Deepening of the Ambrose Channel and the Flow into the Lower Bay of New York Harbor

By

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Introduction

This report discusses "the transect" or the boundary between the Lower Bay of New York Harbor and that part of the Atlantic Ocean known as the New York Bight. The transect runs from the northern tip of Sandy Hook, New Jersey to Breezy Point, New York on Rockaway Beach. Tidal energy and ocean salt pass through the transect into New York Harbor and the Hudson River estuary. The transect is crossed by the main shipping channel into the Port of New York and New Jersey, the Ambrose Channel.

Over the last century, the Ambrose Channel, has been deepened several times. In the last thirty years, concerns have been raised concerning the impacts of a deepened channel on tides and the estuarine circulation. There have been various attempts to predict such changes using numerical hydrodynamic models, but predicted changes have been marginal considering the calibration and resolution of the calculations. There have been no previous attempt to document such changes from measurements. That is the purpose of this report.

Background

In the nineteenth century, the principal shipping channel into New York Harbor crossed the transect immediately north of Sandy Hook, near the modern position of Sandy Hook Channel. The controlling depth was 24 feet. The entrance channel was deepened to 30 feet by 1884 to accommodate passenger ships with increasing draft. A new, more direct route was proposed to cut across what was then known as Sandy Hook Bar. A shallow "East Channel" already existed here but at the turn of the century this would be transformed into the Ambrose Channel with a controlling depth of 35 feet. By the time the Ambrose Project was complete in 1914, the controlling depth was 40 feet. With the approach of World War II, Ambrose Channel was deepened to 45 feet by 1944 to better accommodate military traffic. There it remained, as authorized, until 1986.

In 1986 a private company, McCormack Aggregates, now Amboy Aggregates, owned, in part, by the Great Lakes Dock and Dredge Company, applied for and received a permit for "advance maintenance dredging" of the outer stretch of Ambrose Channel to a depth of 53 feet (seaward of Buoys 7 and 8) except in the vicinity of buried gas pipeline, the Transco Pipeline (which crosses the channel in the vicinity of Buoy 3; Figure 1). The company dredged the channel at no cost to the Federal government, but paid royalties in the sand to the State of New Jersey. Sand was processed at a shore-side facility in South Amboy, New Jersey. The processed sand was sold for fill and construction, much of it to the NJ Department of Transportation. In 1992, Amboy Aggregates was permitted to deepen the outer reaches of the Channel to 67 feet except in a 500-foot band over the Transco Pipeline, which remained at 45 feet. In 2003, a permit was issued that allowed deepening to 90 feet.

There have been two recurring issues associated with the increasing channel depth. These are (1) changes in the tidal range and tidal current velocities and (2) changes in the estuarine gravitational circulation associated with changes in stratification and the flux of salt. Various mathematical models have been used to estimate the magnitude of these interacting, hydrographic processes. These will be discussed briefly below, but the forecasted changes are generally small, less than a few percent, and often within the uncertainty of the calibration. Coupled with the real, natural variability of the hydrodynamics and the paucity of current measurements, any verification of the model results, or detection of changes due to channel deepening, remains elusive. It is the goal of this report to compare measured tidal currents and gravitational circulation along the transect between 1950's and 1999.

The potential for changing tidal ranges and currents in the Bay and Harbor, in principal, is the result of two competing effects. Increasing the cross-sectional area of the transect reduces the tidal current speeds by continuity. However, deepening the channel also reduces the tidal friction increasing tidal current velocities and reducing any Stokes transport. Increasing the conveyance across the transect should increase the tidal range and reduce the elevation of mean sea level.

Within the Channel as the water depth was increased form 45 feet to, say, 70 feet, the current velocities in the deepened reach might decrease by a factor of 45/70 or 0.64; representing a 55% decrease. In 1959, the maximum tidal currents near the bottom of the Ambrose Channel along the transect (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

* from the U.S. Coast and Geodetic survey, 1958-1959 as reported in Doyle and Wilson (1978)

In the deepened compartment, therefore, maximum tidal currents should reach speeds of 52.8 cm/sec, that is, 82.5 cm/sec times 0.64. However, the entire cross-sectional area of the transect would only increase by about 4%, so the reduction in velocity due solely to continuity could be expected to be less.

Wong and Wilson (1979) had modeled the effects of mining pits to a depth of 50 feet both northeast and southwest of Ambrose Channel between Sandy Hook and Coney Island, although they did not explicitly consider deepening the channel. Current velocities slowed within the hypothetical depressions but accelerated outside of them. In various cases the tidal range increased along the Staten Island shore by as much as 0.1 m due, in most part, to tilting of the Bay's surface rather than a regional increase in tidal range. As a result, the authors concluded increasing water depths near the mouth of the bay might increase the tidal range at Staten Island. A similar 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 the increase tidal range might aggravate shoreline erosion. Field studies of the effect of the tidal range on erosion, however, indicate that erosion rates decrease at larger tidal ranges because wave energy is distributed over a wider intertidal zone (Rosen, 1977).

A modeling effort in 1983 (Malcolm Pirnie, 1983, New York Harbor Navigation Study, unpublished report to the New York District, U.S. Army Corps of Engineers) found that increasing the depth of Ambrose Channel from 45 feet to 60 feet resulted in increases in the tidal range by up to 2.4% (or 3.3 cm, roughly, the same percentage magnitude as the increase in the cross-sectional area of the transect). In the Channel near the transect, the depth-average maximum tidal velocity increased by 0.9 cm/sec on the flood (1%) and decreased by 7.5 cm/sec (7%) on the ebb (Oey et al., 1982). It seems, however, that this model did not preserve the 45-foot water depth over the Transco Pipeline, which, being present, might mitigate any changes by serving as a "choke point" along the channel.

