PORT OF BRISBANE SILTATION STUDY

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SUMMARY

The paper describes the constituent parts of a combined field and mathematical model investigation into the processes causing siltation in the Port of Brisbane. It describes the methods of collecting and using field data and laboratory results in conjunction with a variety of mathematical models which were employed to simulate and predict the interaction of tidal and fluvial flows, saline intrusion and sediment transport in the Brisbane tidal river. A newly developed X-Z-T model was used to simulate the unsteady patterns of mud transport and siltation resulting from the interaction of tidal flows with short flashy fluvial floods, which are the main cause of shoaling in the Port. The paper discusses the structuring of the investigation which involved a carefully phased schedule of desk, field, laboratory and mathematical model investigations with the aim of solving the problem with minimum effort and cost. The paper does not discuss predictions.

INTRODUCTION

The recently formed Port of Brisbane Authority (PBA) is developing new port facilities on Fisherman Islands near the mouth of the Brisbane tidal river. The proposed work in the estuary includes lengthening, deepening and widening the existing swing basin area, and deepening the approach channel. PBA also wish to cease or reduce maintenance dredging upstream in the existing port area some 19km from Moreton Bay, Fig 1. In January 1977, PBA commissioned the Hydraulics Research Station (HRS) at Wallingford in the UK to undertake a field and mathematical model study to determine the processes causing siltation in the Port and to predict the effects of the proposed engineering works on sediment transport and siltation in the tidal river. This paper only deals with the collection and use of the field data in developing a variety of mathematical models for simulating and quantifying the processes causing siltation in the Port. The paper describes the structuring of the investigation which involved a carefully phased schedule of desk, field, laboratory and mathematical model investigations with the aim of solving the problem with minimum effort and cost. It does not discuss predictions.

Mr Baxter is the Assistant General Manager for the Port Authority with responsibilities for planning and development of new port facilities. Mr Odd was responsible for the technical direction of the project at HRS, which had about twelve constituent parts involving fifteen different specialists at HRS. The project also involved a number of staff of the Port Authority who carried out a series of observational programmes in the period 1977/79.

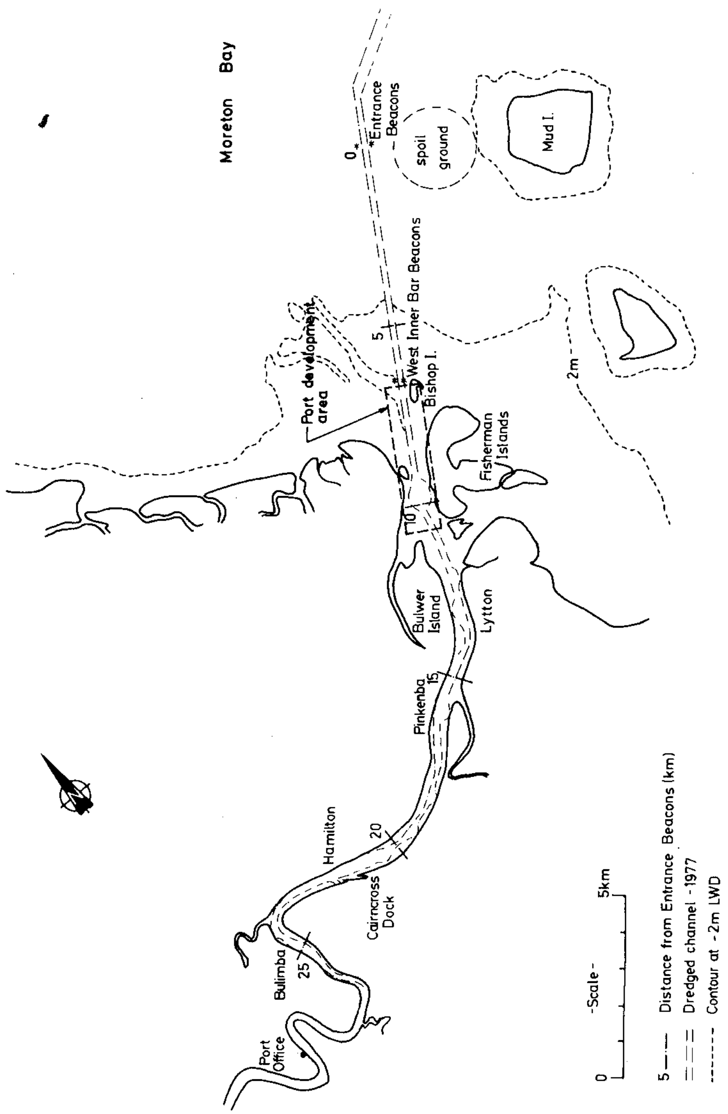

Fig. 1 Brisbane River – Port area

Mathematical model techniques were chosen in preference to a physical model because the depositional and erosional properties of muddy sediments cannot be scaled correctly in physical models. The Brisbane study is the first case in which HRS has applied its latest multi-layer (X-Y-T) multi-process, tidal mathematical model, which was developed during the course of the study.

OBJECTIVES OF THE INVESTIGATION

The main objectives of the investigation were to identify, quantify and simulate the processes causing siltation in the navigation channels, swing basins and berths in the seaward reaches of the Brisbane river estuary. And secondly, to predict the effect of capital dredging works associated with port developments at Fisherman Islands and changes in the pattern of maintenance dredging in the existing port area, on siltation in the tidal river.

CONSTITUENT PARTS OF THE STUDY

The study could be considered to be divided into five constituent parts. The type of work and an approximate estimate of the relative effort put into each part of the study in terms of cost were as follows:

		RELATIVE EFFORT(%)	
		HRS	PBA
1.	Collection of field data in the tidal river	25	80
2.	Analysis of data	25	20
3.	Laboratory experiments	5	-
4.	Construction and validation of mathematical models	25	-
5.	Use of models to predict the effect of engineering works	20	-
		100	100

The above table shows what a large proportion of the effort went into collecting and analysing field data and the relatively small amount of effort that went into the final use of the models to predict the effect of engineering works.

The field studies for the investigation were planned to provide data to determine and quantify processes of tidal propagation, saline intrusion and sediment transport in the estuary, and to validate three types of mathematical model.

HRS supplied the PBA Survey Team with a rapid-drop profiler which was mounted on a fast launch and used to monitor suspended solids and salinity profiles throughout the length of the estuary at regular intervals.

THE BRISBANE RIVER ESTUARY

The river has a typically flashy hydrograph with long periods of practically no flow interspersed with short flood events, which usually occur in the months between December and April and last on average about twelve days. The tidal regime in Moreton Bay is a mixed one with significant diurnal and semi-diurnal constituents. The M_2 semi-diurnal tidal constituent is the largest one with an amplitude of 0.724 metres.

The tidal compartment of the Brisbane river is narrow compared to its length, which is about 100km from the entrance in Moreton Bay to Mount Crosby weir. The original port was about 30km upstream from Moreton Bay. In 1860, there was a shallow bar across the entrance to the river, and its lower reaches consisted of braided channels. During the past 100 years the channel in the lower estuary has been gradually trained and deepened to accommodate the increasing size of vessels using the Port. The deepest berths have moved progressively seaward during this period.

The dredged channel silts up with muddy sediments at the rate of about 1.5 million cubic metres per annum. The bulk of the siltation being located in the existing port area especially in Hamilton reach (Fig 1). There had been no previous investigation of the physical processes causing siltation in the Port.

INTERACTION OF TIDAL AND FLUVIAL FLOWS IN THE ESTUARY

There are two very well defined conditions that prevail in the estuary. Firstly, in the dry season there are negligible fluvial flows for several months and the limit of saline intrusion moves steadily inland. The estuary is in a vertically well-mixed condition but there are significant longitudinal density currents. In these conditions there are deep, sluggish periodic tidal flows in the port area with peak velocities in the order of 0.5 metre a second, superposed on a longitudinal gravitational circulation.

Secondly, there are short flashy fluvial floods, which last about twelve days with the peak discharge being reached on the second or third days. The peak velocity in the upper estuary may exceed three metres per second and most of the fresh water leaves the estuary via the surface layers flowing over a saline wedge, which forms in the port area. Conditions are very unsteady and strongly dependent on the magnitude and duration of the fluvial flows.

DISTRIBUTION OF BED SEDIMENTS

A study was made of the geology and recent sedimentology of the estuary with the aim of defining the distribution of river bed surface sediment types. A variety of historical data was examined including a mixture of seismic, drilling logs, grab sampling analyses and side scan sonar plots. This historical data was supplemented by a series of new field investigations undertaken by HRS and PBA in the top one or two metres of the river bed. This included collection of bed surface grab samples, vibratory core samples, and bulk density profiles using a radioactive transmission probe.

The main findings of this investigation were that the sediments below the dredged project depth were generally in-erodible rock, gravel or clay. The main silting material in the existing port area is a slightly sandy mud with the following average properties.

Total Bulk Density - 1.3 tonnes/m^3
Total Dry Density - 0.5 tonnes/m^3
Sand Fraction (60 - 150 microns) about 25% by weight
Bulk Density of Mud Matrix - 1.25 tonnes/m^3
Dry Density of Mud - 0.4 tonnes/m^3

SOURCES OF SEDIMENTS CAUSING SILTATION

A recurrent problem in all estuarine siltation investigations is the identification of the source of the sediments causing shoaling, namely whether they come from the river catchment or from the coastal region at the mouth of the estuary. This problem was investigated by analysing historical gauging records of discharge and suspended solids at Mount Crosby Weir at the head of the tidal compartment; undertaking velocity and suspended solids sampling in the entrance to the tidal river, and undertaking a radioactive tracer study of the movement of dumped spoil in Moreton Bay.

The main findings of these studies were that fluvial floods carry large mud loads which increase in proportion to the square of the peak discharge, and that the suspended sediment flux at the mouth of the estuary is usually in balance, except in the case of large fluvial floods which flush saline water and suspended sediments out of the estuary. Finally, dredged spoil dumped in Moreton Bay near the approaches to the port hardly moved after an initial period of spreading. However, as usual there was still some doubt about the role of local wave action stirring up mud on the bed of intertidal mud flats which surround the mouth of the estuary.

