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Sediment Transport in Chesapeake Bay During Floods: Analysis Using Satellite and Surface Observations

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ABSTRACT

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Satellite data, when calibrated and compared with surface observations, can provide detailed information on sediment transport during high discharge in estuaries, as shown using LANDSAT and AVHRR reflectance data in Chesapeake Bay. In early March 1979, both the Susquehanna and Potomac Rivers had high discharge. In the Bay's axis, suspended sediment concentrations of 5 - 10 times normal were observed from both satellite and ship. The satellite data further revealed the flux of surface sediment into the tributaries. After two weeks, the surface waters below Annapolis contained 10% of the load of the Susquehanna River, and 5% had entered the surface waters of the northern tributaries. In the Potomac River, satellite imagery shows a turbidity maximum developed in the lower estuary with concentrations estimated at 10 - 20 times normal. Significant quantities of sediment entered the Bay from the Potomac. The satellite data further indicate differences in grain size between the Potomac and the Upper Bay. For the November 1985 event, only AVHRR satellite and USGS gauging station data exist. The imagery shows the movement and high concentrations of suspended sediment in the upper estuary, with estimated concentrations of 3 times 1979 and 100 times normal. This event may have supplied up to 50% of the average annual deposition in the lower Potomac estuary.

ADDITIONAL INDEX WORDS: *Estuarine sediment transport, Chesapeake Bay, LANDSAT, AVHRR, sediment suspension.*

INTRODUCTION

Fluvial events strongly control the flux of fine-grained sediments into estuaries. In coastal plain estuaries, rivers generally supply the bulk of these sediments to the upper portion of the estuary (MEADE, 1969). This is particularly evident in the estuaries of the U.S. east coast. Coarse-grained sediments, in contrast, predominate in the lower estuary and may be oceanic or littoral (eroded from shore) in origin.

Several researchers have discerned the importance of episodic floods in supplying fine-grained sediment to the Chesapeake Bay (SCHUBEL and CARTER, 1976; HELZ *et al.*, 1985). However the fate of sediment once it enters the bay, particularly during these high flow events, remains unclear. Data from bottom sediments show that most of the material from the Susquehanna River remains in the region north of Annapolis (KERHIN *et al.*, 1986). Analyses of budgets for the main bay suggest that material is supplied to the tributaries—including the Potomac River. However, the effect of floods on this distribution has not been investigated owing to constraints of traditional sampling techniques.

In the study of estuarine and coastal sediment transport, measurements from ships or moorings can provide valuable data at discrete points. However, the logistics and expense of these traditional methods of data collection can rarely produce the synoptic coverage, resolution, and temporal detail necessary to study individual events.

One solution to this problem can be remotely sensed data, particularly from satellite. Satellites can provide repetitive and synoptic coverage. Many researchers have mapped turbidity plumes from LANDSAT images and tried to relate these to differences in wind and tidal circulation (MUNDAY and FEDOSH, 1981; KLEMAS *et al.*, 1974). Other researchers have taken a different approach by producing maps of suspended sediment concentrations for particular scenes by statistically correlating satellite observations with *in situ* measurements—then inferring processes from the resultant distribution (MUNDAY and ALFOLDI, 1979; ARANUVACHAPUN

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and LEBLOND, 1981; KLEMAS *et al.*, 1974; KHORRAM, 1985). With the development of physical relationships for estimating sediment concentrations (MUNDAY and ALFOLDI, 1979; STUMPF, 1987), different scenes can be more readily compared, making possible quantitative analysis of sediment distributions.

For estuarine waters, the LANDSAT multispectral scanner (MSS) has been the most commonly used satellite sensor. It has provided bi-weekly coverage for 14 years. From 1975 to 1981, coverage every 8 - 9 days was theoretically possible, owing to the simultaneous operation of two satellites. Although the temporal resolution is inadequate for direct study of many processes, the satellite is adequate for looking at some seasonal and episodic events (Table 1). Also a sufficient number of images now exist to permit statistically significant comparisons of image data with process data, such as currents and wind speed (MUNDAY and FEDOSH, 1981). An alternative sensor, the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA/TIROS-N weather satellites, has been operating since 1979 and can provide high temporal resolution (at reduced spatial resolution) of estuarine turbidity (GAGLIARDINI *et al.*, 1984). Both of these sensors have the additional utility in that they will continue to operate into the forseeable future.

In 1979 and 1985, high-flow events occurred in the Chesapeake Bay basin. In 1979, both the Potomac and the Susquehanna Rivers had high discharge of about a 4-year recurrence. The Potomac estuary and the upper Chesapeake Bay had good coverage from both satellite and ship. In 1985, the Potomac River had a major flood of about 25-year recurrence, however few *in situ* measurements exist for this event. This paper will present investigations of the movement and distribution of material in the surface waters of the Chesapeake and Potomac estuaries during the 1979 event using both remote and *in situ* data, apply the satellite calibration to the 1985 event, and evaluate the two events and the satellite data.

Table 1. *Satellite and sensor characteristics of LANDSAT MSS and the AVHRR.*

	LANDSAT MSS	AVHRR
Resolution	80 m	1.1 km
Overpass Interval days	16 (1982-) 9 (1975-1981) 18 (1972-75, 1981)	0.5-2
Image Width	180 km	2,000 km
Bands	2 visible, 2 near-IR	1 visible, 1 near IR, 3 thermal-IR
In Operation	1972-	1979-

THEORY

The amount and type of sediment in the water column directly influences the reflectance of the water. Reflectance, R, is defined as

$$R(\lambda) = E_u(\lambda)/E_d(\lambda) \quad (1)$$

where E is irradiance, λ is the wavelength or band (Table 2), subscripts u and d denote upwelling (leaving water) and downwelling (entering water) irradiance, respectively. Terms and notation are those found in a standard marine optics text such as JERLOV (1976).

A satellite detects the radiance—namely that portion of irradiance directed toward the satellite—of the earth and atmosphere. In order to determine the reflectance, and ultimately the sediment content, we need to correct for the atmosphere and also for changes in sun angle that affect E_d (Figure 1). With these corrections, (1) becomes:

$$R(\lambda) = \pi L_u(\lambda)/[E_o(\lambda) \sin\theta] \quad (2)$$

where:

$$L_u = [L_*(\lambda) - L_a(\lambda)]/T \quad (3)$$

and L_u is the upwelling radiance, such that $\pi L_u = E_u$; E_o is the solar constant for λ (Table 3); θ is the solar elevation; L_* is radiance measured at the satellite; L_a is the atmospheric path radiance; and T is the atmospheric transmission (proportion of L_u that reaches the satellite).

In turbid estuarine water L_a is assumed uniform over the study area and is calculated from the radiance over clear water (PHILPOT and KLEMAS, 1979). T is estimated from L_a based on GRIGGS (1975) and AHERN *et al.* (1977) (Table 3). Reflectance can be calculated to within ±5%, the atmospheric correction may, at higher turbidity, induce an additional error of 10%.

