceptibility indicates a slow rate of flushing and dilution, whereas a low susceptibility indicates that the mixing and flushing processes more effectively dilute and remove the pollutant. Pollution susceptibility relates the concentration of a pollutant in an embayment to the rate at which it is discharged or flux, i.e., concentration equals discharge rate (flux) times pollution susceptibility:

$$C = Ps \times F$$

where C is the resultant concentrations; F is the discharge rate or flux and Ps is the pollution susceptibility.

The values of pollution susceptibility may be expressed as a mass fraction, i.e. mass of pollutant per unit mass of water. As such it is a dimensionless number, and consequently the dimension of the pollution susceptibility is the reciprocal of the flux or discharge rate per unit mass.

Concentration values of pollution susceptibility may be expressed in parts per billion. As the flux is expressed in metric tons per day, then the pollution susceptibility is the reciprocal of the volume in cubic kilometers into which the daily discharge is dispersed. Thus, values span a range from about 0.1 to 100.

The pollution susceptibility parameter predicts the time and space variation that would result from a hypothetical discharge of a pollutant. It provides the relative response of different bays within one bay type to a unit discharge. For comparison of bays both the temporal variations and the concentrations over a fixed area near the source are necessarily averaged out.

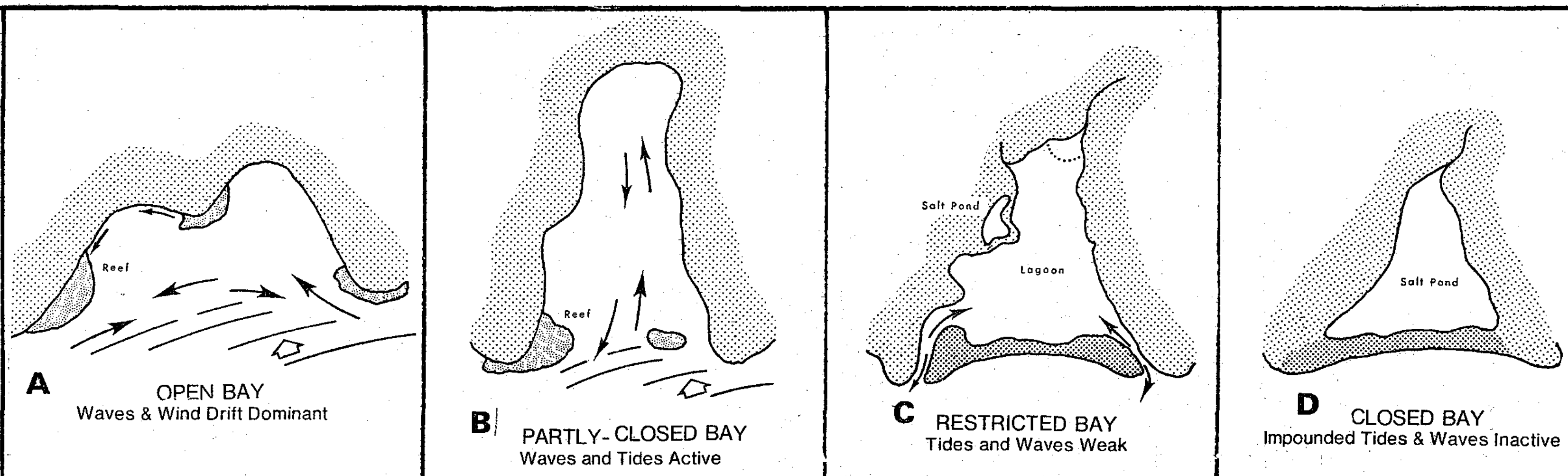
5. Types of Virgin Island Bays

More than 100 bays indent the coastline of the Virgin Islands. Some are broad and open to the sea and others are partly sealed off from the sea. They form where the islands has been carved into stream valleys and subsequently drowned by a relative rise of sea level in the last 5000 years. The ridges or hilltops between valleys now form headlands, peninsulas or islands which project into the sea between the bays. By attack on the headlands, waves have not only modified many of bays but built barriers across their entrances. A few bays are partly enclosed by mangroves while others are partly restricted by submerged coral reefs.

Commonly, the bays evolve from an open embayment toward partial closure and thence into an impounded lagoon or salt pond. Figure 1 summarizes schematically the different types of Virgin Island bays that vary with closure. There are two extreme types, one represented by a wholly open bay and the other by a wholly closed bay or salt pond. In between there is a virtual spectrum of types and shapes according to the degree of closure.

A change in closure can have a profound effect on the water quality and flushing behavior of a bay. In an open bay (Figure 1A) wave mixing, wind drift or coast-parallel currents are relatively strong. Such processes promote high bay-ocean exchange and in turn, rapid flushing.[1] As a result, water quality is excellent; most parameters range within narrow limits at levels close to those of ocean water. By contrast in a restricted bay or lagoon (Figure 1C), tides, waves and wind drift are weak. In turn, exchange with the ocean is poor, flushing is slow, and bay water is affected by freshening and sediment influx. Resulting water quality is poor; most parameters range within wider limits than in the ocean and they attain levels which differ from ocean water. Partly-closed bays have intermediate characteristics whereas salt ponds have extreme ranges and virtually no flushing.

[1]Flushing per unit volume of water.



HIGH ← WAVES & WIND DRIFT — LOW

MODERATE ← TIDES — WEAK

	A	B	C	D
Dominate Processes	Waves, wind drift, const-parallel currents	Tidal currents in and out	Tides and waves Weak, internal waves & wind mixing	Tides and waves inactive
Ocean-Bay Exchange	High	Intermediate	Low	No surface exchange
Flushing Efficiency	Rapid	Moderate	Slow	Sporadic storms only

Figure 1. Different types of Virgin Island bays in a sequence organized according to closure, dominate processes and flushing efficiency.

A. Enclosure Index

To distinguish between an "open-bay" and a "partly-closed bay", an enclosure index was developed. This consists of a ratio between the distance along a chord across the mouth of the bay as drawn between headlands, and the perimeter of the bay. A ratio of 0.60 or greater is taken as an "open bay" and a ratio between 0.60 and 0.06 is taken as a "partly-closed bay". Ratios of 0.06 and below are considered restricted bays or lagoons. Different modeling procedures are necessary to determine the pollution susceptibility of the different types of bays.

6. Open Bays

Pollution susceptibility of open bays along the coast i.e. bays with an enclosure index of 0.60 or greater can be estimated if tidal current data are available. Current measurements must be free of wind and wave drift; i.e. taken during a period of calms. The procedures are applicable to flow directed parallel to the coast, i.e. through a section extending 0.5 km normal to the coastline. The pollution susceptibility is the reciprocal of the mean daily flow through the section regardless of current direction (Weyl, 1974).

The space scale over which the concentrations are averaged is empirical. However, it is consistent from bay to bay and compatible with the purpose of coast-wide planning. It is intended to determine the far-field impacts on bays rather than near-field affects around outfalls. It is assumed that a pollutant is uniformly dispersed through the water column to 0.5 km offshore. Figures 2 and 3 give the bays of appropriate size and openings that are treated in this report together with the scheme of segmentation used.

A. Numerical procedures:

The following procedures are used for open bays.

a. Determine the average depth in meters out to a distance of 0.5 km from the shore.

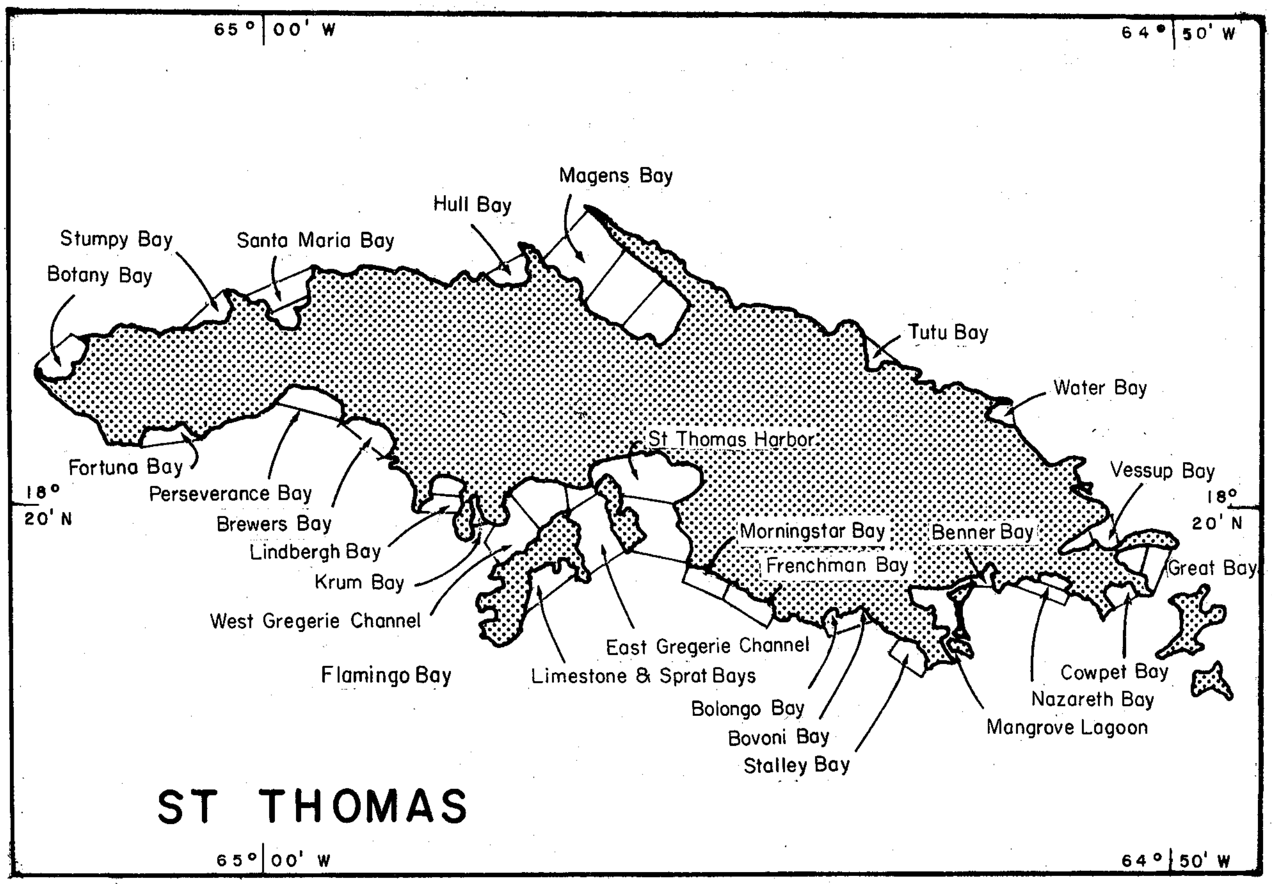
b. The average peak current speed of the tidal current is determined.
For this study measurements were obtained during a 4-day period of calms January 26-30, 1979 and supplemented by measurements previously obtained (Nichols and Towle, 1977), NOS (file data, 1972) and Colburn (1973) along the coast of St. Thomas. Measured values are given in Table 1. Tidal current data for St. John and St. Croix are lacking or inadequate.

c. Obtain the product of the average depth and current speed. For example, in central Perseverance Bay the average depth is 9.6 m or 9.6^{10-3} km. The average tidal current speed is 7.8 cm per sec or 0.078^{10-3} km per sec or (x86,400 = sec per day) 6.74 km per day, and the product is 64.7^{10-3} km^2 per day. For total flow under the line multiply by the line length 0.5 km and one obtains 32.3^{10-3} km^3 per day.

d. Determine the pollution susceptibility by taking the reciprocal of total flow; e.g.

$$\frac{1}{32.3^{10-3}\ km^3 \text{ per day}} = 31$$

A pollution susceptibility value of 31 means that when a conservative pollutant is discharged at the rate of 1 ton per day and is uniformly dispersed through bay water out to a distance of 0.5 km from shore, it would result in an average concentration of 31 ppb.



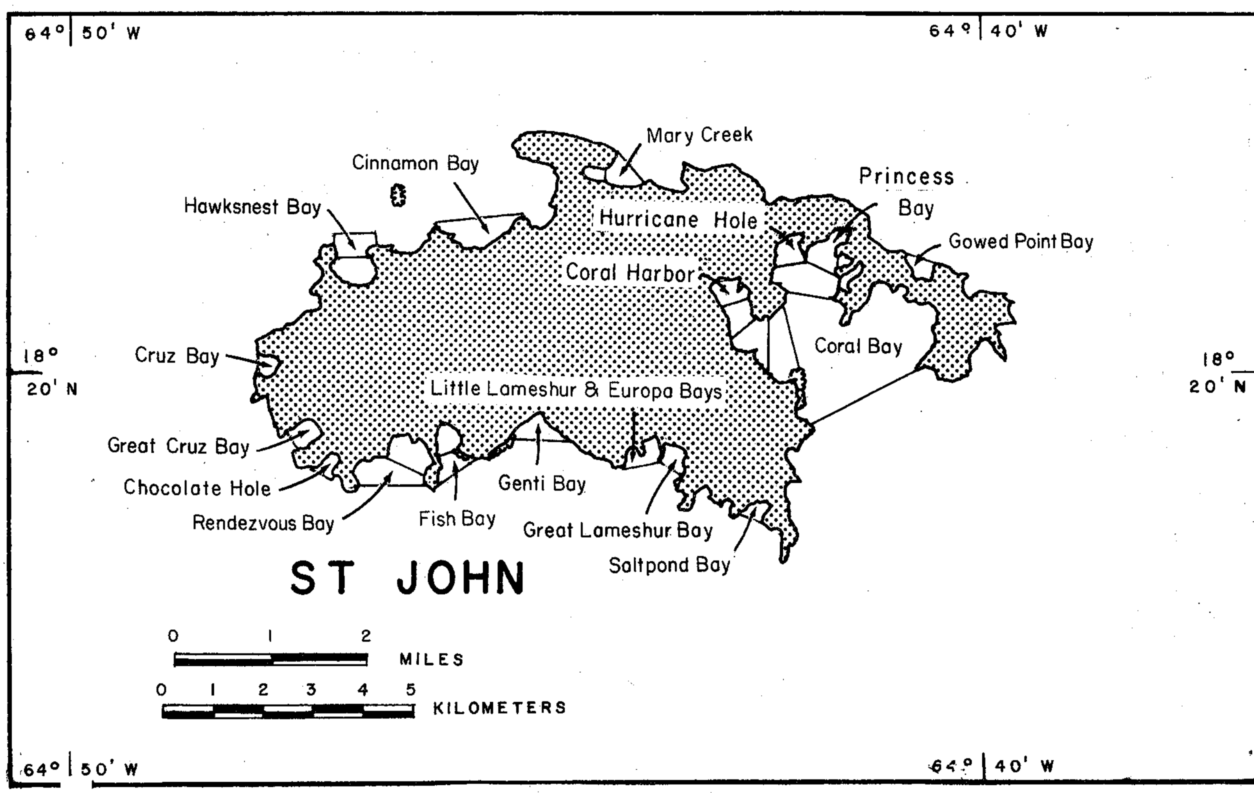


Figure 2 (Upper). Location and segmentation of bays, St. Thomas.

Figure 3 (Lower). Location and segmentation of bays, St. John.

B. Results and Evaluation

Of the seven open bays along the south coast of St. Thomas, Moringstar Bay with a value of 1.3 has the highest pollution susceptibility. By contrast, Fortuna Bay, Bolongo and Bovoni Bay and Stalley Bay, with their relatively great mean depths and moderate current speeds, have low pollution susceptibility. Values for all the open bays, which range from 0.2 to 1.3, Table 1, have been normalized by a factor of 0.01 to allow comparison with values of partly closed bays. In general, difference among the open bays is small and flushing by coast-parallel tidal currents is good.

The treatment assumes that the water that passes the 0.5 km long section has not previously been polluted by the pollutant. This assumption holds so long as the period of discharge is limited to either ebb or flood and that the discharge is short-term (less than one-half tidal cycle). For long periods there is likely to be a return and recirculation of "old" partly polluted water which places an added burden on the bay. In the bays treated, the fraction of old returning water is most likely small. Regional facilities should preferably be sited on well-flushed open bays.

Partly-Closed Bays

A. Modeling Approach

Because the concentration of a pollutant in bay waters varies from full strength at the discharge point to zero in the ocean an infinite distance away, an "average" concentration is calculated in segments over a fixed distance. For Virgin Island bays a distance of 0.5 km is used as an appropriate scale over which to average concentrations. Although this scale is arbitrary, it is possible to segment the bays with the seawardmost line representing a chord drawn between headlands. See Figure 2-3 for the segmentation scheme used in this study. A few bays like Mandel Bay were too small for 0.5 km segmentation and therefore they are not included in this analyses. Nonetheless, application of the procedure is consistent and thus makes possible comparison of pollution susceptibility from bay to bay for the purpose of regional planning.

Once the bays are subdivided into a number of segments on a tographic map (1:24,000 scale with nearshore bathymetry) or a large scale NOS hydrographic chart, it then remains to determine the volume of the bay, its tidal prism and tidal water motions based on the tidal amplitude and phase.

B. Numerical Procedures

For each segment of the bay, or the entire bay where the bay consists of one segment, the following parameters are determined:

1. The surface area of the bay in square kilometers at mid-tide by counting squares on a transparent grid or by a planimeter

on the most suitable chart available.

2. The average tide range for the bay as based on the nearest NOS tide station, Figures 4, 5. Reduce tide ranges from feet to meters by multiplying the values in feet by 0.305.

3. The tidal prism in km^3 by obtaining the product of the tide range (in km) and the bay area (in km^2).

4. The average phase of the tide, p. Assume a diurnal tidal period of 24.8 hours then $\frac{24.0 \text{ hrs.}}{24.8 \text{ hrs.}} = 0.97$ tides per day and the motion of the water in two directions (ebb and flood) is 2 times 0.97 or 1.94 tides per day.

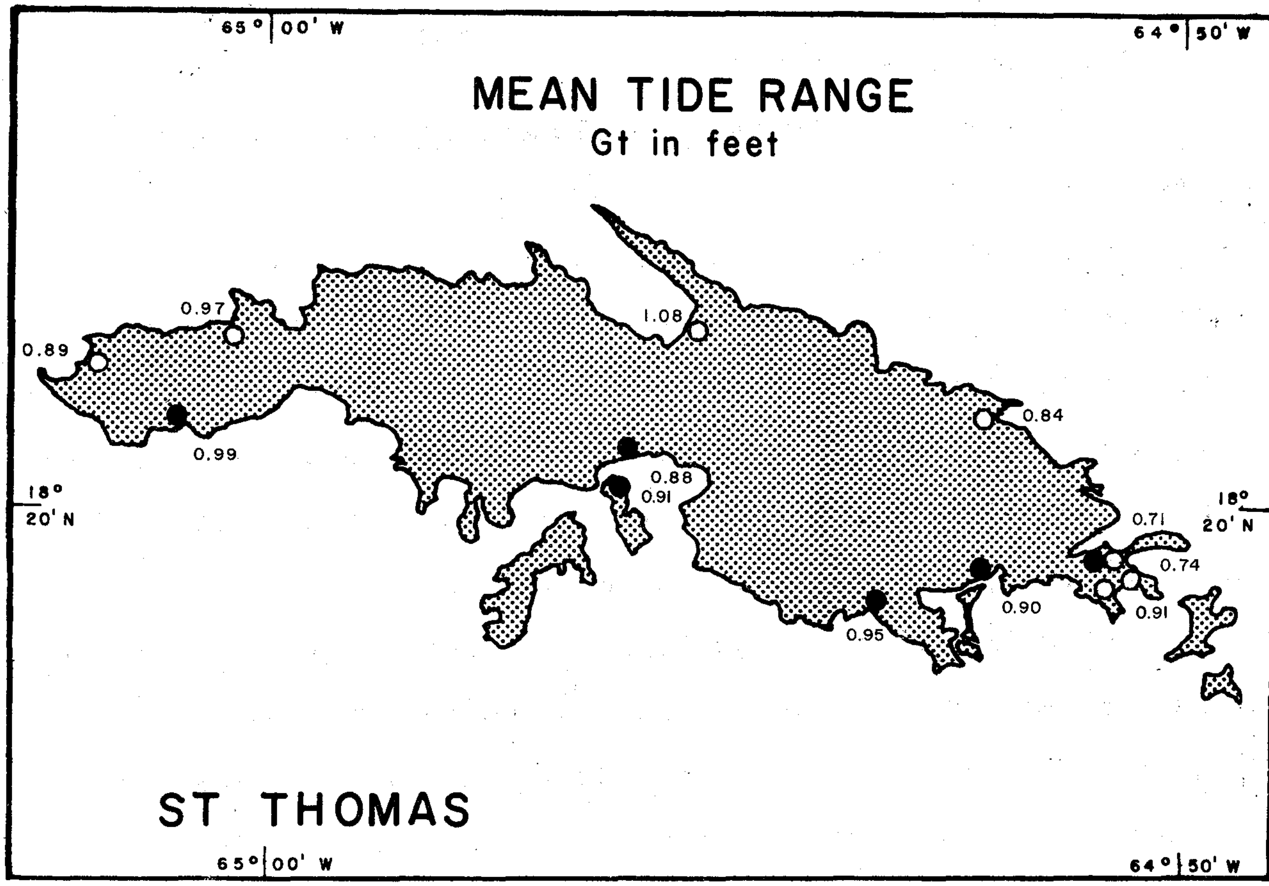
5. The daily discharge or flux of water in the bay is 1.94 times the tidal prism.

6. The pollution susceptibility in the segment is equal to the reciprocal of the water flux in km^3 per day that passes within 0.5 km of the bay head, e.g. divide one by the flux value.

   The instantaneous flow into a segment plus the change in water capacity must equal the flow out. Where there is no change in phase, then the amplitude of the outflow equals the sum of the inflow plus the flow driven by the tidal variations of water level in the segment.

   For successive segments compute the sine and casine components of the tidal flux in each segment, i.e. the total flux is the square root of the sums of the squares of the components following Weyl (1974).

An estimate of the flushing time is obtained by the tidal prism method (Dyer, 1973). In this method, water entering on the flood tide is assumed to become fully mixed with that inside the bay and that on the ebb the same volume of water is removed. If V is the low tide volume and P is the tidal prism then the flushing time in tidal cycles is: $T = \frac{V + P}{P}$



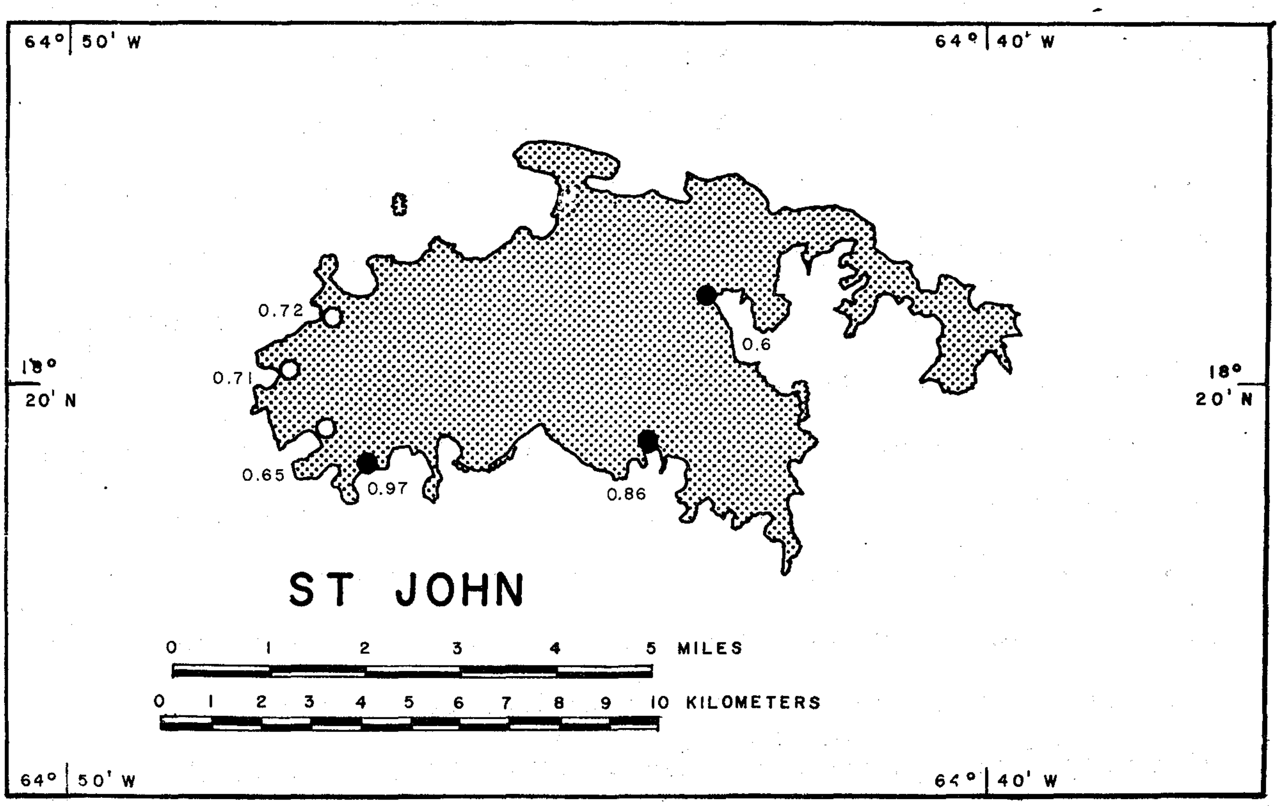


Figure 4 (Upper). Location and mean range of the tide, St. Thomas.

