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A GENERAL ASSESSMENT OF SELECTED DREDGING/DISPOSAL OPTIONS FOR THREE FEDERAL DREDGING PROJECTS IN UPPER CHESAPEAKE BAY

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INTRODUCTION

Schubel et al. (1978) developed a conceptual framework for assessing dredging/disposal options for projects in Chesapeake Bay. That framework is shown schematically in Fig. 1.

Selection of a dredging/disposal option for each project should be based on an identification of the full range of alternatives--including the no dredge option--and on a rigorous assessment of the environmental, public health, socio-economic, and political effects associated with each alternative. We have used the framework shown in Fig. 1 to evaluate the environmental effects of selected alternatives for each of three major projects: (1) Chesapeake and Delaware Approach Channel, (2) Baltimore Harbor Approach Channels, and (3) Baltimore Harbor Channels, Fig. 2. We have not identified all of the alternatives, nor have we evaluated the health, socio-economic, and political effects associated with the alternatives we did identify. Completion of these tasks will require a major effort. But they are tasks that will have to be done in detail only once and tasks that must be done if dredging and dredged material disposal in the Maryland portion of the Bay are to be managed effectively.

In making our assessments of environmental effects we have relied entirely upon available information, and on our own experience and that of selected colleagues with appropriate expertise. No new field or laboratory studies were conducted. Our conclusions are summarized in tabular form at the beginning of the report. Complete references to the information we used and the arguments upon which our judgements are based are contained in appendices to these tables. We have selected key references. Believing that "the value of experience is not in seeing much but in seeing wisely," we have not attempted to produce an exhaustive bibliography.

Where we believe additional data are needed to make decisions, we say so. We have summarized our conclusions in tables and presented the documentation in appendices. There is necessarily some redundancy. This is intentional. We do not expect that most readers will, at any given time, be interested in all three case studies.

The three projects we considered all lie within the upper Chesapeake Bay. Before presenting the individual case studies, we describe some of the more important oceanographic features of the upper Bay.

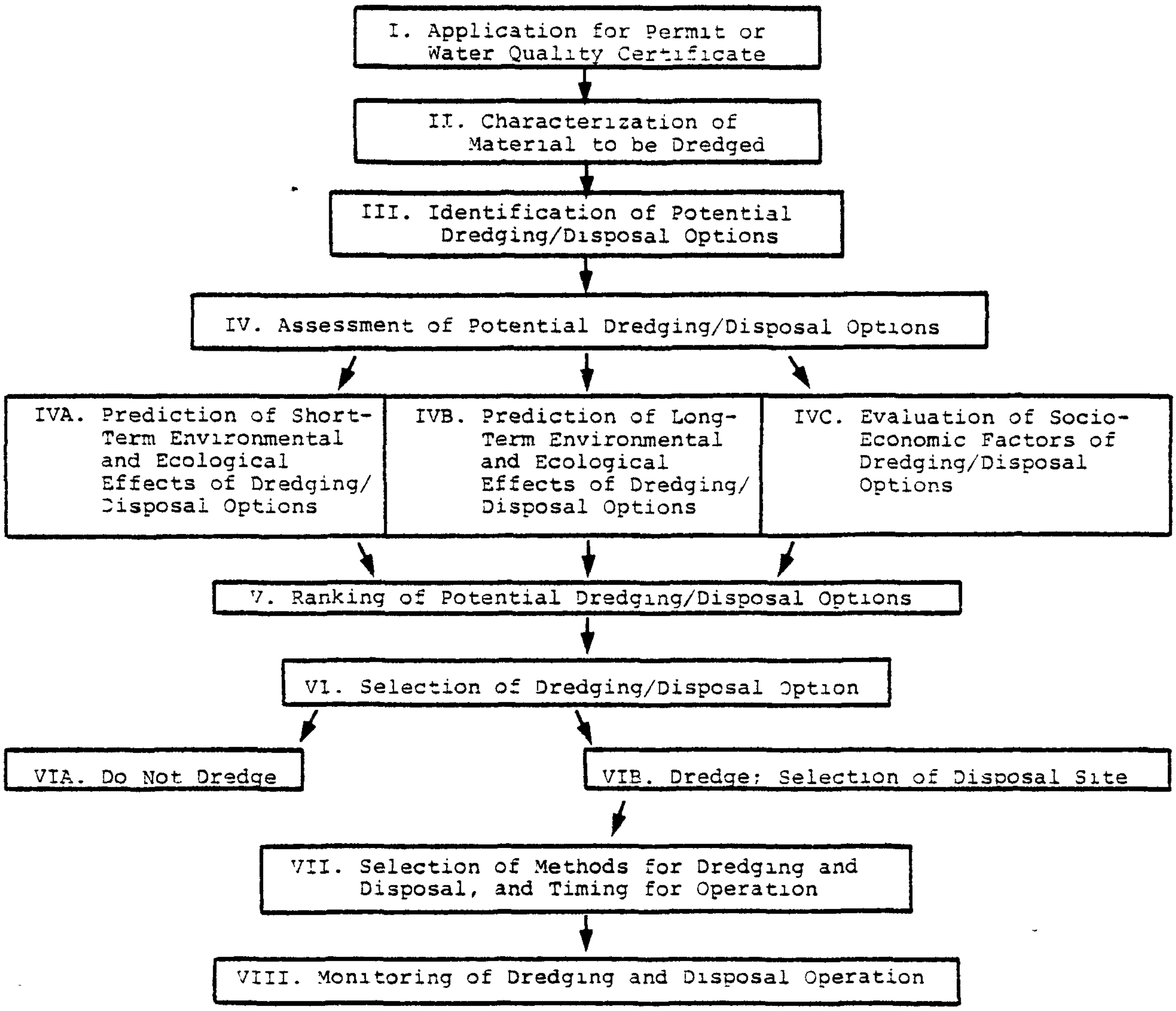

Fig. 1 A conceptual framework for assessing dredging/disposal options in the Maryland portion of Chesapeake Bay (after Schubel et al., 1979).

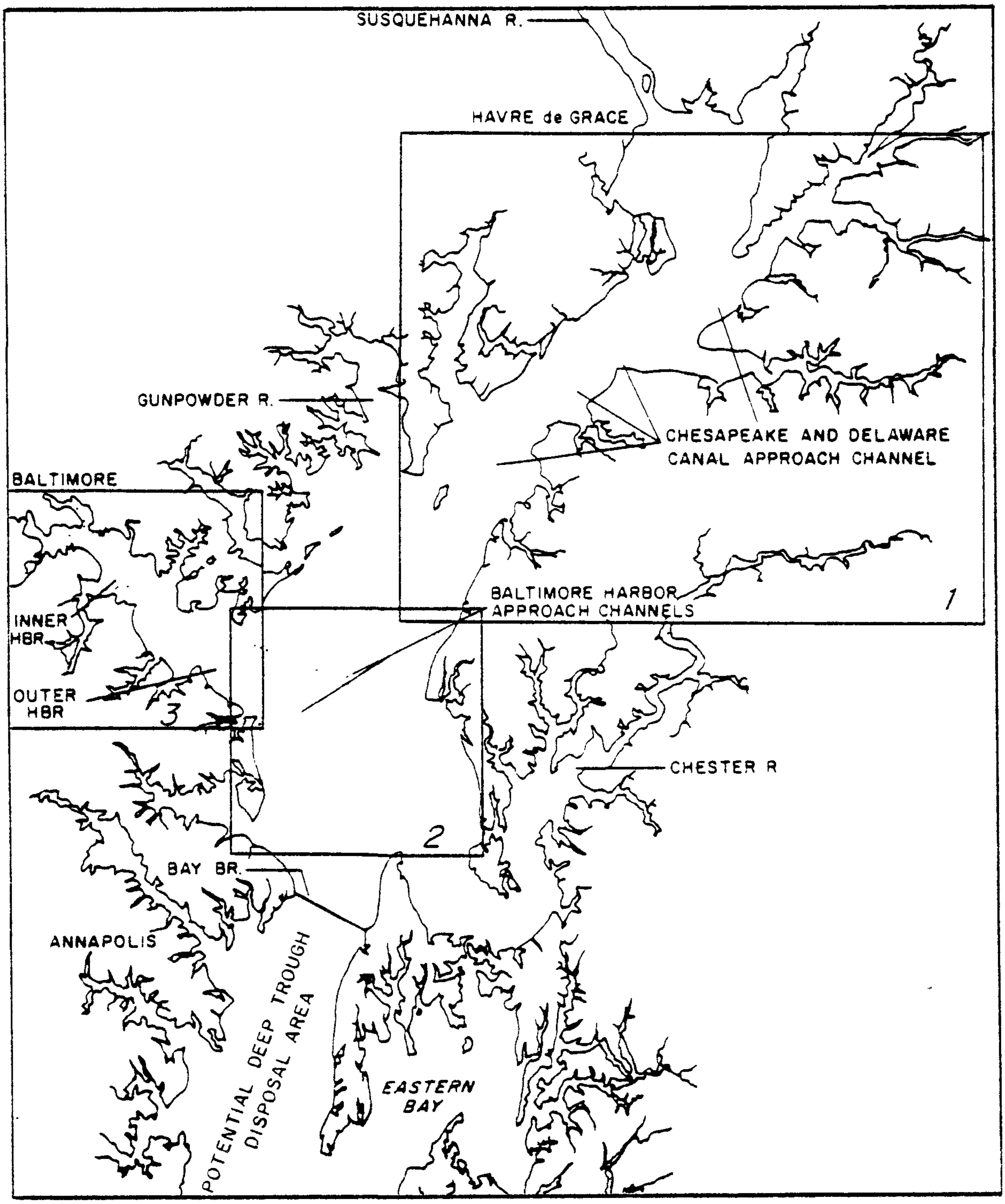

Fig. 2 Index map showing general locations of the three major dredging projects, 1) Chesapeake and Delaware Canal Approaches, 2) Baltimore Harbor Approaches, 3) Baltimore Harbor Channels. Detailed maps showing the Channels involved in each project are presented in appropriate sections of the report.

REGIONAL SETTING

Riverflow and Circulation

The upper Chesapeake Bay is the estuary of the Susquehanna River, Fig. 2. The Susquehanna enters at the head of the Bay and supplies approximately 50% of the total fresh water input to the Chesapeake Bay estuarine system and more than 90% of the total input above (north of) the mouth of the Patapsco. With a long-term mean flow of about 1,000 m^3/sec, the Susquehanna is the largest river discharging to the Atlantic Ocean through the eastern seaboard of the United States. The characteristic annual flow pattern of the Susquehanna--high runoff in spring resulting from snowmelt and rainfall followed by low to moderate flow throughout most of the remainder of the year--is typical of mid-latitude rivers, Fig. 3. At present there is no significant regulation of the flow of the Susquehanna which has an average yearly standard deviation of greater than 20% of the long-term (50 year) mean. Seasonal fluctuations in average flow are even greater; the minimum monthly discharge averages 200 m^3/sec, and the maximum monthly flow averages approximately 3,300 m^3/sec (Schubel, 1972a). Relatively large short-term fluctuations also occur.

During the spring freshet and other occasional short periods of very high riverflow, the Susquehanna discharge dominates the circulation in the upper reaches of the Bay; the charactistic net nontidal circulation is overpowered in the upper 30-50 km of the Bay, and the net flow is seaward at all depths. River domination is expected considering the discharge and the geometry of this segment of the Bay basin. A riverflow of 4,000 m^3/sec produces a mean seaward velocity of about 15 cm/sec through an average cross-section upstream from 39°17'N, Pooles Island. Discharge during the typical spring freshet is frequently so great that the tidal reaches of the Susquehanna are extended as far seaward as

39°13'N--about 50 km from the mouth of the River at Havre de Grace, Maryland (Schubel, 1972b).

During periods of high flow, the transition from river to estuary is marked by a sharp front separating the fresh river water from the salty estuary water. Longitudinal salinity gradients greater than 6 o/oo in 5 km are common during the spring freshet, Fig. 4. The front moves upstream and downstream in response to changing river discharge, but until June 1972, had not been reported farther seaward than about 39°13'N (Tolchester).

The marked variations of the fresh water inflow produce large temporal variations of salinity. The variations are most marked, of course, in the upper reaches of the Bay. Near Pooles Island in the upper Chesapeake Bay the salinity during 1960, a year of relatively high riverflow, ranged from 0.4 o/oo in April to 8.3 o/oo in December--more than a 20-fold range. During 1964, a year of relatively low riverflow, the range in salinity near Pooles Island was from 0.8 o/oo in March to 13.3 o/oo in December--nearly a 17-fold range.

The temporal variations in salinity in the upper Bay provide the basic mechanism for the flushing of tributary estuaries such as the Gunpowder, Bush, Back, Magothy, and Severn. The small fresh water inputs to these tributaries are insufficient to maintain a steady circulation pattern and the water that fills them is derived largely from the adjacent Bay. It is only in the upper reaches of these tributaries that the salinity distributions are significantly affected by their fresh water inflows.

The primary factor controlling the exchange of water between these tributaries and the Bay is the temporal variation in the salinity of the upper layer in the adjacent Bay. The salinity of the surface layers of the upper Bay varies seasonally with maximum values in the fall and minimum values in the spring. The salinity changes in the tributaries lag behind those in the adjacent Bay. During winter and early

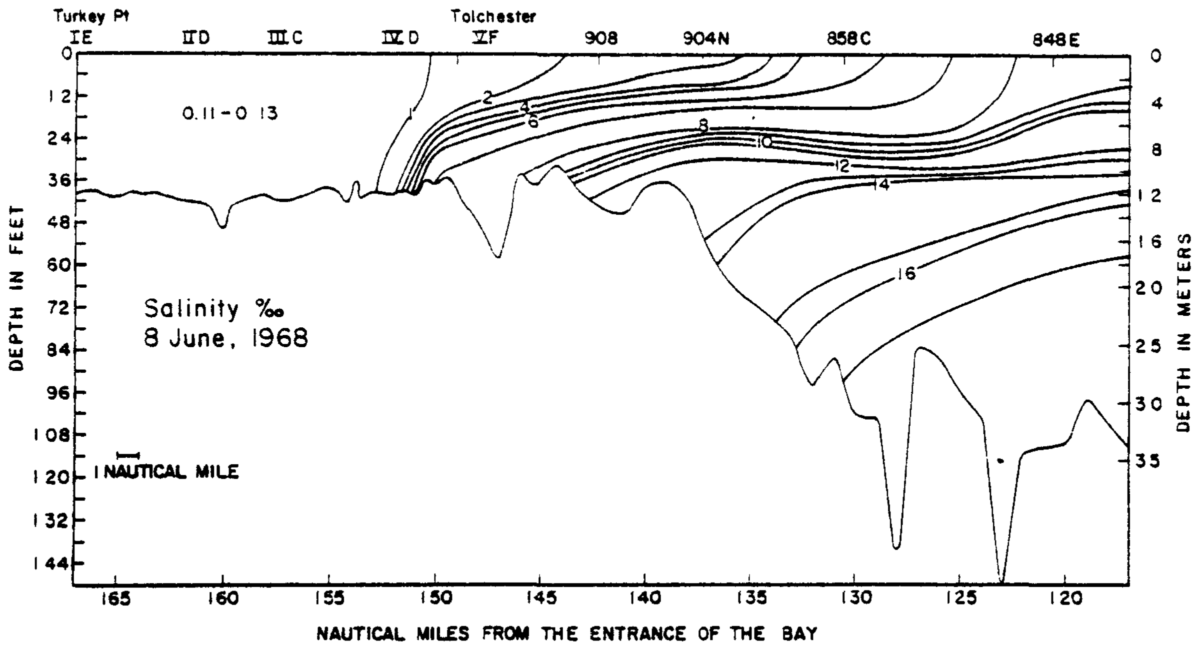

Fig. 3 Susquehanna River flow at Conowingo (MD) ensemble average by month 1929-1966.

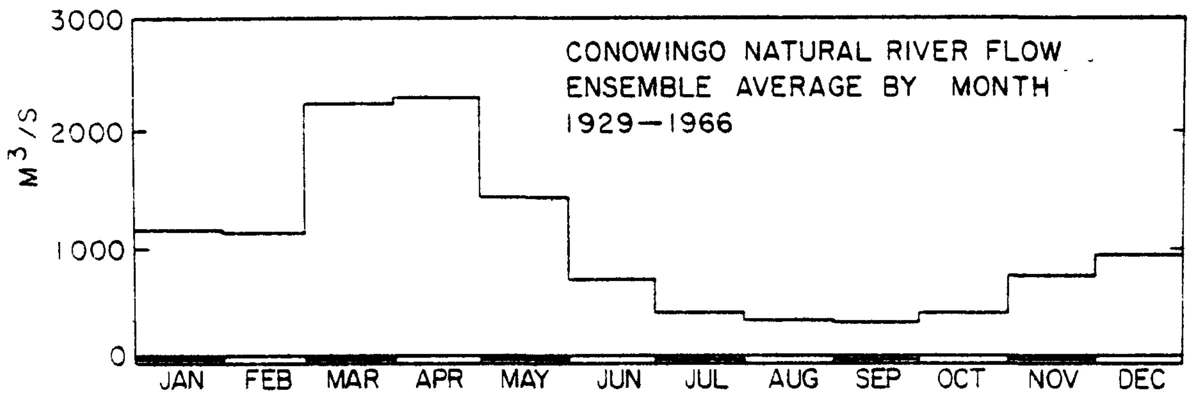

Fig. 4 Longitudinal salinity distribution in upper Chesapeake Bay during a period of high river flow.

spring when the salinity in the Bay is decreasing with time, the salinity in the tributaries is, at any given time, higher than in the Bay. As a result water flows into the tributaries at the surface from the Bay, and out of the tributaries in the deeper layers into the Bay. In late spring, summer, and early fall when the salinity of the Bay is increasing, the salinity in the tributaries is less than in the adjacent Bay, and hence the waters of the tributaries flow out at the surface, while Bay waters flow into the tributaries along the bottom. Since these estuaries are shallow, channel depths generally less than 6 m, only the upper layer of the Bay participates in the exchange with the tributaries.

The circulation pattern in these tributaries is thus reversed at least twice each year. Some of the smaller estuaries tributary to the head of the Bay, such as the Gunpowder and the Bush, show reversal of the mean flow pattern more often. These estuaries are subject to both frequent reversals of the flow pattern and to rapid renewal rates because of large, short-period fluctuations in the salinity of the adjacent Bay; fluctuations produced by sudden, large changes in the discharge of the Susquehanna. Regulation of the flow of the Susquehanna would decrease the frequency of flushing of these tributaries and their water quality would suffer.

While Baltimore Harbor is referred to as the estuary of the Patapsco, its circulation is driven primarily by the adjacent Bay. The average daily inflow of fresh water to the Harbor from the Patapsco and its other tributary streams is only about 1/315 of the volume of the Harbor. Tidal currents are relatively sluggish in the Harbor. Renewal of Harbor water by tidal flushing would require approximately 150 days. Tracer studies show however that the mean residence time for water in the Harbor is only about 10 days. Clearly another mechanism must exist to provide for a renewal rate of about 10% of the Harbor volume per day.

Pritchard (1968) showed that this mechanism is a three-layered circulation pattern driven by differences in the vertical variations in salinity in the Harbor and the adjacent Bay. There is an inflow into the Harbor both at the surface and along the bottom, and a return flow at mid-depth. Rates of inflow and discharge from the Harbor as a result of this circulation pattern are remarkably steady throughout the year; they amount to about 480 m^3/sec, or approximately 10% of the Harbor volume per day.

The dredged navigation channel that is maintained at essentially the same depth as the adjacent Bay plays an important role in the circulation pattern in Baltimore Harbor. If there were no dredged channel, the circulation would resemble that described for the Gunpowder, Bush, and other tributaries. The three-layered circulation pattern also plays an important role in sedimentation processes in the Harbor. The net upstream flow near the bottom carries sedimentary particles from the Bay into the Harbor and accelerates sediment accumulation in the navigation channels.

Variations in surface salinity over the length of the Bay ranges from 25-30 o/oo at its mouth to freshwater of the Susquehanna River, about 0.05 o/oo, near its head. Flows of the other rivers tributary to the upper Bay are small and have little effect on the salinity distribution or sediment deposition of the main body of the upper Bay (Schubel, 1972a).

Sediment Inputs

Sediments are introduced into the upper Chesapeake Bay by rivers, shore erosion, primary production of phytoplankton and aquatic plants, and transport from more seaward segments of the estuary. The sources are thus external, internal and marginal. The Susquehanna is the dominant sediment source to the main body of the Bay from its head, at least as far seaward as the mouth of the Patapsco, and perhaps farther.

During years of "typical" riverflow, when the average flow of the Susquehanna is between about 850 m^3/sec and 1,100 m^3/sec, the Susquehanna discharges between 0.6-1.0 million metric tons of suspended sediment (Schubel, 1968a, 1972b, 1974; Palmer et al., 1975; Gross et al., 1978). The bulk of the total, nearly three-fourths, is usually discharged during the spring freshet when both the riverflow and the concentration of suspended sediment are high, Fig. 5.

During extreme floods the Susquehanna may discharge many times more sediment in a week than during an entire "average" year. In a one week period in June 1972, following the passage of Tropical Storm Agnes, the Susquehanna discharged more than 34 million metric tons of suspended sediment (Schubel, 1974). Following Tropical Storm Eloise (September, 1975), the Susquehanna discharged approximately 10 million metric tons in one week (Gross et al., 1978).

The three hydroelectric dams--Safe Harbor (PA), Holtwood (PA), and Conowingo (MD)--located along the lower reaches of the Susquehanna, trap sediment and reduce the sediment discharge of the Susquehanna to the Bay. According to Gross et al. (1978), one-half to two-thirds of the Susquehanna's suspended sediment discharge at Harrisburg (PA) is deposited in the reservoirs behind these dams during years of low to average discharge and no major floods. During major floods when discharges exceed about 11,000 m^3/sec, these deposits are eroded and transported downstream to the Bay. Schubel (1974) and Hirschberg and Schubel (1979) estimated that as much as 75% of sediment discharged into the Bay by the Susquehanna following Agnes was scoured from the river bottom and particularly from the three reservoirs. Thus, the effect of the dams is to increase the amount of sediment discharged under flood conditions relative to the amount discharged in an average or low-flow year.

The sediment discharged by the Susquehanna is predominantly silt and clay. Most of the sand carried by the River is deposited in the reservoirs along the lower reaches of

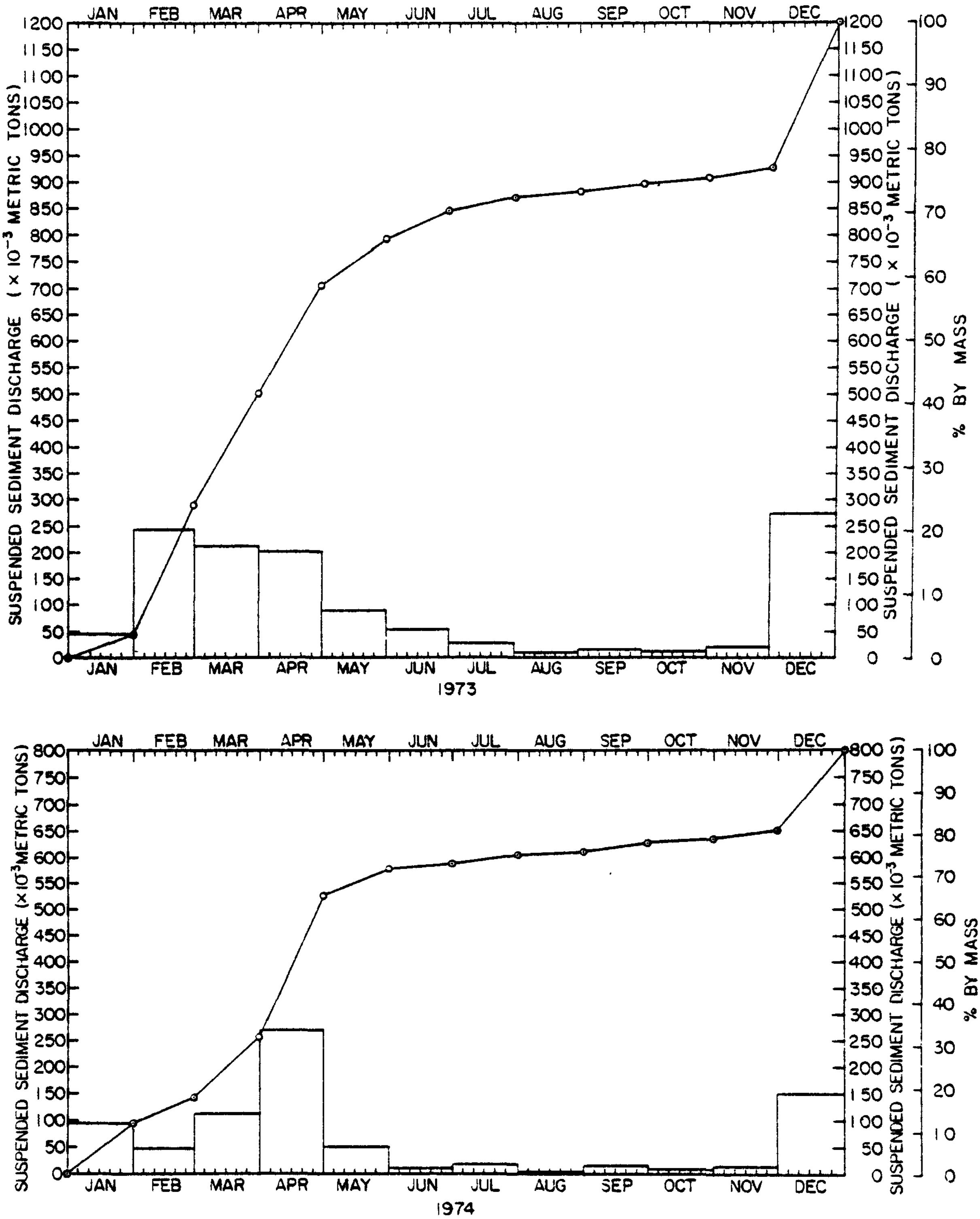

Fig. 5 Suspended sediment discharge of the Susquehanna River at Conowingo (MD) during 1973-1974, plotted as histograms and as cumulative discharges.

of the River and does not immediately reach the Bay. The bulk, more than three-fourths, of the silt and clay that is discharged into the Bay is trapped in the upper reaches of the Bay from Tolchester to Turkey Point by the net nontidal circulation which creates an effective sediment trap. This is the transition zone which marks the boundary between the two-layered estuarine region with upstream net flow along the bottom and the reach of the upper bay where the flow is downstream at all depths (Schubel, 1968a, 1971, 1972b). Fine particles that settle into the lower layer are carried back upstream by its net upstream flow leading to an accumulation of sediment both on the bottom and suspended within the waters of the upper reaches of the Bay.

Since the Susquehanna is the only river discharging directly into the main body of the Bay, it is the only important source of fluvial sediment to the Bay proper (Schubel, 1968a,b, 1971a, 1972b). Most of the sediment discharged by the other rivers is deposited in the upper reaches of their estuaries and does not reach the Bay proper. In the middle and lower reaches of the Bay, shore erosion is not only a major source of sediment, but probably the most important source (Schubel, 1968a,b, 1971; Biggs, 1970; Schubel and Carter, 1977). The margins of the Bay are being eroded at an alarming rate (Singerwald and Slaughter, 1949; Schubel, 1968a; Palmer, 1973). Schubel (1968a) estimated that shore erosion of the segment of the Bay from the mouth of the Susquehanna to Tolchester contributes an average of about 0.3 million metric tons of sediment to the Bay each year. Approximately one-third of this is silt and clay-sized material. The contribution of silt and clay from shore erosion to this segment of the Bay, 0.1 million metric tons/yr, is approximately 10-20% of the input from the Susquehanna during years of average riverflow. Biggs (1970) made a similar estimate for the Bay from a few kilometers north of the northern end of Kent Island south to the mouth of the

Potomac. He reported an annual average input of about 1.4 million tons of which about 25% is silt and clay. According to Biggs (1970), this contribution of silt and clay accounted for about 52% of the total input of suspended sediment to that segment of the Bay.

The relative importance of the contribution of sediment from shore erosion clearly increases in a seaward direction and it may become the dominant source of sediment to the middle reaches of the Bay.

Sediments are also introduced into the Bay by internal sources. Biggs (1970), estimated that primary productivity by phytoplankton acounted for about 4% of the total suspended sediment in the upper reaches of the Bay from the mouth of the Susquehanna to Tolchester, and for about 40% of the total for the segment of the Bay from Tolchester to the mouth of the Patuxent. Approximately half of these totals were attributed to planktonic skeletal material. The contribution of benthic populations to the sediments of the Bay has not been documented.

It is clear that there is a net upstream flow of sediment in the lower layers of the Bay proper and its major tributaries, but the net flux through any cross-section of the Bay is not known. Schubel and Carter (1977) constructed a simple model that indicated that the Bay is a *source* of sediment to its major tributary estuaries, rather than a sink for sediment introduced into these tributary estuaries by their rivers.

Suspended Sediments

The Susquehanna flow regime, and the resulting circulation patterns generated within the upper Bay in response to the varying role of the river, produce two distinctive distributions of suspended sediment and concomitant patterns of suspended sediment transport. The first characterize the spring freshet. The second, characteristic of periods of low to moderate flow, typify most of the remainder of the year.

Periods of High Flow

During the spring freshet, and other occasional short periods of very high river flow when the Susquehanna River dominates the circulation in the upper reaches of the Bay, Fig. 6, a five- to ten-fold decrease in the maximum concentration of suspended sediment between the mouth of the Susquehanna at Havre de Grace (MD) and Tolchester (Station 913R), a distance of 45 km, is common. Simple dilution arguments based on comparisons of the longitudinal gradients of suspended sediment and salinity indicate that usually about 70% of the sediment discharged during a freshet is deposited upstream of Tolchester (Station 913R); upstream of the salinity front associated with the encroaching seawater. Biggs (1970) estimated that about 96% of the sediment introduced by the Susquehanna is deposited upstream (north) of 39°03'N; that is, north of Swan Point.

In the segment of the Bay upstream from the salinity front, the net flow and sediment transport are downstream (seaward) at all depths. Current measurements made in this area during freshets reveal that at all depths ebb currents predominate over flood currents both in duration and in intensity (Schubel, 1972b). Flood tidal periods are generally of short duration, lasting only from 3 to 5 hours, and maximum current speeds commonly fall below the critical erosion speeds--35 to 50 cm/sec--of the fine-grained bottom sediments. Ebb periods are much longer, lasting from 7 to 9 hours, and maximum current speeds typically exceed 100 cm/sec. Removal of the oscillatory tidal currents from the current records shows that the net flow is seaward at all depths (Schubel, 1972b).

Bottom sediments, resuspended by the strong ebb currents, settle out when the current begins to wane, producing marked fluctuations in the concentration of suspended sediment. The fluctuations are of tidal period--not semi-tidal--since the flood currents are commonly too weak to erode the bottom.

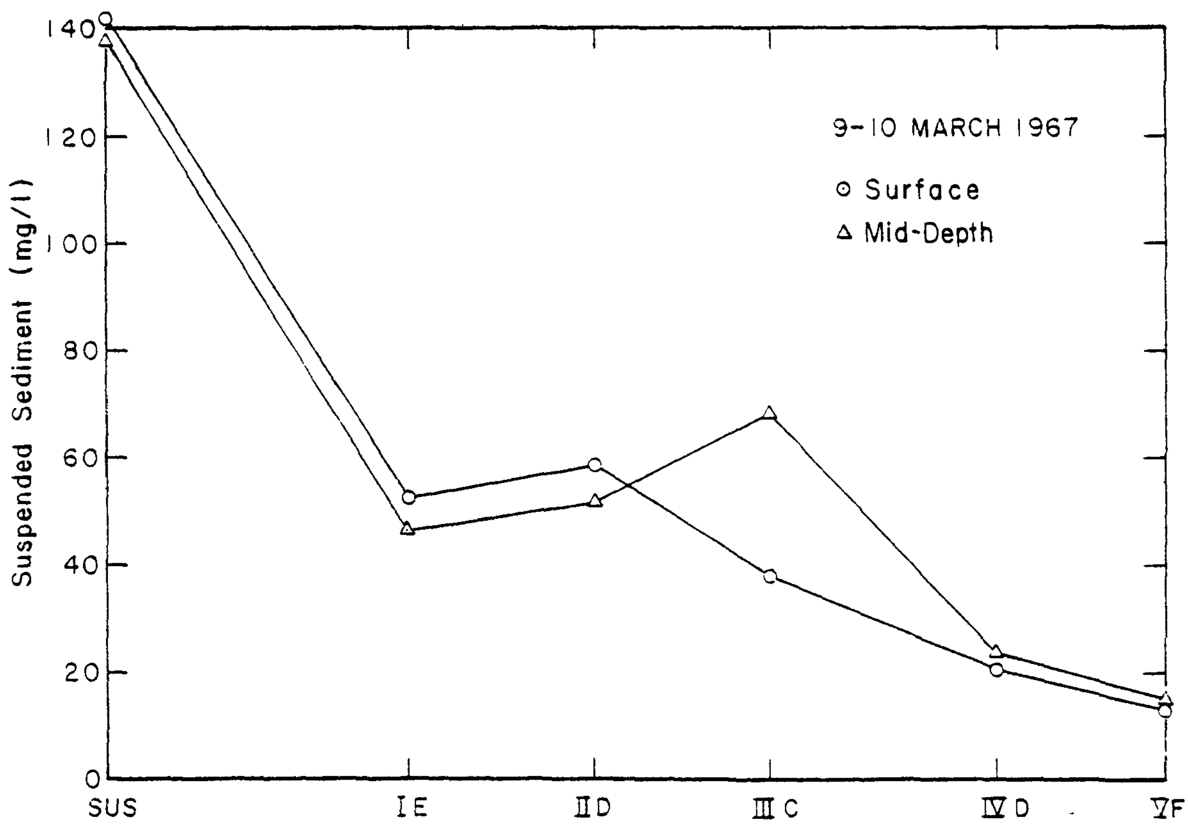

Fig. 6 Variation of concentration of suspended sediment at the surface and at mid-depth at a series of channel stations during the spring freshet of 1967. See Figure 7 for station locations.

These fluctuations, although greatest near the bottom, are observed throughout the water column because of the intense vertical mixing throughout an essentially neutrally stable water column.

The variation of the concentration of suspended sediment over a 30 hour period during the 1968 spring freshet at a station in 6.2 m of water about 3 km upstream from Tolchester, Fig. 7, is shown in Fig. 8. The concentration of suspended sediment which was relatively uniform at the surface, had slightly higher values following maximum ebb current speeds than at other phases of the tide. At 2 m the concentration had nearly a two-fold range with the highest values again being recorded near maximum ebb velocities. At 4 m and at 6 m the same pattern was observed, but the fluctuations of the concentration of suspended sediment were much greater; a four-fold range was observed at 4 m, and an eight-fold range at 6 m. The higher concentrations of suspended sediment following maximum ebb current velocities, although attributable in part to displacement of the longitudinal gradient of suspended sediment, were produced primarily by the resuspension of bottom sediment by strong ebb currents. Maximum ebb current speeds exceeded the "critical erosion speeds," approximately 25-50 cm/sec, of the fine-grained sediments of this segment of the Bay. The maximum flood current speeds fell below this threshold. Fluctuations of suspended sediment concentration, produced by resuspension and deposition, occurred throughout the entire depth because of intense vertical mixing through an essentially neutrally stable water column. The salinity, equal to that of the river, is uniform top to bottom, and the temperature gradient is very small. These conditions are characteristic of the upper 30-35 km of the Bay--from Turkey Point to about 39°13'N (Tolchester)--during the spring freshet when the Susquehanna River dominates the circulation.