Several researchers have found that radiance or reflectance and sediment concentration vary as

$$R = M \log(n_s) + B \quad (4)$$

where n_s is the sediment concentration, and M and B are constants of regression (MUNDAY and ALFOLDI, 1979; KLEMAS *et al.*, 1974; STUMPF, 1984) (Figure

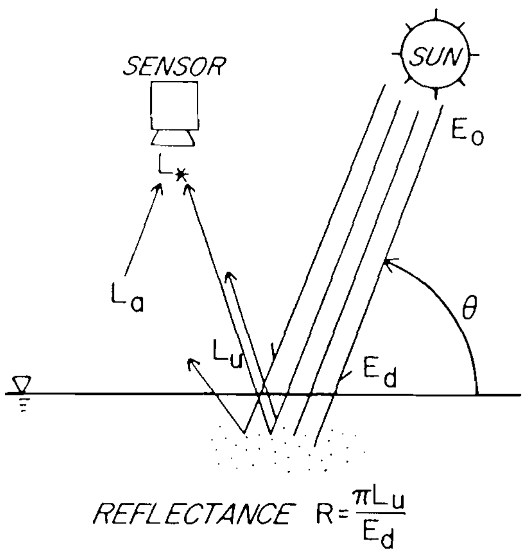

Figure 1. Calculation of reflectance from satellite.

Table 2. *Spectral bands for reflected light for LANDSAT MSS and AVHRR.*

	.5	.6	.7	.8	.9	1.0	1.1
	green	red	near-infrared				
wave-length (μm)	.5	.6	.7	.8	.9	1.0	1.1
LANDSAT MSS	4	5	6	7			
AVHRR		1	2				

Table 3. *Coefficients for calculating reflectance and atmospheric corrections.*

	LANDSAT MSS mW cm^{-2} sr^{-1} μm^{-1}				AVHRR mW cm^{-2} sr^{-1} μm^{-1}	
channel	4	5	6		1	2
Solar constant	186[1]	157	128		156[4]	101
Radiance/Count	.201[1]	.135[2] .139[3]	.115		.052[4]	.034
Path Radiance, L_a						
9 Mar	3.4	1.8	1.0	7 Nov	.80	.25
17 Mar	3.1	1.7	1.0	8 Nov	1.0	.26
Transmission, T	.70	.76	.85		.80	.92
Solar Elevation (degrees)						
9 Mar		37		7 Nov	31	
17 Mar		38		8 Nov	31	

[1]MARKHAM and BARKER (1986)
[2]LANDSAT 2, 17 March 1979
[3]LANDSAT 3, 9 March 1979
[4]KIDWELL (1985) and LAURITSON *et al.* (1979)

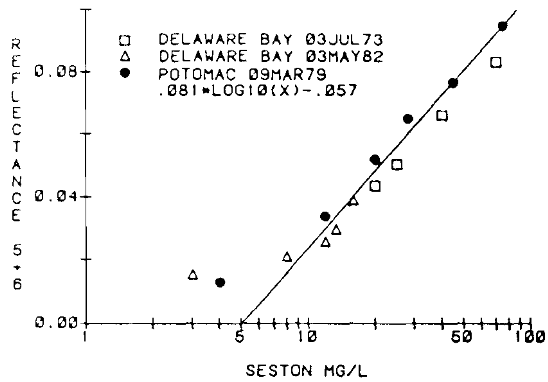

Figure 2. Reflectance, R_T for LANDSAT bands 5+6, *vs.* n_s, from Delaware Bay (data from KLEMAS *et al,* 1974 and STUMPF, 1984) and Chesapeake Bay (this paper). Line shows equation used to calibrate R_T for AVHRR bands 1+2.

2). As R, L_*, and L_u are all linearly related, the same form of relationship applies to all three. Reflectance may also vary with grain size with an approximate relationship (STUMPF, 1987):

$$R = m \log(n_s)/d_o + b \tag{5}$$

where d_o is the optical diameter. The term optical grain size (d_o) refers to ($\rho d/\rho_q$), where d is the cross-sectional diameter, ρ is the mean particle density, and ρ_q is the density of quartz. To find n_s from R, we use the inverse of either equation (4) or (5) in the regression (Table 4).

Within a single scene, we can use L_* in place of R in the relationship shown in equation (4) to map sediments (see MUNDAY and ALFOLDI, 1979; KLEMAS *et al,* 1974; ARANUVACHAPUN and LEBLOND, 1981). In order to apply an equation to another scene or region one must correct for sun angle and atmosphere (especially path radiance, L_a) and assume equivalent optical grain sizes. As we will see, even when considering episodic events the latter requirement is not a severe handicap.

A change in particle size often corresponds to a change in sediment type and related pigments, hence the water color may change as well. Water color can be mapped with multispectral sensors (GORDAN *et al.,* 1983; STUMPF, 1984), therefore if necessary, water color can be used to indicate areas of potentially signficant changes in grain size.

METHODS

The LANDSAT MSS sensor has a fairly low sen-

Table 4. *LANDSAT reflectances and suspended sediment concentration data for Chesapeake Bay and Potomac River*

Observed n_s (mg/l)	Reflectance Band 4	5	6	R_T 4+5+6	R_T 5+6
Chesapeake Bay, 9 March 1979					
190	.082	.118	.081	.094	.101
140	.073	.105	.072	.083	.089
68	.074	.097	.053	.075	.076
28	.064	.083	.045	.065	.065
20	.060	.072	.029	.055	.052
12	.056	.047	.019	.043	.034
4	.030	.018	.007	.020	.013
Potomac River, 9 March, 1979					
75	.100	.125	.062	.097	.095
45	.081	.101	.050	.078	.077
Parameters for equation: $\log_{10} n_s = R_T/M + (-B/M)$				1/M	$10^{(-B/M)}$
Main Bay using R_T for bands 4+5+6:				11.7	1.2
Potomac using R_T for bands 4+5+6:				11.7	5.5
Potomac using R_T for bands 5+6: (used for AVHRR bands 1+2)				12.3	5.1

sitivity, hence, greater precision and detail usually can result by combining bands. The radiance in bands 4, 5, and 6 (also in AVHRR bands 1 and 2) were combined to give reflectance in the form:

$$R_T = \pi \Sigma L_u(\lambda_i) / \Sigma E_d(\lambda_i) \quad (6)$$

where i is the band number.