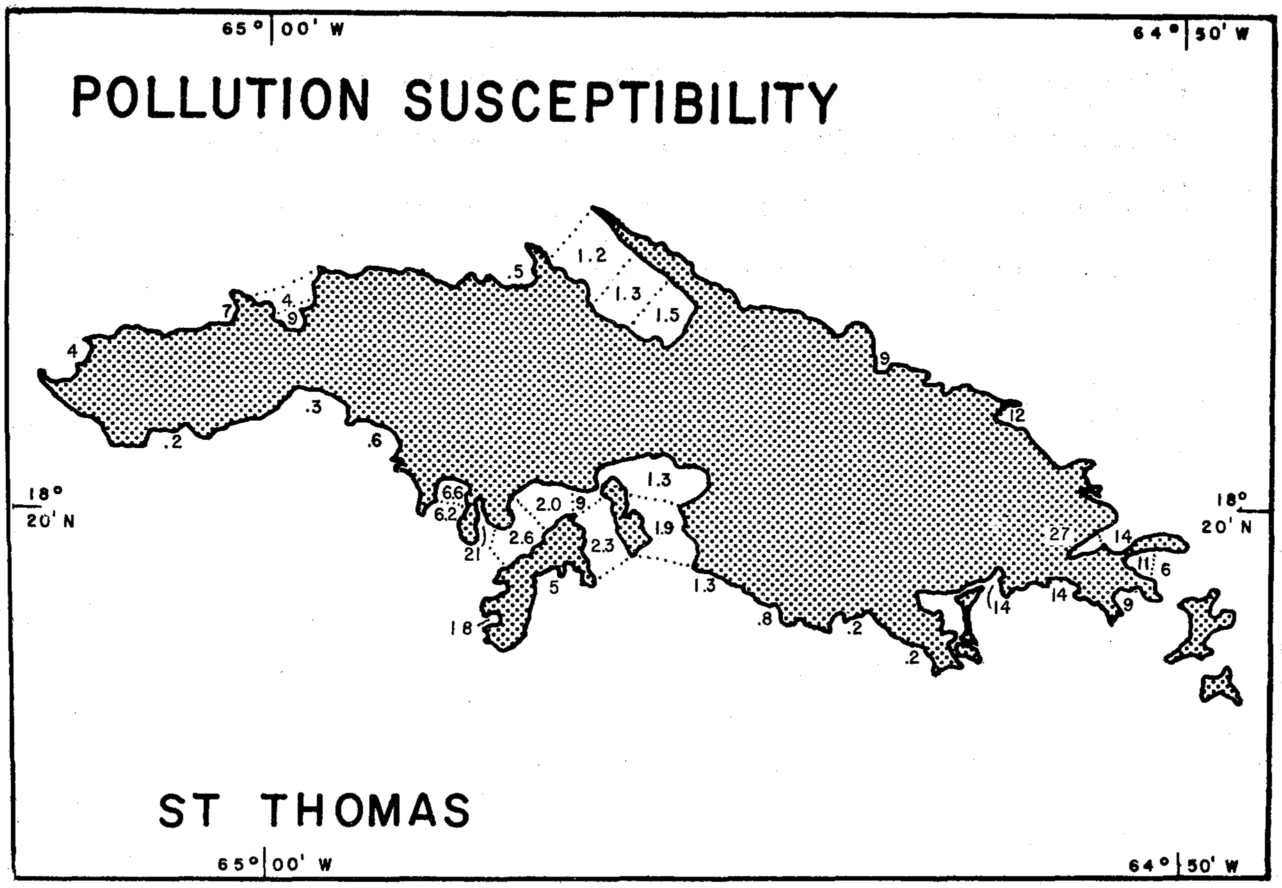
Figure 5 (Lower). Location and mean range of the tide, St. John, from NOS file data.

C. Results and Evaluation

Of the twenty three partly-closed bays along the south or "lee" coast of St. Thomas and St. John, Princess Bay has the greatest pollution susceptible with a value of 28 (Table 1, Figures 6 & 7). This is a small bay with inner backwaters and substantial enclosure. The next most susceptible bays are Cruz Bay, Krum Bay, plus Chocolate Hole and Flamingo Bay with values of 18 and 19. By contrast, the outer reaches of Coral Bay and all of St. Thomas Harbor have relatively low susceptibility values suggesting that these bays are relatively well flushed by the tides. All the north coast bays have relatively low or moderate susceptibility values except inner reaches of Vessup Bay which has a value of 27. This is a shallow elongate bay having backwaters with a high density of boats. It is no wonder that water quality is poor.

The derivation of pollution susceptibility is based only on tidal data and geometric characteristics of the bays. It is not based on explicit observations of mixing processes. Errors may occur in areas of non-uniform mixing as produced by reefs and bottom irregularities.

In a long bay like Magens Bay whose length is greater than the tidal excursion, recirculation will range from a small amount near the mouth to a great amount near the head. However, the pollution susceptibility values are useful as we only consider discharges or short periods. For planning discharges of a continuous nature, as for sewage or thermal



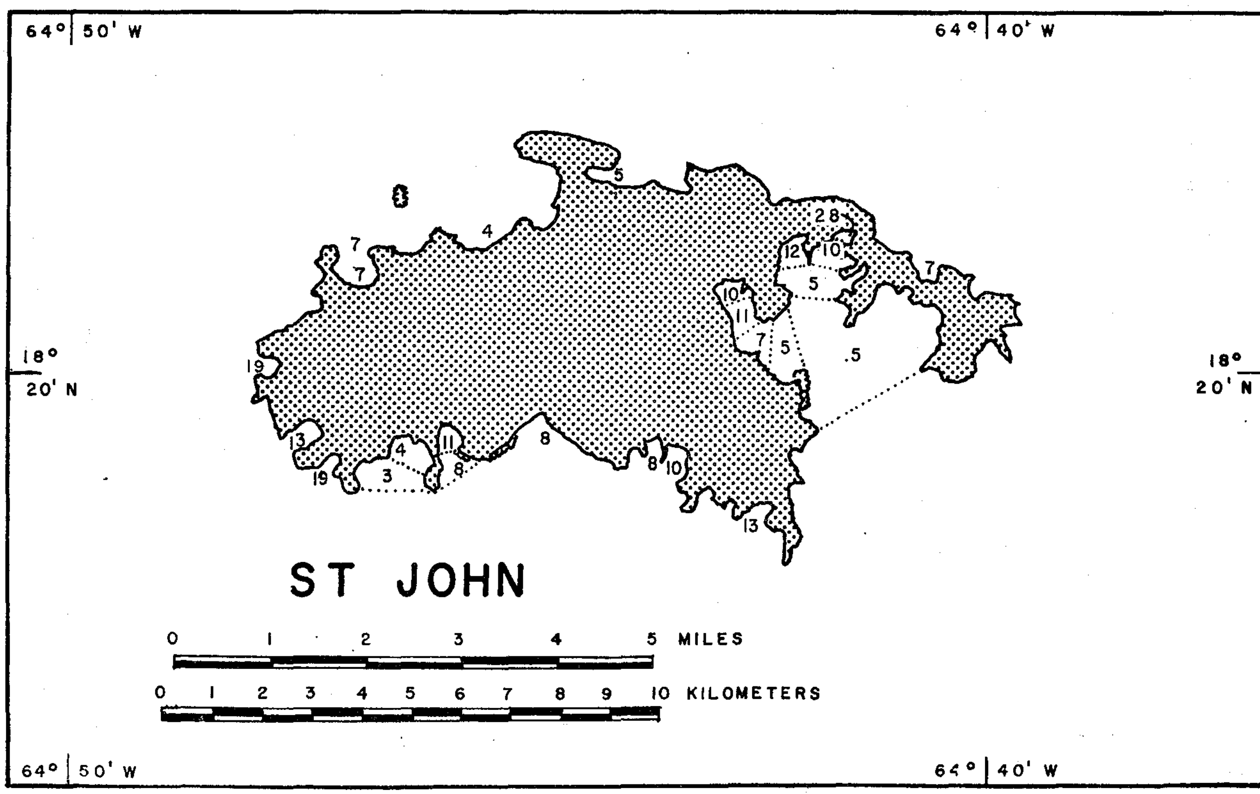


Figure 6 (Upper). Pollution susceptibility values for bays around St. Thomas.
Figure 7 (Lower). Pollution susceptibility values for bays around St. John.

facilities, it is necessary to consider a steady-state treatment (Weyl, 1974). Verification of the pollution susceptibility values obtained is limited by the lack of tidal current observations over a tidal cycle.

D. Applications for Management

The distribution of pollution susceptibility values in the large or elongate bays typically show a increase from the seaward end of the bay toward the landward end. For example in the Coral Bay system values range from 0.5 to 28; and in Vessup Bay from 14 to 27. In the past the land use implications of these changes have been ignored inasmuch as most waterfront development and facilities are concentrated at the landward ends of the bays where pollution susceptibility is greatest. Development was guided by harbor protection and transportation access to towns or plantations.

Where developments as condominiums are planned, the distribution of clusters and open space should take into account the gradients of pollution susceptibility. Areas near bay heads should remain undeveloped whereas potential pollutant facilities should be sited in seaward areas of lower susceptibility. In turn, future transportation arteries should be planned to provide access to areas of low susceptibility and avoid areas of high susceptibility.

The distribution of pollution susceptibility values provides a tool for broad planning which should be supplemented by more detailed studies. Thus, the values permit one to compare bays and broad areas within a bay where a facility or development would produce the minimum or maximum impact. But to select a specific site or optimum configuration requires more detailed on site studies. Nonetheless, the pollution susceptibility distributions enable a coastal planner to be more objective and discriminating in his recommendations.

Table 1. Hydrographic Data and Pollution Susceptibility of Virgin Island Bays

St. Thomas South Coast	Enclosure Index ℓC/ℓ2	Bay Type	Mean Depth m	Bay Area[1] km^2	Tidal Height Range $km\ 10^{-4}$	Tidal Prism $km^3\ 10^{-5}$	Bay Volume[2] $km^3\ 10^{-3}$	Average Tidal Current $km\ 10^{-3}/sec$	Flux $km^3/day\ 10^{-4}$ Segments	Flux Total	Pollution Susceptibility, ppb Segments	Pollution Susceptibility, ppb Total	Flushing Time in Tidal Cycles
Fortuna Bay	.66	Open	10.7	0.302	3.02	9.12	3.23	0.094	-	-	-	0.2	37
Perseverance Bay	.74	Open	9.6	0.703	3.02	21.2	6.74	0.078	-	-	-	0.3	33
Brewers Bay	.68	Open	5.8	0.448	3.02	13.5	2.59	0.064	-	-	-	0.6	20
Lindbergh Bay A	-	Partly	5.2	0.273	2.84	7.75	1.42		1.50		6.6		
B	.31	Closed	7.8	0.291	-	8.26	2.27		1.60		6.2	3.2	23
Krum Bay	.30	Partly Closed	3.7	0.088	2.84	2.50	0.32			0.48		20.8	17
West Gregerie Channel A	-	Partly	5.8	0.937	2.77	25.90	5.43		5.02		2.00		
B	.13	Closed	10.4	0.709	-	19.60	7.37		3.80		2.63	1.1	30
East Gregerie Channel A	-	Partly	7.9	0.206	2.77	5.71	1.63		1.11		9.00	1.8	32
B	.13	Closed	8.8	0.807	2.77	22.40	7.10		4.35		2.30		
St. Thomas Harbor A	-	Partly	6.7	1.496	2.65	40.10	10.02		7.78	13.10	1.28	0.7	27
B	.11	Closed	7.3	1.015		27.20	7.41		5.28		1.89		
Limestone & Sprat Bay	.46	Partly Closed	4.3	0.363	2.65	10.30	1.56			2.00		5.0	16
Flamingo Bay	.17	Partly Closed	1.5	0.100	2.65	2.65	0.15			0.56		17.8	9
Morningstar Bay	.89	Open	5.8	0.390	2.68	10.45	2.26	0.030	-	-	-	1.3	23
Frenchman Bay	.74	Open	5.5	0.400	2.68	10.72	2.20	0.050	-	-	-	0.8	21
Bolongo & Bovoni Bay	.61	Open	7.5	0.378	2.70	10.21	2.80	0.18	-	-	-	0.2	29
Stalley Bay	.74	Open	10.1	0.485	2.72	13.19	4.91	0.09				0.2	37
Mangrove Lagoon	.05	Restricted	1.3	0.614	2.75	16.90	0.79			3.28		3.0	29
Benner Bay	.25	Partly Closed	1.3	0.136	2.75	3.74	0.18			0.73		13.7	6
Nazareth Bay	.57	Partly Closed	7.0	0.131	2.75	3.60	0.92			0.69		14.3	26
Cowpet Bay	.34	Partly Closed	5.0	0.197	2.77	5.46	0.98			1.06		9.4	18

[1] Area of segments at a distance of 0.5 km from the bay head.

[2] Volume below mean low water

[A] Area for inner segment, 0 to 0.5 km

[B] Area for outer segment, 0.5 to 1.0 km

[C] Area for seaward most segment, 1.0 to 1.5 km

Table 1. (Cont'd). Hydrographic Data and Pollution Susceptibility of Virgin Island Bays

St. John North Coast	Enclosure Index ℓC/ℓ2	Bay Type	Mean Depth m	Bay Area[1] km^2	Tidal Height Range km 10^{-4}	Tidal Prism km^3 10^{-5}	Bay Volume[2] km^3 10^{-3}	Perimeter km; ℓ2	Flux km^3/day 10^{-4} Segments	Flux Total	Pollution Susceptibility, ppb Segments	Pollution Susceptibility, ppb Total	Flushing Time in Tidal Cycles
Hawksnest Bay A			12.2	0.348	2.20	7.65	4.24	2.43	1.48		6.7		
Hawksnest Bay B	.18	Partly Closed	9.0	0.339	2.20	7.45	3.05	1.93	1.44		6.9	3.4	49
Cinnamon Bay	.20	Partly Closed	9.0	0.515	2.30	11.84	4.63	3.17	2.29			4.4	39
Mary Creek A		Partly Closed	9.2	0.095	2.75	2.53	0.87	1.30	0.49		2.0		
Mary Creek B	.23	Partly Closed	8.0	0.256	2.75	7.04	2.05	2.54	1.37		7.3	5.4	33
Gowed Point Bay	.48	Partly Closed	6.1	0.275	2.75	7.56	1.68	1.41	1.47	1.47		6.8	25
St. Thomas North Coast													
Botany Bay	.41	Partly Closed	8.2	0.47	2.71	12.70	3.85	2.28		2.46	4.1	4.1	31
Stumpy Bay	.61	Open	4.9	0.257	2.71	6.96	1.26	1.75		1.35	7.4	7.4	19
Santa Maria Bay A		Partly Closed	4.9	0.194	2.96	5.74	0.95	2:4	1.11		9.0		
Santa Maria Bay B	.38		10.7	0.501	2.96	14.80	5.36	4.1	2.87		3.5	3.9	32
Hull Bay	.58	Partly Closed	3.0	0.319	3.02	9.63	0.96	1.56		1.86		0.5	12
Magens Bay A	.33	Partly Closed	6.1	1.022	3.29	33.60	6.23	4.09	6.52		1.5		
Magens Bay B			10.4	1.297	3.29	42.70	13.49	3.42	8.28		1.2		
Magens Bay C	.12	Partly Closed	14.3	1.239	3.29	40.80	17.73	3.73	7.92		1.2	0.5	33
Tuta Bay	.54	Partly Closed	9.7	0.210	2.84	5.96	2.04	1.62		1.16		8.6	35
Water Bay	.34	Partly Closed	4.1	0.167	2.56	4.27	0.68	1.26		0.83		12.1	18
Vessup Bay A			0.9	0.089	2.17	1.93	0.08	1.15	0.37		27.0		
Vessup Bay B	.23	Partly Closed	3.4	0.169	2.17	3.67	0.57	2.56	0.71		14.1	6.3	13
Great Bay A			4.6	0.206	2.26	4.66	0.95	1.33	0.90		11.1		
Great Bay B	.28	Partly Closed	7.0	0.357	2.26	8.07	2.50	3.07	1.57		6.4	4.2	27

Table 1. (Cont'd). Hydrographic Data and Pollution Susceptibility of Virgin Island Bays

St. John South Coast	Enclosure Index ℓC/ℓ2	Bay Type	Mean Depth m	Bay Area[1] km^2	Tidal Height Range $km\,10^{-4}$	Tidal Prism $km^3\,10^{-5}$	Bay Volume[2] $km^3\,10^{-3}$	Perimeter km; ℓ2	Flux $km^3/day\,10^{-4}$ Segments	Flux Total	Pollution Susceptibility, ppb Segments	Pollution Susceptibility Total	Flushing Time in Tidal Cycles
Cruz Bay	.20	Partly Closed	2.8	0.126	2.17	2.73	0.35	1.48		0.53		18.8	13
Great Cruz Bay	.31	Partly Closed	1.8	0.196	1.98	3.88	0.35	1.39	1.39	0.75		13.3	10
Chocolate Hole	.35	Partly Closed	4.3	0.122	2.17	2.65	0.52	1.21		0.51		19.4	18
Rendezvous Bay A	.29	Partly Closed	4.9	0.379	2.96	11.20	1.85	4.26	2.17		4.6		
Rendezvous Bay B			8.8	0.607	2.96	18.00	5.34		3.49		2.8	1.7	25
Fish Bay A	.21	Partly Closed	1.5	0.167	2.90	4.84	0.25	2.99	0.94		10.6		
Fish Bay B			3.9	0.227	2.90	6.58	0.88		1.28		7.8	4.5	11
Genti Bay	.82	Open	3.0	0.285	2.65	7.55	0.86	1.56		1.28		7.8	13
Little Lameshur & Europe Bays	.34	Partly Closed	9.0	0.258	2.62	6.76	2.32	1.92		1.31		7.6	34
Great Lameshur	.34	Partly Closed	8.8	0.202	2.62	5.29	1.78	1.44		1.03		9.7	37
Saltpond Bay	.43	Partly Closed	6.2	0.166	2.47	4.10	1.03	1.35		0.79		12.6	26
Coral Bay Harbor A	.22	Partly Closed	2.0	0.268	1.83	4.90	0.54	2.64	0.95		10.5		
Coral Bay Harbor B			6.1	0.248	1.83	4.54	1.51	2.73	0.88		11.3		
Coral Bay Harbor C			9.2	0.401	1.83	7.34	3.69	2.48	1.42		7.0		
Coral Bay Harbor D	.12	Partly Closed	9.0	0.549	1.83	10.05	4.94	3.49	1.90		5.3	1.9	40
Hurricane Hole	.32	Partly Closed	5.8	0.226	1.83	4.13	1.31	1.62	0.80		12.5		34
Princess Bay A	.17	Partly Closed	2.0	0.108	1.83	1.98	0.22	1.39	0.36		27.7		
Hurricane Hole B			15.0	0.288	1.83	5.27	4.32	2.00	1.02		9.8		
Hurricane Hole C			24.0	0.629	1.83	11.51	15.10	3.26	2.23		4.5		
Coral Bay D			24.3	5.189	1.83	94.96	26.12	11.32	18.42		0.5	0.5	125
Water Creek	.11	Partly Closed	6.0	0.101	1.83	1.85	0.61	1.94	3.59			2.7	31

8. Restricted Bays and Lagoons

A. Modeling Approach and Assumptions

1. Inlets. The dynamics of tidal flow through inlets into bays has been studied by many investigators (King, 1974). Perhaps the best known is the one by Keulegan in 1951. Later investigators recognized that, due to the large number of assumptions, the Keulegan model gave accurate results for only a few inlets. Therefore, they extended his equations, however, but only solved these equations for one or a limited number of cases.

King (1974) employed a shallow water wave model to investigate the surface elevation and discharge in canals and bays that are interconnected to the ocean by multiple inlets. Using this model, King arrived at closed form solutions which may be applied to many inlets. The equations of continuity and motion were solved in terms of canal end conditions, an inlet equation was developed where the discharge is a function of the tide inside the inlet and the ocean tide:

$$q(t) = \frac{Ag}{L(\omega^2 + \lambda^2)} \left(a_o \lambda \cos(\omega t+\alpha) + a_o \omega \sin(\omega t+\alpha) - a_1 \lambda \cos(\omega t+\beta) - a_1 \omega \sin(\omega t+\beta) \right) \quad \text{(I-1)}$$

where

q(t) is discharge in an inlet,

t is time,

A is inlet cross-sectional area,

g is gravitational acceleration,

L is length of inlet,

a_o is amplitude of ocean tide,

α is phase of ocean tide,

a_1 is amplitude of the tide inside the inlet,

β is phase of the tide inside the inlet,

$\lambda = \frac{f}{3\pi RA} q_m$ is the linearized friction parameter,

f is Darcy-Weisbach friction coefficient,

R is depth or hydraulic radius of inlet,

q_m is amplitude of inlet discharge q.

Equation (I-1) is a sinusoidal function of time and may be written as

$$q(t) = q_m \sin(\omega t + \theta) \tag{I-2}$$

with

$$q_m = \frac{Ag}{L\sqrt{\omega^2 + \lambda^2}} \left[(a_o\cos\alpha - a_1\cos\beta)^2 + (a_o\sin\alpha - a_1\sin\beta)^2\right]^{\frac{1}{2}} \tag{I-3}$$

and

$$\theta = \sin^{-1}\frac{\lambda}{\sqrt{\omega^2 + \lambda^2}} + \sin^{-1}\frac{a_o\sin\alpha - a_1\sin\beta}{\left[(a_o\cos\alpha - a_1\cos\beta)^2 + (a_o\sin\alpha - a_1\sin\beta)^2\right]^{\frac{1}{2}}} \tag{I-4}$$

2. Tidal prism considerations. The tidal prism concept has been used to evaluate the ability of a bay to disperse pollutants (Ketchum, 1951 a,b). The tidal prism is equal to the difference between water volumes at high and low tides. In a river estuary, part of this volume is contributed by river flow and part by water which enters through the seaward boundary on the flooding tide. In a small coastal bay, the contribution of river water is often so small that the tidal prism consists wholly of the water brought in by the flood tide. This intertidal volume of water serves to dilute pollutants and eventually flush them out of the bay.

The objective of this modeling phase is to calculate the equilibrium distribution of introduced pollutants. During each tidal cycle, the pollutant concentration at any location varies with the stage of the tide, but on successively similar tidal stages, the pollutant concentration returns to the same value. For the equilibrium condition to exist, the pollutant discharge rates must be kept constant for a period longer than the flushing time of the water body.

Ketchum's tidal prism concept has been modified by Kuo (1975) and applied to small coastal basins and bays. The basic assumptions made by Ketchum are retained while the method of segmenting the water body and calculation of flushing rate are refined. The basic assumptions of the tidal prism theory are:

(1) the water body is vertically homogeneous,

(2) the maximum length of the water body over which complete mixing is possible equals the average excursion of a water particle on the flooding tide.

Based on the above assumptions, it is envisaged that the water entering the coastal bay on flood tide mixes completely with the water present in the most seaward segment at low tide. Portions of this mixture, in turn, enter the next landward segment and mix completely with water present there at low tide. The process progresses landward until the head of the coastal embayment is reached. On the ebb tide the part of water making up the local intertidal volume of each segment escapes to the adjacent seaward segment. The flushing is thus accomplished by a series of tidal exchanges with the pollutants moving progressively seaward.