Another model was exercised by Viera and Bokuniewicz (1990) to estimate the changes caused by an increase in the channel depth to 70 feet in a short stretch of the outer channel southeast of the Transco Pipeline. The increased conveyance though produced minimal changes in tidal range (less than 3 mm) and tidal currents only increased detectably in the immediate vicinity of the deepened section and these only by about 10%.

A "Navigation Study" was also done in 2000 with modeling completed for the entire Harbor, Newark Bay and the Hudson in anticipation of numerous, different, channel-deepening projects. Included in the future a scenario was an element to deepen Ambrose Channel from 45 feet to 53 feet but this was not investigated in isolation, rather, in conjunction with the deepening of other areas. Because the Channel at the transect is actually already deeper than this when the calibration data was collected (1995), the results are not applicable to considering deepening to 67-feet in the outer reaches of the Channel through the transect.

The second issue concerns changes in gravitational circulation associated with increases in stratification. In principle, a deepened channel would allow the intrusion of more dense water from the shelf. One consequence could be an increase in the salt flux, that is, increases in Bay, Harbor and estuary salinity. Increased density stratification would also inhibit mixing and increase the strength of the pycnocline. While a faster moving, well-mixed surface layer might result, the bottom water could become more isolated vertically, perhaps generating lowered levels of dissolved oxygen and enhancing the deposition of fine-grained sediment.

The classical estuarine circulation, of landward, net flow over a tidal cycle at depth and seaward discharge of surface water, can be difficult to document. Usually, the net discharge is a small difference between two large discharges, that is the total flood-tide inflow and the total ebb tide outflow. To look for such changes, however, we will compare the modern ADCP surveys to the earliest available data on the structure of the estuarine circulation across the transect.

Previous Work

The U.S. Coast and Geodetic Survey (now the National Ocean Survey) conducted current meter studies in the transect in 1952, 1958 and 1959 (Kao, 1975 Figure 1). Although many current studies had been conducted in New York Harbor, the 1952 and 1958-59 surveys are the earliest to provide detailed information on the current structure across the transect (Abood, 1972). Seven stations were occupied between May and June in 1952 with currents being measured at up to three depths (0.25, 0.50 and 0.75 of the water depth). Four stations were occupied in May 1958 and August 1959. It should be noted that, because these were moored current meter arrays, the array representing the channel was at its southern edge rather than in mid-channel (Kao's figure 2 and figure 4, 1973). In addition, Kao (1973 p. 60) had concluded that the data in 1958 and 1959 was insufficient to allow him to contour the non-tidal velocities for those years.

In 1952, a well developed estuarine circulation was documented with non-tidal velocities exiting the Lower Bay at speeds in excess of 0.15 m s^{-1} in the surface water over Ambrose Channel and landward flow exceeding 0.05 m s^{-1} in the bottom water of both Sandy Hook and Ambrose channels as well as over the East Bank (between Ambrose Channel and Rocky Point); (Figure 2). The discharge of the Hudson (is gauged at the head of tide in Green Island, 246 km above the Battery in New York City) and corrected for a 20-day time lag between the gauging station and the transect (Table 1). In 1952, the adjusted river discharge was between 600 and 900 m^3 s^{-1}. Landward flow was recorded again in 1958 and 1959 both in the deep water of Sandy Hook Channel and over the East Bank. Landward, nontidal flow was not found in Ambrose channel but the data may not have been sufficiently dense to capture this feature, if it existed. On a tidal average water was exiting the channel in two streams centered over Sandy Hook Channel and Ambrose Channel (Figures 3 and 4). The landward flow over the East Bank is attributed the Coriolis force which tilts of the interface between the seaward flow in the surface water and landward flow at depth. The freshwater discharge was between 300 and 600 m^3s^{-1} in 1958 and between 125 and 141 m^3s^{-1} during the August survey in 1959 (Table 1).

In this report we provide a comparison of velocity fields between the 1950's and our 1995-96 study. The comparison between these data and the ADCP data must be done with reservation because the former are extrapolated from point measurements over many tidal cycles (from four to eleven days) while the later have dense spatial coverage but are averaged one tidal cycle.

Methods

During our study five cruises were completed along the transect (Figure 1). Three of these were done in 1995 while the river discharge was low (below about 200 m^3 s^{-1}). These three were done on: 21-22 May, 1995 during neap tides; 1-2 June, 1995 during Spring tides; and 1-2

October, 1995 during neap tides. Two additional cruises were done in 1996. On 15-16 June, 1996 a cruise was completed during spring tides under a river discharge of about 480 m^3s^{-1}. A final cruise on 27 June, 1996 occurred during neap tides and a river discharge of 232 m^3s^{-1}.

The velocity field was measured continuously using a ship-mounted RD Instruments 600 kHz broadband acoustic Doppler current profiler (ADCP) in bottom-track mode. The measurements were averaged into 30-second ensembles with 0.5 meter vertical bins employing a similar approach similar to that of Lwiza and Connolly (1998). The transducer head of the ADCP was mounted 0.8 m below the sea surface and used a blanking interval of 1.0 m; the top of the first bin, i.e., the shallowest water velocity measurement, was 2.05 m below surface. In addition, due to interference with the bottom (ADCP side-lobe effects) data below 85% of the water depth was discarded. The instantaneous velocity profiles were extrapolated to the surface using the average slope from the topmost three bins, and the quadratic law was applied for extrapolation to the bottom.

The ADCP measurements were calibrated using Joyce's (1989) correction procedure for bottom track velocity data. Each transect was subdivided into horizontal sections, each 200 m long. The data from all surveys were combined, and for each pass along the transect, the velocity data falling into each section were averaged together. This procedure formed a time series of at least 55 points for each section. The least squares technique of harmonic analysis described in Lwiza et al. (1991) was then applied to obtain the semi-diurnal and diurnal tidal components (M_2 was taken to represent all the semi-diurnal constituents, and K_1 for the diurnal), the residual for velocity, and water transport. A major drawback of this approach is that it has a tendency of putting the diurnal components into the residual part because the length of the record was short. However, the least squares fitting extracted most of the tidal energy from the observations.

