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Executive Summary

In creating a deep reach of the Ambrose Channel, a buffer zone 128 to 490 feet wide is recommended within which the water depth would increase gradually from 45 feet to 70 feet. Hydrodynamic modeling showed that a buffer zone 128-feet wide would eliminate recirculating eddies within the compartment that could tend to trap fine-grained sediment and result in the accumulation of contaminated sediment with a high demand for oxygen. A zone 490 feet wide would eliminate a low velocity zone downstream of the eddy by allowing the tidal flow to expand gradually into the compartment reaching velocities above 35 cm/sec at the bottom to prevent any deposition of fine-grained sediments. The deepened compartment with a buffer zone is unlikely to impact local levels of dissolved oxygen or the regional sand budget. The buffer zone should be created where the deepened stretch ends and on both sides of zone where a pipeline crosses the channel.

Background

Ambrose Channel is the main shipping channel into the Lower Bay of New York Harbor. It is nominally maintained at a depth of 45 feet but recent dredging has increased that depth to 53 feet in some sections. The channel is crossed by a pipeline at about -61 feet protected by a layer of sand with a clearance of at least 45 feet at mean low water. If the channel northwest of the pipeline is deepened to -70 feet, a compartment will be created. Its floor would be 25 feet below the 45-foot level of the pipeline and it would extend about 12,000 feet along the axis of the channel. The concern has been raised that the new hydrodynamic conditions in this compartment may allow mud to accumulate. Fine-grained sediment (mud) in the Harbor typically has a high organic content and usually is contaminated since many contaminants are adsorbed onto particles of silt and clay. The subsequent chemical reduction of sediment organic matter may then cause hypoxia. Whether or not this occurs depends upon the hydrodynamic conditions in the deepened reach which is the subject of this article.

Mud has accumulated very rapidly in isolated borrow pits on the West Bank of Ambrose Channel and adverse dissolved oxygen conditions have resulted. It seems unlikely, however, that the relief of the deepened reach of the Ambrose Channel would alter the hydrodynamic conditions sufficiently to cause deposition of fine-grained sediment; the tides should remain effective in preventing the deposition of fine-grained sediments within the compartment. Borrow pits on the nearby East Bank which are hydraulically connected to the Ambrose Channel are flushed sufficiently to prevent the deposition of mud (Swartz and Brinkhuis, 1978). These pits had been dug between 1973 and 1976 and reached charted depths of 70 feet. In 1978, Swartz and Brinkhuis (1978) found that the sediments in this area were coarse grained "with very low levels of organic carbon and sulfide"; as a result they had no impact on the levels of dissolved oxygen on the East Bank. The floors of these pits were still sandy when sampled in 1986 (Cerrato, et al., 1989).

The hydrological conditions are different in pits on the West Bank. Borrow pits on the West Bank are isolated, that is, they are not directly connected to the Ambrose Channel. Fine-grained sediment has been accumulating at a rapid pace in these pits (Bokuniewicz, et al., 1986; Olsen, et al., 1984; Sneed, 1986). They do have a direct adverse effect on the levels of dissolved oxygen because of their hydraulic isolation and the accumulation of mud with a high organic content (Swartz and Brinkhuis, 1978). An aspect ratio (depth below the ambient sea floor divided by the depression's diameter in the direction of the current) can be used to describe the hydraulic conditions. These pits have an aspect ratio greater than 0.005. Based on salinity measurement, this aspect ratio is the minimum value that allows the development of stratification in the presence of the harbor's tides (NY District, U.S. Army Corps of Engineers, 1990). The aspect ratio of the proposed deepened compartment in Ambrose Channel would be 0.002, so that the tides should be sufficient to mix water within the pocket, prevent the development of a salinity stratification in the pocket and the deposition of fine-grained sediment.

By continuity, the current velocities in the deepened reach might decrease by a factor of 45/70 or 0.64. Under existing conditions, the maximum tidal currents near the bottom of the Ambrose Channel approximately along the transect between Rockaway and Sandy Hook (or about 41°30'25"N; 73°58'00"W between buoys R5 and R6) are as follows:

Depth below the surface (feet)	Maximum Tidal Speed Flood	Ebb
	cm/sec	
5.5	86.3	129.1
16.4	91.4	108.9
26.8	86.3	82.5

These velocities were calculated from current meter data of the U.S. Coast and Geodetic survey done in 1958-59 and reported by Doyle and Wilson (1978). In the deepened compartment, therefore, maximum tidal currents should reach speeds of at least 52.8 cm/sec, that is, 82.5 cm/sec times 0.64.

This will be adequate to prevent the widespread deposition of mud. The condition for the deposition of fine-grained sediment has been summarized by McCave (1984; Figure 1). A velocity of 52.8 cm/sec would correspond to a shear velocity of 28.9 cm/sec which is well above the critical velocity required for deposition of mud. The coarsest silt with a grain size of 63 micrometers would not begin to deposit until the velocity one meter above the sea floor fell below 16.5 cm/sec. Smaller particles (silt and clay) require even lower velocities for deposition. In any reversing tidal flow, including the existing conditions, the current speed will fall below this level sometime every tidal cycle so that deposition will occur during that period. The newly deposited material will be resuspended, however, as the current speeds increase again over the next phase of the tide. Whether or not permanent mud deposits form depends on the relative rates at which these processes occur. In the Lower Bay there are places where the maximum tidal velocity is less than 35 cm/sec (Doyle and Wilson, 1978) and yet mud deposits have not formed. For conditions in the Lower Bay, therefore, keeping the maximum tidal velocity above 35 cm/sec should be sufficient to prevent the formation of mud deposits.

Near the upstream and downstream wall of the compartment, however, local conditions may create pockets of recirculating water conducive to the trapping of fine-grained sediments. This flow phenomenon is well known. At the edge of an abrupt change in the bathymetry, a parcel of water moving near the bottom may "separate" or detach itself from the bottom and follow a curving trajectory until it reattaches itself to the sea floor further downstream (Figure 2, Roache, 1972); beneath the trajectory, a recirculating eddy forms. Flow separation plays an important role in the formation and maintenance of many sedimentary structures, but separation will not occur if the bathymetry is streamlined (Allen, 1969). There are no generally applicable, quantitative descriptions of this process so, the following approach was used to investigate the separation flow for conditions in the Ambrose Channel and to recommend a buffer zone to streamline the bathymetry and to mitigate possible adverse effects.

Approach

A generic two-dimensional cross-sectional model was used to calculate the expected current velocities in a deepened channel northwest of the pipeline on the flooding tide. The same situation would occur southeast of the pipeline during the ebbing tide. (In the deepened channel northwest of the pipeline on a flooding tide, or southeast of the pipeline on an ebbing tide,

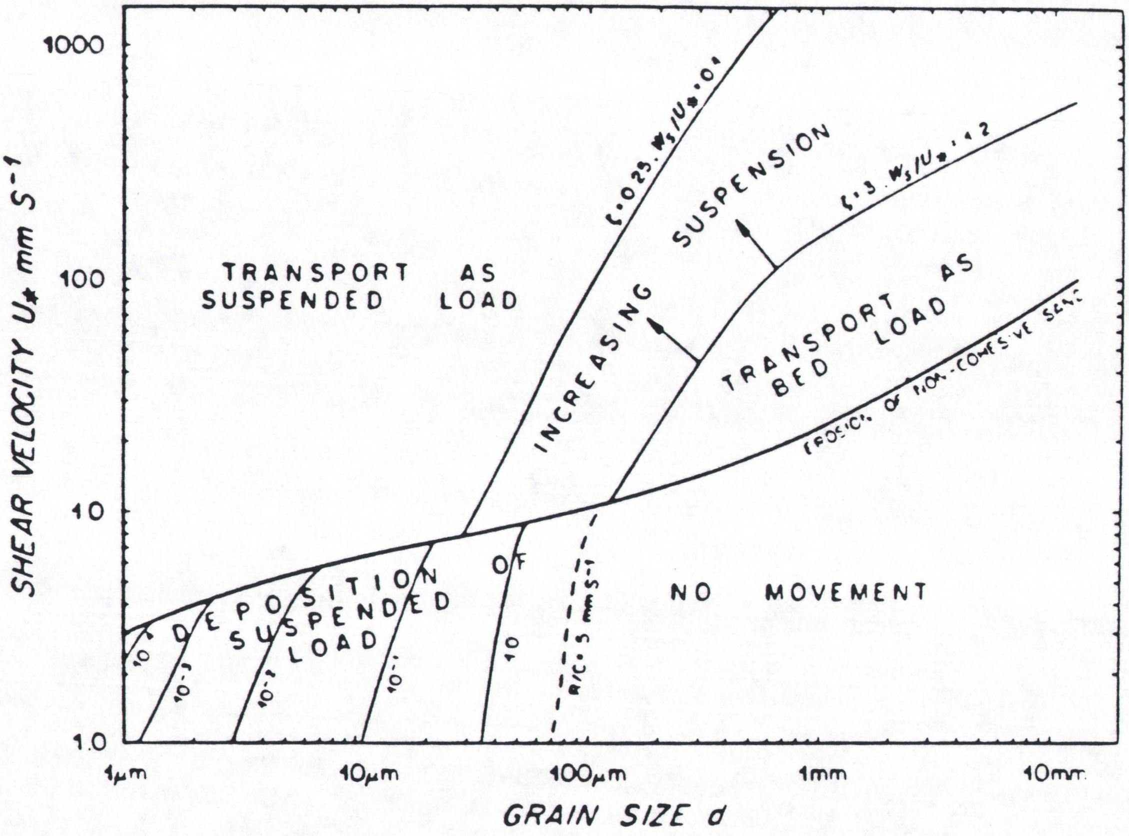


Figure 1. Critical velocities for sediment transport (McCave, 1984) including the velocities required to prevent the deposition of fine-grained sediment (less than 63 micrometers). The "shear velocity" is a measurement of the stress on the bottom; it is approximately equal to 0.0547 times the flow velocity measured one meter above the bottom (Sternberg, 1972).

