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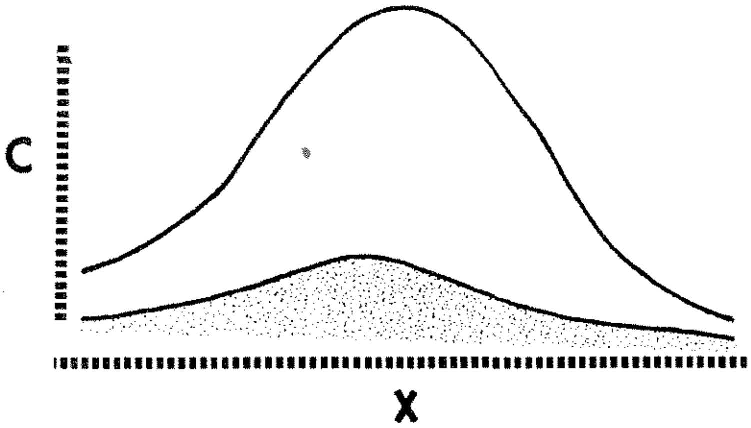
DEVELOPMENT OF THE TURBIDITY MAXIMUM IN A COASTAL PLAIN ESTUARY

FINAL REPORT

by Maynard M. Nichols and Galen Thompson

JULY 1973



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The maximum forms in the middle estuary after freshet or flooding and shifts upstream with a landward shift of the salt intrusion head and diminished river inflow. At the same time, its intensity is reduced by settling out, reduced strength of the convergence and increased mixing. Prime prerequisites for development are a strong convergence and high river inflow.

The maximum modulates transport through estuaries to the sea by trapping materials and deposition. High turbidity can be alleviated by increased haline mixing and reduced inflow.

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FORWARD

This report summarizes results of a study concerning the development of the turbidity maximum in a coastal plain estuary, accomplished under AROD grants, DA-ARO-D-31-124-G1164 and DA-ARO-D-31-124-70-G47. It is prepared in accord with AR 70-31 of 29 June, 1966 and contains: (1) a statement of the problem, (2) the results and conclusions reached, (3) a list of participating personnel, (4) publications and relavent debris on turbid matters.

For centuries estuaries have provided shipping access to major ports and cities of the world. In recent years growth and expansion of U. S. East Coast cities has placed a heavy demand on estuarine approaches. Not only are deeper, more stable channels required for modern deep draft vessels, but also more space is needed for anchorage and docking. At the same time estuaries are a source of food, a site for recreation, a place to dump wastes and a source of cooling water for power plants.

These demands, and the problems arising from intensive use, have proceeded so rapidly in recent years they have outpaced the new knowledge necessary to resolve the problems and to plan for appropriate uses. Problems of a practical nature often can be solved by direct field or model observations. However, other problems require a quantitative knowledge of basic mechanisms and their causes. The present study is mainly directed to this end.

To understand sedimentary phenomena like the turbidity maximum it is necessary to learn how suspended materials behave in response to hydraulic and circulatory processes. Although we have a great wealth of data describing the distributions of suspended material and also the distributions of current velocity, there is little understanding of how currents and suspended material interact. Consequently it would be altogether too superficial to study the phenomena without considering the combined hydraulic, salinity and sedimentologic regimes. An understanding of factors governing sediment behavior in estuarine systems is needed to predict behavior in unknown estuaries and to comprehend processes in more complex systems.

Field observations are the major source of information for this investigation. Although they require a relatively large expenditure of effort and support, they are the chief means of acquiring data pertinent to a transient phenomena like the turbidity maximum. Once acquired they should serve as the basic input for advancing knowledge of suspended sediment transport through other forms of research effort, laboratory experiments, theoretical solutions or hydraulic modeling.

One of the main difficulties in studying partially-mixed estuaries is that river inflow, tidal currents, salinity and sediment distributions are continuously changing and therefore never in a steady-state condition. They are subject to wide variations with time due to meteorological disturbances, tidal inequalities and inflow fluctuations. Therefore, to overcome these variations and to detect relatively small differences representing the magnitude of net flow and residual transport, synoptic time-series observations over many tidal cycles are required. By computing net velocities and resultant transport over 8 or more tidal cycles, the variaions can be averaged out and the tidal motions eliminated. The remaining net-non-tidal components of the current then can be related to density effects, bottom geometry and river inflow.

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INTRODUCTION

Statement of the Problem

Concentrations of suspended material are observed at the head of the salt intrusion in many estuaries throughout the world. The phenomenon, termed a "turbidity maximum" or mud plug by Glangeaud (1938) is found in estuaries of different size, shape and varied dynamic character, Appendix I. Along the U.S. East Coast it is often found in stratified estuaries during times of river flood, but it mainly occurs in partly-stratified estuaries.

When a river-borne suspended load is discharged into the head of an estuary, concentrations should progressively diminish as the load is diluted through seaward increasing (volumetric) sections. And concentrations should further diminish by mixing with less turbid salty water and by settling out. Instead, suspended concentrations reach a peak near the inner limit of salty water (Fig. 1). Such a feature persists despite the rapid fresh water flushing time through the reach of the maximum, which is only two days at high river inflow in the Rappahannock. Because suspended materials are greater than in potential source river or in estuary water, much attention has focused on how these materials accumulate.

The phenomenon has been attributed by some workers (e.g. Luneburg, 1939; Ippen, 1966 and Mathews, 1973) to flocculation. Through this process suspended concentrations are rapidly reduced with distance seaward in the salt intrusion, and flocs which settle out of near-surface water, nourish the estuarine circulation trap. On the other hand, Nelson (1959) suggested deflocculation as the cause because river-borne sediments are often prefloculated and because dispersed sediments at low salt concentrations have low settling rates. Nonetheless, the maximum is defined by high concentrations regardless of their state of aggregation or dispersion. In estuaries with strong tidal currents and narrowed reaches, maxima are locally generated by sediment supplied by erosion of the bottom, as shown by Postma (1967) in the Demerara or by erosion of tidal flats as shown by McManus (1973) in the Tay. The maximum in Upper Chesapeake Bay reportedly is supplied by tidal resuspension of bottom sediments (Schubel, 1968). Tidal currents frequently reach speeds competent to scour and transport fine-grained sediment in many estuaries, and thus are an obvious source of energy that puts much sediment into suspension. However, net transport and residual accumulation by tidal currents develops mainly when processes of tidal settling and scour lag are active or when time-velocity tidal asymmetry is present as shown by Postma (1967). Then too, turbidity maxima are observed at different phases of the tide, at slack water and maximum current as well as at spring and neap tides. The unique character of estuarine circulation and mixing must be taken into account.

Rationale

The rationale behind the approach to this problem lies in the classic concept of estuarine circulation developed by Pritchard (1954). In this circulation (Figure 2) relatively freshened water of the upper estuarine layer moves seaward over many tidal cycles, whereas a lower layer of more salty water moves landward. At the inner limit of salty water, upstream flowing saline water converges with downstream flowing river water near the bottom. Continuity and salt balance considerations require that upstream flowing water mix upward and flow seaward in the upper layer. An essential feature for development of the turbidity maximum is the near-bottom convergence which acts as a virtual trap.

It is postulated that very fine-grained sediment that remains in suspension for a long time will be transported either upstream or downstream by the net non-tidal current depending on the time it spends in the upper or lower layer. Coarse clay or silt which is alternately suspended and settled out near the bottom should be carried upstream or downstream depending on the current strength and the time it spends in one layer or the other, or in the river flow. Thus, material which is suspended by tidal currents and supplied either from the estuary or the river, may be carried into the convergence, accumulate and reside there over long periods since the net velocity is nearly zero and particle settling is faster than vertical mixing.

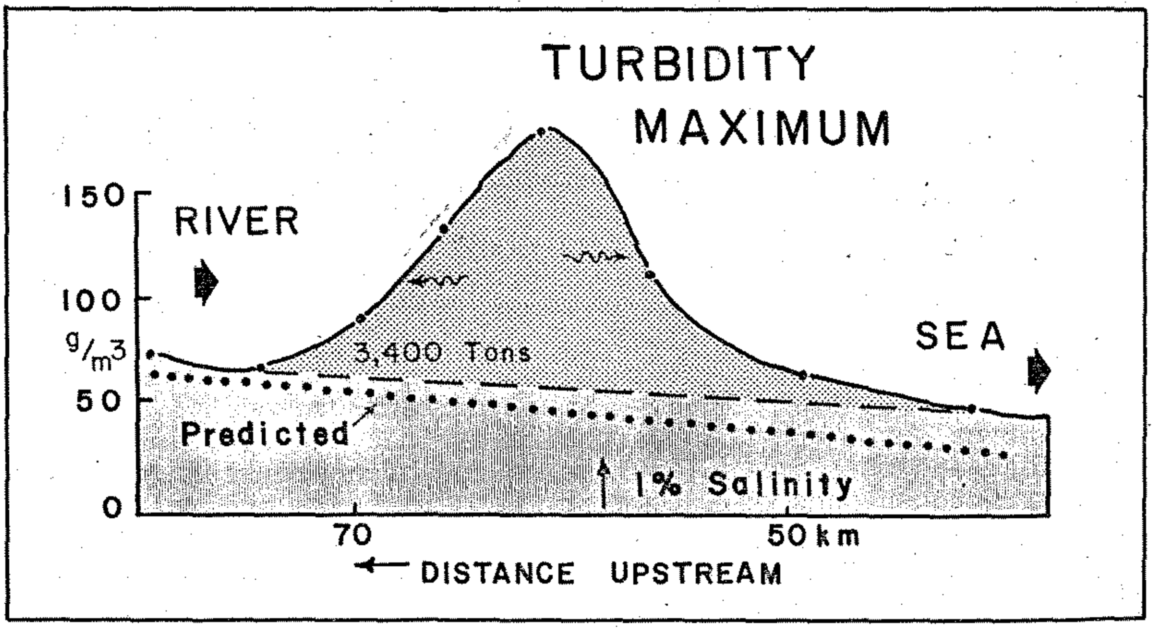


Fig. 1. Longitudinal distribution of mean suspended concentrations displaying a turbidity maximum near the inner limit of salty water; upper Rappahannock Estuary at very high inflow, 141 m^3/sec, April, 1970. Concentrations predicted by dilution, dotted line; longitudinal diffusion, arrows, schematic. Total tonnage in area above baseline, dashed, 3,400 tons.

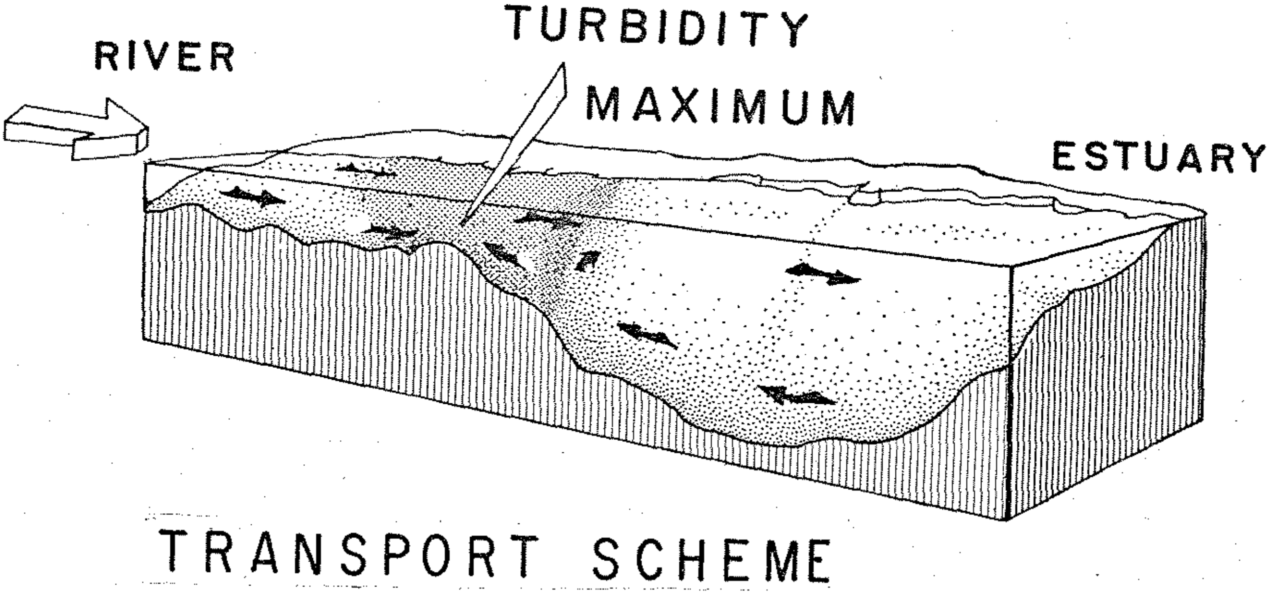


Fig. 2. Transport model of the turbidity maximum in relation to fluvial-estuarine circulation. Net flow direction, black arrows; schematic.

But accumulation of suspended material in the convergence must be compensated by a loss of material acting to reduce the high concentrations. Part of the material may mix upward and disperse downstream in the seaward flowing upper layer. Another part may diffuse longitudinally upstream against the river flow, or downstream, and thus act to lower the turbid gradient. Some material may be lost by settling to the bottom or by deposition in bordering marshes during high water.