SUSPENDED MUD LOAD OF THE RIVER

HRS made an analysis of the discharge and suspended sediment records of the Brisbane and Bremer rivers with the aim of determining the frequency and distribution of fluvial flows and the quantities of suspended sediments brought into the estuary. The analysis showed that the river has a typically flashy hydrograph with long periods of practically no flow interspersed with short flood events, which usually occur in the months between December and April. An approximate correlation was established between the mean daily discharge and the suspended sediment load of the rivers. The recent history of the rate of influx of mud (clay particles) from the catchments into the tidal compartment was hindcast by application of the calibrated sediment rating equations to the Mount Crosby Weir flow records for the period January 1972 to August 1977. The analysis showed that the annual influx of mud into the head of the estuary varied from about 30 000 tonnes in 1975 to over 5 000 000 tonnes in 1974. It is estimated that on average about 600 000 tonnes of mud enters the estuary every year from the rivers, which is equivalent to about 1.4 million m^3 of siltation. This rate of influx matches the reported long-term average rate of maintenance dredging in the port.

Extreme flood events such as occurred in 1974 tend to flush nearly all their load of suspended sediment into Moreton Bay. Medium floods are incapable of flushing the saline wedge from the estuary and hence a large proportion of the total suspended load, which may be as much as 300 000 tonnes in one flood, is trapped within the estuary by the longitudinal gravitational circulation and is redistributed and deposited in the deep reaches where the bed stresses are low. The rate of maintenance dredging in the port can be fully accounted for by the influx of suspended fluvial sediments washed down annually by the Brisbane and Bremer rivers, excluding extreme floods such as the 1974 event.

An analysis of the port dredging records showed that in the years prior to the construction of the Fisherman Islands Swing Basin in 1965, over sixty percent of the siltation occurred in Hamilton Reach. There was relatively little maintenance dredging required in any of the reaches seaward of Hamilton Reach. After the construction of the Fisherman Islands Swing Basin there was evidence to suggest that the distribution of maintenance dredging altered so that on average about twenty percent of the siltation occurred in this new swing basin with proportionately less occurring in the Hamilton Reach. HRS are of the opinion that this redistribution can be explained in terms of the gravitational circulation in the port area and the trapping efficiency of the Fisherman Islands Swing Basin.

Although the rivers bring down considerable quantities of sand and gravel in the case of extreme floods, this sediment does not cause a significant shoaling problem in the port area. There is reason to believe that the trapping efficiency of the estuary in its present configuration is high except for extreme floods.

MUD PROPERTIES

A mineralogical analysis of mud from the bed of the tidal river showed that it had an appreciable proportion of montmorrilinite, which has a high cation exchange capacity, indicating that it has probably been recently eroded from the land surface. Laboratory flume and viscometer tests were made at HRS to determine the critical stress for the initiation of erosion as a function of the density of the exposed mud layer and the rate of erosion as a function of excess shear stress for erosion varied between 0.1 and 3.0 N/m^2 for a range of surface densities varying between 0.1 and 0.4 T/m^3. The tidal currents near the bed in the port area exert a peak shear stress on the bed of less than about 1 N/m^2, which is not sufficient to cause erosion of the main body of the mud bed.

Krone[1] has postulated that when flocculated marine muds settle to the bed they form into a series of very thin layers which have shear strengths in the same order as that required to erode it. A consideration of the over-burden pressure exerted by an increasing thickness of these fluffy surface deposits show that they can only be in the order of a few millimetres thick. As a result the only mud available for resuspension in the port are these thin "slack water deposits". During a phase of deposition as each slack water deposit is covered it is consolidated to form the main body of the bed.

An HRS Owen Tube was used to determine the in-situ settling velocity of mud flocks in the estuary as a function of the concentration of mud in suspension. This was found to be negligible in the fresh water region of the estuary and in the range 0.1 - 1.0 millimetres per second in the saline reaches.

SIMULTANEOUS OBSERVATIONS IN THE PORT AREA

HRS and PBA mounted two identical 2-day long intensive simultaneous observations at seven sections between km 4 and km 26 in the port area in the dry season in August 1977 and again during the passage of small fluvial flood in April 1978. An analysis of simultaneous observations of velocity, salinity and suspended solids throughout the depths at the seven sections during spring tides showed that in the absence of wave action very little mud entered the estuary from Moreton Bay. During low fluvial flows the estuary is only weakly stratified. However, the longitudinal density gradients generate small but significant gravitational flows in the landward direction near the bed in the port area. The gravitational circulation tends to hold suspended mud in the middle and upper reaches of the estuary during the dry season. The concentrations of mud in suspension during spring tides in the deep navigation channels were low in the dry season having a maximum value of about 200 ppm. A calculation of the flux of suspended mud passing each section during the flood and ebb phases of the tide at three levels showed that there was a tendency for a net upstream movement of suspended sediment near the bed and a seaward movement near the surface in the port area. However, the net rate of sediment transport was only about 100 tonnes per tide in the upstream direction.

A similar exercise was undertaken during the latter stages of a moderate fluvial flood in April 1978, which is estimated to have carried about 10 000 tonnes of suspended mud into the tidal compartment, increase suspended solids concentration about four-fold at the landward limit of saline intrusion, which was near km 40 and also in the lower layers of the flow in the port area, compared with the dry-season conditions. This exercise showed that very little of the suspended sediment brought down by the river left the estuary.

It appears that most of the fluvial flood water passes fairly rapidly out of the estuary via the surface layers without greatly affecting the longitudinal salinity distribution in the lower layers in the port area. However, there are considerably longer periods of slack-water in the saline wedge near the bed on the ebb tide in Fisherman Islands Swing Basin and in the Hamilton Reach compared to conditions in the dry-season.

Each fluvial flood carries an extra load of mud into the estuary and uniquely and temporarily alters the pattern of tidal propagation, saline intrusion and sediment transport for a period of several weeks. The suspended sediment moves progressively seaward in each tidal cycle until it becomes flocculated by the seawater, periodically eroded, transported and deposited by the tides, and translated by the gravitational circulation until it settles in the deep dredged reaches of the lower estuary where the currents are no longer strong enough to resuspend it.

The rate and pattern of siltation in any one wet season depends on the frequency, magnitude, duration and sediment load carried by each fluvial flood and the manner in which it interacts with the tidal flows. It seems very likely that the sediment brought into the estuary during fluvial floods is reworked and eventually deposited in the deep dredged areas several months after the flood event.

MATHEMATICAL MODELS

Three types of mathematical model were used in the investigation. Firstly, a one-dimensional bulk-flow model was used to quantify the general characteristics of tidal propagation in the estuary, the longitudinal distribution of roughness on the bed of the estuary, the relative flow carrying capacity of the old and new bar cuttings at the mouth of the estuary, peak fluvial flood levels in the estuary and discharge boundary conditions for the second model.

The second one was a steady-state, two-dimensional-in-plan, vertically averaged mathematical model used for the simulation and prediction of peak tidal currents, bed stress and mud deposition patterns in the wide swing basin area at Fisherman Islands between Km 7 and Km 11.

The third one was a two-dimensional-in-depth, laterally-averaged mathematical model of the whole tidal river, which was used to simulate the interaction of fluvial and tidal flows on the scour, transport and deposition of mud in the estuary during flash fluvial floods.

PBA supplied HRS with 1:2500 scale sounding charts of the estuary dating from the years 1974 and 1976. A total of 268 cross-sections were obtained from these charts to provide the basic data for defining the geometry of the estuary in all three models. For the purpose of the bulk flow and two-dimensional in depth model the estuary was divided into 101 storage elements whose length varied between about 500 and 2500 metres, overlapping a similar set of flow or conveyance elements. The results from the survey of sediments in the surface layers of the bed of the estuary were used to prescribe the weight of sand and mud in a series of horizons or layers in each model element.

A viable mathematical model requires sets of equations to describe the processes represented in the model which should be based on well grounded physical concepts and theory and experiments. Certain aspects of the processes of mixing, energy dissipation and sediment transport, as yet, can only be defined by semi-empirical relationships based on field observations and laboratory experiments. The physical equations and functional relationships determine the structure of the model but the results depend heavily on the values of the constants and engineering coefficients applied to a particular calculation. A viable model from the point of view of engineering applications requires an efficient and reliable and accurate method of solution of the equations, giving due regard to the quality of the data and the accuracy required from any predictive calculation. In the case of the Port of Brisbane investigation HRS employed implicit six point finite difference schemes with second order accuracy and a time-step varying between 5 and 10 minutes depending on the particular application of the model. Such a short time-step is required to define the rapidly varying flows and conditions for scour and deposition that occur at the bed of the estuary at certain stages of the tidal cycles.

A model of sediment transport in an estuary requires boundary conditions in terms of water levels and salinities and suspended solids on the incoming tide at the seaward boundary, and the fluvial discharge and suspended concentrations at the landward boundaries. The main problem in the case of the Brisbane river was defining the salinity and suspended solids at the seaward boundary on the incoming tide during large fluvial floods. The models required a mass of bathymetric and sediment data to define the geometry and distribution and grading of sediments in and along the bed of the estuary. A second mass of field data in terms of water levels, velocity, salinities and suspended solids was required to prove and validate the model for a range of tidal and fluvial conditions.

THE ONE-DIMENSIONAL MODEL OF TIDAL FLOW IN THE ESTUARY

The bulk-flow, area-averaged model of tidal flow in the estuary extended from Km 0 at the Entrance Beacons to the head of the estuary representing both the Old Bar Cutting distributary at the mouth, and the Bremer river a tributary near the head of the tidal compartment. The longitudinal distribution of roughness was adjusted until the model simulated a repeating spring tidal cycle.