The reflectance, R_T, of 9 March 1979 was compared to the sediment concentrations measured on 12 March 1979 (Table 3). The apparent peak in turbidity shifted about 20 km downstream over the three days, therefore the reflectance values 20 km upstream of each field sampling location were used. A regression using equation (4) related the mean reflectance value over a 30×30 pixel block (removes striping and averages out noise) to the observed sediment concentration. The difference in time between *in situ* and remote sampling could introduce a bias in the estimated concentrations. Because the concentrations tend to decrease through deposition early in such an event (SCHUBEL, 1975), the comparison should result in underestimates of concentrations when found from reflectance. The standard error of the regression for concentrations in the bay is .07 log units (±25%). However, the bias could result in underestimates of 30-50%, particularly in the upper Bay ($n_s > 68$ mg/1).

CRONIN *et al.* (1982) calculated the effective optical grain size on these cruises ($d_0\pi = n_s/k$, where k is turbidity measured in nephelometric turbidity units). Their results show no significant decrease in optical grain size for the range of concentrations observed on both cruise dates (12-3 March and 26-27 March). Therefore, it appears reasonable to apply the parameters obtained from the 9 March image to the 17 March satellite image. The upper Bay where n_s exceeded 68 mg/l on 12 March, showed larger optical grain sizes than any other place (Figure 3). From equation (5) we see that a change in grain size could alter the reflectance-concentration relationship. It may be significant that an apparent change in slope occurs at $n_s = 28$ mg/l (Figure 4). (This change in slope may be more substantial if the true value of n_s for $R_T = 0.094$ is greater than 190 mg/l.) In addition, the water in the area where $R_T > 0.06$ ($n_s > 68$ mg/l) was of a different color than that for R_T where $n_s < 28$ mg/l (STUMPF, 1984). A single regression

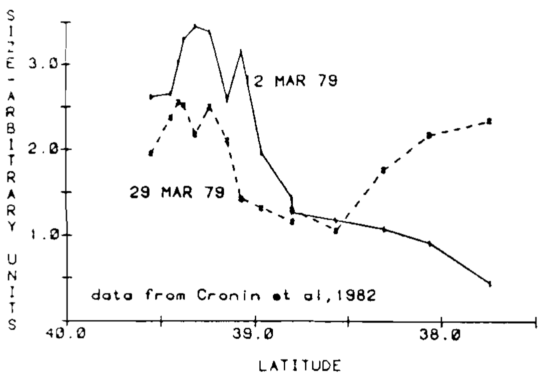

Figure 3. Optical grain size from ship, March 1979 (data from CRONIN *et al.*, 1982).

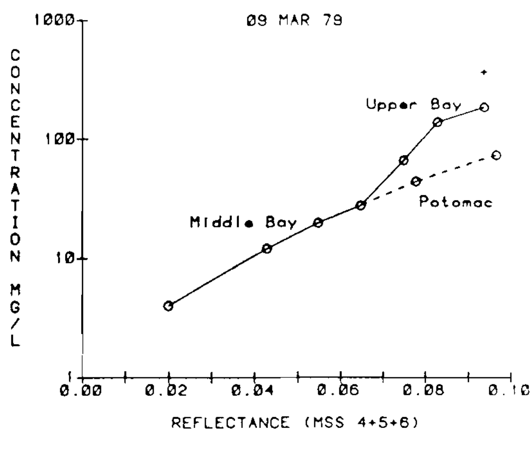

Figure 4. Reflectance *vs.* sediment concentration, upper Chesapeake Bay and Potomac River, 9 March 1979.

line is used for the main Bay in order to provide an acceptable level of significance. The change in grain size in the lower bay on 26-27 March probably resulted from a change in particulate composition owing to an increase in phytoplankton concentrations in the lower turbidity water (CRONIN *et al.*, 1982).

For the Potomac River, suspended sediment data was available on 9 March at Morgantown and Quantico (BLANCHARD *et al.*, 1980). This information was used to determine the parameters in (4) (Table 4).

For November 1985, AVHRR images were available. As *in situ* data from the estuary did not exist at that time, the AVHRR bands 1 and 2 reflectances were calibrated using an equation obtained with R_T for LANDSAT bands 5 and 6. AVHRR band 1 has a similar spectral response to MSS band 5 (Table 2). AVHRR band 2 corresponds to MSS band 6; however it includes longer wavelengths where water has reduced reflectance owing to increased absorbance (STUMPF, 1987). Hence, AVHRR bands 1+2 will tend to slightly underestimate n_s when using a relationship developed from MSS bands 5+6. This point will be considered in the discussion.

River flow and sediment discharge into the estuaries were obtained using flow rate and sediment concentration data from U.S. Geological Survey (USGS) gauging stations. Potomac River data came from the Chain Bridge station just above the fall line at Washington. Susquehanna River data were collected at Conowingo dam, 15 km upstream of the mouth of the river. Additional data for the Potomac in 1985 were

Table 5. *Sediment budget for Upper and Middle Chesapeake Bay, March 1979*

	TOTAL SESTON $\times 10^6$ metric tons
Sediment discharge from Susquehanna into Bay, 6-10 March, 1979	1.4
Average annual discharge (SCHUBEL and CARTER, 1976)	1.1/year
Amount in Middle Bay surface waters (upper 4 m) 17 March 1979	.10
Amount discharged into Middle Bay (40 mg/l at Annapolis with 6-10 March river flow)	.15
BIGGS (1970) fluvial supply to Middle Bay (4 years at .03/year)	.12
Silt and clay from shoreline erosion (KERHIN *et al*, 1986)	1.1/year
Bush, Patapsco, Gunpowder (upper 3 m)	.04
Chester River	.012
Eastern Bay and Choptank Rivers	.011

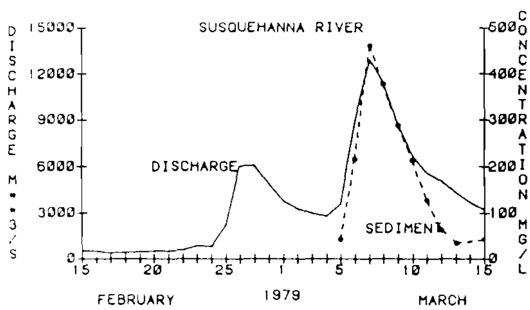

Figure 5. Susquehanna discharge and sediment concentration at Conowingo Dam, February-March 1979.

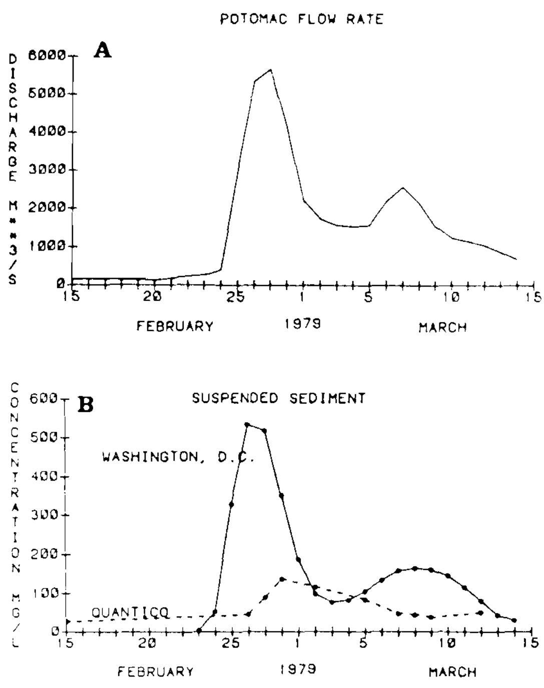

Figure 6. Potomac River discharge and sediment concentration at Washington, DC and Quantico, Virginia, February-March 1979.

supplied by the metropolitan Washington Council of Governments (Table 6).