3. Segmentation of the Lagoons

For the purpose of model construction, a water body is divided into segments each having a length equal to the local tidal excursion. Figure 3 shows the axial view of a coastal embayment with its volume V (x) and tidal prism P (x) plotted as function of distance x from the mouth. V (x) is defined as the accumulated low-tide volume along the main stem from the mouth to the transect at x. P (x) is the intertidal volume landward from the transect at x, including those of branches. The most seaward segment (segment no. 1) is defined between transects 1 and 2 such that its low-tide volume V_1 equals to the tidal prism landward of transect 2, i.e., P_2. In general,

EMBAYMENT SEGMENTATION

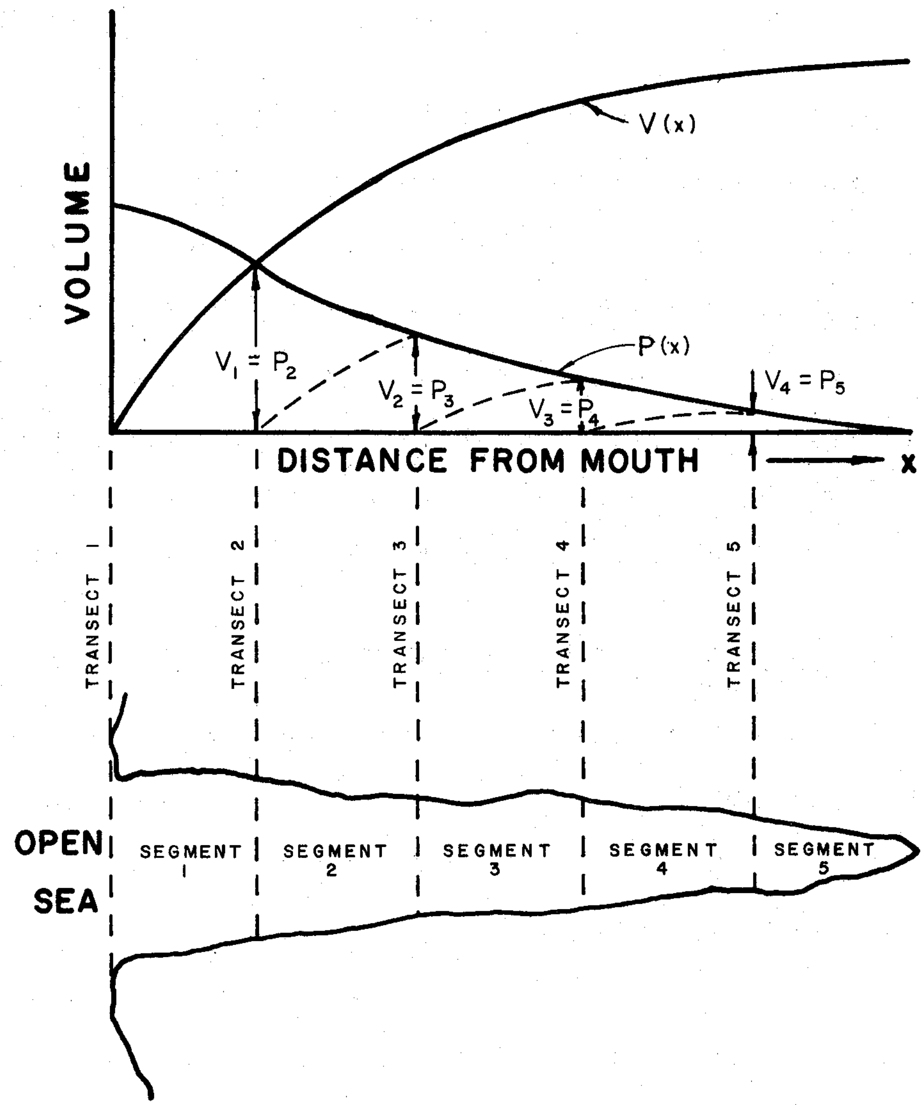


Figure 8. Segmentation of a coastal embayment.

$$V_n = P_{n+1} \qquad \text{(II-1)}$$

$$= P_{n+2} + \rho_{n+1}$$

$$= V_{n+1} + \rho_{n+1}$$

where V_n is the low-tide volume of the nth segment, P_{n+1} is the tidal prism landward from the (n+1)th transect and ρ_{n+1} is the local tidal prism, or intertidal volume of the (n+1)th segment. Therefore, the low-tide volume of a segment equals the tidal prism landward from it and also equals to the high-tide volume of its adjacent landward segment. Each of the branches of the embayment may be segmented in the same way as that of the main stem.

4. <u>Distribution of Conservative Pollutants</u>

If one assumes that a conservative pollutant is discharged into the mth segment at a rate of Q per tide, the pollutant concentration in each segment may be calculated by considering mass balance.

Under equilibrium condition, the net amount of pollutant 'flushed' across a transect seaward of the outfall, i.e., $n \leq m$, must equal to Q. A volume of water P_n is transported seaward and landward on ebb and flood tides respectively. Let C_n be the concentration of the nth segment at high tide, then the total mass transported seaward on ebb tide is $P_n C_n$. Since the flooding water is assumed to mix completely with the water present in the (n-1)th segment at low tide, the water transported landward will have concentration C_{n-1}, the concentration of the (n-1)th segment at high tide. Therefore

$$P_n C_n - P_n C_{n-1} = Q, \text{ or}$$

$$C_n = C_{n-1} + \frac{Q}{P_n} \text{ for } m \geq n \geq 1 \qquad \text{(II-2)}$$

Equation (II-2) requires that C_o be specified before the concentration distribution may be calculated. This is equivalent to the requirement of boundary condition for solution of advection-diffusion equation. Assuming that the water entering the embayment through transect 1 on flood tide contains insignificant amounts of the water that escaped from the bay during the previous ebb tide, then

$$C_1 = \frac{Q}{P_1}$$

if the concentration C_1 is interpreted as the excess concentration over the background value outside of the bay. In general, equation (II-2) becomes

$$C_n = \sum_{i=1}^{n} \frac{Q}{P_i} \qquad \text{(II-3)}$$

If a flushing rate r_n is to be defined as the portion of pollutant removed from the nth segment per tidal cycle, mass balance requires that

$$r_n C_n Vh_n = Q$$

where $Vh_n = V_n + \rho_n$ is the volume of the nth segment at high tide, then

$$r_n = \frac{1}{Vh_n} \cdot \frac{Q}{C_n} \quad \text{and}$$

$$C_n = \frac{Q}{r_n Vh_n} \qquad \text{(II-3a)}$$

Substituting equation (II-2), it is obtained that

$$r_n = \frac{Q}{Vh_n(C_{n-1} + \frac{Q}{P_n})}$$

or, since $P_n = Vh_n$ and $C_{n-1} = \frac{Q}{r_{n-1}Vh_{n-1}}$,

$$r_n = \frac{1}{1 + \frac{P_n}{r_{n-1}Vh_{n-1}}} \qquad \text{(II-4)}$$

and

$$r_1 = \frac{P_1}{Vh_1} = 1 \qquad \text{(II-4a)}$$

If the nth segment is located landward from the outfall, calculation of pollutant concentration may be considered an intrusion problem. Under equilibrium condition, there should be no net transport of the pollutant across the nth transect, thus

$$P_nC_n - P_nC_{n-1} = 0$$

$$C_n = C_{n-1}$$

In general

$$C_n = C_m \text{ if } n \geq m \qquad \text{(II-5)}$$

5. Distribution of Nonconservative Pollutants

In addition to flushing by tidal action, a nonconservative pollutant also undergoes a decaying process which further reduces the pollutant concentration in a water body. The mechanism of tidal flushing and decay may be assumed to work independently and their combined effect may be studied through the principle of mass-balance in a segment of the bay.

If W_n is the total mass of pollutant in the nth segment, then the amount of pollutant removed per tidal cycle by tidal flushing is $r_n W_n$, where r_n is the flushing rate defined previously. The remaining mass of the pollutant $(1-r_n)\ W_n$ will undergo decay. Assuming that the pollutant decays linearly with a decay rate of k per tide, the amount of the pollutant decaying in one tidal cycle will be $(1-r_n)\ W_n\ (1-e^{-k})$. Therefore, the total loss of pollutant per tidal cycle is

$$r_n W_n + (1-r_n) W_n (1-e^{-k}) = \left(1-(1-r_n)e^{-k}\right) W_n$$

Under equilibrium condition, the same amount of the pollutant has to be supplied by the adjacent segment closer to the pollutant source, thus

$$\left(1-(1-r_n)e^{-k}\right) W_n = r_{n+1} W_{n+1}$$

or

$$W_n = \frac{r_{n+1}\ W_{n+1}}{1-(1-r_n)e^{-k}} \qquad \text{(II-6)}$$

If the pollutant were not decaying during the time it is transported from the (n+1)th segment to the nth segment, equation (II-6) might be reduced to

$$(W_n)_o = \frac{r_{n+1}}{r_n}\ W_{n+1} \qquad \text{(II-7)}$$

where $(W_n)_o$ is the total mass of the pollutant in the nth segment with no decay in the segment. By combining equations (II-6) and (II-7), the following is obtained

$$W_n = \frac{r_n}{1-(1-r_n)e^{-k}}\ (W_n)_o \qquad \text{(II-8)}$$

Equation (II-8) states that the factor for pollutant reduction due to decay within the nth segment is

$$\frac{r_n}{1-(1-r_n)e^{-k}}$$

Equations (II-3a) and (II-5) give the concentration distribution due to the flushing by tidal action alone. After applying the decaying factor, the concentration distribution of a nonconservative pollutant may be summarized as follows:

$$C_n = \prod_{i=n}^{m} \frac{r_i}{1-(1-r_i)e^{-k}} (C_n)_o \quad \text{if } n \leq m \qquad \text{(II-9)}$$

and

$$C_n = \prod_{i=m}^{n} \frac{r_i}{1-(1-r_i)e^{-k}} (C_n)_o \quad \text{if } n \geq m \qquad \text{(II-10)}$$

where $(C_n)_o$ is the concentration of a conservative pollutant and is given by equations (II-3a) and (II-5).

6. Effect of Excess Evaporation on Flushing Capability

Where the drainage basin of a coastal bay experiences long periods of drought, the water body may be subject to excessive evaporation. Not only does evaporation concentrate pollutants, but it also leads to a net inflow of sea water to replace water evaporated from the bay. There will be more inflow of sea water on flood tide than outflow of bay water on ebb tide. This process tends to accumulate pollutants in the bay and worsen the water quality.

The flushing capability of a coastal bay under conditions of excessive evaporation may be evaluated in the same way as that described in Section 4. The total mass of pollutant flushed across the nth transect on ebb tide equals

$$(P_n - E_n)\ C_n$$

where E_n is the volume of water evaporated over surface area landward from the nth transect in the half tidal cycle. The total mass of pollutant transported landward across the nth transect on flood tide equals

$$(P_n + E_n)\ C_{n-1}$$

Therefore, under equilibrium condition,

$$(P_n - E_n)\ C_n - (P_n + E_n)\ C_{n-1} = Q,$$

or

$$C_n = \frac{P_n + E_n}{P_n - E_n} C_{n-1} + \frac{Q}{P_n - E_n} \qquad \text{(II-11)}$$

where Q is the discharge rate per tidal cycle of a conservative pollutant. Equation (II-11) is equivalent to equation (II-2) in Section C. If the concentration C_1 is interpreted as the excessive concentration over the background value outside of the bay, then

$$C_1 = \frac{Q}{P_1 - E_1}, \quad \text{and}$$

$$C_2 = Q\left(\frac{P_2 + E_2}{P_2 - E_2} \cdot \frac{1}{P_1 - E_1} + \frac{1}{P_2 - E_2}\right)$$

In general, equation (II-11) becomes

$$C_n = Q\left(\sum_{i=1}^{n-1}\left(\prod_{k=i+1}^{n} \frac{P_k + E_k}{P_k - E_k}\right)\frac{1}{P_i - E_i} + \frac{1}{P_n - E_n}\right) \qquad \text{(II-12)}$$

which is equivalent to equation (II-3) of Section C.

Substituting equation (II-11), the flushing rate as defined in equation (II-3a) becomes

$$r_n = \frac{Q}{Vh_n \cdot \frac{1}{P_n - E_n} \left((P_n + E_n)C_{n-1} + Q\right)}$$

$$= \frac{P_n - E_n}{Vh_n} \cdot \frac{1}{1 + \frac{P_n + E_n}{r_{n-1} \cdot Vh_{n-1}}} \qquad \text{(II-13)}$$

and

$$r_1 = \frac{P_1 - E_1}{Vh_1}$$

If the nth segment is located landward from the pollutant discharge point, equation (II-11) becomes

$$C_n = \frac{P_n + E_n}{P_n - E_n} C_{n-1}, \quad \text{or}$$

in general

$$C_n = \prod_{i=m+1}^{n} \frac{P_i + E_i}{P_i - E_i} C_m \qquad \text{(II-14)}$$

where the mth segment is the location of pollutant source.

In case the pollutant is not conservative, the decaying factors derived in Section D are still applicable, except where the flushing rates have been modified.

B. Application to the Mangrove Lagoon

1. Calculation of Tidal Exchange

The Mangrove Lagoon, located on the south coast of St. Thomas, Virgin Islands, is connected to the open sea through the Bovoni Passage in the northeast, and through the Middle Reach-Patricia Entrance Reach - Cas Entrance Reach System in the south. It has been observed (Nichols, et al., 1977) that the water movement and, thus, the flushing in the lagoon may be driven by (1) wave refraction and breaking on the Patricia-Cas Cay reefs, (2) tidal variation of surface elevation, and (3) wind stress. When the wind is calm and waves are low, the tidal induced circulation becomes the dominant flushing mechanism of the lagoon. Wave-induced and wind-driven current will augment the flushing of the lagoon, but these mechanisms do not constantly exist and cannot be counted on as reliable flushing capabilities for the purpose of water quality planning and management. In the following, only the tidal flushing, a conservative approach, is considered.

The tide in the Mangrove Lagoon is chiefly diurnal, and has a mean range of 27 cm (Michel, 1970; Nichols and Towle, 1977). Nichols and Towle (1977) observed that the rise and fall of the tide is essentially simultaneous throughout the lagoon system. Because of the shallowness of the water in the lagoon no significant vertical stratification of the water column was observed. Such conditions permit application of the tidal prism theory.

Nichols and Towle (1977) calculated the mean tidal prism of the lagoon, including passages, as $1.912 \times 10^5 m^3$. Of this volume of water entering and leaving the lagoon each tidal cycle, part is flowing through the Bovoni Passage, and part is through the passages in the south. Table 3 gives the geometric parameters of the four passages. The data are calculated from the bathymetric information used in the preparation of the report by Nichols and Towle (1977).

Table 3. Geometric Parameters of the Passages

	Surface Area $10^4 m^2$	Length m	Cross-Sectional Area*, m^2
Patricia Entrance Reach	2.23	466	85.8
Cas Entrance Reach	2.85	380	113
Middle Reach	1.47	155	135
Bovoni Passage	6.59	620	100

*average over length of the passages, excluding small embayments along the passages

In the following, the tidal dynamics of inlets are used to estimate the percentage of the tidal prism through each of the two pathways. Equation (I-3) may be written as

$$q_m = \frac{1}{R} \Delta h \qquad \text{(III-1)}$$

where

$$\frac{1}{R} = \frac{Ag}{L\sqrt{\omega^2 + \lambda^2}} \qquad \text{(III-2)}$$

$$\Delta h = \left((a_o \cos\alpha - a_1 \cos\beta)^2 + (a_o \sin\alpha - a_1 \sin\beta)^2\right)^{\frac{1}{2}}$$

Equation (III-1) may be interpreted that the flow through an inlet connecting a bay to the open sea is the product of Δh, a parameter for differential water surface elevation, and $\frac{1}{R}$, the channel 'conductance' or the reciprocal of channel 'resistance'. Therefore, to evaluate the relative magnitude of tidal flows through the two pathways, it is needed to calculate their relative 'conductance'.

As the first order approximation, λ^2 is neglected with respect to ω^2 and the channel 'conductance' becomes

$$\frac{1}{R} = \frac{Ag}{L\omega}$$

where $\omega = 7.27 \times 10^{-5}$/sec, is the angular frequency of the lunisolar diurnal tide. Thus, the channel 'conductance' for the four passages are

Bovoni Passage $= \frac{1}{R_b} = 2.175 \times 10^4 \ m^2/sec$

Middle Reach $= \frac{1}{R_m} = 11.74 \times 10^4 \ m^2/sec$

Cas Entrance Reach $= \frac{1}{R_c} = 4.008 \times 10^4 \ m^2/sec$

Patricia Entrance Reach $= \frac{1}{R_p} = 2.482 \times 10^4 \ m^2/sec$

Since equation (III-1) specifies a linear response between the flow and surface elevation differential, the Middle Reach - Patricia Entrance Reach - Cas Entrance Reach system may be considered as an equivalent channel with channel 'conductance'

$$\frac{1}{R} = \frac{1}{R_m + \cfrac{1}{\cfrac{1}{R_c} + \cfrac{1}{R_p}}} = 4.180 \times 10^4 \ m^2/sec$$

Therefore, the fraction of the tidal prism flowing through the Bovoni Passage is

$$F_b = \frac{2.175}{2.175 + 4.180} = 0.342$$

and the fraction flowing through the system of passages in the south is

$$F_e = 0.658$$

Knowing the fraction of tidal prism going through each passage, the friction parameter λ may be calculated and the channel 'conductances' be recalculated using equation (III-2). The results of this second order calculation change F_b from 0.342 to 0.343 and F_e from 0.658 to 0.657. No further correction was made and the second order results were used in the tidal flushing computation.

2. Segmentation of the Lagoon

The Mangrove Lagoon is segmented according to the principle outlined in Section 9-B. The segmentation is started from the entrances through the Bovoni Passage and the Middle Reach - Patricia Entrance Beach - Cas Entrance Reach complex independently. The lagoon is divided into segments as shown in Figure 4.

The dashed line (Figure 9) along the center of the lagoon is chosen as the main axis along which the distance is measured. Figure 10 shows the accumulated volume and tidal prism as functions of distance along the axis. Figure 10 also demonstrates the process of segmentation by which the transect is located at position where the tidal prism equals the volume between the transect being located and its adjacent seaward transect.

The first segment consists of the Patricia Entrance Reach and Cas Entrance Beach, because the volume of each reach is smaller than the tidal prism passing through the most landward transect of the respective passage. The step increase of tidal prism at x = 1060 m (Figure 10) reflects the additional tidal flushing through the Bovoni Passage. Therefore, there is an increase in volume from segment 9 to segment 10. The volumes of the segments are listed in Table 4.

3. Calculation of Flushing Rates

The flushing rates of the segments seaward of segment 10, where the Bovoni Passage enters the lagoon, may be calculated with equation (II-4). If a steady source of pollutant is discharged into the head of the lagoon, equation (II-3a) may be used to calculate the concentrations in segments

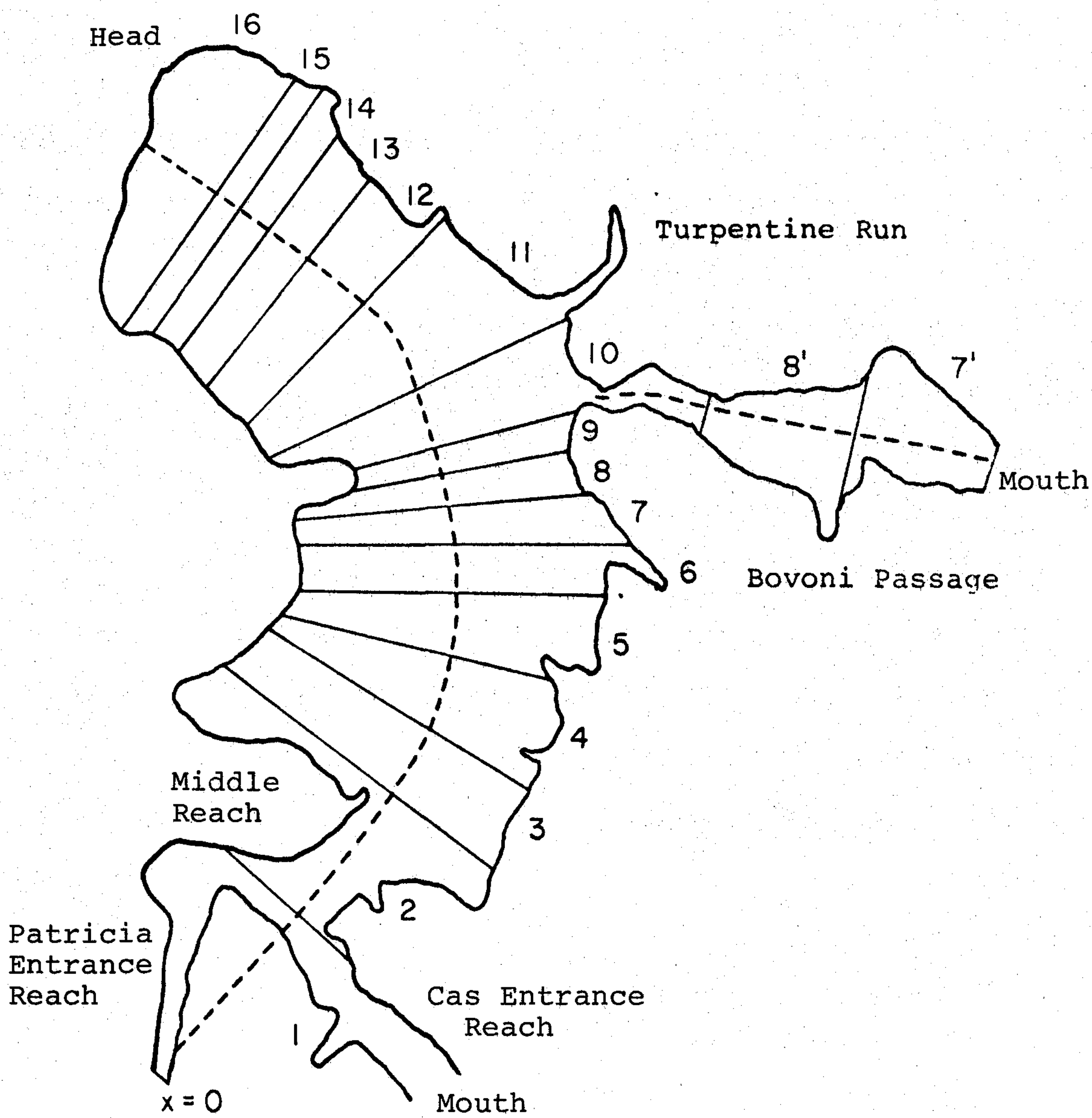


Figure 9. The Mangrove Lagoon segmentation.

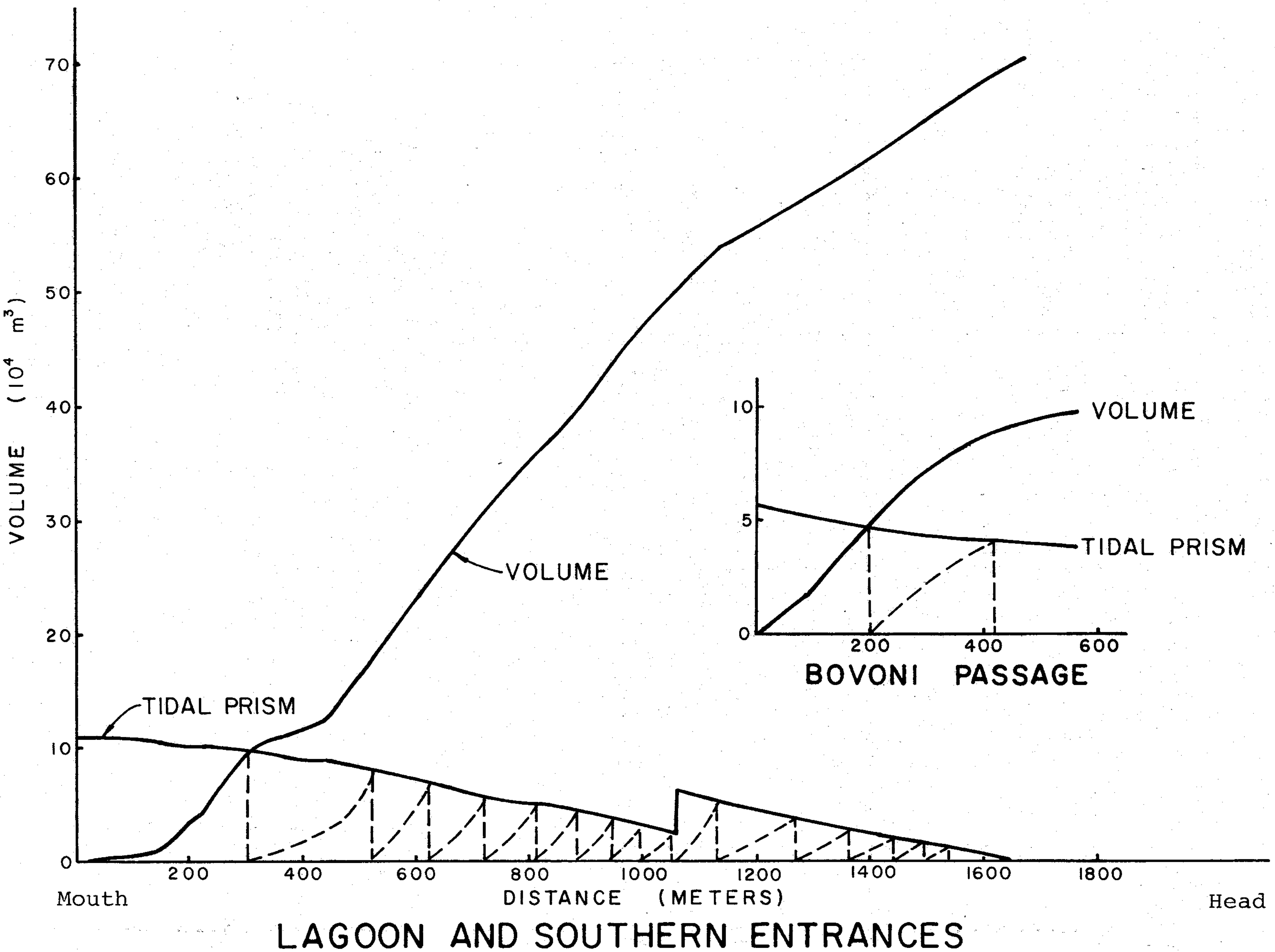


Figure 10. Accumulated volume and tidal prism of the Mangrove Lagoon.