Suspended material forming the maximum must accumulate or dissipate at a rate equal to the rate of supply by the river, by upstream estuarine flow or from the bottom, minus losses by downstream advection, by diffusion or settling out. These relations are expressed by the equation:

$$\frac{\partial}{\partial t}\int_{V} \bar{C}\, d\tau = \int_{A_r} \bar{C}_r \bar{U}_r\, d\sigma + \int_{A_l} \bar{C}_l \bar{U}_l\, d\sigma + B - \int_{A_u} \bar{C}_u \bar{U}_u\, d\sigma - D$$

Rate of change in the total suspended mass	Rate of river-borne supply	Rate of supply by upstream transport	Rate of loss by seaward transport

where V is the volume within the reach of the turbidity maximum
$\bar{C}$ is the mean concentration of suspended material within the maximum

A_r is the cross-sectional area upstream of the maximum in freshwater (river) portion
$\bar{C}_r$ is mean concentration of suspended material in the freshwater cross-section, A_r
$\bar{U}_r$ is the mean velocity in the freshwater cross-section, A_r

A_ℓ is the cross-sectional area of the lower layer
$\bar{C}_\ell$ is the mean concentration of suspended material in the lower layer
$\bar{U}_\ell$ is the mean velocity of the lower layer

B is the rate of supply from the bottom (boundary) in the reach of the maximum
D is the rate of loss by settling out on the bottom (a function of settling velocity and vertical advection and diffusion).
A_u is the cross-sectional area of the upper layer
$\bar{C}_u$ is the mean concentration of suspended material in the upper layer
$\bar{U}_u$ is the mean velocity in the upper layer

Both advective and diffusive transport in longitudinal and vertical directions are recognized as significant internal processes operating to supply or dissipate the maximum. Inasmuch as longitudinal diffusive transport in the Rappahannock was less than two percent of the longitudinal advective transport at the 10 minute measurement interval used, diffusive transport was neglected in this study. Aside from the vertical advection and diffusion rates calculated from salt balance equations of Pritchard and Kent (1953), the transport model used mainly consists of horizontal advection. It remains to be found out: (1) if the mechanism of estuarine circulation is active; (2) if suspended material is in fact, transported in this circulation by the net non-tidal flow and (3) whether the net transport over many tidal cycles actually leads to an "excess" accumulation of suspended material in the form of a turbidity maximum.

OBJECTIVES

The prime purpose of this study was to determine how the turbudity maximum is generated by hydrodynamic processes. The problem is resolved into three parts:

- To determine the temporal character and pattern of estuarine circulation.
- To measure the net transport of water and sediment; determine their interrelationship and causal factors.
- To account for the accumulation of suspended material through application of a sediment budget (rates of supply and loss).

STATE OF KNOWLEDGE

Despite numerous reported occurrences of the turbidity maximum (Appendix I), there are few detailed studies that demonstrate the relative importance of hydrodynamic processes. Early notions were acquired from observations in the Gironde Estuary, France in 1894, reported by Leveque (1936) and Glangeaud (1938-41), which show varying positions of the maximum in relation to changes of river inflow and varying intensity of concentrations in relation to tidal velocity. These observations were strengthened by data of Berthois (1956) who traced a similar maximum in the Loire Estuary with seasonal changes of temperature and river inflow as well as changes in velocity from neap to spring tides. From field measurements and tracer data in the Thames, Inglis and Allen (1957) showed that suspended material near the bed has a tendency to accumulate at the inner limit of landward drift. Similarly, shoaling materials were found to accumulate at a nodal point in the Savannah Harbor (Simmons, 1965). But the existence of a circulatory node alone does not necessarily produce a maximum. As shown by Postma (1967) and Allen (1971) a supply of material is important and the settling velocity of the available material must also be taken into account. These factors were further evaluated by Meade (1968) in an effort to isolate the problem but the relative importance of hydrodynamic factors, which vary with time and with response of suspended sediment to those factors, has remained obscure.

Although the mechanism of estuarine circulation has been established from field measurements and hydraulic model studies in many estuaries, there are few simultaneous measurements of suspended material taken over a sufficiently long duration to derive statistically meaningful net transport values in which meteorologic and tidal disturbances have been averaged out. Most sediment measurements are limited to one or two tidal cycles of measurement. And model studies simulate bed material rather than suspended material. With these limited observations and complicated factors, it is no wonder knowledge of the turbidity maximum has remained clouded.

STUDY AREA

To test the working model, a site was selected for detailed study in a relatively simple situation and a plan of field observations was formulated.

Site selection:

The upper Rappahannock, a tributary estuary of lower Chesapeake Bay (Fig. 3), offered many advantages for study. Its configuration is relatively straight. Its narrow width, less than 2.4 km, afforded a moderate density of stations in cross transects; it provided shelter for anchor stations and minimized effects of local wind-waves in stirring up bottom sediment. From comprehensive hydraulic surveys of NOAA (Nichols and Poor, 1965), Virginia state agencies (VIMS, SWCB) and the U.S. Army, Chesapeake Bay Hydraulic Model program, the estuary has become fairly well known. This information provided substantial baseline control and a predictive understanding for designing phases of this study.

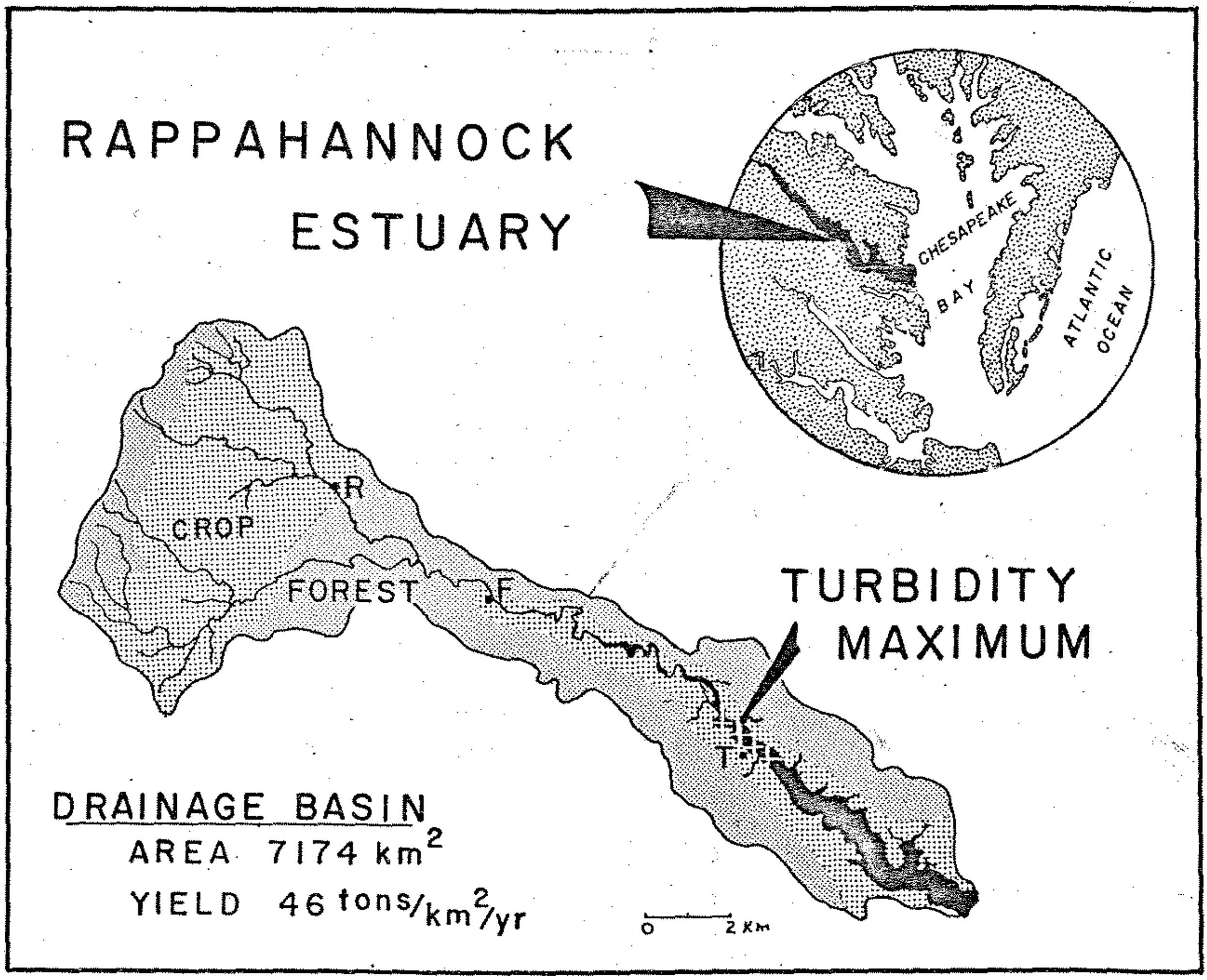


Fig. 3. Location of the Rappahannock Estuary, Virginia in relation to lower Chesapeake Bay, upper right. Drainage basin of Rappahannock River-Estuary showing areas of forest and erodable cropland. Mean position of the turbidity maximum in the upper estuary near T, Tappahannock, vertical lines. Location of water and sediment discharge stations in the river, R, Remington fnd F, Fredericksburg.

Environmental Framework

The estuary is narrowly funnel shaped and relatively straight. Its floor is molded into an axial channel 3-24 m deep bordered by submerged shoals. The longitudinal channel profile shoals to 4m depth within the reach of the maximum. This shoal, locally called Mangoright Bar, is a site of active deposition and a channel cut through the bar at the 3.8 m depth requires maintenance dredging of about 0.8 m every 2 to 4 years. Although the estuary shoals in this reach there is no marked closure of cross-sectional areas. Instead the areas increase with distance seaward; they increase arithmetically above the maximum and exponentially downstream of the maximum (Fig. 4A). Comparison of areas delineated from 1910 charts and the 1970-71 resurvey of this study indicates the exponential trend is steepening with time and with shoaling in the reach of the maximum.

Hydrodynamic conditions in the estuary are relatively mild. Mean tide range is 48 cm and the range varies between 75-39 cm from spring to neap tide. Salinity changes within narrow limits over a tidal cycle and current velocities are less than 70 cm/sec. Mean tide range, established at 4 gauges run for a year, varied only 10 cm along the reach of the maximum over a distance of 40 km (Fig. 4B). And mean current velocities determined from 10 stations occupied at mean tide, varied less than 5 cm/sec except for one point in a narrowed reach and a small seaward decrease 45 km above the mouth (Fig. 4C). Thus, tide range and velocity remain small despite the landward decrease in cross-sectional areas. This suggests that concentration of tidal energy through the narrowed reach of the maximum is offset by the effect of frictional damping which is promoted by greater bottom roughness and greater channel sinuosity. Nonetheless, time-height and time-velocity tidal curves are strongly asymmetrical through the reach, a feature which indicates a degree of energy dissipation.

The estuary is partly-mixed most of the time. Vertical mixing of salt and fresh water is incomplete over the salt intrusion length and the longitudinal transition from fresh to salty water through the maximum is relatively broad. The Rappahannock lacks a sharp interface characteristic of salt wedge systems, except during short periods of extreme flooding. A partly-mixed system like the Rappahannock is the most common type in the Chesapeake Region and along the U.S. East Coast.

River inflow varies annually within moderate limits. High inflows, which occur from January through April, average 67 m^3 per second, whereas low to moderate inflows throughout the remainder of the year average 36 m^3 per second. This broad seasonal distribution of inflow is punctuated by short period floods or freshets of 3 to 15 days duration in spring or summer. Approximately 90 percent of the sediment load is discharged into the estuary during these high inflows which occur 11 percent of the time.

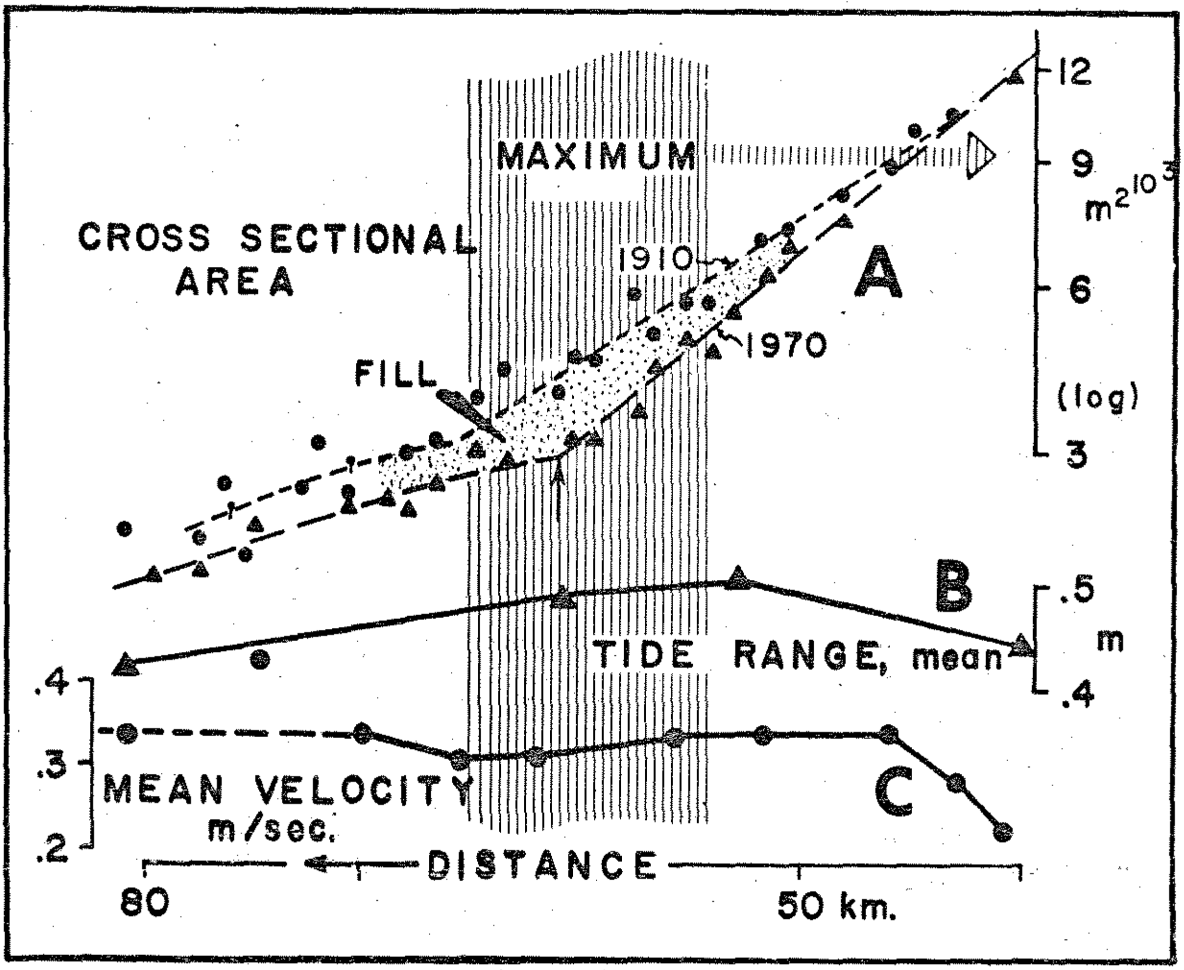


Fig. 4. Longitudinal distribution of selected hydraulic characteristics along the upper Rappahannock Estuary in relation to the mean position of the turbidity maximum (vertical lines) and its downstream excursion during flood.