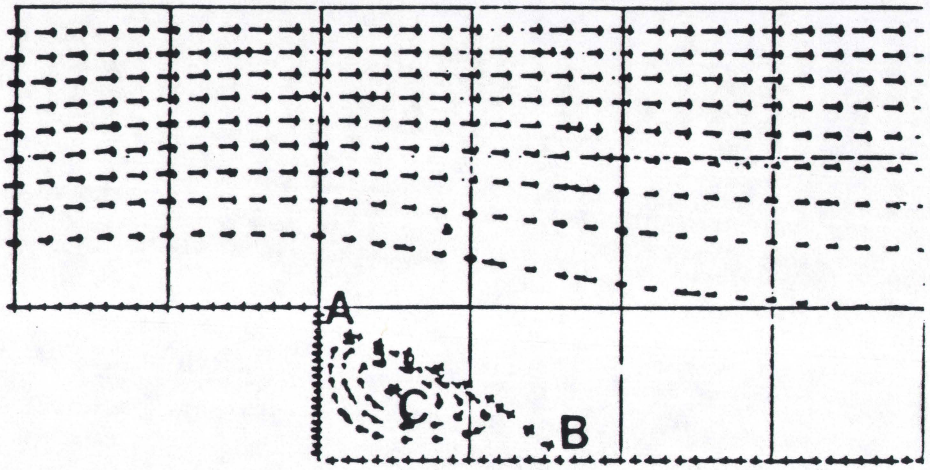
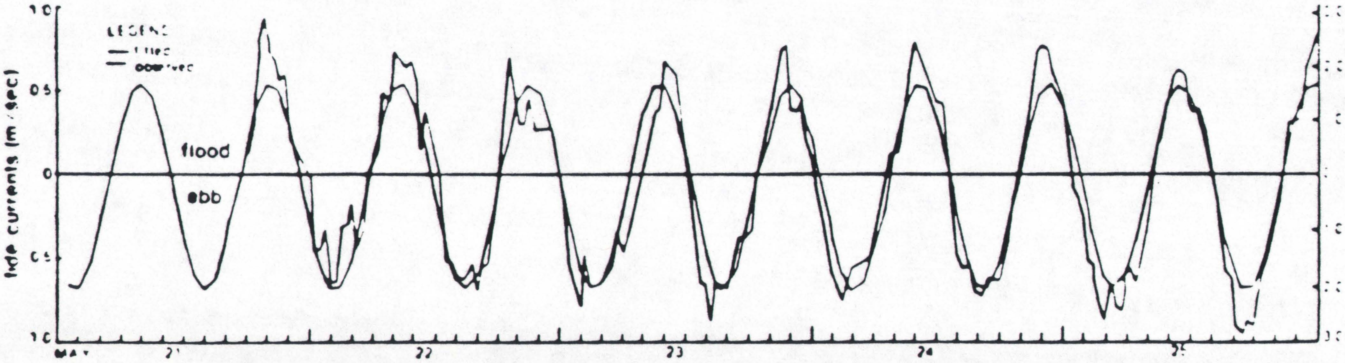


Figure 2. Schematic of a model output showing separation flow over a step (Roache, 1972), including the point of separationre (A), the point of reattachment (B), and the recirculating eddy (C).



Source National Ocean Survey, unpublished current meter records

Figure 3. Observed and averaged tidal currents between Sandy Hook and Rockaway Point (May, 1958: from Duedall, et al.; 1979).

separation would not occur since the flow is converging up the slopes to shallower water). The axial cross-section of the mined channel north of the pipeline was represented as a step in the sea floor where the water depth goes from 45 feet to 70 feet. The flow over this step was modeled using a finite difference scheme on a variable grid for solving the Navier-Stokes equations with a modern k-ε formulation for turbulent closure (e.g., Johns and Oguz, 1987). The calculation was done at between 500 and a 1000 grid points and convergence achieved at better than the 1% level. The flow velocities, degree of turbulence and bottom roughness were adjusted to represent conditions in the channel.

In addition to the geometry of the channel the model requires a choice of (a) maximum current velocity and the turbulent intensity, and (b) bottom roughness which influences the shear stress at the channel floor.

Tidal currents. Measured values of the maximum tidal currents were stated earlier. The turbulent intensity is the magnitude of observed fluctuations in the actual current around a predictable tidal velocity. Figure 3 shows an example of an actual current record from the bay compared to the predicted tidal velocities for the same period (Duedall, et al., 1977). On the average the fluctuations are about 10% above the predicted velocity but, because turbulent energy is contributed by wind and waves, as well as from the tidal flow, the turbulent intensity is higher, sometimes exceeding 100%, when the predicted velocities are small.

Bottom roughness. Preliminary calculation are done with the assumption of a smooth sea floor, but calculation was also done with three degrees of bottom roughness - a sandy sea floor, a rippled sea floor, and a sea floor containing sand waves. The grain size in the channel is about 0.02 inches in diameter so that, if the channel floor was a plane, a roughness of 0.02 inches would be appropriate. Under moderate currents, the sea floor is more likely to be rippled and a roughness element about 0.4 inches high, corresponding to small ripples, would be appropriate. Under strong currents larger bedforms may be produced. Sand waves have been observed in the channel. Under these conditions a roughness element of, say, 12 inches may be appropriate. The effect of these roughness elements on the flow were calculated using friction factors from a standard Moody diagram (Daily and Harleman, 1966).

Results

Flow characteristics

To determine the sensitivity of the model to various choices of the parameters, a series of exploratory calculations were done using the length of the recirculating eddy under each scenario as the standard for comparison.

An example of the results is shown in Figure 4A. This is a vertical section along the length of the channel (i.e. the top is the water surface). The current is flowing from left to right. The water depth increased suddenly from 45 feet to 70 feet. The vertically integrated velocity over the step was 25 cm/sec, the turbulent intensity was taken to be 10%, and the bottom was smooth. The lengths of the line segments are proportional to the current speed at each of 540 points. The figure covers a distance extending about 300 feet downstream of the step. These results show a recirculating eddy extending about 115 feet downstream of the step as indicated in Figure 4B. Within this eddy the near-bottom current velocities are less than 5 cm/sec (Figure 4C). Immediately downstream of the eddy the flow velocities are still low but they increase rapidly over the next 100 feet to a near-bottom velocity reaching about 40% of the initial velocity. The increase is more gradual beyond a distance of 250 feet from the step. In this example, if instead an abrupt drop, the water depth increased gradually from 45 feet to 70 feet over a distance of 250 feet, the recirculating eddy would not form and the low velocity zone immediately downstream of the eddy would also be eliminated. Such a buffer zone would allow the flow to expand gradually to fill the compartment.

The bottom roughness did not turn out to be an important parameter. The model was rerun with bottom roughness elements of 0.02 inches (corresponding to coarse sand), 2.54 inches (ripples) and 12 inches (sand waves) and the length of the recirculated eddy was calculated to be 117.4 feet, 117.6 feet and 121.6 feet respectively. In addition, exploratory calculations show that the size of the recirculating eddy was not sensitive to changes in the maximum current. In changing the inflow velocity from 20 to 50 cm/sec, the length of the recirculating eddy varied from 117 to 132 feet.

The design characteristics

For the design of the buffer zone, a model was run in which the water depth changed abruptly from 45 feet to 70 feet. A roughness equivalent to a rippled bottom was chosen. The flow over the step was specified by a parabolic equation to approximate the observed maximum tidal velocities (Figure 5) with a turbulent intensity of 30%. The velocities were calculated at 918 grid positions to convergence better than 1%. The resultant velocity vectors to a distance of 1148 feet downstream of the step are shown in Figure 6A.

The recirculating eddy extended 129 feet downstream of the step and the velocity one meter above the sea floor reached 35 cm/sec at a distance of 490 feet from the step. Although the recirculating eddy would be eliminated by streamlining the bathymetry out to a distance of 129 feet as shown in Figure 6B, the maximum tidal velocities remain below 35 cm/sec out to a distance of 490 feet. To insure that fine-grain sediment will not accumulate in the compartment, the buffer should probably be extended to a distance of 490 feet along the 35 cm/sec isotach as shown in Figure 6. Neither the resolution nor