Table 4. Segment Volumes and Flushing Rates of the Mangrove-Lagoon

Segment Number	Volume, $Vh_n (=P_n)$ $10^4 m$	Flushing Rates, γ_n, 1/tide ** No Evaporation	With Evaporation
1	10.85	1.0	0.989
2	9.49	0.533	0.522
3	8.14	0.384	0.372
4	6.96	0.310	0.298
5	5.93	0.267	0.254
6	5.06	0.238	0.225
7	4.35	0.217	0.203
8	3.71	0.203	0.188
9	3.09	0.196	0.181
10	6.69 (2.57*)	0.311	0.297
11	5.47	0.276	0.267
12	4.21	0.264	0.253
13	3.21	0.257	0.244
14	2.31	0.263	0.248
15	1.78	0.254	0.239
16	1.34	0.252	0.236
8'	5.62	1.0	0.989
9'	4.82	0.540	0.527
10'	(4.12*)		

*Tidal prisms through the seaward transects of the junction segment.

**The flushing rate is the fraction of pollutant removed from the segment in one complete tidal cycle, which is 24 hours in this case. For example, 31.1% of pollutant in segment 10 is removed over every tidal cycle, if no excessive evaporation exists.

seaward of the junction segment. For those segments in the lagoon

$$C_n = \frac{bQ}{r_n V h_n} \qquad n<10 \qquad \text{(III-4)}$$

and for those segments in the Bovoni Passage

$$C_n' = \frac{b'Q}{r_n' V h_n'} \qquad n<10 \qquad \text{(III-5)}$$

where the primes designate the quantities in the Bovoni Passage, Q is the pollutant discharge rate per tidal cycle, b and b' are the fractions of pollutant flushed out through the southern passages and Bovoni Passage respectively, and

$$b + b' = 1 \qquad \text{(III-6)}$$

Since the junction segment (segment 10) has two flushing routes to the open sea, the flushing rate cannot be calculated with equation (II-4). However, equation (II-3) was derived based on the balance of mass flux through cross-sections of water body, it may be applied to transects up to the seaward boundaries of segment 10. Therefore, for the segments in the lagoon

$$C_n = bQ \sum_{i=1}^{n} \frac{1}{P_i} \qquad n\leq 10,$$

and for those in the Bovoni Passage

$$C_n' = b'Q \sum_{i=8}^{n} \frac{1}{P_i'} \qquad n\leq 10$$

At the junction segment, i.e., n=10,

$$C_{10} = C_{10}'$$

$$b \sum_{i=1}^{10} \frac{1}{P_i} = b' \sum_{i=8}^{10} \frac{1}{P_i'} \qquad \text{(III-7)}$$

Equations (III-6) and (III-7) may be solved simultaneously for b and b'.

The total mass of pollutant transported seaward from segment 10 on ebb tide is

$$(P_{10} + P'_{10})C_{10}$$

and the total mass transported into segment 10 on flood tide is

$$P_{10}C_9 + P'_{10}C'_9$$

The mass balance gives the relationship that

$$(P_{10} + P'_{10})\ C_{10} - P_{10}C_9 - P'_{10}C'_9 = Q$$

or

$$C_{10} = fC_9 + f'C'_9 + \frac{Q}{P_{10} + P'_{10}} \qquad \text{(III-8)}$$

where

$$f = \frac{P_{10}}{P_{10} + P'_{10}}$$

$$f' = \frac{P'_{10}}{P_{10} + P'_{10}}$$

Substituting equations (III-4) and (III-5), equation (III-8) becomes

$$C_{10} = f\ \frac{bQ}{r_9 V h_9} + f'\ \frac{b'Q}{r_9' V h_9'} + \frac{Q}{P_{10} + P_{10}'} \qquad \text{(III-9)}$$

The flushing rate was defined previously as $r_n = \frac{Q_n}{Vh_n \cdot C_n}$

$$\therefore \quad r_{10} = \frac{1}{Vh_{10}} \cdot \frac{1}{\frac{fb}{r_9 Vh_9} + \frac{f'b'}{r_9' Vh_9'} + \frac{1}{P_{10} + P_{10}'}}$$

or

$$r_{10} = \frac{1}{1+(P_{10} + P_{10}')\left(\frac{fb}{r_9 Vh_9} + \frac{f'b'}{r_9' Vh_9'}\right)} \qquad \text{(III-10)}$$

For segments landward of segment 10, equation (II-4) may be used to calculate flushing rates, and concentration may be calculated with equation (II-3a). The flushing rates for all the segments are calculated and listed in Table 4.

In case there is excessive evaporation, the flushing rates may be calculated with equation (II-13), except the junction segment (segment 10). Equations (III-4) and (III-5) may still be used to calculate the concentrations of the segments seaward of segment 10 in the lagoon and those of the segments in the Bovoni Passage respectively. Equation (III-6) still holds for the partition coefficients, b and b', of the two flushing routes. Equation (III-7) should be modified in accordance to equation (II-12). Therefore, we have

$$b\left(\sum_{i=1}^{9} \left(\prod_{k=i+1}^{10} \frac{P_k + E_k}{P_k - E_k}\right) \frac{1}{P_i - E_i} + \frac{1}{P_{10} - E_{10}}\right)$$

$$= b'\left(\sum_{i=8}^{9} \left(\prod_{k=i+1}^{10} \frac{P_k' + E_k'}{P_k' - E_k'}\right) \frac{1}{P_i' - E_i'} + \frac{1}{P_{10}' - E_{10}'}\right) \qquad \text{(III-11)}$$

This equation needs to be solved together with equation (III-6) for b and b'.

The flushing rate for the junction segment may be derived in the same way as the case without evaporation. The mass balance relationship for the junction segment becomes

$$(P_{10} - E_{10} + P_{10}' - E_{10}')C_{10} - (P_{10} + E_{10})C_9$$

$$- (P_{10}' + E_{10}')C_9' = Q$$

or

$$C_{10} = fC_9 + f'C_9' + \frac{Q}{P_{10} - E_{10} + P_{10}' - E_{10}'} \qquad \text{(III-12)}$$

where

$$f = \frac{P_{10} + E_{10}}{P_{10} - E_{10} + P_{10}' - E_{10}'}$$

$$f' = \frac{P_{10}' + E_{10}'}{P_{10} - E_{10} + P_{10}' - E_{10}'}$$

Substituting for the concentrations C_9 and C_9',

$$C_{10} = f\,\frac{bQ}{r_9 Vh_9} + f'\,\frac{b'Q}{r_9' Vh_9'} + \frac{Q}{P_{10} - E_{10} + P_{10}' - E_{10}'} \qquad \text{(III-13)}$$

Then, the flushing rate for the junction segment becomes

$$r_{10} = \frac{1}{Vh_{10}} \cdot \frac{1}{\dfrac{fb}{r_9 Vh_9} + \dfrac{f'b'}{r_9' Vh_9'} + \dfrac{1}{P_{10} - E_{10} + P_{10}' - E_{10}'}} \qquad \text{(III-14)}$$

It has been reported by Bowden (1969) that March and April are the driest months on Virgin Islands. The only station on the Islands having evaporation data reported by U. S. Environmental Data Service is Beth Upper New Works at St. Croix. The monthly evaporation rate in April is about 8 inches, which is also close to the annual maximum. Taking 70% as the correction factor for evaporation rate over a water body, the evaporation rate per half tidal cycle is about 0.25 cm.

To arrive at a reasonable figure of evaporation rate for the Mangrove Lagoon, one may make use of the salinities observed inside and outside of the lagoon. Let S_o and S be the average salinities outside and inside the lagoon respectively, P be the tidal prism of the lagoon and E be the total volume of water evaporated over the lagoon surface in half tidal cycle, then the total mass of salt entering the lagoon on flood tide is

$$(P + E)S_o$$

and the total mass of salt leaving the lagoon on ebb tide is

$$(P - E)S$$

Under equilibrium condition,

$$(P + E)S_o = (P - E)S \qquad \text{or}$$

$$\frac{S}{S_o} = \frac{P + E}{P - E}$$

Since

$$P = R \cdot A, \text{ and } E = E_r \cdot A$$

where R is tidal range, A is surface area of the lagoon and E_r is evaporation rate, therefore,

$$\frac{S}{S_o} = \frac{R + E_r}{R - E_r}$$

It was observed in March 1977 that $S \simeq 37$ ppt, $S_o \simeq 36.2$ ppt, $P = 27$ cm, therefore

$$E_r \simeq 0.3 \text{ cm/half tidal cycle.}$$

A uniform evaporation rate of 0.3 cm/half tidal cycle is assumed over the entire lagoon surface. The flushing rates for all segments are calculated and listed in Table 4.

4. Distribution of Nonconservative Pollutants and Pollution Susceptibility

Two sets of pollution susceptibility are calculated and presented in Figures 11a to 16a and Figures 11b to 16b respectively, one without and the other with excessive evaporation. Figures 11 to 14 show the pollution susceptibility for a pollutant discharged at the head of the lagoon, assuming various values of decay rate. Figures 15 and 16 are the pollution susceptibility for pollutant discharged through Turpentine Run. In all cases, the pollutant discharge rate is 1 ton/day. For a conservative pollutant, equations (III-4) and (III-5) are used to calculate concentrations in segments seaward of the junction segment (segment 10). Equation (II-3a) is used for the segments between the junction segment and the segment where the pollutant is discharged. Equation (II-5) states that all the segments landward of the pollutant source have the same concentration. To calculate concentrations for a nonconservative pollutant, equations (II-9) and (II-10) are used. For all the calculations, the segment volumes and flushing rates listed in Table 4 are introduced into the equations.

Figure 11. Pollution susceptibility of the Mangrove Lagoon for a conservative pollutant discharged at the lagoon head.

A. upper, without evaporation.

B. lower with evaporation.

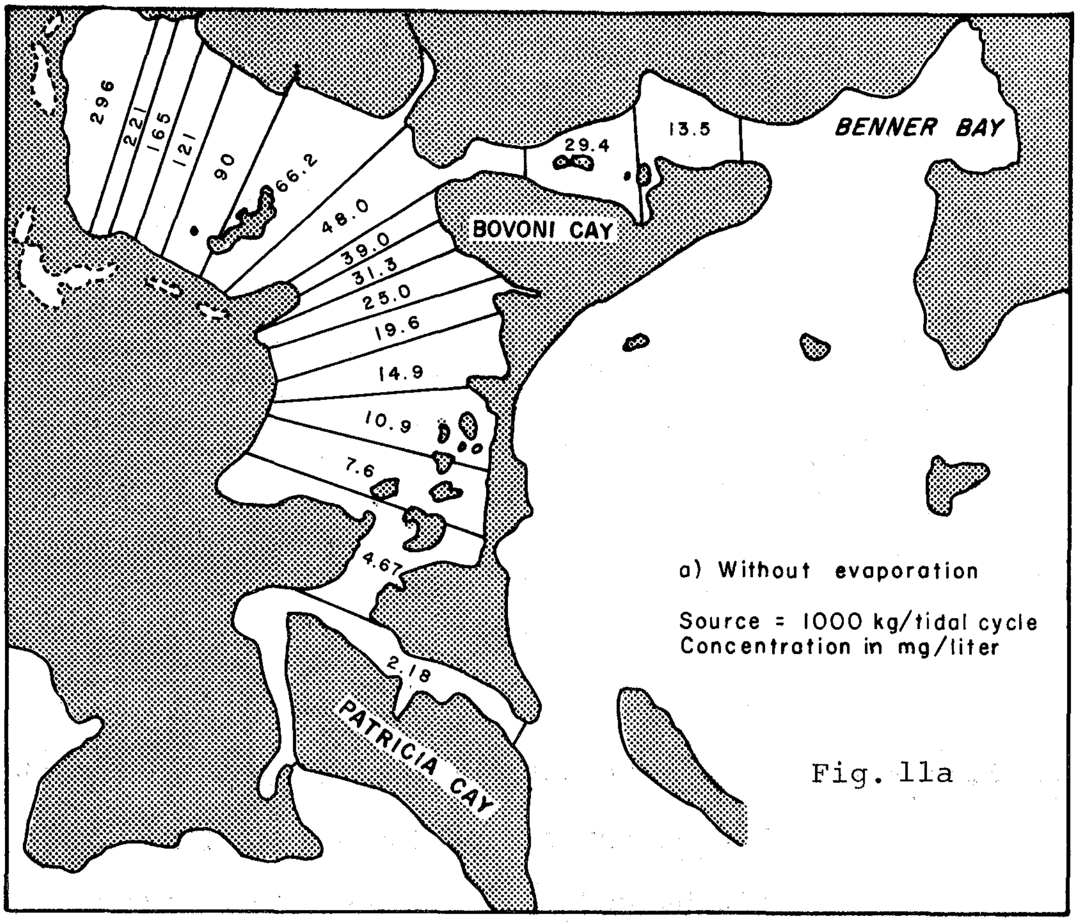


Fig. 11a

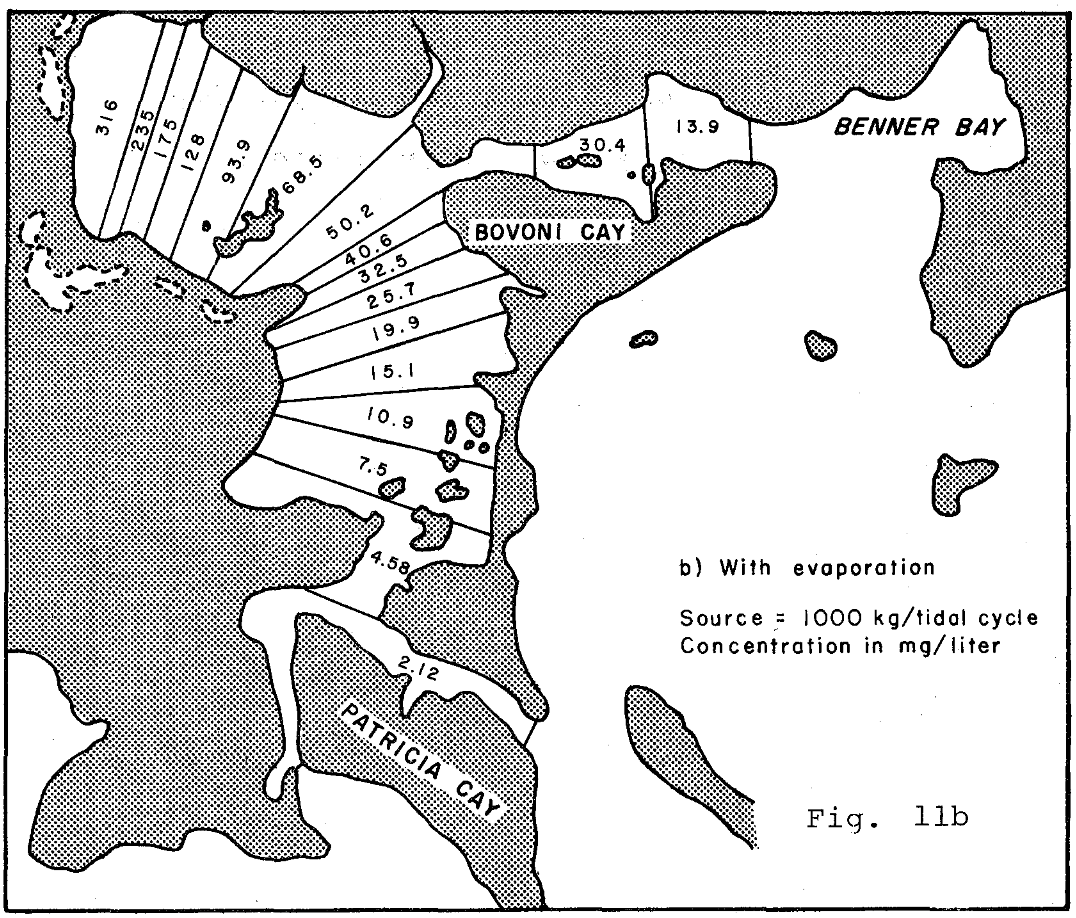


Fig. 11b

Figure 12. Pollution susceptibility of the Mangrove Lagoon for a nonconservative pollutant discharged at the lagoon head with a decay rate of 0.1/tidal cycle.

A. upper, without evaporation.

B. lower, with evaporation.

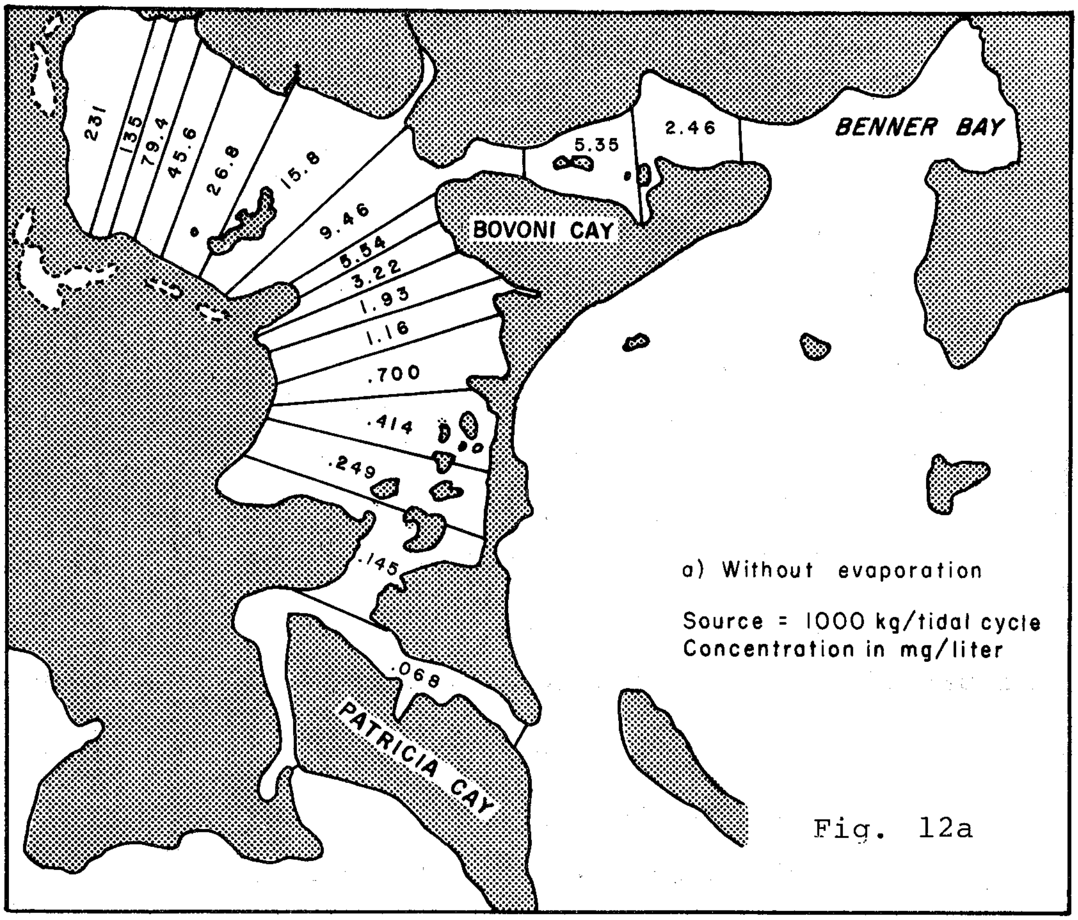


Fig. 12a

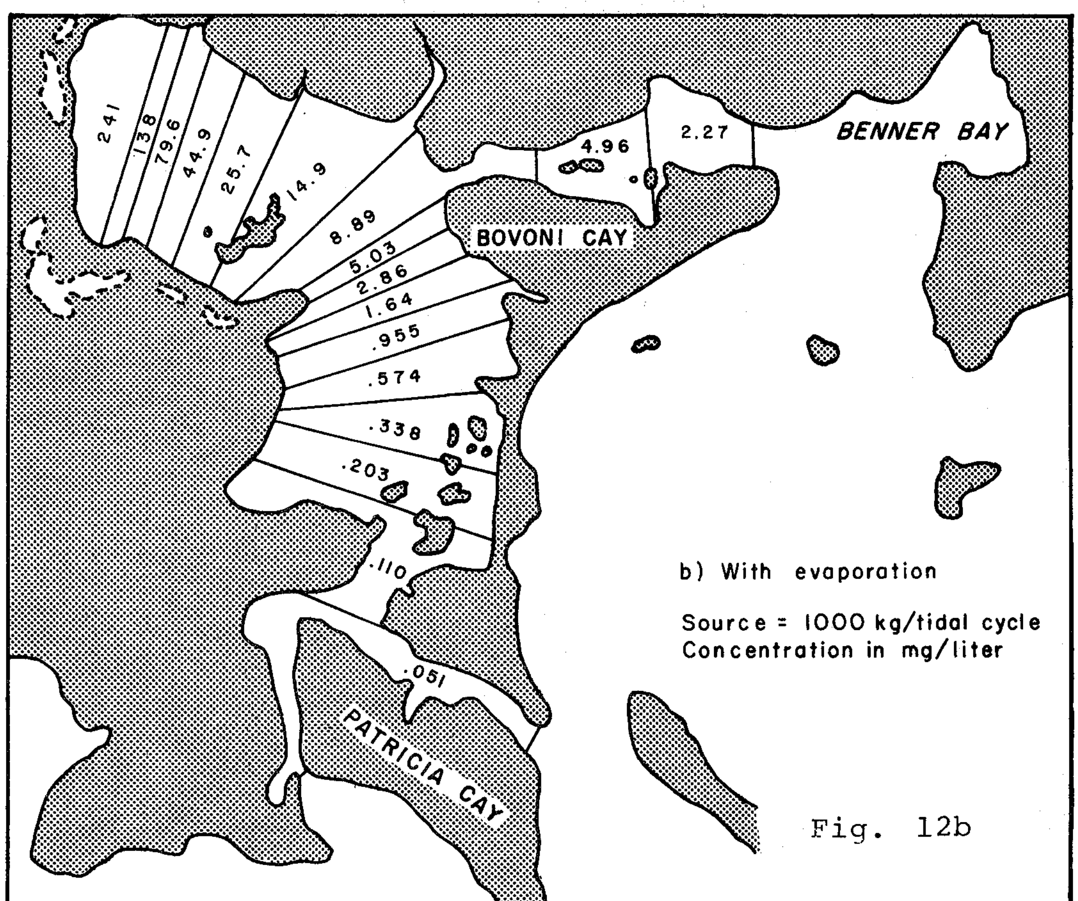


Fig. 12b

Figure 13. Pollution susceptibility of a nonconservative pollutant discharged at the lagoon head with a decay rate of 0.5/tidal cycle.