4A. Seaward change in cross-sectional area through the reach of the maximum, 40-70 km above mouth. Difference between 1910 and 1970 areas indicates zone of fill on channel floor. B. Variation of mean tide range based on one year of height measurements during 1970-1971. C. Longitudinal variation of mean surface velocity derived from 100 hours of measurements at mean tide.

Sediment is supplied to the maximum mainly from the river drainage basin. Contributions from seaward sources via upstream transport near the bottom appear to be minimized by a deep sill across the entrance channel. Imput from lateral tributaries is relatively small, less than 6 percent, of the main river inflow. The river drains 7174 sq. km of Piedmont and Coastal Plain basin of which 41 percent is erodable cropland, 2 percent is urban and the remainder is forest (Fig. 3). The basin produces 46 tons per sq. km on the average each year which is a moderate rate for a basin in this region.

Suspended sediment comprising the maximum consists almost entirely of silt and clay with a mean size range of 2.6 - 3.2 μ from surface to bottom, and from 2.2 - 2.8μ with distance seaward through the maximum. Bed material is very fine-grained; its mean size is less than 3.5 μ. It contains 60-80 percent water (wet weight) and thus is soft and erodes when tidal currents reach 18 to 28 cm per second. Suspended sediments increase near the bed to more than 200 mg per liter but concentrations are not high enough to create special transport or boundary features like turbidity currents or fluid mud lenses. The river-borne load supplied to the maximum consists almost entirely of wash load; sand is scarce and the bed load is relatively small.

The Rappahannock Estuary and contiguous drainage is largely free of pollution and relatively undisturbed by major engineering works. Therefore, processes involved with development of the maximum can be studied more-or-less in their natural state.

In summary, the turbidity maximum studied develops in an estuary having simple geometry, mild hydrodynamic conditions and a moderate influx of river-borne sediment. The fresh-salt transition is relatively broad; suspended sediment size, bed characteristics and current speed vary within narrow limits through the reach of the maximum.

FIELD STUDY PLAN

A series of field observations were designed to meet the objectives within a two-year time span and within the fiscal limits of the AROD grants. They were planned with the belief that an understanding of the maximum could be best gained by measuring rates and patterns of transport over a range of dynamic conditions in a simple situation. Observations consisted of:

1. Forty-two longitudinal transects through the turbidity maximum at various stages of the tide and over a range of river inflows including extreme flooding of Tropical Storm Agnes, 1972.

   These transects define the distributions of suspended concentrations mainly along the channel and with depth. In turn, they reveal the changing position, size and intensity of the maximum with changes in river inflow and salinity at daily and weekly intervals. The data was used to optimize the position of anchor stations as described below.

2. Time-series measurements from anchor stations located upstream, downstream and through the maximum.

   The measurements were made simultaneously at three levels of river inflow and haline mixing as shown in Table 1. Stations were occupied over 4 to 26 tidal cycles as dictated by the objectives and by weather conditions. An attempt was made to recover at least 8 cycles of continuous current velocity and suspended concentration data from most stations . The scheme of station locations used is given in Figure 5.

   The anchor station measurements reveal the short-term variations in suspended concentrations at hourly and daily intervals. They define the internal (density) circulation and the mean distribution of suspended concentrations which in turn provide the necessary data for calculation of net transport.

3. Special measurements were made:

   a. To test and calibrate equipment in the lab and to determine its performance prior to deployment in the field.

   b. To up-date bathymetry along 22 selected cross-sections through the maximum for determination of total sediment discharge as well as to detect depth changes due to scour and fill on the floor.

   c. To observe the maximum in small creeks tributary to the main estuary and to establish their interrelationship.

Table 1. Anchor station data.

Anchor Station Series	Number of Stations	Date	River Inflow* m^3/sec	Mixing Condition
Ia	4	Apr 1-7, 1970	141	Highly Stratified
Ib	4	Apr 7-14, 1970	53	Partly-mixed
II	9	Apr 27-May 15 1971	23	Partly-mixed to well-mixed

* At Fredericksburg, Virginia

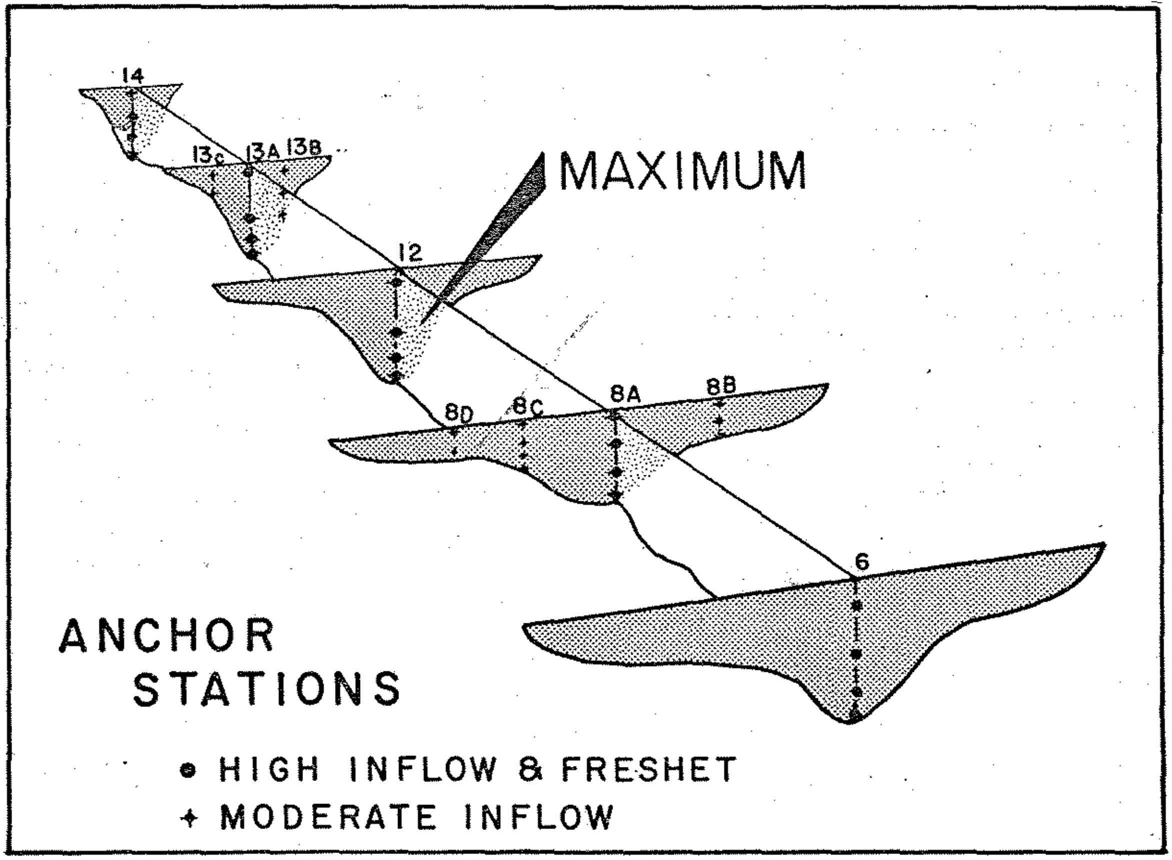


Fig. 5. Scheme of anchor station positions occupied at different levels of river inflow along the channel and in cross transects. View upstream; mean position of turbidity maximum at high inflow, arrow.

DATA COLLECTION

Longitudinal transects:

Water samples were obtained from a fast runabout at one phase of the tide, usually at slack water. They were obtained at three to four depth intervals and at eight to twelve stations along the length of the maximum. Samples were returned to the lab for determination of salinity and total suspended material. The frequency of transects and density of stations was dictated by the rate of change in river flow and variations in the position and intensity of the maximum.

Anchor Station Measurements:

Continuous measurements of current speed, current direction and optical ratio were obtained "around-the-clock", simultaneously at two to four anchor stations and four depth intervals. Additionally, water samples were taken every thirty to sixty minutes and returned to the lab for determination of salinity and total suspended material by filtration. Samples for filtration were taken every two to three tidal cycles to provide a check on, and calibration of, the optical unit.

The scheme of instrument configuration, called a "Turbo System" is shown in Figure 6. It consists of a series of current meters (Savonius) and submersible pumps suspended from a research vessel anchored fore and aft. The lower two current meters are mounted into a tripod to measure velocity near the bottom and at fixed heights down to 23 cm above the bottom. These instruments are connected to deck readouts, a suspended solids analyzer, and recorders, by cables and hose. Power is supplied either by a portable AC generator or a bank of batteries through an inverter. Power fluctuations are stabilized by installing a regulator between the power supply and the electronic units. To sample water, mark recorder chargs, refuel generators and stand vessel watches, the system was manned by a single person.

Use of an optical unit to obtain suspended sediment "concentration" values was required in order to obtain a sufficient number of measurements over a long time to derive statistically meaningful transport values and residual concentrations. The unit expedited the large task of data collection as a substitute in part, for water sampling and filtration. Use of the optical unit was possible because variations in particle size and composition, which affect optical properties, were relatively small with time at one place in the estuary.

Special Measurements:

The "turbo system" was tested in Piscataway creek for eight tidal cycles and in the main estuary near Tappahannock for one tidal cycle. The chief problem was supplying constant power to the suspended sediment optical and electronic units. This problem was largel solved by installing a voltage regulator in the system between the generator, or invertor for battery supply, and the optical-electronic units. The data obtained during these tests contributed to the over-all data base used to evaluate the turbidity maximum.

Measurements in the estuary were supplemented by aerial observations of flow patterns and turbid interfaces which can be clearly seen under certain conditions.

Bottom profiles were run across the estuary at selected interval of about 2.5 km between Wares Wharf (71 km above the mouth) and Owl Hollow (95 km above the mouth). The profiles were run across the same transects used by the Coast Survey in 1910 which is the most recent bottom survey in this part of the estuary. Fathometer traces were positioned horizontally by transit and radio and they were controlled vertically by reference to an operating tide gauge at Tappahannock. Once the data were reduced to a common datum plane, depth changes over the 62-year period were determined, and in turn, rates of fill or scour were estimated.

The discovery of turbidity maxima in creeks tributary to the upper Rappahannock was followed up in a special student study by T. Gu (1970). Water samples were obtained weekly on longitudinal slack tide runs both in Piscataway Creek, a natural system, and in Totosky Creek, a dredged system. Samples were analyzed by the same procedures used for the main study.

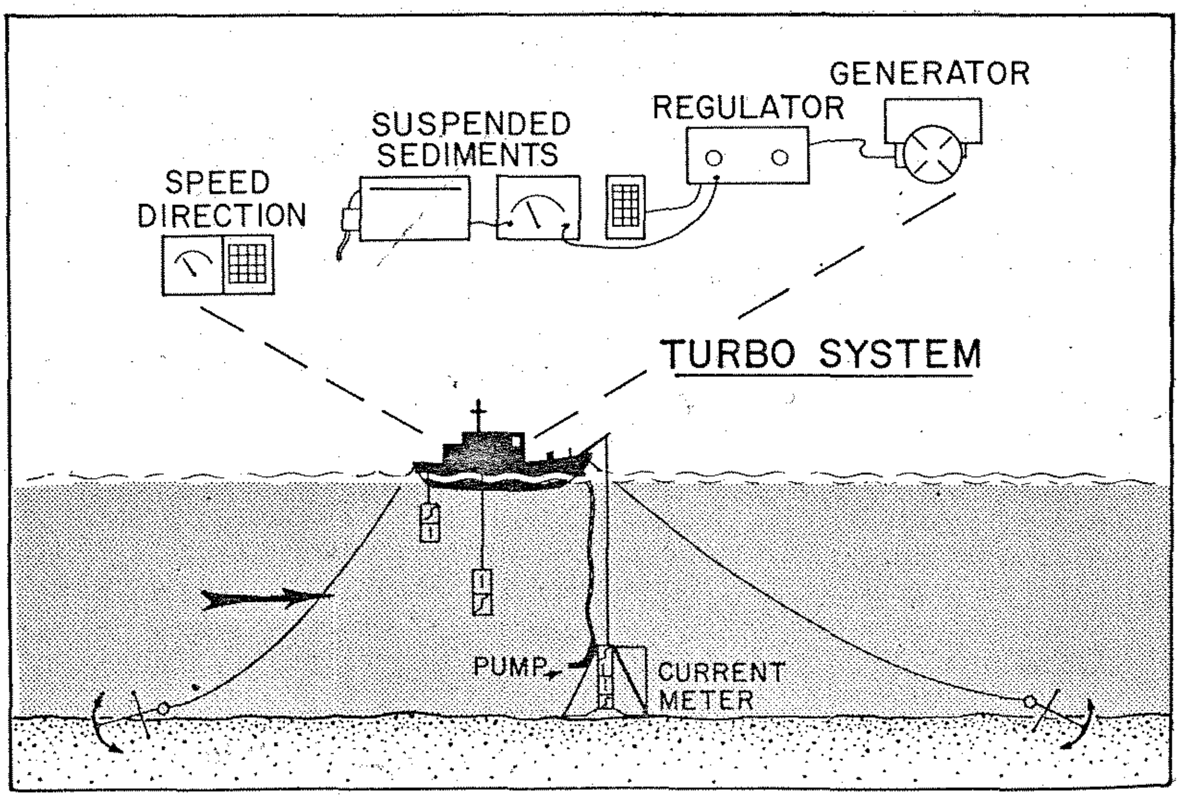


Fig. 6. Scheme of instrument configuration for anchor stations. Upper part of system simplified to show only one set of 4 instrume sets used for continuous measurements.

