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Formation and Variation of Turbidity Maximum in the Neuse River Estuary, North Carolina, U.S.A.

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Suspended sediment distribution and water column processes in the upper Neuse River estuary, North Carolina, were monitored monthly from February 1988 through February 1989, in order to identify the turbidity maximum, to determine its temporal and spatial variation under changing conditions(freshwater runoff, wind, and tide). During most of the observation periods a weak turbidity maximum, associated with the estuarine circulation processes, developed at a flow convergence zone, near the upstream limit of salt intrusion. No turbidity maximum was found when the water column was vertically homogeneous with respect to salinity and when there was no consistent upstream bottom flow. Annual migration of the turbidity maximum, accompanied by migration of salt intrusion, was over 20 *km* of the upper estuary. Due to the coincidence of dominant wind direction(NE－SW) with the main orientation of the Pamlico-Neuse system, wind played the dominant role in dynamics of the turbidity maximum by influencing the degree of salinity stratification and the extent and strength of estuarine circulation. Tidal effects on the sediment dynamics were negligible.

Introduction

One of the most widely recognized dynamic features that may control estuarine sedimentation processes in estuaries is the turbidity maximum (Nichols and Biggs, 1985; Nichols, 1986). The importance of the turbidity maximum in sedimentation processes is that it serves as a potential sediment trap (Biggs and Howell, 1984). In most partially mixed estuaries, density-driven residual circulation, consisting of seaward flow at the surface and landward flow on the bottom, provides the main mechanism for sediment trapping. Particulate material trapped in the turbidity maximum can pose a variety of economic, aesthetic, and environmental problems. Because of its higher sediment concentrations and, reportedly, higher accumulation rates, the turbidity maximum may be a sedimentary focal point that 1) alters the size and distribution of habitats available to important fin fish and shell fish, 2) imposes an oxygen demand due to decomposition of organic matter that may lead to bottom water anoxia and fish kills, and, 3) effectively concentrates particle-associated substances such as heavy metals, pesticides, and other pollutants.

This study focuses on a region of the lower Neuse River where conditions appear to favor the development of a zone of high turbidity. The overall objectives were: 1) to determine whether a turbidity maximum exists in the Neuse River estuary and, if so, to characterize its spatial and temporal variations; 2) to test the hypothesis that the formation and maintenance of any high turbidity region in the lower Neuse River is a result of density driven estuarine circulation.

Study Area and Background

The Neuse River estuary is one of two tributary estuarine systems, the Tar-Pamlico and Trent-Neuse, which provide the major freshwater and sediment input to Pamlico Sound (Fig. 1). Total length of the main stem of the river is about 400 *km*; its drainage area is approximately 14,500 km^2 or about 11% of the total area of North Carolina. The Neuse River originates in the hilly Piedmont Province and flows southeast mostly on the low-lying Atlantic Coastal Plain. The orientation of the river changes to the northeast about 30 *km* upstream of where the river empties into Pamlico Sound. Pamlico Sound, when combined with Albemarle Sound via Croatan Sound, forms one of the largest estuarine systems in the United States, comprising almost one-half of the North Carolina coastal zone. As a receiving basin for the Neuse River, the Albemarle-Pamlico Sound system is of considerable interest physiographically because of its large size (surface area 6,580 km^2), extremely shallow water (average depth, 5 *m*) and lack of free connection to the adjacent ocean. The Outer Banks island chain, which forms the seaward margin of the system, has only four "permanent" inlets along its 270 *km* length from Cape Lookout to north of Currituck Sound near Virginia Beach.

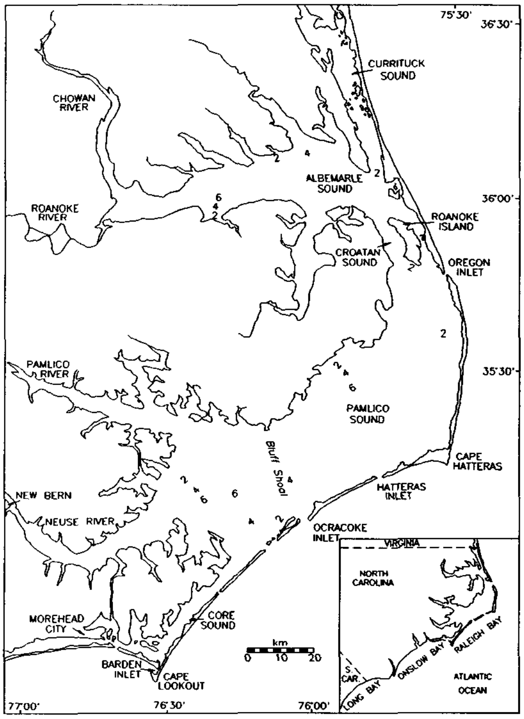

Fig. 1. Index map of Albemarle-Pamlico Sound showing major tributaries, water depths and overall orientation within North Carolina's coastal zone. Bathymetry in meters.

Despite its prominent size and significance, the understanding of the Albemarle-Pamlico Sound system and its tributary estuaries is rather poor compared to that of other principal estuarine systems such as Chesapeake Bay. Furthermore, what is known is mostly descriptive and there is an especially limited understanding of water column processes or sediment dynamics. Past research efforts have been generally limited to two aspects of the system: grain size and mineralogy of bottom sediment (Allen, 1964; Brown and Ingram, 1954; Custer and Ingram, 1974; Duane, 1962 & 1964; Griffin and Ingram, 1955; Park, 1971; Pels, 1967; Petree, 1974; Pickett, 1965); and, subsurface geology (Bellis *et al.*, 1975; Brown *et al.*, 1972; Dubar and Solliday, 1963; Mixon and Pilkey, 1976; Welby, 1971).

In contrast to the abundance of lithologic descriptions of the bottom sediment of North Carolina estuarine systems, very little research has been undertaken with regard to the dynamics of suspended sediment (Wells and Kim, 1989 & 1991). Khorram and Cheshire's study (1983) is the only major published study on suspended sediment in the Pamlico Sound/Neuse River area. This study used a single Landsat image and surface measurements of total suspended solids taken at the time of satellite overpass to develop a regression model for the southern Pamlico Sound area. Other than the few studies which examined current patterns and velocities (Roelofs and Bumpus, 1953; Woods, 1969; Knowles, 1975), little effort has been devoted to the processes by which sedimentary particles are introduced into, redistributed within, and finally stored in the Neuse River estuary and/or Pamlico Sound.

The few published reports on hydrology and flow dynamics in Pamlico Sound show that wind, at least in the short term, is the controlling factor in circulation(Roelofs and Bumpus, 1953; Knowles, 1975;

Singer and Knowles, 1975; Giese *et al.*, 1979; Pietrafesa *et al.*, 1986a, b). The typical wind pattern for the North Carolina coastal area is S−SW wind between April and August and NE−NW wind between September and February.