Over the period of measurements shown in Fig. 8, the net flow and net sediment transport were downstream (seaward) at

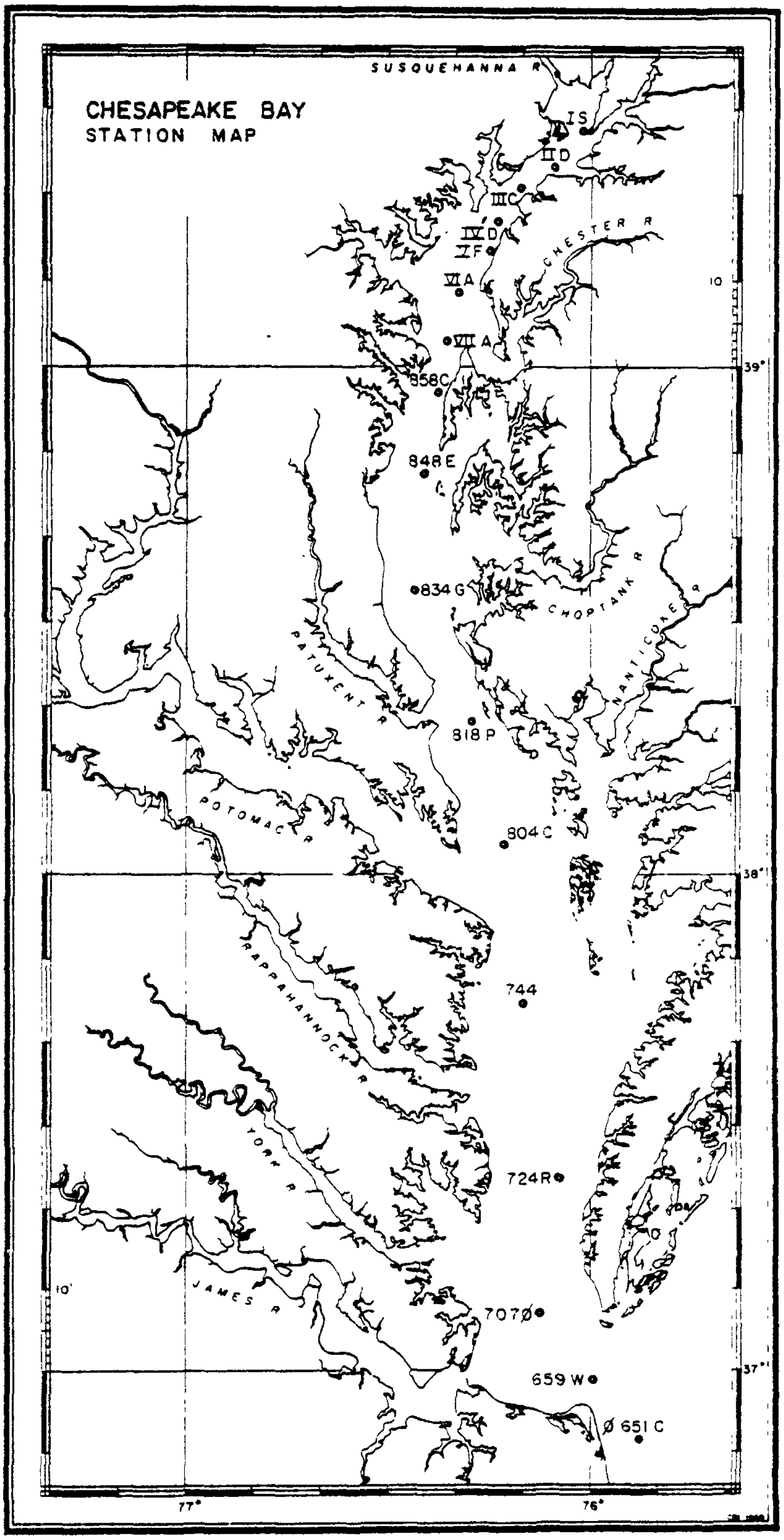

Fig. 7 Station location map. The seven northernmost stations in the upper Bay may have one of two designations in other figures. The pairs of station codes are IS(927SS), IID(SF00), IIIC(921W), IVD(917S), VF(913R), VIA(909), VIIA(903A).

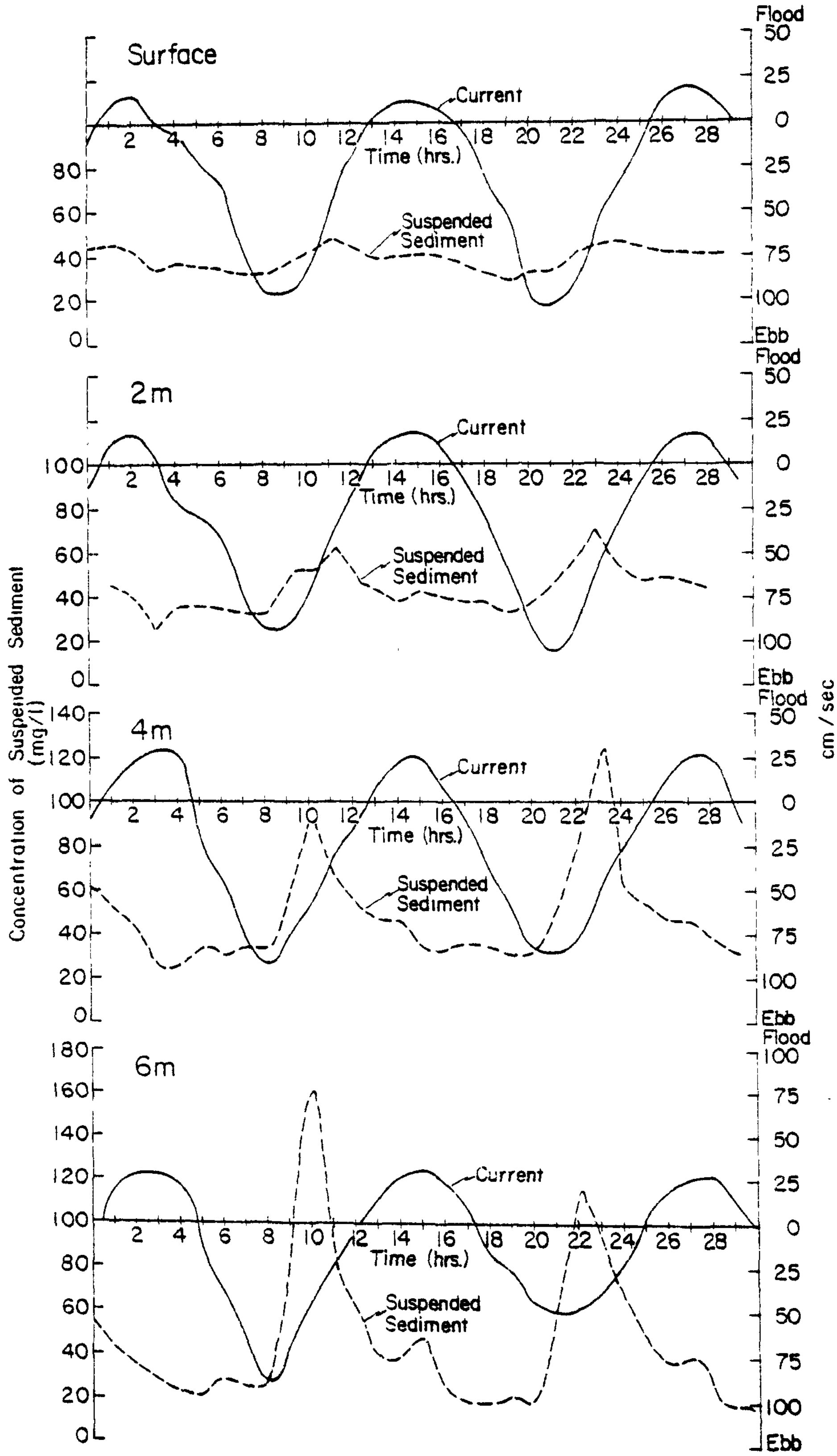

Fig. 8 Variations of current velocity and suspended sediment concentration at a Station just north of Station VF (Fig. 7) during the spring freshet of 1967, based on hourly measurements at six depths.

all depths at this station and at all stations farther upstream.

Farther seaward in the estuary where the characteristic net non-tidal estuarine circulation is maintained, the high freshwater discharge of the freshet causes increased stability of the water column and decreased vertical mixing. Vertical distributions of suspended sediment are influenced by two sediment sources--river discharge in the upper layer and the resuspension of bottom sediments by tidal scour in the lower layer. Fluctuations of the suspended sediment concentration, produced by tidal "scour and fill," are restricted primarily to the lower layer because of the greater stability of the water column which inhibits vertical mixing.

An example of the longitudinal distribution of suspended sediment along the axis of the entire Bay during a period of high riverflow is depicted in Fig. 9. There is a marked downstream gradient in the upper 30-50 km of the estuary. In the middle and lower reaches of the estuary, longitudinal gradients are weak. The slight increases in the concentration of suspended sediment in the upper layer downstream (seaward) of about 38°N may be produced by discharge from the Potomac. Burt (1955) reported that "during times of high river outflow (spring), tongues of highly turbid water were reported in the Bay off the mouth of each river" in the Bay below 38°20'N. At any location along the axis of the Bay, the concentration of suspended sediment increases with depth, Fig. 9. This is attributed in part to settling; and in part to the resuspension of bottom sediments by tidal scour.

<u>Periods of Low to Moderate Riverflow</u>

Except for a few days during peak flow of the spring freshet and other occasional brief periods of very high riverflow, concentrations of suspended sediment are greater within the upper 25-30 km of the estuary than farther upstream in the source river--the Susquehanna--in spite of both the

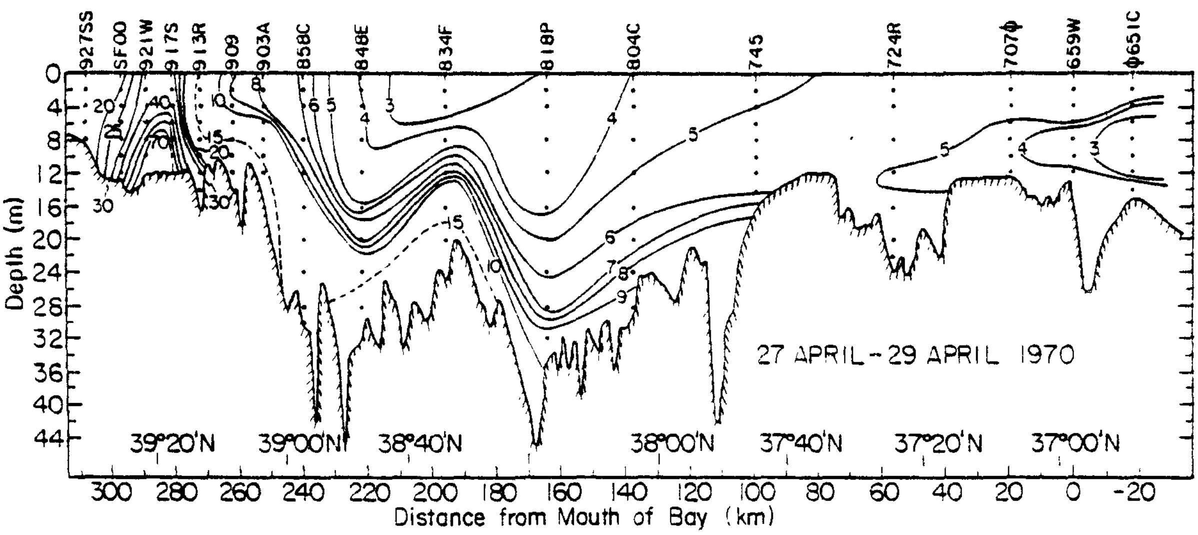

Fig. 9 Distribution of suspended sediment along the axis of the Bay following a period of high riverflow of the Susquehanna River. Values are in mg/ℓ.

dilution of Susquehanna inflow and the settling-out (deposition) of newly-introduced fluvial sedimentary particles. The concentrations of suspended sediment in this segment of the upper Bay are, at all times of the year, greater than those farther seaward in the estuary. Such zones of high concentrations of suspended sediment characterize the upper reaches of all partially mixed estuaries (Schubel, 1971a), and are called "turbidity maxima." Their formation has been attributed to the flocculation of fluvial sediment (e.g., Lüneburg, 1939; Ippen, 1966), to the deflocculation of fluvial sediment (Nelson, 1959), and to hydrodynamic processes (Postma, 1967; Schubel, 1968a,b, 1971a).

A longitudinal distribution of suspended sediment typical of periods of low to moderate river flow is shown in Fig. 10. The steep longitudinal gradient of the suspended sediment concentration between cross sections IV and V marks the seaward boundary of the turbidity maximum. High concentrations of suspended sediment in the upper reaches of the estuary which persist throughout the year can not be explained by a gradual purging out of the sediment-laden freshet water since the renewal time is only of the order of a few weeks, or less. Nor can the anomalous concentrations be explained by either the flocculation (Lüneburg, 1939; Ippen, 1966) or the "deflocculation" (Nelson, 1959) of the fluvial sediment.

Schubel (1968a,b, 1971a,b) showed that the turbidity maximum in the upper reaches of the Chesapeake Bay is produced by a combination of physical processes--the "sediment trap" produced by the net non-tidal estuarine circulation which entraps much of the sediment within this segment of the Bay and periodic local resuspension of bottom sediments by tidal scour. Throughout the year sediment is resuspended by wind waves and by tidal scour. With a mean depth of less than 5 m, resuspension by wind waves is an important factor during periods of rough seas. Wind waves are also important in winnowing the fines out of the eroded coastal sediments. Resuspension by tidal scour, important

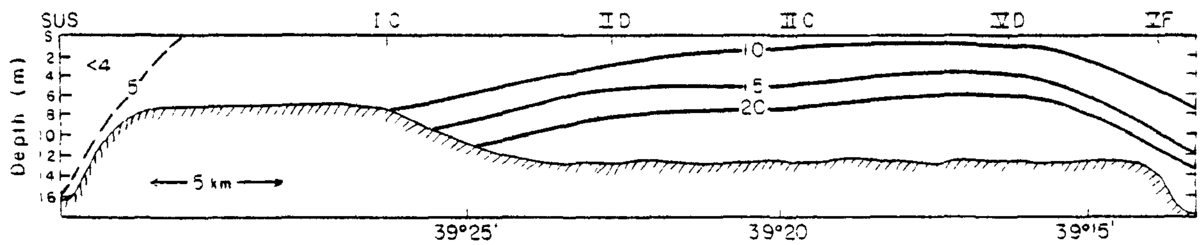

Fig. 10 Longitudinal distribution of suspended sediment (mg/ℓ) in upper Bay typical of periods of low to moderate riverflow. See Fig. 7 for station locations.

at all times of the year and effective at all depths, accounts for most of the resuspended material.

Maximum tidal currents--both ebb and flood--in the upper Bay average more than 50 cm/sec, while the critical erosion speeds of the sediments, away from the littoral zone, fall below this value. In the upper reaches of the Bay, the concentration of total suspended sediment at 1.5 m above the bottom typically fluctuates by a factor of seven, or more, between times of slack water and times of maximum ebb and flood current velocities. At 0.5 m above the bottom, the concentration typically exhibits a fifteen- to twenty-fold fluctuation with a semi-tidal period; variations of 15 to 300 mg/ℓ are representative (Schubel, 1968b).

An example of the effectiveness of tidal currents as an agent of resuspension is shown in Fig. 11. For 38 hours in July 1967 hourly measurements of current velocity, concentration of suspended sediment, and the temperature and salinity of the water were made at the surface and at depths of 2,4,6,8 and 9 m of water just to the west of station IIIC in 9.5 m of water, Fig. 7. Over the period of measurement there was a net flow of water downstream in the upper layer and upstream in the lower layer. In the upper 4 m the fluctuations of the concentration of suspended sediment were relatively small. At 6 m the concentration ranged from 10 to 36 mg/ℓ, but the concentration of suspended sediment was not closely related to the current velocity or the phase of the tide. At 8 and 9 m there were marked fluctuations of the concentration of suspended sediment, and there was obviously a strong relation to the current velocity and the phase of the tide at which the samples were collected. Maximum concentrations occurred near maximum ebb and flood velocities, and minimum concentrations shortly after slack water. At 8 m the concentration of suspended sediment ranged from 14 to 90 mg/ℓ, and at 9 m, the range was from 15 to 280 mg/ℓ--nearly a 19-fold range.

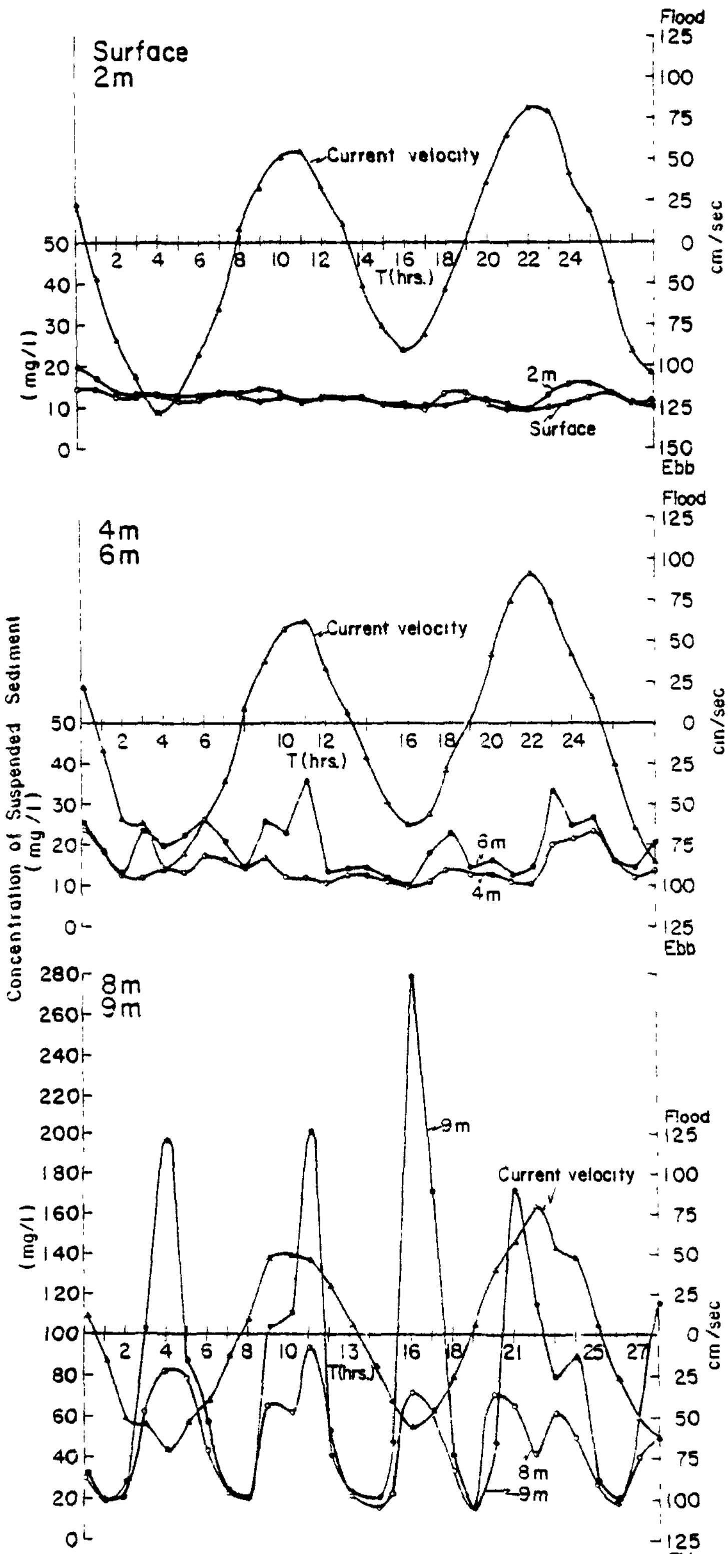

Fig. 11 Variations of current velocity and suspended sediment concentration at a station just to the west of Station IIIC (Fig. 7) during a period of low riverflow, based on hourly measurements at six depths.

Figure 11 shows that there is a "natural background" of suspended sediment which increases with depth and whose intensity at any depth is relatively constant over time scales of at lease two tidal cycles. Other observations (Schubel, 1968a) indicate that it is very uniform over much longer times; weeks or months. This background, increasing in concentration form approximately 15 mg/ℓ at the surface to about 20 mg/ℓ at a depth of 9 m, consists of very fine-grained suspended particles whose settling times are long compared to the mixing time. The volume-weighted mean settling velocity of the background particles which is only about 10^{-3} cm/sec, is of the same order as the mean vertical mixing velocity, and this explains their sustained suspension. A particle with a settling velocity of 10^{-3} cm/sec, Stokes' diameter of about 3 μm, would settle a distance of less than 1 m in still water in more than two tidal periods. The spatial and temporal variations of the size distributions, both number and volume, of the background particles are small (Schubel, 1968a, 1969). This natural background is due in part directly to runoff, and in part to the internal sediment sources--primary production, shore erosion, and particularly resuspension.

Figure 11 also shows that below about 4 m, superimposed upon this natural background are semi-tidal fluctuarions of the suspended sediment concentration which increase in magnitude near the bottom--the sediment source. These large variations are produced by tidal action causing "scour and fill"--erosion and deposition. Large particles, resuspended with increasing ebb and flood velocities during each half tidal period, settle out when the current begins to wane. Maximum current speeds, both ebb and flood, exceed the "critical erosion speeds" and produce suspended sediment fluctuations of semi-tidal period.

Much of the sediment, resuspended and newly introduced, is trapped within the upper 30-40 km of the northern Chesapeake Bay by the net non-tidal estuarine circulation. An effective sediment trap is formed near the head of the estuary where the net upstream flow of the lower layer dissipates until, finally, the net flow is downstream at all depths. Particles that settle out of the seaward-flowing upper layer into the lower layer are transported back upstream by its net non-tidal upstream flow. Sediment accumulates and a "turbidity maximum" forms near the head of the estuary (Postma, 1967; Schubel, 1968a, b, 1971a). The net non-tidal circulation not only effectively entraps much of the sediment introduced directly into this segment of the Bay, but also supplements it with sediment previously carried through this segment during periods of high riverflow, and with sediment introduced by other sources into more seaward segments of the estuary.

Many of the particles suspended in the lower layer are transported back into the upper layer by vertical mixing, and the process is repeated many times. Mixing, as defined here, includes vertical advection and diffusion. Continuity requires that the water flowing up the estuary in the lower layer be returned seaward in the upper layer; hence, there must be a vertical advection of water from the deeper layer into the surface layer. The speed of this net vertical flow is zero at both the surface and the bottom and reaches a maximum speed of about 10^{-3} cm/sec near mid-depth. In addition, a vertical diffusion velocity of order 10^{-3} cm/sec exists due to turbulence.

Schubel (1969, 1971b) showed that the suspended particle population of the Chesapeake Bay's turbidity maximum is comprised of two sub-populations--those particles which are in more or less continued suspension throughout the water column, the "natural background", and those particles which are alternately suspended and deposited by tidal currents. The "natural background", made up of very fine-grained particles whose settling times are long compared to the mixing time, has a relatively narrow size distribution both in terms of the volume-weighted mean Stokes' diameter (settling velocity), and the number-weighted equivalent projected diameter (Schubel, 1969). The volume-weighted mean settling velocity of the background particles is of order 10^{-3} cm/sec. In all the samples analyzed by Schubel, its range was only from slightly less than 10^{-3} to about 10^{-2} cm/sec (3-10 μm).

In the lower layer at stations deeper than about 4-5 m, and throughout the water column at shallower stations, superimposed upon this "natural background" are the semi-tidal period fluctuations of the concentration of suspended sediment that increase in magnitude near the bottom. These fluctuations, described previously, are produced by tidal "scour and fill" and produce marked changes in the volume (and mass) size distributions of the suspended particles. At 1 m off the bottom, Schubel (1971b) reported variations in the mean Stokes' diameter of from less than 4 μm near slack water to more than 12 μm on the preceding and succeeding maximum ebb and flood velocities of about 100 cm/sec. At 0.5 m above the bottom, the corresponding variation was from about 4 μm to 20 μm.

As one moves farther seaward in the Bay, the concentrations of suspended sediment decrease. Shore erosion and primary productivity become increasingly more important as sources of suspended sediment (Schubel, 1968a).

A longitudinal distribution of suspended sediment along the axis of the Bay representative of periods of low to moderate riverflow is depicted in Fig. 12. These data, and others, have been summarized in tabular form along with concomitant measurements of temperature, salinity, and estimates of suspended organic matter (Schubel et al., 1970). Figure 12 shows that during periods of low flow there is sometimes a decrease in the concentration of suspended sediment with depth. The higher values in the surface layer between 858C and about 804C result from primary productivity.

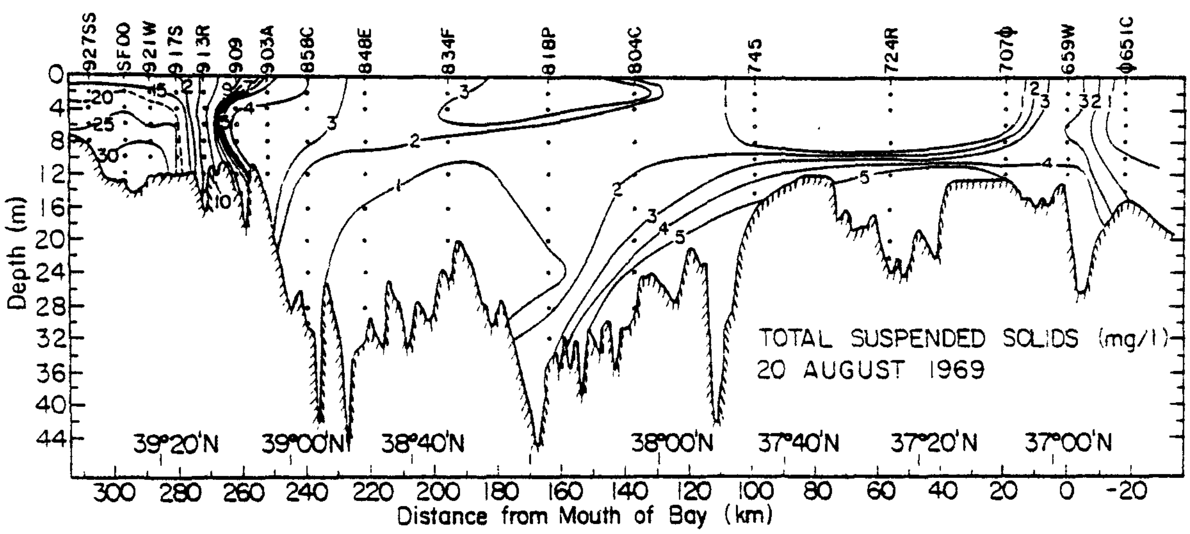

Fig. 12 Distribution of suspended sediment along the axis of the Bay following a period of low riverflow of the Susquehanna River. Values are in mg/ℓ.

Bottom Sediments

Bottom sediments of the upper Bay are predominantly silt and clay except in the nearshore zone where sand locally derived from coastal erosion predominates (Ryan, 1953; Schubel, 1968a; Palmer et al., 1975). Sand is also abundant on the Susquehanna flata--an estuarine delta formed near the head of the estuary by deposition of sand discharged by the Susquehanna during periods of very high flow. Since construction of the dams along the lower reaches of the Susquehanna, very little sand, and all of that fine-grained, is discharged into the Bay during periods of low to moderate riverflow. Conowingo, the last of the dams to be constructed and the one closest to the mouth of the River, was completed in 1928. Except during periods of very high flows such as Tropical Storm Agnes in June 1972, the only active source of sand to the main body of the Bay is erosion of its margins.

Quartz is the dominant mineral in the silt and sand size fractions and generally accounts for more than 90% by mass of the total sand-silt fraction. Muscovite, glauconite, and biogenic particles are also ubiquitous in the silt size fraction. The most common clay minerals are illite, kaolinite, and montmorillonite which occur roughly in the ratios 2:1:1 (Owens et al., 1974).

A map showing the percent by mass of clay in the bottom sediments of the main body of the upper Chesapeake Bay, in the Patapsco estuary and in the lower Chester River estuary is presented in Fig. 13. A map depicting the distribution pattern of the ratio of the mass of the silt fraction to the sand fraction in the same area is shown in Fig. 14. These figures clearly show that the bottom of the upper Bay is blanketed largely by mud (silt and clay), and that the mean grain size of the bottom sediments in the Bay proper tends to decrease downstream. Relatively little has been published about the character of the sediments in the tributary

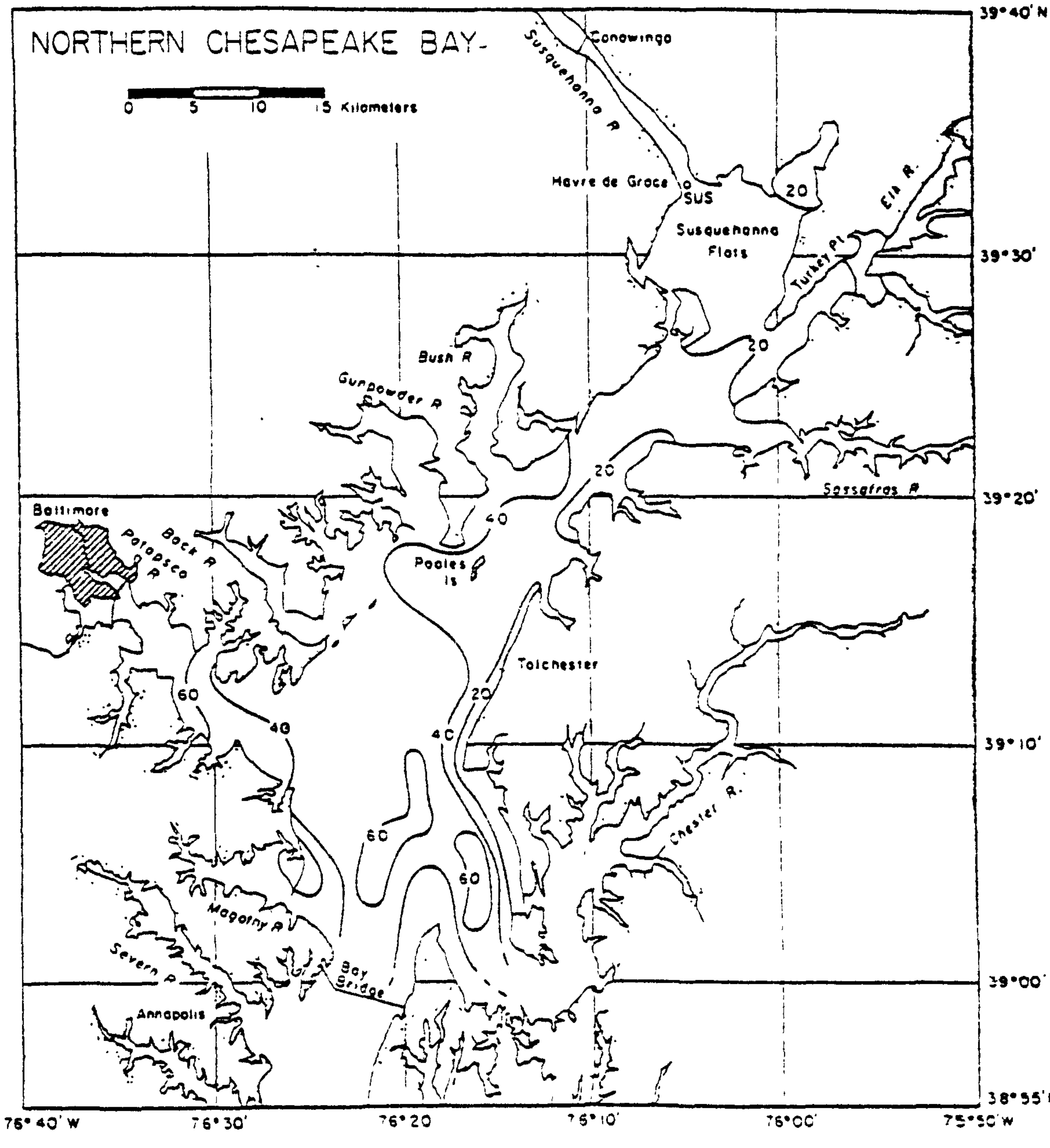

Fig. 13 Map showing the percent by mass clay in the surface sediments of upper Chesapeake Bay (after Palmer et al. 1975).

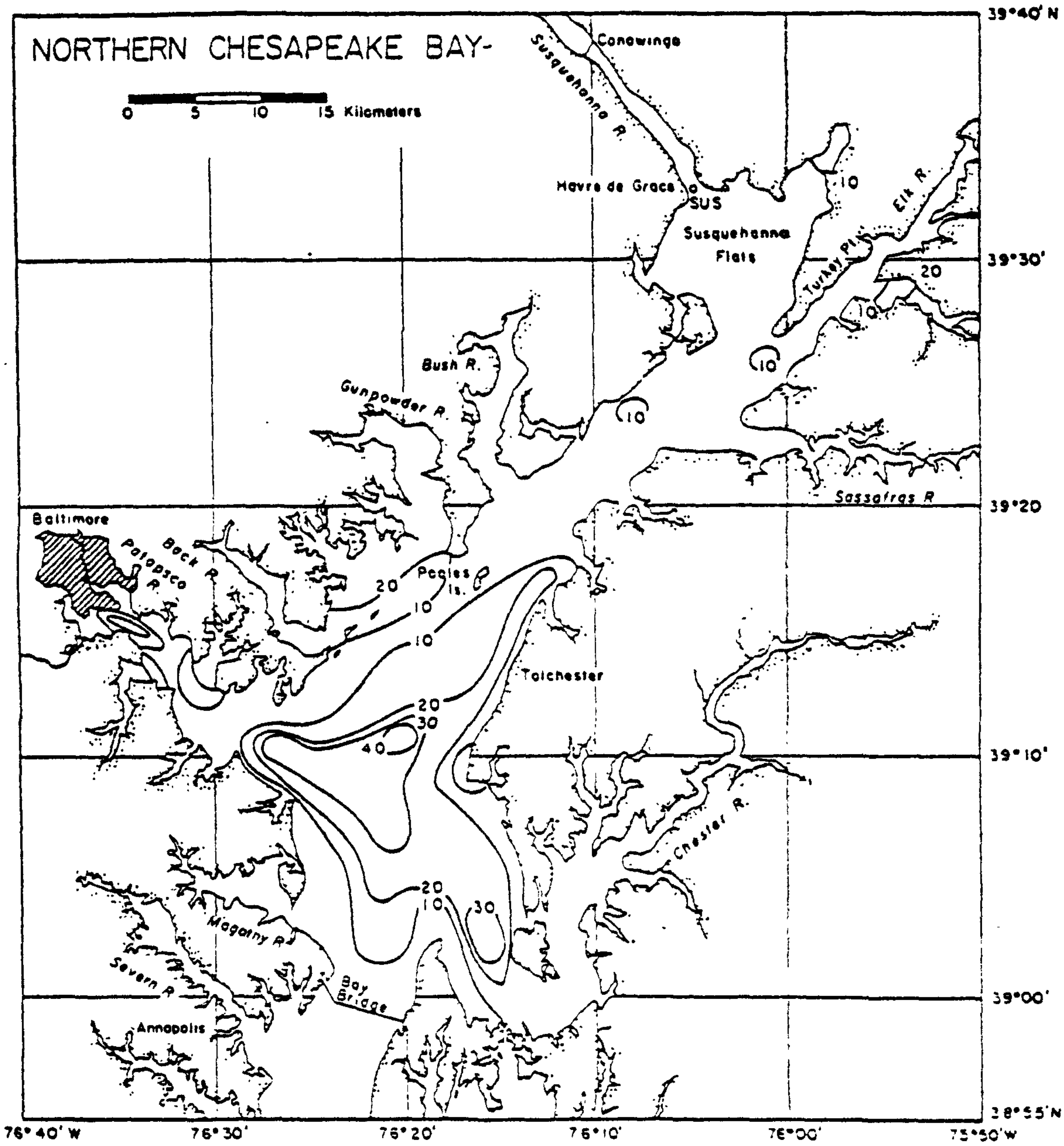

Fig. 14 Map of the ratio of silt to sand in the surface sediments of the upper Bay (after Palmer et al. 1975).

estuaries to the upper Bay, other than the Patapsco and the lower Chester. The sedimentological and geochemical investigations being conducted by the Maryland Geological Survey in the major tributaries will provide much needed information.