Laboratory Analyses:

Water samples returned to the lab were analyzed for salinity, to ∓ .05‰ in a Beckman RS-7A salinometer and for total suspended material by filtration through 0.8μ millipore filters. Concentration of material recovered on the filters was determined gravimetrically. Filters were initially leached of soluble material and weighed in a dehumidified room of constant humidity. Selected filters were ashed in a muffled furnace for estimation of organic content. Procedural details covering gravimetric analyses and operation of the suspended sediment analyzer are given in Nichols (1971).

Early in the data collection effort many samples became degraded during short periods of storage. This resulted in an irregular loss of material at times, or at other times an apparent gain of material, despite the use of preservatives like chloroform and formalin. This problem was resolved by running all samples fresh without use of preservatives, within 24 hours after recovery, by accelerated laboratory processing.

Particle size analyses were done on a limited number of samples from longitudinal transects by electronic counting in a Coulter Counter (Model B).

DATA REDUCTION AND ANALYSES

The mass of field and laboratory data were reduced and processed by graphical plotting and computer manipulation. Chart recordings, field logs and laboratory sheets initially were edited for completeness and accuracy. After values were reduced to standard metric units and standard time intervals of 10 to 20 minutes, they were transferred to standard forms and further processed on punchcards by VIMS Data Processing Section. Each day of operation from 4 vessels yielded more than 8,000 data bits.

Concentration values for long time series were obtained from optical ratio values by regression analyses of short term optical ratio-concentration functions in which the concentrations were measured by filtration.

Computer programs were developed to handle the large number of computations. They follow standard hydraulic practice and include computation of net velocity, residual concentrations and net transport from differences in areas under flood and ebb time curves. Total sediment flux through channel sections was computed by obtaining the product of net transport at each depth interval in cross sections defined as a "layer" across the channel. This procedure permitted computation of flux in the two estuarine layers, above as well as below, the level of no-net-transport. Print-outs of field data are on file in VIMS computerized data bank.

OBSERVATIONS

Suspended Sediment Distribution:

The mean concentration of suspended material at high river inflow reaches 219 mg per liter which is about 3 times greater than in the river or estuary. Locally instantaneous values reach 392 mg per liter during flood. The mean longitudinal gradient of suspended material through the maximum is always steepest near the bottom where concentrations are maximal and intensity of the maximum is greatest following freshet or flooding when the maximum is displaced downstream. At concentrations less than about 50 mg per liter the maximum is absent and concentrations gradually decrease with distance seaward from the river.

Vertical profiles of concentration in the maximum increase from surface to bottom except in flood. As shown in Figure 7A, profile (a) from freshwater displays a minimum at mid-depths. At lower inflows near-bottom gradients become weaker (b and c) but they strengthen slightly at moderate inflow (d) when concentrations are low (40-70 mg/l) and the maximum is relatively weak.

Comparison of mean profiles at different stations along the length of the maximum (Fig. 7B) shows that the highest overall vertical gradient occurs in the maximum (profile c), especially near the bottom. Profile b in freshwater upstream of (c) also has a steep near-bottom gradient but profiles farther upstream in the river and downstream of the maximum in the estuary are remarkably similar.

Behavior of the Turbidity Maximum:

The maximum develops in a broad transition between fresh and salty water. Its mean locus lies in freshwater just upstream of the 1‰ isohaline; its landward portion extends 8-12 km upstream along the bottom in fresh water while its seaward portion extends 8-12 km downstream along the bottom where salinity is about 7‰. Most of the time the mean maximum is nearly symmetrical about a locus in longitudinal sections (e.g. Fig. 8c) but during flood it is slightly skewed downstream in the surface and upstream in the bottom. The maximum mainly resides near the channel floor but laterally it extends over bordering shoals with diminished concentrations. When waters are partly-mixed and the level of no-net motion is oriented vertically in lateral sections (e.g. Fig. 9A), the maximum resides near the intersection of the level and the bottom on the freshened side (Fig. 9B).

The position of the maximum varies within relatively narrow limits. Its excursion with flood and ebb of the tide is less than km but following major flooding it shifts upstream with penetration

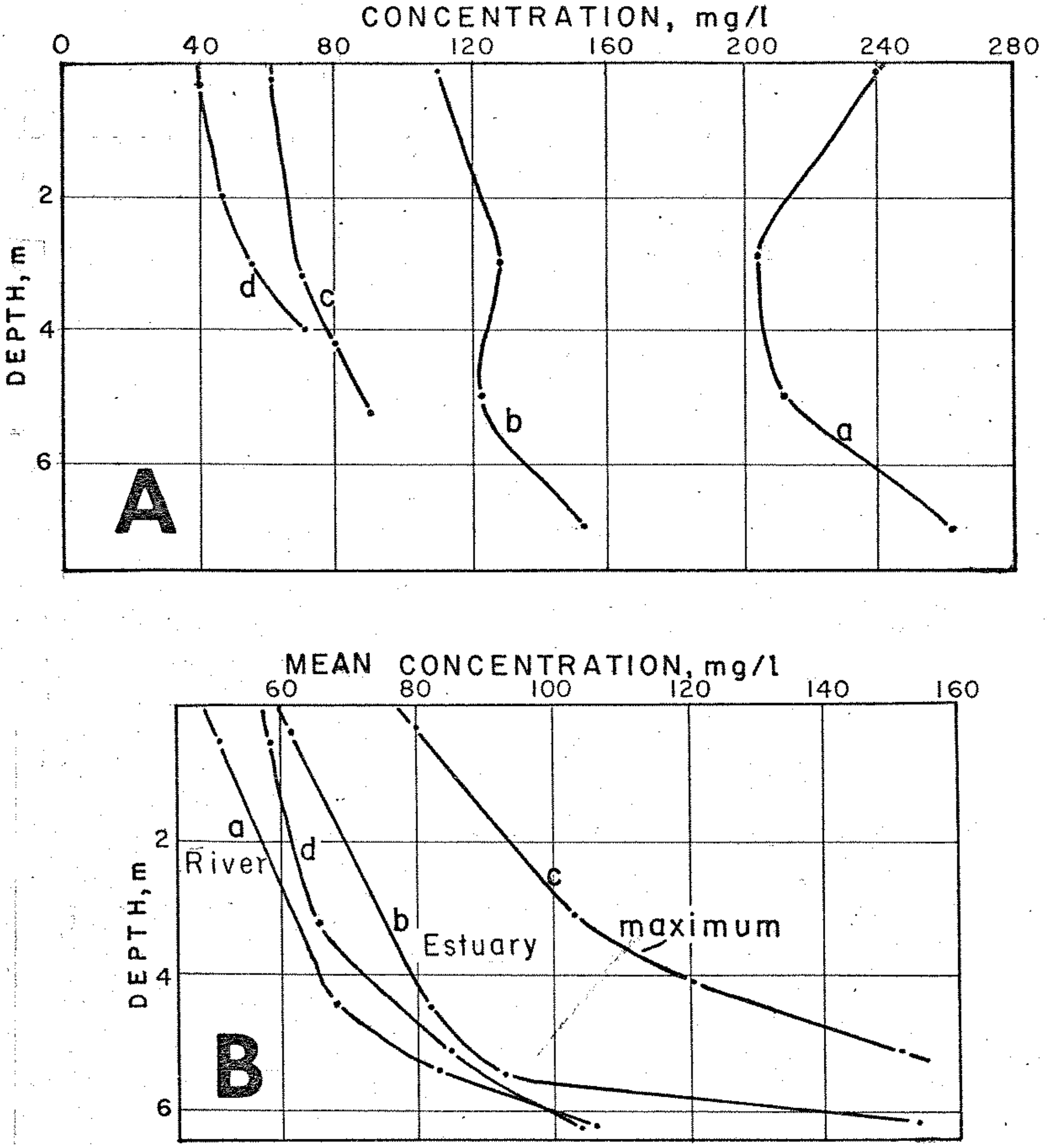


Fig. 7. A. Vertical distribution of suspended sediment through the locus of the turbidity maximum at different levels of river inflow (a) flood (+3 days), 590 m^3/sec, (b) very high inflow (+5 days), 270 m^3/sec, (c) high inflow, 53 m^3/sec, (d) moderate inflow, 23 m^3/sec. Locus at different positions in estuary. Profile (a) and (b) based on instanteous slack tide observations; (c) and (d) are mean concentrations measured over 8 tidal cycles. Fig. 7B. Vertical distribution of suspended sediment at different locations through the turbidity maximum: (a) in river upstream of maximum (b) in maximum upstream of locus (c) in locus of maximum (d) in estuary downstream of maximum. All at high inflow 89 m^3/sec and mean values based on 14 to 18 tidal cycles of data.

of the salt intrusion a distance of 18 to 22 km. Despite extreme flooding such as wrought by Tropical Storm Agnes, June 1972, the maximum was retained within the upper third of the estuary. It persists for 4 to 16 weeks whereas the freshwater flushing time is less than 17 days. Most of the time the maximum resides over a 4m shoal which is one of the major sites of deposition in the estuary.

The mass of suspended sediment tied up in the maximum reaches about 8400 tons. This standing load amounts to about 20 percent of the total river influx supplied during a single freshet or inflow event. The rest of the sediment is either flushed seaward, deposited on the bottom or resides in suspension in other parts of the estuary. The mass of sediment in the maximum is increased very little by spring tidal currents that favor bottom resuspension. The greatest suspended load is present shortly after freshets or floods when the maximum is located in a downstream position.

Flow Features:

Current observations define a near-bottom convergence or node where river and estuarine currents meet. At very high river inflow, 141 m^3 per second, the upstream current extends landward in the channel to 59 km above the mouth where the mean salinity is 1.8‰, Figure 8A, 8B. At the node both upstream and downstream flow dissipates and the net velocity is zero. At very high inflow, the change from upstream to downstream current occurs within a relatively short distance. Such a narrow transition is indicated by a relatively steep line passing through the node.

At moderate river inflow, 23 m^3 per second (Fig. 8A, B), the upstream current extends to 80km where it diminishes at 0.5% salinity, and passes into a downstream current in a relatively broad transition of weak net current. A secondary node is present over a shoal on the channel floor at 65 km upstream. Such "fragmentation" of upstream current is undoubtedly due to bottom topography. At 53 m^3 per second inflow the primary node and the current transition is intermediate between those of the other inflow levels. Thus, a spectrum of current transitions is displayed in which the transition width generally increases as river inflow decreases.

Water-Sediment Relationship:

When a vertical profile of net velocity is compared to a corresponding vertical profile of residual sediment, derived from differences between ebb-flood concentrations alone, for station 6 in the estuary, a striking similarity is evident, Figure 10A. Both net velocity and residual sediment are directed downstream in the upper estuarine layer and upstream in the near-bottom lower layer. And the cross over point for residual sediment is close to the level of

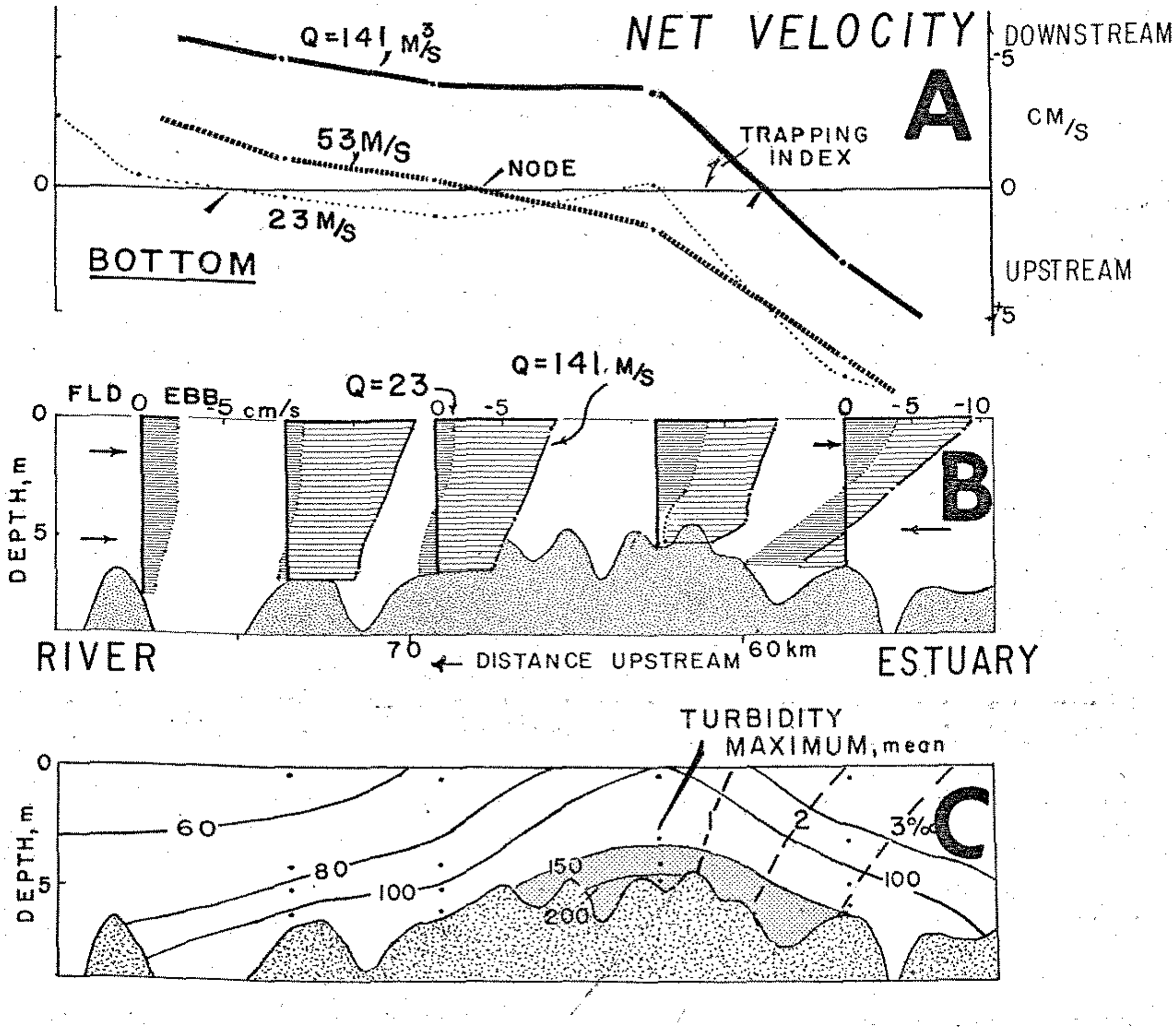
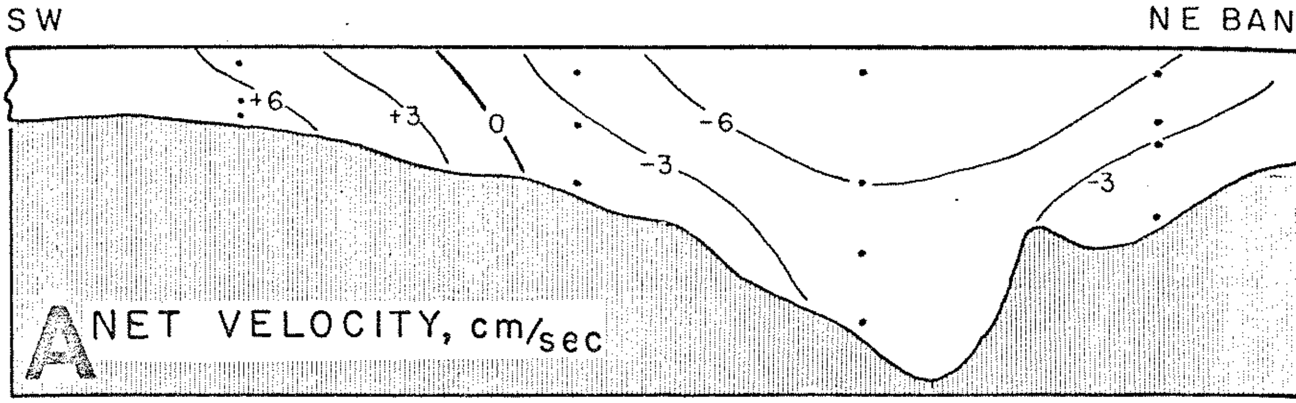