Lunar tide in Pamlico Sound is minor compared to the wind tide. Dampening of lunar tide within the Sound, and coincidence of the major axis (NE−SW) with the predominant wind direction contribute to enhanced meteorological tides and diminished lunar tides (Pietrafesa *et al.*, 1986b). Observations have shown that 0.6 *m* lunar tides at the inlets to Pamlico Sound are dampened rapidly to less than 0.1 *m* range in the Neuse River estuary near New Bern; yet a strong easterly wind has been observed to induce tides of 1 *m* or more above normal (Knowles, 1975).

The most characteristic hydrologic features of the study area within Neuse River estuary are its small freshwater discharge and negligible tide range. Using data obtained at the USGS gauging station in Kinston, the average discharge rate of freshwater during the last 12 years was calculated to be 73 m^3/sec for 7,000 km^2 of drainage area. Monthly flow rate was maximum in March (171.5 m^3/sec) and minimum in October (20.8 m^3/sec). Annual discharge rate at the river mouth was determined, by extrapolating for the total drainage area (14,504 km^2), to be 150 m^3/sec (4.7 km^3/yr); for comparison, this corresponds to less than 1% of the annual discharge of the Mississippi River(580 km3/yr; Milliman and Meade, 1983).

The low rate of freshwater discharge results in a long residence time of water and suspended particles in the estuarine basin, thus increasing the chances for sediment entrapment. Knowles (1975) estimated the transit time for water starting near New Bern and entering Pamlico Sound to be 32 days. However, as he noted, particles could remain in a local area for a considerably longer period of time because of upstream and cross-river flow. The discharge of sediment can be approximated as 2.35×10^5 t/yr(using the same freshwater/sediment discharge ratio as in the Pamlico River; Giese *et al.*, 1979), which corresponds to only 0.1% of Mississippi River sediment discharge (2.1×10^8 t/yr; Milliman and Meade, 1983).

Low freshwater discharge with low suspended sediment concentration(average of 10~20 mg/l) and minimal tidal range reduce the potential for a distinct turbidity maximum in the Neuse River estuary. Well defined estuarine circulation with a partially mixed salinity structure observed in the Neuse River Estuary, however, can still trap sediment near the upper limit of salt intrusion. Sediment which can be easily resuspended from a very shallow bottom (3 *m* deep in average near New Bern) either by current, by local wind or even by boat wakes can be another important source of sediment for entrainment within an estuarine circulation system.

Methods and Materials

The data consist of field observations made during a 13-month study that extended from February 1988 through February 1989. Within the study period, monthly transects of currents, salinity, temperature, and turbidity were made along the estuarine axis of the Neuse River. The study also included an analysis of archived field data on wind speed and direction, water level, and freshwater discharge.

The 20 monthly stations were set up along approximately 30 *km* of the estuarine axis (Fig. 2), where the typical salinity range was 0 to 15‰. Each monthly observation period included two profiling transects, one while the boat was traveling downstream and one while traveling upstream.

At each station, a profile of the water column was made at 1 *m* intervals from near-bottom (50 *cm* above bottom) to surface using an instrument array consisting of an InterOcean S4 electromagnetic currentmeter with conductivity, temperature, and depth sensors, a Sea Tech optical transmissometer, and a submersible water pump for water sampling. These instruments were deployed for 1 minute at selected levels in the water column (typically 4 to 5 levels were obtained).

Upon returning to the laboratory, concentrations of suspended sediment were determined by filter-

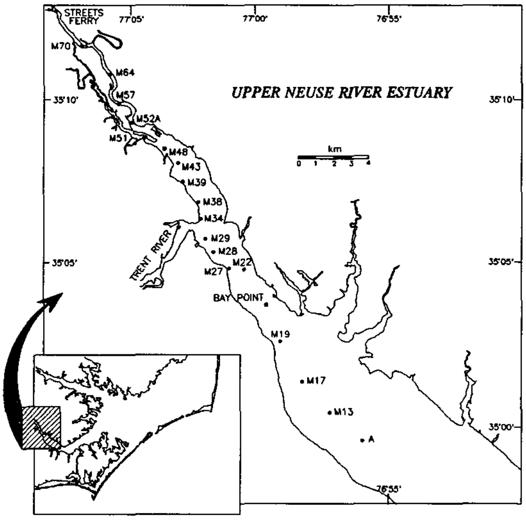

Fig. 2. Map showing the stations for monthly observations in the lower Neuse River.

ing 300~500 *ml* of each water sample through preweighed 0.45 *μm* Millipore filters (type HA, 47 *mm* diameter) using standard gravimetric techniques (McCave, 1979). Current speed and direction were averaged over 1-*min* intervals, thus providing a single representative value at each depth. Current speed was then decomposed into an along-channel component at each station. This information was used to resolve bidirectional movement of water column along the estuarine axis and deter mine the degree to which estuarine circulation was developed. Hourly averaged wind velocities, obtained from the measurements at the Institute of Marine Sciences Meteorological Station in Morehead City, were decomposed into 2 directions for further analysis: NE−SW (main orientation of Pamlico Sound) and NW−SE (orientation of the study area).

Correlation analysis was performed among the main environmental variables (mean salinity, salt intrusion limit, salinity gradient, suspended sediment concentration, current speed, freshwater discharge, wind speed of NE and SE component, and water level) in order to examine relationships that might provide information on dynamics in the study area. Water level data used in the correlation analysis were from archived USGS (United States Geological Survey) data taken at Upper Broad Creek, near the Bay Point Station.

Spectral analysis was performed using time series data(water level data from USGS gauging station in the Neuse River, and wind data from the Institute of Marine Sciences Meteorological Station, Morehead City) obtained during a 12-month period. These analyses were performed to determine the existence and magnitude of lunar and meteorological tide signals in the water level variation of the Neuse River estuary, and to examine the coherence between wind and water level signals.

Results

Table 1 summarizes monthly observations and archived data on wind, water level as well as freshwater discharge. Fig. 3 provides a summary of monthly observations for salinity, current speed, suspended sediment concentration, and freshwater discharge. Each monthly average was calculated from the values over the same area between Station M52A and Station M13.

Salinity Stratification: Monthly average salinities showed a wide range of variation (0.6~8.6‰ in the surface water, 1.9~15.8‰ in the near-bottom water). Minimum salinity occurred in May, 1988, when a south wind was dominant, rather than during the period of the maximum freshwater discharge in February, 1989. During October and November, when north winds were dominant, average salinity was remarkably higher than during April and May when south winds were dominant, even though freshwater discharges during the two periods were comparable. Also, maximum near-bottom salinity occurred in October, 1988 when a north wind was dominant, although this was the time neither of maximum surface salinity nor of minimum freshwater discharge.