The model was then used to simulate a neap spring cycle of tides during the dry season. The results from the model with a smooth bed and with the optimum distribution of roughness were compared with month-long tidal level records made by the Department of Physics at the University of Queensland at nine stations along the estuary in 1974. Both the observations and the results from the model were subjected to a species analysis to define the phase and amplitude of the main constituents of the vertical tide as shown in Fig 2. The length of the tidal compartment is such that the semi-diurnal tide is close to the first resonant mode, with a tendency for the tidal amplitude to increase continuously in the landward direction, as occurred in the case with the smooth bed. However, the middle and upper reaches of the tidal river are hydraulically rough causing a high rate of energy dissipation which damps the resonating semi-diurnal tidal constituents. It should be noted that the muddy bed in the lower reaches of the estuary including the port area acts as an effectively smooth bed, which minimises the shear stress of the bed for a given tidal discharge. A species analysis of the model results showed that the tidal flow in the Brisbane river estuary is mainly semi-diurnal in character as regards the strength of the tidal velocities, which are the main agency for scouring and transporting sediment. The diurnal tidal velocities account for only about 15% of the peak velocities during spring tides. The effect of a high rate of energy dissipation in the middle and upper reaches of the estuary is to keep mud in suspension and to maintain a clear cross-section. The amplitude of the semi-diurnal tidal velocity averaged about 0.5 m/sec over the first 60 km length of the tidal river, except in the vicinity of the swing basins in the port area, where it was considerably lower.

The model showed that the Old Bar Cutting carries only about 10% of the tidal flows entering and leaving the estuary. The tidal discharge at the main run of the flood and ebb phases of a mean spring tide in the Fisherman Islands reach was about 2 600 cumecs. This was used as a boundary condition for the two-dimensional model.

It has been postulated that there is a unique relationship between the peak tidal discharge and local cross-sectional area of an estuary, which is in long-term equilibrium. That is to say that the cross-section is

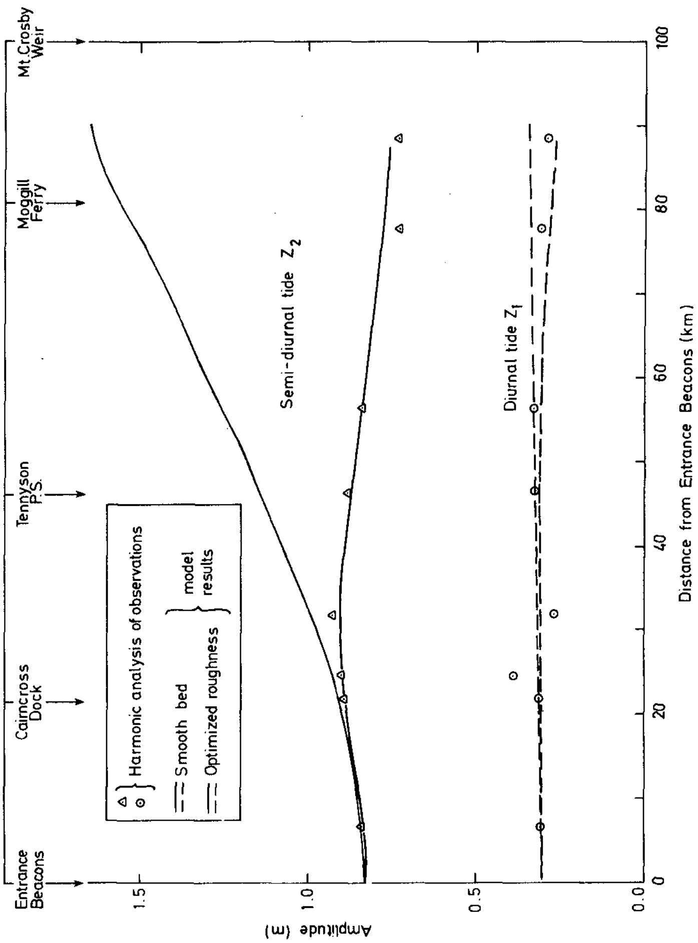

Fig. 2 Effect of bed roughness on tidal amplitudes

neither silting nor eroding over a period of many years. This condition probably applies to the middle reaches of the Brisbane tidal river. The results of the model did in fact show that there was an approximately linear correlation between peak tidal discharge on spring tide and the local cross-sectional area below mean tide level. The fluvial discharges from the infrequent floods appear to have little effect on maintaining the cross-sectional area below mean tide level. In fact during fluvial floods the water level is much higher. The linear correlation implies that a peak tidal velocity of about 0.5 m/sec averaged over the cross-section is sufficient to maintain equilibrium. The consideration of the actual cross-sectional area in the port area suggests that they greatly exceed the equilibrium area in reaches which contain swing basins.

The bulk-flow model was also used to simulate conditions during the peak of the 1974 fluvial flood event. At a peak discharge of 9,600 cumecs, the water level at the head of the estuary rose over 20m above mean sea level. To achieve a good comparison with observed water levels it was necessary to increase the friction factor of the channel by about 24% compared to the dry season proving tests to allow for the bend losses, which become significant with area-mean velocities exceeding 3.5 metres/second.

X-Y MODEL OF PEAK TIDAL FLOW AND MUD DEPOSITION PATTERNS IN SWING BASINS

A steady-state, two-dimensional-in-plan, vertically-averaged mathematical model was used for the simulation and prediction of peak tidal velocities and mud deposition patterns in the Fisherman Islands swing basin and the Inner Bar Cutting reach. The main purpose of this study was to quantify the velocity and bed shear stress distribution pattern in the turning basin and hence help define future patterns of siltation. The boundary conditions of the two-dimensional model were determined from the results of the aforementioned one-dimensional model of the whole estuary. The model was used to hindcast conditions at times of peak flood and ebb discharges during a spring tide, that is to say 2,600 cumecs. The bed of the estuary was assumed to be smooth and the coefficient of lateral exchange momentum was increased until there was a condition with no significant flow reversal in the re-entrance at either side of the swing basin, as shown by float tracks made in May 1977. The bed stress patterns were used to define areas which would be subject to mud deposition at the peak run of the tide and hence at all other stages of the neap/spring cycle (Fig 3). An analysis of the bed surface sediment types and information supplied by PBA based on experience of the dredge master confirmed that the general pattern of mud siltation simulated by the model for conditions in 1977 in the swing basin agreed with reality. The model was then used to predict conditions for different stages of development of Fisherman Islands Reach. Comparisons were made by comparing the results with the base condition in 1977.

X-Z-T MULTI-PROCESS MODEL OF THE WHOLE ESTUARY

The third mathematical model employed in the study was a two-dimensional-in-depth, laterally-averaged mathematical model of tidal propagation, saline intrusion and mud and sand transport in the whole of the tidal river upstream from the West Inner Bar Cutting Beacons. This is the first case in which HRS has used the model which was developed during

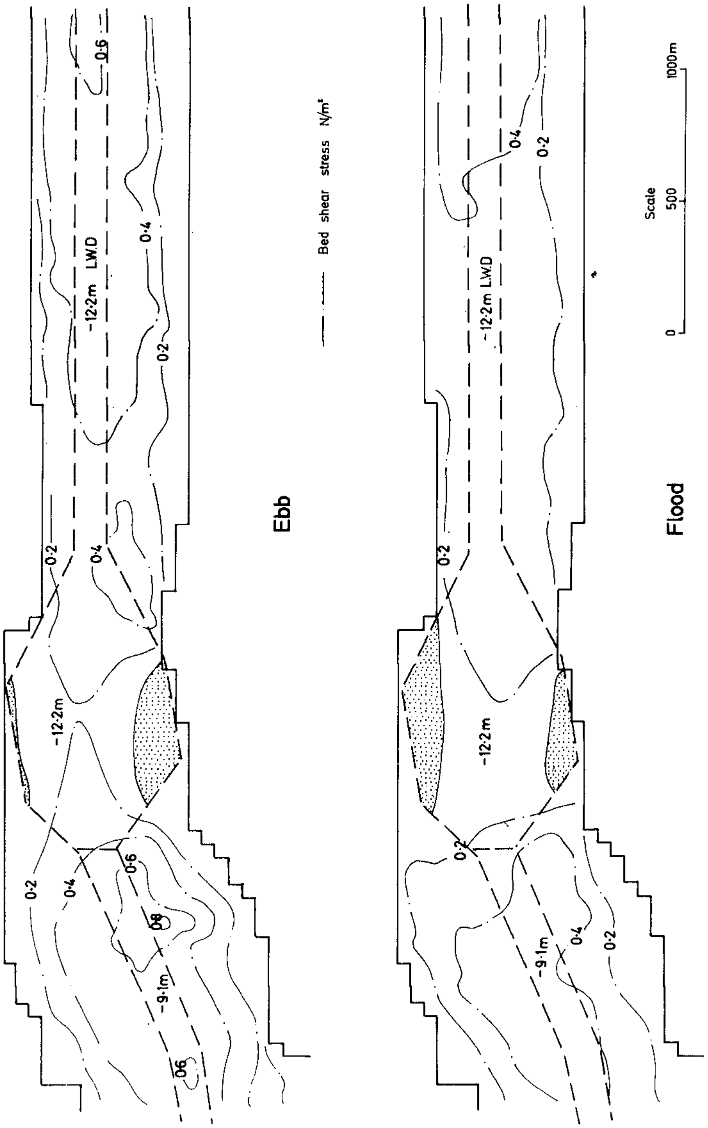

Fig.3 Simulated peak bed shear stress and siltation patterns – 1977

the course of the study as part of HRS's basic research programmes. The method was therefore untried and its application to the Brisbane Siltation Study rather a speculative venture. However, such techniques are the only method of simulating and predicting mud transport and siltation in deep, partially stratified estuaries such as the Brisbane tidal river.

The main purpose of the model was to simulate and predict the interaction of tidal and fluvial flood flows and the resulting pattern of mud transport and siltation for different depths of dredged channels in the port area.

The geometry of the estuary and its roughness were derived from the one-dimensional mathematical model studies, the longitudinal and vertical distribution of bed sediments were determined from an examination of the mixture of seismic, drilling logs, grab sample analyses, sidescan sonar plots, vibratory core samples and density profiles measured with a radioactive transmission probe. The settling properties of Brisbane mud were determined from measurements with an Owen tube in the estuary. The erosional properties of the mud were defined from flume and viscometer tests. The vertical mixing functions employed in the model which took into account the damping effects of saline stratification were based on recent research work[2] undertaken at HRS.

