penetrant sealant; and (iii) enclosure of the material by constructing a barrier between the asbestos material and the building environment.
8. N. M. Meylan, P. H. Howard, S. S. Lande, A. Hanchett, *Document EPA 560/6-78-005* (Environmental Protection Agency, Washington, D.C., August 1978).
9. W. J. Nicholson, report to the National Institute of Environmental Health Sciences under contract 1-ES-7-2113, Research Triangle Park, N.C., June 1978.
10. R. L. Murphy, B. W. Levine, F. J. Al Bazzaz, J. J. Lynch, W. A. Burgess, *Am. Rev. Respir. Dis.* **104**, 576 (1971).
11. A. R. Daly, A. J. Zupko, J. L. Hebb, report prepared for the Asbestos Information Association of North America, Washington, D.C., 29 March 1976.
12. L. F. Novick, O. Rice, M. A. Freedman, D. Oillson, *Am. J. Public Health* **71**, 744 (1981).
13. We thank G. Petit who performed all the analytical work with the electron microscope.

27 October 1981; revised 5 February 1982

York River Destratification: An Estuary-Subestuary Interaction

Abstract. *Destratification in the York River during high spring tides is the result of the interruption of normal two-layer estuarine flow by the advection of relatively fresh water into the river mouth from the Chesapeake Bay. This advection is due to the presence of a longitudinal salinity gradient in the bay and a difference in the tidal current phase between the river and the bay. Similar behavior is seen in other subestuaries of the Chesapeake Bay and may be common in subestuary-estuary interactions.*

Vertical homogeneity in subestuaries of the Chesapeake Bay, which normally exhibit moderate stratification, has been shown by Haas (*1*) to be correlated with high spring tides. Identified by a surface-to-bottom salinity difference of less than 1 per mil in contrast to normal values as high as 10 per mil, these episodes have been termed destratification events (*2*). For example, the lower York River becomes vertically homogeneous 3 to 4 days after the predicted tide height exceeds 0.8 m (*1*), and homogeneity persists for three or more days. These events are not correlated with changes in the flow of fresh water into the river (*1*). Some of the significant consequences of destratification events in the York River include a periodic resupply of oxygen in the bottom water with an accompanying renewal of nutrients near the surface (*3*) and changes in primary productivity including blooms of dinoflagellates and other phytoplankton (*4*).

Two theoretical discussions of spring-neap tidally related stratification variations have been presented (*5*). Both of these models describe reductions in stratification that coincide with the occurrence of strong tidal currents and do not persist in the absence of such currents. This coincidence is in contrast to destratification in the lower York River, where vertical homogeneity first appears a few days after the onset of strong tidal currents and persists for several days thereafter (*1, 2*).

A conceptual model for the onset and disappearance of vertical homogeneity in the York River is as follows. (i) Destratification commences when spring tides exceed a critical height and relatively fresh water from the Chesapeake Bay is advected into the mouth of the York River. (ii) This produces a reduction or possibly a reversal of the pressure gradient driving estuarine circulation. The concomitant diminution of two-layer circulation reduces the tendency toward stratification by limiting the importation of more saline bottom water. (iii) This permits the establishment of homogeneity by the unopposed action of normal mixing processes enhanced by strong spring tidal currents. (iv) Destratification ceases when the decrease in tide height after spring tides halts the advection of the fresher water into the York River. (v) This allows the reestablishment of a normal horizontal salinity gradient, which produces the eventual reinitiation of two-layer estuarine circulation and vertical salinity stratification.

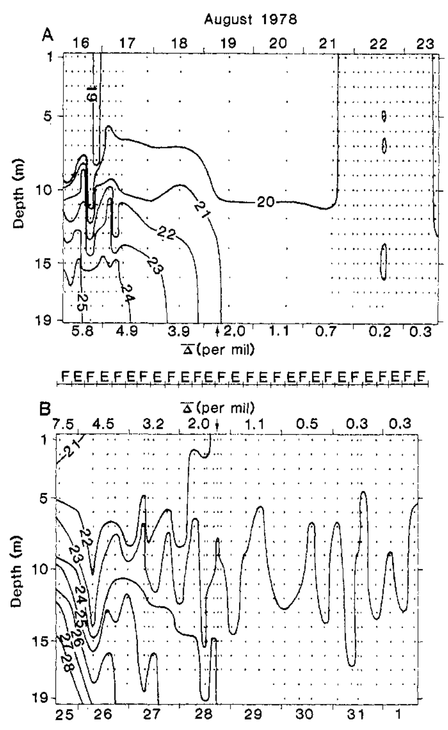

Fig. 1. Salinity data (per mil) from the York River mouth for the periods 16 throught 23 August 1978 (A) and 25 August through September 1980 (B). The arrows indicates the dates of maximum spring tide; $\bar{\Delta}$ is the daily mean of differences in salinity from 1 m to the bottom. Periods of ebb (*E*) and flood (*F*) are indicated. Points indicate measurements (*11*).