It is well known that many contaminants--metals, hydrocarbons, chlorinated hydrocarbons (CHCs), including pesticides and polychlorinated biphenyls (PCBs), micro-organisms, and oils and greases--are adsorbed to particles and are concentrated in the finer size fractions. Since these contaminants are scavenged relatively rapidly from the water by fine-grained particulate matter, their dispersal and accumulation are controlled largely by suspended sediment dispersal systems.

Turekian and Scott (1967) and Carpenter et al. (1975) reported on the introduction of metals to the upper Bay by the Susquehanna. There have been few published studies documenting the levels of metals or other contaminants in the bottom sediments of the upper Chesapeake Bay and its tributary estuaries, except in Baltimore Harbor, and fewer still of the processes that control the occurrence and the distribution of these contaminants in time and space, and their availability for uptake by organisms.

Sediments within Baltimore Harbor are enriched in most metals with concentrations 3 to 50 times those found in sediments of similar texture along the axis of the main body of the Bay (Villa and Johnson, 1974). Chromium, copper and lead values in the Harbor averaged 20, 50 and 13 times the corresponding values in the Bay proper. Cadmium was approximately six times higher in the Harbor than in the Bay. Of all metals analyzed, only manganese had approximately equal concentrations in the two areas. The distribution of metals within the Harbor, as shown by Villa and Johnson's (1974) analyses of samples from 176 stations, generally reflected the industrial inputs. Their report points out "all Harbor metals investigated by manganese were 3 to 50 times greater than their Bay counterparts. These factors should be carefully weighed when considering the disposal of dredged spoil in any open Bay areas."

Tsai et al. (1979) have recently conducted a bioassay analysis of Baltimore Harbor sediments. Their results showed that the toxicity of these sediments to the test organism, fish (mumichogs and spot), varied with location in the harbor and was roughly proportional to the metals concentrations in the sediment. In general sediments of the inner harbor were rated moderately toxic with highly toxic sediment in the marginal creeks. Outer harbor sediment was rated low in toxicity.

High metal concentrations in sediment are not in themselves diagnostic indicators of the potential effects of "pollution" unless all the metals present in sediment are available for biological uptake. The methods of extraction of metals from the sediments for chemical analyses used in Villa and Johnson's (1974) study do not give a reliable indication of the available fraction; that fraction available for biological uptake, or that might be mobilized during dredging and disposal.

Munson (1975) documented the distributions of total PCBs and DDTR (the total residual of the pesticide DDT) in the surficial sediments of the main body of the upper Chesapeake Bay and the Patapsco estuary. His analyses showed "that the sediments of Baltimore Harbor are quite high in PCB compared with the rest of the bay, except the station at the mouth of the Gunpowder River." The highest values of DDTR were also found in Baltimore Harbor and the mouth of the Gunpowder although the range in values was much more restricted.

While there are relatively few observations of contaminant levels in the surfacial sediments of the upper Bay, analyses of the longer-term sedimentary record are even more scarce. Schubel (1972a) reported on the distribution of extractable iron and zinc in a 165 cm long core taken in the upper Chesapeake Bay off Howell Point. The core was sampled at the surface and at 20 cm increments to the bottom of the core. One might have anticipated that the concentrations of iron and zinc would decrease with depth, since man's impact has presumably increased in recent decades. The results showed, however, that below the surficial layer the concentrations were nearly uniform with depth. The concentration of zinc was about 70 ppm (dry weight) and the concentration of iron about 20 ppt (dry weight).

Other more recent data from the central Bay (Schubel and Hirschberg, 1977; Goldberg et al., 1978) show that the vertical distribution of metals over the top meter of sediment are quite variable. Some cores show strong decreasing downward gradients in metal concentrations while others are more uniform. Some of this variability may be the result of the activities of burrowing organisms, which are heterogeneously distributed.

The Susquehanna River is probably the major source of sediment to the main body of the Chesapeake Bay at least as far seaward as the mouth of the Patapsco, and to the lower reaches of the estuaries that are tributary to this segment of the Bay. Near the head of the Bay--from Tolchester to Turkey Point--the sedimentation is completely dominated by the Susquehanna River (Schubel, 1968a,b, 1971a, 1972a,b).

Sedimentation Rates

Sediment deposition rates in the Chesapeake Bay are not well known. Most published estimates of contemporary and recent sedimentation rates are based on simple sediment budget models in which the sedimentation rate was the calculated term required to balance the budget. Using such a model Schubel (1968a) estimated that during years of average riverflow the sedimentation rate in the upper reaches of the

Bay from Tolchester to Turkey Point averaged about 2 to 3 mm/yr. Using a similar model for approximately this same segment of the Bay, Biggs (1970) estimated a mean sedimentation rate of 4 mm/yr. Schubel (1971a, 1976) has at various times estimated mean sedimentation rates of 1 to 2 mm/yr for the middle reaches of the Bay, and Biggs 1970) estimated it at about 1 mm/yr.

Recently, Schubel and Hirschberg (1977) and Hirschberg and Schubel (1979) reported radiometrically-determined contemporary sedimentation rates for the Chesapeake Bay. For a core from a station off Tilghman Island (38°41'30"N, 76°24'00"W) using the Pb^{210} dating method, they estimated a mean sedimentation rate of between 1 to 1.5 mm/yr for the past century or so. For a core from the upper bay, near the mouth of the Sassafras River, they report a "normal" sedimentation rate of 5 mm/yr. They note, however, that sedimentation in this region is strongly dominated by episodic floods, and that the true long-term sedimentation rate is probably twice this value.

Goldberg et al. (1978) also reported Pb^{210} measurements for Chesapeake Bay sediments. Their calculated sedimentation rates appear to us to be anomalously high. We suspect their cores were disturbed by burrowing organisms which destroyed their chronology. George Helz (Personal Communication, 1980) and O.M. Bricker (Personal Communication, 1980) have also dated cores from the Chesapeake Bay using Pb^{210} but their results have not been published.

Average sedimentation rates estimated from sediment budgets from "typical" years are relatively meaningless in the upper reaches of the Bay--above Tolchester. The geological record of this part of the estuarine system is dominated by floods. During Tropical Storm Agnes (June, 1972), Schubel and Zabawa (1978) and Zabawa and Schubel (1974) estimated that the sediment discharged would, if spread uniformly over the area between Tolchester and

Turkey Point, form a layer about 18 cm thick. Cores taken throughout this area showed accumulations of from 10 to 30 cm outside of the channel. Long stretches of the channel shoaled by more than 1 m. The deposit of at least one other large flood, that of March 1936, appears also to have been preserved in the sedimentary deposits of the upper Bay.

Sediment accumulation rates in channels are greater than the rates in shallower areas on the sides. The shoaling rate of the Chesapeake and Delaware Canal Approach Channel can be estimated by dividing the average volume of material that would have to be removed to maintain the Channel at its project depth by the area of the Channel and by the period of time between successive dredgings. The Approach Channel is approximately 52.8 km in length with an average width of 137 m, so it has an area of approximately 5.7 million m^2. Maintenance dredging in this channel averages 0.9 million m^3/yr (1.2 million yd^3/yr). The average rate of sediment accumulation in the channel is then about 0.9 million m^3 $\div$ 5.7 million m^2 = 15 cm/yr.

Farther seaward in the Bay, the sedimentation rate decreases substantially, but the actual value is not well known. In the main body of the Bay between Swan Point and the Maryland-Virginia line, the average sedimentation rate away from the littoral (nearshore) zone and outside of dredged channels is probably between 1 to 3 mm/yr with the higher rate being representative of the northern reaches of this segment.

The annual shoaling rate for the Approach Channels to Baltimore Harbor can be estimated by dividing the amount of material that must be dredged annually to maintain the Craighill and Brewerton Extension Channels, 1.5 million m^3 ($\approx$ 2 million yd^3), by the area of these channels, 6.7 million m^2 (8 million yd^2). This method yields a shoaling rate of about 23 cm/yr.

Effects of a Major Event--Agnes

Distributions described previously are "typical" of "average" conditions in Chesapeake Bay. But in addition to these "normal" variations, marked fluctuations can result from catastrophic events such as floods and hurricanes. There was, until Tropical Storm Agnes in 1972, a dearth of direct observations of "rare" events on the distribution of suspended sediment not only in Chesapeake Bay, but in the entire coastal environment.

Tropical Storm Agnes presented scientists with an unusual opportunity to document the impact of a major storm on a major estuarine system. There was little wind associated with Agnes when she reached the Bay area, but torrential rains sent riverflows of the major tributaries to record or near-record levels. Heavy rains stripped large quantities of soil from throughout most of the drainage basin, and flooding rivers carried significant quantities of sediment into Chesapeake Bay.

Nineteen seventy-two started out not very unlike most years, although it was somewhat wetter. During the spring freshet in March, flow of the Susquehanna was fairly high, exceeding 8900 m^3/sec, and the concentration of suspended sediment in the "mouth" of the River (Conowingo) on one day reached 190 mg/ℓ. Between 1 January 1972 and 21 June 1972 the concentration of suspended sediment at Conowingo exceeded 100 mg/ℓ on only four days--not unlike most years. During May and the first 20 days of June of 1972, the concentration was generally between 10-25 mg/ℓ; somewhat higher than average for that time of year, but not really "abnormal." Then Agnes entered the area and torrential rains fell throughout most of the drainage basin of the Susquehanna producing record flooding. The day the Susquehanna crested, 24 June 1972, the average daily flow at Conowingo exceeded 27,750 m^3/sec--the highest average daily flow ever recorded--exceeding the previous daily high by about 33 percent. The instantaneous peak flow on 24 June of more than 32,000 m^3/sec was the highest instantaneous flow ever reported over the 185 years of record. The *monthly* average discharge of the Susquehanna of about 5100 m^3/sec for June 1972 was the highest average discharge for *any* month over the past 185 years, and was more than nine times the average June discharge over the same period. Comparison of the monthly average discharge of the Susquehanna during 1972 with the ensemble monthly average over the period 1929-1966 clearly shows the departure of the 1972 June flow from the long-term average June flow, Fig. 15.

Even before Agnes, 1972 had been a "wet" year. Salinities throughout much of the Bay were lower than their more normal values. With the large influx of fresh water following Agnes, salinities fell sharply. The lag between time of maximum discharge and the time of minimum salinity varied, of course, with location and depth. In the surface layers of the upper 180 km of the estuary the salinities reached minimum values within 2 to 5 days of the cresting of the Susquehanna. In the near-bottom waters in the same region, minimum salinities were not reached in some areas until 14-15 July 1972, 20 days after cresting. The tidal reaches of the Susquehanna were pushed seaward more than 80 km from the mouth of the river at Havre de Grace, that is, nearly to the Chesapeake Bay bridge at Annapolis, Maryland. The front, separating the fresh river water from the salty estuarine water, was more than 35 km farther seaward than ever previously reported, Fig. 16.

Reestablishment of the "normal" salinity distribution is effected by the flow of more saline waters up the estuary in the lower layer and subsequent slow vertical mixing of the lower and upper layers. The combination of large fresh water inputs accompanying Agnes and the compensating upstream flow of salty water in the lower layer produced vertical salinity gradients larger than any previously recorded throughout much

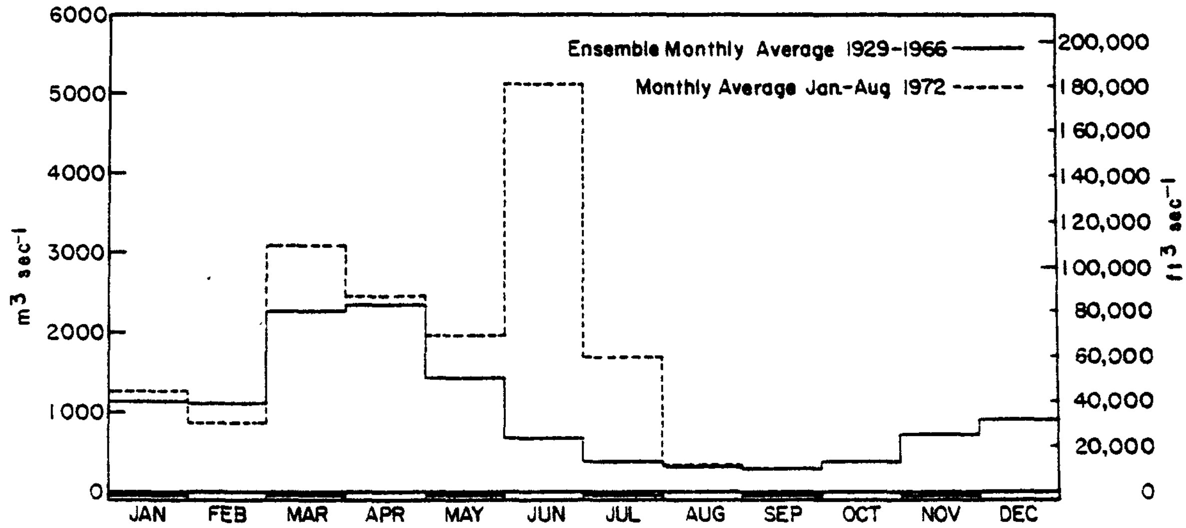

Fig. 15 Susquehanna River flow at Conowingo (MD), ensemble average by month for the period 1929-1966, and the monthly average flow during 1972.

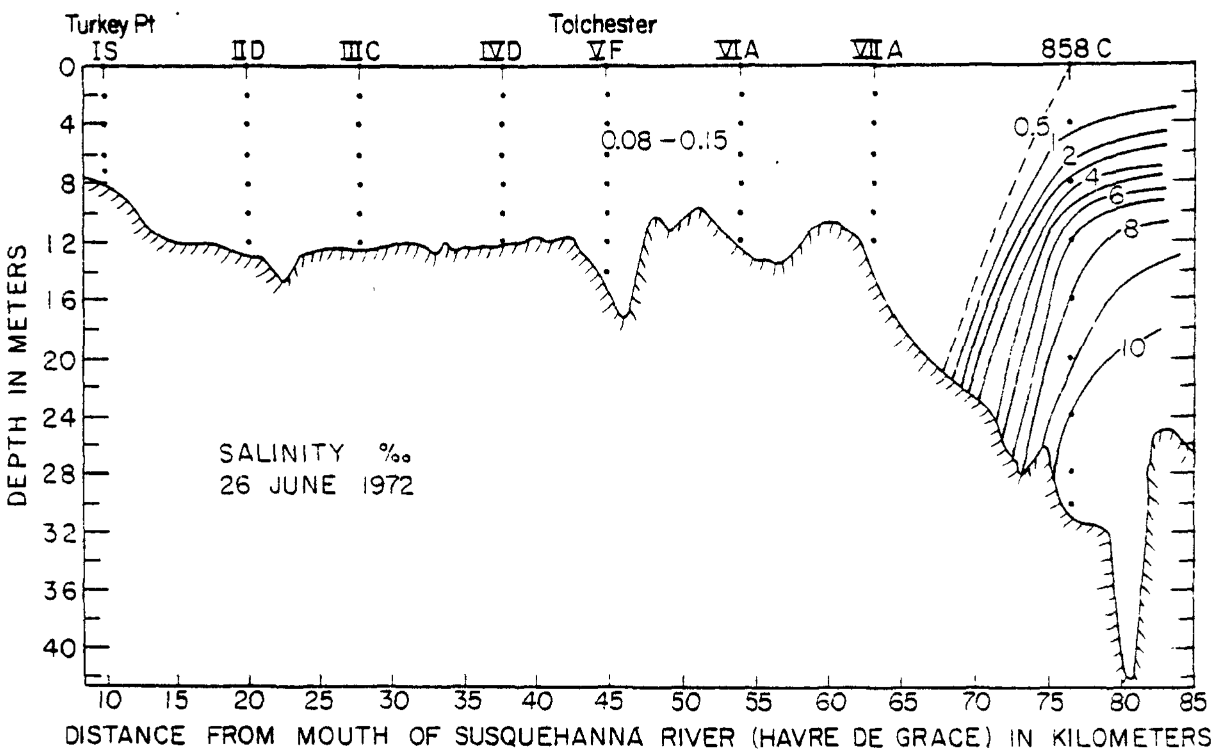

Fig. 16 Longitudinal distribution of salinity in upper Bay on 26 June 1972, two days after the Susquehanna crested at Conowingo (MD) following passage of Tropical Storm Agnes.

of the Chesapeake Bay estuarine system. Abnormally large vertical gradients persisted throughout the summer. Even in early autumn the vertical salinity gradients were more typical of spring conditions that those characteristic of the fall season.

The flooding Susquehanna dumped a large mass of sediment into the upper Bay. On 22 June 1972 when riverflow increased rapidly as a result of heavy rains the concentration of suspended sediment at Conowingo reached 400 mg/ℓ. On 23 June 1972, riverflow exceeded 24,400 m^3/sec, and the concentration of suspended sediment jumped to more than 10,000 mg/ℓ--a concentration more than 40 times greater than any previously reported for the lower Susquehanna. On the 24th of June, no sample was collected because the dam was evacuated for safety reasons. By 25 June, riverflow had decreased to about 23,100 m^3/sec, and the concentration of suspended sediment to about 1,450 mg/ℓ. On 30 June, riverflow was 4,600 m^3/sec, and the concentration of suspended sediment, 70 mg/ℓ, Figs. 17 and 18.

During the ten-day period, 20-30 June 1972, the Susquehanna River probably discharged more than 31 million metric tons of suspended sediment into the upper Chesapeake Bay (Schubel, 1972). This is more than 25 times its sediment discharge of the previous year. In most years the Susquehanna probably discharges between 0.5 to 1.0 million metric tons of suspended sediment into the upper Bay (Schubel, 1968a, 1972b; Biggs, 1970). The bulk of the sediment discharged during Agnes was silt and clay; the remainder was fine sand.

The sediment-laden floodwater produced anomalously high concentrations of suspended sediment throughout much of the Chesapeake Bay estuarine system. In the main body of the Bay, the effects were, of course, most dramatic in the upper Bay. The distribution of suspended sediment along the axis of the upper Bay on 26 June 1972, two days after the Susquehanna crested at Conowingo, is plotted in Fig. 19. The figure shows that the concentration of suspended sediment at

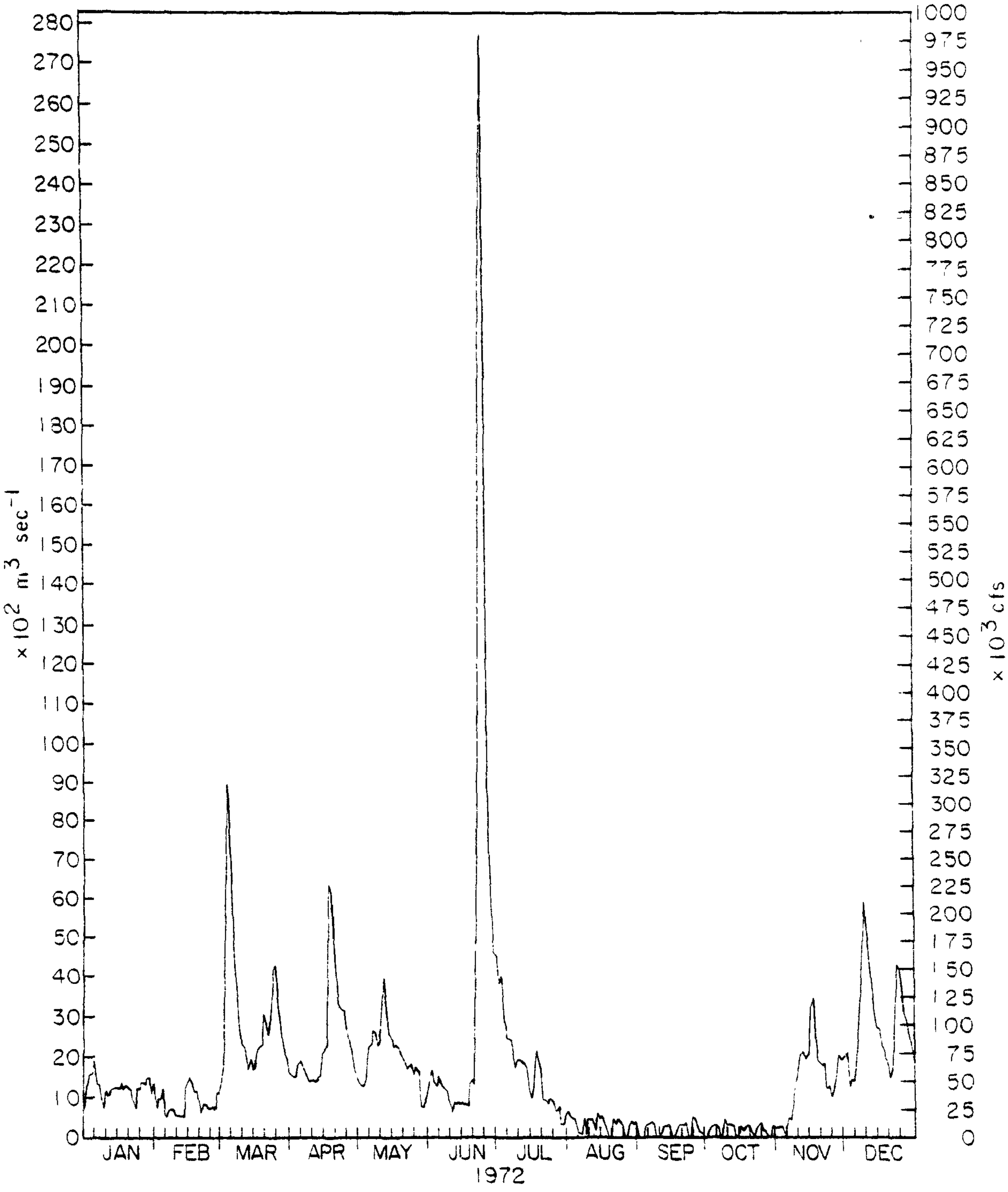

Fig. 17 Discharge of Susquehanna River at Conowingo (MD) during 1972.

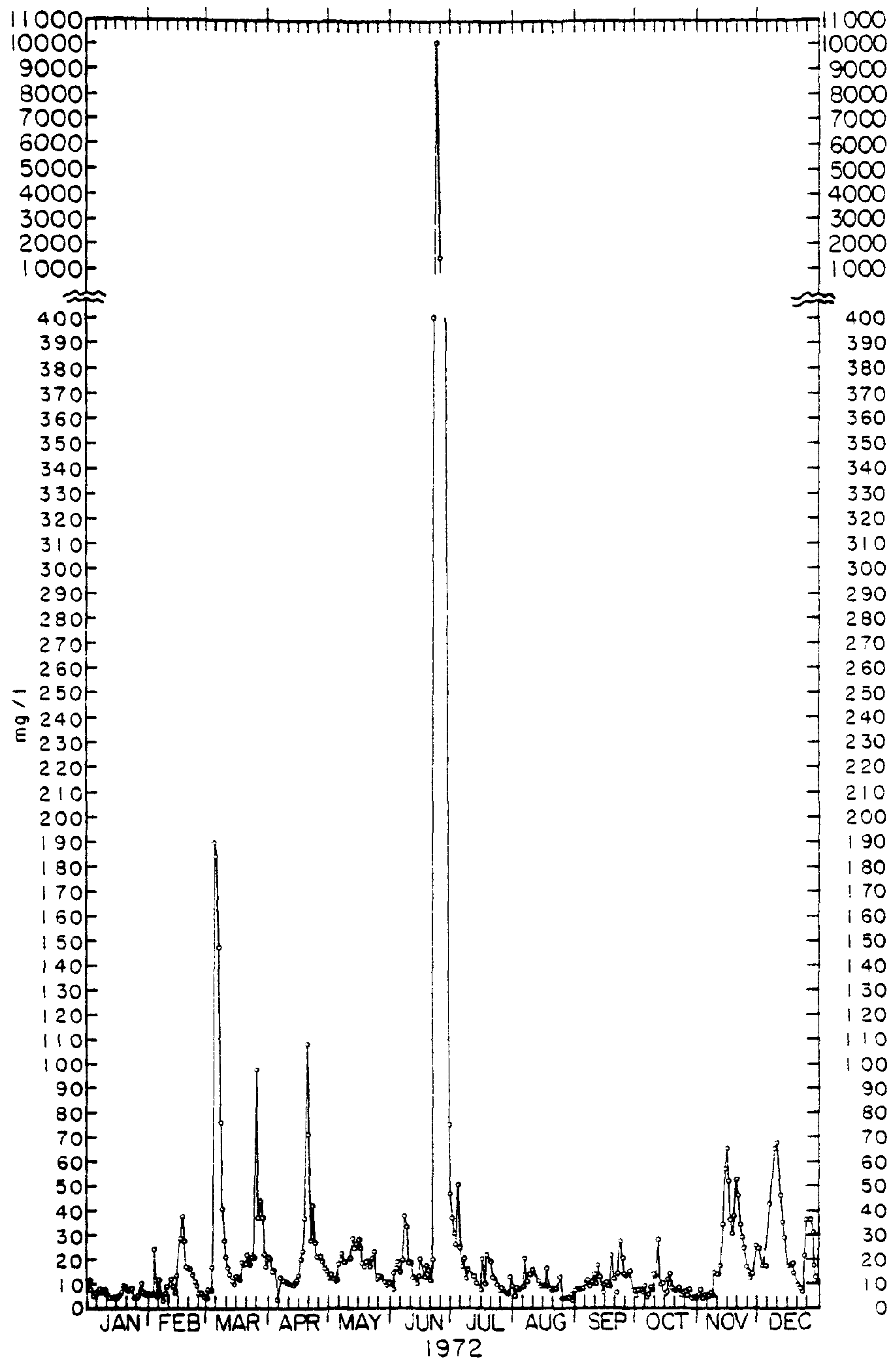

Fig. 18 Concentration of suspended sediment (mg/ℓ) in the Susquehanna River at Conowingo (MD) during 1972.

the surface dropped from more than 700 mg/ℓ off Turkey Point (Station 927SS) at the head of the Bay to about 400 mg/ℓ at Tolchester (Station 913R, 30 km farther seaward), and to approximately 175 mg/ℓ near the Bay Bridge at Annapolis (Station 858C). The concentrations of suspended sediment at mid-depth in the upper reaches of this segment of the Bay showed a similar distribution pattern although the concentrations were generally greater than near the surface. Seaward of Station 903A, however, there was an abrupt decrease in the concentration of suspended sediment below about 10 m. This distribution resulted from the over-riding of the relatively "clean" estuary water by the sediment-laden Susquehanna River water.

The marked downstream decrease in the concentration of suspended sediment in the upper Bay resulted almost entirely from the removal of the material by settling; there was little dilution of the Susquehanna inflow by the Bay water in this segment of the Bay. Riverflow was so great that the tidal reaches of the Susquehanna were pushed seaward nearly to the bridge at Annapolis--more than 35 km farther seaward than ever previously reported.

By 29 June 1972 the concentrations of suspended sediment had decreased significantly throughout the upper Bay. Maximum concentrations at that time were observed between Stations 917S and 909, and did not exceed 300 mg/ℓ. The concentration of suspended sediment decreased both upstream and downstream of this approximately 20 km long legment. The longitudinal gradient of suspended sediment that had characterized the upper Bay on 26 and 27 June had disappeared. Longitudinal distributions of total suspended solids in the upper Bay during the week following Agnes show that the concentrations dropped quickly following peak discharge, and that the bulk of the material discharged into the main body of the Bay at Turkey Point was deposited above Station 903A. Concentrations of suspended solids were relatively high, however, over all of the Maryland portion of the Bay proper,

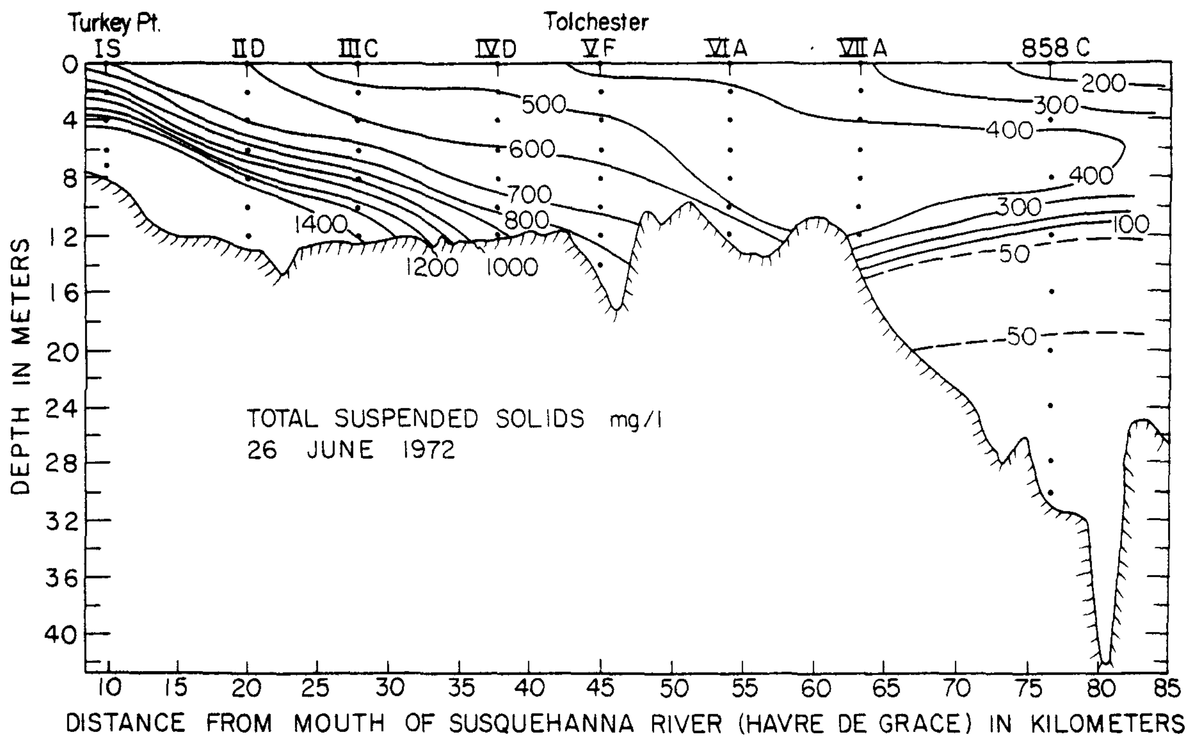

Fig. 19 Longitudinal distribution of suspended sediment (mg/ℓ) along the axis of the upper Bay on 26 June 1972, two days after the Susquehanna nested at Conowingo (MD) following passage of Tropical Storm Agnes.

and the concentrations of total suspended solids remained anamalously high throughout most of the upper Bay for more than a month.

As the normal two-layered circulation pattern was re-established throughout the upper reaches of the Bay, there was a net upstream movement of sediment suspended in the lower layer. Sediment previously carried downstream and deposited by the flooding Agnes waters was resuspended by tidal currents and gradually transported back up the estuary. The routes of sediment dispersal are clear, but the rates of movement are obscure. The data do not permit reliable estimates of the rates of sediment transport, particularly during the recovery period.

Comparison of post-Agnes data from the middle and lower reaches of the Bay with data from more "normal" years indicates that throughout most of the summer, concentrations of suspended sediment were 2 to 3 times higher than average for that time of year. Seaward of Station 858C--just south of the Bay bridge at Annapolis--concentrations in July and August 1972 did not exceed 10 mg/ℓ except near the bottom.

Summary

During the spring freshet and other occasional short periods of very high riverflow, the upper reaches of the Chesapeake Bay behave like the tidal reaches of a river. The Susquehanna overpowers the characteristic net non-tidal estuarine circulation and the net flow and sediment transport are seaward at all depths. The transition from river to estuary, sometimes as far as 40 to 45 km seaward of the mouth of the Susquehanna at Havre de Grace, is characterized by a front separating the fresh river water from the saline estuary water. Generally, most of each year's supply of new fluvial sediment is discharged during the freshet. The bulk of this is deposited in the upper Bay north of Tolchester. The spring freshet, then, is a period of fluvial domination of the upper bay and of its suspended sediment population and is characterized by a close link between the suspended sediment population and the principal "ultimate" source of sediment--the Susquehanna River.

With subsiding riverflow, the characteristic net non-tidal estuarine circulation is reestablished in the upper reaches of the Bay. The concentrations of suspended sediment are greater than those either farther upstream in the source river or farther seaward in the estuary. This zone of high suspended sediment concentration, the "turbidity maximum," is produced and maintained by the periodic resuspension of bottom sediment by tidal scour and by the sediment trap produced by the net non-tidal circulation.

The passage of tropical storm Agnes in June 1972 resulted in record flooding throughout the drainage basin of the northern Chesapeake Bay. On June 24, the day the Susquehanna crested at its mouth, the instantaneous peak flow exceeded 32,000 m^3/sec. The daily average discharge of 27,750 m^3/sec for that day exceeded the previous daily average high by nearly 33 percent. Throughout the bay, salinities were reduced to levels lower than any previously observed. On 26 June 1972, salinities were less than 0.5 $^{o}/oo$ from surface to bottom throughout the upper 60 km of the bay and the surface salinity was less than 1 $^{o}/oo$ in the upper 125 km but had nearly recovered to normal levels by September.

On June 24, the concentration of suspended sediment in the mouth of the Susquehanna exceeded 10,000 mg/ℓ and in a one-week period the sediment discharge exceeded that of the past several decades. The bulk of this was deposited in the upper 40 km of the Bay.

CASE STUDY 1
THE ANALYSIS

Our first case study was for the Chesapeake and Delaware Canal Approach Channel, Fig. 20. We considered two disposal options: overboard adjacent to the Channel, and in the deep trough south of the Bay Bridge at Annapolis.

Principal Findings, Conclusions and Recommendations

1. Most of the sediment accumulating in Chesapeake and Delaware Approach Channel and in contiguous areas comes from erosion of the drainage basin of the Susquehanna River.

2. The sediments in the Chesapeake and Delaware Approach Channel are not measurably different in their physical and chemical characteristics and in their contaminant levels from those accumulating in areas contiguous to the channel or in the deep trough.

3. Upper Chesapeake Bay normally experiences rapid sediment deposition and high turbidity because of suspended sediment and phytoplankton growth. Processes controlling these normal background conditions must be considered in planning, executing, and regulating dredging and disposal operations.

4. Naturally-deposited sediments and dredged materials are resuspended and dispersed in the upper Bay by tidal currents, turbulence due to wind waves and ship wakes, flood-induced currents, and the long-term estuarine circulation. These processes are most effective in shallow waters and least affective in the deep trough of the central Bay.

5. Sediment-associated metals in dredged materials of the upper Bay do not pose a problem to benthic organisms or to the overlying water column, during or subsequent to disposal operations.

6. Sediment-associated organic compounds, such as chlorinated hydrocarbons, deserve particular attention because of high toxicity at low concentrations, significant potential for release from sediment, public concern and the scarcity of data.

7. Physical and chemical effects of the discharge plume from dredging and disposal operations are normally small and have no long-term effects on organisms or environmental quality.

8. Depletion of dissolved oxygen by dredging and disposal is a local, transitory phenomenon in shallow waters, and is unlikely to have a measurable effect on dissolved oxygen levels in near-bottom waters in the trough south of the Bay Bridge.

9. Benthic communities in subaqueous dredged material disposal sites recover to near normal abundances within one to two years. Community diversity may take somewhat longer to recover to pre-disposal levels. Recovery of benthic abundance and diversity is expected to be quicker in the deep trough in the central Bay than in shallow waters of the upper Bay.

10. Containment of dredged materials or utilization of disposal sites far from the channels can be expected to decrease the frequency of dredging required to maintain the Chesapeake and Delaware Canal Approach Channel.

11. The deep trough in the central Bay appears to be an attractive site for disposal of uncontaminated sediments. There are, however, several questions that should be answered before the trough is considered as a disposal site.

a. To what extent is the trough used by over-wintering fish? At what levels in the water column do they congregate and in what concentrations?

b. To what extent is the trough used by blue crabs as an over-wintering area? What parts of the trough do they utilize?

c. To what extent would disposal in the trough alter its characteristic properties?

CASE STUDY 1. CHESAPEAKE AND DELAWARE CANAL APPROACH CHANNEL

The first case study we made was for material dredged from the Chesapeake and Delaware Canal Approach Channel, Fig. 20. The Chesapeake and Delaware Canal Approach Channel extends from approximately Pooles Island northward to the western end of the Canal.