Sediment load (Q_s) was determined from $n_s \times Q$, where Q is the river discharge. For 1979, mean daily discharge was used, for 1985, the data had sufficient temporal resolution to calculate the daily load from several time-weighted measurements.

Suspended sediment data for the estuaries derive from the USGS Potomac estuary study (BLANCHARD *et al.*, 1981), and from the Chesapeake Bay Institute cruises (CRONIN *et al.*, 1982).

DISCUSSION OF EVENTS

Chesapeake Bay, March 1979

High flow in the Bay's drainage basin in late February and early March of 1979 resulted from two events. Runoff of melting snow from a blizzard (up to 60 cm of snow) on February 21 resulted in a peak about 27 February in both the Potomac and Susquehanna Rivers. Heavy rainfall on 5-6 March resulted in high flow again on 7 March. As suggested by the hydrographs (Figures 5 and 6), the rainfall was heaviest to the north, and the snowfall heaviest to the south.

On the Potomac River, 6,000 m^3/s discharge is relatively rare occurring about every 4 years. Similarly, 12,000 m^3/s discharge in the Susquehanna River occurs about every 5 years.

In the Susquehanna River a moderate peak occurred on the 26-27 February (Figure 5), but a second, larger peak occurred on 7 March, when the sediment concentration was 450 mg/l. Uncalibrated satellite imagery clearly shows the sediment-laden water in the estuary (Figure 7). However, the combination of calibrated reflectance data and shipboard data shows the movement and quantities of this material into the upper Bay.

The normal sediment concentration below Annapolis is fairly low, < 8 mg/l (SCHUBEL, 1968), such as found in Eastern Bay and the Choptank River on 9 March. A turbidity maximum, of 30-80 mg/l in the spring, typically occurs south of the Sassafras River (*cf.* Figures 8 and 9), at the upbay limit of the two-layer estuarine circulation (BIGGS, 1970; SCHUBEL, 1972). Thus, by 9 March at 1010 EST, the calibrated reflectance data indicate that the 27 February event had increased concentrations three-fold over normal in the lower Bay as far south as the Patuxent River (Figure 8). The 7 March turbidity peak had reached the Sassafras River (150-200 mg/l). This is about 25 km in 2 days. The estimated 80-150 mg/l region between the Sassafras and Chester Rivers may result from the leading edge of the March flood, this movement is plausible as the volume of water having passed the Conowingo Dam on 07-08 March could fill the bay to mid-way between the Sassafras and Chester Rivers.

Table 6. *Sediment budget for Potomac River, March 1979 and November 1985*

$\times 10^6$ metric tons	Quantity of Sediment 1979 28 Feb-1 Mar	1985 5-10 Nov
Entering esturary at D.C.	.73	1.5
Entering lower estuary (using satellite)	.16 (surface to 4 m)	.3-.5 (estimated)
Lower estuary sedimentation KNEBEL *et al.* (1981) (from seismic data)	upper 1.38/year lower 0.15/year TOTAL 1.53/year	
BENNETT (1983) (from model)	1.0/year	
Entering Bay (BENNETT, 1983)	−.08/year	

By 12 March (Figure 9), shipboard measurements show the peak concentration had shifted 10-20 km further downstream to between the Sassafras and Chester Rivers. High concentrations (>80 mg/l) were found from Annapolis to the Sassafras River. Elevated concentrations existed as far south as the Potomac River. On 17 March at 1015 EST, the satellite image shows an apparent decrease in concentration to 80-150 mg/l, and the maximum turbidity had shifted even further south to the mouth of the Chester River (Figure 8). By the cruise on 26 March, concentrations had decreased substantially. A double turbidity maximum had developed below the Sassafras River, and the concentrations in the surface waters below Annapolis had returned to normal (Figure 9).

The satellite images provide a significant advantage in that they reveal the correct lateral distribution and transport of sediment (Figures 7 and 8). Sediment had entered the lower Chester River and the northwestern tributaries by 09 March. Estimated concentrations at the surface in the lower estuary varied from 15-40 mg/l. By 17 March, the imagery shows sediment had entered the Choptank River and Eastern Bay, with the concentrations increasing five-fold in the week. The western shore tributaries had a more dramatic increase in estimated concentration to over 80 mg/l on 17 March.

The bay axis also contains strong lateral variations in concentration (Figure 8), which cannot be detected from axial sampling from ship (Figure 9). On 9 March, maximum reflectance and concentrations overlay the central channel. This indicates that sediment and water moved most rapidly along that channel. In contrast, on 17 March, the central Bay above the Chester River had lower reflectances (concentrations), whereas the shoreward points had higher reflectances.

Potomac Estuary, March 1979

In the Potomac River, the peak concentrations occurred at Washington on 26-27 February (Figure 6). The concentration at Quantico, 60 km downstream of Washington peaked on 28 February, indicating an approximate velocity of the maximum turbidity of 30 km/day. We might note that the total volume of water passing Washington on 26-27 February could fill the estuary to Quantico (based on CRONIN, 1971) by 28 February.

The decrease in observed concentration to Quantico would result from both deposition and from dilution and spreading of the peak. The relative importance of each mechanism cannot be determined directly from this data.

The distribution of sediment obtained from satellite (Figure 10) suggests the pattern of transport throughout the lower estuary. The greatest concentrations of material appeared to remain in the lower estuary about 50 km from the mouth. The highest estimated concentrations reach 130 mg/l—comparable to those observed at Quantico 9 days earlier. Given the decrease in concentration from Alexandria to Quantico, one would expect a continued decrease in concentration from Alexandria to Quantico, one would expect a continued decrease below Quantico, particularly by dilution.