This hypothesis developed from an examination of salinity data (Fig. 1, A and B) collected during intensive studies of two destratification events that were predicted on the basis of earlier work (*1, 2*). The intrusion of relatively fresh water, which initiated the destratification process, is indicated by the sharp downward displacement of isohalines on 16 August 1978 and 26 August 1980. In each case, this was followed by a progressive reduction of stratification in the water column. As expected, the introduction of fresher water into the river mouth caused a reversal of the longitudinal salinity gradient, producing a midriver salinity maximum. This condition is illustrated in Table 1, where York River salinity values at 1-m depth are shown for the period from 0 to 3 days after the intrusion of fresher water observed on 25 August 1980 (Fig. 1B). The data indicate a reversal of the normal longitudinal salinity gradient as far as 18 km upriver. A similar reversal was observed on several occasions between 15 and 20 August 1978 (*2*).

The reversal of the longitudinal salinity gradient is also evident from the behavior of the isohaline at 23 per mil in the 1980 data (Fig. 1B). The assumption is made that the salinity changes at the station are caused in large part by the advection of water of differing salinity up and down the river by tidal currents. Depressions in the isohaline, indicating the presence of fresher water, coincide with slack before ebb through 28 August, the date of highest tidal heights. After that date, the isohaline at 23 per mil shows a phase reversal. The depressions are coincident with slack before flood, indicating the reestablishment of the normal longitudinal salinity gradient. While tidal heights were increasing, there was a continuing source of fresher water. As tidal heights recede, more saline water is once again present in the river mouth.

The only reasonable source for the relatively fresh water is the Chesapeake Bay. An upriver source is discounted first because the water is introduced into the river mouth on flood tide (Fig. 1B) and second because the nearest riverine source of water of comparable salinity is

0036-8075/82/0625-1413$01.00/0

approximately 30 km upriver (Table 1). On the other hand, because the salinity distribution in the Chesapeake Bay is characterized by a decrease northward (*6*), fresher bay water is not far from the river mouth. For example, daily paired samples taken during a period of mean tidal range, 11 to 16 July 1980, in the river mouth and near New Point Comfort, an area less than 12 km northeast (Fig. 2), revealed a mean salinity difference of 1.7 per mil (*7*).

The tidally synchronized advection of the relatively fresh water into the river mouth during sufficiently strong spring tides occurs as a result of the relationship of the tidal current phases of the river and the bay. An examination of cotidal lines in the lower Chesapeake Bay (Fig. 2) illustrates that areas at and near the river mouth reach maximum flood current 1 to 2 hours earlier than the adjacent bay areas. Thus, as tides are flooding in the river mouth, the current in the adjacent bay water is near slack before flood, at the seawardmost point of its tidal excursion, and the water being drawn into the lower river is derived from the least saline bay water passing the river mouth during the semidiurnal tidal cycle. Because the importation of relatively fresh water is mathematically expressed as a nonlinear advective term, it is expected to vary proportionally more than the tidal range. Therefore, we hypothesize that during neap or mean tidal cycles the tidal excursion is insufficient to introduce relatively fresh water into the river. Spring tides, however, with increased currents and proportionally greater excursion in both the river and the bay, will provide relatively more fresh water to the river mouth.

As a means of testing the hypothesis, surface markers were placed in the Chesapeake Bay Hydraulic Model of the U.S. Corps of Engineers, Stevensville, Maryland. To minimize the effect of fresh water flow, the experiment was performed during tests of low flow conditions. During simulated spring tides, markers placed at the approximate location of the New Point Comfort station (Fig. 2) on the model were carried into the mouth of the York River in a single tidal cycle. During neap tidal cycles, they were transported only 15 to 20 percent of the distance. As a further means of testing the hypothesis, field studies are planned for this summer.

Figure 2 illustrates that bay-subestuary current phase relationships similar to those observed for the York River are also observed in the James, Rappahannock, and Patuxent rivers but not the Potomac River. Haas (*1*) reported that the James and Rappahannock rivers exhibit destratification events similar to those observed in the York. The Patuxent River also destratifies periodically during spring tides when fresh water flow is sufficient for a stratified system (*8*). Destratification has not been reported in the Potomac River.

The significance of variations in vertical stratification for the timing, magnitude, and distribution of primary production in coastal waters has long been recognized (*9*). However, only recently has the potential significance of vertical mixing processes in regulating estuarine production been generally recognized. For example, the frequency of vertical mixing may be directly related to the productivity of estuarine systems (*10*). Because phenomena such as destratification, which are driven by the neap-spring tidal cycle, may contribute to relatively high frequency vertical mixing in estuaries, a better understanding of the role of neap-spring cycles in regulating estuarine hydrography not only will contribute to the theory of estuarine hydrodynamics but also can be expected to have broad implications for understanding biological processes in estuaries.

Table 1. Salinity data for the York River, 25 to 28 August 1980. The depth is 1 m, and all stations are in midchannel (*12*).