The Chesapeake and Delaware Canal Approach Channel is shown in Fig. 20. The rationale for the steps we followed in assessing dredging/disposal options for this project are given in Schubel et al. (1979). The steps are shown schematically in Fig. 2.

Step I. Water Quality Certificate

Since the C & D Approach Channel is an authorized U.S. Army Corps project, it requires only a Water Quality Certificate. Under Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. S401 et. seq.) the U.S. Army Corps of Engineers is charged with the responsibility of evaluating requests to make physical alterations in the navigable waters of the United States. A dredging operation is such a physical alteration. The District Office serves as a clearing house for other Federal, State, and local agencies concerning the environmental effects of a proposed action. The primary Federal agencies reviewing applications for physical alterations to areas under the aegis of the Baltimore District are the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service of the Department of the Interior, and the National Marine Fisheries Service of the Department of Commerce.

The decision to issue a Water Quality Certificate is based on an evaluation of the probable impact of the proposed activity on the public interest. That decision should reflect the national concern for both protection and utilization of

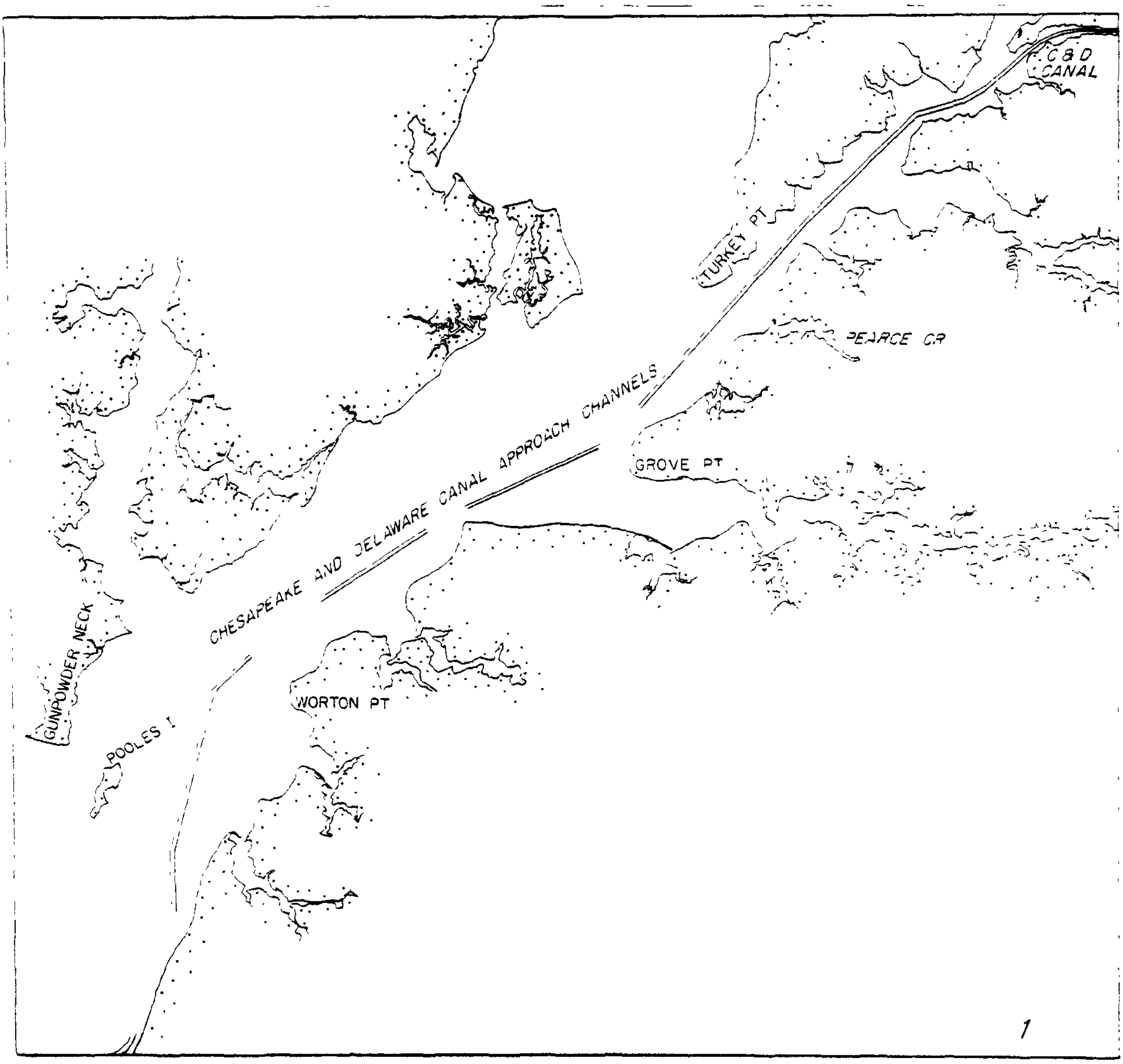

Fig. 20 Map showing the approach channel to the Chesapeake and Delaware Canal.

important resources. The benefit which reasonably may be expected to accrue from the proposal must be balanced against its reasonable forseeable detriments. All factors which may be relevant to the proposal are to be considered; among those are conservation, economics, anesthetics, general environmental concerns, historic values, flood damage prevention, land use classification, navigation, recreation, water supply, water quality, and in general, the needs and welfare of the people. No permit will be granted unless its issuance is found to be in the public interest.

Step II. Characterization of Material to be Dredged

The State of Maryland requires that certain tests be made to characterize materials proposed for dredging and to characterize materials in the proposed disposal area. These tests are listed in Table 1 which also indicates which of the tests have been conducted for sediments in the Chesapeake and Delaware Approach Channel and in the two disposal areas we selected for analysis. Characteristics of the materials accumulating in the Chesapeake and Delaware Canal Approach Channel and in these two disposal areas are summarized in Table 2.

Step III. Identification of Potential Dredging/Disposal Options

We evaluated two dredging/disposal options: (1) hydraulic dredging and overboard pipeline disposal in the area adjacent to the channel, and (2) bucket and scow dredging with disposal by hopper barge in the deep trough south of the Bay Bridge at Annapolis. Another alternative that might be considered is the filling of marginal areas. In the past a large fraction of the material dredged from the C & D Approach Channel has been placed in Pearce Creek. The availability of data for comparative tests of sediments in the two potential disposal sites is summarized in Table 1; the data themselves are summarized in Table 2. Important characteristic properties of each of these two potential disposal areas are summarized in Table 3. The data recorded are typical values.

Step IV. Assessment of Potential Dredging/Disposal Options

The short-term and long term environmental and ecological effects of the two dredging/disposal options we considered are summarized in Table 4. We did not attempt to evaluate the socio-economic factors (Step IVc, Fig. 2).

With respect to environmental and ecological effects *during* disposal, there is little to choose between the two disposal alternatives. The effects of overboard disposal in the upper Bay on the water column and on organisms living in the water column are local in time and space, and negligible (Table 4 and references). Studies in many other areas throughout the world indicate clearly that if this same material from the Approach Channel were dumped in the trough, water-column effects during disposal would also be local in time and space, and negligible (Table 4 and references). In both areas, disposal would result in the immediate burial of most of the benthic organisms. The trough has fewer bottom-dwelling organisms than the area in the upper Bay adjacent to the Channel. The only potential ecological effect *during* disposal we identified which we could not assess with existing data was the uptake of chlorinated hydrocarbons (CHCs) by plankton, benthos, and nekton.

The potential environmental and ecological effects *subsequent* to disposal in the two environments are of greater concern because of their greater uncertainty. The principal problems are not with the metals as is commonly supposed. All available evidence indicates that metals in dredged materials do not pose a significant threat to the environment, to the biota, or to human health if the materials are kept in a geochemical environment similar to that from which they were dredged. According to Turekian (1974) "The best-informed conclusion must be that, as far as metals are concerned, what has been deposited with the dredge spoil has little chance of leaching out of the sediment. The problems of polluted dredge spoil dumping are thus more concerned with mobilized toxic organic compounds and changes in the physical character of the substrate than with the potentially toxic heavy metals."

Since metals and other contaminants may be taken up by benthic animals, particularly by those that burrow into the sediment, appropriate choice of disposal areas can minimize any potential problems. A disposal area should be selected which minimizes the number of benthic animals that are harvested directly from the disposal area, and which minimizes the number of benthic animals that serve as food for animals that are harvested from that area or from other areas of the Bay.

Conclusions and Recommendations

On the basis of existing data on the environmental and ecological effects of the two alternatives, we rank disposal in the trough as being environmentally and ecologically somewhat more acceptable than disposal overboard adjacent to the channel. Neither alternative appears to have any unacceptable short-term or long-term environmental or ecological effects.

The principal advantages of disposal in the deep trough south of the Bay Bridge at Annapolis over disposal in the area adjacent to the Chesapeake and Delaware Approach Channel are:

(1) Disposal in the trough eliminates any possible return of the dredged material to the Chesapeake and Delaware Canal Approach Channel, and therefore decreases the frequency

of dredging required to maintain the Channel. With overboard disposal in the area adjacent to the Channel, much of the material returns to the Channel.

(2) Any mobilization of contaminants to the water column during disposal would be reduced with disposal in the trough because bucket and scow dredging and disposal operations require less water, and produce less agitation that hydraulic pipeline operations. Even if the material were dredged hydraulically and disposed of by scow, dilution of the dredged material by water would be less than that required for a pipeline operation.

(3) Any mobilization of contaminants to the water column *subsequent* to disposal would be reduced because of the substantial reduction in reworking of the material by waves, tidal currents, and burrowing organisms.

(4) Any uptake of contaminants by organisms from the dredged material *subsequent* to disposal would be reduced because of the low density of burrowing organisms and the nearly complete mortality of this population brought on each summer by the naturally occurring anoxic conditions of the near-bottom waters.

(5) Changes in bottom topography by disposal in the trough would have a much smaller impact on circulation and other dynamic characteristics than disposal in the upper Bay. These effects in both areas are small, but objections have been raised by drift-net fishermen in the upper Bay.

The trough appears to be an attractive area for disposal of uncontaminated dredged materials. There are, however, a number of questions that should be answered before any disposal occurs. These include:

(1) What are the distributions of over-wintering blue crabs in the trough in space and in time?

(2) Would disposal of dredged materials substantially increase the mortality of these crabs?

(3) What are the distributions of over-wintering finfish in the trough in space and in time?

(4) Would disposal of dredged materials from scows disturb these populations of over-wintering fish?

If the deep trough south of the Bay Bridge at Annapolis were to be designated as a disposal area for material dredged from the Chesapeake and Delaware Canal Approach Channel, the approved period for dredging, the "dredging window" for this Channel might have to be adjusted.

Table 1. Comparative tests required by State of Maryland's Department of Natural Resources for materials proposed for dredging and for materials in proposed disposal areas. An X in the Table indicates that published data exist.

Parameter	C & D Approach Channel	Overboard Area Adjacent Channel	Trough
Volatile Solids	X	X	X
Chemical Oxygen Demand			
Hexane Extractables	X	X	X
Total Organic Carbon	X	X	X
Zinc		X	
Mercury			
Cadmium	X		X
Copper	X	X	X
Chromium	X	X	X
Lead	X	X	X
Total Keldjahl Nitrogen	X	X	X
Total Phosphorous	X		
Chlorinated Hydrocarbons	X	X	X
Particle Size	X	X	X

Table 2. Characteristics of sediments accumulating in the Chesapeake and Delaware Approach Channel and in two potential disposal areas--the area adjacent to the channel and the deep trough south of the Bay Bridge at Annapolis.

Property	Material to be Dredged	Area Adjacent to Channel	Trough South of Bay Bridge†		
	Concentrations in PPM Dry Mass				
Silver	2	<1	--	0.7	--
Cobalt	117 ± 40	150 ± 52	--	(12)	--
*Chromium	460 ± 110	455 ± 90	(25)	(90)	(85)
*Copper	80 ± 24	85 ± 26	(20)	(24)	(12)
Gallium	54 ± 9	53 ± 16	--	--	--
Nickel	106 ± 37	112 ± 25	(26)	(43)	(43)
*Lead	240 ± 26	225 ± 63	(27)	(33)	(34)
Strontium	270 ± 72	213 ± 44	--	--	--
Vanadium	102 ± 20	103 ± 25	--	74	--
Zirconium	302 ± 115	328 ± 96	--	--	--
*Zinc	--	128	--	--	--
*Mercury	--	--	--	--	--
*Cadmium	--	0.9	--	--	--
*BHC	0.002	0.001	--	--	--
*Chlordane	0.009	0.005	--	--	--
*Dieldrin	ND	ND	--	--	--
*DDT	0.020	0.016	--	--	--
*PCB	0.9	0.19	--	--	--
*Kepone	ND	ND	--	--	--

Table 2. (continued)

Property	Material to be Dredged	Area Adjacent to Channel	Trough South of Bay Bridge†
	Physical Properties, Percent Mass		
Water Content	61.9	56.4	66.8
*Volatile Solids	10.9	10.8	8.4
Montmorillonite	10	10	Trace
Kaolinite	20-30	20-30	10
Chlorite	10	10	20
Illite	40	40	50-60
*Sand	15	15	19.3
*Silt	71.5	71.5	55.0
*Clay	13.4	13.4	25.7
*Carbon	4%	3.9%	1.3%
*Nitrogen	0.2%	0.2%	0.2%
*Phosphorus	0.7%	--	--
*Oxygen Demand			
Initial	300 g/m^3 sed	--	--
Final	90 g/m^3 sed	--	--
Oils and Greases	1%	--	--

† Data from three sources; values have not been averaged because different analytical techniques were used.

* State of Maryland required test.

-- Data not available.
ND Not detected.

Table 2, Sources of Information

1. Metals, CHCs, oxygen demand, volatile solids, oils and greases, and phosphorous data for C & D Approach Channel and overboard area.

Gross, M.G., W.R. Taylor, R.C. Whaley, E. Hartwig and W.B. Cronin. 1976. Environmental effects of dredging and dredged material disposal, approaches to Chesapeake and Delaware Canal, northern Chesapeake Bay. Chesapeake Bay Institute, The Johns Hopkins University, Open File Rept. 6, 87pp.

2. Metals, carbon, nitrogen, volatile solids, and water content data for the trough south of the Bay Bridge at Annapolis.

Helz, G.R. 1976. Trace element inventory for the northern Chesapeake Bay with emphasis on the influence of man. Geochem. Cosmochem. Acta 40:573-580.

Goldberg, E.D., V. Hodge, M. Koide, J. Griffin, E. Gamble, O.P. Bricker, G. Matisoff, G.R. Holdren, and R. Braun. 1978. A pollution history of Chesapeake Bay. Geochem. Cosmochem. Acta 42:1413-1425.

Schubel, J.R. and D.J. Hirschberg. 1977. ^{210}Pb-determined sedimentation rate and accumulation of metals at a station in Chesapeake Bay. Ches. Sci. 18:379-383.

3. Clay mineral data.

Hathaway, J.C. 1972. Regional clay mineral facies in estuaries and continental margin of the United States East Coast. Pages 293-317 *in* B.W. Nelson, ed., Environmental Framework of Coastal Plain Estuaries. Geological Society of America Mem. 133.

4. Sediment grain size data.

Ryan, J.D. 1953. The sediments of Chesapeake Bay. Maryland Department of Geology, MInes, and Water Resources, Bull. 12, 120pp.

Table 3. Characteristic properties of the two alternative disposal sites. The values presented are considered typical.

Property		Disposal Site: Area Adjacent To Channel	Disposal Site: Trough South of Bay Bridge
Distance from Dredging Activity		1-3 km	50 km
Type of Dredging		Hydraulic	Bucket
Type of Disposal		Pipeline	Scow
Depth of Disposal Area		4 m	30 m
Dissolved Oxygen of Near Bottom Waters	Summer	5-6 mℓ/ℓ	1 mℓ/ℓ
	Winter	9 mℓ/ℓ	7 mℓ/ℓ
Salinity of Near Bottom Waters	Summer	7‰	20‰
	Winter	6‰	19‰
Temperature of Near Bottom Waters	Summer	25°C	24°C
	Winter	2.5°C	3.5°C
Turbulence[(A)]		High	Low
Amount of Sediment Resuspension[(B)]		Large	Small
Depth of Euphotic Zone	Summer	1.0 m	2.0 m
	Winter	0.7 m	5.0 m
Abundance of Benthic Organisms		High	Low
Importance of Area to Fish			
Spawning & nursery		High	Low
Over-wintering		Negligible	High
Frequency of maintenance dredging required[(C)]		Unchanged	Decreased

[( )] See Appendices at end of report for documentation.

Table 4. Environmental and ecological effects of disposal alternatives.

a. Environmental effects *during* disposal operations.

	Disposal Alternatives	
	Area Adjacent to Channel	Trough South of Bay Bridge
Possible Effect	Intensity of Effect	
Increased Turbidity of Water Column (D)	Temporary & Local	Temporary & Local
Increased Contaminant Releases to Water Column (E)		
1. Metals	Negligible	Negligible
2. Nutrients	Negligible	Negligible
3. CHCs	Possible	Possible
Oxygen Depletion of Water Column (F)	Temporary & Local	Temporary & Local

( ) See Appendices at end of report for documentation.

Table 4 (Continued)

b. Ecological Effects *during* disposal operations.

Possible Effect	Disposal Alternatives: Area Adjacent to Channel	Disposal Alternatives: Trough South of Bay Bridge
	Intensity of Effect	
Increased Turbidity(G)		
1. Phytoplankton (Suppression of Photosynthesis)	Temporary & Local; Negligible	Temporary & Local; Negligible
2. Zooplankton	Negligible	Negligible
3. Nekton (clogging gills, etc.)	Negligible	Negligible
4. Benthos (clogging gills, etc.)	Negligible	Negligible
Smothering of Benthos(H)	May be complete; temporary	May be complete; temporary; fewer organisms
Exclusion and/or Attraction of Fish(I)	Either; temporary & local	Either; temporary & local
Uptake of Contaminants(J)		
1. Metals		
(a) Benthos	Negligible	Negligible
(b) Plankton	Negligible	Negligible
(c) Nekton	Negligible	Negligible
2. CHCs		
(a) Benthos	Possible	Possible
(b) Plankton	Possible	Possible
(c) Nekton	Possible	Possible

( ) See Appendices at end of report for documentation.

Table 4 (Continued)

c. Environmental effects *subsequent* to disposal.

	Disposal Alternatives	
	Area Adjacent to Channel	Trough South of Bay Bridge
Possible Effect	Intensity of Effect	
Increased Turbidity in Water Column (K)	Negligible	Negligible
Contaminant Release to Water (L)		
1. Metals	Unlikely	More unlikely
2. Nutrients	Small	Small
3. CHCs	Possible	Possible
Oxygen Depletion of Water Column (M)	Undetectable	Undetectable
Movement of Dredged Material After Disposal (N)	Likely	Less Likely
Effect of Changes in Bottom Topography (O)		
1. Circulation	Negligible	Negligible
2. Uses (fishing & boating)	Small	None

( ) See Appendices at end of report for documentation.

Table 4 (continued)

d. Ecological effects *subsequent* to disposal.

	Disposal Alternatives	
	Area Adjacent to Channel	Trough South of Bay Bridge
Possible	Intensity of Effect	
Time for recovery of benthos[(P)]		
1. Biomass	<1.5 yr	<1.0 yr
2. Diversity	<1.5 yr	<1.0 yr
Increased metal uptake by organisms[(Q)]		
1. Metals		
(a) Benthos	Possible	Possible
(b) Plankton	Unlikely	Unlikely
(c) Nekton	Unlikely	Unlikely
2. CHCs		
(a) Benthos	Possible	Possible
(b) Plankton	Possible	Possible
(c) Nekton	Possible	Possible

[( )] See Appendices at end of report for documentation.

CASE STUDY 2
THE ANALYSIS

Our second case study was for the Baltimore Harbor Approach Channels, Fig. 21. We considered five disposal options: (1) dredging and overboard disposal in areas adjacent to channels by hydraulic dredging and pipeline disposal, or by bucket dredging and scow disposal, (2) hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to channels, (3) bucket dredging and hopper barge disposal at the Kent Island Dump Site, (4) bucket dredging and hopper barge disposal in the trough south of the Bay Bridge at Annapolis, and (5) hydraulic dredging and pipeline disposal to create wetlands in fringing areas.

Principal Findings, Conclusions, and Recommendations

1. Most of the sediment accumulating in the Baltimore Harbor Approach Channels comes from erosion of the drainage basin of the Susquehanna River and from erosion of the shoreline of Chesapeake Bay.

2. The sediments in the Baltimore Harbor Approach Channels are not measurably different in their physical and chemical characteristics and contaminant levels from sediments presently at the Kent Island dump site or in areas adjacent to the channels. The data available (Table 6a) suggest that the contaminant levels of sediment in the Baltimore Harbor Approach Channels may be elevated above contaminant levels found in sediments of the trough south of the Bay Bridge. However, because of differences in analytical techniques used to evaluate the contaminant levels in these areas, the differences may not be significant. Further analysis of sediment from both areas (Baltimore Approach Channels and the trough) should be performed by a single laboratory,

especially for metals and CHCs. Analysis for contaminants must be performed also at potential fringing area disposal locations.

3. This portion of Chesapeake Bay is normally subject to large fluctuations in ambient turbidity, dissolved oxygen, temperature and salinity. Processes controlling these normal background conditions must be considered in planning, executing, and regulating dredging and disposal operations.

4. Naturally-deposited sediments and dredged materials are resuspended and dispersed in this region of Chesapeake Bay by tidal currents, turbulence due to wind waves and ships' wakes, and the long-term estuarine circulation. These processes are most effective in shallow waters and least effective in the deep trough of the central Bay. Enclosing proposed disposal areas within structures that nearly reached to the water surface would significantly reduce sediment resuspension and the dispersion of sediment from the disposal site.

5. It is unlikely that sediment-associated metals in dredged materials from the Baltimore Harbor Approach Channels will be made more available to benthic or water column biota during or subsequent to disposal operations.

6. Sediment-associated organic compounds, such as chlorinated hydrocarbons, deserve particular attention because of high toxicity at low concentrations, significant potential for release from sediment, public concern, and the scarcity of data. We recommend that additional analyses of sediment from all proposed disposal options be made, and that the distribution coefficient of CHC compounds between sediment and water be routinely determined for each dredging project.

7. With the possible exception of the

release of chlorinated hydrocarbon compounds, the physical and chemical effects of the discharge plume from dredging and disposal operations are normally small and have no long-term effects on organisms or environmental quality. We believe the large effort currently spent to monitor DO, turbidity, and metals during disposal operations might better be expended in monitoring possible releases of chlorinated hydrocarbons.

8. Depletion of dissolved oxygen by dredging and disposal is a local, transitory phenomenon in shallow waters, and is unlikely to have a measurable effect on dissolved oxygen levels in near-bottom waters in the trough south of the Bay Bridge.

9. Benthic communities in subaqueous dredged material disposal sites recover to near-normal abundances within one to two years. Community diversity may take somewhat longer to recover to pre-disposal levels. Recovery of benthic abundance and diversity is expected to be quicker in the deep trough in the central Bay than in shallow waters of the upper Bay.

10. Containment of dredged materials or utilization of disposal sites far from the channels can be expected to decrease the frequency of dredging required to maintain the Baltimore Harbor Approach Channels. Submerged containment will also significantly reduce the potential for release of sediment-associated contaminants to the water column subsequent to disposal.

11. The deep trough in the central Bay appears to be an attractive site for disposal of uncontaminated sediments. There are, however, several questions that should be answered before

the trough is considered as a disposal site.

a. To what extent is the trough used by over-wintering fish? At what levels in the water column do they congregate and in what concentrations?

b. To what extent is the trough used by blue crabs as an over-wintering area? What parts of the trough do they utilize?

c. To what extent would disposal in the trough alter its characteristic properties?

12. Because of the possibility of oxidizing dredged materials and reducing the strength of the sediment-contaminant association, creation of new wetlands has significant potential for release of metals and other contaminants to nearby waters and to organisms.

CASE STUDY 2. BALTIMORE HARBOR APPROACH CHANNELS

Our second case study was for material dredged from the Baltimore Harbor Approach Channels.

The Baltimore Harbor Approach Channels are shown in Fig. 21. The rationale for the steps we followed in assessing dredging/disposal options for this project are given in Schubel et al. (1979). The steps are shown schematically in Fig. 2.

Step I. Water Quality Certificate

Since the Baltimore Harbor Approach Channels are collectively an authorized U.S. Army Corps project, dredging of them requires only a Water Quality Certificate. Under section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. S401 et. seq.) the U.S. Army Corps of Engineers is charged with the responsibility of evaluating requests to make physical alterations in the navigable waters of the United States. A dredging operation is such a physical alteration. The District Office serves as a clearing house for other Federal, State, and local agencies concerning the environmental effects of a proposed action. The primary Federal agencies reviewing applications for physical alterations to areas under the aegis of the Baltimore District are the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service of the Department of the Interior, and the National Marine Fisheries Service of the Department of Commerce.

The decision to issue a Water Quality Certificate is based on an evaluation of the probable impact of the proposed activity on the public interest. That decision should reflect the national concern for both protection and utilization of important resources. The benefit which reasonably may be expected to accrue from the proposal must be balanced against its reasonably forseeable detriments. All factors which may be relevant to the proposal are to be considered;

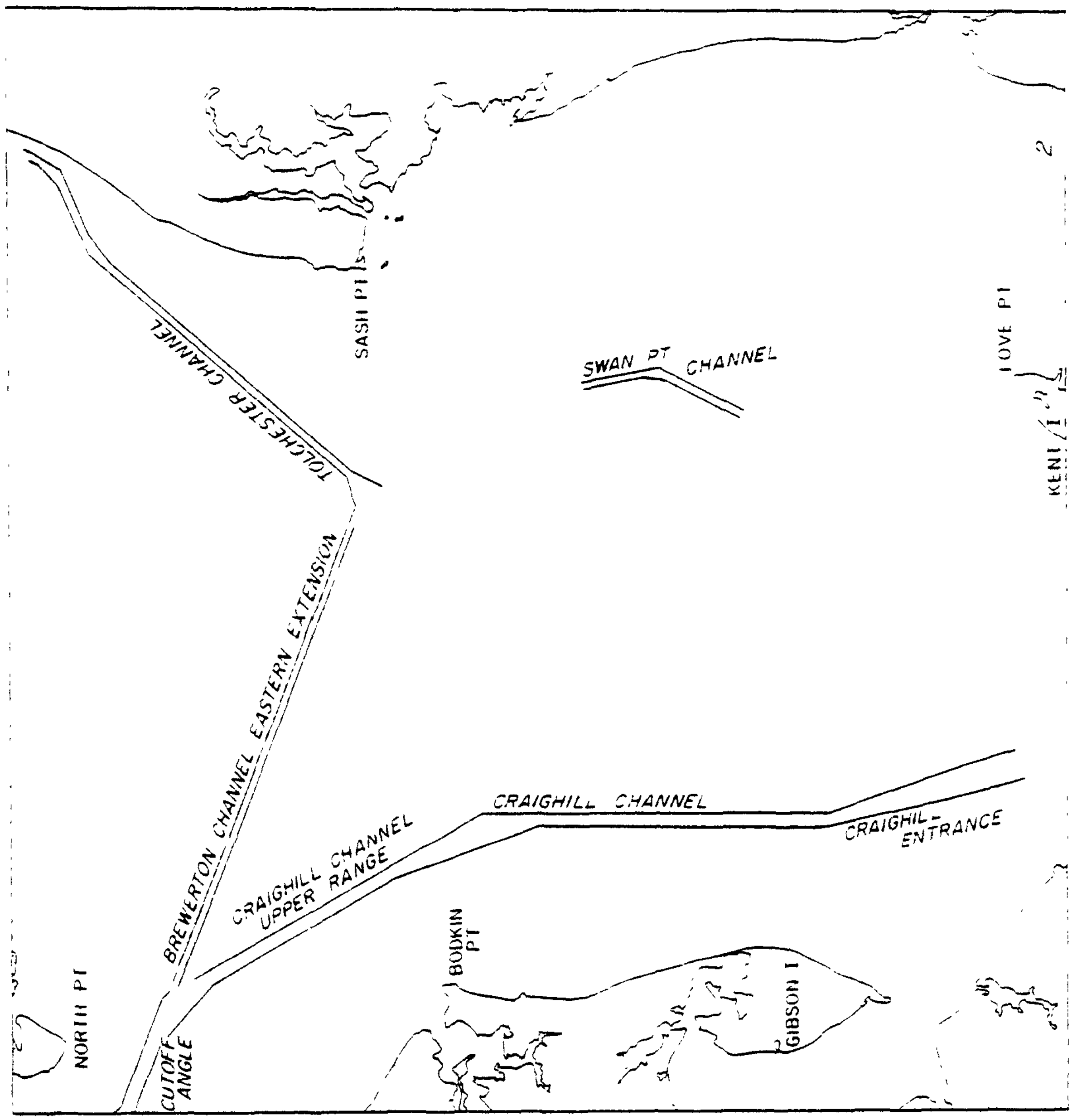

Fig. 21 Map showing the approach channels to Baltimore Harbor.

among those are conservation, economics, aesthetics, general environmental concerns, historic values, flood damage prevention, land use classification, navigation, recreation, water supply, water quality, and in general, the needs and welfare of the people. No permit will be granted unless its issuance is found to be in the public interest.

Step II. Characterization of Material to be Dredged

The State of Maryland requires that certain tests be made to characterize materials proposed for dredging and to characterize materials in the proposed disposal area. These tests are listed in Table 5 which also indicates which of the tests have been conducted for sediments in the Baltimore Harbor Approach Channels and in selected disposal areas. Characteristics of the materials accumulating in the Baltimore Harbor Approach Channels and in selected disposal areas are summarized in Table 6.

Step III. Identification of Potential Dredging/Disposal Options

We evaluated five dredging/disposal options:

(1) hydraulic dredging and pipeline disposal, or bucket dredging and slow disposal, overboard in areas adjacent to the Channels,

(2) hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to Channels

(3) bucket dredging and hopper barge disposal at the Kent Island Dump Site

(4) bucket dredging and hopper barge disposal in the trough south of the Bay Bridge at Annapolis

(5) hydraulic dredging and pipeline disposal in fringing areas to create wetlands.

The availability of data for comparative tests of sediments in the five potential disposal sites is summarized in Table 4; the data themselves are summarized in Table 6. Important characteristic properties of each of the five disposal options are summarized in Table 7. The data recorded are typical values.

Step IV. Assessment of Potential Dredging/Disposal Options

The short-term and long-term environmental and ecological effects of each of the dredging/disposal options we evaluated are summarized in Table 8. We did not attempt to evaluate the socio-economic factors (Step IVc, Fig. 2).

With respect to environmental and ecological effects *during* disposal, there is little to choose among at least four of the five disposal alternatives. The exception may be wetland creation. Water column effects during disposal are local, temporary and small for all five options. In all five cases, disposal would result in the immediate burial of most of the benthic organisms. The only potential ecological effect *during* disposal we identified which we could not assess with existing data was the uptake of chlorinated hydrycarbons (CHCs) by plankton, benthos, and nekton.

The potential environmental and ecological effects *subsequent* to disposal are of greater concern because of their greater uncertainty. The principal problems with contaminants are not with metals as is commonly supposed. All available evidence indicates that metals in dredged materials do not pose a significant threat to the environment, to the biota, or to human health if the materials are kept in a geochemical environment similar to that from which they were dredged. According to Turekian (1974) "The best-informed conclusion must be that, as far as metals are concerned, what has been deposited with the dredge spoil has little chance of leaching out of the sediment. The problems of polluted dredge spoil dumping are thus more concerned with mobilized toxic organic compounds and changes in the physical character of the substrate than with the potentially toxic heavy metals."

Since metals and other contaminants may be taken up by benthic organisms, particularly by those that burrow into the sediment, appropriate choice of disposal areas can minimize any potential problems. A disposal area should be selected which minimizes the number of benthic animals that are harvested directly from the disposal area, and which minimizes the number of benthic organisms that serve as food for animals that are harvested from that area or from other areas of the Bay. The deep trough south of the Bay Bridge has fewer benthic organisms per unit area than any of the alternative disposal areas we evaluated. The benthic population is essentially eliminated every summer because of the nearly anoxic conditions that recur annually.

Conclusions and Recommendations

We considered five dredging/disposal options for maintenance material dredged from the Approach Channels to Baltimore Harbor: (1) dredging and disposal overboard in areas adjacent to the Channels, (2) hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to Channels, (3) bucket dredging and hopper barge disposal at the Kent Island Dump Site, (4) bucket dredging and hopper barge disposal in the trough south of the Bay Bridge at Annapolis, and (5) hydraulic dredging and pipeline disposal in fringing areas to create wetlands.

Based on our evaluation of existing data on environmental and ecological effects subsequent to disposal, we rank the five disposal alternatives in the following order of decreasing acceptability (1) deep trough south of Bay Bridge, (2) submerged, confined overboard adjacent to channels, (3) Kent Island Dump Site, (4) overboard adjacent to channels, (5) wetland creation.

On environmental and ecological grounds, there is little basis for selecting between the first two choices and perhaps among the first four. Disposal in a confined, submerged area has the disadvantages that a structure would be needed to retain the material and it could interfere with other uses of the area and pose a hazard to navigation. Disposal at the Kent Island Dump Site is somewhat less deisrable than the first two choices because of the somewhat greater chance of movement of the material and the potential for uptake of contaminants by important benthic organisms--oysters and clams.

Disposal overboard in areas adjacent to the Channels increases the probability--relative to the first three choices--of dispersal and of release of some contaminants to the overlying water. Its principal disadvantage, however, is that much of the material would return to the channels and, hence, the frequency of dredging would be greater than for any of the first three options. No persistent undesirable environmental or ecological effects have been documented from overboarding material dredged from these channels.

We consider that use of materials dredged from the Baltimore Harbor Approach Channels for wetland creation is the least desirable of the alternatives we examined because of the substantially increased probability of mobilization of contaminants. This conclusion would be altered only if a convincing case could be made for the need for wetland habitat.

The deep trough appears to be an attractive site for disposal of uncontaminated dredged materials. There are, however, a number of questions that should be answered before any disposal occurs. These were stated in Case Study 1 and are repeated here for emphasis.

(1) What is the distribution of over-wintering blue crabs in the trough in space and in time?

(2) Would disposal of dredged materials substantially increase the mortality of these crabs?

(3) What is the distribution of over-wintering finfish in the trough in space and in time?

(4) Would disposal of dredged materials from scows disturb these populations of over-wintering fish?

If the deep trough south of the Bay Bridge at Annapolis were to be designated as a disposal area for material dredged from the Chesapeake and Delaware Canal Approach Channel, the approved period for dredging and disposal, the "dredging window," for these channels might have to be adjusted.

Table 5. Comparative tests required by State of Maryland's Department of Natural Resources for materials proposed for dredging and for materials in proposed disposal areas. An X in the Table indicates that published data exist.

Parameter	Approach Channels	Areas Adjacent to Channel	Kent Island Dump Site	Trough	Fringing Areas
Volatile Solids	X			X	
Chemical Oxygen Demand	X				
Hexane Extractables	X	X		X	
Total Organic Carbon	X			X	
Zinc	X	X	X		
Mercury		X	X		
Cadmium	X	X	X	X	
Copper	X	X	X	X	
Chromium	X	X	X	X	
Lead	X	X		X	
Total Keldjahl Nitrogen	X			X	
Total Phosphorous	X				
Chlorinated Hydrocarbons	X	X		X	
Particle Size	X	X	X	X	

Table 6. Characteristics of sediments accumulating in the Baltimore Harbor Approach Channels and in three potential disposal areas--the areas adjacent to the channels, the Kent Island Dump Site, and the Trough south of the Bay Bridge at Annapolis. There are no published sediment data for fringing areas.