Fig. 8A. Longitudinal distribution of net non-tidal velocity one meter above bottom at three levels of river inflow (Q). B. Corresponding vertical distribution of net velocity for two levels of river inflow at 5 stations along the upper estuary. Distribution of vertical advection for seawardmost station, right. C. Longitudinal distribution of mean suspended sediment concentrations (mg/l) at very high inflow (141 m³/sec) and distribution of mean salinity, dashed.



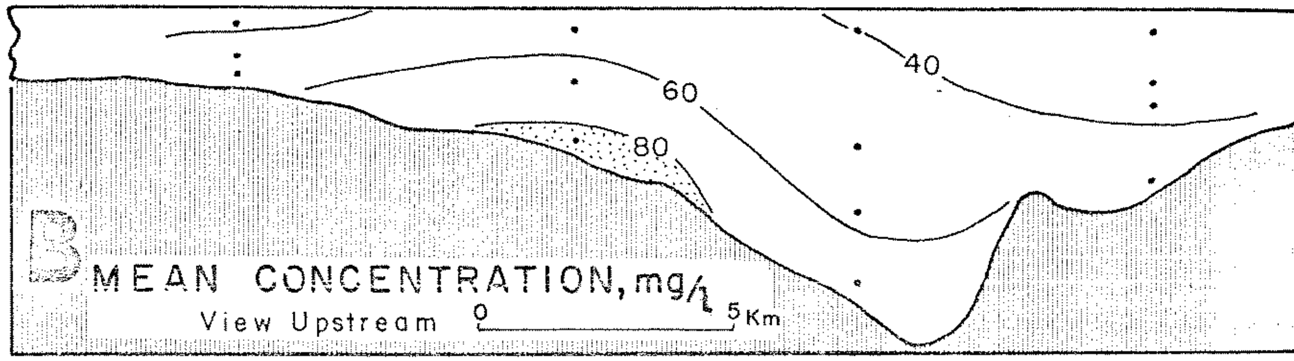


Fig. 9A. Lateral distribution of net velocity (cm/sec) based on 4 anchor stations (dots) at moderate river inflow (23 m^3/sec). Level of no-net motion, dashed. View upstream; net downstream indicated by (-) minus sign; net upstream (+) plus.

Fig. 9B. Corresponding lateral distribution of mean suspended sediment concentrations displaying turbidity maximum in relation to bottom profile and salinity distribution, dashed; transect 8, May, 1971 o-net motion. The profile for residual sediment in the estuary is n contrast to one observed in freshwater upstream of the maximum station 13A) having a normal downstream increase toward the bottom. onetheless, the vertical distribution of residual sediment follows he distribution of net velocity and indicates the transport of sediment is mainly caused by the net transport of water.

A graph of net velocity and net sediment transport substantiates hat the net velocity, or density current, is the dominate mode of transort, Fig. 10B. Values for most net velocity metering points and orresponding net transport define a relatively straightline relation. lowever, as shown by the scatter about the node, which includes several oints with upstream (flood) transport against a downstream (ebb) curents, other transport processes may be active. In this zone of low et velocity, which also includes the zone of the turbidity maximum, ime-velocity tidal asymmetry (Postma, 1967, p. 166) becomes locally mportant in producing an upstream transport. Such a feature may artly account for the apparent landward displacement of the turbidity aximum locus into freshened water often beyond the limit of upstream urrent. Other departures relate to a lag in the response of sediment transport to net velocity such as during the onset of high inflow. Ionetheless, net sediment transport is mainly coupled to net velocity.

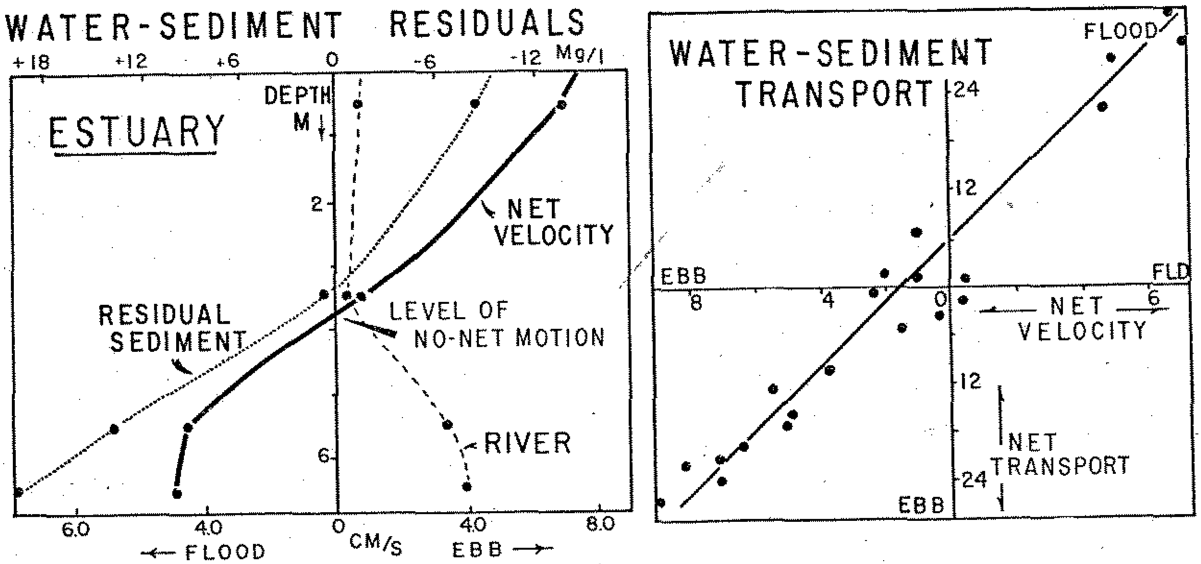


Fig. 10A. Relationship between vertical distributions of net velocity and residual sediment for a station where mean salinity is 4.3%; based on 18 tidal cycles. Compare with residual sediment distribution in fresh water upstream of maximum, dashed line. B. Relationship between net velocity in cm/sec and net sediment transport, $g/m^2hr^{10^3}$.

Sediment Transport:

Net transport through channel cross-sections at upstream and downstream limits of the maximum indicate the rate of sediment accumulation or loss by horizontal advection. For example, at very high inflow, 141 m^3 per second, Fig. 11A, 742 tons per tide is supplied to the maximum from the river and 464 tons per tide is supplied from the estuary via upstream flow in the lower layer. By contrast, 574 tons per tide is lost seaward through the upper estuarine layer. Therefore, the maximum has a net gain of 632 tons per tide and the difference between the rates through upstream and downstream ends indicates an estimated 85 percent of the river-borne imput is trapped. At this level of river inflow the maximum has a steep longitudinal gradient and a relatively large suspended load, 8400 tons.

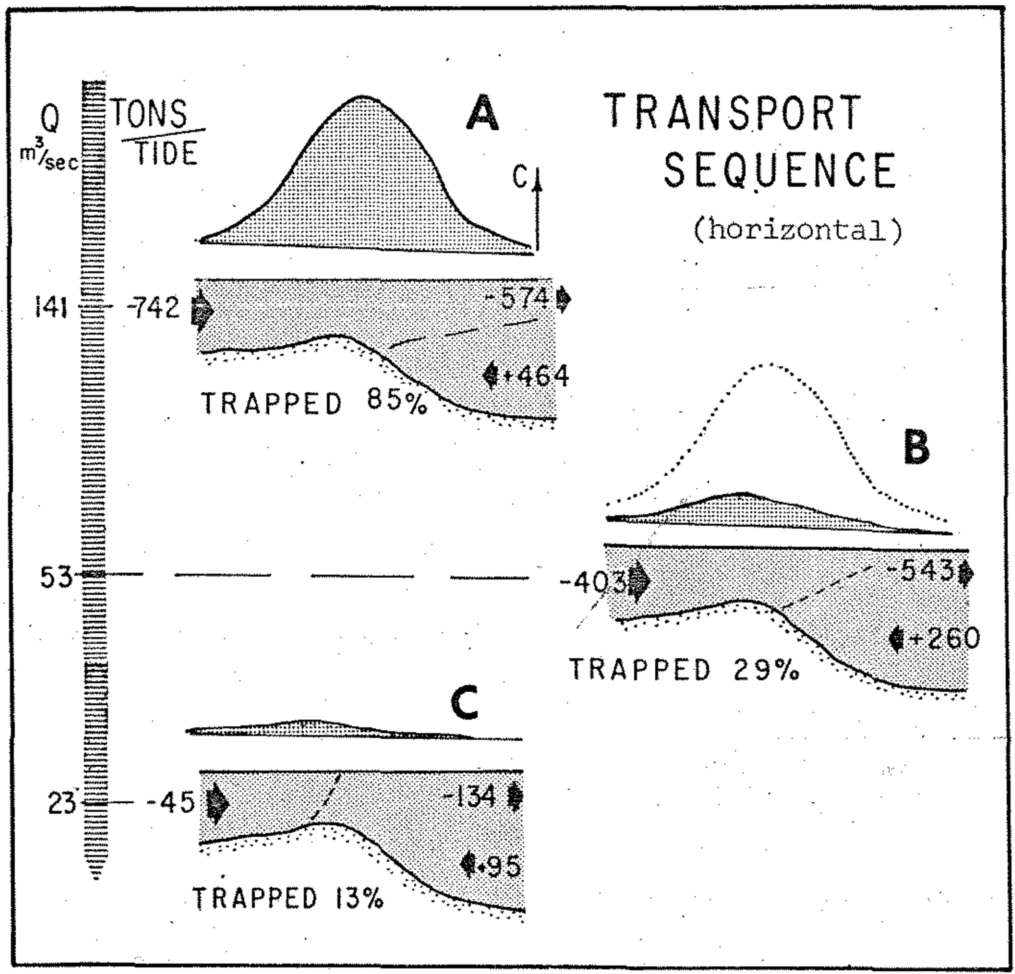


Fig. 11. Sequence of transport rates in tons per tide in the river upstream of the maximum and for upper and lower layers downstream of the maximum. Level of no-net transport, dashed, in relation to bottom topography and turbidity maximum (concentration vs. distance upstream), schematic and at different levels of river inflow, 141, 53, and 23 m^3 per second.

At 53 m^3 per sec inflow, 403 tons per tide enters the maximum and 283 tons per tide leaves; an estimated 29 percent is trapped. At 23m^3 per sec inflow only 13 percent is trapped and the remainder (87%) escapes in the upper estuarine layer. Thus, at about 65m^3 per sec inflow the maximum changes from a trapping mode to an escape mode and thus allows rapid dissipation of the maximum at low inflows.

When the rate of water outflow leaving the maximum through the upper layer is compared to the rate of sediment output through the upper layer it is evident that sediment is discharged at a relatively slower rate than the water. For example, at the 53 m^3 per sec inflow the advective fraction of water lost amounts to .25 of the total imput from the river and lower layer whereas the corresponding fraction of sediment lost is 0.18. Thus, water is circulating through the maximum faster than sediment, and accumulation must take place.

Vertical mixing and transport

Suspended material is subject to vertical transport by settling or upward movement induced by turbulence. It is also subject to mixing by vertical advection and diffusion. Such processes change with river inflow and haline stratification and their affects vary greatly with depth through the water column. They are linked to horizontal variations of advection and diffusion by continuity and salt balance.

The vertical advection of water was calculated from the difference between the horizontal advection through the seaward end of the maximum in the upper layer, and the horizontal advection through the landward end in the river. Thus, any "excess" water passing through the seaward end in the upper layer is assumed to come from the lower layer by upward vertical movement. Advection values are averaged over the area of surface separating the lower and upper layers; they also include the area in the freshwater portion of the maximum.