The tide curve at the seaward boundary was prescribed using harmonic constants determined from long-term records at the West Inner Bar Cutting Beacon. The fluvial discharges into the head of the estuary were based on observations made at the Mount Crosby Weir. The flux of suspended mud into the head of the estuary was based partly on observations and partly on a calibrated sediment load function for the river.

The model was as far as possible based on established laws of physics. However, certain aspects of mixing and sediment transport can only as yet be described by semi-empirical functions based on the analysis of field data. The aim was to prescribe the values of all the various coefficients before the model was used and thereby avoid the complications of a protracted proving process in which the coefficients are adjusted by a trial and error process as has been done in the past. The main unknown was the coefficient of longitudinal dispersion in each of the flow filaments caused by lateral variations in the estuary. However a common scaling factor for the whole estuary was adjusted until the simulated pattern of saline intrusion was in satisfactory agreement with observations.

SIMULATION OF CONDITIONS DURING THE DRY SEASON

Initially, the model was set-up to simulate a repeating 25 hour spring tidal cycle during the dry season. The results from the model were compared with observations made during the simultaneous exercise made in August 1977. This test showed that it satisfactorily simulated the pattern of tidal propagation but there was some difficulty in simulating the absolute values of the salinity in the port area. This was caused in part by the problem of defining the initial conditions from observations solely in the port area and which in the case of the dry season were suspect. However, the model simulated correctly the important features of the pattern of tidal currents in terms of their phase and amplitude throughout the depth (Fig 4). It should be noted that the results from

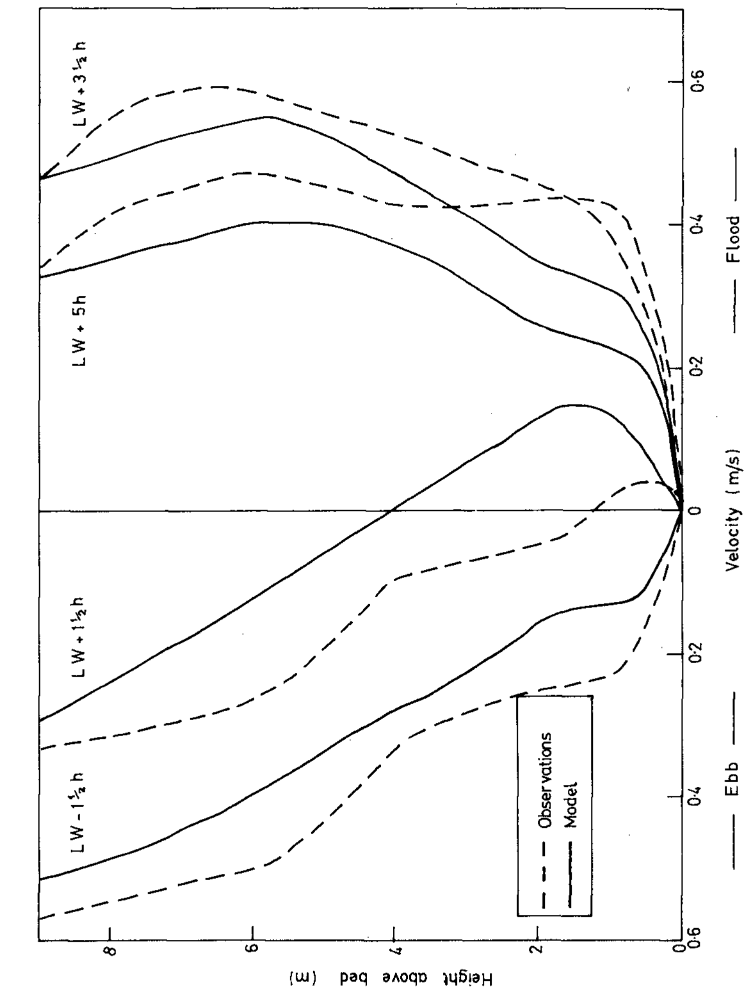

Fig 4 Tidal velocity profiles in the Port area — dry season

the model refer to laterally averaged values, whereas the observations were generally made at mid-stream in the deepest point of the section. As a result the observed velocities are generally higher than the computed laterally averaged velocities. The two-dimensional model studies demonstrated that there are large lateral variations in the velocity especially in the widened reaches of the estuary. The model simulated the important features of the pattern of suspended mud transport. The actual concentrations in suspension and rate of transport are relatively small and unimportant in terms of siltation in the port. The model simulated how muddy sediment is retained in the estuary by the gravitational circulation, and the longitudinal distribution of siltation in the dry season period. This pattern showed that there are two potential zones of siltation in the dry season, one near the toe of the saline wedge upstream of the port and the second one in the deep port area itself.

SIMULATION OF CONDITIONS DURING AND IMMEDIATELY AFTER A FLUVIAL FLOOD

The x-z-t model was then used to simulate the passage of a moderate fluvial flood that was observed in April 1978 after a long period of low fluvial flows. Such fluvial floods are considered to be the main cause of siltation in the port. The interaction of the tide and such flashy fluvial floods result in a very unsteady pattern of sediment transport which is unique to each flood event and which can be only simulated in an x-z-t type model. The results from the model showed that it simulated all the gross features of the unsteady pattern of tidal propagation, saline stratification and the processes of scour, transport and deposition of mud over a period of about two weeks (Figs 5, 6, 7). The results showed that a large proportion of the load of mud brought into the estuary by the fluvial flood would settle in the upper reaches of the dredged port area. It takes a considerably longer time for the mud to reach the lower estuary than for the fluvial water to be evacuated from the estuary. This occurs because a considerable fraction of the new sediment is periodically resuspended and carried up the estuary in the lower layers on the flood tide, whereas the fluvial water passes fairly rapidly out of the estuary via the surface layers without greatly affecting the longitudinal salinity distribution in the lower layers of the flow. The model showed that the mud trapping efficiency of the port area is enhanced during periods of fluvial floods because there are considerably longer periods of slack-water in the saline wedge near the bed on the ebb tide in the Fisherman Islands Swing Basin and in Hamilton Reach compared with conditions in the dry season.

TRAPPING EFFICIENCY OF THE ESTUARY

The investigation has shown that the trapping efficiency of the estuary and the location and longitudinal distribution of siltation is a function of the volume of each individual fluvial flood and the artificial geometry of the lower estuary imposed by capital and maintenance dredging works. For practical purposes one can assume that most floods in the Brisbane river have a duration of about twelve days and that the volume of flood water is approximately proportional to the peak discharge. The mud load of a flood on the other hand increases with approximately the square of the peak discharge. Observations and mathematical model calculations show that almost the entire sediment load of small and medium