A. upper, without evaporation.

B. lower with evaporation.

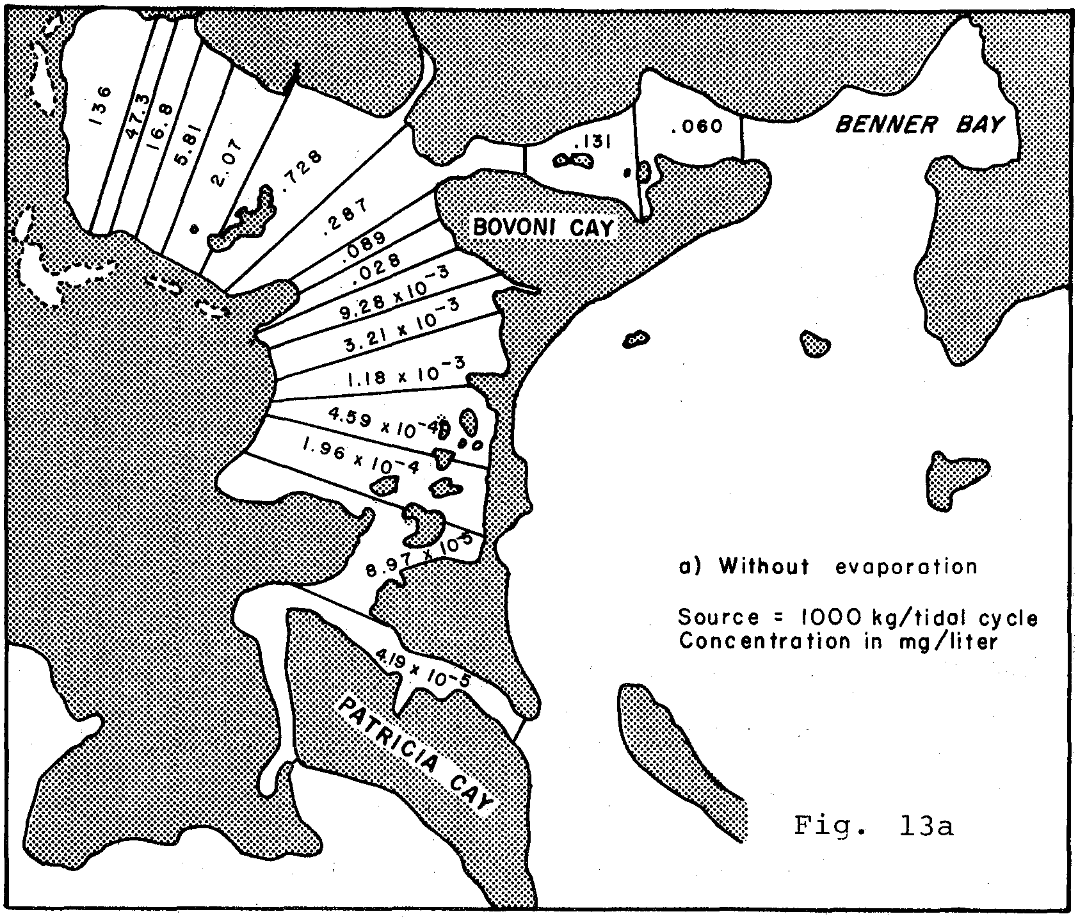


Fig. 13a

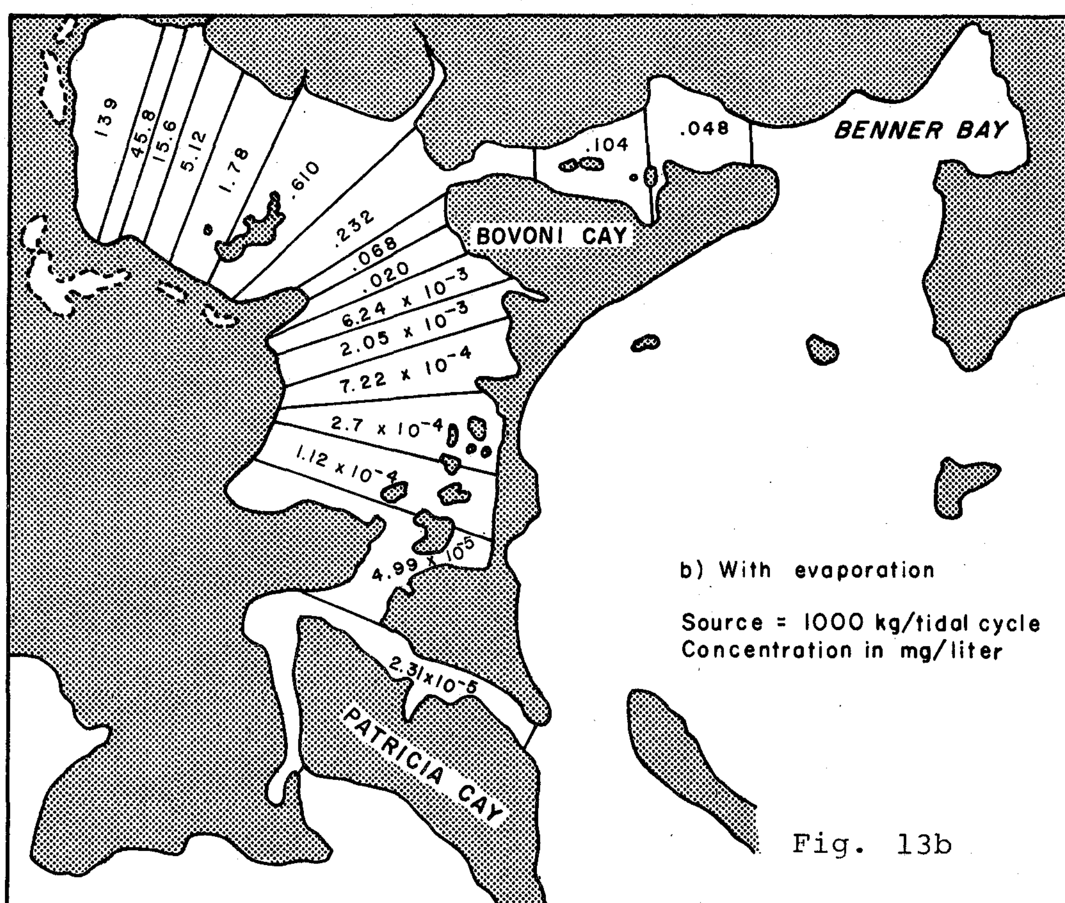


Fig. 13b

Figure 14. Pollution susceptibility of a nonconservative pollutant discharged at the lagoon head with a decay rate of 1.0/tidal cycle.

A. upper, without evaporation.

B. lower with evaporation.

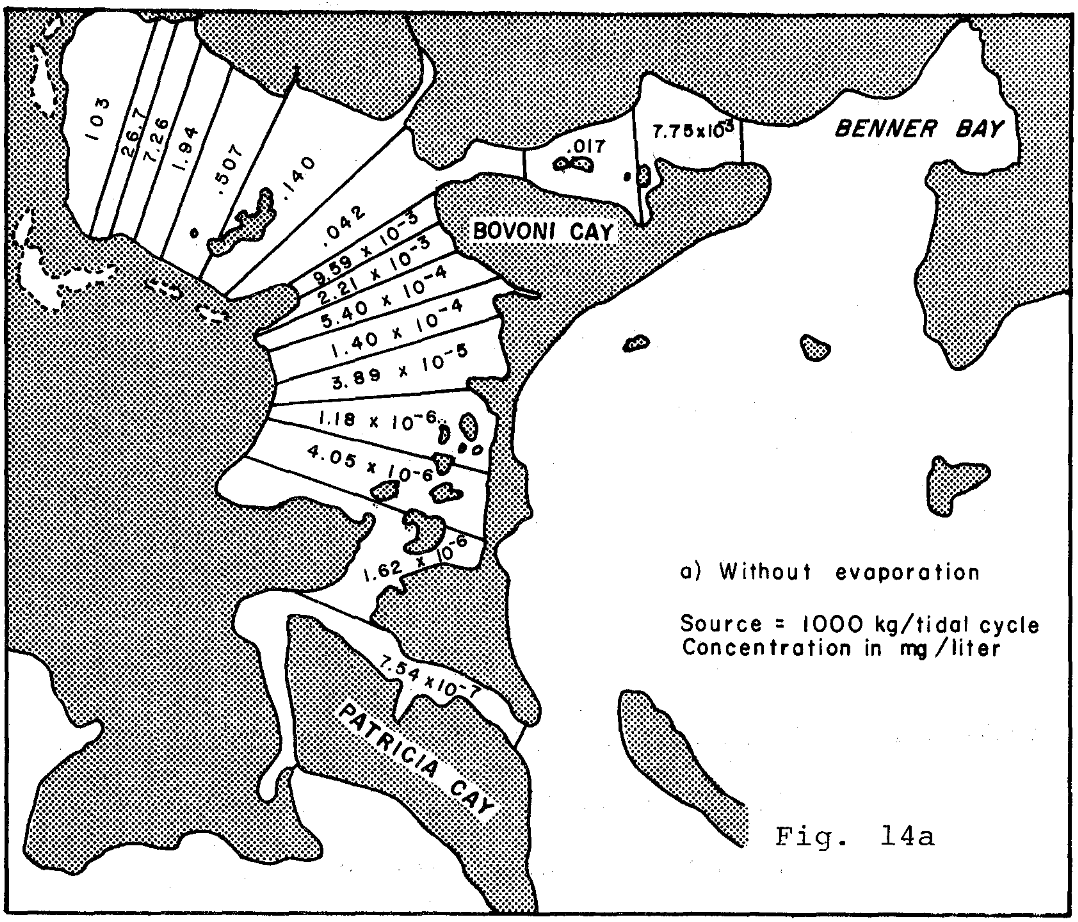


Fig. 14a

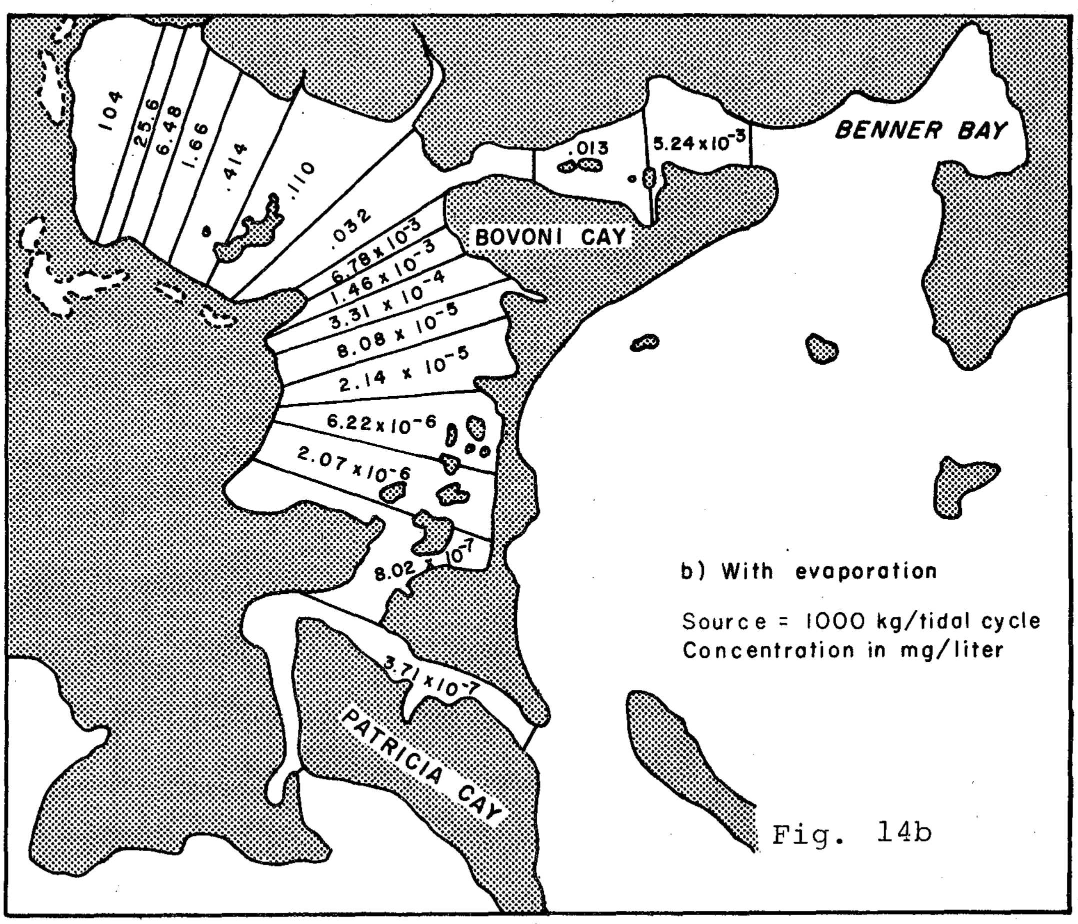


Fig. 14b

Figure 15. Pollution susceptibility of a conservative pollutant discharged from Turpentine Run.

A. upper, without evaporation.

B. lower with evaporation.

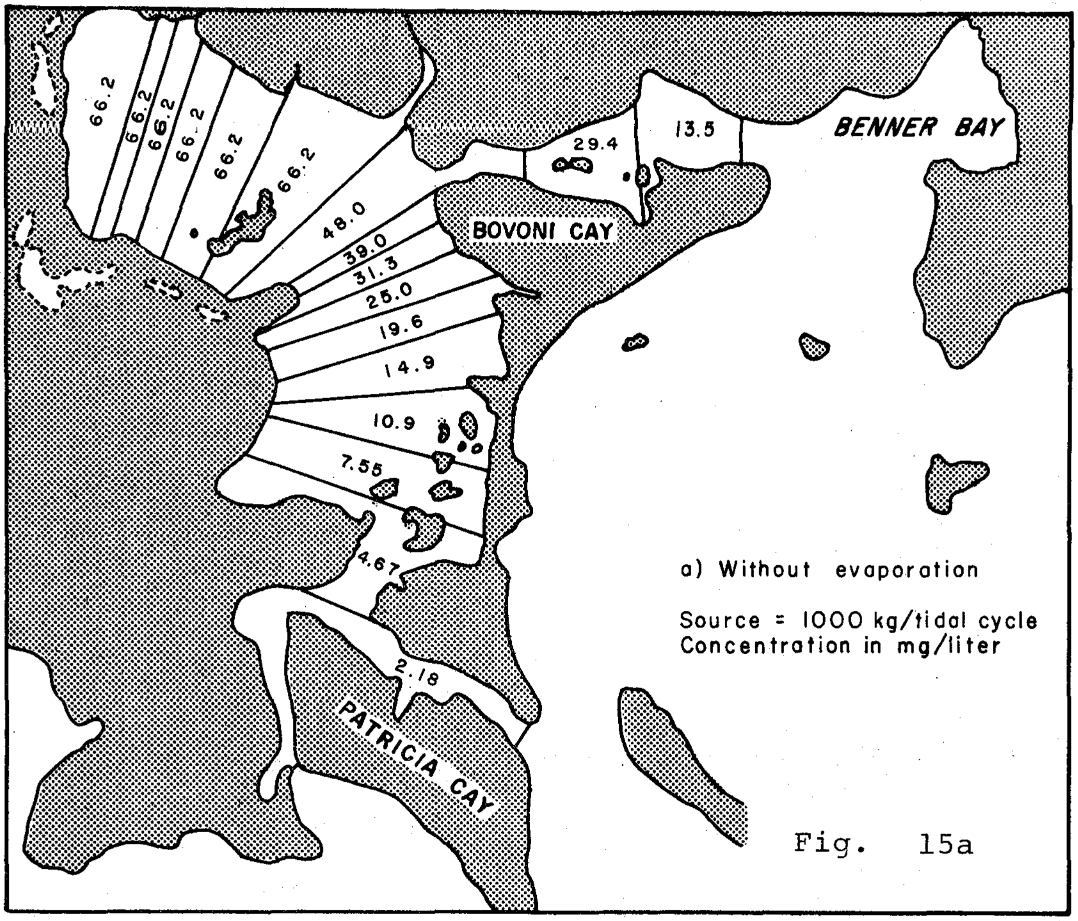


Fig. 15a

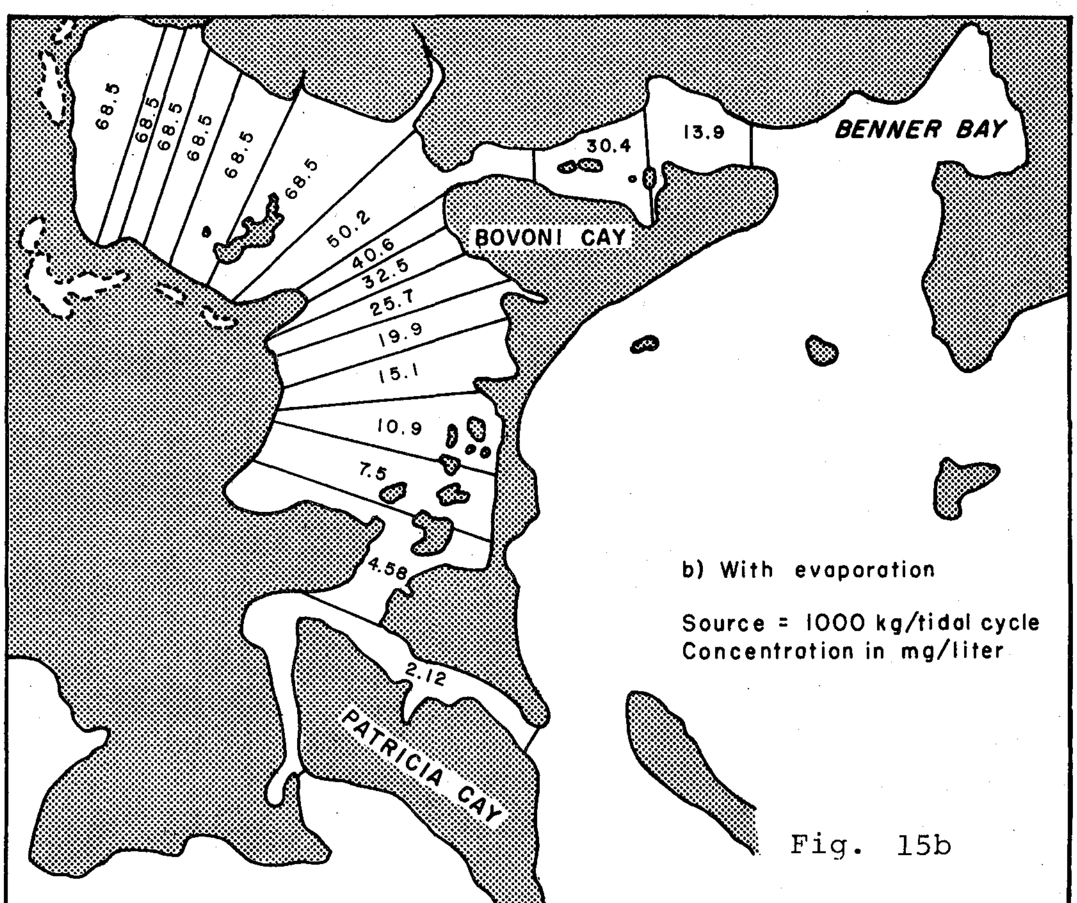


Fig. 15b

Figure 16. Pollution susceptibility of a nonconservative pollutant discharged from Turpentine Run with a decay rate of 0.1/tidal cycle.

A. upper, without evaporation.

B. lower with evaporation.

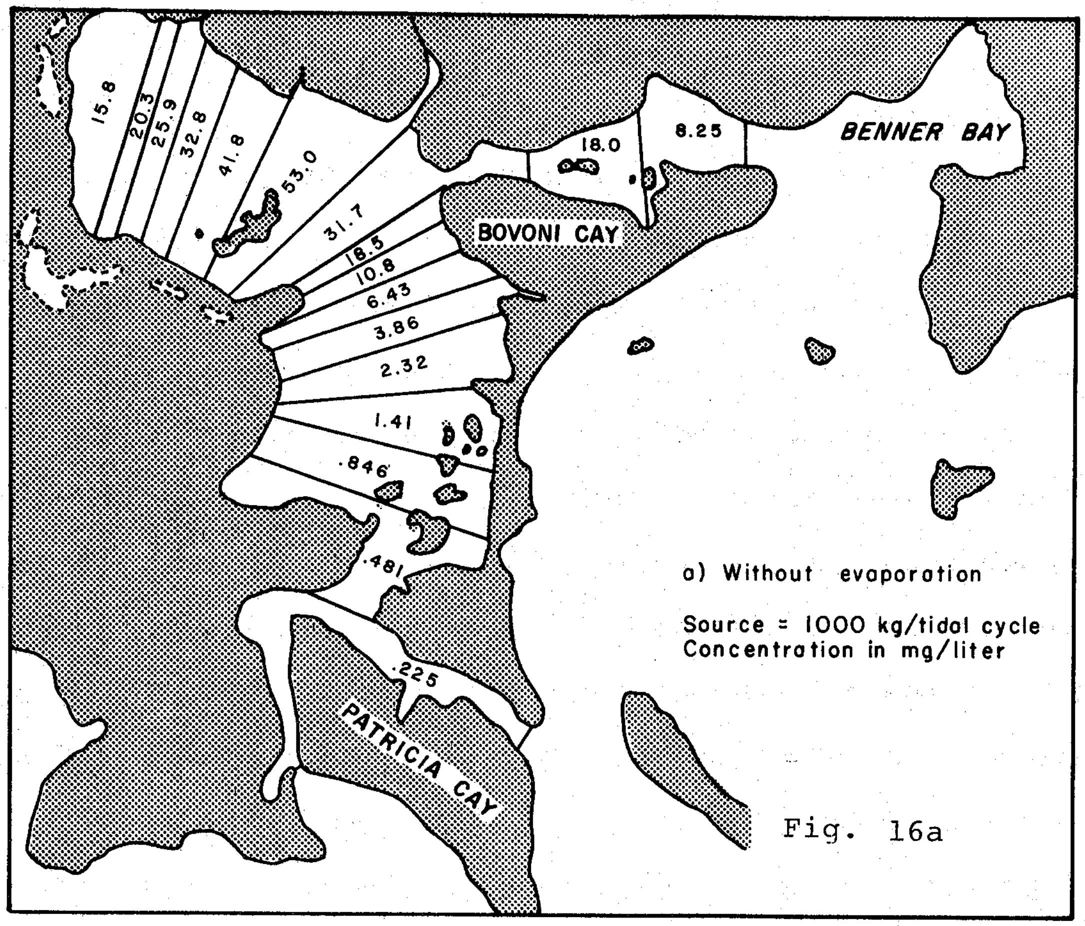


Fig. 16a

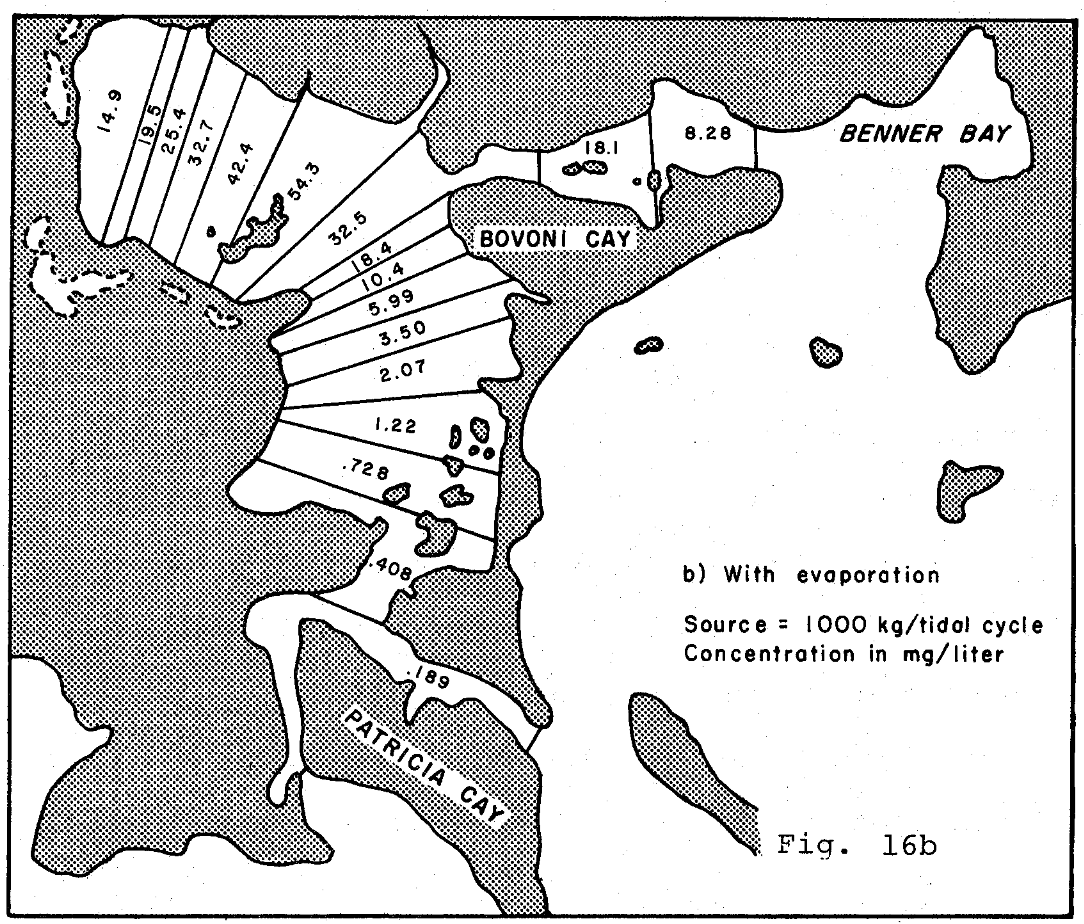


Fig. 16b

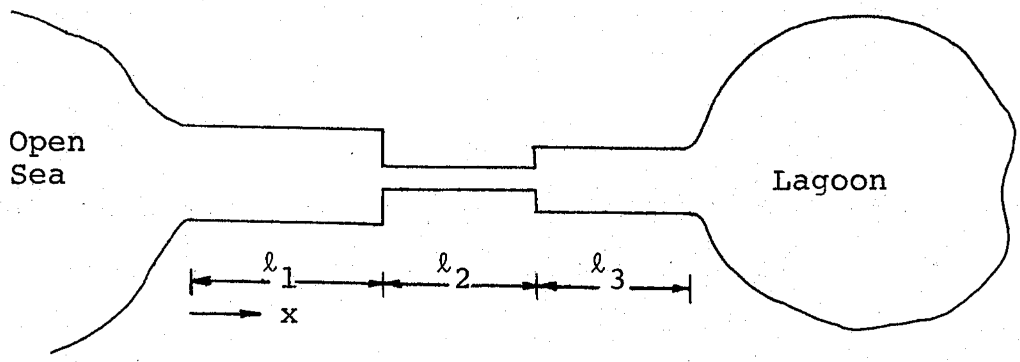
C. Application to Altona Lagoon

Altona Lagoon is a small enclosed body of water on the northern coast of St. Croix, U. S. Virgin Islands which lies to the east of Christiansted Harbor. The 1924-1926 survey by U. S. Coast and Geodetic Survey shows a free opening from the lagoon to the Christiansted Harbor. Currently, a highway running along a strip of broad sand beach connects Fort Louise Augusta to the upland, separating the lagoon from the harbor. A culvert underneath the highway is the only normal connection between the lagoon and harbor. This opening severely limits the exchange of water between the lagoon and the harbor. Consequently flushing capability of the lagoon is impaired and water quality deteriorated.