The imagery indicate as much as 36 mg/1 of sediment was entering the main Bay by 9 March. Quan-

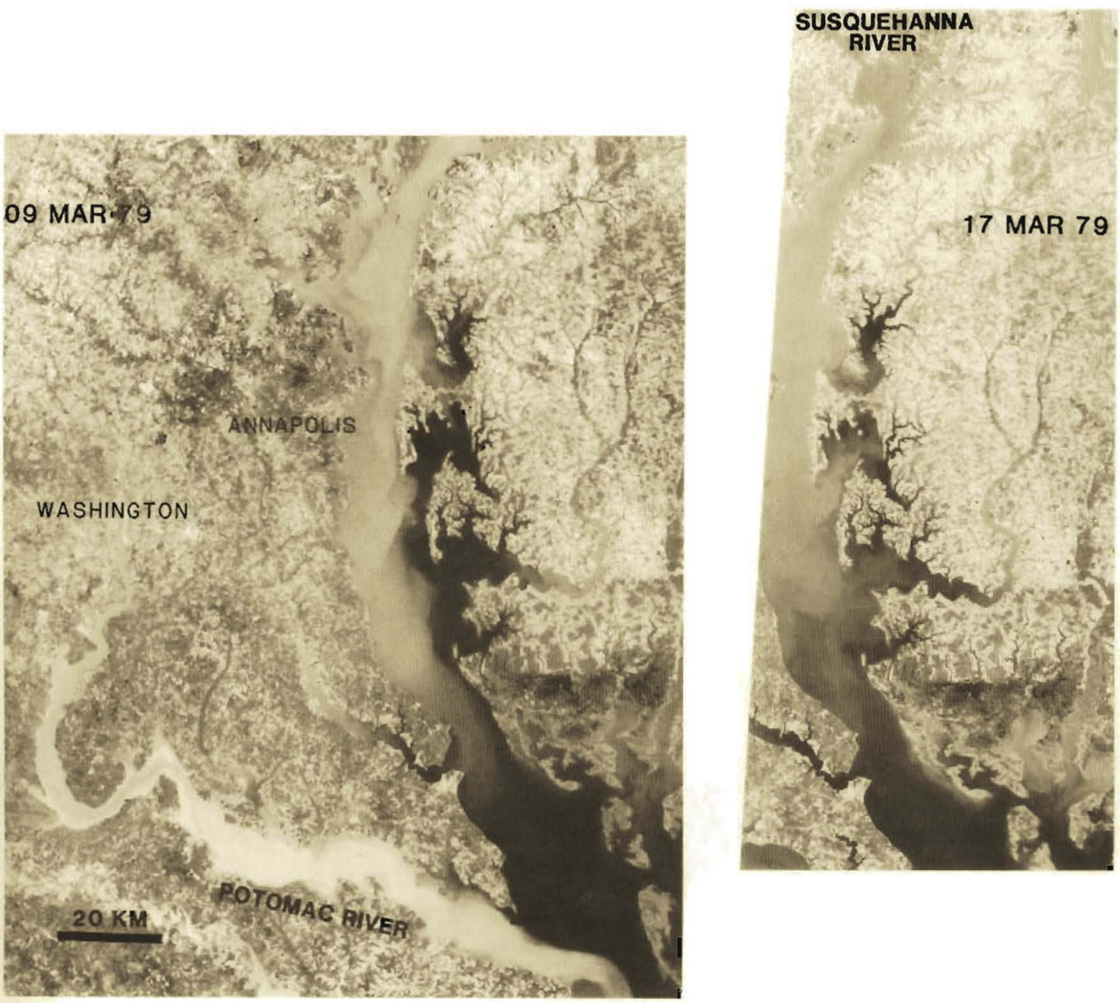

Figure 7. LANDSAT band 5 (red band) images, 9 March 1979 and 17 March 1979.

tico is 125 km from the mouth, suggesting that the sediment front had moved downstream at a speed of at least 14 km/day.

The high concentrations in the lower estuary suggest the presence of a mechanism that concentrates the material—probably estuarine circulation. The turbidity maximum is normally found in the bend between Morgantown and Quantico, the storm freshwater flow could shift the maximum 30-50 km downstream and intensify the two layer flow that produces it.

The concentrations along the Maryland shore are considerably lower than those along the Virignia shore. This lateral variation is compatible with the rightward tendancy of flow expected from Coriolis force and indicates a potential for greater fine-grained deposition along the southern shoreline.

Grain Size Variations, March, 1979

An indication of the relative grain size in the Potomac and Chesapeake can be found in Figure 4.

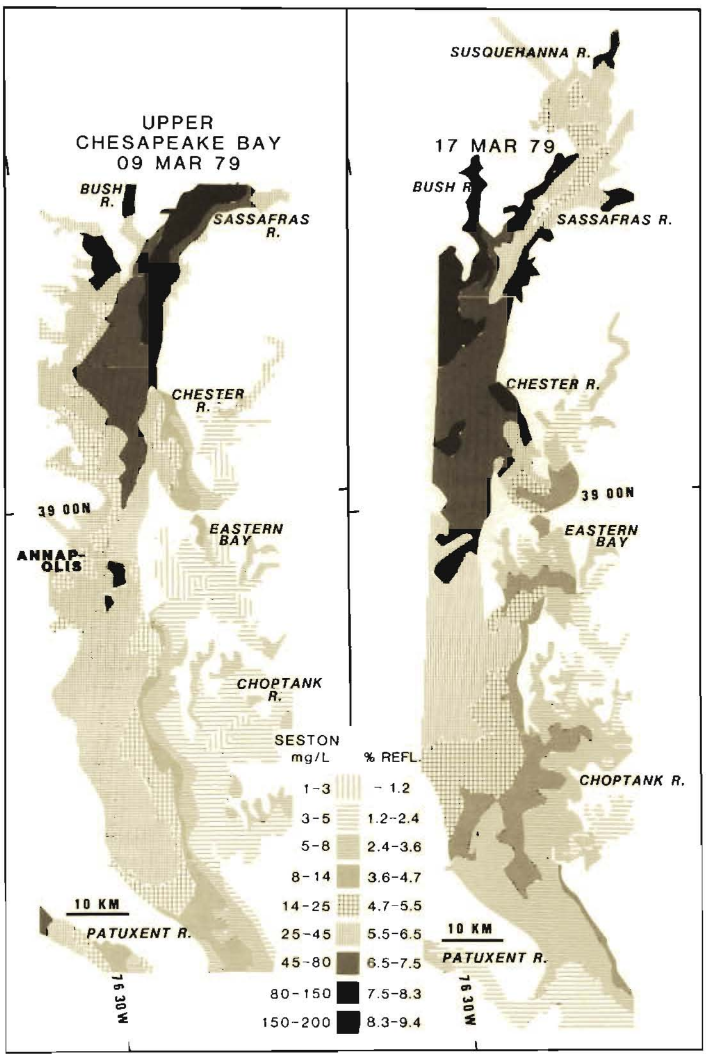

Figure 8. Reflectance and seston (suspended sediment concentration) from LANDSAT bands 4+5+6, 9 March 1979 and 17 March 1979.