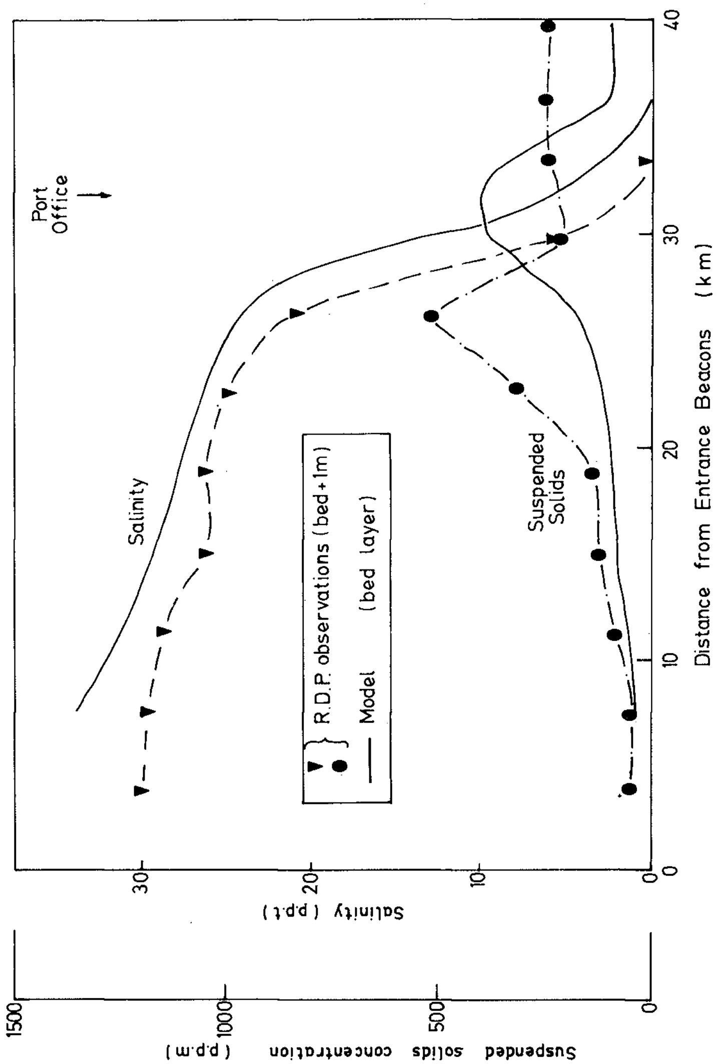

Fig. 5 Longitudinal profiles on flood tide – wet season. 4 April 1978

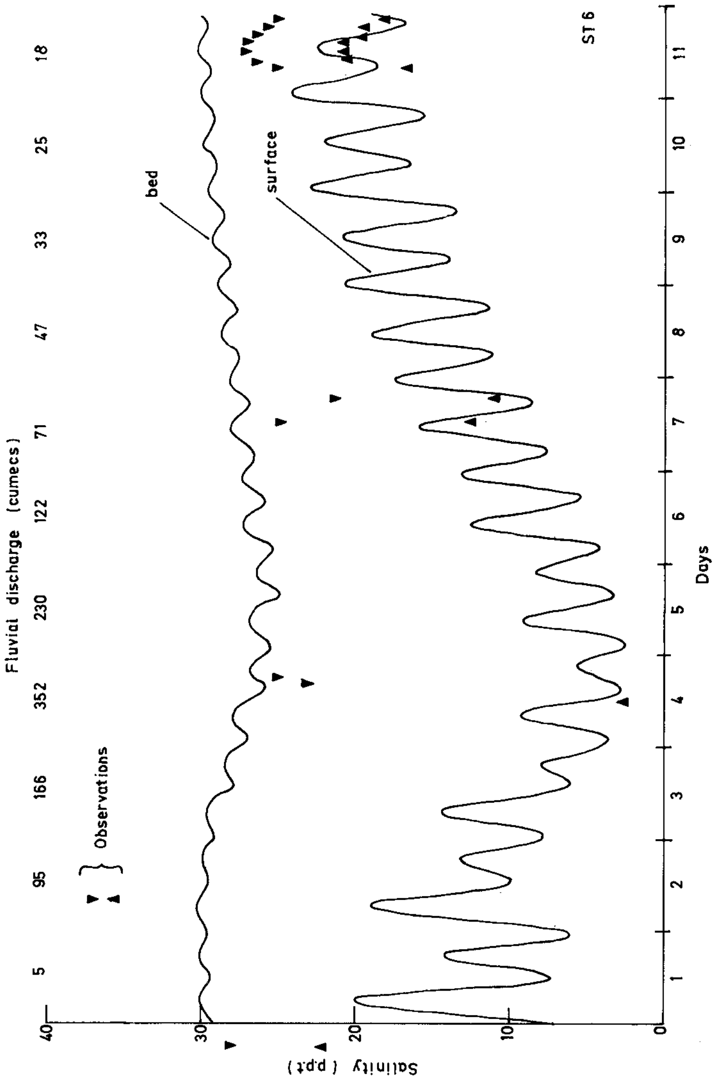

Fig. 6 Simulated salinities in Hamilton Reach during the passage of a small flood. 1–12 April 1978

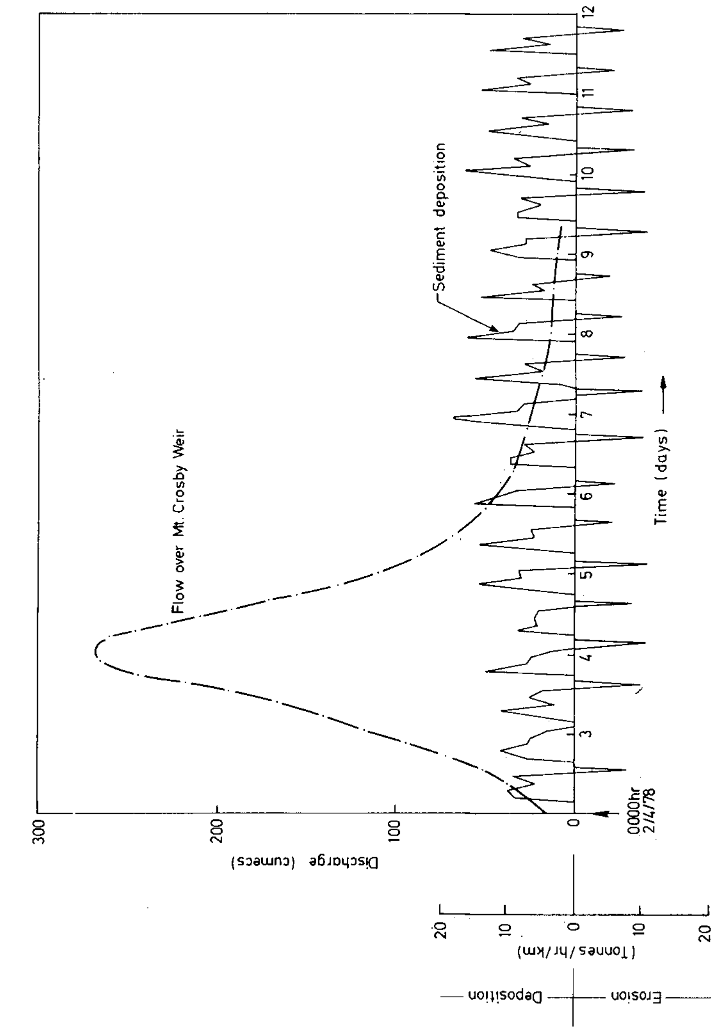

Fig. 7 Pattern of deposition and erosion in Hamilton Reach. 2–12 April 1978

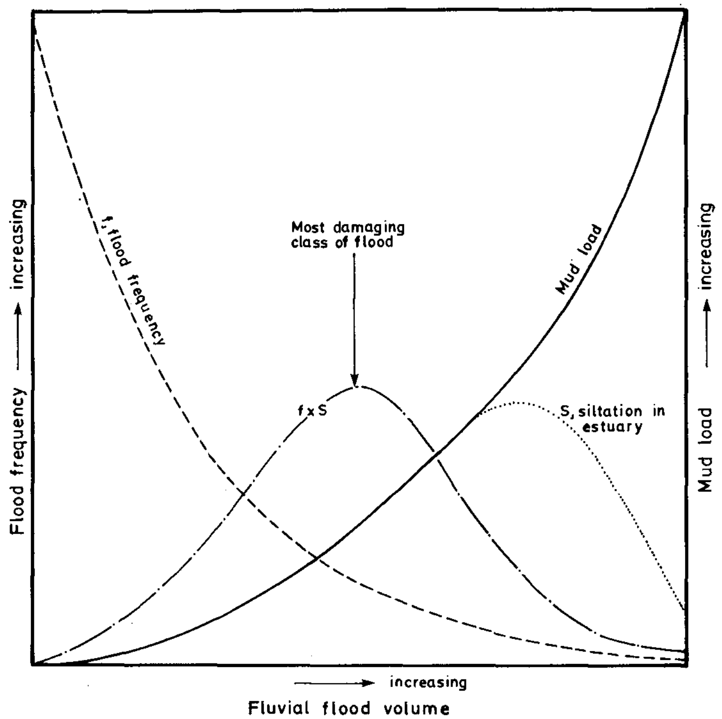

Fig. 8 Trapping efficiency of the estuary

floods is trapped within the estuary with little loss to Moreton Bay. The effect of the larger floods is to push the centre of gravity of siltation further seaward and to spread the zone of siltation over a longer reach.

At some critical flood stage, depending on the depth of the estuary, the fluvial discharge is big enough to flush the saline wedge out of the estuary, which allows a large proportion of the mud load brought down by the flood to pass out of the estuary. The flood causing the worst amount of siltation is therefore not the largest one. For example the 1974 flood caused little damage to the port in terms of mud siltation. A consideration of the frequency of given flood events shows that there is some smaller flood which on average causes the most damage to the port. The relationship between the trapping efficiency of the estuary and the size of the fluvial flood is illustrated in Fig 8. The main purpose of the x-z-t multi-process model was to calculate the trapping efficiency of the estuary for a range of flood magnitudes and for several different dredged channel configurations in the lower estuary.

CONCLUSIONS

The paper showed how an analysis of historical data, a programme of intensive field observations using traditional and specialised techniques, laboratory experiments, and a combination of different mathematical model techniques can be used to identify, quantify and simulate the main processes causing siltation in an estuary and be used to predict the effect of engineering works on that pattern.

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A 3-D MODEL FOR PENOBSCOT BAY, MAINE

by

Bryan R. Pearce[1], Bruce R. Fidler[2], Adrian C. Humphreys[3]

Introduction

Penobscot Bay is a deep, geometrically complex, partially stratified estuary (Figures 1 & 2) lying on Maine's Atlantic Coast. Like other Maine estuaries, the Penobscot supports economically important fisheries and tourist industries, and is a significant transportation artery. It is frequently proposed as a region suitable for new industrial and port development. Once heavily polluted by upstream papermills, the estuary has today been substantially restored by enforcement of discharge regulations under the National Pollution Discharge Elimination System. The goal of this study was to improve our knowledge of

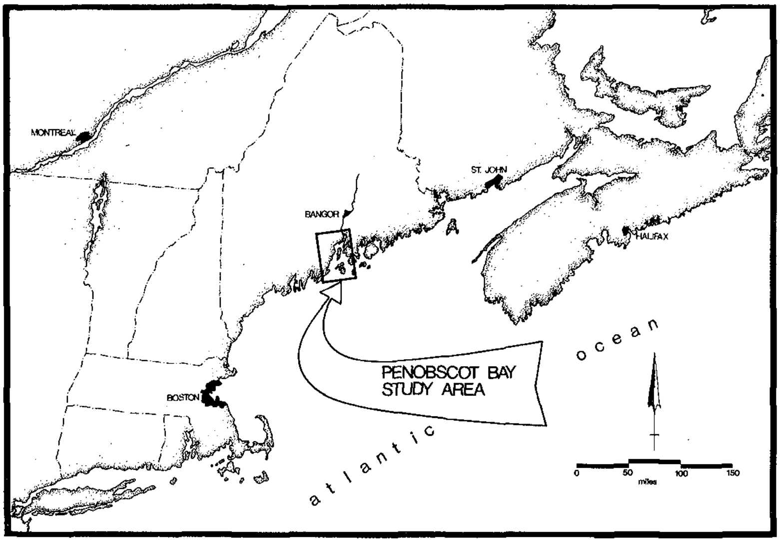

Figure 1: Study Area

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the Penobscot estuary's circulation patterns, as an important factor in maintaining the estuary's water quality and economic resource capacity. A previous effort to model Penobscot Bay (Fidler, 1978) laid the foundation for this study, but concentrated on instantaneous tidal velocities, and was hampered by a shortage of data suitable for model tuning and for comparison of modelled output. The present study concentrated on modelling residual currents, which are somewhat more interesting than instantaneous currents from the point of view of pollution control. In addition, an extensive data set, hitherto largely unanalyzed, became available for tuning and comparison.

The numerical model "GAL" was applied to a 36 km by 51 km rectangular grid covering the entire lower estuary from Fort Point to the southern end of Vinalhaven Island (Figure 3). Developed by Pearce, et al (1978), it is a three dimensional model which has a finite difference formulation in the horizontal but is continuous in the vertical. Model inputs are bathymetry, vertical eddy viscosity, wind velocity, tidal excitation at the seaward boundary, and a river inflow. Model outputs are current velocities at each grid element for specified depths, velocity profiles and net drift information.