At one level of river inflow, e.g. 53 m^3 per sec, Fredericksburg maximal vertical advection between lower and upper layers increases with distance seaward away from the locii of the turbidity maximum, e.g. from 68 m^3 per sec, or about the same magnitude as the river inflow (R) just seaward of the maximum, to 178 m^3 per sec, about 3R. Corresponding vertical velocities near the interface between layers also increase, e.g. from $27^{10^{-5}}$ cm per sec to $71^{10^{-5}}$ cm per sec. The increased upward flow relates to increased discharge of the upper layer downstream with additions of water to the upper layer to maintain the salt balance. It must also reflect the mean vertical velocity gradient which increases with distance seaward to the middle estuary.

The vertical advection of water, 68 m^3 per sec, calculated by difference, i.e. outflow in the upper layer minus river inflow, exceeds the inflow of the lower layer by 27 m^3 per sec. This departure may result because the estuary was not in a steady state (inflow was diminishing) and because the inflow was calculated through the landward end of the maximum in freshwater rather than through the end of the salt intrusion. Nonetheless, the values give the order of magnitude of vertical advection in relation to river inflow.

At high river inflow, 141 m^3 per sec, vertical advection is 92 m^3 per sec. This value is higher than that for lower river inflow (53 m^3 per sec) but it is only about two-thirds of the river inflow or .6R. Thus, vertical advection increases with an increase in river inflow from 60 to 130 percent, within the range of inflows considered. Additionally, there is an upward diffusion contributed by salt exchange which amounts to 280^{10^4}gm per m^3 per sec at an inflow level of 53 m^3 per sec. Thus, a solely advective model predicts an upward flux of suspended sediment but it does not include fluxes due to particle settling and diffusion.

The vertical flux of sediment through the surface separating upper and lower layers was calculated from the horizontal advective flux of sediment (Fig. 11) in a manner like that used for vertical advection of water. Such flux rates are "bulk" values that include ongoing processes of settling and diffusion. They necessarily assume that all material passing vertically through the surface between layers is derived from the river or the lower layer.

At very high river inflow, 141 m^3 per sec, the rate of horizontal seaward flux through the upper layer amounts to 574 tons per tide whereas the river-borne imput is 742 tons per tide. Thus, the vertical flux must be downward at a rate of 168 tons per tide. Additionally, 464 tons per tide are supplied by horizontal advection through the lower layer. Of the total 1206 tons per tide supplied to the maximum, 574 tons per tide are flushed seaward through the upper layer and 632 tons per tide are trapped in suspension and thus available for deposition. The rate of settling of 3.2 μ size particles (1.2^{10-5} m/sec) is about 3 times faster than the vertical velocity ($.37^{10-5}$ m/sec). Such a vertical rate differential explains why a large percentage of river-borne sediment is effectively trapped in the maximum.

At a lower level of inflow, 53 m^3 per sec, the vertical flux is directed upward and amounts to 140 tons per tide. Since 260 tons per tide is supplied by the lower layer it appears 120 tons per tide are "lost" and therefore available for deposition; the rest is available for recycling through the upper layer. Settling rates of 2.8μ size particles at this hydraulic condition exceed vertical velocities by about 2 times. Thus, trapping is active but less effective than at the higher inflow (141 m^3 per sec).

A similar trend developed at moderate inflow, 23 m^3 per sec, in which 95 tons per tide are supplied by the lower layer and 89 tons per tide passes through the surface separating lower and upper layers. Since less than 13 percent of the river-borne load is trapped in the maximum, the bulk of the suspended material presumably is recycled downstream in the upper layer.

Available data for vertical advection and transport, presented in Table 1, permit comparison of rates for different levels of river inflow.

Table 2. Rates of vertical velocity and advection, vertical sediment transport (flux) in the turbidity maximum between stations 6 and 13 at different levels of river inflow. + indicates upward direction, - downward.

River Inflow* m^3/sec	Vertical Velocity m/sec	Vertical Advection m^3/sec	Vertical Sediment Transport tons/tide	Settling Rates m/sec
141	$+ .37^{10-5}$	+ 92	- 168	1.2^{10-5}
53	$+ .27^{10-5}$	+ 68	+ 140	0.8^{10-5}
23	---	---	+ 89	0.7^{10-5}

* at Fredericksburg

Development Sequence

Development of the maximum follows a time sequence with changes in river inflow, salinity, haline mixing and strength of the river-estuarine convergence. This sequence is displayed in a series of longitudinal panels (Fig. 12) representative of important stages in a "life cycle" beginning with extreme flooding, June 24, 1972. In the sequence the maximum is distinguished by changes in its position, turbid structure and intensity.

1. In the first panel, Figure 12, +1 day, relatively high energy conditions prevail with a seaward surge of fresh flood water and high sediment influx, first from the lateral tributaries and then from the main drainage. Backed by a high hydrostatic head, surface currents flow continuously seaward. During the first day of surge about 2 percent of the total flood imput passed through the middle estuary.

   In response to initial flooding, the salt intrusion is pushed seaward, reduced to two-thirds its normal length, and forms a relatively high gradient at the fresh-salt transition. Near bottom tidal and density currents are diminished in magnitude and upstream extent.

2. In the next stage (+3 days), the turbidity maximum first appears in freshwater as an enriched turbid aureole with a lean core at mid-depth. As river inflow diminishes and stratification intensified, upstream flow accelerates and the salt intrusion head begins to move upstream. Start of this rebound in the bottom creates an intense convergence in a narrow zone or front, fresh and salty water. River water impinges on salty water and upward mixing must ensue. Suspended sediments introduced during early stages of flooding that are relatively coarse-grained and too heavy to be carrier upward, settle into the convergence and accumulate. During this stage tidal currents are reestablished throughout the estuary and actively resuspend freshly deposited sediment but entrapment in the convergence is the main starter mechanism for the turbidity maximum.

3. With lowered river inflow (+ 5 day) upstream flow increases near the bottom, the salinity rebound proceeds farther upstream and stratification becomes intense. Such conditions provide optimal entrapment. Despite the large reduction of sediment influx, now only a fraction (1/35) of the initial influx, the turbidity maximum is well organized, and it supports a steep longitudinal concentration gradient. At this stage the maximum is characterized by vertically homogeneous turbid structure.

4. At moderate inflow (+30 day), upstream penetration of salty water is diminished and the estuary returns to its normal partly-mixed state. Position of the maximum is stabilized over a major shoal in the upper estuary where it decays and disperses over a broad zone. As sediment settles out the vertical concentration gradient becomes steeper.

The maximum reappears quickly after each flood or freshet and it subsists largely in a decaying state for 4 to 16 weeks.

There are a variety of modifications that take place within the developmental framework outlined above. At times, successive discharges of freshwater and sediment temporarily reinforce or intensify previously formed maxima. Secondary maxima often form around secondary nodes associated with shoals athwart the channel. Influx of sediment from seaward sources via upstream transport in the lower layer may intensify the maximum and displace its locus downstream into more salty water. Intense wind wave stirring of bottom sediment temporarily enriches near-bottom parts of the maximum. Any process which supplies suspended sediment or enhances the river-estuarine convergence is favorable for development.

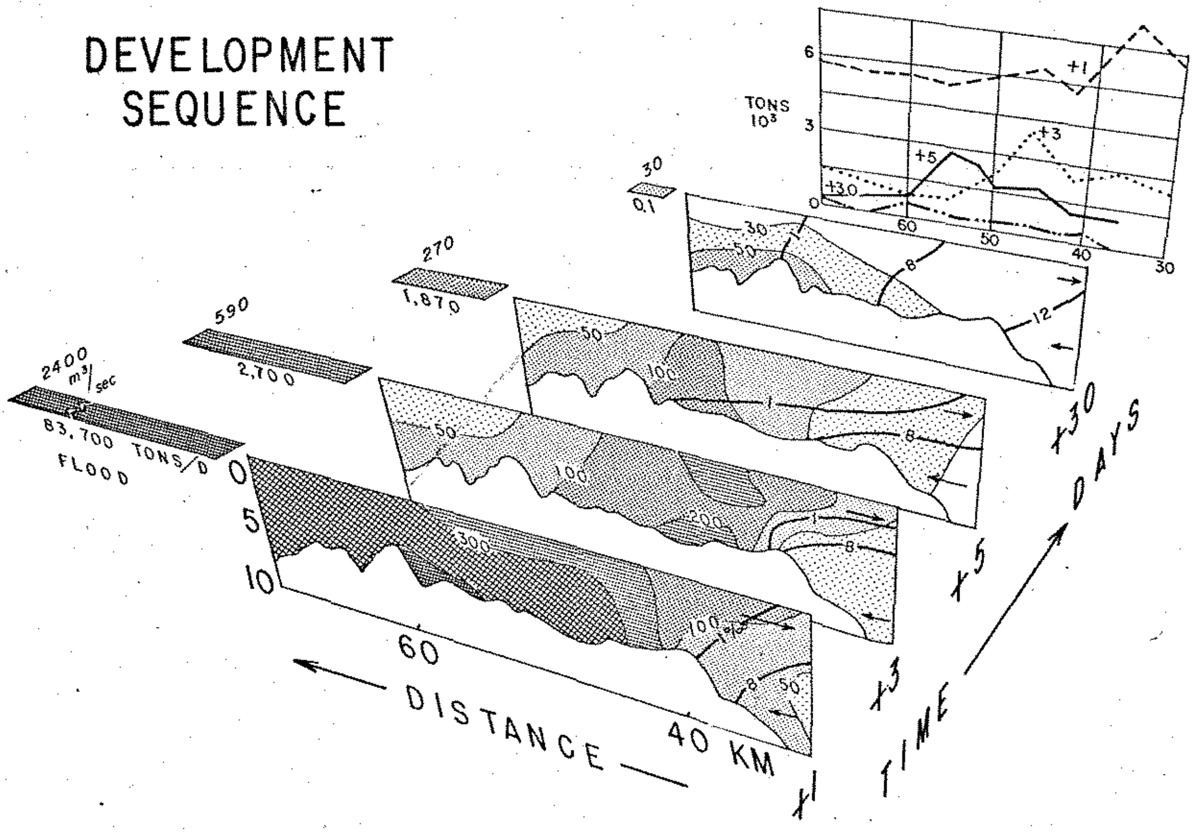


Fig. 12. Longitudinal distribution of suspended sediment concentrations (mg/l) along the upper Rappahannock 30-70 km showing development of the turbidity maximum with time beginning with major flood June 24, 1972. Data based on selected transects made near slack tide. Salinity (‰), heavy solid line. Bars left indicate magnitude of inflow and sediment discharge at Fredericksburg. Rear graph represents longitidunal distribution of total sediment tonnage along sections of the estuary for each day, +1, +3, etc.

DISCUSSION

Controlling Processes

Of the many processes attributed to producing the turbidity maximum (e.g. such as listed in Appendix I), flocculation is not an important process in the Rappahannock. Suspended floccules are scarce except during short periods of intense wind stirring and extreme flooding. However, organic floc-like aggregates are present and some river-borne sediment in the estuary reportedly is preflocculated in upland soils and drainage. The mineralogy and distribution of clay minerals in the Rappahannock Estuary (Nelson, 1960) showed no evidence for flocculation. Ideally, aggregation or flocculation enhances settling rates of suspended material and therefore should allow good trapping in the convergence and enrichment of the lower layer. However, effectiveness of trapping not only depends on settling rates but on the strength of vertical mixing that supports and transports particles in suspension.

Although tidal currents reach speeds competent to erode and resuspend bottom sediment more than 60 percent of the time, maximum and mean velocities are relatively uniform with distance seaward through the reach of the maximum (Figure 4C). Thus, changes in the longitudinal distribution of suspended material due to tidal resuspension of bottom sediment supplied locally from shoals, is unlikely. However, erodability of the floor may vary through the reach with a change in sediment character, but the distribution of bed shear stress is unknown. Direct measurements have not been made. And stress determinations from velocity profiles close to the bed at one place yield such a wide range of values with time, over 8 successive ebbs and floods, they preclude meaningful results. Depth changes through the reach of the maximum due to shoaling should lead to higher vertical velocity gradients and thus increase the amount of material in suspension. However, no major increase of suspended sediment persists in the shoaling reach. Tidal resuspension is active throughout the year, long after the maximum has dissipated. Thus, tidal resuspension alone, or the interaction of flow with bottom geometry, does not appear to control development of the turbidity maximum in the Rappahannock. Other processes must be taken into account, the strength of the fluvial-estuarine convergence and vertical mixing, in addition to the magnitude of river-borne supply and inflow.

The field observations and transport measurements of this study define a circulatory mechanism responsible for development of the turbidity maximum. The mechanism consists of essential two features: (1) a near-bottom convergence where downstream river flow and a net upstream estuarine flow meet. (2) an upward vertical mixing in the convergence which is comparable to or slightly greater than, the sediment settling rate. (3) a relatively high vertical gradient of sediment in the convergence attendant by upward diffusion. Tidal currents serve to provide the energy to support a large amount of sediment in suspension. This in turn allows it to be transported by the net density currents and to be mixed vertically.

The turbidity maximum is linked to the convergence of net density currents by correlative distribution patterns and temporal change of suspended concentrations and net current. The linkage is based on the supposition that suspended material in the maximum is effectively transported by density currents. This is substantiated by the following observations:

- The vertical distribution of residual concentrations follows the vertical distribution of net velocity values in the estuarine portion of the maximum. In this distribution the ebb-flood cross over point of residual concentrations lies close to the level of no-net motion.
- The net velocity values are linearly proportional to the net transport values.
- The longitudinal distribution of transport values follows the distribution of net velocities with a near-bottom transport node close to a net velocity node. The nodes shift upstream with diminished landward shift of the salt intrusion head.