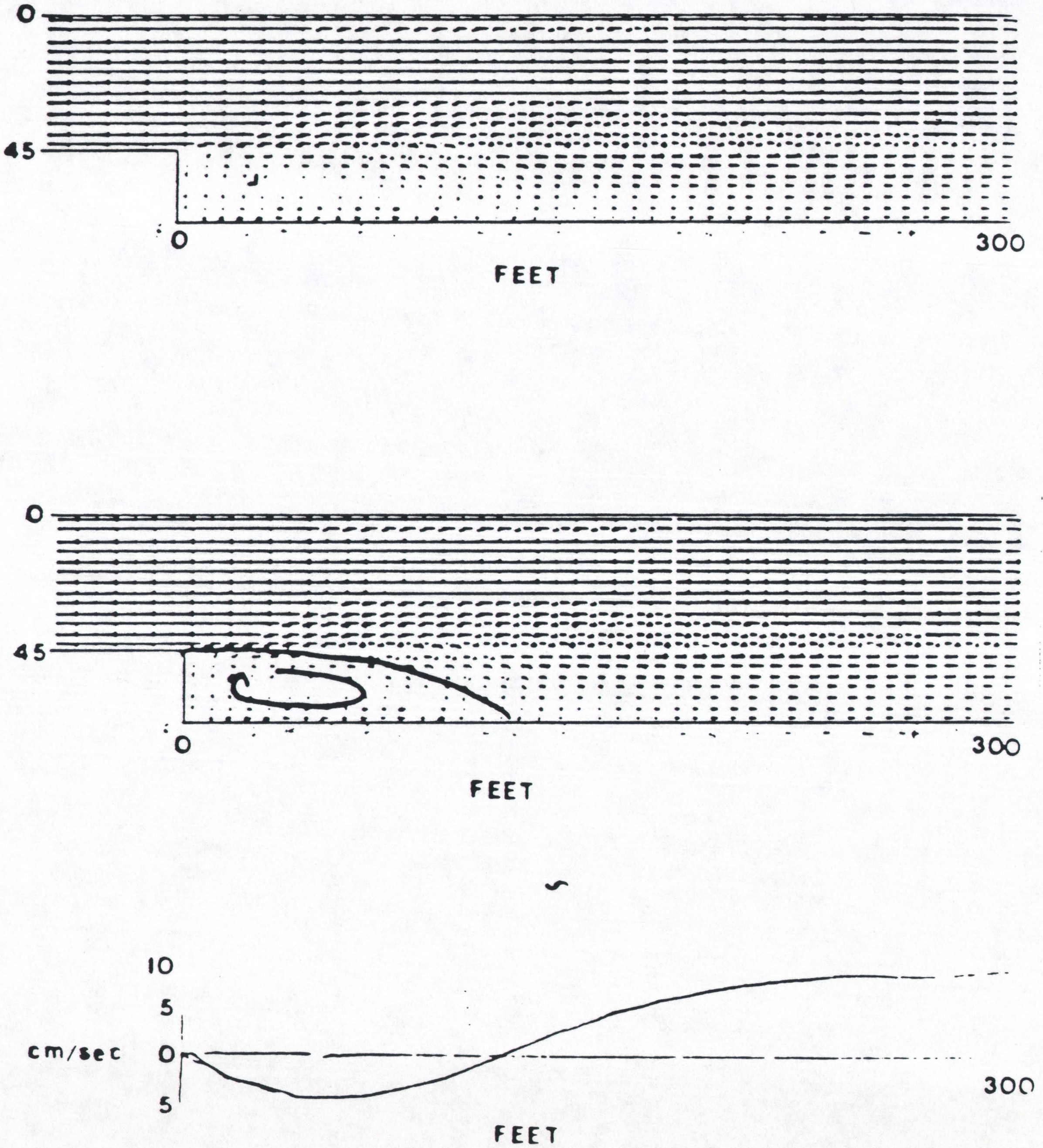


Figure 4. Representation of flow over a step as described in the text.

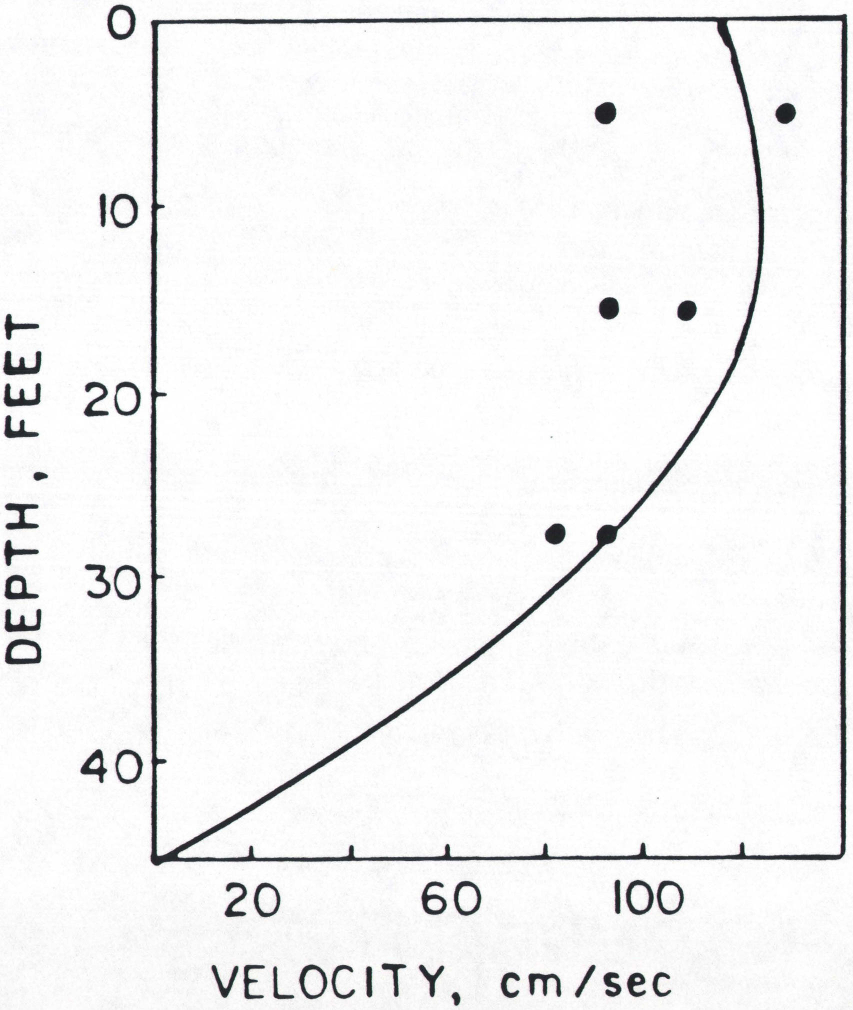


Figure 5. Profile of the distribution of the maximum tidal velocity used for the design of the buffer zone. Dots indicate measured values (Doyle and Wilson, 1979).

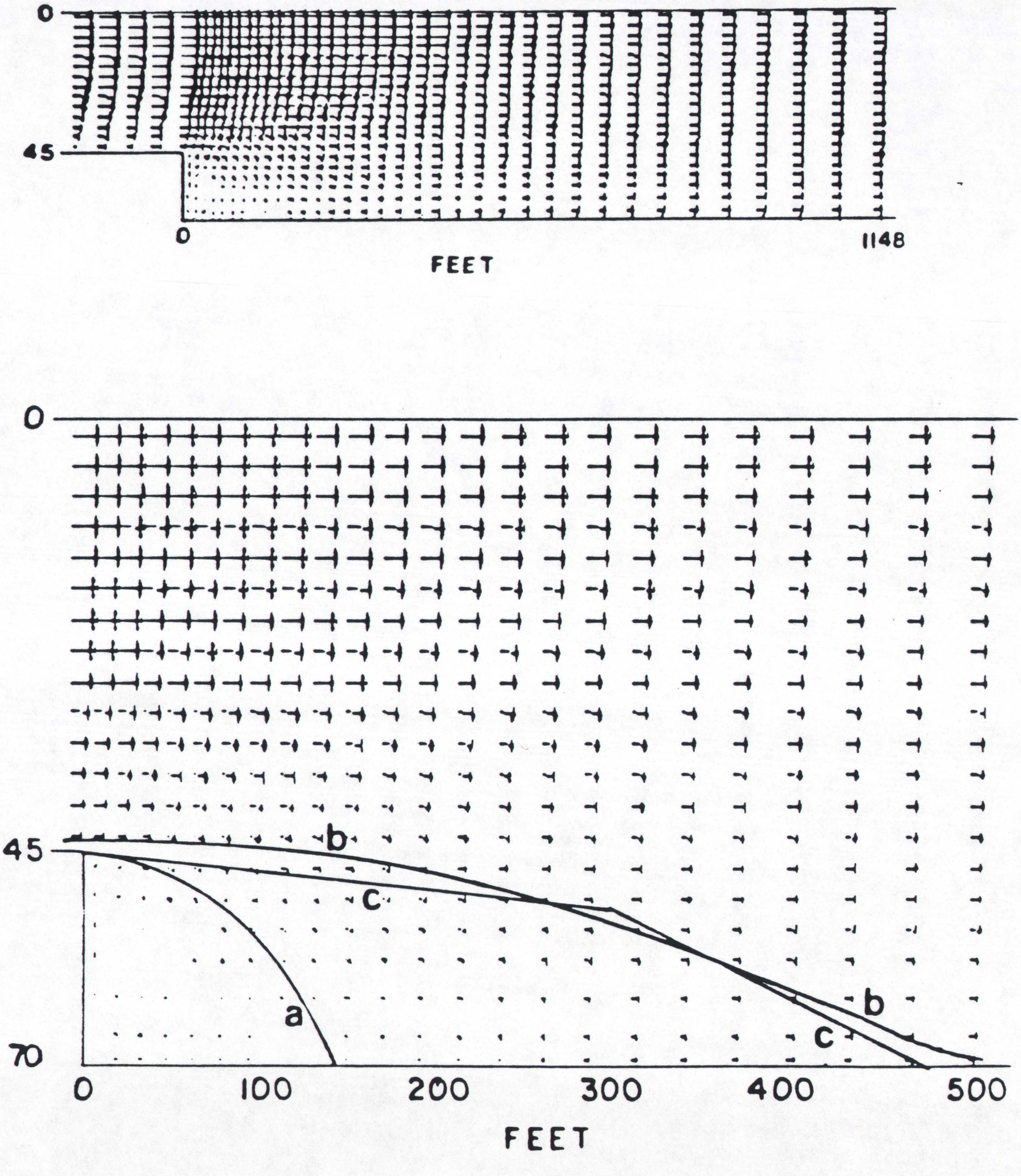


Figure 6. A. Results for the design of the buffer zone.
B. Enlargement of the separation flow over the step, designating (a) the recirculating eddy and (b) the 35 cm/sec isotach in relation to the recommended buffer zone (c).

the accuracy of the model justify the exact shape of this slope so that in practice, two facets to the slope in the buffer zone will probably be sufficient. I would recommend a gradient of 1:40 to a distance of 300 feet and 1:10 beyond that to the project depth of 70 feet.

Discussion

Although the flow characterization discussed here does not explicitly include water quality parameters or calculations of sand transport, the results have implications for both.

Anoxic conditions can arise if bottom waters are isolated by strong stratification while it is simultaneously subjected to a large oxygen demand as from the decay of organic matter either in the water column or on the sea floor. These conditions can and do sometimes arise naturally in coastal waters, but they are acerbated by human activity especially the discharge of nutrient-rich sewage into poorly flushed waters. Conditions in the deepened compartment of Ambrose Channel, however, are unlikely to result in local anoxic events for the following reasons.

The design of the compartment is intended to prevent the deposition of fine-grained sediment which is expected to have a high organic content and a correspondingly high sediment-oxygen demand (e.g. Schartz and Brinkhuis, 1978). The tidal currents will remain relatively high which, when coupled with the exposed location at the bay mouth, should inhibit the development of strong stratification even though slightly more saline and cooler water may enter the deepened channel. In addition, the channel is swept by a slow circulation superimposed upon the tides and driven by regional water density gradients. This current flows into the harbor up the channel at speeds of about 4 cm/sec (Bowman, 1977: Figure 7). It alone would exchange the water in this stretch of the channel in about one day and supplement the tidal flushing.