During most months, average salinity in the near-bottom water was 5~10‰ higher than the average surface salinity (Fig. 3). However, in April, May, and August, 1988, surface and near-bottom salinity showed less than 2‰ difference. An exceptionally well-developed stratification, with near-bottom salinity of 13~16‰ underlying surface sal-

Table 1. Summary of monthly observations and archived data.

	SALINITY		SSC	CURRENT		WIND		WATER LEVEL	FRESH-WATER DISCHG
	ANGE(AVG)	5‰[1]	RANGE(AVG)	RANGE (AVG)	DECOM[2]	AVG	DECOM[3]		
DATE	SFC BOT [%]	SFC BOT [*km*]	SFC BOT [*mg/l*]	SFC BOT [*cm/s*]	SFC BOT [*cm/s*]	DIR SPEED [*km/h*]	NE-SW [+][-] SE-NW	24 HR MONTH [*cm*]	24 HR 5 DAY [m^3/s]
2/25/88	0.1~7.0(2.2)	22.5	8.7~13.0(10.9)	*	*	293	-6.3	*	48.4
	0.1~13.0(8.8)	8.0	10.0~23.6(15.2)	*	*	16.9	-15.7	*	57.9
3/18/88	0.1~4.6(1.3)	27.4	5.7~15.7(10.8)	*	*	152	-2.1	15.1	62.0
	0.1~8.0(6.3)	12.1	14.3~30.0(20.8)	*	*	7.2	6.9	14.8	69.1
4/21/88	0.1~4.8(0.8)	26.5	9.2~21.6(13.0)	3.3~41.7(16.9)	14.3	226	-30.9	12.2	69.1
	0.1~8.3(2.5)	19.3	9.6~28.4(17.4)	7.6~32.4(18.0)	-6.5	30.9	-0.5	25.7	51.6
5/13/88	0.1~3.2(0.6)	29.0	4.4~12.8(7.9)	0.8~15.4(6.4)	2.6	162	-6.7	21.2	26.0
	0.1~7.9(1.9)	21.7	5.2~25.6(10.6)	1.5~21.9(7.5)	0.7	14.8	13.2	22.0	36.9
6/13/88	0.1~6.1(1.9)	24.9	5.3~15.3(8.0)	2.0~24.5(12.6)	8.8	189	-11.3	14.3	39.9
	0.1~9.4(5.5)	16.1	5.0~20.7(8.9)	1.8~30.1(7.2)	-4.3	14.0	8.2	16.8	30.2
7/28/88	0.1~9.3(2.5)	22.2	5.1~16.3(8.5)	2.5~16.8(8.3)	1.9	199	-15.0	0.0	63.7
	0.1~17.5(7.3)	14.2	7.1~14.3(10.6)	2.7~19.2(10.2)	-2.3	16.7	7.3	1.1	45.2
8/29/88	0.1~13.2(5.5)	14.5	4.0~15.7(7.2)	5.8~32.5(17.7)	4.2	151	-8.7	13.7	22.3
	0.2~14.8(6.8)	13.7	5.9~18.8(9.0)	3.2~24.3(8.6)	5.5	31.5	30.3	13.1	27.2
9/20/88	0.4~11.0(5.0)	16.1	4.0~10.6(6.9)	2.6~44.0(9.6)	3.7	156	-6.3	14.5	23.7
	2.0~14.5(10.4)	4.8	5.4~16.3(8.0)	1.6~21.8(7.4)	3.9	17.5	16.4	28.0	26.6
10/27/88	1.2~9.0(5.6)	11.3	4.4~20.4(8.3)	2.8~54.1(11.5)	5.7	30	12.0	30.7	29.7
	12.0~20.0(15.8)	4.2	3.5~9.9(6.5)	2.4~16.2(9.4)	-8.4	12.4	-3.2	27.2	31.7
11/22/88	0.1~12.0(4.2)	18.5	5.1~23.2(10.1)	4.2~41.6(15.2)	14.1	21	16.8	31.3	64.3
	1.5~15.0(11.0)	8.8	4.4~16.5(8.8)	3.3~18.5(7.9)	-3.2	18.3	-7.5	16.1	54.4
12/19/88	0.5~14.7(8.6)	11.6	2.9~13.8(7.2)	1.8~45.8(10.4)	-2.3	218	-17.9	-0.8	24.9
	12.8~18.5(14.9)	1.3	3.2~20.6(8.6)	2.4~15.0(8.0)	-6.6	18.0	2.2	6.4	26.1
1/27/89	0.3~14.5(6.3)	14.0	4.4~15.9(7.5)	4.2~51.4(22.4)	21.0	243	-18.4	-2.4	45.0
	3.6~18.0(14.6)	7.2	3.1~21.8(11.6)	7.0~30.0(16.7)	-15.1	19.3	-6.0	11.3	45.3
2/28/89	0.0~5.3(1.2)	23.8	11.7~40.0(24.1)	6.1~43.9(23.7)	22.3	261	-17.6	23.3	177.0
	0.0~15.7(12.0)	8.0	8.3~27.2(16.0)	4.1~27.5(10.8)	-4.9	21.7	-12.8	15.5	142.0

[1] Salt introsion limit represented as the distance (*km*) from the Streets Ferry Station to the location where 5‰ isohaline intersects the bottom profile.

[2] *Decomposed current speed along the channel orientation.* Positive and negative speed denote downstream and upstream component, respectively.

[3] Decomposed wind speed along the main orientation of Pamlico Sound (NE-SE) and the upper Neuse River estuary (SE-NW). Positive speed denotes NE or SE wind component, negative speed component denotes SW or NW wind component.

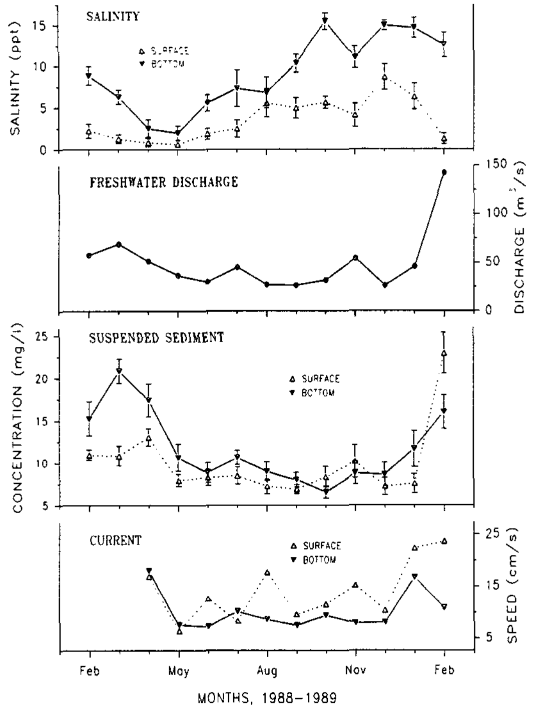

Fig. 3. Monthly variation in average salinity, 5-day averaged freshwater discharge at Kinston USGS station, average suspended sediment concentration, and average current speed. Error bars represent 95% confidence intervals.

inity of 0~5‰, occurred in February, 1989 when freshwater discharge was at maximum. Generally, vertical gradients were higher in fall and winter months than in spring and summer months (Fig. 3). High vertical salinity gradient was associated with low SE wind speed ($r=-0.71$, $p=0.01$, $n=13$), and with high freshwater discharge($r=0.49$, $p=0.09$, $n=13$).