From (5), an increase in grain size would produce an increase in concentration for a given reflectance. Therefore, in the most turbid areas of both estuaries, the satellite shows larger material in the upper Bay than in the Potomac River or middle Bay. The Susquehanna probably supplied coarser sediments (Figure 3). In addition, the material in the lower Potomac estuary had 10 days to settle whereas that in the uppermost Bay had just been placed in the system.

Potomac Estuary, November 1985

In early November 1985, tropical storm Juan crossed West Virginia and western Virginia, dropping as much as 40 cm of rain in 3 days. Severe flooding resulted in the Potomac River basin. At Washington, the flow on 7 November, at 8,500 m^3/s, was surpassed by only 4 other floods in this century.

The peak discharge in November was about 25% greater than that of 27 February. However, the 1985 flood carried far more sediment. The mean concentration at Washington approached 2000 mg/l on 7 November, four times that observed on 27 Febuary 1979 (Figure 11).

In this case, a combination of detailed ground measurements from the gaging stations with satellite data of the estuary provide insight into the event as no shipboard measurements were made in the estuary.

The sediment concentrations rose dramatically on 5 November, however discharge did not begin to increase until the night of 5-6 November. By 0900 EST on 6 November, instantaneous discharge at Washington, DC was 4900 m^3/s. This initial pulse resembled the 1979 event. By the time of the satel-

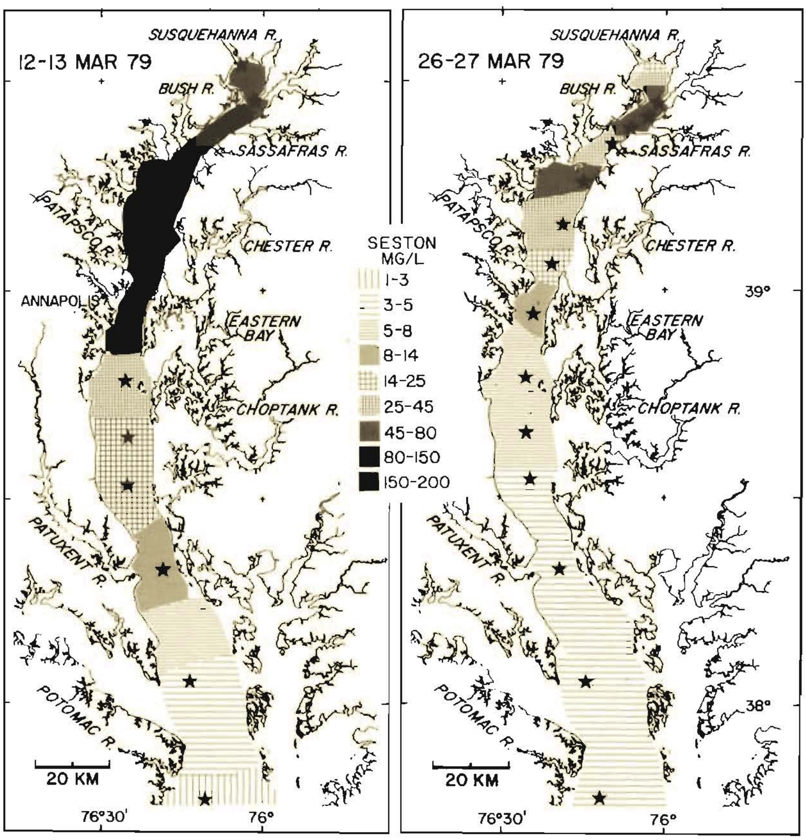

Figure 9. Seston (sediment concentration) from shipboard data, 12-13 March 1979 and 26-27 March 1979 (from CRONIN *et al.*, 1982). Station locations (starred) were the same on both cruises. With only axial stations, the concentrations were assumed to be laterally uniform. Blank areas indicate unknown concentrations.

lite overpass at 1430 EST on 7 November, the resultant volume of water could have filled the estuary to just above Quantico (Q in Figure 12). In the satellite image the highly turbid water covers that same reach of the estuary, with an estimated maximum concentration of 200 mg/l (Figure 12). (Note, both scattering by the atmosphere and response lags in the satellite electronics will slightly smear reflectances from adjacent pixels. As a result, where the river is less than 3 pixels wide, high reflectances over water will be reduced by the lower surrounding land reflectances, hence high concentrations will be underestimated.) By 1430 EST on 8 November, the leading edge of the turbid water had passed Morgantown (M), whereas the maximum reflectance was still near Quantico. Estimated n_s at Morgantown is about 100 mg/l, and at Quantico is 600 mg/l. The maximum below Quantico on 8 November would be expected, as the concentration maximum passed Washington on 7 November; the water would have reached Quantico in this time.

Unfortunately, clouds (the bane of remote sensing) moved into the area on 9 November, precluding additional observations.

On 19 November, *in situ* data was collected in the Potomac estuary by the Maryland Department of Natural Resources (pers. comm.). Even at that time, concentrations remained abnormally high, up to 200 mg/1 in the surface waters 20 km downstream of Quantico, and 28 mg/1 at Morgantown. These are an order of magnitude greater than those on 28 October, just before the storm reached the area and about 3-4 times the concentrations observed during moderate flow conditions. Significantly, these high concentrations at that late time are consistent with the very high measured and estimated concentrations (loads) in the river and upper estuary on 7-8 November.

The question may arise concerning the accuracy of the estimated concentrations for 1985. At high turbidity, the two major errors are statistical—through extrapolation from the 1979 relationship—and physical, through a change in particle size. The physical error would be the most significant, namely whether this event has the same effective optical size as the 1979 event. Such data are normally scarce and, in this case, non-existent. As the Potomac and Susquehanna rivers appear to have different sizes, a difference in the Potomac is possible. Based on Figure 4, the error could be as much as a factor of two. However, as the AVHRR bands 1+2 would tend to underestimate the reflectance, the concentrations would also be underestimated by 0.1 to 0.2 log units. Given an estimated peak at 600 mg/l, the maximum concentration may have been between 350 and 1,300 mg/l. The persistence of high (200 mg/l) concentrations until late November indicates that 600 mg/1 is probably a conservative estimate. Also, a reduction of 75% in concentration between Washington and Quantico, as observed in 1979 (Figure 6), would produce peak concentrations on 08 November of 500-700 mg/1.