Changes in the tidal flow will also alter the natural transport of sand in the region. Sand is supplied to the harbor from several sources. Along the south shore of Long Island, the littoral transport of sand from the east carries about 450,000 cubic yards per year; similarly littoral sand moves northward and up the coast of New Jersey at a rate of about 493,000 cubic yards per year (Kastens, et al., 1978). These rates are controlled by waves approaching either coasts so the longshore transport of sand into the mouth of New York Harbor will not be affected by the alteration of the channel. A small amount of sand may be provided by any existing erosion of the shoreline around the Lower Bay itself but this sediment is redistributed locally along the Staten Island shore and it is very unlikely that it participates substantially in the sediment budget around the bay mouth.

More sand may be supplied directly to the Lower Bay from the Atlantic shelf. An onshore supply of sand has been postulated along Long Island's south shore to account for increases in the

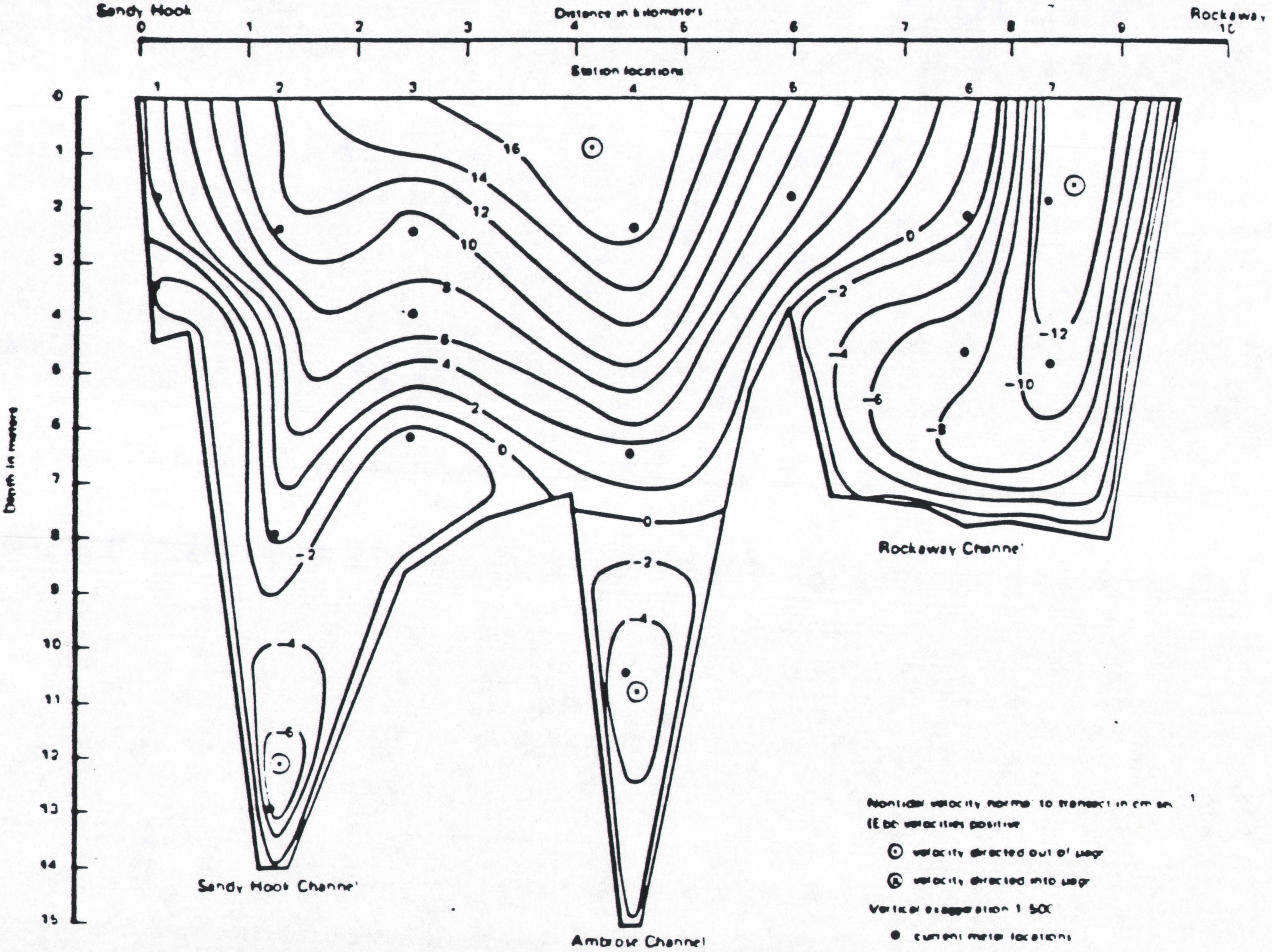


Figure 7. Average non-tidal velocities between Sandy Hook and Rockaway showing the inflow into Ambrose Channel (June 1952 from Bowman, 1977).

magnitude of the longshore drift of sand along Long Island (McCormick and Toscano, 1980: Research Planning Institute, Inc., 1985; Niedoroda et al., 1985; and Williams and Meisburger, 1987). Where any offshore sand supply reaches the beach along either the Long Island or New Jersey shore, it is incorporated into the longshore littoral transport and included in the above figure. Some of the onshore supply from the shelf, however may enter the Harbor directly. Underwater sand waves have been found on the floor of Ambrose Channel indicating a transport of sand landwardly along the channel (Coch and Bokuniewicz, 1985). The strength of this source is uncertain, but the amount is probably small. Although detailed information on sand waves in the channel is not available, in other estuarine locations, sand waves represent a transport of sand at rates between 0.08 and 0.50 cubic meters of sand per meter of wave crest per day:

Location	Transport Rate $m^3/m/day$	Citation
St. Andrews Bay, FL	0.01	Salsman, et al., 1966
Warts Bank, Isle of Man	0.50	Jones, et al., 1965
North Sea	0.17	Terwindt, 1971
Chesapeake Bay	0.25	Ludwick, 1972
Long Island Sound	0.08	Bokuniewicz, et al., 1977

Such rates in Ambrose Channel would correspond to a total transport of between 22,000 and 129,000 cubic yards of sand per year.

The total supply from all sources, therefore, could be as high as 1,072,000 cubic yards per year. Most of the sand filling the channel, therefore, probably is swept from the surrounding sea floor by waves and currents and this process will not be altered. Mined sand and gravel would be replaced by fine sand like the current maintenance material which is classified as clean sand (Schubel and Summers' class IV material, 1985).

Once in the channel the sand supplied is effectively removed from the littoral system. An average of 834,000 cubic yards of sand is dredged annually from Ambrose Channel (Schubel and Summers, 1985); in other words, with allowance for uncertainties in the estimates, all the sand that enters the channel presently is trapped there and removed by dredges. Most of the maintenance material has been fine sand which is of inferior quality for beach nourishment and disposed of at the Ocean Disposal Site. Sand discharged at this site is in water sufficiently deep that it is not likely to be returned to the coastal zone.

As a result of the situation described above, deepening the channel is unlikely to substantially alter the sand budget. In places where there is an overabundance of sediment supply, deepening a channel usually leads to an acceleration in the rate of deposition. This is often the case where mud is being deposited from a suspension in the water. Around the Ambrose Channel sand is being moved primarily as "bed load" that is along the bay floor; the channel probably traps all the sand that enters it as indicated by the records of maintenance dredging. In this case, the deposition rate would be limited by the supply rate; and the rate of supply would not be changed by deepening the channel. So, as long as the up-channel migration of sand from the shelf does not substantially change, the rate of accumulation in the deepened channel would be expected to be essentially the same as the current rate. There may be some increase in the rate of supply because the deeper channel would allow waves to penetrate the harbor more easily. This effect, however, will be slight since the principal resistance to incoming waves over the shoals will be unchanged.

There will also be changes in the transport of sand along the axis of the channel. The tidal flow velocity and the resulting sediment transport should remain essentially unchanged over the pipeline, but, as discussed earlier, the flow velocities would be reduced in the deepened compartments and, although the maximum currents there will be adequate to prevent the deposition of mud, the rates of sand transport would be slower in the deepened compartment than they are presently on the channel floor.

The channel sediment distributions would adjust to the new conditions. During the flood tide (or the ebb tide), sand would be removed from the shallow stretch of the channel over the pipeline at a more rapid rate than it is being transported into the area from the deeper, seaward (or landward) stretch. The fine sand driven by the longshore drift into the bay mouth and then into the channel would not accumulate over the pipeline and existing fine sand there will be removed. The size of sand that can be transported, however, depends on the current speeds. If the vertically integrated, maximum tidal current is 82.5 cm/sec over the pipeline, the velocity 1 meter above the channel floor there would be about 60 cm/sec. This corresponds to a shear velocity (Figure 2) of about 3.28 cm/sec. Sediment particles greater than about 2.4 mm in diameter would not be moved by this, the maximum current over the pipeline. A sample of sand taken by McCormack Aggregates in this section of the channel consisted of about 45% by weight of gravel greater than 2.4 mm in diameter. This fraction of the material would not be moved from the site and over time the substrate would adjust. Fine sand would be winnowed out and the gravel would remain as an immobile lag deposit over the pipeline. If the water depth over the pipeline is increased by one foot by this winnowing process, an armoring cover one foot thick would be naturally created and no further changes would occur.

Other Issues

In considering the effect of deepening the outer reaches of the Ambrose Channel to seventy feet on either side of the pipeline, there are three other questions that need to be addressed. These are:

1. What are the likely effects of any plume caused by the dredging?
2. How will waves and tides be changed and what effect might this have on shore erosion?
3. How will the fisheries resources be changed?

The model results presented in this paper are not relevant to these questions. Nevertheless, each of these issues will be reviewed here.

1. Plumes. There have been extensive studies of turbidity generated around dredges and a recent review has been done by Herbich and Brahme (1983). In general, elevated turbidity levels are limited to within a few hundred meters of the dredge and high levels are due to the suspension of silt and clay.