To minimize errors in the depth-dependent current calculations due to changes in water depth over the tidal cycle, the depth was non-dimensionalized. Harmonic analysis was performed on the measurements in the non-dimensional depth bins. The tidal constituents and non-tidal components were then converted back to real depth coordinates.

Transect lines used in 1952, 1958-59, and 1995-96 are shown in Figure 1. The direction for the transect in 1952 was 45 ° , in 1958-59 was 35 °, and 1995-96 was 37°. In order to make a reasonable comparison between the 1950's data and ours, we first projected the transect line to ours (1995-96) by taking the cosine of the angle between the lines. Then the velocity fields from Kao (1975) were digitized and resolved into along-and across-transect components.

Results

The amplitude of the M_2 tidal velocity has highest values (0.87 ms^{-1}) near the surface over the Sandy Hook Channel, and dropped to about 0.65 ms^{-1} towards the bottom (Figure 5). On the shoals the amplitude is larger on the Sandy Hook side than the Rockaway Point side where it drops to 0.10 ms^{-1} near the bottom. Overall the tidal structure is strongly controlled by the bathymetry. Figure 6 shows the M2 phase structure. There is a 20-minute phase lag between the bottom and the surface flow in both the Sandy Hook and Ambrose channels. Maximum phase lag of 20 degrees (about 40 minutes) is found on the eastern shoal between Ambrose Channel and Rockaway Point. The Amplitude for K_1 constituent is small compared to M2, with maximum values of 0.14ms^{-1} found over the Sandy Hook shoal area (Figure 7). The Sandy Hook Channel has amplitudes between 0.06 and 0.10 ms^{-1} whereas the Ambrose Channel exhibits values between 0.02 and 0.06 m s^{-1} with larger values inside the channel. The K_1 amplitude values are not associated with the bathymetry as well as the M2 values, probably because the signal is too weak, and the signal to noise ratio is higher. Figure 8 shows the phase structure for K1. In the channels the phase lag ranges from 6 hours for Sandy Hook channel to 2 hours in the Ambrose Channel. Our results are essentially the same as the results of Kao (1975).

The non-tidal velocity for 21-22 May, 1995 shows a strong outflow at the surface over the axis of Ambrose Channel with velocities in excess of 0.1 m s^{-1} (Figure 9). Inward flowing water is found over the shoal north of Ambrose Channel, in the Channel bottom water and, more strongly in Sandy Hook Channel. This pattern is essentially the same as that recorded in 1952 with one exception. In 1995, landward flow was seen over the shoal to the south of Sandy Hook Channel whereas such an inflow was not detected in 1952 and fairly strong outflow was detected in this general area in 1958 and 1959.

A similar pattern was seen on 1-2 June, 1995 (Figure 10). The principal seaward discharge appears centered over the Ambrose Channel both in 1952 and 1995 with landward flow in the Channel's bottom water (below the ambient shoal elevation) in both time periods, as well as in Sandy Hook Channel. However, in 1995 the inflow along the Channel floor and the extent of inflow over the shoal north of the channel were reduced below their values in 1952 and, in 1995 a strong inflow south of Sandy Hook Channel was seen that was not present in the 1952 profile. The weaker inflow inside Ambrose Channel in June 1995 was similar to that seen in both 1958 and 1959. Nevertheless, in both of the earlier dates strong outflow was present over Sandy Hook Channel while and inward flow was seen in 1995.

On 1-2 October 1995 (Figure 11) inflowing water seemed slightly more extensive over the shoals and was still prevalent south of Sandy Hook Channel. The gradients in velocity were sharper especially in Ambrose Channel in the modern surveys but this could be an artifact of the higher resolution of the ADCP data. The records for 15-16 June, 1996 show a more intense landward flow in the channel floors (over 0.1 m s^{-1}) as well as over the shoals at either end of the transect (Figure 12). This was a period of relatively high freshwater discharge and the estuarine circulation may have been intensified by the episode.

The patterns seen on 27 June 1996 (Figure 13) were again very similar to those seen in 1952 both in distribution and magnitude (with the exception previously noted of landward flow south of Sandy Hook Channel in 1996).

Conclusions

There is no unambiguous evidence for changes in either the tidal or the non-tidal circulation across the transect due to the actual deepening of the outer reach of the Ambrose Channel. There were, however, four noteworthy features of the patterns.

1. Landward flow was seen in Ambrose Channel, below the depth of the ambient shoals, in all the modern ('95 and '96) surveys. It was also seen in the 1952 records but noticeably absent in 1958 and 1959. However, the coverage in 1958 and 1959 was deemed by Kao (1975) as inadequate to resolved contoured patterns, so the noticeable lack of inward flow at the floor of Ambrose Channel during those periods could be an artifact of the data. It is possible that the feature could have been missed.
2. In two of the modern surveys (21-22 May 1995 and 1-2 October, 1995) the interface between landward and seaward non-tidal flow was tilted upward to the north within Ambrose Channel; landward flows tending to the north side of the Channel. This was not seen in the other three modern records or in any of the earlier sections. In fact, the section made in 1952 had a suggestion of the strongest inward flow on the south side of the channel.

3. The strongest inward flow occurred coincident with spring tides and the largest freshwater discharge. The currents during a similar discharge period in 1952 also showed landward flow in the Ambrose Channel.
4. The modern surveys all showed inflow south of Sandy Hook Channel. This was not seen on any of the earlier sections, but it could be due to a lack of spatial resolution.