1. Calculation of Tidal Exchange

Since King's formulation, equation (I-1), was derived based on the assumption that the inlet connecting two broad bodies of water has a uniform cross-section, it cannot be applied directly to the Altona Lagoon. The lagoon is connected to the Christiansted Harbor via a narrow channel as well as a culvert in series. Both offer restriction to the tidal propagation. Therefore, King's derivation of equation (I-1) tends to be modified to account for the changing cross-section along the passage of inlet.

As shown in the following sketch the embayment is connected to the open sea through a series of channels of different cross-sections. The equation



of motion for fluid flow in the channels may be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} - \frac{f}{8R}\, u|u| \qquad \text{(IV-1)}$$

where u is velocity, η is water surface elevation and R is hydraulic radius.

The equation may be integrated over the entire length of the channels from ocean entrance to the bay end of the inlet. To perform the integration, it is assumed that the length of tidal wave is much longer than the length of inlet and that the velocity in each channel is constant. Carrying out the integration over each channel separately, it is obtained that

$$\sum_{i=1}^{n} \ell_i \frac{\partial u_i}{\partial t} = -g(\eta_b - \eta_o) - \sum_{i=1}^{n} \left(\frac{\alpha_i}{2} + \frac{f_i \ell_i}{8R_i}\right) u_i |u_i| \qquad \text{(IV-2)}$$

where n is the number of channels, ℓ_i, u_i, f_i and R_i are the length, velocity, friction coefficient and hydraulic radius, respectively, of the ith channel; η_o and η_b are the surface elevations at the ocean entrance and in the bay respectively. α_i is the coefficient relevant to the advective acceleration, or the energy loss over channel transition; $\alpha_i \rightarrow 1.0$ as $A_i/A_{i+1} \rightarrow 0$, where A_i and A_{i+1} are cross-sectional areas of the ith and (i+1)th channels.

The last term in equation (IV-2) is nonlinear, which may be approximated with a linear term on the constraint that the energy dissipated over a tidal cycle be the same for linear and nonlinear models (Ippen, 1966). The result is

$$\sum_{i=1}^{n} \ell_i \frac{\partial u_i}{\partial t} = -g\ (\eta_b - \eta_o) - \sum_{i=1}^{n} M_i u_i \tag{IV-3}$$

$$M_i = \frac{8}{3\pi} \left(\frac{\alpha_i}{2} + \frac{f_i \ell_i}{8R_i}\right) U_i \tag{IV-4}$$

where U_i is the amplitude of tidal current in the ith channel. If the surface elevation at the ocean entrance is described by a sinusoidal function

$$\eta_o = \eta(0,t) = a_o \sin\omega t \tag{IV-5}$$

then the velocity in the channels and tidal variation in the bay may be written as

$$u_i = U_i \sin(\omega t + \theta_i) \tag{IV-6}$$

$$\eta_b = \eta(\ell,t) = a_b \sin(\omega t + \beta) \tag{IV-7}$$

The continuity condition requires that

$$u_i A_i = S\frac{\partial \eta}{\partial t} \quad \text{at } x=\ell, \text{ for all } i \tag{IV-8}$$

where S is the surface area of the embayment and $\ell = \sum_{i=1}^{n} \ell_i$, the total length of the channels.

Substituting equations (IV-6) and (IV-7) into equation (IV-8), it is obtained that

$$U_i A_i = S a_b \omega, \quad \text{and} \tag{IV-9}$$

$$\theta_i = \frac{\pi}{2} + \beta \quad \text{for all } i \tag{IV-10}$$

Let $\theta = \theta_i$, and substitute equations (IV-5), (IV-6), (IV-7) and (IV-10) into equation (IV-3), the following relationship may be arrived after lengthy algebraic manipulation,

$$\left(\sum_{i=1}^{n} M_i U_i / g a_o\right)^2 + \left(\frac{a_b}{a_o} - \sum_{i=1}^{n} \ell_i \omega U_i / g a_o\right)^2 = 1 \tag{IV-11}$$

Substituting M_i and U_i from equations (IV-4) and (IV-9), equation (IV-11) may be simplified to

$$\left(\sum_{i=1}^{n} F_i A r_i^{\,2} W_i d_i \left(\frac{a_b}{a_o}\right)^2\right)^2 + \left(1 - \sum_{i=1}^{n} W_i A r_i\right)^2 \left(\frac{a_b}{a_o}\right)^2 = 1 \tag{IV-12}$$

where the non-dimensional parameters

$$F_i = \frac{1}{3\pi}\left(f_i + \alpha_i \frac{4R_i}{\ell_i}\right)$$

$$Ar_i = \frac{S}{A_i}$$

$$W_i = \ell_i \omega^2 \tag{IV-13}$$

$$d_i = \frac{a_o}{R_i}$$

By grouping these parameters, equation (IV-12) may be further simplified to

$$K_1^2 \left(\frac{a_b}{a_o}\right)^4 + K_2^2 \left(\frac{a_b}{a_o}\right)^2 - 1 = 0 \tag{IV-14}$$

where

$$K_1 = \sum_{i=1}^{n} F_i Ar_i{}^2 W_i d_i$$

$$K_2 = 1 - \sum_{i=1}^{n} W_i Ar_i$$

Finally, the solution to equation (IV-14) is

$$\frac{a_b}{a_o} = \left(\frac{-K_2^2 + \sqrt{K_2^4 + 4K_1^2}}{2K_1^2} \right)^{1/2}, \qquad \text{(IV-15)}$$

which may be used to calculate the tidal response, a_b, inside an embayment in terms of the parameters in equation (IV-13).

Two sets of tidal measurements were conducted for the Altona Lagoon to calibrate the friction coefficient and verify the applicability of equation (IV-15). On August 8-9, 1977, the tidal range in the lagoon was observed to be 7.4 cm while the forcing tide in the Christiansted Harbor had a range of 22.9 cm. The culvert under the highway is 14m long with a diameter of 1.83m (6 ft.). It was also observed that a 33.5 cm layer of sand was deposited in the culvert and the mean water level was 61 cm below the top of culvert. To apply equation (IV-15), the passage between the lagoon and harbor was considered to compose of two parts, the culvert and a channel of uniform cross-section. The following are the pertinent data used in evaluating the parameters:

a_o = 11.45 cm, $\omega = 7.27 \times 10^{-5}$/sec, $S = 4.8 \times 10^5 m^2$

for the culvert,

$\ell_1 = 14\text{m}$, $A_1 = 1.53\ \text{m}^2$, $R_1 = 0.46\ \text{m}$, $\alpha_1 = 1$,

$f_1 = 0.02$, the average value for unfinished concrete, for the channel,

$\ell_1 = 204\ \text{m}$, $A_2 = 3.4\ \text{m}^2$, $R_2 = 0.46\ \text{m}$, $\alpha_2 = 1$,

$f_2 = 0.07$, the average value for natural earth channel. With these data, equation (IV-15) predicted that $\frac{a_b}{a_o} = 0.347$, compared fairly with the measured value of 0.322.

A tidal range of 10.2 cm was observed in the lagoon on December 4, 1978 while the forcing tide in the Christiansted Harbor was 33.0 cm, a spring tide condition. No sediment deposit was observed in the culvert, and the mean water level was 61 cm below the top of culvert. The following values were used for calculation,

$a_o = 16.5\ \text{cm}$,

$A_1 = 1.86\ \text{m}^2$, $R_1 = 0.53\ \text{m}$

and the other data were the same as the previous case. Equation (IV-15) predicted that $\frac{a_b}{a_o} = 0.312$, compared very well with the observed value of 0.308.

To calculate the tidal response in the lagoon to the mean tide in the Christiansted Harbor, it is assumed that no sediment is deposited in the culvert. The mean tidal range in the harbor is 24.4 cm (NOS, 1978), and equation (IV-15) predicts that the tidal range in the lagoon will be 8.8 cm. Equation (IV-15) may also be used to calculate the tidal response in the lagoon with the assumption that the culvert is replaced by a bridge and the channel runs underneath the highway without changing cross-section. Under the mean tide condition, the tidal range in the lagoon will be 10 cm.

2. Application of Tidal Flushing Model

The model was applied to the Altona Lagoon with two tidal conditions, and the pollution susceptibilities for the two cases were calculated and compared. The tidal conditions used for the model application were 8.8 cm and 10.0 cm tidal ranges respectively. The tidal range of 8.8 cm is the tidal response of the Altona Lagoon to the mean tide in the Christiansted Harbor, with the existing culvert and waterway connecting them. The 10 cm tidal range is the tidal response with assumption that the culvert is replaced with a bridge, thus allowing the waterway to run straight through without a reduction in cross-section.

The lagoon was segmented according to the principle presented in Section II-B. Figures 17a and 17b show the lagoon segmentations under the two tidal conditions respectively. The dashed line along the center of the lagoon was chosen as axis along which the distance was measured. The accumulated volume and tidal prism as function of distance are shown in Figure 18, which also demonstrates the process and principle of segmentation.

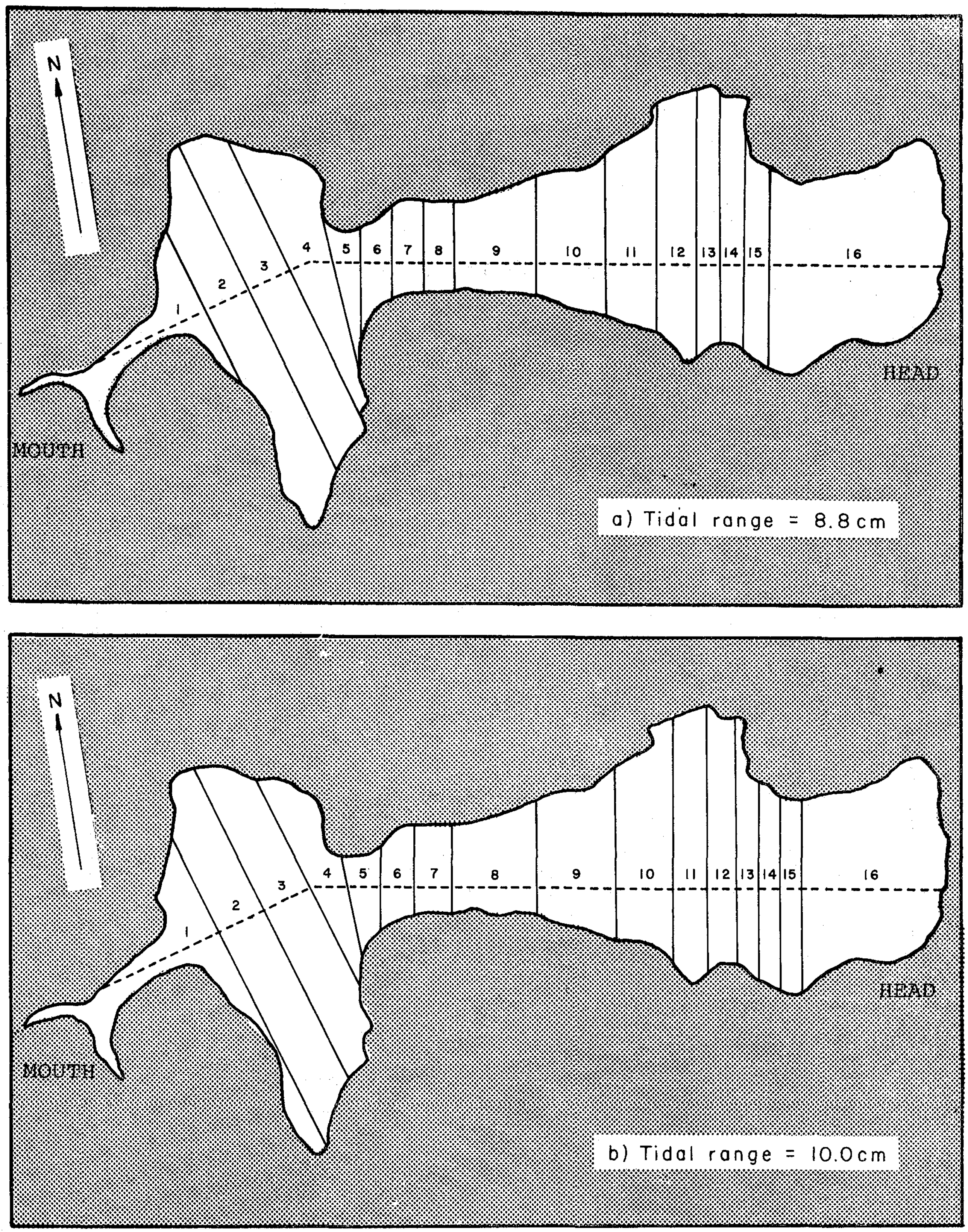


Figure 17. Segmentation scheme for Altona Lagoon.
A. upper, for 8.8 cm tide range and
B. lower, for 10.0 cm tide range.

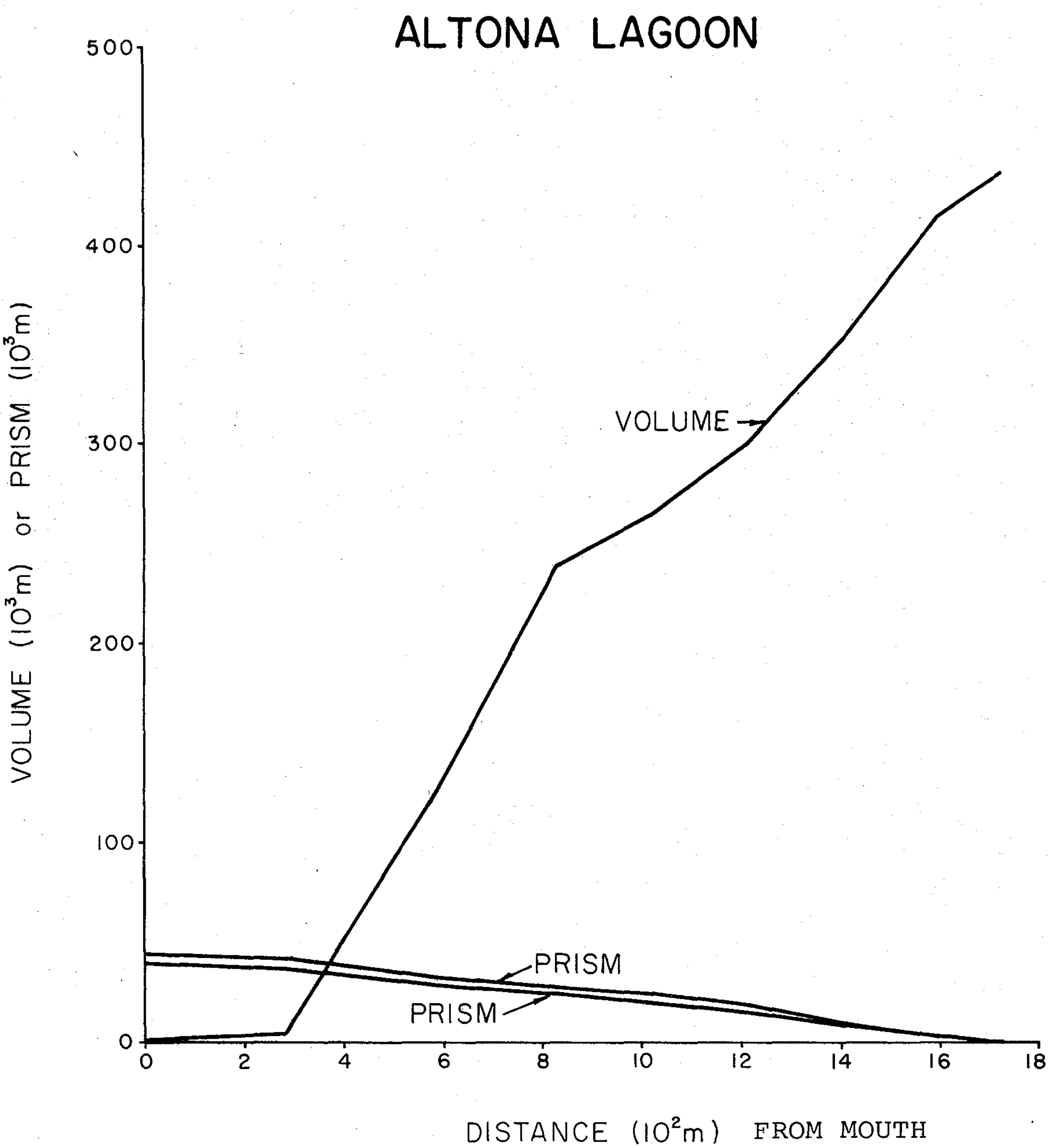


Figure 18. Accumulated volume and tidal prism of the Altona Lagoon.

Table 5. Segment Volumes and Flushing Rates of the Altona Lagoon

Segment Number	Tidal Range = 8.8 cm Volume $Vh_n(=P_n), 10^4 m^3$	Flushing Rate γ_n, 1/tide*	Tidal Range = 10.0 cm Volume $V_n(=P_n), 10^4 m^3$	Flushing Rate γ_n, 1/tide*
1	3.98	1.0	4.53	1.0
2	3.60	0.524	4.05	0.525
3	3.33	0.362	3.70	0.365
4	3.07	0.281	3.38	0.287
5	2.87	0.232	3.20	0.231
6	2.77	0.194	3.07	0.195
7	2.67	0.167	2.95	0.169
8	2.57	0.148	2.83	0.150
9	2.48	0.133	2.55	0.142
10	2.25	0.128	2.20	0.142
11	1.98	0.127	1.86	0.143
12	1.71	0.128	1.63	0.141
13	1.50	0.127	1.43	0.138
14	1.34	0.125	1.26	0.135
15	1.20	0.122	1.11	0.133
16	1.07	0.012	0.99	0.015

*The flushing rate is the fraction of pollutant removed from the segment in one complete tidal cycle, which is 24 hours in this case. For example, 12.8% of pollutant in segment 10 is removed over every tidal cycle if the tidal range is 8.8 cm.

The flushing rate of each segment was calculated with equation (II-4), and presented in Table 5. The segment volumes are also listed in Table 5.

To calculate pollution susceptibility, a point source of 1 ton/day is assumed to discharge pollutant at the head of the lagoon. The resulting concentration distributions were calculated with equation (II-3a), in case of conservative pollutant, and with equation (II-9), in case of nonconservative pollutant. The results are presented with iso-concentration curves in Figures 19 to 22.

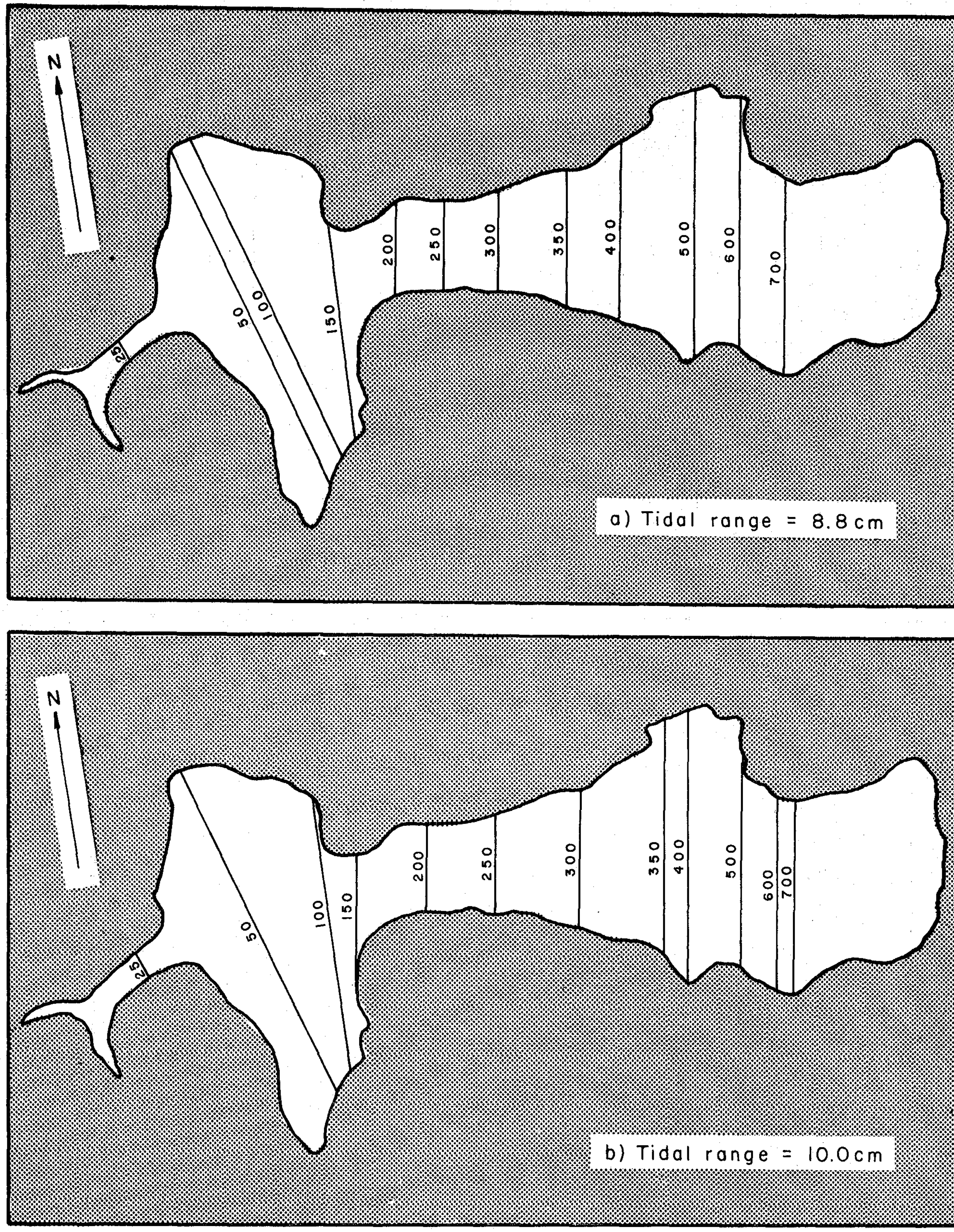
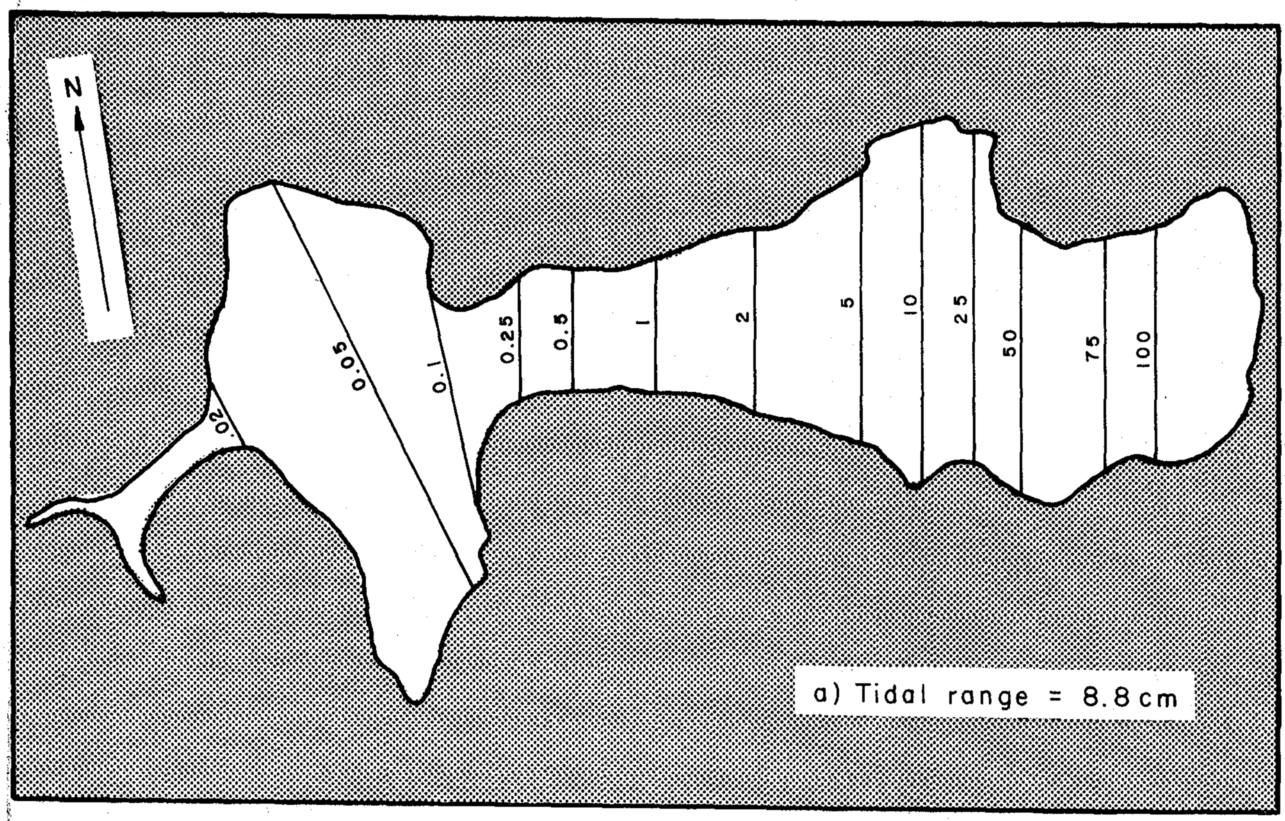


Figure 19. Pollution susceptibility of the Altona Lagoon for a conservative pollutant, source = 1000 kg/tidal cycle, concentration in mg/ℓ. A. upper for 8.8 cm tide range; B. lower for 10.0 cm tide range. Numbers in segments are average concentrations in mg/l.