The upstream limit of salt intrusion(defined here as the intersection of the 5‰ isohaline with the bottom) migrated over 20 *km* of the estuarine axis from Streets Ferry in December, 1988 to Station M19 in May, 1988 (Fig. 4).

Annual mean salinity from Station M52A to Station M13, 18.5 *km* apart along the estuarine axis, showed a consistent increase from 0.6 to 9.5‰ at the surface and from 3.5 to 14.6‰ in near-bottom water (Fig. 5A) with a gradient of about 0.5~0.6‰ /*km*.

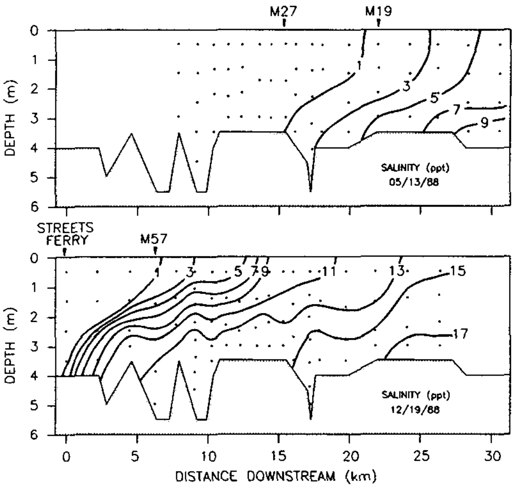

Fig. 4. A) Minimum and B) maximum salt intrusion during the study period observed on May 13, and December 19, 1988, respectively.

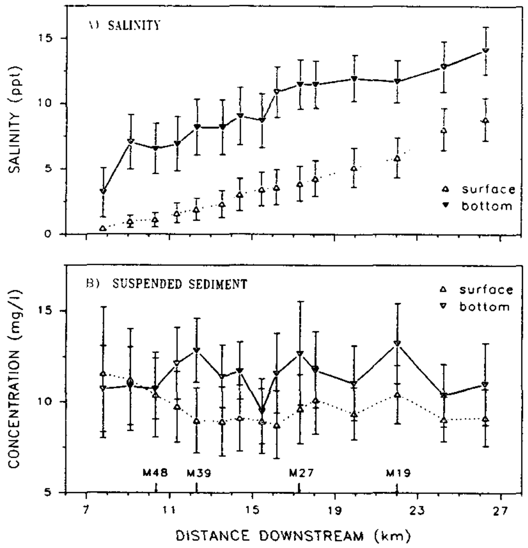

Fig. 5. Annual mean A) salinity, and B) suspended sediment concentration over 15 stations along the estuary. Error bars represent 95% confidence intervals.

Estuarine Circulation: Monthly average current speeds in surface water varied from 6.6~23.7 *cm/sec* with the highest value observed when the freshwater discharge was maximum (Fig. 3). Near-bottom current generally showed a lower average speed (ranging 7.2~18.0 *cm/sec*) and less monthly variation than surface current. During each month, however, the maximum speeds in the surface and near-bottom water reached 50 *cm/sec* and 30 *cm/sec*, respectively. The direction of current, both in the surface and near-bottom water, was not always aligned with the channel orientation and opposite directions were often observed at adjacent stations, indicating a complicated flow patterns that may have been due to cross-channel flow, eddy-like circular flow, or seiching of the Neuse-Pamlico system.

However, the current measurements, when decomposed into the direction of channel orientation, showed two-layered structure of net movement during most of the observation periods; that is, surface water flowed downstream and near-bottom water flowed upstream (*i.e.*, Figs. 6, 7, and 8). The flow convergence zone usually coincided with the upper limit of salt intrusion. During most of observation periods, consistent upstream flows with maximum speeds of 5.4~29.3 *cm/sec* were observed.

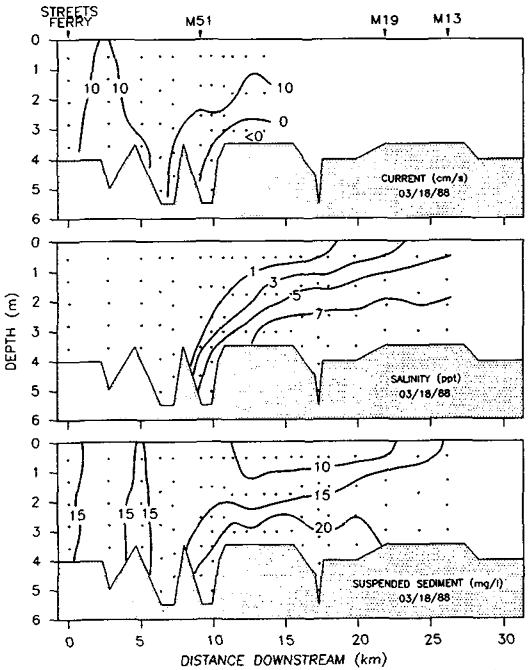

Fig. 6. Along-channel distribution of current speed (+, downstream flow; −, upstream flow), salinity and suspended sediment concentration in the upper Neuse River estuary on March 18, 1988.

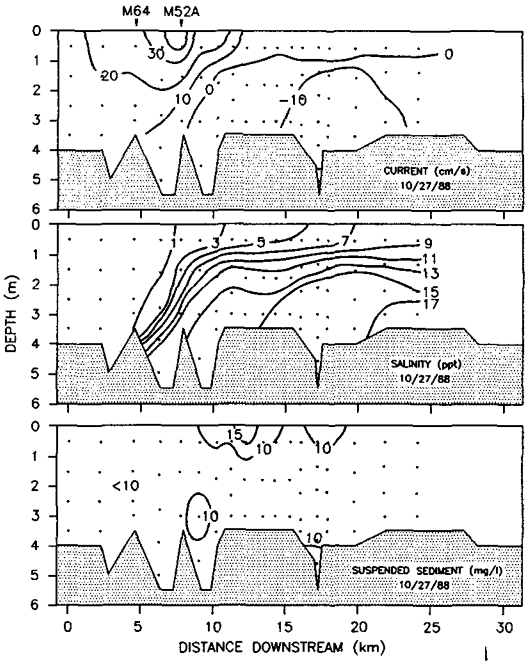

Fig. 7. Along-channel distribution of current speed (+, downstream flow; −, upstream flow), salinity and suspended sediment concentration in the upper Neuse River estuary on February 28, 1989.