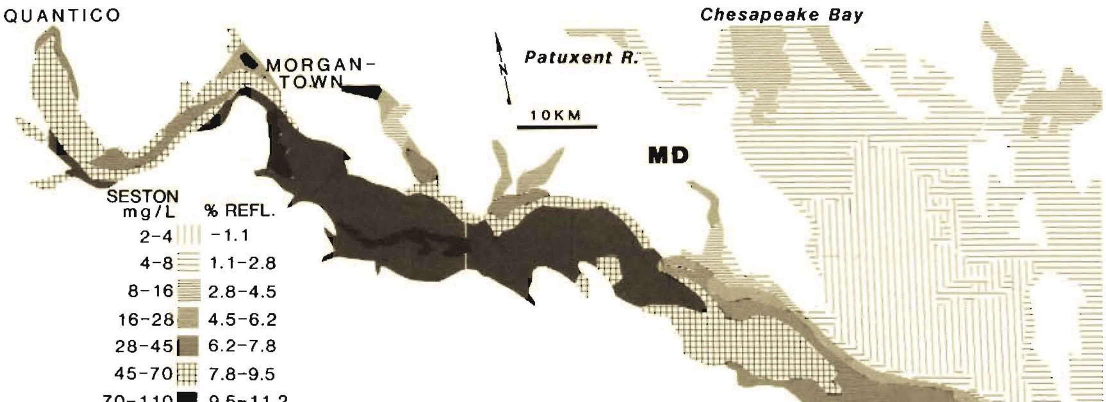

Figure 10. Reflectance and Seston from LANDSAT bands 4+5+6, Potomac River, 9 March 1979.

SEDIMENT BUDGETS

The apparent loss of material in the main Bay and the Potomac estuary support previous studies on sedimentation. The decrease in concentration in the upper Bay from Conowingo to below the Sassafras River suggests that 1/2 of the Susquehanna River's sediment load was lost in that reach, about what SCHUBEL (1971) estimated for high discharge. The concentration at Annapolis is 1/10 of that entering the Bay. Assuming continuity for the water flow and that the change in concentration resulted only from settling, about 1/10 the load from the Susquehanna River entered the Bay below Annapolis (Table 4). Reductions in concentration resulting from diffusion of the sediment would result in an estimate of a greater load past Annapolis. The amount calculated here for a 4-year event corresponds to the flux over 4 years that would result using the annual average fluvial input calculated by BIGGS (1970). Note however, that the fluvial input of sediment to the middle Bay is only 10% of the total (KERHIN *et al.*, 1986).

In the Choptank River and Eastern Bay, on 17 March, about 0.011×10^6 m. tons were in the surface waters (to the mean depth of 3 m). The western shore tributaries above Annapolis, although small in area would have had 0.04×10^6 m. tons. The total is about 5% of the Susquehanna's load.

In the Potomac River, less than 3/4 of the suspended material entering the estuary deposited above Quantico. If we take the material in the surface waters (to 4 m) of the estuary below Morgantown, we find about 0.16×10^6 m. tons (20% of freshwater input). This is comparable to 100 mg/l passing Morgantown for the total flow of 25-28 February. In comparison, 6-8 November 1985, with a freshwater load of 1.5×10^6 m. tons may have had 2-3 times the sediment discharge into the lower estuary.

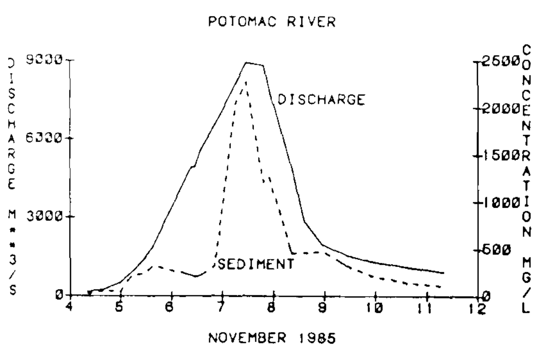

Figure 11. Potomac River discharge and sediment concentration, November 1985.

KNEBEL *et al.* (1981) calculated 1.53×10^6 m. tons/year of deposition of estuarine mud in the lower Potomac (below Morgantown). BENNETT (1983), using a budget model, found 1.7×10^6 m. tons/year for 1979-1981, 50% of which derived from local shore erosion. KNEBEL *et al.* determined that the 25 km-long section directly below Morgantown receives an average of 1.38×10^6 m. tons/year, whereas the lower 40 km reach to the main Bay receives only, 0.15×10^6 m. tons/year. The influx of material for the 1979 event is less than 10% of the average annual deposition for the upper reach, but is comparable to the deposition in the lower reach. For the 1985 event, the flux would have been 20-40% of the average annual deposition for the entire lower estuary.

The satellite data raises questions about the transfer of fine-grained material between the Bay and the tributaries. The western shore tributaries above Annapolis clearly receive a significant quantity of sediment (0.04×10^6 m. tons). Given their location, events of lower discharge could supply sediment as well. The lower Chester River received sediment probably through advection (Figures 7 and 8a). In Eastern Bay and the Choptank River, either advection or diffusion may produce the transport. However as the sediment settles into the bottom it may also be advected into these tributaries.

However, is the Potomac estuary a sink for sediment from the Bay? During the 1979 event, about 0.06×10^6 m. tons entered the Bay at the surface With the greater load in November 1985, perhaps 0.18×10^6 m. tons may have entered the Bay. Under most conditions, the middle Bay off the Potomac has < 3 mg/l of sediment throughout the water column, not conducive to supplying significant quantities of material. In addition, KERHIN *et al.* (1986) show extensive deposition of fine-grained sediments from about 38°15′ N to 37°50′ N (Patuxent River to the Potomac River), unlike the area north to Annapolis. This suggests that the Potomac may, in fact be supplying fine-grained sediments, either fluvial or littoral in origin, to the Bay.

Budgetary models have estimates of $< 0.08 \times 10^6$ m. tons/year (BENNETT, 1983) to $< 0.13 \times 10^6$ m. tons (for all tributaries; SCHUBEL and CARTER, 1976) of sediment entering the Potomac from the Bay. These estimates are, however, less than 10% of the annual deposition in the lower Potomac estuary, placing them well within the error of estimate for flux estimates (BOON, 1974). They also cannot easily account for extreme events. Even Bennett's model, which was continuously calibrated, used data collected only once a month at 2 stations at the mouth of the Potomac. The flux of material during episodic events may exceed the average annual flux.