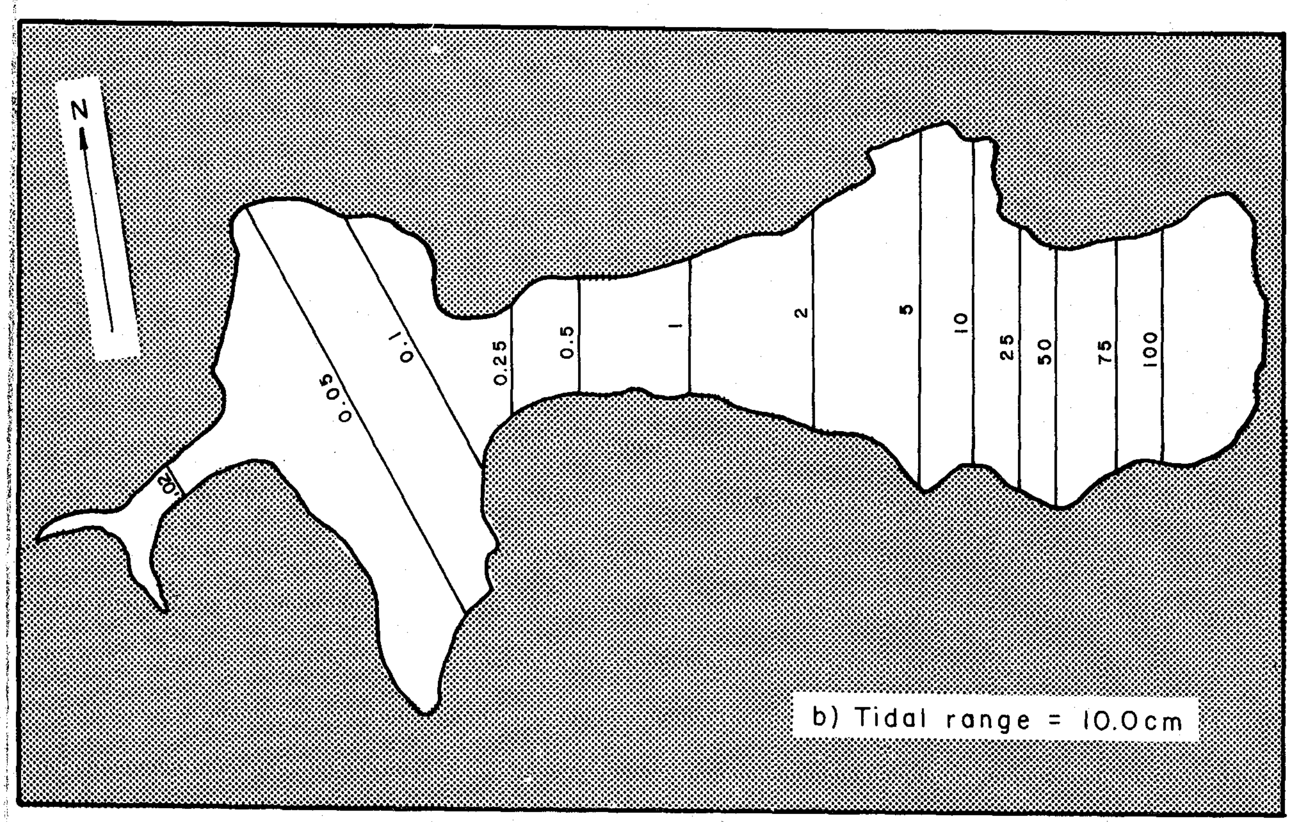


Figure 20. Pollution susceptibility of the Altona Lagoon for a nonconservative pollutant, decay rate = 0.1/tidal cycle, source = 1000 kg/tidal cycle, concentration in mg/ℓ. A. upper, for 8.8 cm tide range; and B. lower, for 10.0 cm tide range. Numbers in segments are average concentrations in mg/l.

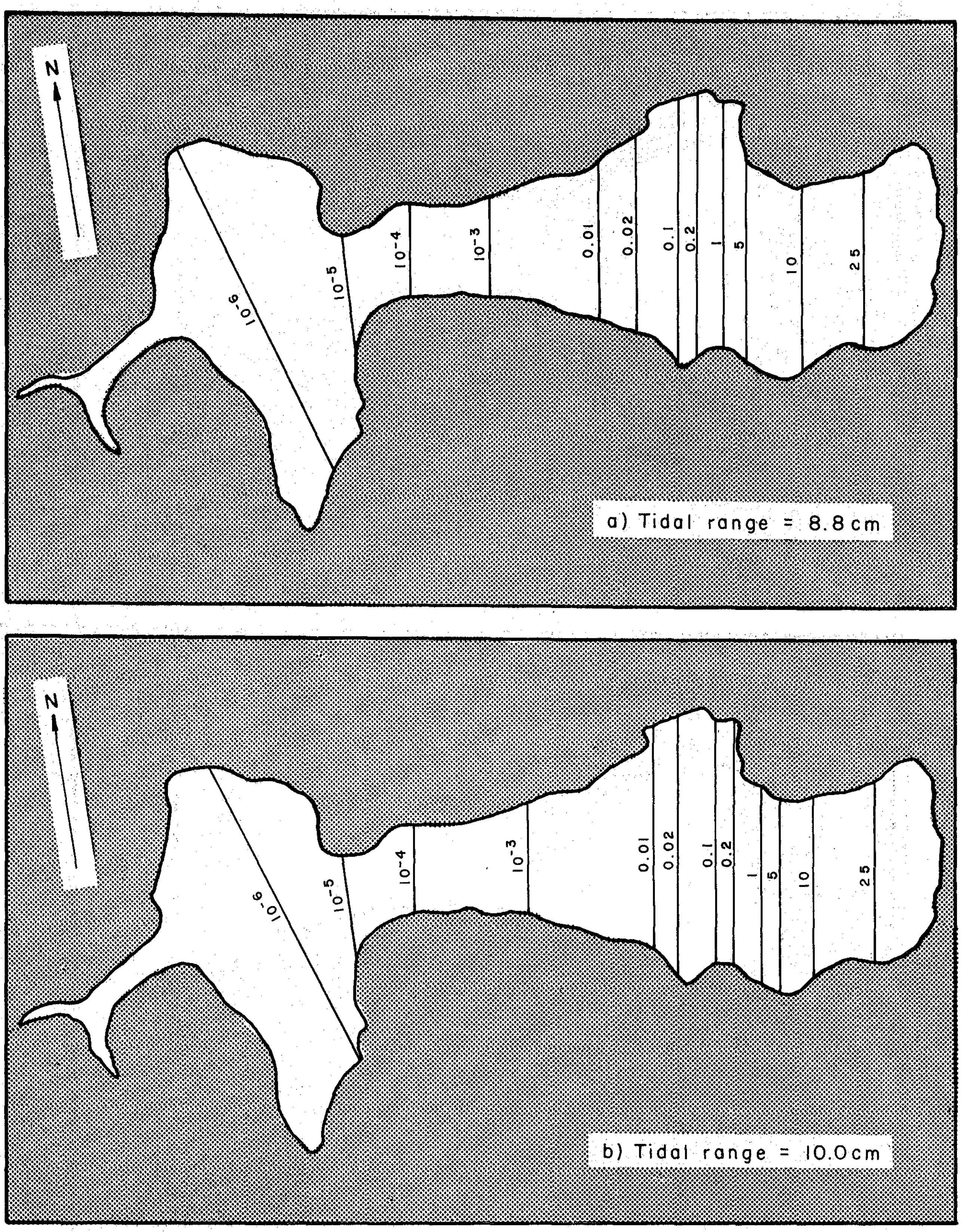


Figure 21. Pollution susceptibility of the Altona Lagoon for a nonconservative pollutant, decay rate = 0.5/tidal cycle, source = 1000 kg/tidal cycle, concentration in mg/ℓ. A. upper for 8.8 cm tide range and B. lower for 10.0 cm tide range. Numbers in segments are average concentrations in mg/l.

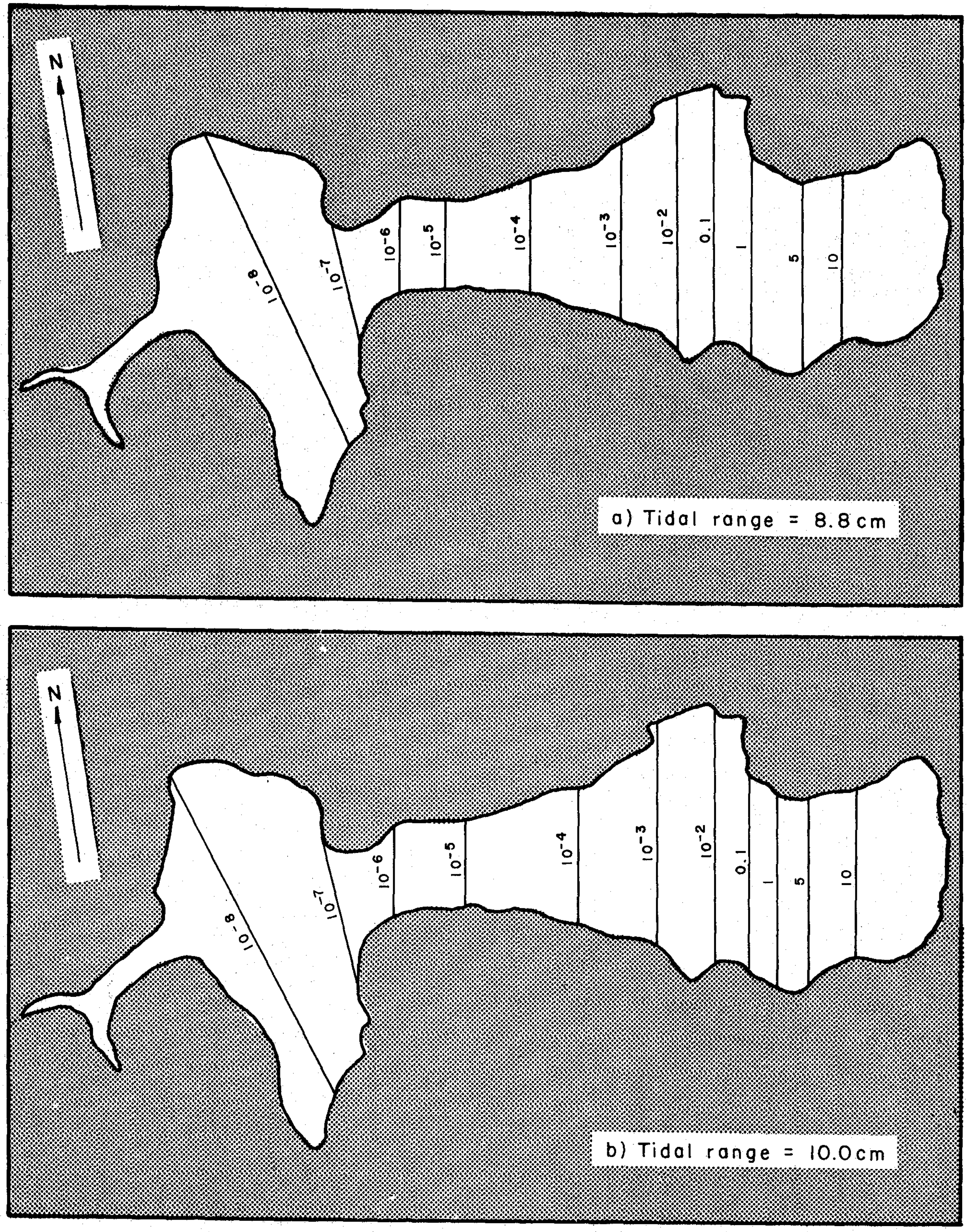


Figure 21. Pollution susceptibility of the Altona Lagoon for a nonconservative pollutant, decay rate = 1.0/tidal cycle, source = 1000 kg/tidal cycle, concentration in mg/ℓ. A. upper for 8.8 cm tide range, B. lower for 10.0 cm tide range. Numbers in segments are average concentrations in mg/l.

D. Summary

A model of tidal flushing is presented with its basic theory of tidal prism. The procedures of segmenting the lagoon and calculating the pollutant concentration are described in detail. Furthermore, the effect of excess evaporation on flushing capability is investigated.

The model is applied to the Mangrove Lagoon and the Altona Lagoon of U. S. Virgin Islands. King's (1974) shallow water wave model of the inlet tidal dynamics is modified and adapted to the particular geometric conditions of the two lagoons. The shallow water wave model calculates the flow through the inlets to the lagoons and provides the basic data for the tidal flushing model.

The results of the model are presented with pollution susceptibility, or unit response. The pollutant concentrations, in milligrams per liter, which would result from a pollutant loading of 1 metric ton per tidal cycle (equivalent to 1 metric ton per day in this case) are calculated and presented for pollutants with decay rates of 0.0, 0.1, 0.5 and 1.0 per day. For practical applications, the pollution susceptibility may be linearly scaled up or down for a given waste loading. For example, if a conservative pollutant is discharged from the Turpentine Run at a rate of 5,000 kg per day, the resulting concentration distribution may be obtained by multiplying the values in figure 15A by five. Therefore, the concentration landward from the Turpentine Run would be 331 mg per liter and that of Cas Entrance Reach would be 10.9 mg per liter.

A hypothetical case is investigated for the Altona Lagoon. The average tidal range in the lagoon would increase from 8.8 cm to 10 cm if the culvert restricting the lagoon entrance where replaced by a bridge. The pollution susceptibility corresponding to this increased tidal range is calculated and presented.

9. Runoff Impact in Closed Bays and Salt Ponds

When bays are sealed off from the sea by sand or cobble barriers or by growths of mangroves, hydrology of the enclosed pond is markedly affected by direct runoff and evaporation. Only during extreme storms is the barrier topped by flood waters from the land or by waves and storm surges from the sea. In some ponds water may enter from the sea by subsurface percolation through the barrier. The ponds are a virtual trap for sediment and water supplied by streams. Additionally, chemical constituents are concentrated by evaporation. Consequently, pollution susceptibility is higher than in restricted lagoons or partly-closed bays.

Because the ponds are mainly linked to watershed drainage, their susceptibility to pollution depends on characteristics of the watershed area, runoff, soils, slope and pollution generation rate. Tidal characteristics, such as used for the partly-closed bays, are not applicable to ponds sealed off from the ocean. Instead an impact parameter is developed to provide a means of comparing the relative magnitude of impacts in different ponds. Basically, the methods utilizes existing stormwater runoff procedures and data which were compiled for the islands by Black, Crow and Eidsness (1976). Following their computational procedures:

1. The total drainage area of watershed landward of the pond is determined utilizing U.S.G.S. topographic maps or the areas already calculated by BC & E (1976)

2. Compute the coefficient called a CN value (B C & E, 1976) which is a measure of the watersheds potential runoff. A table modified for different land uses is provided, B C & E, Table A1. The coefficient is further adjusted by a slope adjustment factor following B C & E's, Table A2. As non-point source pollution data become available for the Virgin Islands, the CN value could be modified further by multipling the value by a pollutant generation coefficient such as sewage generation coefficients for different land uses used by Holzmacher, McLendon and Murrell (1975).

3. The product of the adjusted CN coefficient and the corresponding drainage area gives a runoff impact parameter for the pond watershed. As new data become available an average runoff for different watersheds and storage capacity of the ponds, it should be possible to determine the concentrations that can result from a unit discharge.

Table 6 gives the impact parameters determined for selected salt ponds.

Table 6. Watershed pond areas and impact parameters for selected salt ponds.

St. Thomas	Pond Area km^2	Drainage Area, km^2	CN Value	Impact Parameter
Sprat Point	.009	.026	85	2
Water Island	.007	.037	81	3
Bolongo Bay	.005	.193	85	16
East Gregerie	-	.037	84	3
Cabrita Hill, west	0.017	.023	86	2
Cabrita Hill, east(2)	0.007	.043	86	4
Vessup Bay	0.029	.695	85	59
St. John				
Enighed Salt Pond	.086	.544	80	43
Chocolate Hole	.039	.478	87	42
Hart Bay	.011	.088	87	8
Europa Bay	.055	.450	77	35
Grootpan Bay	.097	1.353	77	104
Concordia	.023	.338	79	27
Southside	.039	.146	78	11
Privateer Bay	.003	.081	78	6
Newfound Bay	.030	.148	79	12
St. Croix				
Robin Bay Salt Pond	-	.993	83	82
Coakley	-	1.176	84	98
Prune Bay	-	.081	85	7
Westend	-	1.956	85	166

10. Recommendations

a. Monitoring of water quality in Virgin Island bays should be continued to provide information on which to base year-to-year changes throughout the bay systems. The surveys would be enhanced by measurement of nutrient concentrations for 3 months during and following periods of runoff.

b. Discharge of pollutants into the inner parts of the bays should be avoided. The possibility of programing sewage discharges to avoid periods of low flushing or runoff and concentrate during periods of high flushing and maximum dispersion, should be examined.

c. Additional studies are need to determine the pollution susceptibility of salt ponds as it relates to runoff potential, land use, episodic runoff from the watershed or storm surges from the sea. Almost nothing is known about the water quality and storage capacity of the more than 60 salt ponds, all of which have a high pollution susceptibility.

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12. Acknowledgements

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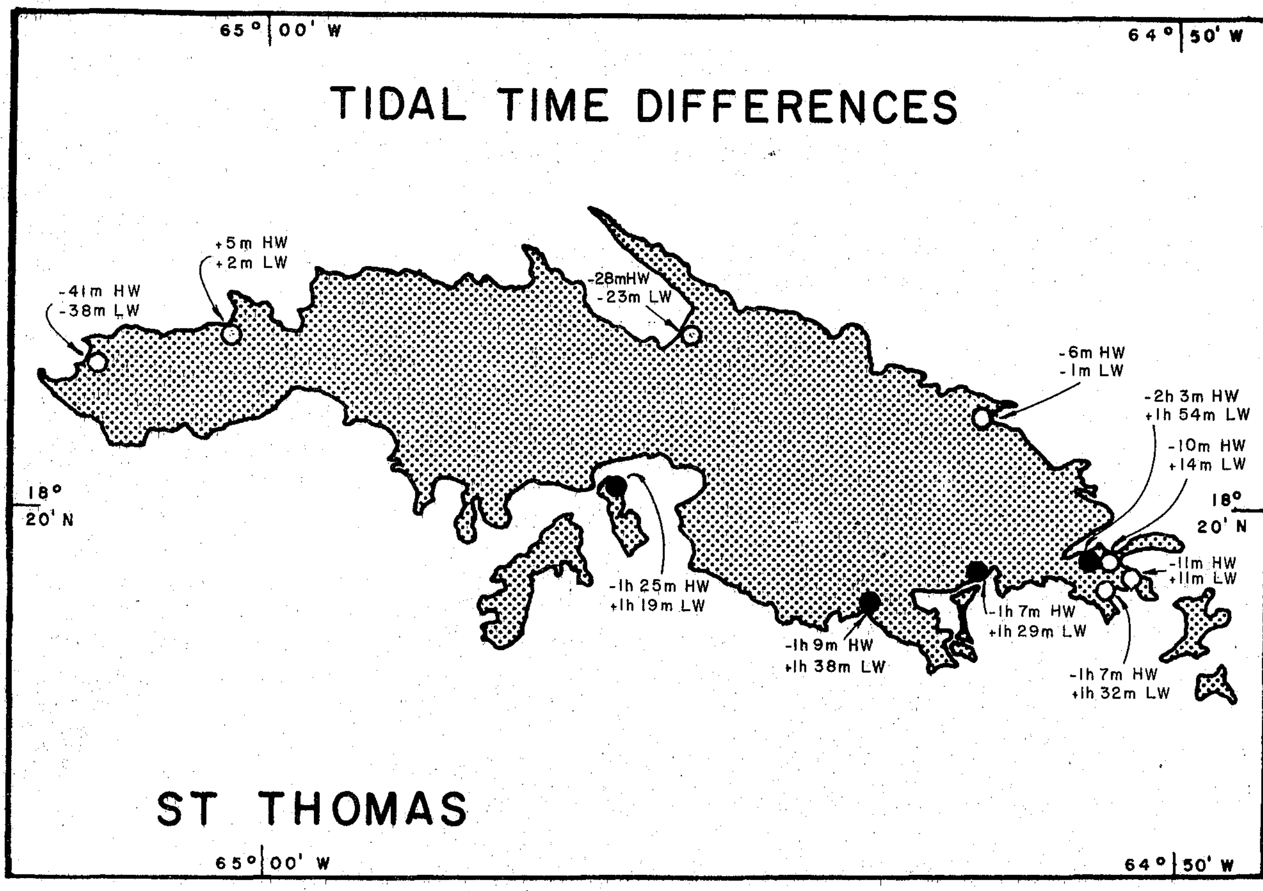
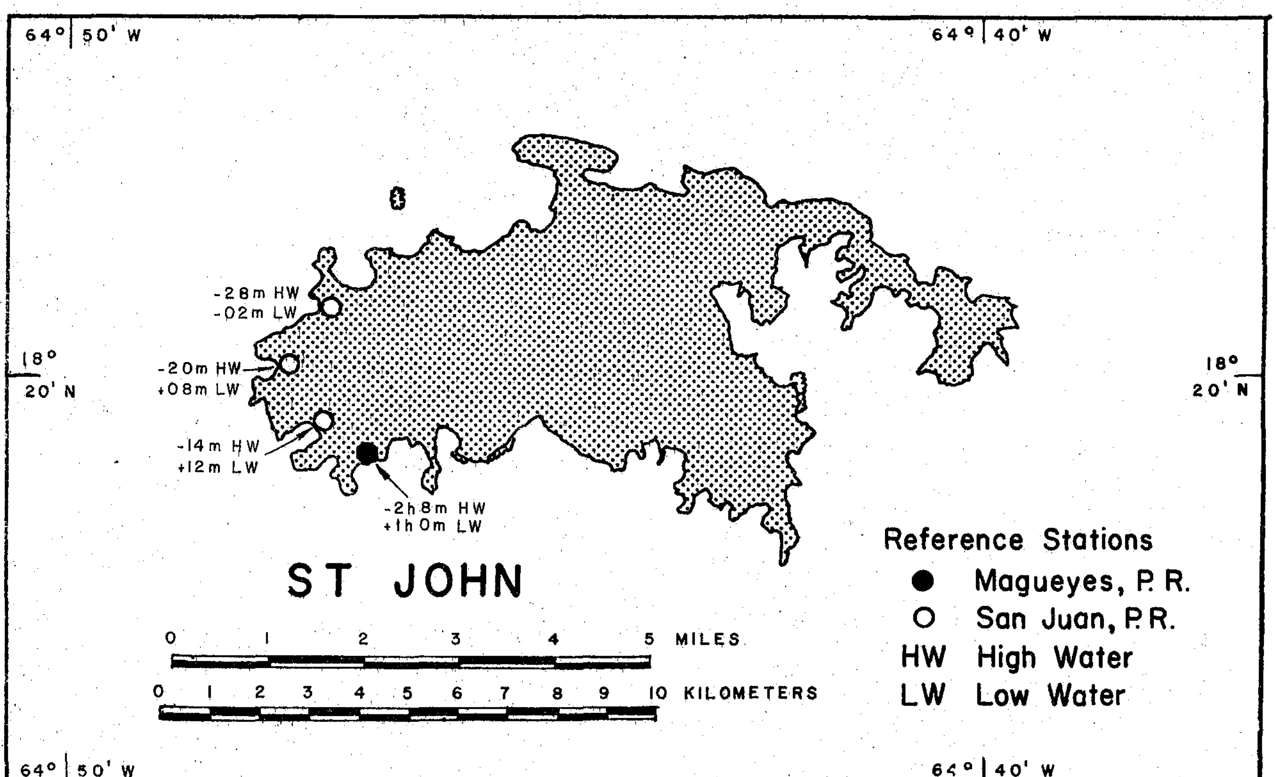




Appendix 1. Tidal time differences for St. Thomas and St. John based on reference stations at Magueyes, P.R. and San Juan, P.R. From NOS file data.