The proposed site has, of course, been subject to dredging on a regular schedule so that this type of disturbance has been routine. In addition, since the site has been proposed specifically for the recovery of sand and gravel, the fine-grained fraction for the new work will probably be less than 10% and the turbidity should be minimized. During the mining, however, the total amount of resuspended sediment will exceed that would have been generated by maintenance dredging alone.

Brinkhuis (1980) had applied a model of a continuous mining operation to a site on the East Bank near Ambrose Channel. This site is sufficiently close to the proposed site so that the results are applicable. The predicted plumes under worse-case conditions (Brinkhuis, 1980), including maximum tidal currents, are of relatively small extent, long and narrow, with high concentrations only within a few hundred meters of the source (Figure 1). Brinkhuis (1980) also reviewed the biological impacts of such plumes on 40 invertebrate species and 16 fish species. In particular, estuarine fish species are often subjected to elevated levels of suspended sediments by natural processes and do not appear to be strongly affected by temporary excess turbidity (Brinkhuis, 1980). They also avoid areas with high levels of suspended sediment (Steckney, 1973). As a result, it seems extremely unlikely that a plume generated by the proposed operation will cause an unacceptable impact on the fish populations.

2. Waves and tides. Without costly, site-specific models, the forecast of changes in the waves and tides can only be addressed in general terms. Deepening the channel to 70 feet will increase

the cross-sectional area of the harbor mouth by about 5%. The effects of such a change would be in the direction of increasing the flow of wave energy, increasing the tidal range and increasing the penetration of salt water. All of these changes may reasonably be expected to be below 5% locally and to decrease rapidly away from the site, but the physical situation is complex; the actual changes may be negligible but their forecast is uncertain. There are two models that have been applied to this area, and, although the effect of the proposed deepening were not examined, similar hypothetical situations of similar magnitude were examined and the results may be illustrative.

Kinsman et al. (1979) use a wave model to predict the effects of mining pits in the Lower Bay on the wave energy reaching the shoreline, a parameter that determines the amount of shoreline erosion. One scenario examined by Kinsman et al. (1979) called for the mining of an area of the East Bank, 3000 feet wide along the bend in the Ambrose Channel to a depth of 90 feet. This change reduced the amount of energy reaching the Staten Island shore by as much as 20% while the wave attack at Coney Island was increased by 4% (Kinsman et al., 1979).

Wong and Wilson (1979) model the effects of mining large pits to a depth of 50 feet both northeast and southwest of Ambrose Channel between Sandy Hook and Coney Island. In various cases the tidal range increased along the Staten Island shore by about 10%. The authors concluded sand and gravel mining near the mouth of the bay might increase the tidal range at Staten Island. A similar, but smaller, effect might be expected if the channel is deepened. An increase in tidal range could improve the flushing rates between Raritan Bay and the eastern part of the Lower Bay (Wong and Wilson, 1979). Wong and Wilson (1979) also suggest that the increased tidal range might aggravate shoreline erosion, however, field studies of the effect of tidal range on erosion in Chesapeake Bay indicate that erosion rates decrease at larger tidal ranges (Rosen, 1977). This has been attributed to two conditions. First, the berm elevation tends to be higher in areas where the tidal range is larger so that storm surges are less likely to reach the dune or bluff. Second, a larger tidal range distributes the incident wave energy over a greater distance during the tidal cycle such that the erosive intensity at any particular elevation is reduced (Rosen, 1977).

The U. S. Army Corps of Engineers has used a numerical model to investigate the effects of deepening the Ambrose Channel to -70 feet (J. Letter, 1988, U.S. Army Corps of Engineers' Waterways Experiment Station, personal communication). Unfortunately, the results were never published as a report but apparently the effects were comparable to those anticipated above; the maximum changes in the tidal range were a few tenths of a foot and salinity changes were less than 1 part per thousand.

Another hydrodynamic model of the Lower Bay was used to assess the consequences of increasing the cross-section of the bay mouth by deepening the channel to -70 feet (Vieira and

Bokuniewicz, 1990). A vertically integrated finite difference numerical model calculated the tidal currents on a 200-meter grid throughout the bay. The model was not calibrated but the results suggest a very slight increase in tidal range of 1 or 2 mm.

These illustrations seem to indicate that deepening the channel will result in marginally measurable changes in the tides and currents. Such changes, however, will not necessarily aggravate shore erosion, in fact they may be beneficial. In Chesapeake Bay, an increase in the tidal range was found to correspond to decreased erosion (Rosen, 1977).

3. Fisheries. This issue was considered by Dr. Peter Woodhead of the Marine Sciences Research Center and his conclusions are presented here.

"To assess possible material effects upon fish populations caused by dredging to deepen the outer reaches of the Ambrose Channel to 70 feet, we have reviewed data from a number of studies and surveys of fish populations both in the Ambrose Channel and on the related banks and shoals in its vicinity, and also more widely for the fish populations of the Lower-Bay-Raritan Bay area, as a whole (termed the Lower Bay Complex). The fisheries studies reviewed included published reports, work in <u>draft</u> and some unprocessed catch data from fishery surveys from 1974 to 1986; the principal reports used are listed in the bibliography.

"Based on our review of this literature, we believe that effects of dredging to deepen the Ambrose Channel would be unlikely to cause material adverse impact upon the fish populations inhabiting the Channel. The following summarizes the bases for our conclusions.

"The diversity of the fish community in the Ambrose Channel, as number of species, is high but all of the fish species which occur there are common species in the Hudson Raritan estuary system or in the Apex of the New York Bight. None is known to have a unique population, nor a unique habitat in the Ambrose Channel.

"Dredging the Ambrose Channel to depths of about 70 ft will cause some disturbance of the local fish community during the periods of the dredging operation and this must be expected. Many fish will avoid the immediate area of perturbation during dredging and there will be loss of benthic organisms, worms, clams, shrimps and related invertebrates on which groundfishes feed. Dredging would not be expected to have effects on the pelagic fishes swimming in the upper water column (the herrings, anchovies, menhaden, and such gamefish as adult bluefish or weakfish which feed on them), other than a short plume of resuspended sediments immediately down current from the dredge operation. Biological recolonization of newly dredged areas by benthic invertebrates is rapid once the sediment resuspension and heavy deposition from the dredging operations has stopped, recolonization of the dredged bottom by groundfishes is almost equally rapid, taking place within months.

"The deepened Ambrose Channel will remain in use as a shipping channel but in some respects, including habitat for fishes, it will resemble a borrow pit. There are already several large borrow pits, the disused sites of earlier sand dredging operations, in the Lower Bay area. The bottom sediments in the outer reaches of the Ambrose Channel area sands and the fish habitat in the deepened outer Channel, after dredging, is likely to resemble most closely the habitat which exists in the Large East Bank Pit. That borrow pit was also dredged into a sandy seabed lying close to the Ambrose Channel, it is a large pit ranging in depth from about 40 ft to 70 ft.

"The fish populations living in several of the larger borrow pits in the Lower Bay area, including the Large East Bank Pit, have been sampled by ground-trawling on several occasions since 1981. The surveys have simultaneously sampled the fish populations living on undredged banks and shoals associated with the borrow pits (Gandarillas and Brinkhuis, 1981; Conover et al., 1983; Pacheco, 1983; Woodhead and McCafferty, 1986); some surveys also sampled the fish populations inhabiting nearby deep ship channels in the Lower Bay Complex (Woodhead and McCafferty, 1986; Woodhead, 1988). The fish communities living in the borrow pits of the Lower Bay area and the communities sampled in the dredged ship channels near to the pits show close similarities in community species composition and species richness (number of species present). Although fish are generally more abundant in the borrow pits than in the ship channels, the relative dominance of the commoner species is similar. By contrast, the fish communities inhabiting the undredged banks and shoals in the Lower Bay Complex are less abundant and less diverse, containing fewer species, than the communities in either the borrow pits or the channels. These differences in abundance and diversity between the communities living on the shoal areas and in the deeper channels and pits were found consistently in several comprehensive trawl surveys, covering the annual cycle, which were made in the Lower Bay Complex between 1981 and 1986; the differences were maintained through each season of the year.

"Cluster analysis has been used to make statistical comparisons for similarity in the annual fish catches taken at 38 fishery survey stations at a variety of sites distributed throughout the Lower Bay Complex (Woodhead and McCafferty, 1986; Woodhead, et al., 1987). The analysis used the species composition and the abundance of species at each station to make the comparisons. The fish communities sampled in the ship channels clustered together with the communities sampled in borrow pits, forming a single group of similar samples. The fish community sampled in the Large East Bank Pit is not different, its samples cluster together with those from other pits and with those from the Ambrose Channel. Throughout the Lower Bay there was little difference between the two communities in the pits and in the deep channels.

"The results of these comparisons are of direct relevance to assessment of possible effects on fish populations from deepening the Ambrose Channel. The Channel at present contains an abundant and diverse fish community, despite the disturbances from periodic dredging to maintain channel depth and from the continuous passage of large ships. Dredging the outer reaches of the Channel to 70 ft will eventually produce a habitat at the bottom similar to that in some of the borrow pits in the Lower Bay area. But the fish communities which inhabit the ship channels and those in the borrow pits show close similarities in species composition and their relative abundance, and so no substantive long-term change would be expected in the fish community inhabiting the outer reaches of the Ambrose Channel as a result of deepening the channel by dredging.

"A possible contingency from deepening the Channel to 70 ft would be to allow immigration of fishes from the deeper community in the Apex of the New York Bight. Sea-bed depths of 60 ft are found only a half mile from the outer Ambrose Channel. The fish community in the Apex at 60 ft and deeper, shows some differences from the shallower nearshore community, in particular there is some decrease in fish abundance and in diversity, the number of species (data from Wilk et al., 1977). Most of this decrease is from the disappearance from bottom-trawl catches of herrings, sandlance and other species which feed in the water column, off the bottom. Inspection of the data on catches of the groundfish species shows that the differences in these communities are not large, all of the common species in the groundfish community at 60 to 90 ft are also relatively common in shallower waters. The most important species to decrease in abundance at 60 ft is the winter flounder, numbers of spotted and silver hake increase. It is very unlikely that the deeper groundfish community from the Apex at 60 to 90 ft would replace the present fish fauna following deepening of the Channel. Instead there would be some mixing of fish and since the groundfish composition of the two communities is similar in their more abundant species, little significant change overall would be expected to occur.