While these features are interesting, we do not believe they are necessarily indicative of an alteration of the non-tidal circulation by the deepening of the channel. To a first approximation the magnitudes and patterns of the non-tidal discharge are similar between 1952 and 1996. The comparison is confounded, however, by the fact that the earlier current meter data was fairly dense in time (extending over many days) but sparse in spatial coverage while the reverse was true for the ADCP data, which had dense spatial resolution but limited temporal coverage. The differences between the modern surveys were, in our opinion, as striking as the differences between the modern surveys and the early work.

A note on suspended sediment transport

Various lines of evidence suggest that many estuaries, including the Hudson River estuary, import sediment from the sea. The landward flow of bottom water combined with higher suspended sediment concentrations near the sea floor provide a good physical explanation. During the ADCP surveys suspended sediment concentrations were also collected and can be used to estimate the flux of sediment into and out of the Bay across the transect.

There are three earlier estimates of the magnitude of this exchange. All suggest an import of sediment from the ocean. The first has been made using long-term current records and suspended sediment data that were collected along the transect between Rockaway Point and Sandy Hook

Point (Swift et al., 1983). The net flux over a year was calculated to be into the bay from the ocean at a rate of 328,000 MT/yr. Using plutonium as a geochemical tracer, Olsen et al. (1984) provided a second estimate that marine sources supplied about 350,000 MT/yr, even though the uncertainty in this value was given as ±100%. Third, the net budget for the Lower Bay shows a deficit of between 943,000 and 1,602,000 MT/yr. All or part of this deficit might be balanced by an oceanic source (Bokuniewicz and Ellsworth, 1986).

During the modern ADCP surveys reported suspended sediment samples were collected at five stations (Lwiza and Bokuniewicz, undated). In the laboratory onshore the sediment samples were filtered on to pre-weighted polycarbonate nucleopore filters with pore size 0.4 μm. The filters were rinsed with distilled water to ensure removal of salt. The filters were then placed into labeled jars containing desiccating crystals and left to dry for a minimum of 48 hours prior to being re-weighed and combusted in a muffle furnace at 500 degrees centigrade for a minimum of five hours. The dry filter weights provided the total suspended sediment concentrations.

Combining these concentrations with the current velocity, a net inward flux of sediment is calculated with a value of 2,610 kg s^{-1}. Much of this supply entered through the Ambrose Channel. While the finding of a net landward flux is consistent with earlier conclusions the magnitude is very unlikely to be representative of a long-term average since it would correspond to an annual influx of almost 10^{11} metric tons per year.

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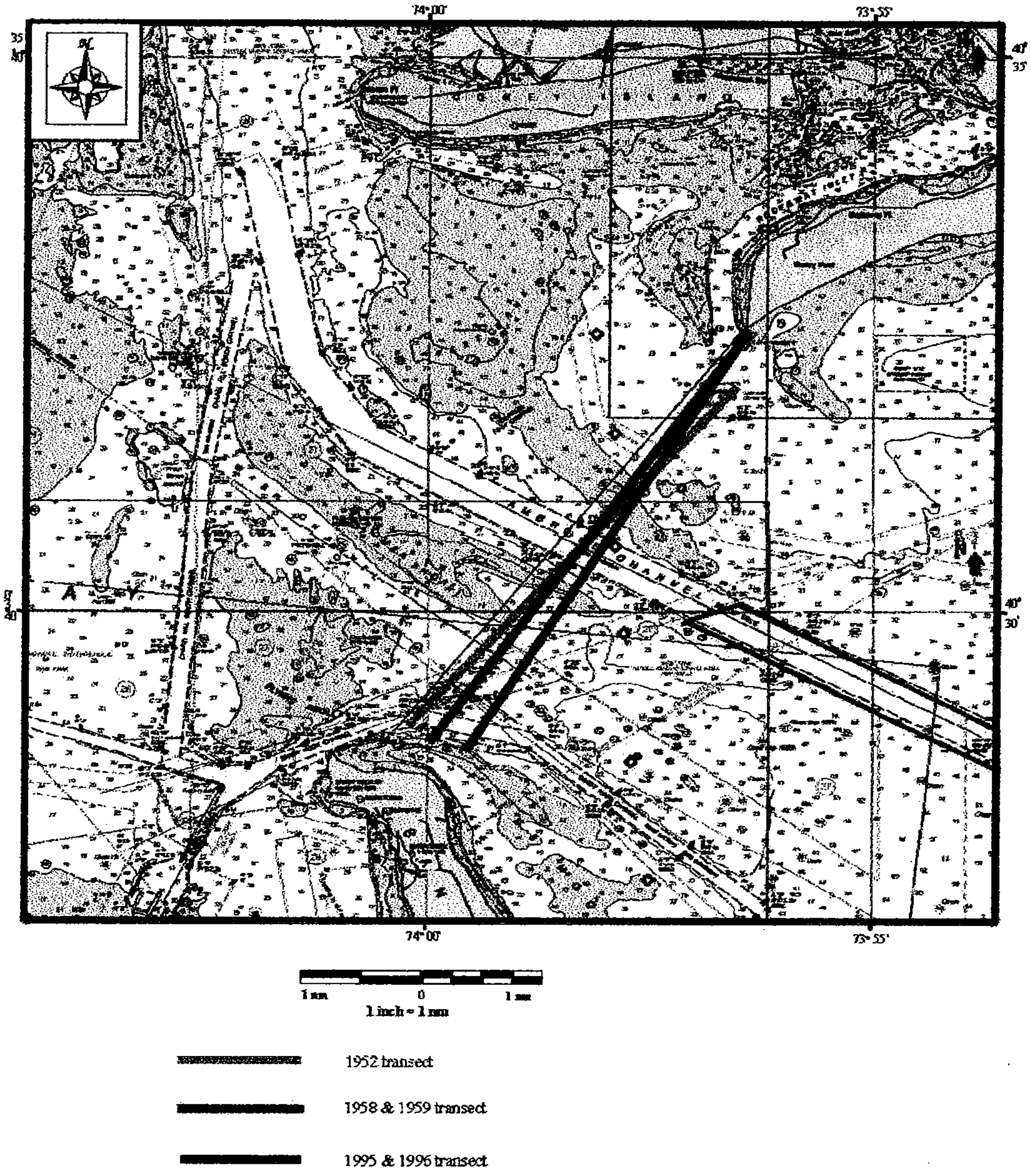
DATE	Discharge (m^3/s)	DATE	Discharge (m^3/s)
5 June 1952	632	16 May 1952	889
23 May 1958	312	3 May 1958	575
14 August 1959	141	25 July 1959	125
21-22 May 1995	136	1-2 May 1995	220
1-2 June 1995	136	12-13 May 1995	177
1-2 October 1995	106	13-14 September 1995	113
15-16 June 1996	478	27-28 May 1996	424
27 June 1996	232	7 June 1996	238