Property	Material to be Dredged	Areas Adjacent to Channels	Kent Island Dump Site	Trough south of Bay Bridge		
		Concentrations in PPM Dry Mass				
*Chromium	---	102	55	25	90	85
*Copper	51	84	63	(20)	(24)	(12)
*Lead	---	127	126	27	33	34
*Zinc	327	538	385	---	---	---
Manganese	1522	1547	1953	---	---	---
Nickel	45	33	47	26	43	43
*Cadmium	<1	1	<1	---	---	---
*Mercury	---	0.53	0.04	---	---	---
*PCB	0.06	0.09	---		---	
*Chlordane	0.002	0.003	---		---	
*DDT	0.008	0.009	---		---	
*Kepone	ND	ND	---		---	

* - State of Maryland required test.
--- - Data not available.
( ) - Value substantially exceeded by those in materials to be dredged from Baltimore Harbor Approach Channels.
ND - Not Detected.

Table 6 (Continued)

Property	Material to be Dredged	Areas Adjacent to Channels	Kent Island Dump Site	Trough south of Bay Bridge
		Physical Properties, Percent Mass		
Water	---	---	---	66.8
*Volatile Solids	---	---	---	8.4
*Sand	12.9	12.9	7.2	19.3
*Silt	52.8	52.8	56.1	55.0
*Clay	34.3	34.3	36.7	25.7
Montmorillonite	Trace	Trace	Trace	Trace
Kaolinite	10	10	10	10
Chlorite	20	20	20	20
Illite	50-60	50-60	50-60	50-60
*Carbon	---	---	3.2	1.3
*Nitrogen	---	---	---	0.2
*Phosphorus	---	---	---	---
*Oxygen Demand	---	---	---	---
*Oils and Greases	0.15	0.15	---	---

* - State of Maryland required test.
--- - Data not available.
( ) - Value substantially exceeded by those in materials to be dredged from Baltimore Harbor Approach Channels.
ND - Not Detected.

Table 6, Sources of Information

1. Metals, CHCs, volatile solids, oils and greases, and water content data for Baltimore Harbor Approach Channels and adjacent areas.

Cronin, W.B., M.G. Gross, W.R. Taylor, R.C. Whaley, W. Boicourt, and J.R. Schubel. 1976. Investigations of dredging operations, Brewerton Channel Cut-Off Angle--Patapsco River mouth disposal site, 10 April 1976 - 26 May 1976. Chesapeake Bay Institute, The Johns Hopkins University, Open File Rept. 10, 50pp. + appendices.

2. Metals data for Kent Island Dump site.

Villa, O. and P.G. Johnson. 1974. Distribution of metals in Baltimore Harbor sediments. Environmental Protection Agency Tech. Rept. 59, Annapolis, Md., Field Office, Region III, NTIS EPA-903/9-74-012.

3. Clay mineral data.

Hathaway, J.C. 1972. Regional clay mineral facies in estuaries and continental margin of the United States East Coast. Pages 293-317 *in* B.W. Nelson (ed.), Environmental Framework of Coastal Plain Estuaries. Geological Society of America Mem. 133.

4. Sediment grain size data.

Ryan, J.D. 1953. The sediments of Chesapeake Bay. Maryland Department of Geology, Mines, and Water Resources, Bull. 12, 120pp.

5. Data for trough.

See sources enumerated for Table 2.

TABLE 7 CHARACTERISTIC PROPERTIES OF THE FIVE DREDGING/DISPOSAL ALTERNATIVES FOR BALTIMORE HARBOR APPROACH CHANNELS. THE VALUES ARE CONSIDERED TYPICAL

Property		Dredging/Disposal Alternative: Areas Adjacent to Channels	Confined, Submerged Disposal Adjacent to Channels	Kent Island Dump Site	Trough South of Bridge	Wetland Creation in Fringing Areas
Distance from Dredging Activity						
Type of Dredging		Hydraulic or bucket	Hydraulic	Bucket	Bucket	Hydraulic
Type of Disposal		Pipeline or scow	Pipeline	Scow or Hopper	Scow or Hopper	Pipeline
Freq. of Maint. dredging (R)		Unchanged	Decreased	Decreased	Decreased	Decreased
Depth of Disposal Area		3-6 m	3-6 m	12-15 m	30 m	Intertidal†
Dissolved Oxygen of Near Bottom Waters	Summer	2 mℓ/ℓ	2 mℓ/ℓ	3 mℓ/ℓ	< 1 mℓ/ℓ	N/A
	Winter	7 mℓ/ℓ	7 mℓ/ℓ	7 mℓ/ℓ	7 mℓ/ℓ	
Salinity of Near Bottom Waters	Summer	12°/oo	12°/oo	12°/oo	20°/oo	N/A
	Winter	11°/oo	11°/oo	11°/oo	19°/oo	
Temperature of Near Bottom Waters	Summer	25°C	25°C	25°C	24°C	N/A
	Winter	3°C	3°C	4°C	3.5°C	
Turbulence (S)		High	Low*	Low	Low	Moderate
Amount of Sediment Resuspension (T)		Large	Small*	Smaller	Smallest	Small, after Vegetation
Depth of Euphotic Zone	Summer	1.5 m	1.5 m	2.0 m	2.0 m	Surface
	Winter	3.0 m	3.0 m	5.0 m	5.0 m	
Abundance of Benthic Organisms		High	High	Low	Low	Low initially; recolonization
Importance of Area to Fish: Spawning & Nursery		Low	Low	Low	Low	High
Over-wintering		Negligible	Negligible	High	High	Low

*After enclosure of disposal area with a submerged dike †After completion of marsh NA: Not Applicable

( ) See Appendices at end of report for documentation.

TABLE 8. ENVIRONMENTAL AND ECOLOGICAL EFFECTS OF DREDGING/DISPOSAL ALTERNATIVES FOR BALTIMORE HARBOR APPROACH CHANNELS.

a. Environmental Effects During Dredging/Disposal Operations

Possible Effect	Dredging/Disposal Alternative: Areas Adjacent to Channels	Confined, Submerged Disposal Adjacent to Channels	Kent Island Dump Site	Trough South of Bay Bridge	Wetland Creation
	Intensity of Effect				
Increased Turbidity of Water Column (U)	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local
Increased Contaminant Releases to Water Column (V)					
1. Metals	Negligible	Negligible	Negligible	Negligible	Negligible
2. Nutrients	Negligible	Negligible	Negligible	Negligible	Negligible
3. CHCs	Possible	Possible	Possible	Possible	Possible
Oxygen Depletion of Water Column (W)	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local

( ) See Appendices at end of report for documentation.

8b Ecological Effects *During* Dredging/Disposal Operations

Possible Effect	Dredging/Disposal Alternative: Areas Adjacent to Channels	Confined, Submerged Disposal Adjacent to Channels	Kent Island Dump Site	Trough South of Bay Bridge	Wetland Creation
	Intensity of Effect				
Increased Turbidity[(X)]					
1. Phytoplankton (suppression of photosynthesis)	Temporary & local negligible	Temporary & local; negligible	Temporary & local; negligible	Temporary & local negligible	Negligible; new habitat
2. Zooplankton	Negligible	Negligible	Negligible	Negligible	Negligible; new habitat
3. Nekton (clogging of gills, etc.)	Negligible	Negligible	Negligible	Negligible	Negligible; new habitat
4. Benthos (clogging of gills, etc.)	Negligible	Negligible	Negligible	Negligible	Negligible; new habitat
5. Rooted aquatic plants	Negligible	Negligible	Negligible	Negligible	Possible
Smothering of Benthos[(Y)]	May be complete; temporary	May be complete; temporary	May be complete; temporary	May be complete; temporary	May be complete new habitat
Exclusion and/or Attraction of fish[(Z)]	Either; temporary & local	Either; temporary & local	Either; temporary & local	Either; temporary & local	Either; new habitat
Uptake of Contaminants[(AA)]					
1. Metals					
(a) Benthos	Negligible	Negligible	Negligible	Negligible	Negligible
(b) Plankton	Negligible	Negligible	Negligible	Negligible	Negligible
(c) Nekton	Negligible	Negligible	Negligible	Negligible	Negligible
2. CHCs					
(a) Benthos	Possible	Possible	Possible	Possible	Possible
(b) Plankton	Possible	Possible	Possible	Possible	Possible
(c) Nekton	Possible	Possible	Possible	Possible	Possible

( ) See Appendices at end of report for documentation.

Table 8c Environmental Effects *Subsequent* to Disposal

Possible Effect	Dredging/Disposal Alternative: Areas Adjacent to Channels	Confined, Submerged Disposal Adjacent to Channels	Kent Island Dump Site	Trough South of Bay Bridge	Wetland Creation
	Intensity of Effect				
Increased Turbidity in Water Column* (BB)	Negligible	Negligible	Negligible	Negligible	Negligible**
Increased Contaminant Releases to Water Column* (CC)					
1. metals	Unlikely	Very unlikely	Very unlikely	Very unlikely	Likely
2. nutrients	Probable, but small	Probable, but small	Probable, but small	Probable, but small	Probable, but small
3. CHCs	Possible	Possible	Possible	Possible	Possible
Oxygen Depletion of Water Column* (DD)	Undetectable	Undetectable	Undetectable	Undetectable	New habitat
Movement of Dredged Material After Disposal (EE)	Likely	Negligible	Negligible	Negligible (less than Kent Island)	Negligible**
Effect of Changes in Bottom Topography (FF)					
1. circulation	Negligible	Possible	Negligible	Negligible	Definite, localized; new habitat
2. uses (fishing and boating	Negligible	Probable	Negligible	Negligible	Definite; new habitat

*For marshland creation, read to (of, in) nearby open waters.
**After stabilization with marsh plants.
( ) [illegible]

8d Ecological Effects *Subsequent* to Disposal

Possible Effect	Areas Adjacent to Channels	Confined, Submerged Disposal Adjacent to Channels	Kent Island Dump Site	Trough South of Bay Bridge	Wetland Creation
	Dredging/Disposal Alternative — Intensity of Effect				
Time for recovery of benthos[(GG)]					
1. Biomass	<1.0 yr	<1.0 yr	<1.0 yr	<1.0 yr	New habitat
2. Diversity	<1.0 yr	<1.0 yr	<1.5 yr	<1.0 yr	New habitat
Increased uptake by organisms[(HH)]					
1. Metals					
(a) Benthos	Possible	Possible	Possible	Possible	Possible
(b) Plankton	Unlikely	Unlikely	Unlikely	Unlikely	Possible, but small
(c) Nekton	Unlikely	Unlikely	Unlikely	Unlikely	Possible, but small
(d) Emergent and submergent grasses	Unlikely	Unlikely	None	None	Possible
2. CBCs					
(a) Benthos	Possible	Possible	Possible	Possible	Possible
(b) Plankton	Possible	Possible	Possible	Possible	Possible
(c) Nekton	Possible	Possible	Possible	Possible	Possible
(d) Emergent and submergent grasses	Unlikely	Unlikely	None	None	Possible

( ) See Appendices at end of report for documentation.

CASE STUDY 3. THE ANALYSIS

Our third case study was for the Baltimore Harbor channels, Fig. 22. We evaluated five disposal options: (1) dredging and overboard disposal in areas adjacent to the channels by one of the following combinations: hydraulic dredging and pipeline disposal, or bucket dredging and pipeline disposal, or bucket dredging and scow disposal, (2) Hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to channels, (3) a combination of hydraulic dredging with pipeline and scow disposal techniques to create an island, either inside or outside the harbor, (4) a combination of hydraulic dredging and scow or pipeline disposal in nearshore fringing areas to create or extend wetlands, and (5) a combination of hydraulic or bucket dredging and disposal at an unspecified upland site.

Principal Findings, Conclusions, and Recommendations.

1. Most of the sediment accumulating in the Baltimore Harbor Channels comes from erosion of the drainage basin of the Susquehanna River and from erosion of the shoreline of Chesapeake Bay.

2. The sediments in the Baltimore Harbor Channels are highly contaminated with metals, PCBs, and oils and greases. Close examination of the extensive data available for metals (Table 10 and Refs.) and more limited data for CHCs suggest that Inner Harbor sediments (Fort McHenry Channel) are significantly more contaminated than Outer Harbor (Brewerton Channel) materials.

3. With the exception of CHCs, which may be solubilized during disposal operations, the potential disposal options for Baltimore Harbor materials are not limited by the possible release of contaminants *during* disposal operations. Because our ability

to predict the possible remobilization of contaminants in the period subsequent to disposal is limited by lack of information, great care should be exercised in the choice of disposal option.

4. Oxidation of reduced dredged materials significantly enhances the possibility of solubilization of metals to the water column.

5. Resuspension and dispersal of dredged sediment, by increasing surface area available for exchange with water, significantly increases the rate of dissolution of contaminants, including CHCs.

6. Although the characteristics of artificial islands required to physically contain the dredged sediment probably have been adequately addressed, much more study is needed of the possible geochemical consequences of subaerially exposing previously reduced sediment in artificial islands. Such studies must account for the motion and oxidizing ability of rainwater and runoff, on the surface of the island and groundwater in its interior. Present geochemical theory of sediment suggests that these waters have significant potential to act as vectors of dissolved contaminants to nearby waters.

7. Confining highly contaminated dredged materials underwater minimizes oxidation and resuspension, limiting the potential release of contaminants.

8. Confinement of highly contaminated materials underwater at the base of an island may be acceptable if studies can demonstrate convincingly that development of a local oxygenated water table will not occur and that there will be no motion of groundwaters through the structure.

9. Upland disposal, because of the high probability of oxidation of the dredged sediment, is highly likely to result in mobilization of contaminants by runoff and groundwater.

CASE STUDY 3. BALTIMORE HARBOR CHANNELS

The third and final case study we made was for material dredged from Baltimore Harbor Channels. Baltimore Harbor Channels are shown in Fig. 22. The rationale for the steps we followed in assessing the dredging/disposal options are described in Schubel et al. (1979) and shown schematically in Fig. 2.

Step I. Water Quality Certificate Application

Since the Baltimore Harbor Channels are collectively an authorized U.S. Army Corps project, dredging requires only a Water Quality Certificate. Under Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. S401 et. seq.) the U.S. Army Corps of Engineers is charged with the responsibility of evaluating requests to make physical alterations in the navigable waters of the United States. A dredging operation is such a physical alteration. The District Office serves as a clearing house for other Federal, State, and local agencies concerning the environmental effects of a proposed action. The primary Federal agencies reviewing applications for physical alterations to areas under the aegis of the Baltimore District are the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service of the Department of the Interior, and the National Marine Fisheries Service of the Department of Commerce.

The decision whether to issue a Water Quality Certificate is based on an evaluation of the probable impact of the proposed activity on the public interest. That decision should reflect the national concern for both protection and utilization of important resources. The benefit which reasonably may be expected to accrue from the proposal must be balanced against its reasonably forseeable detriments. All factors which may be relevant to the proposal are to be considered; among those are conservation, economics, aesthetics, general

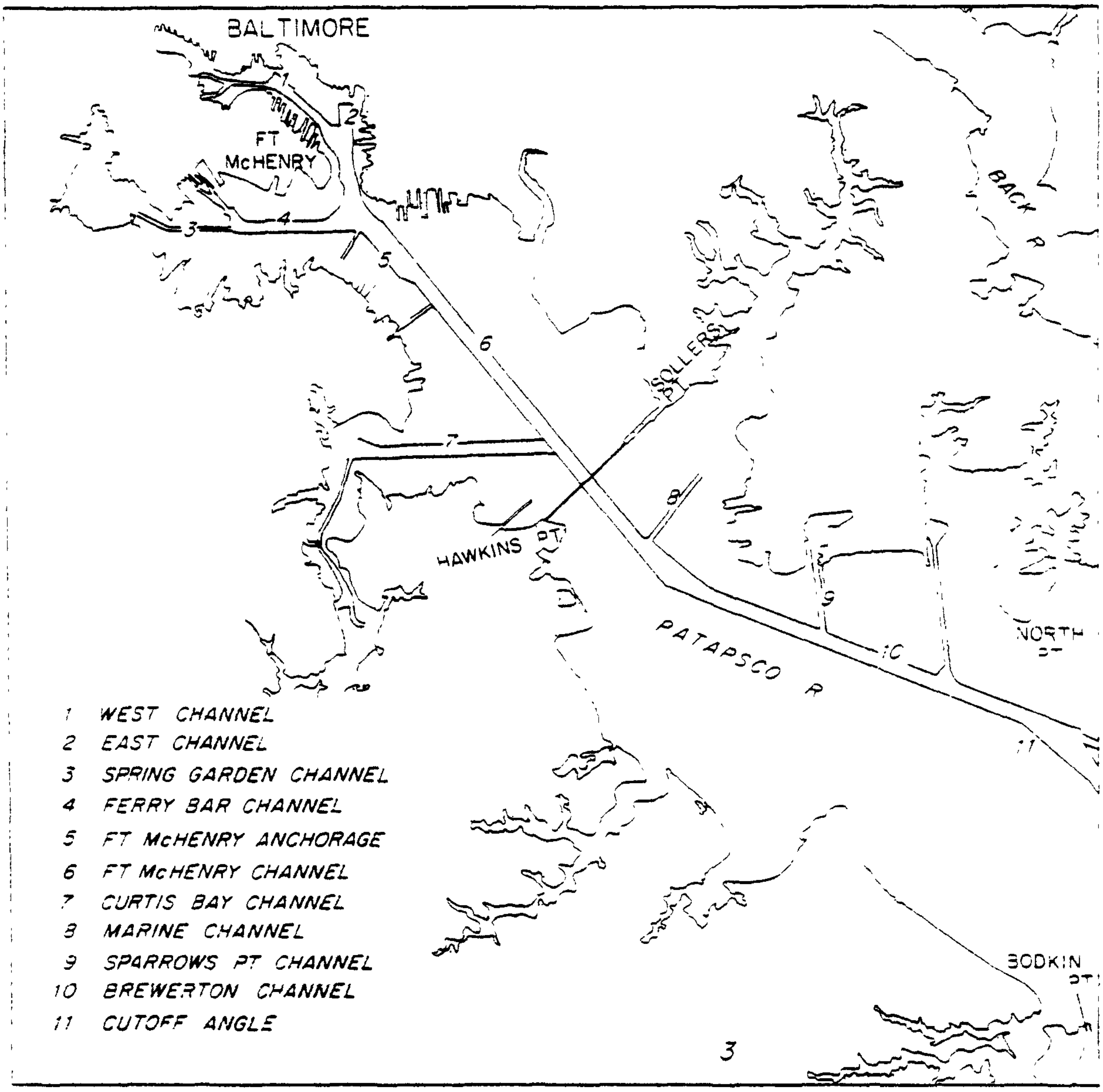

Fig. 22 Map showing Baltimore Harbor Channels.

environmental concerns, historic values, flood damage prevention, land use classification, navigation, recreation, water supply, water quality, and in general, the needs and welfare of the people. No permit will be granted unless its issuance is found to be in the public interest.

Step II. Characterization of Material to be Dredged

The State of Maryland requires that certain tests be made to characterize materials proposed for dredging and to characterize materials in the proposed disposal area. These tests are listed in Table 9 which also indicates which of the tests have been conducted for sediments in Baltimore Harbor Channels and in the disposal areas we selected for analyses. Characteristics of the materials accumulating in Baltimore Harbor Channels and in the disposal areas we considered are summarized in Table 10.

Step III. Identification of Potential Dredging/Disposal Options

We evaluated five dredging/disposal options:

(1) hydraulic dredging and pipeline disposal or bucket dredging and scow disposal, overboard in areas adjacent to the channels,

(2) hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to channels,

(3) a combination of hydraulic dredging with pipeline and scow disposal techniques to create an island, either inside or outside the harbor,

(4) a combination of hydraulic dredging and scow or pipeline disposal in nearshore fringing areas to create or extend wetlands,

(5) a combination of hydraulic or bucket dredging and disposal at an unspecified upland site.

The availability of data for comparative tests of sediments in potential disposal sites is summarized in Table 9; the data themselves are summarized in Table 10. Important characteristic properties of the potential disposal sites are summarized in Table 11. The data recorded are typical values.

Step IV. Assessment of Potential Dredging/Disposal Options

We assessed the probably short-term and long-term environmental and ecological effects of each of the five dredging/disposal options using existing data, Table 12. We did not attempt to evaluate the socio-economic factors (Step IVc, Fig. 2).

With respect to environmental and ecological effects *during* dredging and disposal, there is little to choose among at least three of the five alternatives. Wetland creation and island construction may be exceptions, but even for these any adverse effects *during* dredging and disposal are expected to be transitory and small. All available data indicate that water column effects during dredging and disposal are local in extent, temporary, and small. In every disposal alternative we examined, except upland, disposal would result in the immediate burial of most of the benthic organisms. The only potential effect during dreding and disposal which we identified which we could not assess with existing data was the uptake of chlorinated hydrocarbons (CHCs) by plankton, benthos, and nekton.

The potential environmental and ecological effects *subsequent* to disposal are of greater concern because of their greater uncertainty and their greater potential for adverse impact. It is ironic that we have less information to predict the environmental and ecological effects of disposal of materials dredged from Baltimore Harbor than we do for materials dredged from Baltimore Harbor Approach Channels and particularly for those materials dredged from the Chesapeake and Delaware Approach Channel. This is a matter of concern since much of the material dredged from Baltimore Harbor is contaminated while materials dredged from the other two projects are not. The potential for adverse environmental and ecological effects are far greater for materials dredged from Baltimore Harbor than for materials dredged from either of the other projects we considered.

Metals in dredged sediment are not the principal environmental problems as is commonly supposed. All available evidence indicates that metals in dredged materials do not pose a significant threat to the environment, to the biota, or to human health if the materials are kept in a geochemical environment similar to that from which they were dredged. According to Turekian (1974) "The best-informed conclusion must be that, as far as metals are concerned, what has been deposited with the dredge spoil has little chance of leaching out of the sediment. The problems of polluted dredge spoil dumping are thus more concerned with mobilized toxic organic compounds and changes in the physical character of the substrate than with the potentially toxic heavy metals."

Since metals and other contaminants may be taken up by benthic animals, particularly by those that burrow into the sediment, appropriate choice of disposal areas can minimize any potential problems. A disposal area should be selected which minimizes the number of benthic animals that are harvested directly from the disposal area, and which minimizes the number of benthic animals that serve as food for animals that are harvested from that area or from other areas of the Bay.

Conclusions and Recommendations

We considered five dredging/disposal options for maintenance material dredged from Baltimore Harbor Channels: (1) dredging and overboard disposal in areas adjacent to the channels, (2) hydraulic dredging and pipeline disposal in confined, submerged areas adjacent to channels, (3) a combination of hydraulic dredging with pipeline and scow disposal techniques to create an island either inside or outside the Harbor, (4) a combination of hydraulic dredging with pipeline or scow disposal in nearshore finging areas to create or extend wetlands, and (5) a combination of hydraulic or bucket dredging and disposal at unspecified upland disposal sites.

Based on our evaluation of existing data on environmental effects we rank the five disposal alternatives in the following order of decreasing acceptability: (1) hydraulic dredging and pipeline disposal in confined submerged locations adjacent to Harbor channels, (2) overboard disposal adjacent to Harbor channels in unconfined locations, (3) marsh creation, (4) island construction, (5) upland disposal. On environmental and ecological grounds the first two alternatives are more acceptable than the latter three. Disposal of Harbor sediments at submerged locations within the harbor is much less likely to cause the release of associated contaminants than the latter three alternatives, each of which involves subaerial exposure of the dredged sediment. Disposal within a confined, submerged structure is preferable to unconfined overboard disposal because confinement will minimize disturbance of the dredged material, decrease the likelihood of mobilization of contaminants, and limit the return of the dredged material to the channels. This will reduce the frequency of maintenance dredging required.

We consider those options--island construction, marsh creation, and upland disposal--that result in subaerial exposure of the dredged material less desirable than submerged disposal because of the higher probability of release of the sediment-associated contaminants to surrounding water or groundwater. If the exposed part of the island were constructed entirely of uncontaminated sediments, and if the island were surrounded by an impermeable dike, many of our objections would be removed.

For contaminated materials dredged from the Harbor, disposal options should be selected which minimize the movement of the particles; the mobilization of the contaminants from the particles; and the uptake of contaminants by organisms, including people. Construction of containment/island disposal facilities is one approach to the problem. Another method is burial beneath the Bay floor and capping with clean material.

Construction of a large disposal island/containment facility is an essentially irreversible decision. It represents a permanent sacrifice of a segment of the Bay for this purpose. Because of this, and also because of the expense involved, construction of such a facility should be undertaken only after careful analysis and thorough assessment of the full range of alternatives. Environmentally and ecologically, the most compelling argument for construction of an island/containment facility is to isolate contaminants from the environment and the biota, including people. Environmental conditions should be selected which minimize both movement of the contaminated particles themselves and the release (mobilization) of the contaminants from the particles and their movement in solution. This indicates that to maximize containment of the contaminants, the contaminated particles should be confined by barriers and kept submerged beneath the surface of the Bay at all stages of the tide. If contaminated materials are deposited above the water surface a number of potential problems must be carefully evaluated. These include: (1) contaminant movement in groundwater, (2) release of contaminants by pumping action resulting from alternate wetting and drying of the materials, (3) uptake of contaminants by plants, and (4) release of contaminants in runoff.

Since construction of an island/containment facility is expensive and permanently sacrifices a segment of the Bay, the underwater storage capacity of such a facility should be reserved for contaminated materials.

There will be a continuing need to find a site suitable for disposal of contaminated materials dredged for maintenance of Baltimore Harbor channels. A proper facility would, in our opinion, be one designed and managed to accept only contaminated materials until it had been filled nearly to the water surface and one large enough to accomodate materials generated over a relatively long period of time, at least several decades. If such a facility were to be used for construction of the proposed 50 foot channel, materials that would be dredged should be assessed for their contaminant levels. If, as we expect, the more deeply-buried materials are uncontaminated, openwater disposal should be considered for these materials, reserving the containment facility for contaminated sediments. If it is desirable to extend the dredged material above the water surface to create an island, this should be done with uncontaminated materials.

Table 9 Comparative tests required by State of Maryland's Department of Natural Resources for materials proposed for dredging and for materials in proposed disposal areas. An X in the Table indicates that data exist. Wetland and upland disposal sites have not been included in the Table.

Parameter	Baltimore Harbor Channels	Overboard Areas Adjacent to Channels	Trough
Volatile Solids			X
Chemical Oxygen Demand			
Hexane Extractables	X		X
Total Organic Carbon			X
Zinc	X	X	
Mercury	X	X	
Cadmium	X	X	X
Copper	X	X	X
Chromium	X	X	X
Lead	X	X	X
Total Keldjahl Nitrogen			X
Total Phosphorous			
Chlorinated Hydrocarbons	X		X
Particle Size			X

Table 10 Characteristics of sediments accumulating in Baltimore Harbor Channels and disposal areas adjacent to Channels.

SEDIMENT CHARACTERISTICS

	Fort McHenry Channel	Brewerton Channel	Fort McHenry Disposal Adjacent to Channel	Brewerton Adjacent to Channel
Concentrations in PPM Dry Mass				
*Cr	434	139	520	188
*Cu	562	107	271	132
*Pb	270	117	241	262
*Zn	612	503	933	982
Mn	780	1754	328	1191
Ni	37	36	37	37
*Cd	1.5	1.3	3.2	2.5
*Hg	1.39	0.52	0.95	0.73
*PCB	2.7	0.06	---	---
*Chlordane	---	---	---	---
*DDT	---	---	---	---
*Kepone	---	---	---	---
Physical Properties, % Mass				
Water	---	---	---	---
*Volatile Solids	---	---	---	---
*Sand	---	---	---	---
*Silt	---	---	---	---
*Clay	---	---	---	---
Montmorillonite	---	---	---	---
Kaolinite	---	---	---	---
Chlorite	---	---	---	---
Illite	---	---	---	---
*Carbon	---	---	---	---
*Nitrogen	---	---	---	---
*Phosphorous	---	---	---	---
*Oxygen Demand	---	---	---	---
*Oils and Greases	1.1	0.12	---	---

*State of Md. Required Test ---Data not available

Table #10 Sources of Information

1. Metals Data for Baltimore Harbor Channels and Adjacent Areas from:

Villa, O. and P.G. Johnson. 1974. Distribution of metals in Baltimore Harbor sediments. Tech. Rept. #59, Annapolis, Md., Field Office, Region III, Envir. Prot. Agency., NTIS #EPA-903/9-74-012.

2. CHC and Oils and Greases Data from:

Tsai, C., J. Welch, K. Chang, J. Schaeffer, L. Cronin. 1979. Bioassay of Baltimore Harbor sediments. Estuaries 2:141-153.

Table 11 Characteristic properties of the five dredging/disposal alternatives for Baltimore Harbor Materials. The values are considered typical.

Characteristics		Areas Adjacent to Channel	Confined, Submerged Disposal Adjacent to Channel	Island Inside or Outside of Harbor	Wetland Creation	Upland Disposal
Distance from Dredging Activity						
Type of Disposal		Scow and Hydraulic Pipeline	Hydraulic Pipeline	Combination	Combination	Combination
Frequency of Maintenance Dredging Required (II)		Unchanged	Decreased	Decreased	Decreased	Decreased
Depth of Disposal Site		4 m	4 m	4 m	Intertidal†	NA
Dissolved O_2 in Near Bottom Waters	summer winter	1 mℓ/ℓ 5-6 mℓ/ℓ	1 mℓ/ℓ 5/6 mℓ/ℓ	NA	NA	NA
Salinity of Near Bottom Waters	summer winter	13 °/oo 12.5 °/oo	13 °/oo 12.5 °/oo	NA	NA	NA
Temperature of Near Bottom Waters	summer winter	25 °C 4 °C	25 °C 4 °C	NA	NA	NA
Turbulence at Disposal Site (JJ)		High	Low*	Moderate	Moderate	NA
Amount of Sediment Resuspension (KK)		Large	Small*	Small, after Vegetation	Small, after Vegetation	NA
Depth of Euphotic Zone	Summer winter			surface	surface	NA

*After enclosure of disposal area with a submerged dike

( ) See Appendices at end of report for documentation

†After completion of marsh

NA: Not Applicable

Table 12a Environmental Effects During Disposal Operations for Baltimore Harbor Material

Possible Effect	Dredging/Disposal Alternative: Areas Adjacent to Channel	Confined, Submerged Disposal Adjacent to Channel	Island Inside or Outside of Harbor	Wetland Creation	Disposal
Excess Turbidity in Water Column* (LL)	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local	Negligible
Increase in Contaminant Releases to Water Column* (MM)					
Metals	Negligible	Negligible	Negligible	Negligible	Negligible
Nutrients	Negligible	Negligible	Negligible	Negligible	Negligible
CHCs	Possible	Possible	Possible	Possible	Possible
Oxygen Depletion of Water Column* (NN)	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local	Temporary and Local

*For Fringing Areas, read to (of, in) nearby open waters.
For Upland Disposal, read to (of, in) nearby open waters and groundwater.

( ) See Appendices at end of report for documentation.

Table 12b Ecological Effects *During* Dredging/Disposal Operations

Possible Effect	Areas Adjacent to Channel	Confined Submerged Disposal Adjacent to Channel	Island Inside or Outside of Harbor	Wetland Creation	Upland Disposal
	Dredging/Disposal Alternative — Intensity of Effect				
Increased Turbidity (OO)					
1. Phytoplankton (suppression of photosynthesis)	Temporary and Local Negligible	Temporary and Local Negligible	Temporary and Local Fringing Areas	Negligible; new habitat	NA
2. Zooplankton	Negligible	Negligible	Negligible; new habitat	Negligible; new habitat	NA
3. Nekton (clogging of gills, etc.)	Negligible	Negligible	Negligible; new habitat	Negligible; new habitat	NA
4. Benthos (clogging of gills, etc.)	Negligible	Negligible	Negligible; new habitat	Negligible; new habitat	NA
5. Rooted Aquatic Plants	Negligible	Negligible	Negligible; new habitat	Possible	NA
Smothering of Benthos (PP)	May be complete; temporary	May be complete; temporary	Complete and permanent	May be complete; new habitat	NA
Exclusion and/or (QQ) Attraction of Fish	Either; temporary and local	Either; temporary and local	Either; new habitat	Either; new habitat	NA
Uptake of Contaminants (RR)					
1. Metals					
a. Benthos	Negligible	Negligible	Negligible	Negligible	NA
b. Plankton	Negligible	Negligible	Negligible	Negligible	NA
c. Nekton	Negligible	Negligible	Negligible	Negligible	NA
2. CHCs					
a. Benthos	Possible	Possible	Possible	Possible	NA
b. Plankton	Possible	Possible	Possible	Possible	NA
c. Nekton	Possible	Possible	Possible	Possible	NA

NA: Not Applicable

( ) See Appendices at end of report for documentation.

Table 12c Environmental Effects *Subsequent* to Disposal

Possible Effect	Areas Adjacent to Channel	Confined Submerged Disposal Adjacent to Channel	Island Inside or Outside of Harbor	Wetland Creation	Upland Disposal
	Dredging/Disposal Alternative — Intensity of Effect				
Increased Turbidity in Water Column* (SS)	Possible	Negligible	Negligible	Negligible**	Negligible
Increased Contaminant Release to Water Column* (TT)					
1. Metals	Unlikely	More unlikely	Possible	Likely	Possible
2. Nutrients	Small	Small	Larger	Small	Larger
3. CHCs	Possible	Possible	Possible	Possible	Possible
Oxygen Depletion of Water Column* (UU)	Undetect-able	Undetectable	Undetectable	New Habitat	Undetectable
Movement of Dredge Material After Disposal (VV)	Likely	None	None	Negligible**	None
Effect of Changes of Bottom Topography (WW)					
1. Circulation	Negligible	Possible	Possible	Locally Large	None
2. Uses (fishing and boating)	Negligible	Possible	Possible	Locally Large	None

*For Fringing Areas, read to (of, in) nearby open waters.
For Upland Disposal, send to (of, in) nearby open waters or groundwater.

**After stabilization with marsh plants

( ) See Appendices at end of report for documentation.

Table 12d Ecological Effects Subsequent to Disposal

Possible Effect	Areas Adjacent to Channels	Confined Submerged Disposal Adjacent to Channels	Island Inside or Outside of Harbor	Wetland Creation	Upland Disposal
	Dredging/Disposal Alternative — Intensity of Effect				
Time for recovery benthos (XX)					
1. Biomass	<1.5 yr	<1.5 yr	No recovery	No recovery	---
2. Diversity	<1.5 yr	<1.5 yr	No recovery	No recovery	---
Increased uptake by organisms (YY)					
1. Metals					
(a) Benthos	Possible	Possible	Possible; around fringes	Possible	Unlikely
(b) Plankton	Unlikely	Unlikely	Possible	Possible, but small	N/A
(c) Nekton	Unlikely	Unlikely	Possible	Possible, but small	N/A
(d) Emergent and Submergent Grasses	Unlikely	Unlikely	Possible	Possible	N/A
(e) Terrestrial Plants	N/A	N/A	Possible	Unlikely	Possible
2. CHCs					
(a) Benthos	Possible	Possible	Possible	Possible	Unlikely
(b) Plankton	Possible	Possible	Possible	Possible	Unlikely
(c) Nekton	Possible	Possible	Possible	Possible	Possible
(d) Emergent and Submergent Grasses	Unlikely	Unlikely	Possible	Possible	Possible
(e) Terrestrial Plants	Unlikely	Unlikely	Possible	Possible	Possible

( ) See Appendices at end of report for documentation.

APPENDIX A

Degree of Turbulence at Proposed Disposal Sites for Chesapeake and Delaware Canal Approaches Materials (Table 3).

Bottom water turbulence originates from three sources of energy input: wind waves, tidal forces, and laden ships' wake. Two of these, wind waves and ships' wake, have their origin at the water surface. Tidal energy is transmitted throughout the water column. Because wave energy becomes less intense as depth increases, bottom waters in deeper areas are subject to less wave induced turbulence than shallower areas. It is quite rare that wind waves generated in Chesapeake Bay have the ability to affect bottom waters in the deep trough (average depth 30 m), but wind waves must frequently affect bottom waters in the shallow (average depth 4 m) waters of the northern Bay.

An additional source of turbulent energy to the bottom waters of the northern Bay is the wake resulting from the passage of heavily laden ships. These waves, 1 to 2 m in height, propagate longitudinally in the estuary from the channel, and have the ability to significantly stir bottom waters.