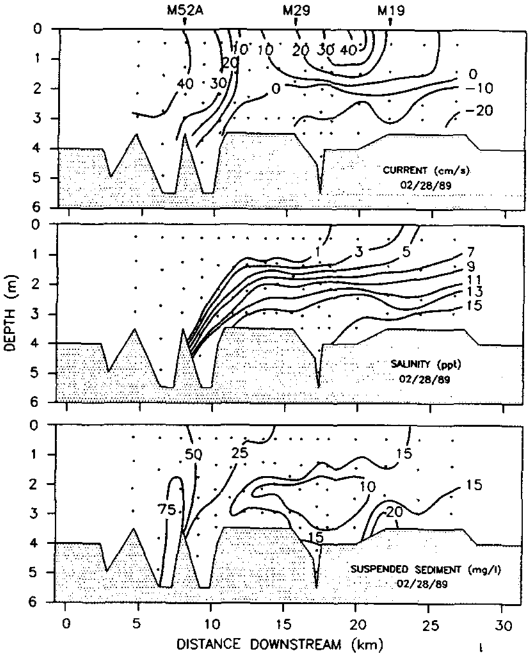

Fig. 8. Along-channel distribution of current speed (+, downstream flow; −, upstream flow), salinity and suspended sediment concentration in the upper Neuse River estuary on October 27, 1988.

Average surface current speeds of the downstream component show a positive correlation with the freshwater discharge(r=0.65, p=0.02, n=13) and a negative correlation with the SE wind (r=-0.71, p=0.01, n=13). Upstream component of bottom current speed decreases with higher SE wind speed(r=0.59, p=0.03, n=13), and increases with higher NE wind speed(r=-0.38, p=0.20, n=13).

August 1988 was the only month which did not show any sign of consistent upstream bottom flow (Fig. 9). It was noted that during this period a strong southeast wind was blowing over the area. Local effects of a prevailing southeast wind minimized the stratification by suppressing the downstream surface flow and by increasing turbulence. Also regionally, it could have pushed the sound water toward the north causing retreat of bottom saline water from the Neuse River estuary.

Variations in Suspended Sediment Concentration: The monthly averages of suspended sediment concentration varied from 7.4 to 20.0 *mg/l* with a minimum and a maximum in October, 1988 and February, 1989, respectively(Fig. 3). The average concentrations were usually higher near the bottom than at the surface, except during October and November, 1988, and February, 1989. The overall variation of average monthly concentration in the surface water was remarkably similar to the variation of freshwater discharge (r=0.94, p<0.01, n=15), indicating that terrestrial input is the main source of suspended sediment in the area. Average surface concentration was highest (24.1 *mg/l*) in February, 1989 when freshwater discharge was maximal, and lowest (6.6 *mg/l*) in September, 1988 when freshwater discharge was minimal. Near-bottom averages ranged from 6.5 *mg/l* in October, 1988 to 20.8 *mg/l* in March, 1988. From late winter through early spring (February to April), the average concentration in the near-bottom water was above 15 *mg/l*. During the rest of the year the concentration dropped to below 12.5 *mg/l*. Monthly mean concentrations of suspended sediment in near-bottom waters were best correlated with the mean near-bottom current speeds within the measured range of 7~18 *cm/sec* (r=0.72, p<0.01, n=13).

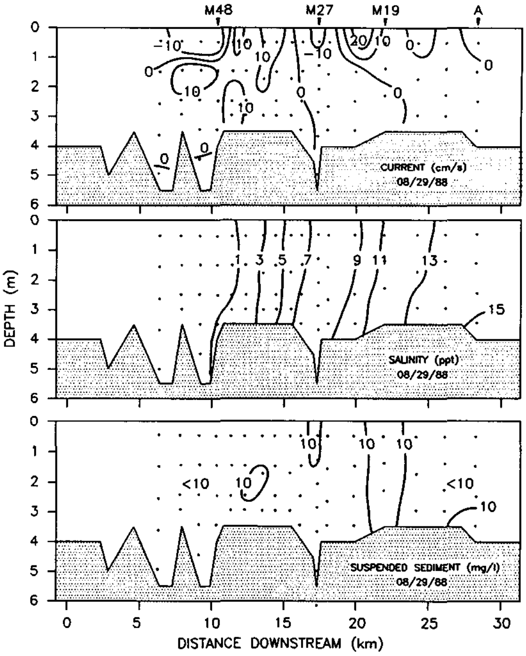

Fig. 9. Along-channel distribution of current speed (+, downstream flow; −, upstream flow), salinity and suspended sediment concentration in the upper Neuse River estuary on August 29, 1988.

The Neuse River Turbidity Maximum: A weak turbidity maximum was usually observed near the flow convergence zone at the head of salt intrusion. The best-defined turbidity maxima were observed in March(Fig. 6) and April, 1988, when freshwater discharge and suspended sediment concentration were relatively high. Yet even during these months, the concentrations within the turbidity maxima were barely twice the surrounding turbidity levels. Although the highest freshwater discharge and terrestrial input of suspended sediment were observed in February, 1989 there was no distinguishable development of a turbidity maximum at the flow convergence zone during this period (Fig. 8). The strong downstream surface flow (average 22.3 *cm/sec*, maximum 43.9 *cm/sec*) was apparently flushing the majority of the sediment load out of the lower estuary.

During the August, 1988 transect, when the water column was vertically homogeneous with respect to salinity and no persistent upstream bottom flow was observed, suspended sediment was distributed evenly throughout the upper estuary (Fig. 9) and a turbidity maximum was absent. Also, no sign of a turbidity maximum was observed in October, 1988 when the water column was highly stratified(Fig. 7). October, 1988 was also a period of maximum salinity and minimum suspended sediment concentration near the bottom (Fig. 3).

Throughout the year, the turbidity maximum migrated over the entire upper estuary. The upstream boundary of the turbidity maximum fluctuated between Station M51 and Station M28, where salinity at the upstream boundary ranged from 0.1 to 14‰. During the months when the water column was well stratified(November, 1988 through February, 1989), the turbidity maximum was observed not at the flow convergence zone, but farther downstream where salinities were considerably higher. Greater stratification allows the surface flow to carry the suspended sediment farther downstream, until such time as it mixes with the bottom water, presumably allowing suspended particles to be carried upstream.