"In conclusion, we have reviewed scientific/technical literature and data on fish populations living in the Ambrose Channel and on its associated banks and shoals, together with information on the wider fish communities of the Lower Bay Complex and the Apex of the Bight, with reference to potential material effects on fish populations from deepening to 70 ft the outer Ambrose Channel. We have given particular attention to information on the fish communities inhabiting existing sand dredging sites, borrow pits, and their close similarities to the fish communities living in the deep ship channels. We infer from our review that deepening of the outer Ambrose Channel by dredging is unlikely to cause material adverse impacts, nor large changes in composition of the fish populations inhabiting the Channel."

Conclusion

Streamlining the bathymetry in a deepened compartment of Ambrose Channel can prevent separation of the flow and allow the tidal currents to remain sufficiently high to prevent the formation of mud deposits. A buffer zone 490 feet wide is recommended on both sides of the pipeline within which the slope is 1:40 within 300 feet of the pipeline and 1:10 thereafter. This buffer zone should also be established at the landward limit of the mined stretch.

Recommendations for Monitoring

Precision bathymetric surveys should be conducted after the excavation of every one million cubic yards or twice a year to insure the development of the channel bathymetry as intended. Monitoring of environmental conditions should also be done for the following reasons.

The model forecasts made in this report should be verified by measurements during the mining operation. Profiles of the current velocities over selected tidal cycles should be made periodically during the operation both over the pipeline and in the deepened stretches of the channel on either side of the pipeline. In addition, sediment samples should be collected from the mined areas to insure that fine-grained sediment is not accumulating.

The available hydrodynamic model results suggest small changes in the tidal range might be observed. Although none of the Bay-wide models explore the specific conditions for the proposed deepening, all indications are that changes in the hydrodynamics will be marginally detectable. It seems unlikely that a more specific, Bay-wide model for this project would give any substantially different results so that the cost and the time required to develop new models would not be justified. Instead, the tides should be monitored to insure that unexpectedly large changes do not begin to develop. The long-term, continuing tidal records from Fort Hamilton could be used and a supplementary tide gage established on the Staten Island shore.

The channel floor over the pipeline is expected to adjust to new conditions by a small increase in water depth accompanied by a coarsening of the surficial sediments. An attempt to more exactly model this situation would be very difficult and contain large uncertainties because (a) sediment transport is highly non-linear so that small errors in forecasting the water currents produce large uncertainties in the calculated rate of sediment transport (Sternberg, 1972), (b) combined effects of waves and currents are complex (Grant and Madsen, 1979; Pattiaratchi and Collins, 1984), and (c) the response of mixtures of sediment grain sizes are not well known (Ludwick, 1990). As a result, the direct monitoring of any changes in bathymetry and sediment grain size is the recommended approach.

In summary, a monitoring program should include:

1. periodic precision bathymetric surveys over the entire length of the channel
2. the establishment of a tide gage on the Staten Island shore and analysis of both those measurements and measurements available from Fort Hamilton
3. periodic measurements of the current profiles during selected tidal cycles over the pipeline and in the deepened stretches of the channel on both sides
4. documentation of any changes in the grain size of the bottom sediments over the pipeline and in the mined areas on both sides.

Continuance of the mining operation would require that no unexpected changes are detected. In the event that the mining is stopped, for whatever reason, it would be preferable to manage the operation to remove thin layers over the entire area rather than to mine isolated sections deeply .

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Appendix I

The Design Model Calculation

The calculation was done using "Fluent" in metric units which have been converted into convenient units of the British system in the text. The computational grid was specified by the following modes:

```
NO.      X-GRID        Y-GRID
 1    -6.2500E+00  -2.5000E-01
 2     6.2500E+00   2.5000E-01
 3     1.8750E+01   1.0000E+00
 4     3.1250E+01   2.2500E+00
 5     4.3750E+01   3.5000E+00
 6     5.6250E+01   4.5000E+00
 7     5.9943E+01   5.5000E+00
 8     6.3821E+01   6.5000E+00
 9     6.7893E+01   7.5000E+00
10     7.2168E+01   8.5000E+00
11     7.6657E+01   9.5000E+00
12     8.1370E+01   1.0500E+01
13     8.6320E+01   1.1500E+01
14     9.1516E+01   1.2500E+01
15     9.6973E+01   1.3500E+01
16     1.0270E+02   1.4500E+01
17     1.0872E+02   1.5500E+01
18     1.1503E+02   1.6500E+01
19     1.2167E+02   1.7500E+01
20     1.2863E+02   1.8500E+01
21     1.3594E+02   1.9500E+01
22     1.4362E+02   2.0500E+01
23     1.5168E+02   2.1500E+01
24     1.6015E+02   0.0000E+00
25     1.6903E+02   0.0000E+00
26     1.7837E+02   0.0000E+00
27     1.8817E+02   0.0000E+00
28     1.9845E+02   0.0000E+00
29     2.0926E+02   0.0000E+00
30     2.2060E+02   0.0000E+00
31     2.3251E+02   0.0000E+00
32     2.4502E+02   0.0000E+00
33     2.5815E+02   0.0000E+00
34     2.7194E+02   0.0000E+00
35     2.8642E+02   0.0000E+00
36     3.0162E+02   0.0000E+00
37     3.1758E+02   0.0000E+00
38     3.3434E+02   0.0000E+00
39     3.5194E+02   0.0000E+00
40     3.7041E+02   0.0000E+00
41     3.8981E+02   0.0000E+00
42     4.1019E+02   0.0000E+00
```

These modes defined the following domain:

```
23  I1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1W1 O
22  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
21  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
20  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
19  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
18  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
17  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
16  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
15  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
14  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
13  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
12  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
11  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
10  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 9  IO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 8  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 7  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 6  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 5  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 4  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 3  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 2  WOWOWOWOWOWO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . O
 1  WOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWOWO
J I-   2   4   6   8  10  12  14  16  18  20  22  24  26  28  30  32  34  36  38  40  42
```

The boundary conditions were that the velocity was zero at the bottom of the domain (WO). Water entered from the left with a velocity distribution specified by the y-grid coordinate a

$$u = -2.1766437 + 0.38774868\ (J) - 0.0109339\ (J)^{2}$$

The top surface was free and the flow left the domain through the right hand boundary.

The horizontal velocity (u) vectors were calculated to have the following magnitudes:

Figure 1. Critical velocities for sediment transport (McCave, 1984) including the velocities required to prevent the deposition of fine-grained sediment (less than 63 micrometers). The "shear velocity" is a measurement of the stress on the bottom; it is approximately equal to 0.0547 times the flow velocity measured one meter above the bottom (Sternberg, 1972).

Figure 2. Schematic of a model output showing separation flow over a step (Roache, 1972), including the point of separationre (A), the point of reattachment (B), and the recirculating eddy (C).

Figure 3. Observed and averaged tidal currents between Sandy Hook and Rockaway Point (May, 1958: from Duedall, et al., 1979).

Figure 4. Representation of flow over a step as described in the text.

Figure 5. Profile of the distribution of the maximum tidal velocity used for the design of the buffer zone. Dots indicate measured values (Doyle and Wilson, 1979).

Figure 6. A. Results for the design of the buffer zone.
B. Enlargement of the separation flow over the step, designating (a) the recirculating eddy and (b) the 35 cm/sec isotach in relation to the recommended buffer zone (c).