Data

The National Ocean Survey collected current data at 37 stations in Penobscot Bay during the spring and summer of 1969; at 103 stations in 1970. In addition, extensive salinity/temperature data was taken coincidently with the 1970 current survey. Photo-Geodyne meters were used during the 1970 survey; several stations had up to five meters on a mooring. Monitoring periods ranged from a few days to three months. Because of the coincident density information and larger data set available, most of the data analysis was conducted on the 1970 data and particularly on those stations which had simultaneously collected data during the period 23 May to 6 June.

Maximum recorded velocities were 1.3 kts (0.67 m/s) at the near-surface meters at the mouth (southern end) of the bay, which if reduced by a factor of 0.25 to allow for wave rectification, means that actual maximums were on the order of 1 knot (0.5 m/s). In general, the current records were dominated by the semi-diurnal tide, although the near-surface records (meters positioned at 4.6 meter depth) were quite noisy, due to wave action on the surface buoy that was typical of the mooring installations.

In order to examine the residual current characteristics of the estuary, progressive vector plots were made of the data at those stations with the same record period (21 May to 8 June). A typical set of plots is shown as Figure 4. The resultant vector in each case (drawn from the origin to last point of record) represented the residual current with tidal components removed. The resultants are plotted in Figure 5 and indicate the general pattern of the residual circulation in the estuary. Bold arrows indicate data taken during the indicated time period; light arrows show data taken during non-coincident time periods, but also in

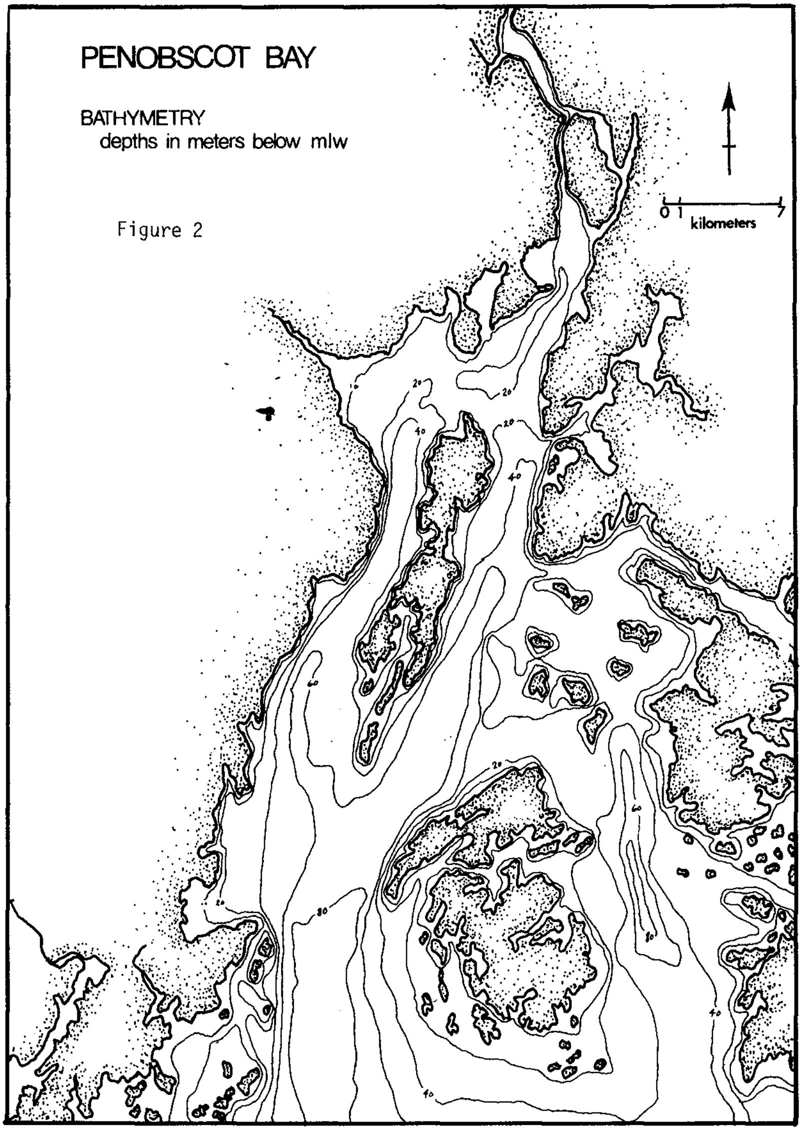
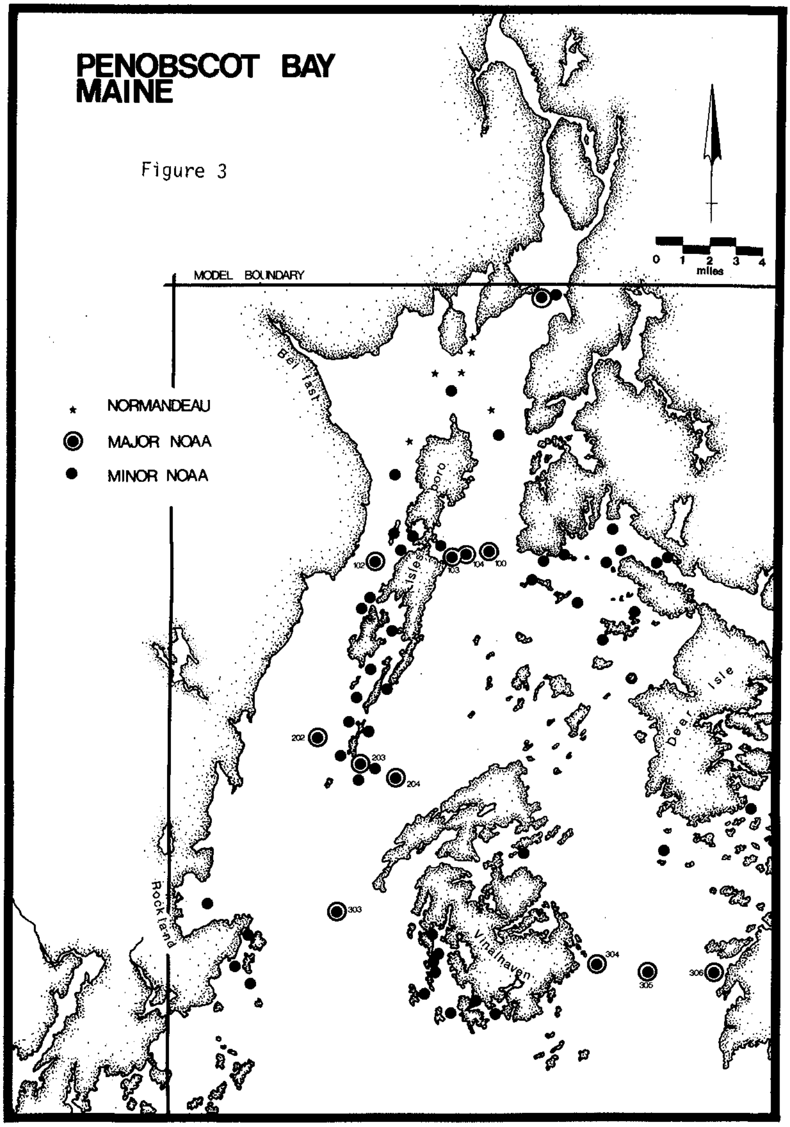

PENOBSCOT BAY
BATHYMETRY
depths in meters below mlw
0 1 kilometers 7
20
40
60
80

Figure 2


PENOBSCOT BAY
MAINE
Figure 3
MODEL BOUNDARY
0 1 2 3 4
miles
NORMANDEAU
MAJOR NOAA
MINOR NOAA
Belfast
Islesboro
Deer Isle
Vinalhaven
Rockland
100
102
103
104
202
203
204
303
304
305
306

the spring. Residual speeds are on the order of 1 to 5 kms/day (1 to 6 cms/sec), and generally trend down estuary in the upper layers and up-estuary in the low layers, although station 201 presents an anomaly at several depths.