Table 1. Hudson River discharge at Green Island Dam when surveys were done, and their corresponding 20-day lag discharge.



New York Harbor Chart 12327_1: Depth in Feet

Figure 1: Map of study area showing positions of survey lines for 1952, 1958, 1959, 1995, and 1996.

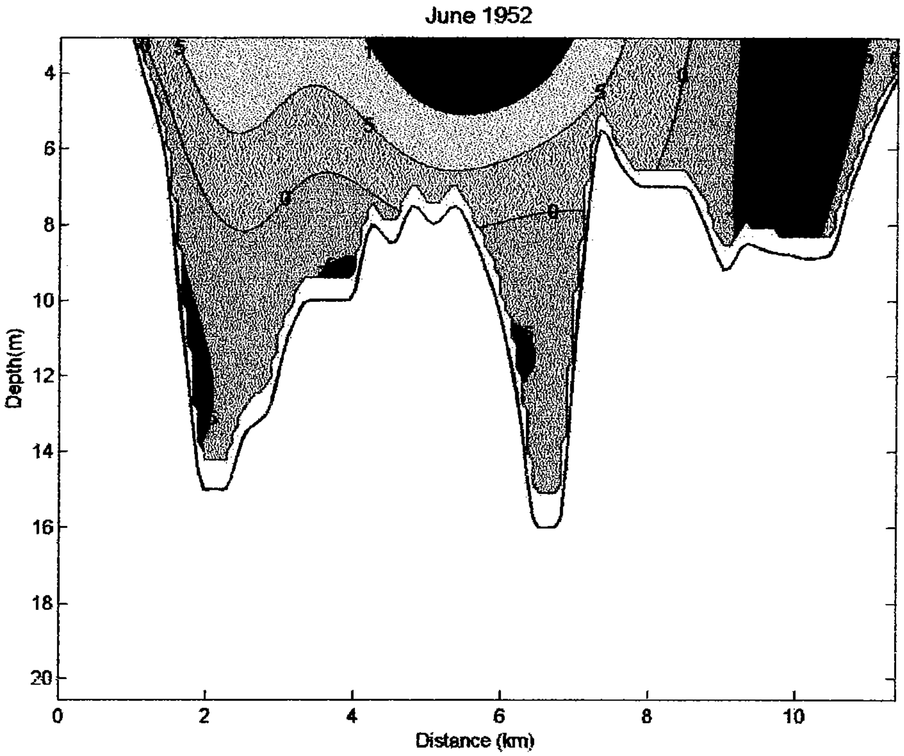


Figure 2: Non-tidal flow (cm s^{-1}) on 3 June 1952.

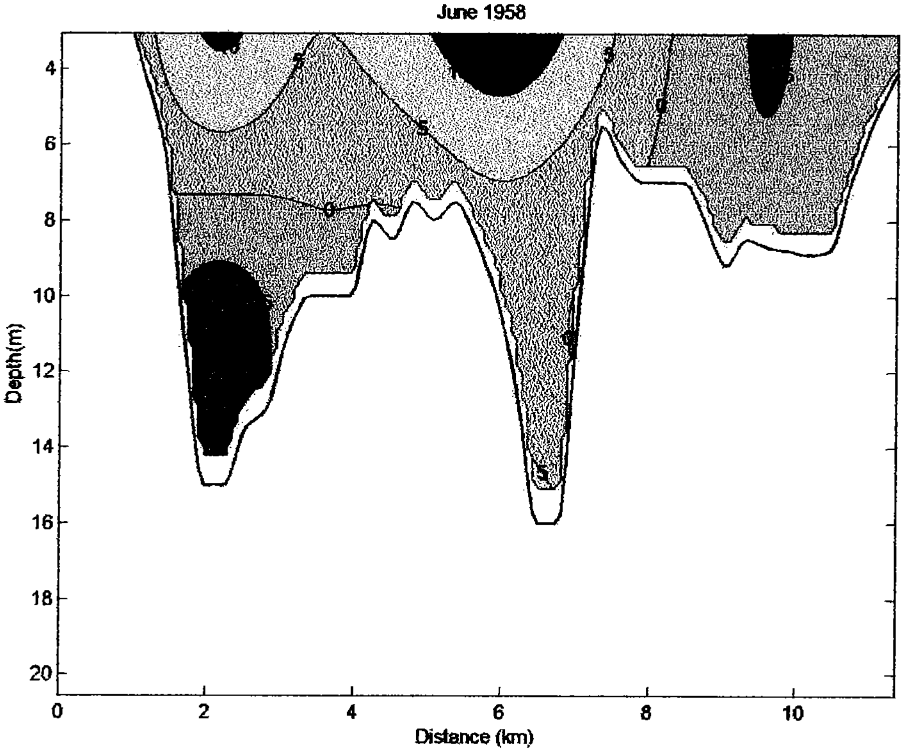


Figure 3: Non-tidal flow (cm s^{-1}) on 24 May 1958.