Figure 7. Average non-tidal velocities between Sandy Hook and Rockaway showing the inflow into Ambrose Channel (June 1952 from Bowman, 1977).

```
        Y            N            N            N            N            Y


 INJECT ...............................INITIAL VALUES.................................
 NO TYP   (X)          (Y)          (Z)          (U)          (V)          (W)          (T)      (DIAM)    (MFLOW)




FLOW FIELD AFTER   846 ITERATIONS--
------------------------------------




                    K =   1   FOR U-VELOCITY   (STAGGERED)
                    ----------------------------------------------------(UNITS = METRES/SEC)


 I=       1            2            3            4            5            6            7            8            9           10
 J
  23  1.1400E+00   1.1719E+00   1.1706E+00   1.1649E+00   1.1605E+00   1.1580E+00   1.1555E+00   1.1540E+00   1.1509E+00   1.1454E+00
  22  1.1719E+00   1.1719E+00   1.1706E+00   1.1649E+00   1.1605E+00   1.1580E+00   1.1555E+00   1.1540E+00   1.1509E+00   1.1454E+00
  21  1.2217E+00   1.2217E+00   1.2030E+00   1.1886E+00   1.1786E+00   1.1720E+00   1.1684E+00   1.1659E+00   1.1618E+00   1.1553E+00
  20  1.2497E+00   1.2497E+00   1.2191E+00   1.1984E+00   1.1844E+00   1.1747E+00   1.1704E+00   1.1674E+00   1.1625E+00   1.1553E+00
  19  1.2559E+00   1.2559E+00   1.2201E+00   1.1958E+00   1.1791E+00   1.1672E+00   1.1624E+00   1.1589E+00   1.1536E+00   1.1459E+00
  18  1.2401E+00   1.2401E+00   1.2029E+00   1.1776E+00   1.1597E+00   1.1466E+00   1.1417E+00   1.1381E+00   1.1326E+00   1.1246E+00
  17  1.2025E+00   1.2025E+00   1.1660E+00   1.1416E+00   1.1240E+00   1.1107E+00   1.1061E+00   1.1027E+00   1.0974E+00   1.0895E+00
  16  1.1431E+00   1.1431E+00   1.1088E+00   1.0870E+00   1.0712E+00   1.0586E+00   1.0548E+00   1.0519E+00   1.0472E+00   1.0398E+00
  15  1.0617E+00   1.0617E+00   1.0314E+00   1.0141E+00   1.0014E+00   9.9077E-01   9.8822E-01   9.8629E-01   9.8259E-01   9.7614E-01
  14  9.5852E-01   9.5852E-01   9.3454E-01   9.2390E-01   9.1613E-01   9.0896E-01   9.0828E-01   9.0789E-01   9.0580E-01   9.0070E-01
  13  8.3345E-01   8.3345E-01   8.1974E-01   8.1878E-01   8.1821E-01   8.1644E-01   8.1840E-01   8.2024E-01   8.2029E-01   8.1674E-01
  12  6.8651E-01   6.8651E-01   6.8994E-01   7.0255E-01   7.1186E-01   7.1789E-01   7.2325E-01   7.2792E-01   7.3015E-01   7.2749E-01
  11  5.1770E-01   5.1770E-01   5.5063E-01   5.8118E-01   6.0309E-01   6.1926E-01   6.2841E-01   6.3552E-01   6.3828E-01   6.3404E-01
  10  3.2702E-01   3.2702E-01   4.1143E-01   4.6315E-01   4.9938E-01   5.2691E-01   5.3792E-01   5.4268E-01   5.4026E-01   5.3059E-01
   9  1.1448E-01   1.1448E-01   2.5622E-01   3.2684E-01   3.7691E-01   4.1638E-01   4.2047E-01   4.1293E-01   4.0752E-01   4.0222E-01
   8  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.6782E-01   2.3129E-01   2.6114E-01
   7  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   5.2983E-02   1.1047E-01   1.4675E-01
   6  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   4.0935E-03   3.0097E-02   5.7838E-02
   5  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -2.2507E-02  -2.5515E-02  -1.1449E-02
   4  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -4.9009E-02  -7.5277E-02  -7.6373E-02
   3  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -7.2735E-02  -1.1253E-01  -1.2359E-01
   2  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -8.5862E-02  -1.3274E-01  -1.4905E-01
   1  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00


 I=      11           12           13           14           15           16           17           18           19           20
 J
  23  1.1375E+00   1.1276E+00   1.1163E+00   1.1044E+00   1.0924E+00   1.0806E+00   1.0694E+00   1.0587E+00   1.0487E+00   1.0392E+00
  22  1.1375E+00   1.1276E+00   1.1163E+00   1.1044E+00   1.0924E+00   1.0806E+00   1.0694E+00   1.0587E+00   1.0487E+00   1.0392E+00
  21  1.1463E+00   1.1354E+00   1.1232E+00   1.1103E+00   1.0974E+00   1.0847E+00   1.0725E+00   1.0608E+00   1.0497E+00   1.0391E+00
  20  1.1457E+00   1.1341E+00   1.1212E+00   1.1077E+00   1.0940E+00   1.0807E+00   1.0678E+00   1.0553E+00   1.0432E+00   1.0312E+00
  19  1.1357E+00   1.1236E+00   1.1102E+00   1.0962E+00   1.0820E+00   1.0680E+00   1.0543E+00   1.0408E+00   1.0272E+00   1.0131E+00
  18  1.1142E+00   1.1017E+00   1.0880E+00   1.0737E+00   1.0591E+00   1.0445E+00   1.0298E+00   1.0148E+00   9.9894E-01   9.8188E-01
  17  1.0791E+00   1.0667E+00   1.0530E+00   1.0385E+00   1.0236E+00   1.0082E+00   9.9214E-01   9.7504E-01   9.5659E-01   9.3682E-01
  16  1.0298E+00   1.0178E+00   1.0043E+00   9.8983E-01   9.7448E-01   9.5807E-01   9.4036E-01   9.2125E-01   9.0101E-01   8.8028E-01
  15  9.6693E-01   9.5553E-01   9.4248E-01   9.2800E-01   9.1203E-01   8.9446E-01   8.7547E-01   8.5558E-01   8.3558E-01   8.1622E-01
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 14 [illegible]  [illegible]  [illegible]  [illegible]  [illegible]  8.1038E-01   8.0657E-01   7.8203E-01   [illegible]  7.4842E-01
 13  8.0947E-01   7.9901E-01   7.8542E-01   7.7041E-01   7.5354E-01   7.3637E-01   7.1946E-01   7.0475E-01   6.9116E-01   6.7977E-01
 12  7.1215E-01   7.0852E-01   6.9435E-01   6.7813E-01   6.6364E-01   6.4953E-01   6.3729E-01   6.2707E-01   6.1973E-01   6.1222E-01
 11  6.2399E-01   6.1054E-01   5.9620E-01   5.8294E-01   5.7140E-01   5.6248E-01   5.5545E-01   5.5130E-01   5.4840E-01   5.4709E-01
 10  5.1749E-01   5.0446E-01   4.9357E-01   4.8561E-01   4.8056E-01   4.7801E-01   4.7766E-01   4.7901E-01   4.8164E-01   4.8524E-01
  9  3.9704E-01   3.9288E-01   3.9079E-01   3.9115E-01   3.9377E-01   3.9819E-01   4.0415E-01   4.1121E-01   4.1899E-01   4.2725E-01
  8  2.7587E-01   2.8524E-01   2.9376E-01   3.0303E-01   3.1332E-01   3.2439E-01   3.3627E-01   3.4858E-01   3.6105E-01   3.7353E-01
  7  1.7058E-01   1.8927E-01   2.0646E-01   2.2345E-01   2.4050E-01   2.5747E-01   2.7460E-01   2.9155E-01   3.0816E-01   3.2438E-01
  6  8.2948E-02   1.0676E-01   1.3015E-01   1.5326E-01   1.7591E-01   1.9788E-01   2.1949E-01   2.4042E-01   2.6058E-01   2.8001E-01
  5  1.0979E-02   3.7180E-02   6.4842E-02   9.2631E-02   1.1980E-01   1.4588E-01   1.7120E-01   1.9541E-01   2.1852E-01   2.4062E-01
  4 -5.9373E-02  -3.2645E-02  -1.7344E-03   3.0219E-02   6.1641E-02   9.1732E-02   1.2058E-01   1.4787E-01   1.7377E-01   1.9844E-01
  3 -1.1147E-01  -8.5613E-02  -5.3366E-02  -1.8979E-02   1.5430E-02   4.8665E-02   7.9792E-02   1.0904E-01   1.3671E-01   1.6301E-01
  2 -1.4002E-01  -1.1533E-01  -8.3157E-02  -4.8359E-02 .-1.3163E-02   2.2311E-02   5.4057E-02   8.3882E-02   1.1209E-01   1.3887E-01
  1  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00


I=      21           22           23           24           25           26           27           28           29           30
J
 23  1.0303E+00   1.0217E+00   1.0135E+00   1.0052E+00   9.9647E-01   9.8639E-01   9.7417E-01   9.5933E-01   9.4196E-01   9.2260E-01
 22  1.0302E+00   1.0217E+00   1.0135E+00   1.0052E+00   9.9647E-01   9.8639E-01   9.7417E-01   9.5933E-01   9.4196E-01   9.2260E-01
 21  1.0288E+00   1.0184E+00   1.0077E+00   9.9582E-01   9.8223E-01   9.6659E-01   9.4911E-01   9.3032E-01   9.1075E-01   8.9083E-01
 20  1.0190E+00   1.0061E+00   9.9180E-01   9.7582E-01   9.5826E-01   9.3963E-01   9.2049E-01   9.0127E-01   8.8223E-01   8.6351E-01
 19  9.9797E-01   9.8136E-01   9.6323E-01   9.4397E-01   9.2426E-01   9.0471E-01   8.8575E-01   8.6755E-01   8.5012E-01   8.3340E-01
 18  9.6337E-01   9.4362E-01   9.2322E-01   9.0288E-01   8.8317E-01   8.6449E-01   8.4702E-01   8.3075E-01   8.1556E-01   8.0128E-01
 17  9.1617E-01   8.9535E-01   8.7502E-01   8.5569E-01   8.3767E-01   8.2109E-01   8.0597E-01   7.9220E-01   7.7961E-01   7.6797E-01
 16  8.5980E-01   8.4019E-01   8.2186E-01   8.0504E-01   7.8977E-01   7.7605E-01   7.6379E-01   7.5285E-01   7.4304E-01   7.3414E-01
 15  7.9805E-01   7.8137E-01   7.6631E-01   7.5286E-01   7.4095E-01   7.3050E-01   7.2136E-01   7.1341E-01   7.0646E-01   7.0031E-01
 14  7.3401E-01   7.2128E-01   7.1016E-01   7.0053E-01   6.9227E-01   6.8524E-01   6.7933E-01   6.7440E-01   6.7030E-01   6.6687E-01
 13  6.6989E-01   6.6157E-01   6.5467E-01   6.4901E-01   6.4446E-01   6.4089E-01   6.3818E-01   6.3623E-01   6.3491E-01   6.3411E-01