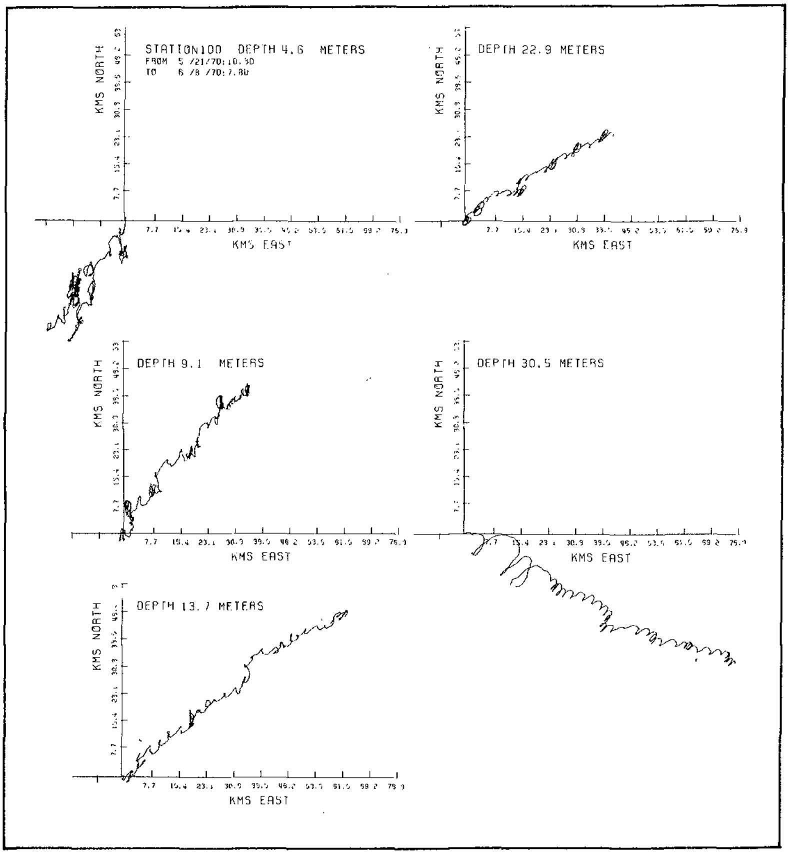


Figure 4: Progressive Vector Plots

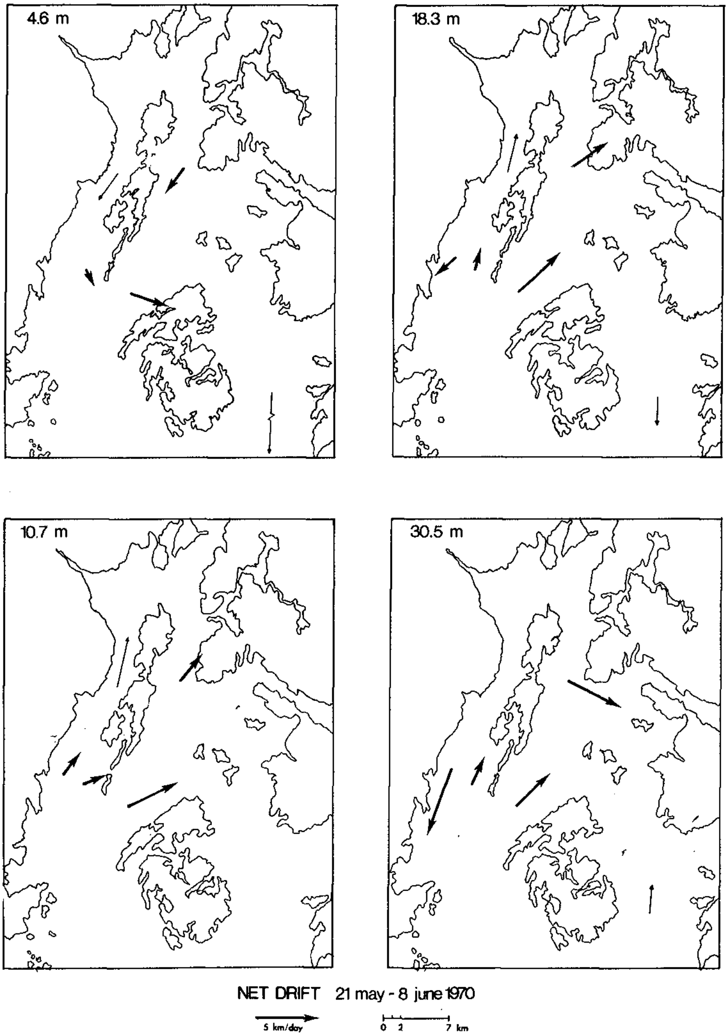


Figure 5

Salinity and temperature data provided some insights into the layered structure of the estuary. Figure 6 shows densities across the bay at several points on both sides of Islesboro Island, confirming earlier work by Haefner (1967) that a deeper fresh water layer lies on the west side of Islesboro. The order of magnitude of the observed data is predicted by application of the Margueles equation (Neumann and Pierson, 1966):

$$\tan \gamma = \frac{-f}{g}\left(\frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 - \rho_1}\right) \tag{1}$$

where:
γ = tranverse slope of the density interface
f = coriolis parameter
ρ_1, ρ_2 = densities of upper and lower layers
v_1, v_2 = longitudinal current velocities

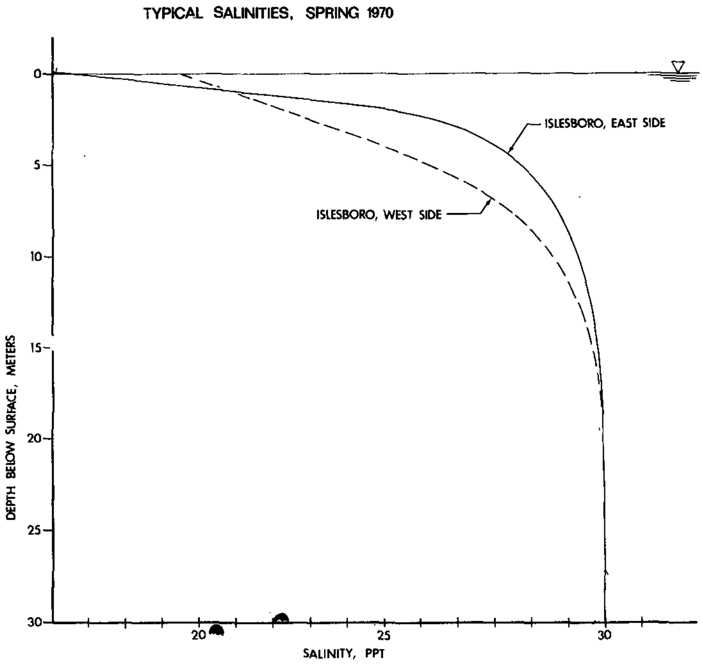


Figure 6

Within the range of observed transverse density gradients and with velocities of 5 cm/s upstream and downstream, equation (1) predicts that the pycnocline would be about 0.5 to 1.0 meter deeper on the western shore of the bay than on the eastern shore. Using the longitudinal density slope of the interface (from figure 7), it is possible to estimate the current velocities due to the density gradient alone (no wind) (after Defant, 1961):

$$i_2 = \frac{-2N_z\gamma}{g} \tag{2}$$

$$\gamma = \frac{-i_2\, g}{2\, N_z} \tag{3}$$

$$u_2 = A(z + h_1)(z + h_2) \qquad \text{with } A = -4a\left(\frac{h_2}{h_1} - 1\right)^{-3} \tag{4}$$

$$\gamma = \frac{\rho_1}{\rho_2 - \rho_1}\, a\left[1 - \frac{\rho_2}{\rho_1} A\right] \tag{5}$$

where:
i_2 = slope of the density interface (taken as $3\text{x}10^{-4}$ m/m)
N_z = vertical eddy viscosity (taken as 0.01 m^2/s)
h_2 = depth to bottom (taken as 25m.)
h_1 = depth of surface layer (taken as 5 m.)
ρ_1 = density of upper layer (1.025)
ρ_2 = density of lower layer (1.012)

For small A, iterative solution of equations (2)through (5), suggests that density driven currents on the order of 2 km/day could exist in the Penobscot estuary. Although this is the same order of magnitude as the observed residual currents, this analysis is suggestive only, since the calculated velocity is critically dependent on the observed slope of the density interface. A further test was made of the importance of the density driven flow to the net circulation in the estuary, by applying the numerical model without including the density driven terms. Successful simulation of observed currents would indicate that the density terms could be safely ignored. Failure to achieve reasonable results would require that further modelling efforts be made with the computionally more complex (and expensive) version of the model incorporating the density terms.

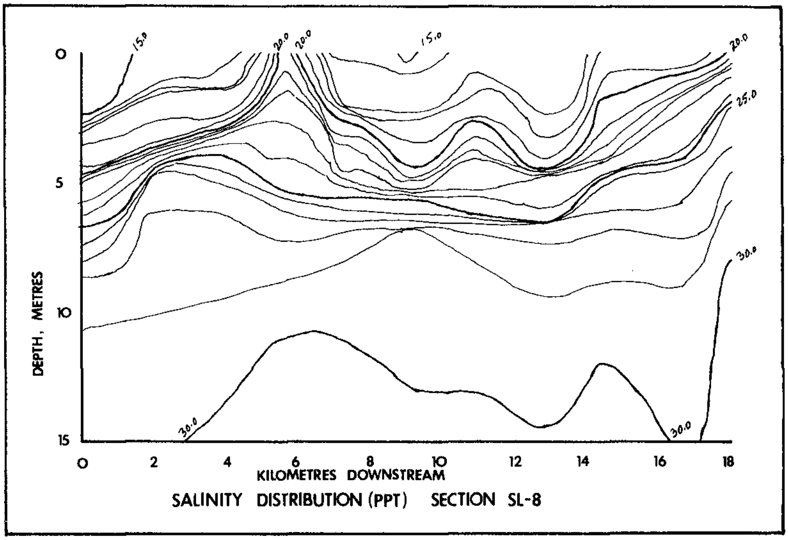


Figure 7

The Computer Model

The three-dimensional computer model "GAL" (Galerkin), described in detail in Pearce, et al. (1978), was used in this study to simulate currents in the Penobscot estuary. It uses the following expression of the Navier Stokes equation, neglecting vertical accelerations, density driven currents, and atmospheric pressure gradients:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -g \frac{\rho_s}{\rho} \frac{\partial \eta}{\partial x} + fv +$$

$$\frac{\partial}{\partial x} (N_H \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (N_H \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z} (N_V \frac{\partial u}{\partial z}) \qquad (6a)$$

in the y direction,

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -g \frac{\rho_s}{\rho} \frac{\partial \eta}{\partial x} - fu +$$

$$\frac{\partial}{\partial x} (N_H \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y} (N_H \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z} (N_V \frac{\partial v}{\partial z}) \qquad (6b)$$

The surface boundary condition is specified as a set of horizontal shear stresses:

$$\tau_{sx} = -\rho_s N_V \frac{\partial u}{\partial z} \quad ; \quad \tau_{sy} = -\rho_s N_V \frac{\partial v}{\partial z} \tag{7}$$

A linear slip coefficient defines the bottom boundary:

$$\frac{\partial u}{\partial z} = \frac{-C_b u_b}{N_b} \quad ; \quad \frac{\partial v}{\partial z} = \frac{-C_b v_b}{N_b} \tag{8}$$

where:

N_v = vertical component of the eddy viscosity

N_b = value of the vertical eddy viscosity at the bottom boundary

N_H = horizontal component of the eddy viscosity

c_b = bottom slip coefficient

u,v = x and y components of velocity

τ_{sx},τ_{sy} = x and y components of wind shear stress at surface

u_b,v_b = velocities at the bottom boundary in the x and y directions

η = height of water surface above still water level

ρ_s = water density at surface

ρ = water density at any depth

g = acceleration of gravity

f = coriolis parameter

These equations are solved by assuming a trial solution which specifies the x and y components of velocity as a continuous function of depth, z. The functions used here are:

$$\hat{u} = \frac{\tau_{sx}\, z^2(z-H)}{\rho_s H^2 N_b} + \frac{\tau_{sx}}{\rho_s \alpha} \ln\left(\frac{N_b}{N_v}\right) + \sum_{I=1}^{I'} c_I \cos\left(\frac{a_I z}{H}\right) \tag{9a}$$

$$\hat{v} = \frac{\tau_{sy}\, z^2(z-H)}{\rho_s H^2 N_b} + \frac{\tau_{sy}}{\rho_s \alpha} \ln\left(\frac{N_b}{N_v}\right) + \sum_{I=1}^{I'} d_I \cos\left(\frac{a_I z}{H}\right) \tag{9b}$$

where the a_I's are given by the solution to:

$$a_I \tan a_I = \frac{c_b H}{N_b}$$

and where:

$$\alpha = \frac{\partial N_v}{\partial z}$$

c_I, d_I = undetermined parameters whose values represent a solution at location x, y, and time t, and