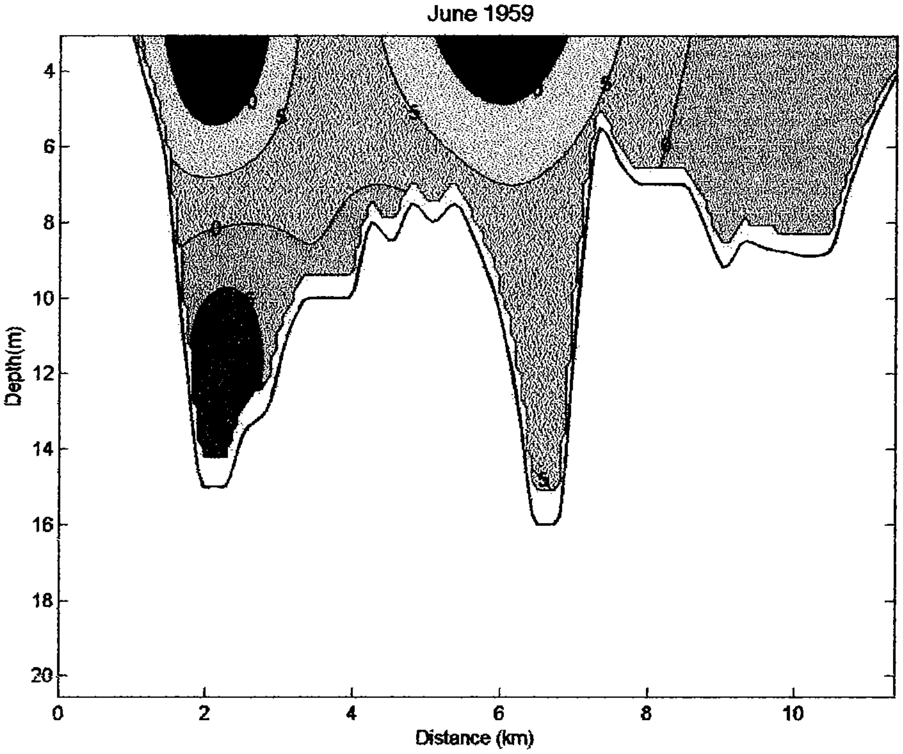


Figure 4: Non-tidal flow (cm s^{-1}) on 14 August 1959.

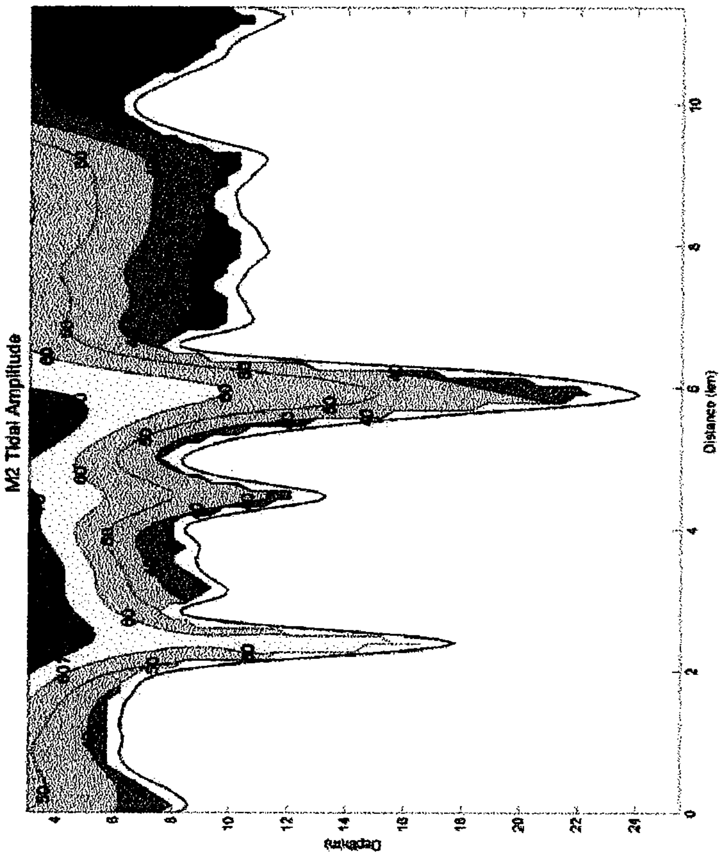


Figure 5: M2 tidal amplitude (cm s^{-1}) calculated from 1995-96 study.