Several features demonstrate that development of the maximum relates to accumulation of suspended material in the convergence system:

- The locus of the maximum resides close to, though slightly upstream, of the locus of the convergence near the bottom.
- The position of the maximum shifts landward with upstream penetration of the salt intrusion head and therefore with an inferred landward shift of the convergence.
- The intensity of the maximum diminishes with strength of opposing net currents, i.e. with strength of the convergence, and with increased vertical mixing. Reduced intensity also follows a major influx of sediment from the river.
- The relative volume rate of water flowing through the convergence zone is proportionately greater than the relative flux of sediment.
- The rate of sediment supplied by the river and lower layer exceeds the rate of loss through the upper layer.

Development of the maximum proceeds through a sequence controlled by river inflow. As a result, it provides the best index to factors controlling the position, intensity and duration of the maximum. It supplies the bulk of the suspended sediment load at high levels of discharge and determines the position of the salt intrusion head. It generates salinity gradients and thus determines the magnitude of vertical mixing as well as the strength of converging fluvial-estuarine density currents. Low inflows allow tidal and diffusive mixing to release suspended material from the maximum whereas high inflows are favorable to trapping.

Trapping Index

The trapping ability of an estuary depends on the relation of particle settling to vertical mixing rates and on the strength of the net current convergence. Since the distribution of net transport follows net velocity in near-bottom water and in turn, since velocity is associated with varying intensities of the maximum, an indication of the trapping ability can be gained (in the horizontal aspect) by considering the width of the net current transition. As shown in Figure 8A, a spectrum of net current transitions is displayed that vary in steepness with changing intensity and width of the maximum. Thus, the slope of velocity trends through the node, and gives an indication of the trapping ability (Fig. 8A). This relation includes the influence of the vertical salinity gradient, and to some degree river inflow, inasmuch as the magnitude of ebb-flood velocities is determined by th factor. It remains to include the settling rates for the appropriate particle sizes involved.

Although it has not been possible to trace the effect of trapping over a full annual cycle of inflow, one of its end products is evident in deposition rates on the estuary floor. Figure 13 shows the rates of fill in sections of the upper Rappahannock through the reach of the maximum. It is evident that deposition is greater in the reach of the maximum than elsewhere. These rates account for more than 90 percent of annual sediment influx. Thus, over the long-term, trapping in the maximum appears to be very effective.

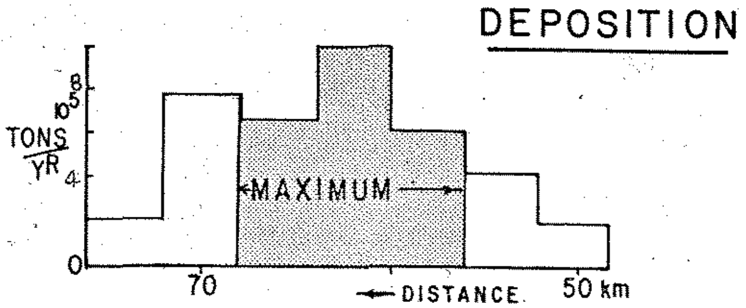


Fig. 13. Distribution of fill rates, tons per year, in sections of the Upper Rappahannock, 48 to 75 km upstream including the reach of the turbidity maximum. Based on depth changes between 1910-1971.

SIGNIFICANCE OF RESULTS AND APPLICATIONS

Although the new knowledge gained in this study is mainly a contribution to basic research, it has many practical applications. The results should be of value to engineers, geologists and military men faced with problems arising from circulatory action and excess turbidity. Because turbidity is closely linked to other factors, results of this study should be enhanced especially when combined with other studies such as those dealing with water quality or hydraulic modeling. Prospective applications and contributions include the following:

Effect on Other Properties:

The processes that accumulate suspended material in a turbidity maximum are essentially the same processes responsible for trapping nutrients, pollutants and other components in particulate form. As shown by data from the James Estuary Figure 14, suspended organic material increases in the same reach where total suspended material is also high. As expected total phosphate, mainly particulate material, is also high but chlorophyll "a" concentrations are locally reduced. There trends suggest river-borne plankton transported into or trapped in the maximum, are partly eliminated by slightly salty water and production is further limited by high turbidity.

In the Sacramento-San Joaquin River, Peterson et. al. (1973) observed a turbidity maximum at low river inflow which consisted of phytoplankton and zooplankton. Blooms developed because the long water replacement time resulting from density current stagnation permitted plankton to reside, and grow in the maximum over a long period.

Thus, the entrapping processes are responsible for accumulation of different sorts of materials in particulate form and these effects are extended to ecological functions through diminished circulation or dampening of light energy.

Ecological Impacts:

Since turbidity is a factor determining the character of habitats, conditions imposed on organisms by high turbidity are a factor in the viability and productivity of an estuary. High turbidity impairs light penetration, diminishes thickness of the euphotic zone and in turn limits basic productivity. Additionally, planktonic larvae of oysters and clams are often vulnerable to high concentrations of suspended material. And likewise, extreme turbidity degrades the habitat of fishes by clogging gill structures and interfering with respiration.

Concentration of Pollutants:

As a form of pollution, concentrations of turbid materials degrade water quality for recreation and for industrial use. When trace metals like lead, copper or zinc, are adsorbed or bound on clay or silt particles they accumulate in the turbidity maximum along with the total suspended materials. Concentration factors of more than 100,000 have been observed in some estuaries (Postma, 1969). In the Rappahannock concentrations of copper in bottom sediments reaches 23 ppm or 2 times greater than in the river or estuary (Huggett, personal communication). Because of rapid accumulation and long residence time the turbidity maximum is one of the most vulnerable sites of pollution in an estuary.

Enhanced Knowledge of the Environment:

The distributions of turbidity and related circulatory features affect the testing of defense equipment and operation of acoustical or electronic sensing devices. Like atmospheric clouds, turbidity affects water visibility thus offering concealment. It may obscure buried objects affecting the location of submerged targets or navigation. And shoals that are products of the turbidity maximum are a factor in river trafficability. Since turbid patterns are displayed by aerial and space imagery, the new information gained in this study may be applied to operational problems in remote estuaries through remote sensing imagery.

Source of shoaling:

Accumulation of fine-grained suspended material manifest in the turbidity maximum, is the first stage whereby shoaling materials concentrate and subsequently change into fluid mud lenses or consolidated masses. As shown by Berthois (1956), the turbidity maximum leads to massive siltation in ports and harbors along the Loire Estuary, France. Therefore, the expanded knowledge of the maximum should assist engineers in predicting where channel shoaling will occur and where channel maintenance will be high. By utilizing the river inflow-net flow-suspended concentration relationships, it should be possible to forecast both the sites and the conditions for maximum shoaling.

Improved Predictive Capability:

It is generally recognized that hydrodynamic and sedimentological processes operating in an estuary are extremely complex and incompletely understood. Yet, it is these processes upon which management decisions must be based. And it is these processes that must be inferred from structural and textural patterns in ancient rocks. Because engineering modifications and hydrologic management often required an advanced knowledge of consequences and "side effects", the results of this study should assist planning engineers in predicting effects of major structure or modifications before they are accomplished. By controlling river flow through damming or diversion it should be possible to change the location of the maximum and thus change the site of shoaling or reduce its intensity. By disposing dredge spoil within the zone affected by converging currents (e.g. in channel reaches upstream and downstream of the maximum), the maximum will be enriched and shoaling enhanced. By contrast, dispersal of spoil will be minimized by dumping in the maximum where retention of suspended material is better than elsewhere.

Inasmuch as the turbidity maximum is an intrinsic feature common to partly-mixed and stratified systems, the information gained in this study may have general application to other estuaries. Although the maximum studied in the Rappahannock has characteristics all its own, a predictive understanding is feasible because the maximum is linked to a basic process, the estuarine circulation and river inflow. But quanitized predictions must await development of a mathematical model.

The results of this study are not intended to be a panacea for all problems of the turbidity maximum. However, they should permit identification or isolation of hydraulic and salinity factors affecting entrapment. This information is also important for improving analytical studies and in refining hydraulic model studies. It should be of use for comprehending processes in more complex estuaries.

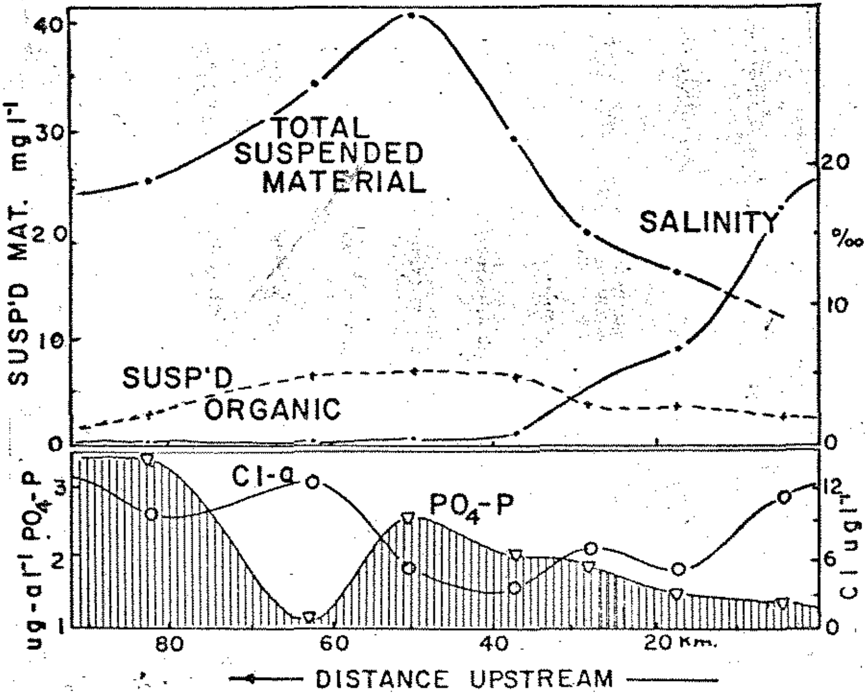


Figure 14. Distribution of total suspended concentrations, salinity, suspended organic matter, total phosphate, and chlorophyll "a". Data based on near-surface slack water samples in James Estuary, May 9-11, 1966

PROBLEMS FOR FUTURE STUDY

Results of this study have exposed gaps in our knowledge that define further problems for future study.

1. Knowledge of dispersion rates and residence time of both water and suspended sediment in the maximum is inadequate. Tracer studies are needed to determine recycling rates and to calculate mixing coefficients. Such studies would serve to verify results of hydraulic and transport measurements. They would strengthen the link between sediment movement and hydraulic conditions, and permit prediction of dispersion rates.

2. Relatively little is known about the "starter mechanism" for development of the maximum. Although observations of this study embraced time-series at several levels of river inflow they were made mainly when the maximum was in a dissipat mode. Detailed hydraulic and transport measurements need to be made at the onset of flooding or freshet to trace generation, or regeneration of the maximum, during very early stages of development, the first 24-48 hours. Since the maximum loses most of its load early in "life", initial stages are the most important for predicting deposition.

3. Sedimentologic processes which interact with hydrodynamic processes in an estuary, are extremely complex and incompletely understood. Results emerging from this study could be expanded by more quantitative treatment of transport processes. Basic equations describing the observed phenomena need to be solved, and a two-dimensional model formulated to substantiate the postulated mechanism. Once tested and verified such a model would show how the maximum responds to changes in many variables. It would permit quantitative transfer of the Rappahannock data to other estuaries and its predictive value could be used to evaluate the benefits, or consequences, of channel maintenance and engineering works.

4. Changes in sediment mineralogy and texture, from rivers into the sea, have long been of interest to geologists. Such changes have been studied around river mouths like the Mississippi but information on changes in turbidity maxima that relate hydraulic processes are few. It would be of considerable interest to know if mineralogic and chemical changes affect the turbidity maximum, and if such changes are leading to differential transport or preferential recycling. Analyses of mineralogic differences is of obvious importance in a feature composed of contrasting source materials and where mixing is active.

5. Although many studies have contributed to our knowledge of bottom sediments and of fine-grained sediments in suspension, the <u>interaction</u> of bottom and suspended sediments in development

of the maximum requires more study. The bottom acts at times as a source, and at other times as a sink. Its geometry affects flow conditions. Supply from the bottom of the Rappahannock was necessarily accounted for indirectly. As is often the case, transport was determined from short period measurements whereas deposition was determined from depth changes over a long time span. Since the maximum changes from trapping to an escape mode with time, rates of supply and loss are required on a continuous basis over a full cycle of development.

6. Since the turbidity maximum is the first stage in a sequence whereby shoaling materials accumulate prior to deposition, it is logical to ask how the materials are transformed near the bottom into consolidated masses. Detailed study of near-bottom fluid mud lenses and zones of "fluff", which are a critical link in such a transition, should be of great interest and value.

SUMMARY

A study of the turbidity maximum was conducted in the Rappahannock Estuary to determine how high concentrations of suspended sediment accumulate to form a maximum. The estuary has relatively simple geometry, low tide range, moderate inflow and moderate sediment influx. Waters are partly-mixed and the transition from fresh to salty water is relatively broad and diffuse.

Time-series observations of current velocity, salinity and suspended sediment over 8 to 18 tidal cycles reveal that the maximum forms in a convergence of bottom residual currents near the salt intrusion head. Since the residual movement of sediment relates to the net movement of water, sediment must be transported into the convergence zone, where net velocity approaches zero, and reside there for a relatively long time. Accumulation is enhanced by particle settling that proceeds faster than upward mixing and diffusion. Active accumulation is supported by the fact that the rate of sediment supplied by the river and lower layer exceeds the rate of loss through the upper layer.

The dynamic behavior of the maximum was traced through a life cycle with changes in river inflow and haline mixing. The maximum forms in the middle estuary after a freshet or flood and shifts upstream with a landward shift of the salt intrusion head and diminished river inflow. At the same time intensity is reduced by increased mixing, reduced strength of converging near-bottom currents and settling out. The maximum reappears with each high inflow and subsists for a life span of 4 to 16 weeks. River inflow is the prime factor controlling supply of sediments, the salinity gradient, strength of the convergence; and therefore, the development of the maximum.