H = still water depth

Equations (9a) and (9b) are substituted into the Navier-Stokes equation. Since the trial functions are not the exact solutions, there will be an error, or residual, R, associated with this substition, where:

$$R = \frac{du}{dt} + \frac{\rho_s}{\rho} g \frac{\partial \eta}{\partial x} - \frac{\partial}{\partial x} (N_H \frac{\partial u}{\partial x}) - \frac{\partial}{\partial y} (N_H \frac{\partial u}{\partial y}) - \frac{\partial}{\partial y} (N_V \frac{\partial u}{\partial z}) - fv$$

$$+ \frac{1}{\rho} \frac{\partial P_a}{\partial x} \neq 0 \qquad (10)$$

The Galerkin technique is used to minimize the error by specifying that the sum of the residuals, multiplied by an arbitrary weighting function, over the depth of the water column be zero:

$$\int_{-\eta}^{H} R\Omega_I dz = 0$$

The weighting function chosen here is:

$$\Omega_I = \cos (\frac{a_I z}{H})$$

which takes advantage of the orthogonality of the cosine function to simplify the integrations in the resulting Galerkin statement:

$$\int_0^H R\Omega_I dz = \int_0^H \{\frac{d\hat{u}}{dt} + g\rho_s \frac{\partial \eta}{\partial x} \frac{\Omega_I}{\rho} - [\frac{\partial}{\partial x} (N_H \frac{\partial \hat{u}}{\partial x}) + \frac{\partial}{\partial y} (N_H \frac{\partial \hat{u}}{\partial y})] - (\frac{\partial N_v}{\partial z} \frac{\partial \hat{u}}{\partial z})$$

$$-N_v \frac{\partial^2 \hat{u}}{\partial_z 2} - f\hat{v} + \frac{1}{\rho} \frac{\partial P_a}{\partial x} \} \Omega_I dz = 0 \qquad (11)$$

Equations (11) are integrated under the following additional assumptions:

(a) the convective terms are small and may be neglected
(b) a linear approximation to the horizontal shear stress terms is appropriate
(c) η is small with respect to H.

This results in the reduction of the original second order, non-linear momentum equations and the non-homogeneous vertical boundary conditions to a set of 2I' linear, first-order partial differential equations in 2I' + 1 unknown parameters, c_I (x component), d_I (y component), and η. These are coupled to the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{\partial \eta}{\partial t} \qquad (12)$$

and the horizontal boundary conditions. These equations are discretized and solved explicitly for the coefficients by a "split-time" finite difference scheme. The coefficients are substituted into the Galerkin trial solutions (Equations (9)) to yield values for u and v at each grid element.

Model Applications: Inputs

1. Vertical eddy viscosity. GAL should prove useful in modelling stratified flow since the model uses a vertically varying vertical eddy viscosity, N_v. For this application, two different methods of specifying N_v were tried, figure 8. In both cases, the break-point in the piece-wise linear form occurred at the assumed density interface, 5 meters below the surface.

2. Wind. A southwest wind at 5 m/s was applied to the modelled estuary, ramped up from zero to maximum velocity in one tidal cycle. The appropriateness of this input was confirmed with lighthouse keepers' observations of wind at Matinicus Rock (26 kms. south of the study area's southern boundary). They had been taken at approximately 3 hour intervals and showed that southerly winds prevailed during the study period.

3. Other input parameters. River discharge was taken as 1300 m^3/s. This is near the maximum discharge for the Penobscot and is a representative flow for the study period.

The bottom slip coefficient was used as a tuning parameter and varied in magnitude from 0.01 to 0.001 m/s.

A rectangular grid spacing of 1016 meters was chosen as the maximum that could place at least three grid elements across the narrowest section of the bay. With less than three elements in the transverse direction, the no-flow horizontal boundary condition leads to spurious results at those points. The Courant condition, equation (13), governed model stability with the result that for the maximum depths of 130 meters encountered, a maximum time step of 20 seconds was used in the model runs.

$$\Delta t \leq (2gh_{max})^{-\frac{1}{2}} \Delta L \tag{13}$$

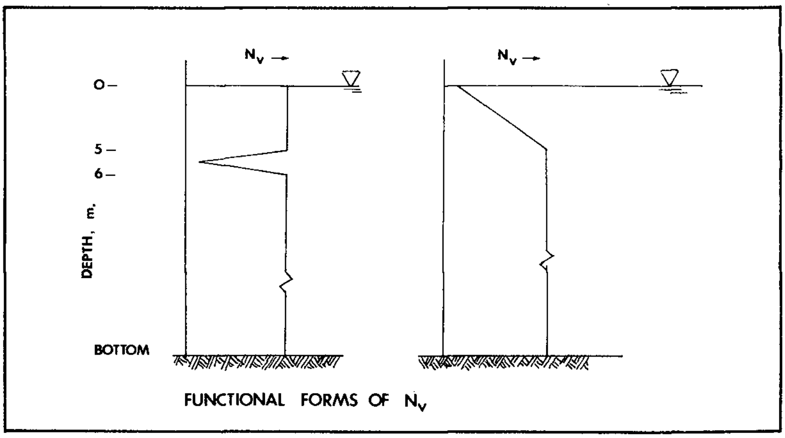


Figure 8

Model Application: Results

The model provides a reasonable representation of the instantaneous currents as shown by a typical velocity profile, Figure 9 (Figure 9 shows the modelled currents at maximum flood and five profiles of the measured data taken about the time of maximum flood). Residual currents were not well represented. Figure 10 shows a plot of the residual currents from one of the most encouraging runs to date. While the magnitudes compare favorably to data, directions are merely suggestive of those found in the data.

We conclude, based on these comparisons and on the evidence cited earlier, that during the time of spring runoff, the density driven residual currents are of the same order of magnitude as the residual currents from other causes. In order to properly consider density driven currents, the model GAL is now being appropriately modified.

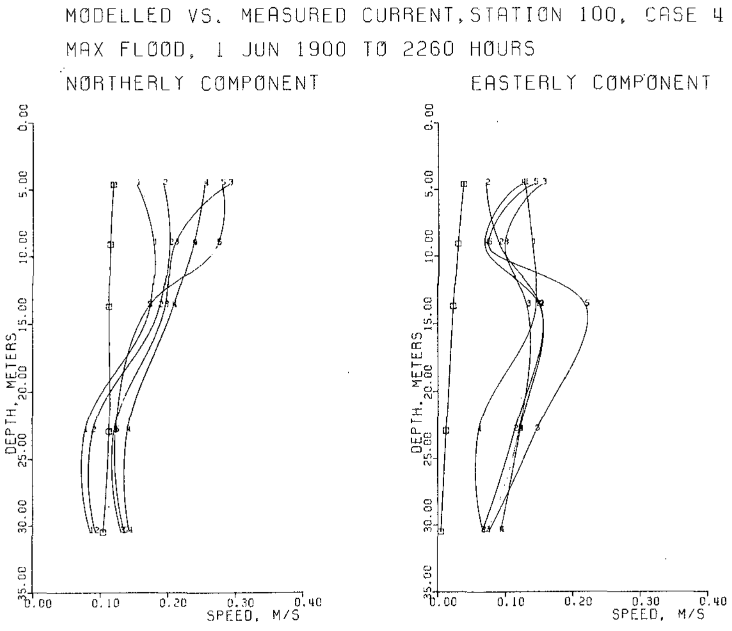


Figure 9

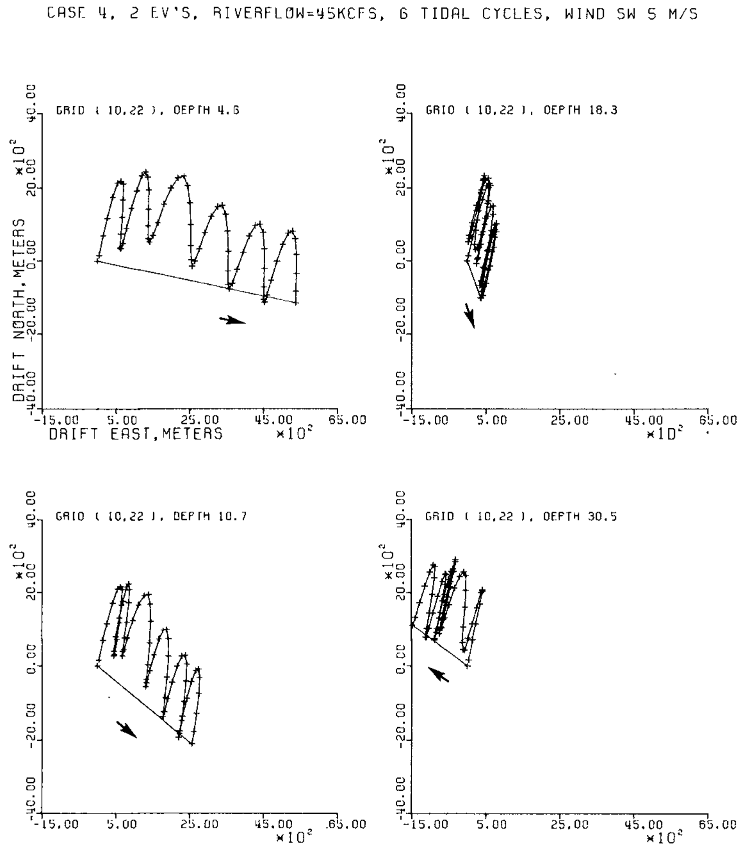


Figure 10: Residual Currents

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