When examined as annual mean concentrations, bottom suspended sediment showed three minor peaks of higher concentration (Stations M39, M27 and M19; Fig. 5B). There was no vertical gradient of concentration landward of Station M48, and seaward of this location the surface concentration decreased to below 10.0 *mg/l* and near bottom concentration increased to about 12.5 *mg/l*.

Time Series Analysis of Tide and Wind; Although Knowles (1975) noted a semi-diurnal signal in his measurements of the current velocities of the Neuse River estuary, the cyclicity of water level fluctuation is still in question. The questions addressed in this analysis include: 1) Is there a significant semi-diurnal and/or spring-neap tidal signal in water level of the Neuse River estuary ? , and 2) Are wind speed and water level coherent as has been observed in Pamlico Sound (Pietrafesa *et al.*, 1986b) ? In this study, spectral analysis was performed to elucidate the cyclic signal of wind speed and water level, as well as any coherency between two signals. Two different components (NE−SW and SE−NW) of wind speed were analyzed separately. Water level data were obtained from the same USGS gauging station in Upper Broad Creek described in the previous section.

Fig. 10 shows the power spectral distribution of the NE and SE components of wind speed and water level, averaged at hourly intervals during the period between March, 1988 and February, 1989. In the power spectra of water level, there is a peak at 0.081 *cph* (cycles per hour) frequency (12.4-*hour* period). However, there is no corresponding peak in the power spectra of either NE or SE wind speed. This indicates that the peak at 12.4-*hour* period is semi-diurnal lunar tidal signal. At the frequency of 0.04 *cph*(24-*hour* period), water level and both wind speeds show a peak. Given that there is no diurnal lunar tide in the study area, the peak at this frequency is the result of diurnal sea

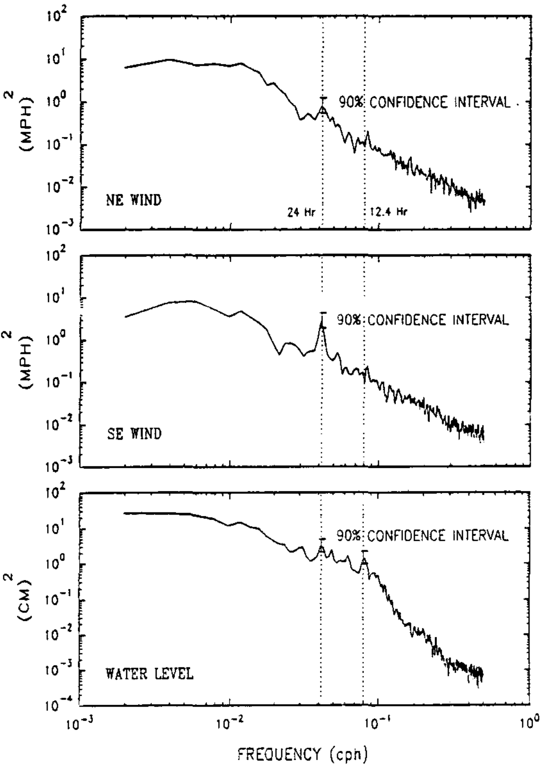

Fig. 10. Power spectral distribution of 1 hour-averaged A) NE and B) SE wind speed, and C) water level. Two vertical lines at the periods of 24-hr and 12.4-hr locate the frequency of diurnal sea breeze and semi-diurnal tide, respectively. Degree of Freedom is 32.

breeze effect as was observed by Pietrafesa *et al.* (1986b). The magnitude of the semidiurnal tidal signal was estimated to be 3.1 *cm* by summing up the power spectral values under the peak. Roelofs and Bumpus (1953) calculated a 5-*cm* tidal range using data on the area of the Sound and the volume transport of flood tidal water through the inlets, assuming an even distribution of tidal energy throughout the area. Even though a significant peak exists at M2 tidal frequency, it accounts for only 3.2% of total variance of water level. At Cape Hatteras, the M2 component was reported to account for 49% of water level variance (Pietrafesa *et al.*, 1986b).

Fig. 11 shows the coherence and phase relation between wind speed and water level. NE wind speed shows better coherency with water level than SE wind speed, and water level and NE wind speed are highly coherent with each other at all periods longer than 1.5 days (0.028 *cph*). The coherency between water level and NE wind speed was also observed from correlation analysis($r=0.74$, $p<0.01$, $n=14$). The near-zero phase difference between NE wind speed and water level at those periods indicates that a dominant NE wind increases the water level in the study area. This is consistent with the findings of Pietrafesa *et al.* (1986b) that persistent NE wind sets up the water level in the Neuse River and SW wind drives the water out toward the northern part of Pamlico Sound system, causing a set down of water level. In contrast, SE wind speed and water level are almost 180° out of phase at lower frequencies, which suggests that SE wind tends to lower the water level in the Neuse River estuary.

The two components of wind speed apparently have an opposite effect on the dynamics of the upper estuary in terms of near-bottom salinity, vertical stratification and circulation. NE winds (oriented along the main axis of Pamlico Sound) tend to increase the bottom salinity and the vertical salinity gradient by pushing more saline bay water upstream, which results in an increase in the water level at the Neuse River station. On the other hand, SE winds(along the main orientation of the upper reach of the Neuse River estuary) decrease the bottom salinity as well as the vertical salinity gradient ($r=-0.71$, $p=0.01$, $n=13$) by increasing the turbulent mixing and/or by inducing a circulation which offsets the gravitational estuarine circulation. The effect of turbulent mixing by wind-generated waves is expected to be larger for a SE wind than for a NE wind because of the larger fetch for SE winds.

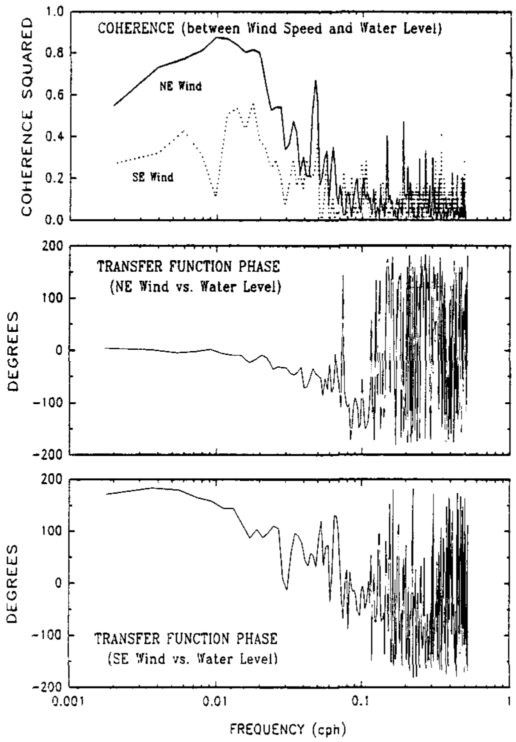

Fig. 11. Coherence and phase relation between wind speed (NE and SE) and water level.