The turbidity maximum modulates transport of materials from rivers, through estuaries, to the sea by trapping large amounts of sediment as well as nutrients or pollutants and plankton supplied locally. High turbidity reduces water quality, degrades ecological habitats and leads to siltation of channels and ports. Conditions for development of the maximum are being enhanced by man through accelerated land erosion and deepening of channels. The maximum can be controlled by any means that increases haline mixing and reduces river inflow or sediment influx.

PARTICIPATING PERSONNEL AND ACKNOWLEDGEMENTS

This study was formulated by Dr. Maynard Nichols, through discussions with Drs. Bruce Nelson, Robert Meade and William Van Royen. Dr. Nichols, VIMS Associate Marine Scientist supervised the overall field and laboratory work assisted by Mr. Galen Thompson, VIMS Research Assistant, who directed the field operations and supervised data reduction.

Cruise preparation, laboratory filtrations and data reductions were accomplished by Mr. J. Mercer and B. Weaver, VIMS Laboratory Technicians. Their efforts were supplemented by graduate student assistants, C. Wenner and W. Norton.

Field operations consisting of round-the-clock observations from anchor stations were supported for short periods by Institute laboratory technicians: W. Hale, W. Cowden, T. Blakley, C. Pinter and R. Collins, C. Leigh, J. Brown, R. O'Quinn, S. Snyder, D. Burrage and B. Matthews. In addition, VIMS graduate students who participated include: L. Suydan, H. Kerby, J. Boon, M. McGinty, A. Lawler, R. Elder, J. Weaver, J. Olman, M. Dietz, R. Burbidge, M. Fine, P. Bullock, W. Cooke, L. Shotton, and J. Lanier.

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Data processing was expedited by use of equipment at the NASA-Langley Research Center. Mr. R. Moncure and F. Wojcik of VIMS Data Processing Section prepared numerous computer programs to perform lengthy computations and evaluate the data statistically. Particle size analyses were run by Mr. D. Walsh of VIMS on a Coulter Counter unit. Clay mineralogy of selected samples was performed by the National Bureau of Standards.

Figures for this report and related papers were drafted by Mrs. Jane Davis and Mrs. Kay Stubblefield of VIMS Graphic Arts section. Reductions and photography were done by Mr. W. Jenkins and Ken Thornberry and Mrs. Cindy Otey typed the report.

Information gained from ongoing water quality stations, tide stations and other projects reinforced the present study. Suspended sediment discharge in the river at Remington was acquired from the U.S. Geological Survey; river discharge data at Fredericksburg came from the Virginia Department of Conservation and Economic Development; tidal height and tidal datums from the National Oceanic and Atmospheric Administration; supplemental cross-sectional area and velocity data came from ongoing VIMS research projects in cooperation with the Virginia State Water Control Board and the U.S. Army, Chesapeake Bay Hydraulic Model program.

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APPENDIX I. List of reported occurrences of the turbidity maximum in different estuaries of the world and predominate processes active in their development.

Location	Reference	Mixing Regime	Predominate Process
North America			
St. Lawrence River, Canada	D'Anglejan, 1969	Partly-mixed	Refluxing of material settled into bottom water, tidal resuspension.
Montsweag Bay, Kennebec River, Maine	Schnitker, 1973	-----	Bottom resuspension by storm waves.
Chesapeake Bay	Schubel, 1968	Partly-mixed	Tidal resuspension and residual currents.
Patuxent River, Md.	Stross et.al., 1965	Partly-mixed	-----
Rappahannock River, Va.	Nelson, 1959	Partly-mixed	Deflocculation
York River, Va.	Nelson, 1960	Partly-mixed	-----
James River, Va.	Nichols, 1972	Partly-mixed	Residual currents and estuarine circulation.
Savannah River, Ga.	Meade, 1967	Partly-mixed	Residual currents and estuarine circulation.
	Krone, 1973		Recycling, flocculation; settling.
Mississippi River	Wright, 1970	Highly stratified	Flocculation, interfacial turbulence; settling retarded by salt water, recycling by density currents.
Columbia River	Hubbell et al, 1971	Partly-mixed	Estuarine circulation.
San Francisco Bay-San Joaquin River	Peterson et.al., 1973	Partly-mixed to well-mixed	Estuarine density currents and plankton growths.
Acharon Channel-Yukon River, Alaska	Matthews, 1973	Highly stratified	Flocculation and recycling by the estuarine circulation.

APPENDIX I. (Cont'd.)

Location	Reference	Mixing Regime	Predominate Process
Central South America			
Demerara and Essequibo Rivers, Br. Guiana	Demerara Coastal Inves., 1962	Partly-mixed to well-mixed	a. Tidal currents (seasonal) b. Residual density currents and longitudinal diffusion.
Rio de la Plate	Ottman, 1968 Urien, 1972	Partly-mixed Highly-stratified	----- Tidal resuspension and estuarine circulation.
Boca Vagre, Orinoco River, Venz.	Van Andel & Postma, 1954	Highly-stratified to partly-mixed	Flocculation and re-cycling in the estuarine circulation.
Gulf of San Miguel, Panama	Swift and Pirie, 1970	Partly-mixed	a. Estuarine density currents. b. Tidal resuspension on shoals.
Europe			
Gironde River, France	Allen, 1972	Highly stratified to partly-mixed	Residual density currents.
Bristol Channel-Severn Estuary, U.K.	Bassindale, 1943	Partly-mixed to well-mixed	River inflow and tidal resuspension.
Loire River, France	Berthois, 1956	Highly stratified to partly-mixed	River inflow and neap-spring tidal currents (seasonal).
Thames River, U.K.	Inglis and Allen, 1957	Partly-mixed to well-mixed	Residual density currents.
Ems-Dollart Estuary, Netherlands	Van Stratten, 1960	Partly-mixed to well-mixed	Estuarine density currents.
Elbe River, Germany	Postma and Kalle, 1955	-----	Flocculation, settling and estuarine density currents.
	Luneburg, 1939	------	Flocculation.
	Ramming, 1972	Partly-mixed	Residual currents and plankton growth.

APPENDIX II A. Summary of Residual Water and Sediment Movement, Mean Salinity and Sediment Transport Data for Very High Inflow, 141 m^3 per sec at Fredericksburg.

Station	depth above bottom	number of tidal cycles	Date	net velocity cm/sec	residual sediment mg/l	net sediment transport $g/m^2/hr$	mean sediment mg/l	mean salinity ‰
6	6.5	8	4-1-70	- 9.0	- 7.3	- 27,873	66.4	2.1
	3.3		to	- 3.4	+ 1.6	+ 12,368	85.6	2.7
	1.3		4-7-70	- 0.0	+15.1	+ 32,053	115.2	3.1
	0.3			+ 2.8	+33.9	+ 42,908	142.4	3.1
8A	5.6	8	4-3-70	- 7.9	-18.4	- 32,484	102.3	0.6
	2.2		to	- 6.4	+ 3.4	- 6,550	140.7	0.7
	1.2		4-7-70	- 6.1	+ 8.0	+ 1,165	170.0	0.7
	0.2			- 3.8	+ 9.2	+ 12,832	219.8	0.7
12	6.7	8	4-3-70	- 8.2	- 8.2	- 22,023	64.1	< 0.1
	2.3		to	- 5.4	-12.3	- 28,119	91.3	< 0.1
	1.3		4-7-70	- 4.5	-13.4	- 22,813	105.7	< 0.1
	0.3			- 4.2	-15.8	- 20,514	134.6	< 0.1
13A	6.7	8	4-3-70	- 9.8	- 5.7	- 21,525	52.3	< 0.1
	2.2		to	- 6.8	- 5.4	- 22,100	70.7	< 0.1
	1.2		4-7-70	- 5.7	- 7.3	- 23,405	85.2	< 0.1
	0.2			- 5.3	- 6.1	- 20,505	106.0	< 0.1

Note: Minus (-) indicates downstream direction, plus (+) upstream.

APPENDIX II B. Summary of Residual Water and Sediment Movement, Mean Salinity and Sediment Transport Data for Very High Inflow, 53 m^3 per sec at Fredericksburg.

Station	depth above bottom	number of tidal cycles	Date	net velocity cm/sec	residual sediment mg/l	net sediment transport g/m^2/hr	mean sediment mg/l	mean salinity ‰
6	6.5	8	4-9-70	- 6.5	- 8.2	- 20,428	61.2	3.3
	3.3		to	+ 0.3	+ 0.4	- 1,393	65.3	4.4
	1.3		4-14-70	+ 7.2	+15.3	+ 31,743	83.3	6.1
	0.3			+ 6.8	+27.3	+ 33,743	101.9	6.4
8A	5.6	8	4-9-70	- 4.9	- 4.8	- 16,157	63.3	1.3
	2.2		to	- 1.6	+ 1.8	- 5,591	72.5	1.7
	1.2		4-13-70	- 0.1	+ 2.0	- 3,547	80.0	1.9
	0.2			+ 0.3	+ 2.5	- 622	93.6	1.9
12	6.7	8	4-9-70	- 2.2	- 8.4	- 12,117	58.6	0.1
	2.3		to	- 0.6	- 9.6	- 11,888	76.7	0.1
	1.3		4-12-70	- 0.3	-12.6	- 10,756	87.4	0.2
	0.3			- 0.2	-17.4	- 7,614	92.7	0.3
13A	6.7	2	4-11-70	- 3.5	- 3.5	- 9,651	53.2	< 0.1
	2.2		to	- 1.6	- 6.4	- 13,934	67.0	< 0.1
	1.2		4-12-70	- 1.4	-17.3	- 26,126	80.2	< 0.1
	0.2			- 1.0	-24.7	- 30,874	99.6	< 0.1

Note: Minus (-) indicates downstream direction, plus (+) upstream.

APPENDIX II C. Summary of Residual Water and Sediment Movement, Mean Salinity and Sediment Transport Data for Very High Inflow, 71 m^3 per sec at Fredericksburg.

Station	depth above bottom	number of tidal cycles	Date	net velocity cm/sec	residual sediment mg/l	net sediment transport $g/m^2/hr$	mean sediment mg/l	mean salinity ‰
6	6.5	14	4-2-70	- 7.1	- 8.2	- 24,043	58.6	3.1
	3.3		to	- 0.9	- 0.8	- 1,597	65.6	4.0
	1.3		4-14-70	+ 4.5	+11.4	+ 22,154	85.8	5.3
	0.3			+ 4.9	+23.6	+ 29,301	104.7	5.5
8A	5.6	18	4-3-70	- 5.0	- 9.6	- 17,583	80.1	1.2
	2.2		to	- 2.4	+ 1.7	- 460	103.2	1.5
	1.2		4-13-70	- 2.1	+ 4.5	+ 2,022	120.0	1.5
	0.2			- 1.1	+ 7.2	+ 7,041	151.8	1.6
12	6.7	12	4-4-70	- 5.4	- 7.7	- 10,212	57.7	<0.1
	2.3		to	- 3.3	- 9.8	- 12,390	76.9	<0.1
	1.3		4-14-70	- 2.7	-11.3	- 13,384	88.8	<0.1
	0.3			- 2.3	-27.0	- 12,177	95.6	<0.1
13A	6.7	10	4-5-70	- 5.3	- 8.3	- - -	51.7	<0.1
	2.2		to	- 4.0	-10.1	- - -	68.5	<0.1
	1.2		4-12-70	- 3.2	-10.5	- - -	83.7	<0.1
	0.2			- 3.1	-12.2	- - -	106.2	<0.1

Note: Minus (-) indicates downstream direction, plus (+) upstream.

APPENDIX II D. Summary of Residual Water and Sediment Movement, Mean Salinity and Sediment Transport Data for Very High Inflow, 23 m³ per sec at Fredericksburg.

Station	depth above bottom	number of tidal cycles	Date	net velocity cm/sec	residual sediment mg/1	net sediment transport g/m²/hr	mean sediment mg/1	mean salinity ‰
8A	4.2	8	5-5-71	- 8.0	- 1.6	- 8,207	40.4	3.0
	2.3		to	- 6.2	- 0.9	- 2,861	48.2	3.2
	1.3		5-9-71	- 5.1	+ 2.5	- 776	56.3	3.3
	0.3			- 3.7	+ 7.9	+ 4,462	71.0	3.4
8B	2.5	4	5-8-71	- 6.0	- 1.7	- 1,371	35.8	3.0
	1.5		to	- 4.6	+ 0.3	- 1,686	33.9	3.4
	1.2		5-10-71	- 3.1	+ 1.3	- 269	36.5	3.5
	0.2			- 0.5	+ 2.3	+ 2,446	49.9	3.5
8C	2.3	4	5-10-71	- 5.1	- 2.9	- 11,316	53.7	2.8
	1.3		to	- 2.6	- 1.9	- 4,668	70.4	2.8
	0.3		5-12-71	- 0.8	+ 2.7	+ 5,876	86.1	3.0
8D	1.2	4		+ 7.6	+ 1.0	+ 18.3	41.5	2.9
	0.4			+ 5.7	+ 1.3	+ 8.7	36.4	2.9
	0.2			+ 5.5	+ 1.6	+ 0.8	52.3	3.0
12	6.7	6	5-3-71	- 1.6	+ 3.2	+ 2,000	26.5	0.5
	2.7		to	- 0.5	+ 1.3	+ 1,687	22.1	0.6
	1.2		5-6-71	- 1.1	+ 0.7	- - -	29.5	0.5
	0.2			+ 0.1	+ 2.4	+ 2,262	32.0	0.5
13A	6.0	8	5-5-71	- 1.4	- 0.8	- 439	24.0	0.1
	3.0		to	- 0.6	- 2.8	- 2,778	40.0	0.1
	1.2		5-9-71	+ 0.8	- 0.4	+ 1,428	32.2	0.1
	0.2			- - -	+ 1.1	+ 2,295	36.3	0.1
14	6.9	8	4-28-71	- 1.6	- 1.0	- 1,737	28.2	< 0.1
	3.4		to	- 3.0	- 0.5	- 4,006	33.6	< 0.1
	1.2		5-01-71	- 2.0	- 6.7	- 6,944	48.4	< 0.1
	0.2			- 0.4	- 5.4	- 6,193	69.7	< 0.1

Note: Minus (-) indicates downstream direction, plus (+) upstream.