Tidal forces cause an oscillatory flow in both the shallow waters of the overboard disposal areas of the northern Bay and the bottom waters of the deep trough. During the approximately six hours of the ebb half-tidal cycle, the flow is directed down the Bay toward the ocean, while during the flood, half-tidal cycle the flow is directed toward the head of the Bay. Except in the upper Bay, during periods of high river inflow, these tidal flows are large (on the order of five to ten times the flows required to move the fresh water seaward) and density driven two-layered estuarine flow results. Winds, both local winds blowing on the surface waters of the upper Bay and the mid-Bay, and remote winds blowing over the lower reaches of the Bay and even on the continental shelf produce aperiodic currents in the upper and mid-Bay which at times approach the speed of the pure tidal currents.

The magnitudes of the peak ebb and flood velocities in the shallow overboard disposal areas of the upper Bay and those in the near bottom waters of the deep trough are very similar; about 40 to 50 cm per second. However, because the frictional effects of the side boundaries of the narrow trough are added to the effects of bottom friction, the tidal velocities in the turbulent boundary layer within about one meter of the bottom in the trough are less than those in the same layer above the bottom in the shallow overboard disposal area. Also, the wind induced currents which sometimes add to the flood flow and sometimes add to the ebb flow are stronger in the shallow waters of the overboard disposal areas of the upper Bay than in the deep waters of the trough. Note that this effect of the wind is quite distinct from the turbulence induced by wind generated waves. In any case, the tidal currents, and even more particularly, the combined tidal and wind currents, result in more resuspension of the bottom sediments in the shallow overboard disposal areas of the upper Bay than in the deep trough below the Bay Bridge.

The bottom waters of the northern Chesapeake Bay are more turbulent than the bottom waters of the central Bay because their shallow depth makes them susceptible to two sources of turbulence, wind waves and ships wake, which do not affect deeper bottom waters in the central Bay.

APPENDIX B

Amount of Sediment Resuspension at Proposed Disposal Sites for Materials Dredged from Chesapeake and Delaware Canal Approach Channel (Table 3)

Bottom sediment resuspension is determined by the degree of near-bottom turbulence and the shear strength of the surficial sediments. The shear strength is determined by a variety of factors, including grain size, state of particle agglomeration, and water content. Agglomeration of sediment grains is the result of activities of microorganisms in the sediment that secrete mucoid films which bind sedimentary particles (Rhoads, et al., 1978), of filter feeding organisms on the bottom and in the water column, and of physico-chemical processes (flocculation) that bind particles together. These agglomerates may be broken down by the feeding activities of burrowing organisms, principally protobranchs, tube worms, and other organisms living at or near the sediment-water interface, which act to stabilize the surface and enhance its resistance to erosion. Erodability of sediment is thus a complicated function of particle size and benthic community structure.

Although sediments in the deep trough and upper bay disposal areas are similar in their basic textural properties--both are fine-grained--observational evidence (Schubel, unpublished data) indicates a given tidal current speed, less sediment is resuspended in the trough than in the upper bay. This effect may be due to a difference in benthic community structure at the two locations. Few data are available to establish this however. Because the sedimentation rate in the trough is an order of magnitude less than the rate in the upper reaches of the Bay (Schubel and Carter, 1977) surficial sediments in the trough have had an order of magnitude more time available to become agglomerated and stabilized than upper bay sediments--assuming the rates of binding are similar. Equally important, the energy available from wind waves for sediment resuspension in the trough is significantly less (see Appendix A) than in the upper Bay because of the trough's much greater depth.

Although the processes that control the long term stability of sediments at the two proposed disposal sites remain obscure, observations show that in addition to being more resistant to erosion, the sediments of the trough are subject to less intense erosional forces. Bottom sediment resuspension is a much more important geological process in the northern Bay than in the trough.

References

Rhoads, D.C., P. McCall, J.Y. Yingst. 1978. Disturbance and Production on the Estuarine Seafloor. American Scientist 66:577-583.

Schubel, J.R. and H.Y. Carter. 1977. Suspended sediment Budget for Chesapeake Bay, Vol. 2 *in* M. Wiley, (ed.), Estuarine Research: Recent Advances, Academic Press. 250 pp.

APPENDIX C

Effects of Disposal Options on the Frequency of Dredging Required to Maintain the Chesapeake and Delaware Approach Channel. (Table 3).

An undetermined, but probably significant, fraction of the dredged materials disposed overboard alongside the channel in the upper Bay is returned to the Channel as a result of resuspension and fluid mud flow. Disposal of the dredged material completely outside of this area, or in confined areas, would eliminate return of this sediment to the channel and therefore decrease the frequency of dredging required to maintain the Chesapeake and Delaware Approach channel. The decreased cost of dredging would at least partially offset the added costs of disposal.

APPENDIX D

Extent of Excess Turbidity Generated During Disposal Operations. (Table 4a)

Schubel et al. (1978) have considered in detail the extent of turbidity generated by open-water pipeline disposal operations. Of the material discharged during disposal, between 90% and 99% by mass settles directly to the bottom as a density flow. Excess turbidity plumes therefore contain only between 1 and 10% of all the material dredged and discharged. The spatial extent of the dredged material plume is determined by the mean grain size of the sediment, the depth of the water, and the dispersal characteristics of waters at the disposal site.

During a pipeline dredging operation in the upper Chesapeake Bay in 1966, Biggs (1970) observed that the concentration of total suspended sediment in the turbidity plume fell to less than 50 mg/ℓ within 3.5 km of the discharge. Since this was *total*, not excess, suspended sediment, the actual size of the plume produced by the discharge was less than this. Theoretical calculations (Wilson, 1979) substantiated by field measurements (Schubel et al., 1978) using the mean grain size of sediments from upper Chesapeake Bay, indicate that six hours after disposal operations cease, maximum concentrations in the turbid plume would have dropped to one-tenth their initial values. Twelve hours later these values would be one-hundredth the levels at six hours. This same theory can predict the spatial and temporal extent of turbidity plumes generated by open water pipeline disposal *before* a dredging project is undertaken, for a wide variety of conditions. This is a valuable tool for managers; one which can be used to predict the local influence of excess turbidity in the disposal area. Field observations obtained to verify this model in several estuaries showed that while the spatial extent of turbidity varied with local conditions, it never exceeded 1 km^2 and the area of highest turbidities was usually less than 1/10 this area.

Gordon (1974) considered the turbidity effects and dispersion of dredged materials dumped into nearshore waters by scow and hopper dredge. He concluded that 99% of the mass of material rapidly reaches the bottom as a density current. Three stages in scow disposal of dredged materials have been recognized (Bokuniewicz et al., 1978): descent, impact, and surge. Dredged materials released into the receiving waters fall either as a high density current of dispersed particles or as large sediment aggregates or "clods" which fall at nearly constant velocity and entrain large volumes of water. The impact point of this sediment jet can be predicted with good accuracy if the ambient current structure is known. Because much of the initial potential energy of the dredged material is used up in accelerating entrained water, the density jet strikes the bottom with relatively little kinetic energy and produces only a small impact. A radial bottom surge is created by the impact of the dredged material in the form of a density current. The greatest thickness of this surge has been found to be about 15% of the water depth. The radius of the surge is between 150 and 300 m from the point of impact and deposition begins to occur about 100 m from the impact area.

The characteristics of the disposal pile and the effect upon the water column are mostly determined by the mechanical properties of the dredged material, the speed at which the material is discharged into the water, the water depth, and the current in the receiving waters. The kind of dredge has a major effect on the mechanical properties of the sediment after dredging and disposal. Mechanical dredging alters the *in-situ* mechanical properties of material less than hydraulic dredging. It is important that the less cohesive the dredged materials are, the greater the surface/volume ratio of the deposited pile will be. Strong currents do not result in a dispersion of the dredged materials during disposal and they are not necessarily a cause of inaccurate placement in a designated area.

After disposal, residual turbidity in the water column amounts to less than 1% of the total amount of material discharged. This material settles from suspension over a period of several hours and may drift with tides and currents during that time.

References

Biggs, R.B. 1970. Project A, Geology and hydrography. Pages 7-15 *in* Gross Physical and Biological Effects of Overboard Spoil Disposal in Upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Bokuniewicz, J. Gebert, R.B. Gordon, J. Higgins, P. Kaminsky, C. Pilbeam, M. Reed, G. Tuttle. 1978. Field study of the mechanics of the placement of dredged material at open-water disposal sites. V.1 Main Text and Appendices A-1. U.S.A.C.E. Dredged Material Research Program Tech. Rept. D-78-7. 99pp with Appendices.

Gordon, R.B. 1974. Dispersion of dredge spoil dumped in nearshore waters. Est. Coast. Mar. Sci. 2:349-358.

Schubel, J.R., H.H. Carter, R.E. Wilson, W.M. Wise, M.G. Heaton, and M.G. Gross. 1978. Field investigations of the nature degree and extent of turbidity generated by open-water pipeline disposal operations. Tech. Rept. D-78-30, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wilson, R.E. 1979. A model for the estimation of the concentrations and spatial extent of suspended sediment plumes. Est. Coast. Mar. Sci. 9:65-79.

APPENDIX E

Contaminant Releases to Water Column During Disposal of Material Dredged From Chesapeake and Delaware Canal Approach Channel (Table 4c).

1. Metals

No significant release of metals has ever been observed during aquatic disposal operations in the U.S. (Wright et al., 1978). The chemical equilibria that govern the solubility of metals in the presence of sediment do not appear to be affected by the disposal process. This is partly because of the rapidity of descent and consolidation of the dredged materials which provide limited time for oxidation. It is also because of the variety of chemical mechanisms that are responsible for the strength of the sediment-metal binding relationships.

Metals become bound to fine-grained sediments principally by three mechanisms: (1) they become bound to sediment-associated organic matter, (2) they precipitate as insoluble sulfide compounds under reducing conditions, and (3) they co-precipitate with those metals (Fe and Mn) that are insoluble under oxidizing conditions. It appears that the generally extremely low dissolved metals concentrations in nearshore waters are the result of these effects (Turekian, 1977).

Because the dredged materials under consideration here contain metals concentrations that are not significantly elevated over the metals levels in sediments naturally accumulating in the proposed disposal areas, and because geochemical theory can adequately explain the field results which show essentially no metals released to solution during disposal operations, such release should not be considered an environmental hazard at the locations under consideration in this report.

According to Turekian (1974), "The best-informed conclusion must be that as far as metals are concerned, what has been deposited with the dredge spoil has little chance of leaching out of the sediment. The problems of polluted dredge spoil dumping are thus more concerned with mobilized toxic organic compounds and changes in the physical character of the substrate than with the potentially toxic heavy metals."

2. Nutrients

Only minor nutrient releases have been observed during open water disposal operations (Wright et al., 1978). These are associated with dilution of the dredged material pore waters during disposal. The extent of nutrient increases, where observable, was always confined to the spatial extent of the turbidity plume. Flemer (1970) investigated the release of nutrients from an open-water pipeline disposal operation for material dredged from the C & D Approach Channel between November 1965 and November 1968. He reported that total phosphate and nitrogen levels were increased by factors of 50 and 1,000 respectively, but that the increases were local and did not persist.

Excess nutrient levels in the water column may have two effects: to increase plankton biomass by stimulating primary productivity, and to poison organisms by high nutrient levels, especially of NH_4.

Biostimulation is probably prevented from occurring by reduced light levels associated with increased turbidity during disposal. Flemer's (1970) investigation in the upper Bay did not show any detectable effects of increased nutrient levels on primary productivity. Nutrients released during disposal operations have never been observed to reach levels toxic to water column organisms, plankton or nekton.

3. CHCs

The interaction of chlorinated hydrocarbons with abiotic and biotic constituents of the marine ecosystem is enormously complex and cannot be evaluated from fundamental physical and biochemical considerations at the present time. Experiments designed to determine the relative rate of release of CHC compounds from dredged sediment (Fulk et al., 1975) have failed to detect significant correlation between such release and standard environmental factors (temperature, salinity, pH, dissolved 0_2). Because of this, most investigators have adopted the use of an empirical distribution coefficient K_1 where K is the ratio of the concentration of CHCs in two phases; usually a biotic or sediment phase (numerator) and in solution (denominator) (Pavlou and Dexter, 1979; Dexter and Pavlou, 1978; Faust, 1978; Choi and Chen, 1976). Although K has not been determined for Chesapeake Bay sediment, typical values for other estuaries approximate 10^4. Persistent release from sediment may occur if dissolved CHC concentrations are less than this factor smaller than sediment values. Since the average PCB concentration per gram of upper bay bottom sediment is 0.9×10^{06} and in water 0.1×10^{-12} (Munson, 1975), K is exceeded and release of CHCs to solution during dredging and disposal operations may be possible.

These results suggest that caution must be exercised in the disposal of dredged materials highly contaminated with CHCs, but provide little information to evaluate strategies designed to minimize CHC release during dredging and disposal. The distribution coefficient between dissolved and solid phases is probably low enough so that CHC release to water will occur with relatively uncontaminated upper Bay sediment. Because it is an equilibrium process, release may be minimized by providing minimum dilution of sediment during dredging. We make, therefore, two recommendations. First, that the K value for water-sediment interaction in the Chesapeake Bay be determined, preferably for each dredging project. We also recommend that the feasibility of clamshell dredging be studied in both the upper bay and other dredged areas, since this type of dredging minimizes the dilution of dredged sediment.

References

Choi, W.W. and K.Y. Chen. 1976. Associations of Chlorinated Hydrocarbons with Fine Particles and Humic Substances in Nearshore Surficial Sediments. Envir. Sci. Tech. 10:782-786.

Dexter, R.N. and S.P. Pavlou. 1978. Distribution of stable organic molecules in the marine environment: physical chemical aspects. Chlorinated Hydrocarbons. Mar. Chem. 7:67-84.

Flemer, D.A. 1970. Project B, Phytoplankton. Pages 16-25 *in* Gross Physical and Biological Effects of Overboard Spoil Disposal in Upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Fulk, R., D. Gruber and R. Wallschleger. 1975. Laboratory study of the release of pesticide and PCB materials to the water column during dredging and disposal operations. Contract Report D-75-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Pavlou, S.P. and R.N. Dexter. 1979. Distribution of PCB in Estuarine Ecosystems. Testing the concept of equilibrium partitioning in the Marine Environment. Envir. Sci. Tech. 13:65-76.

Turekian, K.K. 1977. The fate of metals in the oceans. Geochem. Cosmochem. Acta. 41:1139-1144.

Turekian, K.K. 1974. Heavy metals in estuarine systems. Oceanus 18:32-33.

Wright, T.D., D.B. Mathis, J. Brannon. 1978. Aquatic Disposal Field Investigations: Galveston, Texas Offshore Disposal Site, U.S.A.C.E. Dredged Material Research Program Tech. Rept. D-77-20. 89pp.

APPENDIX F

Oxygen Depletion of Water Column During Disposal of Material Dredged from the Chesapeake and Delaware Canal Approach Channels (Table 4a).

Oxygen depletion of the water column during dredged material disposal operations is caused by the chemical oxidation of reduced compounds such as FeS which are normally abundant in fine-grained estuarine sediments. Bacterial action is too slow to measureably affect the water column during disposal operations (Gross et al., 1976). Numerous field investigations of the disposal of dredged materials at various localities including: Columbia River (Boone et al., 1978); Galveston Bay (Wright et al., 1978); Atchafalaya estuary, Corpus Christi Bay and Appalachacola Bay (Schubel et al., 1978); and upper Chesapeake Bay (Gross et al., 1976; Cronin and Gross, 1976) have established that depletion of dissolved oxygen during dredging/disposal operations is confined approximately to the spatial and temporal extents of the associated turbidity plume (see Appendix N).

Gross et al. (1976) compared the calculated oxygen demand resulting from dredged material disposal in upper Chesapeake Bay with the quantity of oxygen available in the water affected by the disposal operation. Their results showed that for dredged material with an initial oxygen demand of 300 g/m^3 of sediment and a final demand of 75 g/m^3 of sediment (measured values for upper bay sediments, see Table #2) there was, under "worst case" conditions, enough oxygen in a disposal area of 2.56 km^2 (1 mi^2) with an average depth of 3.5 m (10 ft) to satisfy 48 days of continuous discharge of dredged materials at a rate of 1000 m^3/hr. Worst case conditions were defined to be typical, low summer dissolved oxygen levels and no importation of dissolved oxygen into the disposal area either from the atmosphere or from contiguous segments of the Bay.

If more reasonable conditions are considered, including tidal mixing, the oxygen supply of the disposal area is more han 8,000 times the total oxygen demand associated with the dredged materials. If the water column is well mixed, the oxygen sag associated with the discharge would be virtually undetectable. Conditions in the middle Bay are even more favorable because of the greater depth which provides more opportunity for dilution during discharge. Also, the deepest water in the trough south of the Annapolis Bay Bridge becomes naturally anoxic in the summer time. Disposal of dredged sediment into this area at this time would probably have no effect upon the oxygen levels near the bottom. The effect on upper water layers remains unevaluated.

The spatial scale of oxygen depletion during disposal operations is of the order of km^2 and the temporal scale is limited to hours after disposal stops. Because of the semi-diurnal nature of the tidal currents in Chesapeake Bay, the turbidity plume and the associated plume of oxygen depression shift location every six hours with a new plume forming on each ebb and flood tide. The area affected by the old plume recovers approximately to background pre-disposal, oxygen levels within hours after tide turns.

The extent of water column oxygen depletion is partially determined also by the type of disposal operation used. Pipeline disposal, which tends to create a more dilute, slowly settling, turbidity jet than hopper disposal, will probably have a somewhat greater effect on water column oxygen concentrations. This is because the greater sediment transit time from the water surface to the bottom allows more sediment oxidation which utilized dissolved oxygen. Also, the greater surface area of the resultant pipeline deposit will create a greater oxygen demand on the overlying waters.

References

Boone, C.G., M.A. Granat, M.P. Farrell. 1978. Aquatic disposal field investigations; Columbia River Disposal Site, Oregon. Tech. Rept. D-77-30 U.S.A.C.E., Dredged Material Research Program.

Cronin, W. and M.G. Gross (1976). Environmental effects of hydraulic dredging operations in Northern Chesapeake Bay. Approaches to Chesapeake and Delaware Canal (Pearce Creek Onshore Disposal) 14 Feb.-17 March 1976. Final Report to State of Md. Dept. Natural Res. Open File Report #7, Chesapeake Bay Inst., Johns Hopkins University, 25pp with Appendices.

Gross, M.G., W. Taylor, R. Whaley, E. Hartwig and W. Cronin. 1976. Environmental effects of dredging and dredged material disposal, Approaches to Chesapeake and Delaware Canal, Northern Chesapeake Bay. Open File Report #6, Chesapeake Bay Inst., Johns Hopkins University. 87pp plus Appendices.

Schubel, J.R., H.H. Carter, R.E. Wilson, W.M. Wise, M.G. Heaton, and M.G. Gross. 1978. Field investigations of the nature, degree, and extent of turbidity generated by open-water pipeline disposal operations. Tech. Rept. D-78-30, U.S.A.C.E. Dredged Material Research Program.

APPENDIX G

Ecological effects of increased water column turbidity during disposal of Chesapeake and Delaware Canal Approaches Material (Table 4b).

1. Phytoplankton

Reductions in incident illumination and the consequent possible decrease in phytoplankton photosynthetic activity as the result of increased water column turbidity are confined to the temporal and spatial limits of the turbidity plume. Because this plume is transitory and local (see Appendix D) in extent, associated decreases in phytoplankton photosynthesis are also temporary and local. It is highly unlikely that the small area affected by the increased turbidity caused by disposal operations can have more than a negligible effect on the total estuarine phytoplankton primary production (Flemer, 1970).

2. Zooplankton

The temporary and local nature of the turbidity plume associated with dredged material disposal (see Appendix D) limits any effect upon zooplankton to a small area. Estuarine zooplankton must already be adapted to coping with levels of suspended sediment similar to those found over much of the excess turbidity plume from dredged material disposal (Goodwyn, 1970).

3. Nekton

The generally small area that is temporarily affected by excess turbidity during dredged material disposal can have no more than a negligible effect on nekton populations in the estuary (Dovel, 1970).

4. Benthos

The generally small area that is temporarily affected by excess turbidity during dredged material disposal can have no more than a negligible impact on benthic populations outside of the immediate disposal area (Pfitzenmeyer, 1970).

5. Fish Eggs and Larvae

Numerous studies (Schubel and Wang; 1973, Sherk et al.; 1970, Auld and Schubel; 1978) have indicated that the survival of eggs and larvae of typical estuarine fishes (yellow perch, blueback herring, alewife, American shad, white perch, striped bass) are not significantly decreased by exposure to suspensions of natural fine-grained relatively uncontaminated sediments with concentrations much greater than those typically observed, even during dredging and disposal. Based on these studies we conclude that the excess concentrations of suspended sediment that result from dredging and disposal of relatively uncontaminated sediments do not represent a significant hazard to fish eggs and larvae as far as acute effects are concerned. Chronic effects have, however, not been adequately investigated.

References

Auld, H.H. and J.R. Schubel. 1978. Effects of suspended sediment on fish eggs and larvae: a laboratory assessment. Est. Coast. Mar. Sci. 6:153-164.

Flemer, D.A. 1970. Project B, Phytoplankton. Pages 16-25 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Goodwyn, F. 1970. Project D, Zooplankton. Pages 39-41 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Pfitzenmeyer, H.T. 1970. Project C, Benthos. Pages 26-38 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Richie, D.E. 1970. Project F, Fish. Pages 50-63 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Material Resources Inst., Special

Rept. #3, Ches. Biol. Lab., Univ. of Md.

Schubel, J.R. and J.C.S. Wang. 1973. The effects of suspended sediment on the hatching success of *Perca flavescens* (yellow perch), *Morone americana* (white perch), *Morone saxatilis* (striped bass) and *Alosa pseudoharengus* (alewife) eggs. Special Rept. #30, Chesapeake Bay Inst., Johns Hopkins University, Ref. 73-53, 77pp.

Sherk, J.A. and L.E. Cronin. 1970. the effects of suspended and deposited sediments on estuarine organisms. An annotated bibliography of selected references. Univ. of Md., National Res. Inst., Ref. 70-19, 61pp + Addendum.

APPENDIX H

Smothering of benthos by disposal at proposed sites of materials dredged from the Chesapeake and Delaware Canal Approach Channel (Table 4b).

At the submarine disposal sites considered in this section smothering of benthos by the disposal of dredged material will probably be complete. Recolonization will occur relatively rapidly, however (see Appendix P).

The trough has a lower density and a lower diversity of benthic organisms than the overboard area adjacent to the Chesapeake and Delaware Approach Channel. The benthic assemblage in the trough is essentially eliminated every summer by the anoxic, or nearly anoxic, conditions that characterize its near-bottom waters (H. Pfitzenmeyer, Personal Communication, 1980).

APPENDIX I

Exclusion/Attraction of Fish at C & D Approaches Alternatives (Table 4b).

During disposal operations attraction of local finfish to the turbidity plume has been occasionally observed. This attraction has been attributed to releases of particulate organic matter associated with the dredged material which serve as a food source for the fish. Finfish have also been observed to be repelled by the turbidity plume, perhaps in response to the generally lowered dissolved oxygen levels in its immediate vicinity. Generally it has been observed that fish are more sensitive to oxygen depletion than to excess turbidity, and appear to be repelled from the disposal area before encountering the high turbidity levels located within the plume. Because of this defensive mechanism, and also because of the limited area strongly affected by increased turbidity during disposal (see Appendix D), disposal operations do not pose a threat to resident finfish populations at locations where sufficient space is available to enable fish to avoid the plume. This is true for all the locations under consideration in this report.

APPENDIX J

Uptake of contaminants by biota during the disposal of Chesapeake and Delaware Canal Approach Channel materials at proposed disposal sites (Table 4b).

1. Metals

Because the release of soluble metals during disposal operations is considered unlikely (see Appendix E), uptake of metals by benthos, plankton, and nekton at either disposal location will be negligible.

2. CHCs

Because the release of soluble CHCs during disposal is considered possible (see Appendix E), their subsequent uptake by benthos, plankton, and nekton is possible at either disposal location.

APPENDIX K

Excess turbidity in water column subsequent to disposal of material dredged from the Chesapeake and Delaware Canal Approach Channel (Table 4b).

Potential environmental impacts of excess turbidity resulting from resuspension of sediment from dredged material piles include the reduction in the penetration of sunlight, clogging of filter feeding benthos and nekton with excess sediment, and interference of movement of nekton. Concern about these possible effects arises because for some period after disposal, material in the disposal pile is more susceptible to resuspension than the surrounding bottom, and could become a persistent local source of excess turbidity.

Immediately after disposal, a dredged material pile contains significantly ($\sim$ 20%) higher amounts of pore water than the surrounding, naturally deposited, sediments. This, combined with its positive relief, makes the disposal pile more susceptible to disturbance by wind waves and tidal currents than the surrounding bottom. The possible significance to the biota of this added source of turbidity and suspended sediment must be put into perspective in assessing its possible environmental and ecological effects by considering (1) the point of introduction of this turbidity relative to the location of the important organisms in the disposal area, and (2) its magnitude relative to natural variation in turbidity at the particular disposal site.

Although the dredged material pile has positive relief, its height composes a small to insignificant fraction of the water column at either disposal location (see Appendix O). A 1.5 m high mound in the disposal area in the upper Bay represents about 25% of the average water depth and less than 5% of the water depth in the trough. The point of introduction of any excess turbidity is therefore essentially the same as that for the surrounding water--the ambient Bay bottom. Observations of the periodic resuspension of bottom sediment in the Chesapeake Bay (Schubel, 1972) by tidal currents show that the effect of excess turbidity usually reaches no closer than within 2 m of the water surface in the upper bay and no closer than 20 m of the surface in the trough of the middle Bay. There is no reason to suspect that the dredged material would be resuspended significantly higher into the water column than sediments naturally accumulating on the surrounding bottom since their textures are similar (Table 2). Examination of the typical euphotic depths (Table 3) in the potential disposal areas suggests that resuspension of dredged materials would have little effect on primary production.

The shallow and variable euphotic depths in the Chesapeake Bay are the result of persistent and variable natural turbidity. Organisms adapted to migrating through the Bay (nekton), and living on its bottom (benthos), must be accustomed to these conditions. Although it is impossible to accurately predict what the magnitude of excess turbidity at the disposal sites would be, it is unlikely that significant excess turbidity could be generated for a prolonged period of time. As the more readily erodable fractions are removed and as the pile consolidates, an equilibrium of erosion resistance will be reached. If the location is carefully chosen so as to minimize turbulence, desirable for other reasons as well (see Appendix L), excess turbidity will be minimized.

Because of the high and variable natural levels of turbidity at the disposal sites under consideration in this section, we consider any excess turbidity generated by the disposal pile to be negligible.

Reference

Schubel, J.R. 1972. Distribution and transportation of suspended sediment in upper Chesapeake Bay. Pages 151-167 *in* Geol. Soc. Am. Memoir #133 P:151-167.

APPENDIX L

Evaluation of possible contaminant releases to water column subsequent to disposal of material dredged from Chesapeake and Delaware Approach Channel at various disposal options.

1. Metals (Table 4b)

Most of the metals of environmental concern are bound to sedimentary particles as reduced compounds. The solubility of these compounds is determined mostly by the dissolved oxygen level of the water in immediate contact with the particles. Strategies for keeping sediment-associated metals within the dredged material pile should maintain the reducing character of the sediment's interstitial waters. Geochemical theory indicates that the release of metals subsequent to disposal by chemical solubilization is unlikely if the reducing character of the pore waters is maintained.

The vast bulk of all sediment contained within the disposal pile will be surrounded by its own interstitial waters; only a thin surface layer will be in contact with overlying waters. In fine-grained estuarine sediments typical of the dredged materials considered here, pore waters develop a chemical micro-environment determined largely by the interaction of various sediment-associated constituents, principally organic compounds, and their sulfur-containing degradation products. The conditions of this environment approach an oxygen free state indicating the large capacity of the sediments to sequester oxygen. Under these conditions, the formation of reduced insoluble sulfur-metal compounds is favored, and most metals, with the exception of iron and manganese, become bound to the sediment as insoluble sulfides. Iron and manganese, which form soluble reduced compounds in the interstitial waters, migrate to the top of the sediment pile and have been shown to diffuse into the near-bottom waters. This is a natural process that is widespread in estuaries containing fine-grained sediment (Matisoff et al., 1975), (Turekian, 1977).

There are no data to suggest that once compaction of the spoil pile is complete the diffusive flux of iron and manganese to the overlying waters will be either enhanced or retarded relative to the natural rate before dredging and disposal. This is because a principal determinant of the diffusivity of the pore waters, the sediment grain size, will be unchanged (see Table #2). The possibility exists that during a period of several months after disposal the expulsion of sediment pore waters from the sediment pile will enhance the flux of dissolved Fe and Mn (and nutrients) to the near bottom waters. As calculated in appendix m, compaction of a disposal pile containing 0.75×10^6 m^3 (1×10^6 yds^3) of dredged material will release 1.8×10^9 g of pore waters. If these contain 100 PPM Mn (average values for Chesapeake Bay Sediments), 1.8×10^5 g of soluble Mn are released. This is almost certainly an over-estimate since a significant fraction of this Mn will precipitate as insoluble hydroxides on the sediment water interface, and will not be dissolved. If this were to totally dissolve into the waters of the upper Bay ($\approx 3.8 \times 10^{12}\ell$), it would result in a Mn concentration of 4.7×10^{-8} g/ℓ or 4.7×10^{-5} PPM--an undetectable increase. If this amount were to be dissolved into a disposal area of 2.56 km^2 (1 mi^2) with an average depth of 3.5 m (10 ft), the increase in the concentration of Mn would still be only 1.9×10^{-5} g/ℓ or 1.9×10^{-2} PPM.

Geochemical theory indicates that the sequestering of metals within the disposal pile will be complete if reducing conditions are maintained. Observations of turbulence and sediment resuspension at the two locations under consideration as disposal sites indicates that the disposal pile would be less likely to be disturbed in the deeper waters of the trough south of the Bay Bridge at Annapolis. For this reason, the trough is preferable with regard to the long term sequestering of metals. Release of metals from sediment disposed in the upper Bay is, however, also unlikely.

The extent of contamination of the sediments naturally accumulating in the northern Chesapeake Bay, including those in the C & D Approach Channel, is determined by an equilibrium between the sediment sources, mostly the Susquehanna River, and the physico-chemical conditions found at the site of deposition. Because the bottom waters in the upper Bay are more turbulent and more highly oxygenated than they are in the trough site, materials accumulating in the Chesapeake and Delaware Approach Channel have already adjusted to conditions less favorable to the retention of metals than are found in the trough south of the Bay Bridge at Annapolis. The geochemical equilibria that control metals solubility in a sediment column favor retention of metals in the bottom sediments of the upper Bay and are even more favorable in the trough.

2. Nutrients

The processes that control the rate of nutrient regeneration from sediments are the rate of bacterial decay of organic matter in sediments, the grain size of the sediments, the rate of physical and biological reworking, and the sedimentation rate. Nutrient profiles in the pore waters of undisturbed sediments develop in response to an equilibrium between the diffusional flux and the rate of production at depth. Benthic regeneration of nutrients is an important natural process that supplies a large portion of the nutrients required for primary production in many estuaries. As with similar arguments made under part (1) of this appendix for dissolved iron and manganese, there is no reason to believe that the regenerative flux of nutrients ($NO_3^{=}$, $PO_4^{=}$, NH_3) from the dredged material pile will be different from that naturally occurring in the sediments around the pile, after compaction of the pile has taken place. During the compaction process, the fluxes of nutrients will be enhanced. The magnitude of enhancement can be placed into perspective by comparing it with the natural nutrient regeneration rate.

Ammonia, as NH_4 is the principal species of dissolved nitrogen in reducing sediments which contain an average of 2-3 m mol NH_4. Typical NH_4 regeneration rates from fine-grained reducing sediments average 872 μ mol/m^2/d^1 (Hartwig, 1976). The compaction of 0.8 x $10^6 m^3$ of (1 x $10^6 yd^3$) of dredged material will release 1.8 x $10^6 \ell$ of pore waters over a period of about a year. This results in a flux of NH_4 to the overlying water of 5.4 x 10^3 moles of NH_4. The amount of NH_4 added to the water column by fine-grained sediments in the upper Bay (worst case, minimum area) is the area of the upper Bay (814 x $10^6 m^2$ Turkey Point to Mouth of Patapsco River without tributaries) multiplied by the average regeneration rate (872 x 10^{-6} m/m^2/d) which gives 2.6 x 10^8 moles NH_4 per year. Five orders of magnitude more NH_4 is regenerated each year naturally to the upper Bay than would be contributed by expulsion of pore waters from dredged materials.

3. Chlorinated Hydrocarbons

Although these substances may have a greater potential to impact the marine ecosystem than any of the contaminants previously described, relatively little is known about their geochemical behavior. In part this is because chlorinated hydrocarbons have only recently been recognized as serious pollutants and research results are only beginning to be synthesized. Lack of information is also due to the analytical difficulties these diverse compounds present; much of the earlier work on the environmental chemistry of CHCs must be considered unreliable because of analytical uncertainty. The combination of high toxicity at low concentrations and analytical difficulty makes research both difficult and necessary. At the present time statements about the long term geochemical behavior of chlorinated hydrocarbons cannot be made with the same degree of confidence as similar statements made in this report about metals.

A "worst case" analysis may be made by determining the levels of dissolved chlorinated hydrocarbons that would result from dissolution from dredged material into the overlying waters in various parts of the Chesapeake Bay using a portion coefficient of 10^4. As calculated from values in Table #2, 1 x 10^6 metric tons of sediment dredged from the C & D Approach Channel contains 9 x 10^5 g PCB and 2 x 10^4 g DDT. The dissolved levels resulting from the dissolution of this material to equilibrium with the overlying waters at the two disposal sites are shown in the table below. The volumes of the Bay used in the calculation are, for the northern disposal site (overboard) from Turkey Point to the mouth of the Chester River, and from the Lane Bridge at Annapolis to Sharps Island for the proposed trough disposal site.

Disposal Area	Volume	PCB*	
Overboard	3827 x $10^6 m^3$	0.02 x 10^{-4}	5 x 10^{-9}
Trough	8806 x $10^6 m^3$	0.01 x 10^{-4}	2 x 10^{-8}

*Dissolved levels in PPM resulting from total dissolution from dredged material (1 x 10^6 tons).

Ninety g of PCB and 2 g of DDT would be released. This should be compared with the estimated input of PCBs from the Susquehanna River to this region of 506 kg/y (Munson, 1975), most of which is bound to suspended sediment. The releases from dredging and disposal, depending upon the season, might be more available for biological uptake than the river supplied material however.

References

Matisoff, G., O.P. Bricker, G.R. Holdren and P. Kaerk. 1975. Spatial and temporal variations in the interstitial water chemistry of Chesapeake Bay sediments. Pages 343-363 *in* T.M. Church, ed., Marine Chemistry in the Coastal Environment. A. C. S. Symp. Ser. #18.

Berner, R.A. 1972. Principles of Chemical Sedimentology. McGraw Hill Pub. 239pp.

Stumm, W. and J.J. Morgan. 1970. Aquatic Chemistry. Wiley Interscience Pub. 583pp.

Turekian, K.K. 1977. The fate of metals in the oceans. Geochem. Cosmochem. Acta. 41:1139-45.

Munson, T.O., D.D. Ela, and C. Rutledge Jr., eds. 1975. Upper Bay Survey, Final Report to the Department of Natural Resources, V.II. Westinghouse Electric Corp., Oceanic Division, Annapolis, Md.

Matisoff, G., O.P. Bricker, G.R. Holdren, and P. Kaerk. 1975. Spatial and temporal variations in the interstitial water chemistry of Chesapeake Bay sediments. Pages 343-363 *in* F.K. Church, ed., Marine Chemistry in the Coastal Environment. A. C. S., Washington, D.C.

APPENDIX M

Evaluation of possible oxygen depletion of the water column subsequent to disposal of material dredged from the Chesapeake and Delaware Canal Approach Channel under various disposal options (Table 4c).