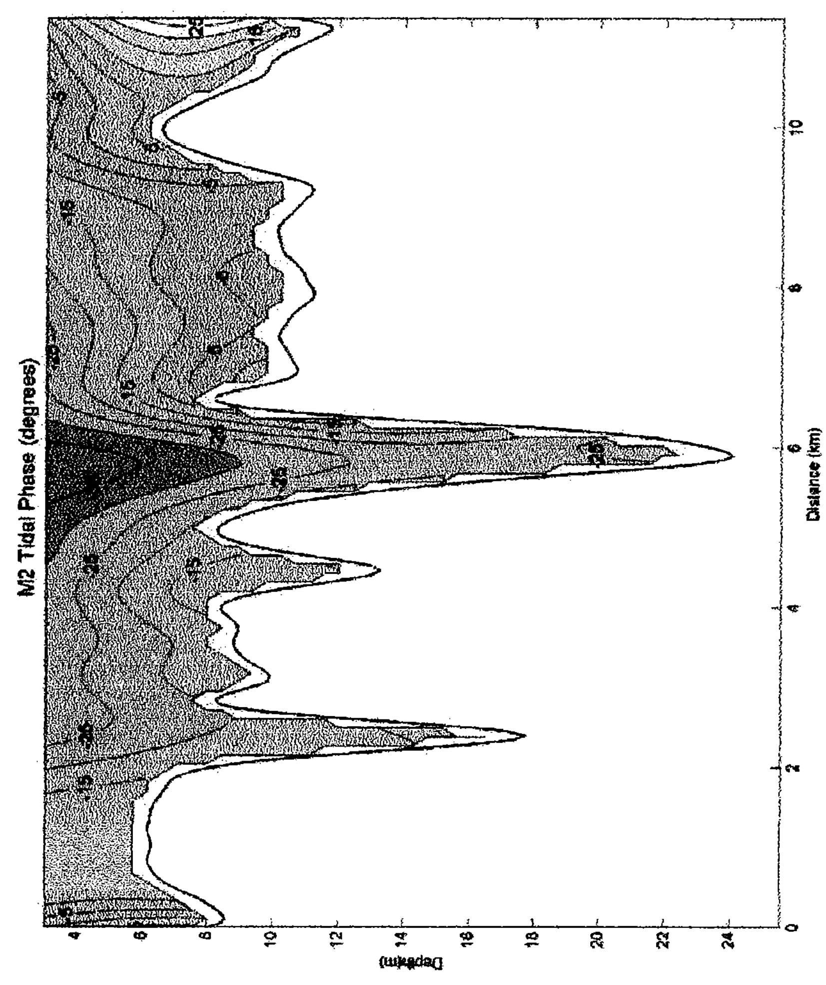


Figure 6: M2 tidal phase (degrees) calculated from 1995-96 study.

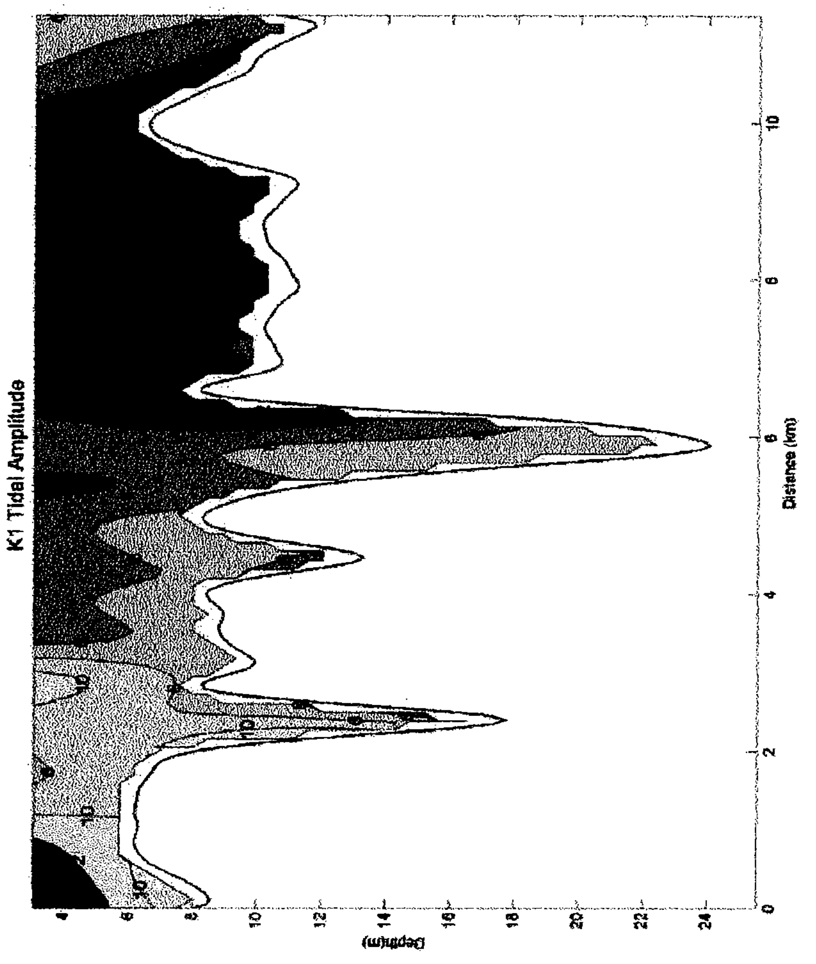


Figure 7: K1 tidal amplitude (cm s^{-1}) calculated from 1995-96 study.