Discussion

Water Column Dynamics

One of the most significant findings of this study is that strong upstream bottom flow exists (Fig. 12), regardless of the wind and tidal stage. Although the observed current speed and direction are the net result of gravity, tidal, wind, and density gradient forcings, the persistent nature of upstream bottom flow under varying combinations of wind and tide suggests that the density gradient is

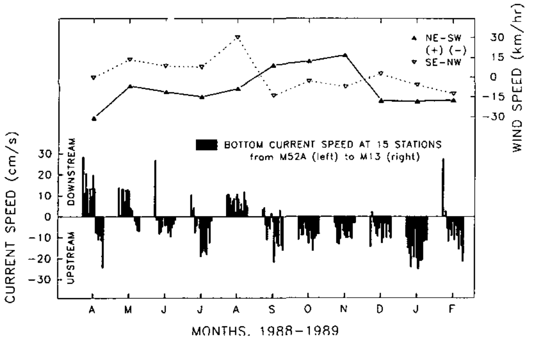

Fig. 12. Average wind speeds(decomposed into NE-SW and SE-NW) and near-bottom current speeds(decomposed into the channel orientation at each of 15 stations) during monthly observations. Each bar represents decomposed near-bottom current speed at each of 15 stations from the upstream station(M52A) in the left, to the downstream station in the right (M13).

primarily responsible for this observed flow. Even though persistent, it is doubtful that observed near-bottom currents, generally on the order of 10 *cm/sec,* are strong enough to resuspend sediment from the bottom. However, upstream flow still provides the potential for turbidity maximum development at the zone of flow convergence.

Since the strength and areal extent of density circulation are dependent on salinity distribution, mean salinity, gradient in salinity, and upstream limit of salt intrusion are important factors which control the water column dynamics of the area. During most of the monthly observations, this part of the Neuse River estuary exhibited the characteristics of the 'partially mixed' estuary in Pritchard's(1955) classification. However, two end-members of estuarine type were also observed, depending on different dynamic conditions: 'vertically homogeneous' in August, 1988 (Fig. 7), and 'highly stratified' in December, 1988 and February, 1989 (Fig. 9).

Mean salinity over the study area showed a wide range of seasonal variation, which was generally related to the variation of river discharge. However, there was a trend toward higher salinity during fall and winter months, especially in near-bottom water, than during spring months when freshwater discharges were similar (Fig. 3). Salinity gradient showed a similar trend of higher values during fall and winter. This can be explained by wind-driven advection within Pamlico Sound, by the seasonal variation of coastal water level, or by both. Dominant northeast winds during fall and winter push saline water from the sound into the estuary, and the dominant southwest winds during spring and summer suppress salinity by keeping saline water out of the estuary.

Long-term, monthly to seasonal, variation of water level of the Neuse-Pamlico System is affected by sea level along the Atlantic coast (Pietrafesa *et al.,* 1986b). Sea level in the coastal water is lower during winter due to lower heat content of the North Atlantic Central Water. In early spring, sea level begins to rise as the heat content increases. Sea level rise slows down as a southwest wind system develops over the area during mid-spring, driving coastal water offshore and causing a set-down of coastal sea level. A substantial strengthening of southwest wind during summer (June to August) overwhelms the rise of sea level due to the increase of heat content.

The extent and strength of upstream bottom flow are also affected by the variation in the wind field, regionally and locally, and in water level. The regional effects of winds on water level and circulation in Pamlico Sound have been broadly discussed by Pietrafesa *et al.* (1986b). They emphasized the effect of wind-induced slopes of the water surface on tidal flows and water level of the Pamlico Sound system. Northerly wind over the upper estuary probably has the local effect of increasing downstream surface flow, whereas the regional effect of northerly wind, noted above by Pietrafesa *et al.*(1986b), is to drive Pamlico Sound water toward the south, thus pushing it into rather than out of the Neuse River estuary. The net effects of a north wind on the study area appear to be increasing water level, enhancing upstream bottom flow, increasing mean bottom salinity and vertical salinity gradient, and forcing an upstream extension of the salt intrusion.

Local wind effects on the vertical circulation and stratification in the partially mixed part of an estuary were also examined by Kreeke and Robaczewska(1989). They found that wind can affect the circulation in two ways. First, the surface wind stress forces a wind-driven vertical circulation similar to the gravitational circulation. Depending on the main direction of the wind stress, the wind-driven circulation can amplify or offset the density-driven gravitational circulation. In the upper reach of the Neuse River estuary, local winds blowing from northwest and southeast (along the estuarine axis) have a tendency to enhance and offset the intensity of estuarine circulation, respectively. Second, wind-generated waves intensify the turbulent exchange of momentum, which lessens the stratification and gravitational circulation. The absence of data in this study on wind-driven waves precludes making a determination of wave effects on the water column stratification.

During most of the monthly observations, water level variations over the 7~8 *hours* required for the transects were minimal (usually less than 10 *cm*), and its effect on the salinity and suspended sediment concentration was negligible. However, when water level fluctuations were significant (for example, on April 21, 1988, when water level varied about 20 cm during two transects) the current patterns observed during downstream and upstream transects were different, in contrast to the nearly identical distribution of salinity and suspended sediment concentration. During significant rise of water level, bottom flow stretched farther upstream.

The astronomical tide, examined by spectral analysis of water level and wind speed, indicates that, while both semi-diurnal and fortnightly tidal signals may be present in the water level variation of the Neuse River, these signals have only a small contribution to the total variance of water level fluctuation (Fig. 10) and to the circulation in the study area. Water level in the Neuse River estuary responds to the NE wind contemporaneously, especially with a period of longer than a day and half (Fig. 12). These observations support the conclusion that the variation of astronomical tide plays an insignificant role in suspended sediment concentration, salinity, and current speed and direction.

Formation and Maintenance of the Turbidity Maximum

The term turbidity maximum has been used to define an area of high suspended-sediment concentration in the upper or middle reaches of many estuaries. Concentration levels are usually 10~100 times higher than levels found either upriver or farther seaward in the estuary (Allen *et al.*, 1980; Schubel, 1968; Gibbs, 1977; Nichols and Biggs, 1985). For purposes of this study, the turbidity maximum was defined as an area in the upper estuary of noticeably higher suspended sediment concentration (usually by 10 *mg/l*) which, when contoured in cross section, could be visually separated from sediment concentration in the adjacent water column. This definition, based on comparative rather than absolute concentration, is less rigid than other definitions and allows emphasis on relative variations in a large estuarine system where water column signals appear to be weak.