The main source of oxygen demand exerted by the dredged material pile upon the overlying water over and above the normal oxygen demand of the sediments at the disposal site results from the gradual expulsion of reduced pore waters under the influence of gravitational compaction. During the hydraulic or hopper dredging/disposal process, water content of the dredged material is increased by approximately 20% by mass. Subsequent to disposal, gravitational compaction gradually expels this water, probably over a period of years. For $0.75 \times 10^6 m^3$ ($1 \times 10^6 yd^3$) of dredged material (9.18×10^9 g of sediment plus water with a mean density of 1.2 g/cm^3), compaction of $\sim$ 20% results in the expulsion of 1.8×10^9 g H_2O. The typical oxygen demand of highly reducing pore waters ($HS^=$ concentration $\sim 7 \times 10^{-3}$ moles/ℓ) is 1.5×10^{-2} moles O_2/ℓ (Schubel et al., 1978). If all the pore water were expelled at once, it would produce an oxygen demand of 8.6×10^5 g O_2 (2.7×10^4 moles).

In the summer, oxygen levels in the deep trough drop below 1 μg/g. Since the volume of the deep hole below 20 m is about 528×10^{10} cm^3, it might contain 5.2×10^6 g O_2--almost an order of magnitude more oxygen than is required to satisfy the oxygen demand of the pore water assuming it were all expelled at once and there was no mixing with the overlying waters. During most of the year, dissolved oxygen levels in the trough are closer to 5 μg/g which would provide 2.6×10^7 g O_2--more than two orders of magnitude more than required to satisfy the total oxygen demand of the pore waters under worst case conditions.

In reality the expulsion of reduced pore waters occurs at a very slow rate, and the expelled water is rapidly mixed with the overlying waters so that the immediate oxygen demand would not produce a detectable oxygen sag in the near-bottom waters of the trough. Similar arguments can be made for the more highly oxygenated waters of the upper Bay.

Reference

Schubel, J.R., H.H. Carter, R.E. Wilson, W.M. Wise, M.G. Heaton, M.G. Gross. 1978. Field investigations of the nature, degree, and extent of turbidity generated by open-water pipeline disposal operations. Technical Rept. D-78-30 U.S.A.C.E. Dredged Material Research Program.

APPENDIX N

Movement of materials dredged from Chesapeake and Delaware Canal Approach subsequent to disposal at various sites (Table 4c).

Substantial movement of disposed dredged materials outside the designated disposal area is a perceived environmental hazard to commercially important benthic organisms, particularly oysters. Large scale movement may be the result of two processes:

Fluid flow of sediment which may occur immediately after disposal and

Resuspension of sediment and transport by advective and diffusive processes--a process which may occur over a long time period.

Biggs (1970) monitored the disposal and ultimate fate of dredged materials discharged into the upper bay overboard site in 1967. He found that the dredged material pile immediately after disposal had an average slope of 500:1 and an average height of 1.5 m. An area at least five times that of the intended disposal site was covered by "fluid mud flow" and < 90% of the total volume of material dredged could be accounted for within the pile five months after disposal. The long term effect of sediment resuspension on this pile remains unevaluated.

The physical and bathymetric characteristics of a disposal site in the trough below the Bay Bridge place limits on the extent of migration of the dredged materials subsequent to disposal. In contrast to the upper Bay disposal area, which is shallow and has relatively little relief, the middle Bay site is at the bottom of a deep trough. Fluid flow of the material disposed in the trough will be limited by the sides of the trough. There is no possibility that this material could *flow* out of the trough and impact the oyster bars near its margins. Also the decreased turbulence (Appendix A) at this site makes long-term resuspension (Appendix B) less likely than in the upper Bay.

Reference

Biggs, R.B. 1970. Project A, Geology and Hydrography. Pages 7-15 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

APPENDIX O

Effect of changes of bottom topography from disposal of materials dredged from the Chesapeake and Delaware Canal Approach Channel (Table 4c).

Significant alteration of bottom topography by the creation of dredged material mounds could affect circulation in the disposal area and also interfere with the activities of commercial drift net fishermen. The extent of such effects can be predicted by considering the reduction of bay cross sectional area caused by the disposal process and the geometry of the disposal mounds.

In the upper Bay the average height of the dredged material pile created during disposal activities in 1967 (Biggs, 1970) was 1.5 m. Although this is about 25% of the depth in this area (4 to 6 m) the reduction of cross sectional area is very small because the disposal pile runs roughly parallel to the axis of the Bay. The dimensions of this pile are ≅ 100 m wide x 3 km long x 1.5 m high and it has no measurable effect on circulation. If it interferes with drift nets used by commercial fishermen in this area, the relief of the pile could probably be reduced during disposal, or afterward, by drag-line operations. Such an operation, however, would remove a principal advantage of creating a pile, the minimization of exposed sediment surface area, which limits the release of contaminants (see Appendix L).

In the trough the much greater depth (average depth ≈ 31 m) virtually precludes any measurable effects on circulation. The volume of the trough from 20 m to the bottom in this area is 528 x 10^6 m^3. This should be compared with the total projected volume of dredged material for the next twenty years in the Maryland portion of the Bay of 50 x 10^6 m^3. Disposal of all this material within the trough could not be expected to produce a measurable effect on circulation in this area (Schubel and Wise, 1979).

References

Biggs, R.B. 1970. Project A, Geology and Hydrography. Pages 7-15 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Schubel, J.R. and W.M. Wise, eds. 1979. Pages 90-94 *in* Questions About Dredging and Dredged Material Disposal in the Chesapeake Bay. Special Rept. 20, Marine Sciences Research Center, State University of New York.

APPENDIX P

Time for recovery of benthic communities subsequent to disposal operations at sites under consideration for the disposal of material dredged from the Chesapeake and Delaware Canal Approach Channel (Table 4c).

1. Biomass

A possible significant effect of dredged material disposal is the long term destruction, by burial, of benthic communities which serve as a food resource for many commercially important fishes. Studies of the recovery of the benthic communities on dredged material piles have been made in upper Chesapeake Bay, following overboard disposal of material dredged from the C & D Approach Channel in 1967 (Pfitzenmeyer, 1970), and in Long Island Sound at a deep (20 m) disposal site for materials dredged from New Haven Harbor (Rhoads et al., 1978), and in other areas.

Pfitzenmeyer (1970) studied the changes in benthic biomass (mass of organisms/mass of sediment) caused by overboard disposal of material dredged from the Chesapeake and Delaware Approach Channel. An immediate decrease of 64% in the dry biomass was followed by an 85% *increase* in biomass within four months of disposal. This was in turn followed by a lesser increase over the next six months. During the same period, the number of individuals represented by this biomass fluctuated widely, apparently following a natural cycle keyed to salinity variations in the overlying waters. Within a year and a half there was no apparent difference between the predisposal and post-disposal communities, as measured with standard parameters and compared with normal variation outside the disposal area.

The Long Island Sound Disposal Site studied by Rhoads et al. (1978) is a deep, relatively quiescent area similar in some respects to the mid-Chesapeake Bay trough. At that site, relatively contaminated material from New Haven Harbor was discharged by hopper barge. the immediate recruitment of organisms on the pile was slower than at nearby control areas, suggesting inhibition by toxic substances released from the pile. Relatively contaminated dredged material was covered with a thin layer of "cleaner" material obtained during the dredging of less contaminated areas of the harbor. Recovery of benthic community biomass at the disposal site subsequent to disposal was at first extremely rapid. The initial increase in biomass was followed by a decline which was related to ecological conditions at the disposal site. Within one and a half years the density of organisms on the surface of the dump site had recovered to within the range of apparent variability of the surrounding bottom. This variability is probably due to a combination of factors including large changes in planktonic recruitment, inter-species competition, and the possible effect of sediment contaminants.

Changes in benthic communities due to dredged material disposal should be evaluated in comparison with the normal large, natural variability which results in response to complex and often unknown factors that characterizes the natural bottom. In the northern Chesapeake Bay bottom-dwelling organisms are frequently subject to environmental "catastrophes" unrelated to man's activities, storm and floods. The benthic community in the trough is also subject to periodic mortality in summer due to depression of dissolved oxygen to near zero levels.

Studies show that total biomass is not significantly affected by dredged material disposal in areas similar to the Chesapeake Bay.

2. Diversity

Diversity is a measure of the complexity and variety of an ecosystem and is strongly affected by the degree of environmental variability encountered by the community. A high degree of diversity is thought by ecologists to be the result of continued stability of the environment for a prolonged period, allowing complex interrelationships to be developed among organisms.

The two disposal sites under consideration in this case are quite different in the degree of environmental variability encountered by the benthic community. This is perhaps not fully reflected in the parameters stated in Table 3 because of extreme episodic nature of some of the changes. Salinity, for example, in the upper reaches of the Bay drops to zero for a period of several weeks during the annual Susquehanna freshet. Aperiodic large floods carry tremendous quantities of sediment to this area, burying the bottom fauna. While salinity of the mid-Bay trough site is variable, it rarely, if ever, drops to zero and variability in sediment input is greatly reduced this far from the Susquehanna River--the principal source of fluvial sediment.

Disposal of dredged materials in the upper Bay is another variable "event" covering a small area in addition to many natural changes. Because the benthic community in this area has a low diversity index to begin with (Pfitzenmeyer, 1970), changes caused by dredged material disposal are small and readjust rapidly. Subsequent to disposal of dredged material at the upper Bay location in 1967, the diversity index of benthic organisms in the disposal area dropped. Complete recovery of the benthic community to predredging levels was observed within one year.

This was not the case for the disposal of dredged material in Long Island Sound; a much more stable environment populated by a mature benthic community. Here even several years subsequent to disposal, the benthic community at the disposal site was still significantly less diverse than that of surrounding bottom (Rhoads et al., 1978). The near-bottom environment in the Chesapeake Bay trough site is more variable than that in Long Island Sound. No information on the structure of the benthic community in the Chesapeake Bay trough is available. Until this information is obtained, ecological studies in other areas suggest that recovery of species diversity of the benthic community in the trough to predisposal levels would probably be similar to, or more rapid than in the upper Bay. The diversity of the benthic assemblage in the trough is almost certainly lower than that in the overboard disposal area in the upper Bay. The benthic organisms in the trough are eliminated, in all likelihood, every summer when the oxygen content of near-bottom waters falls to near zero levels.

The possible ecological effect that alterations in the benthic community might have on the nekton remains unevaluated, but probably is small. Considerable controversy exists regarding the species characteristics of the most productive benthic communities. Some authors suggest that dredging affected communities may be even more productive than undisturbed bottoms (Rhoads et al., 1978) because of the sudden explosive increase in biomass associated with the recruitment of opportunistic species. It remains unclear whether these organisms are necessarily readily utilized as food by higher trophic levels (nekton). The areas of Chesapeake Bay, affected by dredged material disposal are a fraction of the total area and probably do not have a measureable effect on higher trophic levels because of alterations in the benthic community structure. Studies of the benthic community of the trough should be made. This is essential if the trough is to be considered as a potential site for disposal of dredged material.

References

Pfitzenmeyer, H.T. 1970. Project C, Benthos. Pages 26-38 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Rhoads, D.C., P. McCall, J.Y. Yingst. 1978. Disturbance and production on the estuarine sea floor. American Scientist 66:577-583.

APPENDIX Q

Uptake of contaminants by organisms at the proposed disposal sites for materials dredged from the Chesapeake and Delaware Canal Approach Channel (Table 4c).

A. Metals

1. Benthos. Benthic organisms living in or on the sediment ingest sediment particles as part of their regular feeding activities. The characteristics of the digestive tracts of these organisms are such that dissolution and uptake of metals from sediments may occur. Although benthic organisms must be adapted to sediment-associated metals at natural levels, added anthorpogenic loadings may be in chamical forms more easily desorbed which may cause deleterious effects to the benthos themselves, or may be concentrated higher in the food chain. Benthic organisms, low in the trophic structure of marine ecosystems, may provide the entry point into biological cycles for the otherwise generally unavailable metals.

Although many experiments on the effects of increased metals concentrations on benthic organisms have been performed, most of the data generated are of little value in predicting the environmental effects of metal loadings in dredged sediments. Most studies have utilized soluble metals at far higher concentrations than those found in the environment. In studies of sediment uptake, many investigators have failed in their analyses to differentiate between sediment-associated metals in the digestive tract and metals that have been incorporated into the organism's tissues.

We have very limited ability to predict the effects of sediment-associated metals on the benthos or on higher trophic levels. Experiments (Bryan and Hammerstony, 1973a,b; Shuster and Pringle , 1968) have demonstrated that uptake of metals by crustacea, polycheates, and mollusks is possible. A conservative criterion at this time is to restrict disposal to materials whose metals concentrations are at or below those in the proposed disposal area to minimize the elevation of these contaminants at the disposal site. The sites chosen to receive the dredged materials under consideration in this report have been chosen using this criterion.

2. *Plankton.* Because the release of *soluble* (see Appendix L) metals from the disposal pile is negligible, uptake of metals by plankton is unlikely.

3. *Nekton.* Uptake of metals by nekton results principally from ingestion of dissolved metals and contaminated benthic or planktonic organisma.

B. CHCs

Because long-term desorbtion of chlorinated hydrocarbons from the disposal pile is considered a possibility (Appendix L) and these substances are known to be taken from solution by plankton (H.B. O'Connors, personal communication, 1979), mollusks (Duke et al., 1970), and nekton (Smith and Cole, 1970), uptake of CHCs by these organisms cannot be discounted. Careful comparisons between the CHC content of the dredged material and the sediments of the disposal area should be made.

References

Bryan, G.W. and L.G. Hammerstony. 1973a. Adaptation of the polychaete *Nereis deversicolor* to manganese in estuarine sediments. Journal of the Marine Biological Association of the United Kingdom. 53:859-872.

Duke, T.W., J.I. Lowe, and A.J. Wilson, Jr. 1970. A polychlorinated biphenyl (Aroclor 1254) in water, sediment, and biota of Escambia Bay, Florida. Bull. of Environmental Contamination and Toxicology. 5(2):121-180.

Schuster, C.N., Jr. and B.H. Pringle. 1968. Effects of trace metals on estuarine mollusks. Prod., 1st Mid-Atlantic Industrial Waste Conf., Univ. Delaware. CE-5:285-304.

Smith, R.M. and C.F. Cole. 1970. Chlorinated hydrocarbon insecticide residues in winter flounder, *Pseudopleuronectus americanus*, from the Weweantic River Estuary, Massachusetts. J. of the Fisheries Res. Bd. of Canada. 27(12)2374-2380.

APPENDIX R

Frequency of maintenance dredging of Baltimore Harbor Approach Channel as affected by utilization of various disposal options (Table 7).

If dredged materials are not removed sufficiently or isolated from the dredging site, resuspension by waves and tidal currents, and mass movements may cause the return of these materials to the channel. Since most material dredged previously from Baltimore Harbor Approach Channels has been disposed overboard, continued utilization of this option will not result in any change in the historical frequency of dredging required to maintain the channel. Confinement of dredged material, or utilization of more removed sites, could be expected to decrease the frequency of maintenance dredging required.

APPENDIX S

Degree of turbulence at disposal sites proposed for materials dredged from the Baltimore Harbor Approach Channels (Table 7).

As previously discussed (Appendix A), secondary sources of turbulence in addition to tidal stresses are probably the cause of significant differences in the turbulence of near bottom waters at various locations in the open Chesapeake Bay. These secondary sources, wind waves and the wakes of ships, have a surface origin and are therefore depth dependent.

The undiked overboard option is considered most turbulent because of its shallowness and proximity to frequent ship traffic. It is also exposed significantly to the effects of wind generated waves. Diking of this site with structures that approached the water surface would reduce the effects of surface waves significantly. The two other sites, near Kent Island and in the deep trough, are significantly deeper and removed from the effects of surface waves. Fringing wetland areas which are alternately submerged and exposed by the tides are subject to turbulent stress from tidal currents and wind waves. Once vegetated, the plants are effective in stabilizing the bottom.

APPENDIX T

Intensity of sediment resuspension at disposal sites proposed for materials dredged from Baltimore Harbor Approach Channels (Table 7).

Bottom sediment resuspension results from turbulent stresses exerted by near-bottom waters on the surficial sediments. It is greatest where shear stresses are high and shear strengths (critical erosion speeds) of the sediments are low. Without additional information on the physical and biologically-mediated sediment characteristics (Appendix B) that determine the critical erosion speed of sediments at the various disposal sites, we assume the velocities required for resuspension are similar. All sites are characterized by fine-grained materials of similar texture. The amount of sediment resuspension of the various sites is therefore considered only as a function of water turbulence, and the sites are ranked accordingly.

The shallow overboard site is similar to the upper Bay site in this regard and is ranked most turbulent with most sediment resuspension. Diking of this site would probably reduce significantly the effect of wind waves, ship wakes, and tidal currents with a consequent reduction in sediment resuspension if the dikes approached the water surface. The Kent Island and deep trough sites are less susceptible to resuspension than the undiked overboard option because their greater depth limits disturbance of the bottom by waves. Once fringing areas are vegetated, roots stabilize the sediments and the plant stems dissipate wave and current energy.

APPENDIX U

Excess turbidity in water column during disposal at disposal sites proposed for materials dredged from Baltimore Harbor Approach Channels (Table 3a).

The origin and extent of excess turbidity generated during disposal by the methods under consideration have already been discussed in detail in Appendix D. The conclusion stated there that excess turbidity during disposal is temporary and local in extent, holds for the sites under consideration in this section.

APPENDIX V

Contaminant releases to water column during disposal operations at disposal sites proposed for materials dredged from Baltimore Harbor Approach Channels (Table 8a).

The possible release of contaminants from dredged materials during disposal operations is determined, in decreasing order of importance, by (1) the geochemical characteristics of the dredged materials, (2) the method of disposal, (3) and the physical conditions at the disposal site. Because the essential geochemical characteristics of the sediments under consideration in this section from the Baltimore Approach Channels (fine-grained, high organic content, reducing character) are the same as those of the C & D Approach Channel material, the detailed arguments of Appendix E are equally applicable here. Further, the physical characteristics of the water column at the locations under consideration in this section are not significantly different from those in the previous section. For these reasons, the conclusions expressed below are the same as those in the previous section and referred to Appendix E.

1) Metals

The possible release of metals from dredged materials during disposal operations of the type considered here has been discussed in detail in Appendix E. The conclusion, that any release is negligible, holds for these locations.

2) Nutrients

The release of nutrients by the expulsion of interstitial waters from material during disposal operations has also been considered in detail in Appendix E. The conclusion, that such release will have a negligible impact on the water column, is equally valid for the sites under consideration here.

3) CHCs

The conclusion expressed regarding the possible release of CHCs during disposal in Appendix E must be considered applicable to these sites as well in the absence of a solid geochemical understanding of these complex substances. The conflicting data about their potential for release from sediment requires that the possibility of such release is not excluded.

APPENDIX W

Oxygen depletion of water column during disposal operations at disposal sites proposed for materials dredged from Baltimore Harbor Approach Channels (Table 8a).

As discussed in detail in Appendix F, oxygen depletion of the water column during disposal is caused by the presence of reduced compounds of sulfur in the sediment and its interstitial waters. Numerous investigations of both hopper and hydraulic disposal methods in a wide variety of environments have demonstrated that the spatial and temporal extent of dissolved oxygen depression is always restricted to the limits of the turbidity plume. There is no reason to believe that more significant oxygen depression will occur at the locations under consideration here. See Appendix F for references.

APPENDIX X

Ecological effects of increased turbidity of water column associated with the disposal of Baltimore Harbor Approach Channels materials at various disposal options (Table 8b).

1. Phytoplankton

As discussed Appendix g, decreases in phytoplankton photosynthesis resulting from increased turbidity because of dredging and disposal are temporary and local in extent, and have negligible ecological effects.

2. Zooplankton

As discussed in Appendix G, the temporary and local nature of the areas of substantial increases in levels of excess turbidity generated during disposal make possible significant effects upon zooplankton very unlikely.

3. Nekton

As discussed in Appendix G, the temporary and local nature of excess turbidity generated during disposal make possible significant effects upon nekton populations unlikely.

4. Benthos

The area affected by increased turbidity is sufficiently small so that the amount of the benthic community affected is insignificant.

5. Rooted Aquatic Plants

Most of the bottom affected by increased turbidity is well beneath the euphotic depth and contains no rooted plant life. Some rooted plants might be affected by construction of new marshes in fringing areas.

APPENDIX Y

Smothering of benthos by disposal of Baltimore Harbor Approaches materials in various disposal options (Table 8b).

At the submarine disposal sites considered in this section smothering of benthos by the disposal of dredged material will probably be complete. Recolonization will occur relatively rapidly, however (see Appendix GG).

APPENDIX Z

Exclusion/attraction of fish at Baltimore Approaches alternatives (Table 8b).

During disposal operations attraction of local finfish to the turbidity plume has been occasionally observed. This attraction has been attributed to releases of particulate organic matter associated with the dredged material which serve as a food source for the fish. Finfish have also been observed to be repelled by the turbidity plume, perhaps in response to the generally lowered dissolved oxygen levels in its immediate vicinity. Generally it has been observed that fish are more sensitive to oxygen depletion than to excess turbidity, and appear to be repelled from the disposal area before encountering the high turbidity levels located within the plume. Because of this defensive mechanism, and also because of the limited area strongly affected by increased turbidity during disposal (see Appendix U), disposal operations do not pose a threat to resident finfish populations at locations where sufficient space is available to enable fish ot avoid the plume. This is true for all the locations under consideration in this report.

APPENDIX AA

Uptake of contaminants by biota during the disposal of Baltimore Harbor Approach Channels material at various disposal sites (Table 3b).

1. Metals

Because the release of soluble metals during disposal is considered unlikely, benthos, plankton, and nekton will not be subject to metals concentrations higher than ambient and the rate of uptake of metals will not be affected. See Appendix V for more detail.

2. CHCs

Because the release of soluble CHCs during disposal operations is considered possible, benthos, nekton, and plankton might take up these compounds at faster rates and in greater amounts as the result of disposal. See Appendix V for more detail.

APPENDIX BB

Excess turbidity in water column subsequent to disposal of materials dredged from Baltimore Harbor Approach Channels at the alternative disposal sites (Table 8c).

The sources and possible environmental effects of persistent excess turbidity in the water column as the result of disposal activities have been discussed in Appendix K. The general conclusion, that the location and strength of this source of excess turbidity is masked by natural variations in turbidity at the disposal sites, holds for the deep trough and Kent Island sites.

This conclusion may not hold for undiked overboard sites. The shallowness of the area, its fetch, and characteristic tidal currents make sediment resuspension by wind waves, shipping wakes and tidal currents likely. Although conditions similar to these are characteristic of the upper Bay overboard site adjacent to the C & D Canal Approach Channel, the waters in that area were normally subject to larger and more rapid natural changes in turbidity. At the overboard disposal locations for the Baltimore Approach Channels, natural variability in turbidity levels is reduced relative to that of the upper Bay. Organisms migrating through this area may not be well adapted to cope with high turbidity levels which could result over a significant area for months after disposal. We consider the biological impact to be small, however.

Diking of overboard disposal areas would reduce the effects of surface waves from wind and ships, as well as tidal currents, and would minimize sediment resuspension and eliminate this source of excess turbidity. Diked disposal in fringing areas, if properly constructed, does not allow escape of sediment by subaerial erosion processes. Vegetation of fringing marshlands stabilizes the sediment, and dampens resuspension and therefore excess turbidity.

Appendix CC

Contaminant releases to water column subsequent to disposal of materials dredged for Baltimore Harbor Approach Channels (Table 8c).

Subsequent to disposal, the most important factors governing the possible release of contaminants from the disposal pile are the environmental conditions experienced by the sediment. As pointed out in Appendix L, the most important factor in minimizing release of contaminants is the maintenance of anoxic conditions within the disposal pile. Physical factors at the site play an important role in determining geochemical conditions within the pile. The geochemical effects of waves and currents as agents of sediment resuspension are to oxygenate the sediment pore waters and to increase the normally slow rates of molecular diffusion. The result is to enhance the transfer of contaminants from the sediment to the overlying water.

The submarine disposal options considered in this section are therefore ranked according to the potential turbulence and sediment resuspension at the sites. The considerations are similar to those used in ranking the disposal options in Case Study I, and a detailed geochemical justification of this strategy may be found in Appendix L to that section. Artificially created land areas, which are subaerially exposed, present quite different geochemical conditions and are discussed in detail in this section.

(1) Metals

Using the criteria developed previously for assessing the potential release of contaminants in which we considered the degree of sediment resuspension as the determining factor, the undiked overboard option has the greatest potential of the submarine sites considered here for release of metals. Diking of subaqueous sites and keeping the dredged material below the water surface, would significantly reduce sediment resuspension and the potential for release of metals. Disposal at the two other submarine sites--Kent Island and the deep trough--would also probably effectively retain metals within the disposal pile because of their relatively quiescent conditions.

The construction of new fastland or wetland using dredged materials and the consequent exposure of these materials to the atmosphere permits large masses of sediment to be oxygenated (Mang et al.; 1978). One result of this oxygenation is a reduction in the strength of the sediment-contaminant association with a corresponding increase in the availability of contaminants to solution. The subaerial exposure of land created from dredged materials provides opportunities for mobilization and movement of contaminants by percolating rainwater. The freshwaters, which are highly oxygenated, will eventually satiate the large oxygen demand of the sediment pile and begin to dissolve the once insoluble reduced metals compounds. These might then work their way into streams and the nearby Bay, and be available for direct uptake by organisms. They might also penetrate into groundwaters causing contamination of drinking waters.

Detailed monitoring performed at the Pearce Creek onshore disposal site in November 1976 (Harmon, 1976) revealed considerable water quality degradation. The effects on the main body of the Chesapeake Bay from this operation are unknown because no monitoring was performed in adjacent open waters. Pearce Creek itself, which discharges to the open Bay through sluices, showed significant levels of dissolved heavy metals, and smaller, but measurable decreases in dissolved oxygen. The pH of the Creek was significantly reduced. The biota were apparently stressed as evidenced by substantially reduced benthic community diversity indices. The possibility exists that these impacts are caused by the confined disposal area which provides limited dilution potential for contaminants. Significant concentrations of dissolved metals such as those reported for Pearce Creek, have never been observed at open water locations where dilution is rapid and effective.

We consider that the release of metals from onshore disposal sites is likely because the metals have the potential to be soluble and to come in contact with migrating solutions. Oxygenated rain water provides the dissolution mechanism and a vector for the dissolved products.

(2) Nutrients

The expected rate of expulsion of nutrients from a submarine disposal pile with a volume of $0.75 \times 10^6\ m^3$ ($1 \times 10^6\ yds^3$) of material has been calculated and compared with natural nutrient regeneration rates in Appendix L, part 2. The conclusion reached that the amount of nutrients released from the compacting pile was small compared with the amount of natural nutrient regeneration is valid for the submarine sites under consideration in this section as well.

The amount of nutrients released through disposal in fringing areas is likely to be larger for two reasons. First, the amount of compaction is larger than for submerged sediment piles and therefore more pore waters are expelled. Second, subaerial exposure of the disposal area allows rain water to replace and "flush out" pore waters from the pile, enhancing the flux of nutrients. It is still unlikely, however, that the amount of nutrients released from such a pile over an extended period, if given ample opportunity for dilution, would cause significant increases in nutrient concentrations in adjacent open waters. This may not be the case for small semi-enclosed water bodies, such as tidal creeks that receive the effluent from large deposits of dredged materials.

(3) Chlorinated Hydrocarbons

At the present time predictions of the long-term geochemical behavior of chlorinated hydrocarbons cannot be made with the same degree of confidence as predictions for metals (see Appendix L). A conservative approach requires that we assume that the distribution coefficient of CHCs between the solid and dissolved phases in sediment-water systems is measurably large (as opposed to metals, for example), and that this results in the molecular diffusion of CHCs across the sediment-water interface to the near-bottom waters. The environmentally conservative disposal strategy is to minimize this flux. Disturbance of the sediment pile by physical processes and by bioturbation increases the rate of diffusion and should be minimized.

Although the release of chlorinated hydrocarbons from dredged materials is possible for all the disposal strategies we considered, theoretically the rate of release is likely to be greatest in those environments where the sediments are disturbed most frequently. Using this criterion, the possible rate of release of CHCs from dredged material disposed at the various submarine locations considered here can be ranked from slowest to fastest as: diked and submerged, deep trough, Kent Island dump site, and undiked overboard. The greater amount of compaction and subaerial exposure of material disposed in fringing areas may enhance the rate of CHC release over that at submarine locations.

References

Harmon, G.H. 1976. Report on the impact of the Chesapeake and Delaware Canal dredged spoil disposal operation of November 1976 on the water quality at the Pearce Creek Disposal site. Maryland Water Resources Administration. 13pp (also unpublished data).

Mang, J.L., J.S. Lu, R.J. Lofy, R.P. Stearns. 1978. A study of leachate from dredged material in upland areas and/or in productive uses, DMRP Tech. Rept. D-78-20, U.S.A.C.E., Vicksburg, Miss.

APPENDIX DD

Oxygen depletion of water column subsequent to disposal of materials dredged from Baltimore Harbor Approach Channels at proposed disposal sites (Table 8c).

As discussed in detail in Appendix M, it is unlikely that the oxygen demand exerted by the submarine disposal piles on the overlying waters will result in detectable decreases in the dissolved oxygen content of near-bottom waters. A similar argument can be made for disposal in fringing areas.

APPENDIX EE

Movement of material dredged from Baltimore Harbor Approach Channels subsequent to disposal at proposed sites (Table 3c).

Movement of dredged materials subsequent to disposal results primarily by sediment resuspension by waves and tides and fluid mud flow (Appendix N). Of the alternatives considered, diked areas and stabilized fringing areas are least susceptible to sediment movement and shallow, unconfined open water sites most susceptible. Movement of dredged materials from the trough south of the Bay bridge and from the Kent Island Site has been discussed in Appendix N. Movement of sediment in the trough is considered to be less likely than at the Kent Island site because of the trough's greater depth and its steep sides.

APPENDIX FF

Effect of changes in bottom topography at Baltimore Approaches alternatives (Table 8c).

Possible effects of changes in bottom topography as a result of dredging and spoil operations would include changes in the distribution and strength of the currents; changes in the intensity of turbulence; and changes in the usability of the area for fishing and boating.

Disposal of spoil overboard in areas adjacent to the Baltimore Harbor approach channels would have negligible effect on the distribution of currents in the cross-section and on the intensity of turbulence. Since the material being dredged from these channels is for the most part silt and clay, the spoil will, soon after disposal, be spread by the effects of gravity and by the currents over a wide area. Much of it in fact ultimately will return to the channel. Any temporary decrease in depth over the adjacent area will be small, and will be offset by the increase in depth of the channel as a result of dredging. Thus, the average current speed in any given cross-section would not be changed by the dredging and spoiling operation, and any change in the distribution of currents in the section would be negligible.

Subsequent to disposal of the spoil, there would not be any significant effects of overboard disposal in areas adjacent to the channel on the use of such areas for fishing and boating. Note that we are here discussing any physical effects , such as interference with fishing gear or creation of hazards to navigation (i.e., shoal areas), and not to any strictly biological effects on fishing success.

The creation of confined, submerged disposal areas adjacent to the Baltimore Harbor Approach Channels could possibly have some effects on the distribution of currents in the reach of the Bay containing such a disposal area, and also on the use of such areas for fishing and boating. The degree of impact of a confined, submerged disposal area will depend on specific features of location and size. In order to examine possible effects of such disposal areas, we have considered two plausible cases with respect to location and dimensions of the confinement structures.

We have first considered the possible effects of locating a confined, submerged disposal area in the existing designated spoil area that runs parallel to the Brewerton Channel Eastern Extension, and lies to the north of this channel. Depths in this area range from about 15 feet (4.6 meters) to about 18 feet (5.5 meters) below mean low water. A rectangular diked containment area, 8000 feet long (in the direction parallel to the Brewerton Channel Eastern Extension) and 7000 feet wide could hold 2.07 million cubic yards per foot of fill. (5.21 million cubic meters per meter of fill). Constructing the dikes to extend from the bottom with an average depth of 16 feet (4.9 meters), to within 8 feet (2.4 meters) of the surface would provide confined, submerged disposal for 16.6 million cubic yards (12.7 million cubic meters) of spoil.

Such a disposal area would extend along the bottom for 16% of the width of the cross-section that extends from North Point to Swan Point. It would, however, reduce the area of this cross-section by only 9.7%. Tidal elevations upstream from this section would not be measurably affected by such a structure. Peak ebb and flood current speeds in this cross-section would increase, on the average, by about 10%, with somewhat larger increases near the submerged structure. The maximum ebb and flood current speed through this section is about 1.2 ft sec^{-1} (37 cm sec^{-1}), and a 10% increase would not result in current speeds exceeding those naturally found at sections both north and south of this cross-section.

This area cannot be used for fishing with deep drift nets since there are natural shoals which run laterally across the Bay, with minimum depths of only 4 feet, just to the north, and Sevenfoot Knoll and Sixfoot Knoll lie to the south of the Brewerton Channel Eastern Extension. Construction of such a submerged confinement area would limit, to some extent, navigation of vessels with drafts greater than eight feet through the area. However, the above-mentioned shoals already limit navigation outside the established channel areas for such craft.

We also considered a confined, submerged disposal area running parallel to and to the east of the Craighill Channel. A rectangular diked area 3000 feet (915 m) wide and 18,000 feet (5490 m) long (in a direction parallel to the channel) could hold 2.0 million cubic yards per foot of fill (5.02 million cubic meters per meter of fill). The bottom depths in this reach average about 15 feet (4.6 m). If the confining dikes were built to within 8 feet (2.4 m) of the surface, such a disposal area could contain 14.0 million cubic yards (10.7 million cubic meters) of spoil.

Such a disposal area would occupy about 6.9% of the width of the bottom of the cross-section between Bodkin Point and Swan Point. Construction of such a containment facility to within 8 feet of the surface would reduce the area of this cross-section by about 3.0%. The peak tidal currents would, on the average, be increased by about this same amount (3.1%). Such an increase would not result in current speeds exceeding those found in sections in the Bay both north and south of this section.

Because of Sixfoot Knoll and Sevenfoot Knoll, navigation of vessels having drafts greater than the 8 foot depth of the example containment area is already severely restricted. For this same reason, fishing using drift nets is not practical in this region.

The construction of such submerged dikes could be a local benefit to sports fishermen. Such dikes could serve to provide hard substrate for sessile organisms, and a consequent attraction for forage fish and game fish.

The use of the Kent Island Dump Site to continue to receive spoil from the dredging of the Baltimore Harbor Approach Channels would result in small increases in the maximum speed of the tidal currents in that area of the Chesapeake Bay. The active area of dump site extends from just north of the Bay Bridge to just south of Love Point. The area of this dump site is some 50 million square ft (4.65 million square meters). Each foot of fill over this area represents 1.85 million cubic yards (4.64 million cubic meters per meter of fill). Five feet more of spoil disposed of over the area of the Kent Island Dump Site would represent 9.25 million cubic yards (7.1 million cubic meters) of dredged material.

The Kent Island Dump Site as now laid out occupies about 18% of the bottom width of the cross-section extending from Sandy Point to Kent Island, along a line perpendicular to the axis of the Bay. Five feet of additional fill over the area of the dump site would result in a decrease in the present cross-sectional area by some 2.8%. There would then be a 2.9% increase in the maximum ebb and flood currents in the cross-section. This small increase would not significantly increase scour nor adversely affect navigation. Deep draft vessels traverse the designated channel to the west of the dump site and hence the decrease in depth over the spoil area would not have any significant effect on waterborne transport through the area.

The deep trough south of the Bay Bridge has a width between the 60 ft (18.3 m) depth contours of from 3800 ft (1160 m) to over 6000 ft (1830 m) with an average of 4620 ft (1400 m). For each nautical mile (6080 ft or 1854 meters) of length of this trough, one foot of fill at and below the 60 ft (18.3 m) contour would represent 1.04 million cubic yards (2.61 million cubic meters per meter of fill). Five ft (1.5 meters) of fill distributed over a disposal area in the trough contained within the 60 foot (18.3 meter) contours and extending over a length of five nautical miles

(9270 meters), or over several segments aggregating to 5 nautical miles, would then provide for the disposal of about 26 million cubic yards (19.9 million cubic meters) of spoil.

Such a 5 foot (1.5 m) fill between the 60 ft (18.3 m) depth contours in the deep trough would represent about 2% of the cross-sectional area for the typical cross-section south of the Bay Bridge. The corresponding 2% increase in maximum ebb and flood current speeds averaged over the cross-section where such fill took place would not cause any significant effect on scour or on navigation.