Distance upriver (km)	Salinity (per mil)			
	25 August	26 August	27 August	28 August
0.00	20.5	21.0	21.0	21.8
3.38			21.6	22.4
5.66		23.7	21.8	22.3
8.33			22.0	22.4
12.34	21.3	24.1	23.3	
18.09	22.5			
22.53			21.7	
30.18	20.3		20.0	

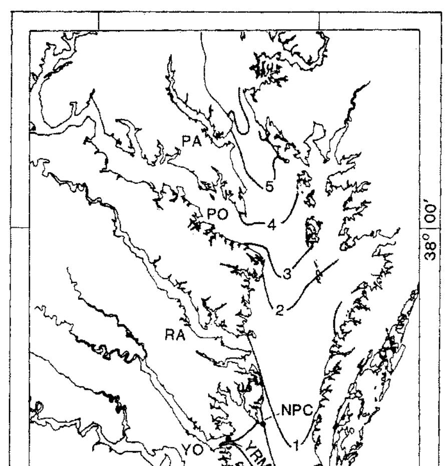

Fig. 2. Chesapeake Bay cotidal lines (in hours) for slack before flood (with reference to Chesapeake Bay entrance) and station locations. Location designations are as follows: *JA*, James River; *YO*, York River; *RA*, Rappahannock River; *PO*, Potomac River; *PA*, Patuxent River; *YRM*, York River mouth station; and *NPC*, New Point Comfort station (*13*).

DON HAYWARD
CHRISTOPHER S. WELCH
LEONARD W. HAAS

Virginia Institute of Marine Science, School of Marine Science, College of William and Mary, Gloucester Point 23062

References and Notes

1. L. W. Haas, *Estuarine Coastal Mar. Sci.* **5**, 485 (1981).
2. ——, F. J. Holden, C. S. Welch, in *Estuaries and Nutrients*, B. J. Neilson and L. E. Cronin, Eds. (Humana, Clifton, N.J., 1977), p. 585.
3. C. F. D'Elia, K. L. Webb, R. L. Wetzel, in *ibid.*, p. 597; W. C. Phoel, K. L. Webb, C. F. D'Elia, in *ibid.*, p. 607; K. L. Webb and C. F. D'Elia, *Science* **207**, 983 (1980).
4. L. W. Haas, S. J. Hastings, K. L. Webb, in *Estuaries and Nutrients*, B. J. Neilson and L. E. Cronin, Eds. (Humana, Clifton, N.J., 1981), p. 619.
5. K. F. Bowden and P. Hamilton, *Estuarine Coastal Mar. Sci.* **3**, 281 (1975), figure 10; J. S. Godfrey, *ibid.* **11**, 295 (1980). A mechanism similar to that reported by us was suggested here.
6. D. W. Pritchard, in *Estuaries*, G. H. Lauff, Ed. (Publication 83, AAAS, Washington, D.C., 1967), p. 37; *J. Mar. Res.* **11**, 106 (1952).
7. Instrumentation for these data was as for Fig. 1B (*11*). Pairs of values were taken daily during the period 11 to 16 July 1980 from the R.V. *Judith Ann*. Data were taken first at the York River mouth station and then at the New Point Comfort station. The time differences ranged from 1 hour 22 minutes to 1 hour 7 minutes. Salinity differences ranged from 1.30 to 2.33 per mil, with fresher water always occurring at New Point Comfort.
8. S. L. Domotor and C. F. D'Elia, unpublished data.
9. G. A. Riley, *J. Mar. Res.* **5**, 67 (1942); H. U. Sverdrup, *J. Cons. Cons. Int. Explor. Mer* **18**, 287 (1953).
10. L. Legendre, *Ecohydrodynamics* (Elsevier, Amsterdam, 1981), p. 191.
11. Data for Fig. 1A are from (*2*). Data for Fig. 1B were collected from the R.V. *Retriever* with an inductive conductivity temperature instrument (ICTI), on loan from Johns Hopkins University, which was lowered through the water column.
12. Data at 0.00 km are the same as at 1 m in Fig. 1B (*11*). Other data were collected from the R.V. *Pumpkin* with a Yellow Springs Instrument Company model 33-S-C-T salinometer, with the probe lowered through the water column. Values were standardized to the ICTI used on the *Retriever* (*11*).
13. R. C. Seitz, *Graphical Summary No. 5* (Chesapeake Bay Institute, Johns Hopkins University, Baltimore, 1971), p. 7 (modified).

14. We thank K. L. Webb for fruitful discussions and continued work on the York River, E. Ruzecki and P. Hyer for helpful reviews, and J. Price for editing. We express particular appreciation to F. Holden. We thank D. Bruno for allowing us access to the Chesapeake Bay Hydraulic Model for a few hours during the calibration period. This research was supported by the Virginia Institute of Marine Science and by Environmental Protection Agency grant CR 807637-01 to Johns Hopkins University. Contribution 1053, Virginia Institute of Marine Science.

16 February 1982; revised 5 April 1982