As a result of generally low levels of suspended sediment concentration in the Neuse River estuary, the development of a turbidity maximum was not distinguishable during most of the year. The best-defined turbidity maxima were observed in March and April, 1988, when freshwater discharge and suspended sediment concentration were relatively high. Turbidity maximum could not be clearly detected when suspended sediment concentrations were lower than 10 *mg/l*, even though a two-layered current structure was well developed. Apparently, the presence of high suspended sediment load is a prerequisite condition for a turbidity maximum to develop.

Annual average suspended sediment concentration along the estuary (Fig. 5B) shows a broad area of higher concentration extending downstream from Station M48. Since the upstream limit of salt intrusion migrated up and down the estuary over a range of 20 *km* (Fig. 4), the same degree of migration of the turbidity maximum would be expected, if it is controlled by processes of estuarine circulation. The upstream boundary of typical area of turbidity maximum development was noted by the region where vertical differentiation in concentration started to develop (Station M48), whereas the downstream boundary was not clear.

In the Neuse River estuary, suspended sediment concentrations both in the surface and near-bottom water are controlled mainly by the varying freshwater discharge, although near-bottom concentrations show a weak correlation with the near-bottom current speed (Fig. 3). From late winter through early spring (February to April), the average concentration at near-bottom was above 15 *mg/l*. During the rest of the year the concentration dropped to below 12.5 *mg/l*. Monthly discharge rate averaged from the last 12 years' data also presented an obvious contrast between higher discharge from January to April(>100 m^3/sec) and lower discharge after May(<80 m^3/sec)(Fig. 3).

The main driving mechanisms for sediment trapping in the Neuse River, when suspended sediment concentration was sufficient to form a recognizable turbidity maximum, appeared for two reasons to be the density circulation. First, the turbidity maximum was always located near the upstream limit of salt intrusion or bottom flow convergence zone (Fig. 6). Second, there was no development of the turbidity maximum when the water column was vertically homogeneous and no upstream bottom flow was observed (Fig. 9). A highly stratified water column due to strong runoff or enhanced salt intrusion driven by winds appeared to reduce the potential for a turbidity maximum by flushing the suspended sediment out of the estuary or by pushing less turbid water of the lower estuary upstream(Fig. 8).

The fact that the turbidity maximum was not better developed, given the strong estuarine circulation, might be explained by the drought condition of 1988. The Neuse River drainage basin experienced a severe drought, especially during the spring of 1988, which not only reduced terrestrial input of suspended sediment but probably allowed greater intrusion of less turbid, saline water from Pamlico Sound. Given the above, it is reasonable to expect that a weak turbidity maximum exists in the Neuse River estuary, at least seasonally, and that development may be enhanced during years of normal or greater than normal freshwater discharge.

Summary and Conclusion

1. In contrast to other large estuaries on the east coast of United States, the Neuse River estuary is characterized by 1) extremely low freshwater discharge (about 150 m^3/sec) and suspended sediment load (most of the year, near to or lower than 10 *mg/l*), and by 2) extremely shallow depth (maximum 5 *m* at the mouth) relative to its width (10 *km* at the mouth). Sediment discharge, based on average concentration and freshwater discharge during the study period, was in the range of $50 \sim 100 \times 10^3$ *t/yr*.
2. One of the most significant findings was that during most of the observation periods, there was a consistent upstream flow in the near-bottom water due to density-driven estuarine circulation. This provided a potential for a turbidity maximum development at a flow convergence zone in the upper estuary.
3. Wind played an important role in the salinity structure and estuarine circulation, and consequently in the dynamics of the turbidity maximum. Regionally, a northeast wind tends to increase the salinity stratification in the study area by pushing saline sound water into the estuary, whereas a southwest wind tends to push Pamlico Sound water toward the north causing a retreat in salt intrusion. Locally, a southeast wind tends to decrease the vertical salinity gradient by generating a wind-driven vertical circulation opposite to the direction of estuarine circulation.
4. Lunar tidal signals were present in the water level variation, but their amplitudes (less than 5 *cm* range) were not significant enough to drive the water circulation in the study area. Salinity structure and suspended sediment concentration were not associated with semidiurnal

tidal cycle.

5. First hypothesis about the existence of turbidity maximum can be accepted, since the presence of turbidity maximum was observed during 85% of observation periods, even though the concentration level in the turbidity maximum was not remarkably higher than the adjacent water column. The best defined turbidity maxima were observed during spring months when suspended sediment input through freshwater runoff was higher and water column was moderately well stratified (*i.e.* in March and April, 1988).
6. Second hypothesis that 'the formation and maintenance of the turbidity maximum is a result of density-driven estuarine circulation' is accepted based on the facts first, that the location of a turbidity maximum was near the flow convergence zone, and second, there was no sign of turbidity maximum when there was no consistent upstream bottom flow (*i.e.*, August, 1988).
7. A prerequisite condition for a well-developed turbidity maximum is the availability of suspended sediment. In other words, if there was not enough suspended sediment available, no turbidity maximum was defined even though estuarine circulation was well developed (October, 1988).
8. When suspended sediment concentrations at each station were averaged over a year, a typical region of turbidity maximum development was noted as a broad area of higher concentration downstream of Station M48. The downstream boundary was not clearly defined, whereas the upstream boundary was defined by the region where vertical differentiation of suspended sediment concentration started to develop(Station M48).

Acknowledgements

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Neuse강 하구의 최대혼탁수 형성과 변동

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미국 북캐롤라이나의 동해안에 위치하는 뉴우스강 하구를 대상으로 1988년 2월부터 1989년 2월까지 매월 부유퇴적물의 분포와 유속 및 염분을 조사하여, 최대혼탁수의 형성과 물리적 환경요인(담수유출량, 풍향 및 풍속, 조석 등)에 따른 시간적, 공간적 변화를 조사하였다.

대부분의 조사기간동안, 염하구 순환과 관련된 미약한 최대혼탁수의 형성이 염수 침입한계 근처에서 관측되었으며, 염수 침입한계의 연중 이동과 수반하여 강 상류의 약 20 *km* 지역에 걸쳐 이동하면서 분포하였다. 이 지역 계절풍의 주된 풍향(북동－남서)과 Pamlico Sound의 지형적 방향성의 일치로 인하여, 염분 성층구조와 염하구 순환의 발달정도는 바람의 영향을 크게 받으며, 따라서 최대혼탁수의 형성과 변동 양상도 조석의 영향보다는 담수유출량과 바람의 영향을 뚜렷이 나타내었다.