The disposal option which used spoil to create marshland from protected shallow water areas adjacent to the upper Bay would obviously change the local circulation, providing, in fact, an entirely new hydrodynamic regime as well as an entirely new biological habitat. The effects that the creation of wetlands by spoil disposal in protected shallow water areas adjacent to or along the shores of the upper Chesapeake Bay would have on currents in adjacent open waters would depend on the fraction of the cross-section of the Bay represented by such fill operations. In general, the effects of this option of spoil disposal would be negligible on the distribution of currents in the waters of the adjacent open Bay.

APPENDIX GG

Time for recovery of benthic communities at disposal sites considered for materials dredged from Baltimore Harbor Approach Channels (Table 8d).

1. Biomass

Numerous studies (see Appendix P) have described the rapid repopulation of the bottom by infaunal organisms in areas following dredged material disposal. In the absence of detailed ecological information for the specific disposal sites we considered, there is no reason to expect that recovery of biomass would be less rapid at these sites than at other sites which have been studied. Any benthos existing at a site that is built-up to above the water surface will of course be permanently destroyed (VIMS, 1977).

2. Diversity

The entries in Table 8d regarding the time required for recovery of benthic diversity at the various disposal sites reflect the arguments presented in Appendix P. Briefly summarized, communities naturally exposed to large environmental variability have a low diversity and will be quick to recover to pre-disposal conditions. More mature communities, characteristic of more stable environments, take longer to recover to pre-disposal diversity levels.

Lack of detailed information on the structure of the benthic communities at the Kent Island disposal site and at the overboard sites near the Baltimore Harbor Approach Channels precludes documentation of the times required for recovery of diversity by the inbenthic communities. It seems likely that the low summer dissolved oxygen levels of bottom waters at the Kent Island and trough sites cause significant seasonal mortality of benthic organisms. These communities must be re-established by recruitment of juveniles each year to maintain even tenuous populations in these areas. It appears very unlikely that disposal of dredged materials would reduce significantly the already low diversity that must characterize these areas, particularly in the trough.

Reference

VIMS. 1977. Habitat development field investigations, Windmill Point Marsh Development Site, James River, Va., D.M.A.P. Tech. Rept. D-77-23, U.S.A.C.E., Vicksburg, Miss.

APPENDIX HH

Uptake of contaminants by organisms at alternative disposal sites for materials dredged from the Baltimore Harbor Approach Channels (Table 8d).

A. <u>Metals</u>

1. *Benthos.* The mechanisms of trace metal uptake by infaunal and epifaunal benthic organisms have been discussed in Appendix G, part 1a. Uptake of metals by benthos does occur, but we have only limited knowledge of its effects. The possibility exists that metals in material dredged from this project are in forms that are readily available to organisms, but experimental confirmation of this is lacking. The best disposal site selection criterion appears to be "like-on-like." This criterion calls for selection of a site where ambient metals concentrations are comparable to those in the materials to be dredged. As discussed in the introduction, disposal of materials dredged from the Baltimore Approach Channels at the sites proposed in this section would not result in significant elevation of contaminant concentrations in sediments at those sites. This is not to suggest that trace metal uptake by benthic organisms will not occur, only that it will not be accelerated by disposal. At present, there is no way of evaluating the relative possibilities of uptake at the various disposal site options.

2. *Plankton.* Uptake of metals by plankton occurs mostly from the soluble form (Bryan, 1971) and therefore will be increased only in those disposal areas where significant dissolved metals are released. Examination of Table 8c shows that release of dissolved metals is likely to occur only in fringing wetland sites. Therefore, uptake of metals from dredged materials by plankton may possibly occur in the open waters adjacent to such sites.

3. *Nekton.* Uptake of metals by fish occurs from the dissolved state and also from metals incorporated into plankton and benthos. Disposal sites which neither release dissolved metals nor impact benthos will not lead to uptake of metals by nekton.

4. *Emergent grasses.* Several studies (Lee et al., 1978; Gambrell et al., 1977; Center for Wetland Resources, 1977) have described the ability of marsh grasses to take-up significant quantitite os heavy metals from fine-grained sediment. Because salt marsh detritus may be exported from marshes to surrounding open waters, this provides a mechanism for the dispersal of toxic metals over a larger area and for their entry into numerous organisms. Only fringing area disposal sites are subject, of course, to emergent grass uptake of metals.

B. CHCs

Because long term desorption of chlorinated hydrocarbons from submarine disposal piles can not be ruled out (see appendices L, v), and because these substances are known to be taken up from solution by plankton, mollusks (Duke et al., 1970), and nekton (Smith and Cole, 1970), uptake of CHCs by these organisms is probable. It is unlikely, but not impossible, that significant quantities of CHCs desorbed from submarine sites would impact fringing areas. If fringing areas are constructed from CHC contaminated materials, uptake by marsh plants is possible.

References

Bryan, G.W. 1971. The effect of heavy metals (other than mercury) on marine and estuarine organisms. Proceedings Royal Society of London. B177:389-410.

Center for Wetland Resources, Louisiana State Univ. 1977. Trace and Toxic Metal Uptake by Marsh Plants as Affected by Eh, PH and Salinity. D.M.R.P. Tech. Rept. D-77-40 U.S.A.C.E., Vicksburg, Miss.

Duke, T.W., J.I. Lowe, and A.J. Wilson, Jr. 1970. A polychlorinated biphenyl (Arochlor 1254) in water sediment, and biota of Escambia Bay, Fl. Bull. of Environmental Contamination and Toxicology. 5:171-180.

Gambrell, R.P., V.R. Collard, C.N. Reddy, and W.H. Patrick, Jr. 1977. Trace and toxic metal uptake by marsh plants as affected by Eh, pH, and salinity. Tech. Rept. D-78-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Smith, R.M. and C.F. Cole. 1970. Chlorinated hydrocarbon insecticide residues in winter flounder, *Pseudopleuronectas americanus*, from the Weweantic River Estuary, Ma. J. of Fisheries Res. Bd. of Canada. 27:2734-2380.

APPENDIX II

Effects of different disposal strategies on the frequency of dredging required to maintain Baltimore Harbor Channels (Table 11).

If dredged materials are not sufficiently removed or isolated from the dredging site, waves and tides may cause the return of these materials to the channel. Inasmuch as most previous disposal of Baltimore Harbor materials has been at the Kent Island site or on fringing areas (Md. Dept. of Natural Resources, 1976), continued use of this and other geographically removed locations will not result in any change in the historical frequency of dredging required to maintain the Harbor channels at their present project depth. Use of uncontained, overboard sites close to the channels might increase the frequency of dredging required for channel maintenance because of increased return of dredged materials to the channel.

Reference

Hamons, F., ed. 1976. Monitoring of open water dredge material disposal operations at Kent Island disposal site and survey of associated environmental impacts. Maryland Dept. of Natural Resources Final Rept., 310pp.

APPENDIX JJ

Assessment of the degree of turbulence at the proposed disposal sites for materials dredged from Baltimore Harbor Channels (Table 11).

Unconfined overboard disposal sites are the more turbulent of the two submarine options we considered for disposal of materials dredged from the Baltimore Harbor Channels. The confined, submerged, overboard option is less turbulent.

APPENDIX KK

Amount of sediment resuspension at the proposed disposal sites for materials dredged from Baltimore Harbor Channels (Table 11).

For a discussion of the factors controlling bottom sediment resuspension see Appendix B. Without detailed information on the physical and biological characteristics of sediment at the proposed disposal sites, we must rank the sites in terms of the degree of bottom water turbulence. There are two submarine disposal options under consideration to receive Baltimore Harbor channels material. The confined overboard site will be subject to substantially less sediment resuspension than the unconfined, overboard disposal option.

APPENDIX LL

Excess turbidity in the water column during disposal operations for materials dredged from Baltimore Harbor Channels (Table 12a).

The possibility of generation of excess turbidity by the disposal methods under consideration has been discussed in detail in Appendix D. The conclusion, that any excess turbidity generated during disposal will be temporary and local in extent, holds for the disposal options considered for materials dredged from Baltimore Harbor Channels.

APPENDIX MM

Assessment of contaminant releases to the water column during disposal operations of materials dredged from Baltimore Harbor Channels (Table 12a).

See Appendix E for a detailed discussion of the geochemical processes that control the possible release of metals, nutrients, and CHCs from dredged materials during disposal operations.

(1) Metals

The conclusion reached in Appendix E, that release of metals from dredged materials during disposal operations is unlikely, holds for the disposal methods and locations we considered for materials dredged from Baltimore Harbor Channels.

(2) Nutrients

The conclusion reached in Appendix E, that releases of nutrients from the dredged material during disposal will have a negligible impact on the water column, is equally applicable to all the dredging/disposal options considered for materials dredged from Baltimore Harbor Channels.

(3) CHCs

The difficulties involved in predicting the environmental behavior of CHCs have been described in detail in Appendix E. Release of CHCs from Baltimore Harbor Channels material during disposal operations may be more likely than from sediments considered in the other case studies in this report for two reasons. First, the Baltimore Harbor materials are much higher in CHC content (see Table 10). If, as has been assumed, there is a measurable distribution coefficient for CHCs between the solid and dissolved states, a higher CHC concentration in the adsorbed state produces a higher concentration in the water. Second, Baltimore Harbor materials contain significant levels of hexane extractable compounds (see Table 10). Since CHCs are fat soluble, these may increase the solubility of sediment-associated CHCs.

Both of these effects remain unevaluated. Until experimental evidence indicates otherwise, we should consider that significant release of CHCs from Baltimore Harbor Materials during disposal operations is a distinct possibility.

APPENDIX NN

Oxygen depletion of the water column during disposal of materials dredged from Baltimore Harbor Channels (Table 12a).

In Appendix F we considered the possible oxygen depletion of the water column during disposal operations. The conclusion reached there, that any reduction is temporary and local in extent, holds for the disposal options considered for materials dredged from the Baltimore Harbor channels as well.

APPENDIX OO

Ecological effects of increased water column turbidity during disposal of Baltimore Harbor Channels material (Table 12b).

1. Phytoplankton

Reductions in incident illumination and the consequent possible decrease in phytoplankton photosynthetic activity as the result of increased water column turbidity are confined to the temporal and spatial limits of the turbidity plume. Because this plume is transitory and local (see Appendix D) in extent, associated decreases in phytoplankton photosynthesis are also temporary and local. It is highly unlikely that the small area affected by the increased turbidity caused by disposal operations can have more than a negligible effect on the total estuarine phytoplankton primary production (Flemer, 1970).

2. Zooplankton

The temporary and local nature of the turbidity plume associated with dredged material disposal (see Appendix D) limits any effect upon zooplankton to a small area. Estuarine zooplankton must already be adapted to coping with levels of suspended sediment similar to those found over much of the excess turbidity plume from dredged material disposal (Goodwyn, 1970).

3. Nekton

The generally small area that is temporarily affected by excess turbidity during dredged material disposal can have no more than a negligible effect on nekton populations in the estuary (Dovel, 1970).

4. Benthos

The generally small area that is temporarily affected by excess turbidity during dredged material disposal can have no more than a negligible impact on benthic populations outside of the immediate disposal area (Pfitzenmeyer, 1970).

5. Fish Eggs and Larvae

Numerous studies (Schubel and Wang; 1973, Sherk et al.; 1970, Auld and Schubel; 1978) have indicated that the survival of eggs and larvae of typical estuarine fishes (yellow perch, blueback herring, alewife, American shad, white perch, striped bass) are not significantly decreased by exposure to suspensions of natural fine-grained relatively uncontaminated sediments with concentrations much greater than those typically observed, even during dredging and disposal. Based on these studies we conclude that the excess concentrations of suspended sediment that result from dredging and disposal of relatively uncontaminated sediments do not represent a significant hazard to fish eggs and larvae as far as acute effects are concerned. Chronic effects have, however, not been adequately investigated.

References

Auld, H.H. and J.R. Schubel. 1978. Effects of suspended sediment on fish eggs and larvae: a laboratory assessment. Est. Coast. Mar. Sci. 6:153-164.

Flemer, D.A. 1970. Project B, Phytoplankton. Pages 16-25 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Goodwyn, F. 1970. Project D. Zooplankton. Pages 39-41 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Pfitzenmeyer, H.T. 1970. Porject C, Benthos. Pages 26-38 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Richie, D.E. 1970. Project F, Fish. Pages 50-63 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst., Special Rept. #3, Ches. Biol. Lab., Univ. of Md.

Schubel, J.R. and J.C.S. Want. 1973. The effects of suspended sediment on the hatching success of *Perca flavescens* (yellow perch), *Morone americana* (white perch), *Morone saxatilis* (striped bass) and *Alosa pseudoharengus* (alewife) eggs. Special Report No. 30, Ches. Bay. Inst., Johns Hopkins Univ., Ref. 73-53, 77pp.

Sherk, J.A. and L.E. Cronin. 1970. The effects of suspended and deposited sediments on estuarine organisms. An annotated bibliography of selected references, Univ. of Md., National Res. Inst., Ref. 70-19, 61pp + addendum.

APPENDIX PP

Smothering of benthos by disposal of Baltimore Harbor materials in various disposal sites (Table 12b).

At the submarine disposal sites considered in this section smothering of benthos by disposal of dredged material will probably be complete. Recolonization will occur relatively rapidly, however, in unconfined (overboard) sites (See Appendix XX). Recovery in confined submarine sites will be slower and complete recovery may not occur. With wetland and island construction, the pre-disposal communities will be permanently altered.

APPENDIX QQ

Exclusion/attraction of fish at Baltimore Harbor Alternatives (Table 12b).

During disposal operations attraction of local finfish to the turbidity plume has been occasionally observed. This attraction has been attributed to releases of particulate organic matter associated with the dredged material which serve as a food source for the fish. Finfish have also been observed to be repelled by the turbidity plume, perhaps in response to the generally lowered dissolved oxygen levels in its immediate vicinity. Generally it has been observed that fish are more sensitive to oxygen depletion than to excess turbidity, and appear to be repelled from the disposal area before encountering the high turbidity levels located within the plume. Because of this defensive mechanism, and also because of the limited area strongly affected by increased turbidity during disposal (see Appendix D), disposal operations do not pose a threat to resident finfish populations at locations where sufficient space is available to enable fish to avoid the plume. This is true for all the locations under consideration in this report.

APPENDIX RR

Uptake of contaminants by biota during the disposal of Baltimore Harbor Channels material at various submarine disposal sites (Table 12b).

1. Metals

Because the release of soluble metals during disposal is considered unlikely, benthos, plankton, and nekton will not be subject to metals concentrations higher than ambient and the rate of uptake of metals will not be affected. See Appendix V for more detail.

2. CHCs

Because the release of soluble CHCs during disposal operations is considered possible, benthos, nekton, and plankton might take up these compounds at faster rates and in greater amounts as the result of disposal (see Appendix E). Evaluation of the magnitude of this uptake is impossible without knowledge of the CHC distribution coefficient. We recommend that this be determined particularly for Baltimore Harbor materials, some of which are highly contaminated with CHCs.

APPENDIX SS

Excess turbidity in water column subsequent to disposal of materials dredged from Baltimore Harbor Channels (Table 12c).

The conclusion reached in Appendix K that excess turbidity subsequent to disposal operations would be negligible is true for all the sites under consideration here except the undiked overboard site within Baltimore Harbor. The possibility exists that, because the Harbor is not normally subject to extreme changes in turbidity, possible sediment resuspension from the undiked site (see Appendix KK), might create a persistent source of excess turbidity. The effects, however, would be local and small.

APPENDIX TT

Increased contaminant releases to water column subsequent to disposal of Baltimore Harbor dredged materials.

1. Metals

Although contaminated with metals to a greater degree than material dredged from either of the other Projects, the geochemical mechanisms binding the metals to these sediments are expected to be similar. Because of this, the conclusions expressed in Appendix E, that with subaqueous disposal releases of metals to solution will be minor, hold true here as well. A confined *submerged* disposal site is considered best because it minimizes sediment resuspension and oxidation of reduced metal compounds.

The subaerially exposed disposal alternatives, island or marsh creation, and upland disposal, all are considered more likely to result in increased metal releases to solution (Mang et al., 1978). This is because of the increased probability that the reduced sediments will be oxidized. Although no studies have been published on the chemical composition of runoff and groundwater flow from dredged material islands, and the possibility exists that the most highly contaminated materials could be isolated through appropriate engineering structures such as the use of "nested dikes," the critical studies have not, in our opinion, been conducted to demonstrate that contaminants would not be released in solution with subaerial disposal.

2. Nutrients

Releases of nutrients from the submerged disposal options considered for Baltimore Harbor materials are expected to be small in relation to the amount of nutrients naturally regenerated from Bay sediments, the calculations leading to this conclusion are detailed in Appendix E-2.

This is not true for the subaerially exposed alternatives.

Here percolating groundwater solutions have a high potential for releasing large quantities of N and P compounds (Mang et al.; 1978).

3. <u>CHCs</u>

As discussed in Appendix E-3, the release of CHC compounds from dredged materials is considered possible. There is a somewhat larger probability of such release occurring from subaerially exposed disposal alternatives because of the possible role of percolating groundwater solutions as a vector.

Reference

Mang, J.L., C.S. Lu, R.J. Lofy, R.P. Stearns. 1978. A study of leachate from dredged material in upland areas and/or in productive uses. DMRP Tech. Rept. D-78-20, U.S.A.C.E., Vicksburg, Miss.

APPENDIX UU

Oxygen depletion of the water column subsequent to disposal of materials dredged from Baltimore Harbor (Table 12c).

This has been considered in detail in Appendix M. The conclusion that oxygen depletion would be undetectable under the turbulent conditions encountered at the disposal sites is unchanged for the disposal options considered for materials dredged from Baltimore Harbor Channels.

APPENDIX VV

Movement of materials dredged from Baltimore Harbor Channels and placed at various disposal sites (Table 12c).

As discussed previously in Appendix M, movement of dredged materials subsequent to disposal is by sediment resuspension and "fluid mud" flow along the bottom. Of the two submarine disposal options considered for materials dredged from Baltimore Harbor--confined and unconfined overboard disposal--significant sediment movement can occur only from the undiked option. The principal advantage of enclosing the site is to reduce post-disposal movement of sediment.

Movement of sediment from land sites by subaerial erosion processes can be minimized if proper sediment control measures are taken.

APPENDIX WW

Effect of changes of bottom topography at Baltimore Harbor Alternatives (Table 12c).

Possible effects of changes in bottom topography as a result of dredging and spoil operations would include changes in the distribution and strength of the currents; changes in the intensity of turbulence; and changes in the usability for the area for fishing and boating.

Disposal of spoil overboard in areas adjacent to the Baltimore Harbor channel would have negligible effect on the distribution of currents in the cross-section and on the intensity of turbulence. Since the material being dredged from these channels is for the most part silt and clay, the spoil will, soon after disposal, be spread by the effects of gravity and by the currents over a wide area. Much of it, in fact, ultimately will return to the channel. Any temporary decrease in depth over the adjacent area will be small, and will be offset by the increase in depth of the channel as a result of dredging. Thus the average current speed in any given cross-section would not be changed by the dredging and spoiling operation, and any change in the distribution of currents in the section would be negligible.

Subsequent to disposal of the spoil, there would not be any significant effects of overboard disposal in areas adjacent to the channel on the use of such areas for fishing and boating. Note that we are here discussing any physical effects such as interference with fishing gear or creation of hazards to navigation (i.e., shoal areas), and not to any strictly biological effects on fishing success.

The creation of confined, submerged disposal areas adjacent to the Baltimore Harbor Channel could influence the distribution of currents in the reach of the Harbor containing such a disposal area, and also on the use of such areas for fishing and boating. The degree of impact of a confined, submerged disposal area will depend on specific features of location and size. There is very little space in Baltimore Harbor inside of Hawkins Point (Francis Scott Key Bridge) for confined, submerged disposal areas. The cost of dike construction per cubic yard of capacity of the disposal area decreases with increasing area inside the dikes. Thus from considerations of cost effectiveness, it is doubtful that confined, submerged disposal areas would be justifiable in the inner half of the harbor. The only area in the Harbor that appears suitable for such use is the reach just south of the Brewerton Channel, and extending from the inner end of Sparrows Point out to the mouth of the Harbor at the Rock Point shoal/North Point section. In order to examine the possible effects of a confined, submerged disposal area adjacent to the Baltimore Harbor Channel we have considered one plausible case of such a disposal facility located in this outer Harbor area.

The case we considered assumes that a confined, submerged disposal facility is established in the currently discontinued spoil area south of the Brewerton Channel. A rectangular shaped diked area, 4000 ft (1220 m) wide and 12,000 ft(3,660 m) long (in the direction parallel to the Brewerton Channel) in the area just south-southwest of the Channel, extending from the mouth of the Harbor (the Bodkin Point to North Point transect) inwards to about opposite the western end of Sparrows Point, is considered. The depths in the region of this assumed facility average about 15 ft (4.6 m). If the dikes were built upwards from the bottom to within seven ft (2.1 m) of the surface, this facility could hold 14.22 million $yards^3$ (10.88 million m^3).

This facility would occupy 28.5% of the width of the bottom of the Bodkin Point to North Point transect. Filled to within 7 ft (2.1 m) of the surface, this diked facility would result in a decrease in the cross-sectional area by 15.3% and a consequent increase in the sectionally averaged peak ebb and flood velocities by 18%. The tidal current velocities are, however, quite small within the Harbor, and even at the transect at the mouth, the maximum ebb and flood velocities are only about 0.34 ft sec^{-1} (10.3 cm sec^{-1}). Increasing these values by 18% would not result in any significant increase in scouring or hazard to navigation.

The construction of such a submerged diked facility would result in restrictions for transit of vessels having drafts of between 7 ft (2.1 m) and 15 feet (4.6 m). The dikes of this disposal area could be located so that such craft having as a destination Rock Creek or Stony Creek could pass southward of the facility.

The construction of a diked island inside or outside of the Harbor for confinement of dredging spoil would have effects on circulation similar to those described for the submerged diked areas. To illustrate the possible effects of such a facility, we have considered the case of the proposed Hart and Miller Islands disposal area.

This facility as currently planned will be a rectangular diked enclosure extending out from Hart Island and Miller Island. These islands would form the bulk of the west-northwest boundary of the enclosure. The critical cross-section of the Bay with respect to this structure runs from Miller Island in a east-southeast direction to the eastern shore just south of Tolchester Beach. The width of this section would be reduced by about 14.3% by construction of the diked enclosure at Hart and Miller Islands. The area of this cross-section would be reduced by 7.2%, and consequently the peak ebb and flood tidal velocities would be increased by 7.8%. The resulting maximum tidal velocities would average about 0.8 ft/sec (24 cm sec^{-1}) over the cross-section. Velocities of this magnitude are found at sections of the Bay both north and south of this transect. No significant increase in scour or hazard to navigation would occur as a result of this increase in velocity.

Turbulence would be somewhat increased in the vicinity of the dikes forming the enclosure. The outside of the dikes might also prove to be a desired substrate for sessile organisms. These two facts could make the area of the Bay adjacent to the site attractive to forage fish, and hence to game fish. This possible benefit is at least somewhat offset by the loss of the area of the Bay covered by the artificial island for pleasure boating. Note that there is no commercial fishing or any significant commercial boat traffic in this area.

The disposal option which uses spoil to create marshland from protected shallow water areas adjacent to the Harbor would obviously change the local circulation, providing in fact an entirely new hydrodynamic regime as well as an entirely new biological habitat. The effect that the creation of wetlands by spoil disposal in protected shallow water areas adjacent to or along the shores of the Harbor would have on currents in adjacent open waters would depend on the fraction of the cross-section of the Harbor represented by such fill operations. In general, the effects of this option of spoil disposal would be negligible on the distribution of currents in the waters of the adjacent open Harbor.

APPENDIX XX

Time required for the recovery of the benthic community subsequent to the disposal of material dredged from Baltimore Harbor Channels (Table 12d).

A. Biomass

Although specific information on benthic community recruitment is limited for Baltimore Harbor, data obtained from similar environments (see Appendix P) indicate that recovery of benthic biomass subsequent to disposal of Baltimore Harbor Materials will be rapid; complete recovery within 1.5 years. The benthos in the inner Harbor are generally impoverished (Tsai et al., 1979) and are dominated by worms. It is unlikely that the temporary destruction of a small part of this biomass by disposal operations could produce a significant and persistent ecological effect.

B. Diversity

Although specific information on the recovery of benthic diversity following depopulation of Baltimore Harbor sediments is not available, similar areas (see Appendix P) have recovered diversity within 1.5 years.

Reference

Tsai, C-F, J. Welch, K-Y Chang, J. Shaeffer and L.E. Cronin. 1979. Bioassay of Baltimore Harbor Sediments. Estuaries 2(3):141-153.

APPENDIX YY

Uptake of contaminants by organisms subsequent to disposal of Baltimore Harbor Channel materials (Table 12d).

A. Metals

1. Benthos. The conclusion reached in Appendix Q, that benthic organisms have the ability to take up metals directly from sediment, remains unchanged for the Baltimore Harbor materials. It is important, however, that the benthic populations currently in the inner Harbor are impoverished, and that therefore there are few organisms available for uptake of metals if the dredged materials are disposed within this area.

2. Plankton. Because the most important mechanism of planktonic metals uptake is directly from solution (see Appendix Q), only those disposal options that may release soluble metals have the possibility to directly affect plankton. Of the disposal options considered for material dredged from Baltimore Harbor Channels, island construction, fringing areas, and upland disposal, all are considered to have the potential for release of soluble metals. Possible planktonic uptake of metals is limited to open waters adjacent to these disposal sites. Because release of soluble metals from the submarine sites is considered unlikely, disposal of Baltimore Harbor Materials in these sites is considered unlikely to affect metals levels in plankton.

3. Nekton. Fish also dominantly take up metals from the dissolved state. Therefore only those sites where soluble metals release is considered possible may impact fish. These are the same disposal options that will directly affect plankton and include upland disposal, island construction, and fringing areas.

4. Emergent Grasses. Emergent grasses--plants growing in the intertidal zone--have the potential to take up metals from their substrate (see Appendix HH). Of the disposal options considered here, only salt marsh creation, and possibly island construction, would place dredged materials in the intertidal zone. These are therefore the only options where metals uptake by emergent grasses would be possible.

5. *Terrestrial Plants.* Terrestrial plants have the ability to take up metals from their soil. Of the disposal options for Baltimore Harbor materials considered here, new terrestrial land will be created only in island creation and upland disposal. Terrestrial plants may possibly uptake metals from dredged materials if these options are used.

B. CHCs

1. *Benthos.* Benthic organisms have the ability to take up CHCs from the sediments they inhabit (see Appendix Q). Of the disposal options considered here to receive Baltimore Harbor materials, only disposal sites alongside the channel, confined or unconfined, are inhabited by benthic organisms. Uptake of CHCs by benthic organisms may occur if these options are utilized. There is no reason to believe, however, that the uptake of CHCs by benthos will be increased necessarily if these disposal options are utilized. Organisms inhabiting these areas are already exposed to sediment CHC levels similar to those of the dredged material.

2. *Plankton.* Plankton are most likely to take up CHCs directly from solution. All the disposal options considered here for Baltimore Harbor materials may lead to release of CHCs in the soluble state. Therefore plankton inhabiting waters near these proposed disposal options have the potential for increased CHC uptake subsequent to disposal operations. Increased uptake of CHCs by plankton is much less likely at the submerged inner Harbor sites, then at the alternative sites considered. Because little is known about the environmental chemistry of CHC compounds, there is little reason to believe that the process of

dredging and disposal increases CHC solubilization from sediment. Plankton inhabiting the inner Harbor are already exposed to high CHC levels which probably will be neither reduced nor increased if dredged material disposal occurs there.

3. *Nekton.* Fish dominantly take up CHCs from solution. Therefore the previous discussion of the possible planktonic uptake of CHCs applies also to nekton. Increased uptake of CHCs by nekton is possible from utilization of all the disposal options considered, but is less likely if the along-channel submerged option is used.

4. *Emergent Grasses.* Emergent grasses--plants growing in the intertidal zone--have the ability to take up CHCs from their substrate (see Appendix HH). Of the disposal options for Baltimore Harbor materials considered here, only salt marsh creation and possibly island construction would place dredged materials in the intertidal zone. These are therefore the options where CHC uptake by emergent grasses would be most likely.

5. *Terrestrial Plants.* Terrestrial plants may have the ability to take up CHCs from their soil. Of the disposal options for Baltimore Harbor materials considered here, new terrestrial land will be created only in island creation and upland disposal. Terrestrial plants are most likely to take up CHCs from dredged materials at these locations.

References

Biggs, R.B. 1970. Sources and distribution of suspended sediment in northern Chesapeake Bay. Marine Geol. 9:187-201.

Burt, W.V. 1955. Distribution of suspended materials in Chesapeake Bay. J. Mar. Res. 14:47-62

Carpenter, J.H., W.L. Bradford and V. Grant. 1975. Processes affecting the composition of estuarine Waters (HCO_3, Fe, Mn, Cu, Ni, Cr, Co, and Cd). Pages 188-214 *in* L.E. Cronin, ed., Estuarine Research, Vol. 1, Chemistry, Biology, and the Estuarine System. Academic Press, New York.

Goldberg, E.D., V. Hodge, M. Koide, J. Griffin, E. Gamble, O.P. Bricker, G. Matisoff, G.R. Holdren and R. Braun. 1978. A pollution history of Chesapeake Bay. Geochemica et Cosmochemica Acta. 42:1413-1425.

Gross, M.G., M. Karweit, W.B. Cronin, J.R. Schubel. 1978. Suspended sediment discharge of the Susquehanna River to northern Chesapeake Bay, 1966 to 1976. Estuaries 1(2):106-110.

Hirschberg, D.J. and J.R. Schubel. 1979. Recent geochemical history of flood deposits in the northern Chesapeake Bay. Estuarine and Coastal Marine Science 9:771-784.

Ippen, A.T. 1966. Sedimentation in estuaries. Pages 648-672 *in* A.T. Ippen, ed., Estuary and coastline hydrodynamics. McGraw-Hill, New York.

Lüneburg, H. 1939. Hydrochemische Untersuchungen in der Elbmündung mittels Elektrokolorimeter: Arch. Deutsch Seewarte 59:1-27.

Munson, T.O. 1975. Biochemistry. Pages 6-1 - 6-30, Chapt. 6, *in* Upper Bay Surrey, Vol. II. T.O. Munson (Project Chief Scientist), D.K. Ela (Project Manager) and C. Rutledge, Jr. (Project Engineer and Coordinating Editor). Technical Rept., Westinghouse Electric Corp., Oceanic Div., Annapolis, Md. 21404.

Nelson, B.W. 1959. Transportation of Colloidal sediment in the fresh water marine transition zone. Am. Assoc. Adv. Sci., 1st Internat. Oceanog. Cong., p.640-641 (preprint) (Abstr.).

Owens, J.P., L.A. Sirkin and K. Stefansson. 1974. Chemical, Mineralogic, and Polynologic Character of the Upper Wisconsinan-Lower Holocene Fill in Parts of Hudson, Delaware, and Chesapeake Estuaries. J. Sed. Petrology 44:390-408.

Palmer, H.D. 1973. Shoreline Erosion in Upper Chesapeake Bay: The Role of Graoundwater. Shore and Beach 41:18-22.

Palmer, H.D., J.R. Schubel and W.B. Cronin. 1975. Estuarine Sedimentology. Pages 4-11 - 4-63, Chapt. 4, *in* Upper Bay Survey, Vol. II. T.O. Munson (Project Chief Scientist), D.K. Ela (Project Manager), and C. Rutledge, Jr. (Project Engineer and Coordinating Editor). Technical Rept., Westinghouse Electric Corp., Oceanic Div., Annapolis, Md. 21404.

Postma, H. 1967. Sediment transport and sedimentation in the estuarine environment. Pages 158-179 *in* G.H. Lauff, ed., Estuaries. Am. Assoc. Adv. Sci. Pub. No. 83.

Pritchard, D.W.. 1968. Chemical and Physical Oceanography of the Bay. Pages II-49 - II-74 *in* Proceedings of the Governor's Conference on Chesapeake Bay. Summary of the Governor's Conference held at Wye Inst. in Md. 12-13 September 1968. 213pp + appendices.

Ryan, J.D. 1953. The sediments of Chesapeake Bay. Bulletin No. 12 of the Maryland Dept. of Geology, Mines and Water Resources. 120pp.

Schubel, J.R. 1968a. Suspended sediment of the northern Chesapeake Bay. Tech. Rept. 35, Chesapeake Bay Inst. of the Johns Hopkins Univ. 264pp.

Schubel, J.R. 1968b. Turbidity maximum of northern Chesapeake Bay. Science 161:1013-1015.

Schubel, J.R. 1969. Size distributions of the suspended particles of the Chesapeake Bay turbidity maximum: Netherlands Jour. Sea Research. 4:283-309.

Schubel, J.R., ed. 1971a. The Estuarine Environment, Estuaries and Estuarine Sedimentation. Amer. Geol. Inst., Washington, D.C. Short course lecture notes. 324pp (not numbered consecutively).

Schubel, J.R. 1971b. Tidal variation of the size distribution of suspended sediment at a station in the Chesapeake Bay turbidity maximum. Netherlands Jour. Sea Research. 5:252-266.

Schubel, J.R. 1972a. the physical and chemical conditions of the Chesapeake Bay. Jour. Wash. Acad. Sci. 62:56-87.

Schubel, J.R. 1972b. Distribution and transportation of suspended sediment in upper Chesapeake Bay. Pages 151-167 *in* B.W. Nelson, ed. Environmental Framework of Coastal Plain Estuaries. Geol. Soc. Amer. Memoir 133. 619pp.

Schubel, J.R. 1974. Effects of Tropical Storm Agnes on the suspended solids of the northern Chesapeake Bay. Pages 113-132 *in* R.J. Gibbs, ed. Suspended Solids in Water. Plenum Press, New York. 320pp.

Schubel, J.R. 1976. Suspended sediment in Chesapeake Bay. Pages 245-264 *in* Proceedings, Civil Engineering in the Oceans III, Vol. 1. Amer. Soc. of Civil Engineers, N.Y.

Schubel, J.R. and H.H. Carter. 1977. Suspended sediment budget for Chesapeake Bay. Pages 48-62 *in* M.L. Wiley, ed., Estuarine Processes Vol. II, Circulation, Sediments, and Transfer of Material in the Estuary. Academic Press, N.Y. 428pp.

Schubel, J.R. and D.J. Hirschberg. 1977. Pb^{210}-determined sedimentation rate, and accumulation of metals in sediments at a station in Chesapeake Bay. Chesapeake Sci. 18:379-382.

Schubel, J.R., C.H. Morrow, W.B. Cronin and A. Mason. 1970. Suspended sediment data summary, August 1969-July 1970 (Mouth of Bay to Head of Bay). Spec. Rept. 18, Chesapeake Bay Inst. of The Johns Hopkins Univ. 39pp.

Schubel, J.R. and C.F. Zabawa. 1976. Agnes in the geological record of the upper Chesapeake Bay. Pages 240-250 *in* The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System. The Chesapeake Res. Consortium, Inc., CRC Pub. No. 54.

Singewald, J.T. and T.H. Slaughter. 1949. Shore erosion in tidewater Maryland. Maryland Dept. of Geology, Mines and Water Resources, Bull. 6. 140pp.

Tsai, C-F., J. Welch, K-Y. Chang, J. Schaeffer and L.E. Cronin. 1979. Bioassay of Baltimore Harbor sediments. Estuaries 2:141-153.

Turekian, K.K. and M.R. Scott. 1967. Concentrations of Cr, Ag, Mo, Ni, Co and Mn in Suspended Material in Streams. Environ. Sci. Tech. 1:940-942.

Villa, O., Jr. and P.G. Johnson. 1974. Distribution of Metals in Baltimore Harbor Sediments. Technical Rept. 59, Annapolis Field Office, Region III, EPA. 64pp, not numbered consecutively.

Zabawa, C.F. and J.R. Schubel. 1974. Geological effects of tropical storm Agnes on upper Chesapeake Bay. Maritime Sediments 10:79-84.