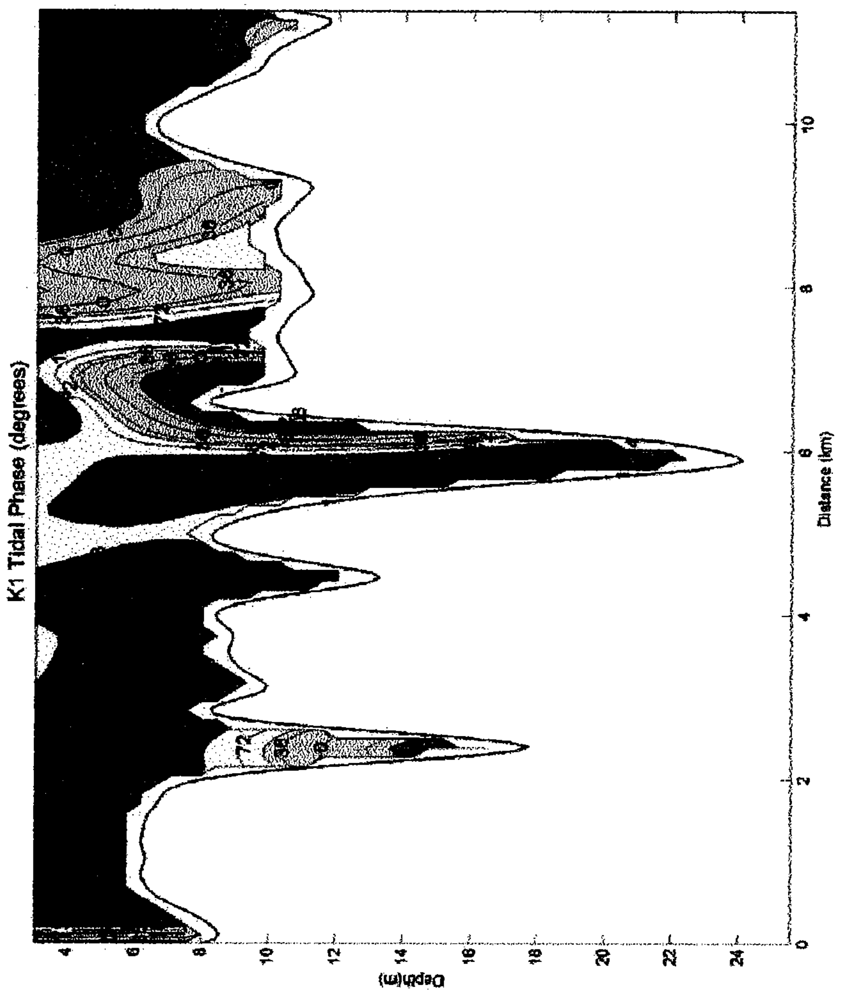


Figure 8: K1 tidal phase (degrees) calculated from 1995-96 study.

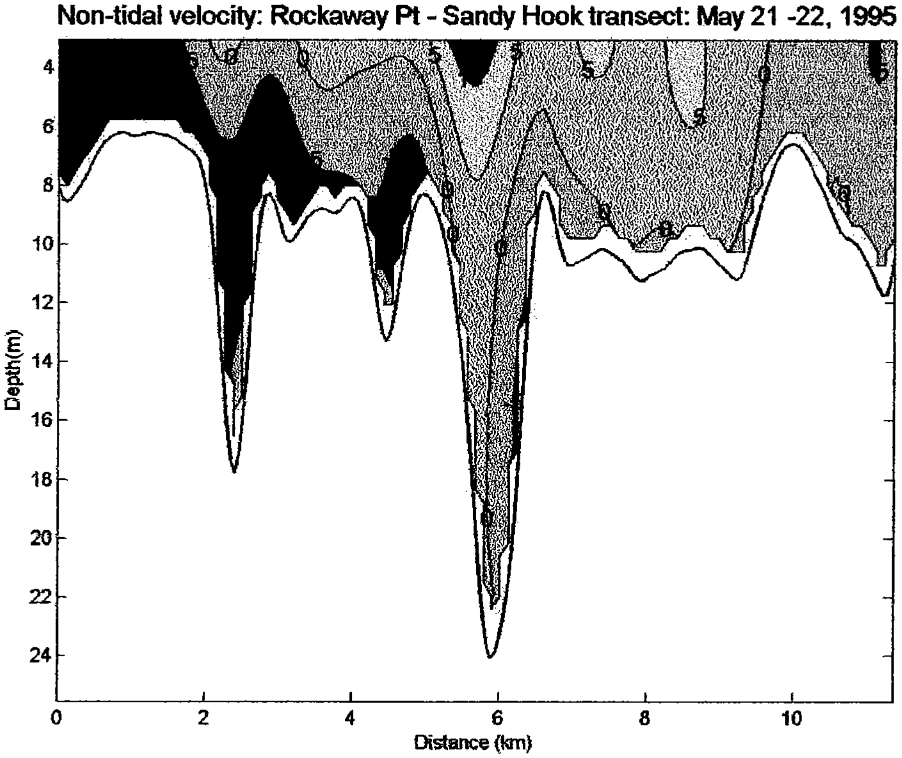


Figure 9: Non-tidal flow (cm s^{-1}) from May 21-22, 1995.

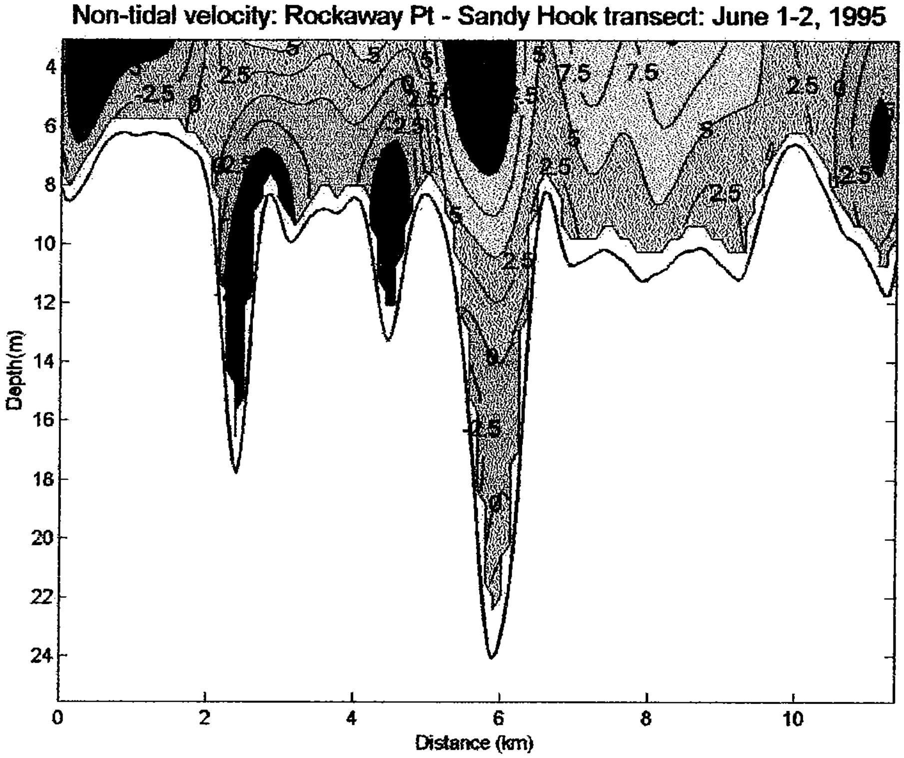


Figure 10: Non-tidal flow (cm s^{-1}) from June 1-2, 1995.