 12  6.0716E-01   6.0339E-01   6.0072E-01   5.9899E-01   5.9808E-01   5.9787E-01   5.9827E-01   5.9920E-01   6.0056E-01   6.0227E-01
 11  5.4682E-01   5.4749E-01   5.4892E-01   5.5097E-01   5.5353E-01   5.5653E-01   5.5990E-01   5.6356E-01   5.6747E-01   5.7156E-01
 10  4.8955E-01   4.9442E-01   4.9970E-01   5.0529E-01   5.1113E-01   5.1714E-01   5.2328E-01   5.2952E-01   5.3582E-01   5.4214E-01
  9  4.3581E-01   4.4455E-01   4.5338E-01   4.6225E-01   4.7110E-01   4.7990E-01   4.8862E-01   4.9724E-01   5.0576E-01   5.1415E-01
  8  3.8593E-01   3.9818E-01   4.1023E-01   4.2207E-01   4.3367E-01   4.4501E-01   4.5608E-01   4.6688E-01   4.7743E-01   4.8772E-01
  7  3.4017E-01   3.5553E-01   3.7045E-01   3.8494E-01   3.9899E-01   4.1261E-01   4.2579E-01   4.3856E-01   4.5093E-01   4.6293E-01
  6  2.9874E-01   3.1679E-01   3.3421E-01   3.5101E-01   3.6722E-01   3.8283E-01   3.9787E-01   4.1237E-01   4.2635E-01   4.3986E-01
  5  2.6181E-01   2.8214E-01   3.0166E-01   3.2042E-01   3.3845E-01   3.5576E-01   3.7239E-01   3.8836E-01   4.0371E-01   4.1849E-01
  4  2.2199E-01   2.4451E-01   2.6608E-01   2.8675E-01   3.0655E-01   3.2553E-01   3.4369E-01   3.6110E-01   3.7778E-01   3.9379E-01
  3  1.8809E-01   2.1203E-01   2.3492E-01   2.5680E-01   2.7773E-01   2.9774E-01   3.1685E-01   3.3511E-01   3.5256E-01   3.6925E-01
  2  1.6436E-01   1.8867E-01   2.1185E-01   2.3398E-01   2.5508E-01   2.7518E-01   2.9431E-01   3.1250E-01   3.2979E-01   3.4622E-01
  1  0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00


I=      31           32           33           34           35           36           37           38           39           40
J
 23  9.0200E-01   8.8091E-01   8.6000E-01   8.3978E-01   8.2066E-01   8.0293E-01   7.8678E-01   7.7230E-01   7.5953E-01   7.4847E-01
 22  9.0200E-01   8.8091E-01   8.5999E-01   8.3978E-01   8.2066E-01   8.0292E-01   7.8676E-01   7.7227E-01   7.5948E-01   7.4840E-01
 21  8.7095E-01   8.5141E-01   8.3252E-01   8.1456E-01   7.9776E-01   7.8231E-01   7.6836E-01   7.5595E-01   7.4509E-01   7.3575E-01
 20  8.4524E-01   8.2756E-01   8.1063E-01   7.9463E-01   7.7975E-01   7.6614E-01   7.5391E-01   7.4310E-01   7.3368E-01   7.2563E-01
 19  8.1734E-01   8.0194E-01   7.8727E-01   7.7346E-01   7.6066E-01   7.4899E-01   7.3855E-01   7.2936E-01   7.2140E-01   7.1462E-01
 18  7.8773E-01   7.7484E-01   7.6261E-01   7.5113E-01   7.4051E-01   7.3086E-01   7.2225E-01   7.1471E-01   7.0819E-01   7.0267E-01
 17  7.5707E-01   7.4679E-01   7.3708E-01   7.2799E-01   7.1959E-01   7.1198E-01   7.0521E-01   6.9929E-01   6.9420E-01   6.8989E-01
 16  7.2594E-01   7.1828E-01   7.1108E-01   7.0437E-01   6.9818E-01   6.9259E-01   6.8762E-01   6.8330E-01   6.7959E-01   6.7645E-01
 15  6.9477E-01   6.8969E-01   6.8496E-01   6.8057E-01   6.7654E-01   6.7291E-01   6.6969E-01   6.6690E-01   6.6451E-01   6.6250E-01
 14  6.6392E-01   6.6133E-01   6.5898E-01   6.5684E-01   6.5489E-01   6.5314E-01   6.5160E-01   6.5027E-01   6.4914E-01   6.4819E-01
 13  6.3366E-01   6.3346E-01   6.3339E-01   6.3339E-01   6.3342E-01   6.3346E-01   6.3351E-01   6.3357E-01   6.3363E-01   6.3369E-01
 12  6.0421E-01   6.0628E-01   6.0836E-01   6.1039E-01   6.1229E-01   6.1402E-01   6.1558E-01   6.1694E-01   6.1813E-01   6.1915E-01
 11  5.7575E-01   5.7996E-01   5.8407E-01   5.8799E-01   5.9164E-01   5.9497E-01   5.9794E-01   6.0054E-01   6.0280E-01   6.0472E-01
 10  5.4844E-01   5.5464E-01   5.6064E-01   5.6633E-01   5.7162E-01   5.7643E-01   5.8072E-01   5.8449E-01   5.8775E-01   5.9054E-01
  9  5.2240E-01   5.3044E-01   5.3818E-01   5.4551E-01   5.5232E-01   5.5851E-01   5.6404E-01   5.6890E-01   5.7313E-01   5.7674E-01
  8  4.9775E-01   5.0747E-01   5.1680E-01   5.2563E-01   5.3382E-01   5.4129E-01   5.4798E-01   5.5387E-01   5.5900E-01   5.6340E-01
  7  4.7457E-01   4.8580E-01   4.9657E-01   5.0674E-01   5.1620E-01   5.2484E-01   5.3259E-01   5.3944E-01   5.4542E-01   5.5056E-01
  6  4.5290E-01   4.6547E-01   4.7749E-01   4.8886E-01   4.9944E-01   5.0913E-01   5.1785E-01   5.2559E-01   5.3235E-01   5.3818E-01
  5  4.3273E-01   4.4643E-01   4.5951E-01   4.7190E-01   4.8345E-01   4.9405E-01   5.0363E-01   5.1215E-01   5.196        5.
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 4  [illegible]   [illegible]   [illegible]   [illegible]   [illegible]   [illegible]   [illegible]   [illegible]   [illegible]   5.1014E-01
 3  3.8524E-01    4.0052E-01    4.1507E-01    4.2480E-01    4.4162E-01    4.5340E-01    4.6402E-01    4.7345E-01    4.8166E-01    4.8867E-01
 2  3.6144E-01    3.7665E-01    3.9061E-01    4.0364E-01    4.1561E-01    4.2633E-01    4.3588E-01    4.4401E-01    4.5075E-01    4.5613E-01
 1  0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00    0.0000E+00
```

```
I=      41            42
J
 23  7.3956E-01  7.3956E-01
 22  7.3947E-01  7.3956E-01
 21  7.2832E-01  7.2842E-01
 20  7.1927E-01  7.1937E-01
 19  7.0929E-01  7.0940E-01
 18  6.9834E-01  6.9844E-01
 17  6.8653E-01  6.8662E-01
 16  6.7400E-01  6.7407E-01
 15  6.6092E-01  6.6097E-01
 14  6.4743E-01  6.4747E-01
 13  6.3372E-01  6.3373E-01
 12  6.1993E-01  6.1992E-01
 11  6.0622E-01  6.0619E-01
 10  5.9273E-01  5.9269E-01
  9  5.7959E-01  5.7953E-01
  8  5.6689E-01  5.6682E-01
  7  5.5467E-01  5.5458E-01
  6  5.4287E-01  5.4278E-01
  5  5.3129E-01  5.3119E-01
  4  5.1582E-01  5.1572E-01
  3  4.9422E-01  4.9413E-01
  2  4.5990E-01  4.5982E-01
  1  0.0000E+00  0.0000E+00
```

```
              K =   1   FOR V-VELOCITY    (STAGGERED)
              ------------------------------------------(UNITS = METRES/SEC)


I=      1           2           3           4           5           6           7           8           9           10
J
 23  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
 22  0.0000E+00 -1.0290E-04 -4.5449E-04 -3.5414E-04 -1.9949E-04 -3.0748E-04 -3.7979E-04 -7.9199E-04 -1.3133E-03 -1.8033E-03
 21  0.0000E+00 -1.6044E-03 -1.6036E-03 -1.1536E-03 -7.3208E-04 -7.4930E-04 -1.0235E-03 -1.8421E-03 -2.8717E-03 -3.8370E-03
 20  0.0000E+00 -4.0590E-03 -3.2560E-03 -2.2747E-03 -1.5032E-03 -1.2816E-03 -1.8361E-03 -3.0648E-03 -4.5989E-03 -6.0322E-03
 19  0.0000E+00 -6.9220E-03 -5.1982E-03 -3.6134E-03 -2.4525E-03 -1.8709E-03 -2.7597E-03 -4.4059E-03 -6.4492E-03 -8.3500E-03
 18  0.0000E+00 -9.8985E-03 -7.2283E-03 -5.0447E-03 -3.5012E-03 -2.4715E-03 -3.7187E-03 -5.7900E-03 -8.3555E-03 -1.0731E-02
 17  0.0000E+00 -1.2820E-02 -9.1840E-03 -6.4501E-03 -4.5677E-03 -3.0329E-03 -4.6279E-03 -7.1288E-03 -1.0238E-02 -1.3103E-02
 16  0.0000E+00 -1.5561E-02 -1.0927E-02 -7.7193E-03 -5.5710E-03 -3.5017E-03 -5.3945E-03 -8.3230E-03 -1.2004E-02 -1.5384E-02
 15  0.0000E+00 -1.7986E-02 -1.2312E-02 -8.7357E-03 -6.4193E-03 -3.8162E-03 -5.9047E-03 -9.2539E-03 -1.3551E-02 -1.7485E-02
 14  0.0000E+00 -1.9905E-02 -1.3163E-02 -9.3573E-03 -6.9932E-03 -3.8996E-03 -6.0084E-03 -9.7792E-03 -1.4773E-02 -1.9344E-02
 13  0.0000E+00 -2.1002E-02 -1.3240E-02 -9.4031E-03 -7.1343E-03 -3.6581E-03 -5.5225E-03 -9.7654E-03 -1.5624E-02 -2.1001E-02
 12  0.0000E+00 -2.0727E-02 -1.2231E-02 -8.6578E-03 -6.6522E-03 -2.9956E-03 -4.2903E-03 -9.2034E-03 -1.6262E-02 -2.2721E-02
 11  0.0000E+00 -1.8092E-02 -9.7871E-03 -6.9047E-03 -5.3588E-03 -1.8658E-03 -2.4118E-03 -8.5103E-03 -1.7277E-02 -2.5016E-02
 10  0.0000E+00 -1.1340E-02 -5.6496E-03 -4.0056E-03 -3.1570E-03 -5.0605E-04 -1.1522E-03 -9.1211E-03 -1.9593E-02 -2.8005E-02
  9  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00 -3.1466E-03 -1.0481E-02 -2.0863E-02 -2.9188E-02
  8  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  4.1185E-02  5.4888E-03 -1.3710E-02 -2.5826E-02
  7  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  5.5182E-02  1.9952E-02 -5.0180E-03 -2.0389E-02
  6  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  5.6263E-02  2.6495E-02  1.6289E-03 -1.4659E-02
  5  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  4.9574E-02  2.5643E-02  5.4206E-03 -8.9008E-03
  4  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  3.3391E-02  1.7382E-02  5.0924E-03 -4.0517E-03
  3  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  1.4176E-02  7.3714E-03  2.4422E-03 -1.2874E-03
  2  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  1  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
```