APPENDIX 2

Definition of Terms

Conservative: A water property whose value changes only by physical processes, mainly mixing. Heat content and salinity are examples of conservative properties. They are affected by diffusion and current advection but not by living organisms. Their decay rate is zero. A conservative pollutant is one that is not removed from the water by physical, chemical or biological mechanisms.

Decay: The fraction of a substance, e.g. a contaminate, that decomposes and breaks down per unit time; usually expressed as per hour or per day. For example, in a sewage effluent, coliform bacteria change with time and distance due to their mortality.

Flushing rate: The rate at which water in a bay or lagoon is replaced. Flushing rate is equal to the reciprocal of the flushing time.

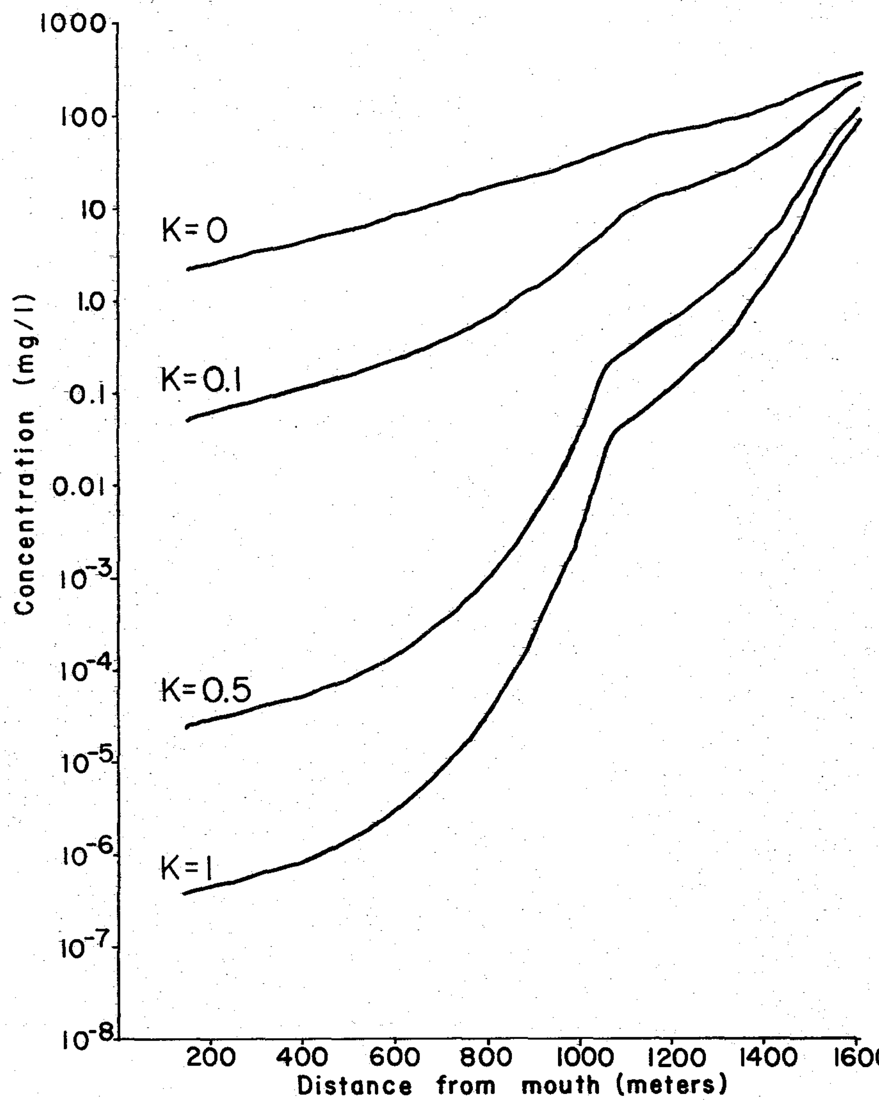
Flushing time: A measure of the time required to replace the existing water in a bay or lagoon with an equal amount of "new" ocean water or a volume of river water. Usually expressed as the time for one complete replacement as one tidal cycle.

Non-conservative: A water property whose value changes by biological and chemical processes. Dissolved oxygen and dissolved phosphate are examples of non-conservative properties. They are affected by processes of photosynthesis and organic metabolism. Their decay rate is not equal to zero.

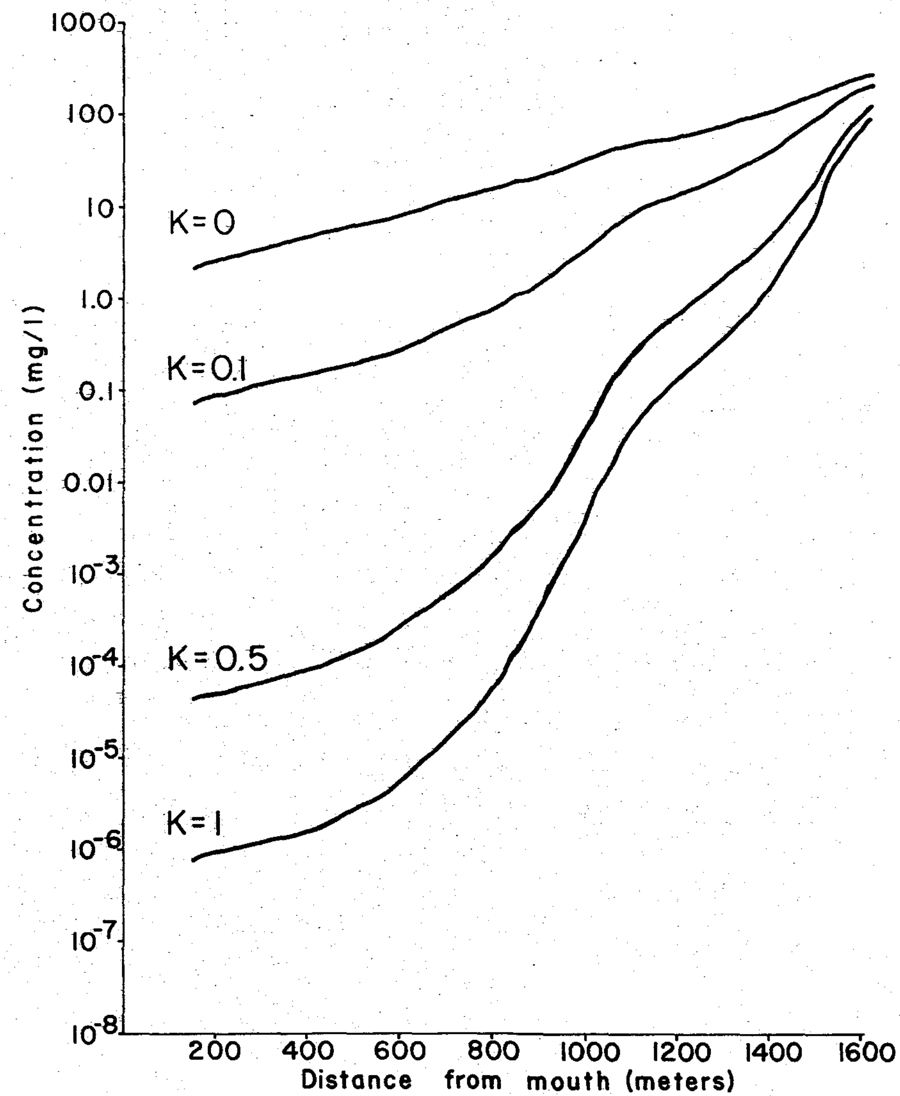
Pollution susceptibility: The average concentration of a pollutant in a bay or lagoon that would result from a unit rate of discharge or flux. It is the reciprocal of the discharge rate (flux) or time per unit mass.

Steady state: The absence of change with time. For example, the continuous discharge of a pollutant.

Tidal prism: The volume of bay water contained between the plane of low water and the plane of high waters; that is, the intertidal volume.

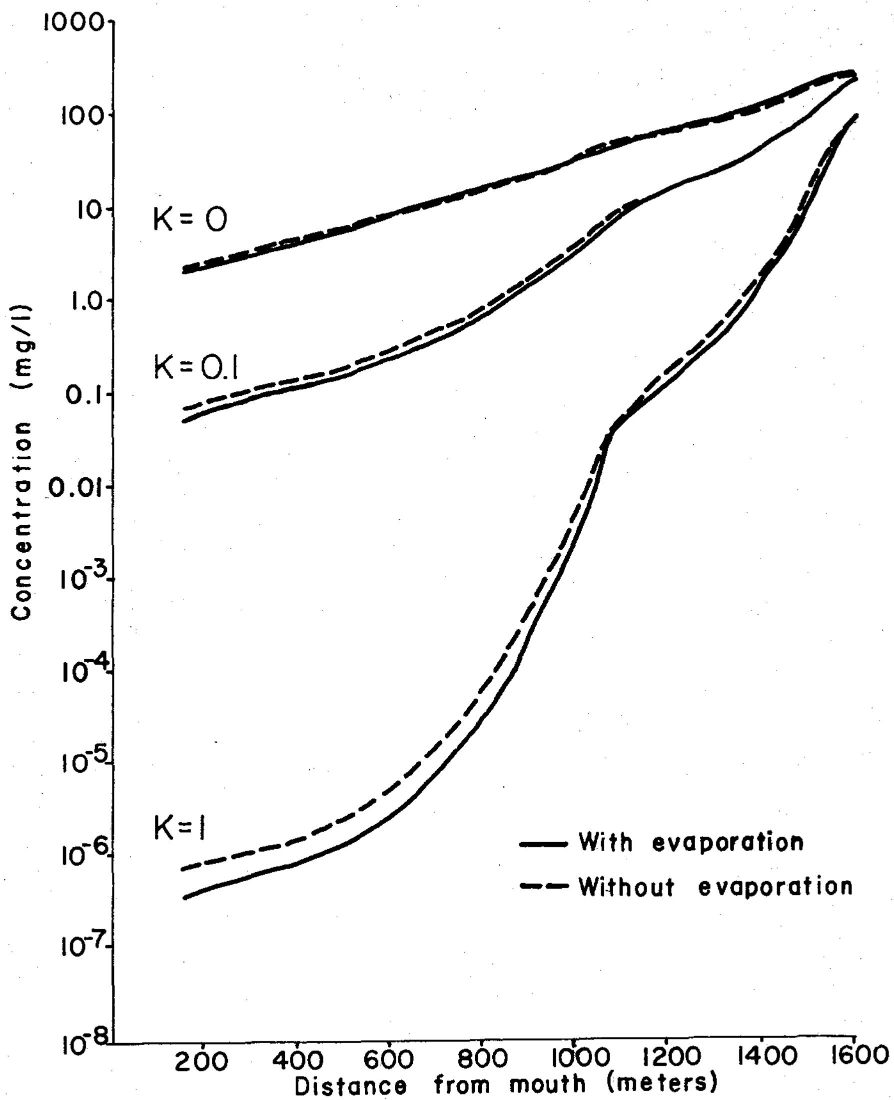


A1. Pollution susceptibility of the Mangrove Lagoon with pollutant discharged at the lagoon head, with evaporation.

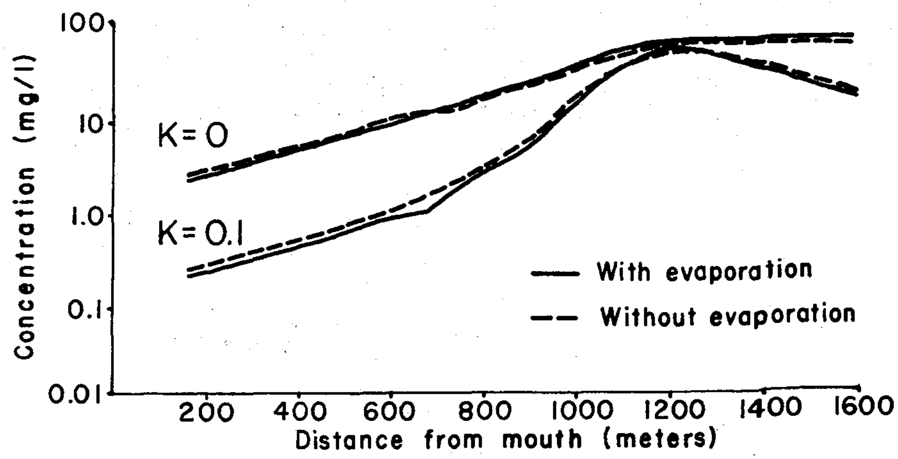


A2. Pollution susceptibility of the Mangrove Lagoon with pollutant discharged at the lagoon head, without evaporation. k is the decay rate, $\frac{1}{\text{day}}$.

APPENDIX 3

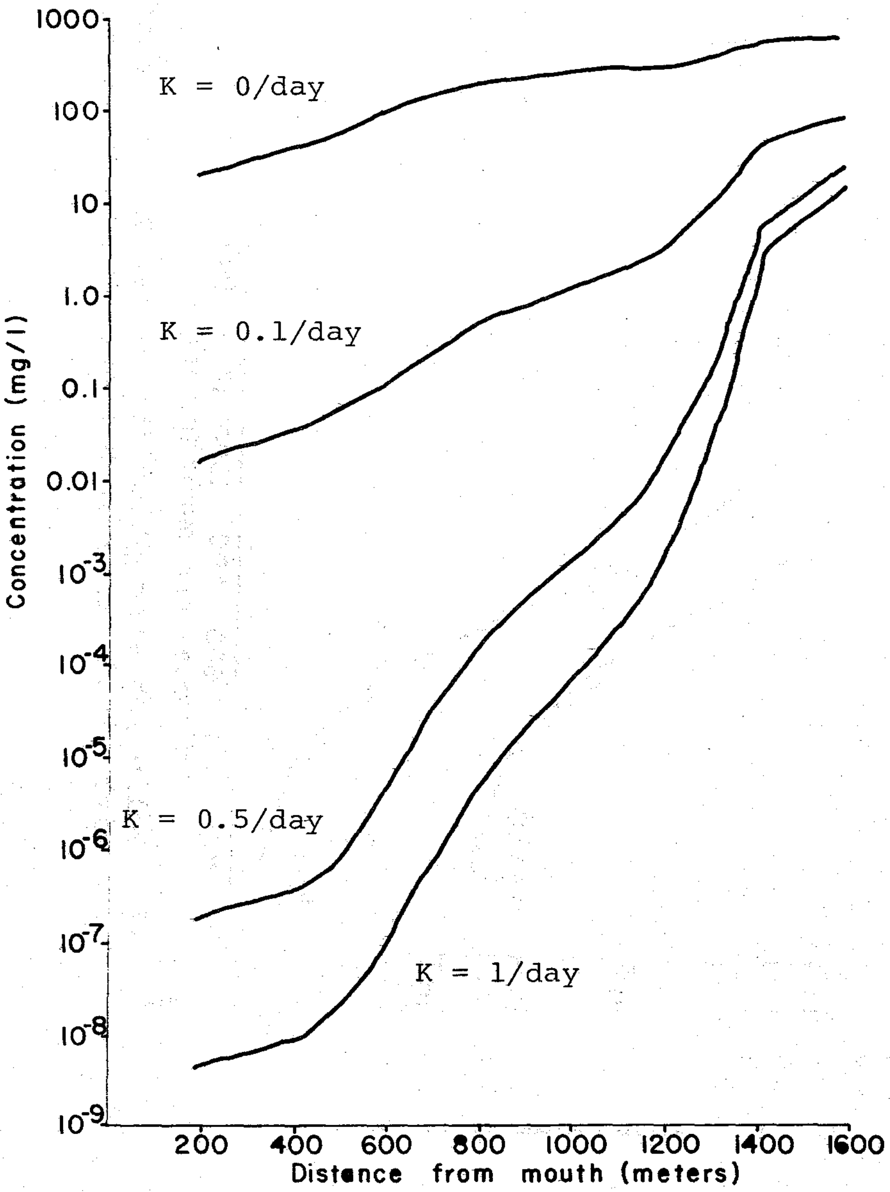


A3. Comparison of pollution susceptibility of the Mangrove Lagoon with and without evaporation. k is the decay rate, $\frac{1}{\text{day}}$.

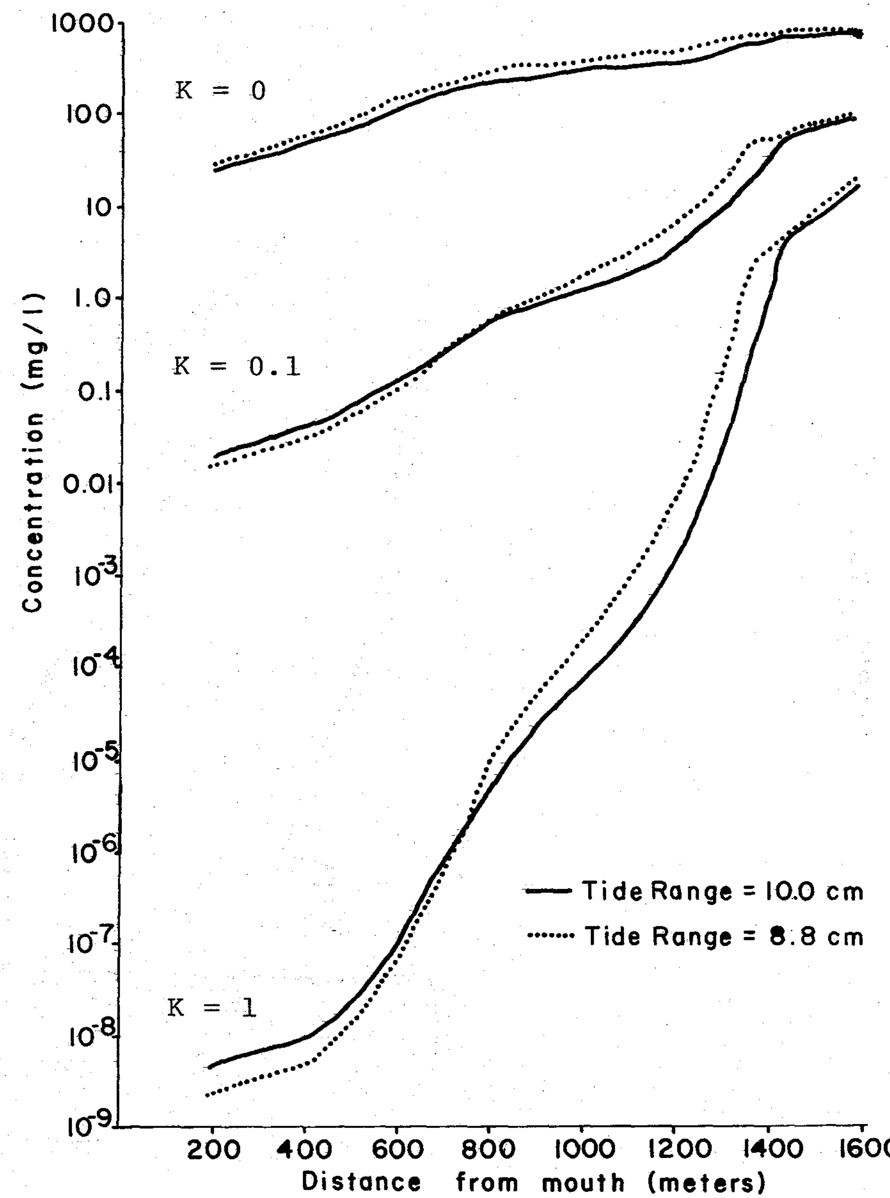


A4. Pollution susceptibility of the Mangrove Lagoon with pollutant discharged from the Turpentine Run, with and without evaporation.

APPENDIX 3



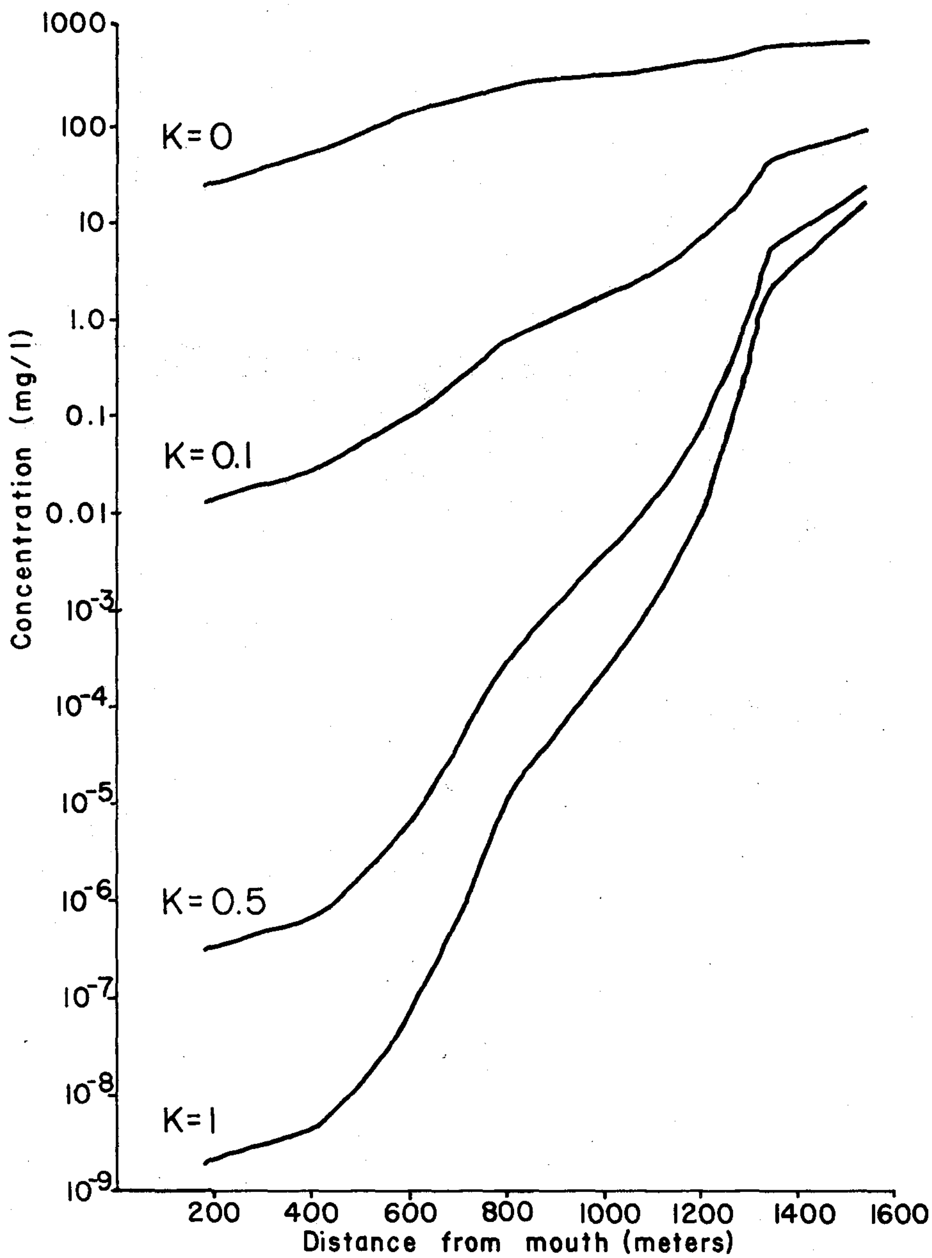
A5. Pollution susceptibility of the Altona Lagoon with tidal range of 10.0 cm.



A6. Comparison of pollution susceptibility of the Altona Lagoon with tidal ranges of 8.8 cm and 10.0 cm.

APPENDIX 3

APPENDIX 3



A7. Pollution susceptibility of the Altona Lagoon with tidal range of 8.8 cm. k is the decay rate.