CONCLUSIONS

Floods occur unpredictably and produce rapid variations in estuarine sediment distributions. Therefore the study of these events has been limited through logistics of sampling from ship. However, as we have seen, satellite data can complement *in situ* sampling and provide good temporal resolution and spatial coverage. The satellite data gave results that were consistent with the *in situ* data for March 1979. Both show the decrease in turbidity through the month. In addition, the Bay shows similar characteristics to those observed by SCHUBEL (1975) after the more severe tropical storm Agnes. In both cases, a turbidity maximum

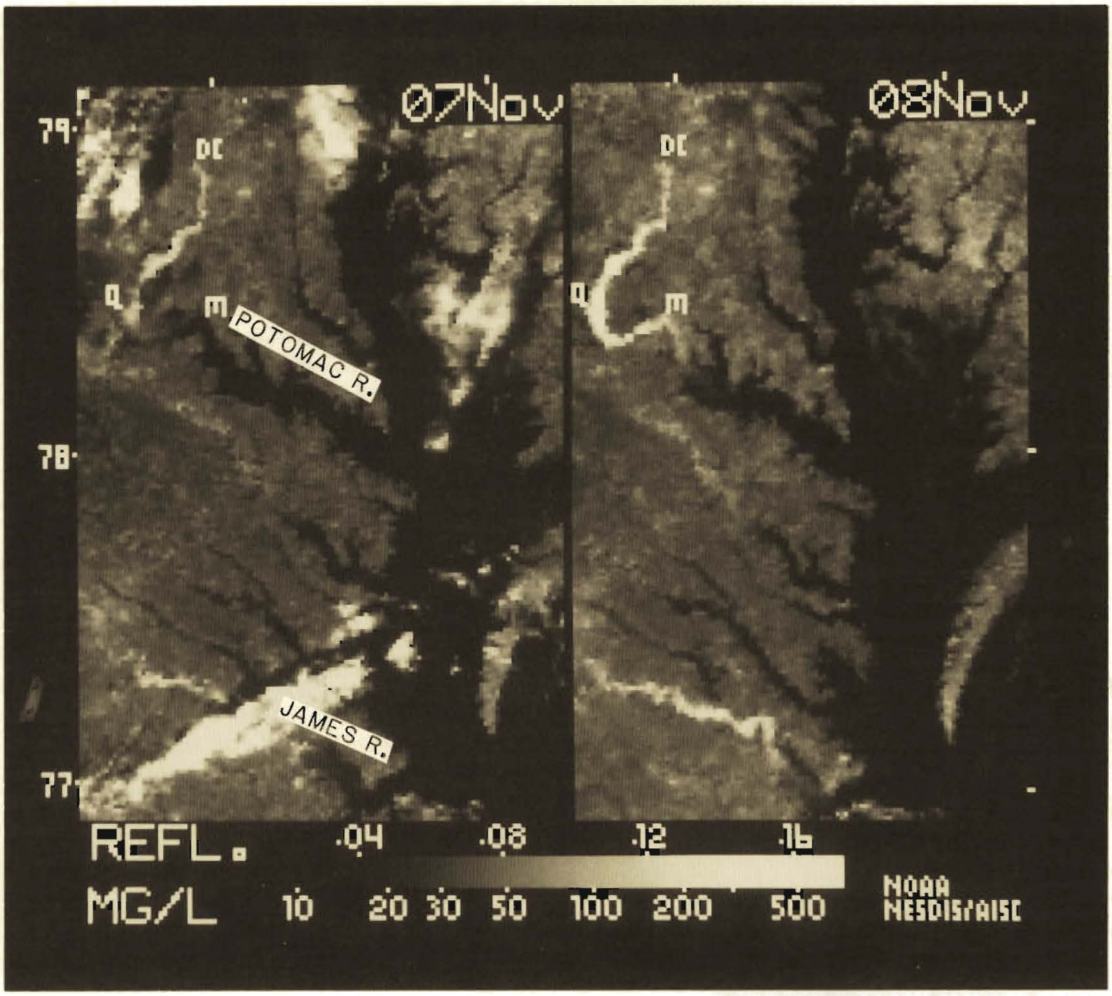

Figure 12. AVHRR reflectance (R_T) and estimated sediment concentration in Chesapeake Bay and tributaries, 7 and 8 November 1985. DC indicates Washington; Q indicates Quantico; and M indicates Morgantown (301 Bridge). High reflectivity appears in both the Potomac and James Rivers (the latter partially obscured by a cloud at the bottom of the 7 November scene). The heaviest rainfall occurred in western Virginia and West Virginia, outside of the basins of the other western shore rivers and the Susquehanna River (at the head of the Bay), hence these rivers show generally low reflectivities. White patches over the upper Bay on 7 November are clouds.

developed just above Annapolis after a week. Here the concentrations were about 100 mg/l, after Agnes they reached 150 mg/1. A "typical" turbidity maximum reestablished itself south of the Sassafras River about 2 weeks after both events.

The most striking result of the satellite scenes is the display of lateral variations in the sediment distributions and the implications for transport in the Bay. The low concentrations in the bay axis off the Sassafras River on 17 March 1979 suggest that significant mixing does not occur between the shoreward platform and the central channel. Fronts induced by the bathymetric change along the channel edge may reduce the exchange of material and water between the platform and channel. Control of mixing by fronts has been observed in Delaware Bay (KLEMAS, 1974; STUMPF, 1984).

Sediments were also seen entering the tributaries. The northwestern tributaries received high concentrations. The eastern shore tributaries received moderate but significant amounts of material. Unfortunately the mechanism carrying the sediment into these estuaries remains unknown, for concentration data cannot usually distinguish between advection and diffusion. This could be an important area in which to apply numerical modelling.

In the Potomac River, the satellite imagery reveals, in 1979, the movement of sediment into the main bay, and the development of an apparent turbidity maximum in the lower estuary. The 1979 calibration curve gave consistent results for the 1985 AVHRR data. With the high discharge and a peak concentration of 3-4 times that in 1979, the 1985 event should have produced higher sediment concentrations in the estuary than in 1979. Indeed, the peak of 600 mg/l at Quantico in 1985 is proportionately greater than the peak in 1979.

Although the fluvial material entering the lower Potomac and the middle Bay during floods appears to be only 10-40% of the annual deposition, the pulse of sediment can have a significant impact on the sedimentation and on the characteristics of the bottom sediments. The material is deposited within a few days, and it may have constituents— such as metals, organic compounds, and minerals— that differ from those in material derived from the shoreline.

The disturbance of the normal estuarine circulation could influence transport patterns throughout the estuary. The ability of these floods to carry material further down estuary than normal can influence the distribution of other substances. For example, HELZ *et al.* (1981) report Mn/Fe ratios in the middle Bay higher than can be explained from supply from shoreline erosion. They attribute the excess Mn to supply from the upper Bay, perhaps through remobilization of Mn during later summer. However, both upper bay and fluvial sediments have higher Mn/Fe ratios; the influx of sediment into the middle Bay during floods may account for some of the difference.

Satellite imagery is limited to detection of surface properties. Yet, an understanding of the vertical structure and behavior of the estuary and the development of numerical models can allow reasonable inferences of 3-dimensional behavior from satellite data. Several satellites can be used for these types of analyses, including LANDSAT Thematic Mapper, SPOT, and, to a limited degree, the (now non-operational) Coastal Zone Color Scanner. LANDSAT MSS and AVHRR complement each other, however; MSS by having an extensive archive of detailed imagery, and AVHRR by providing inexpensive temporal resolution, which can also aid in finding cloud-free scenes. The production of quantitative data from satellite appears to provide an excellent complement to ship and gaging station data in evaluating sediment transport in estuaries. More systematic measurements of transport during floods should become possible through the use of satellite and *in situ* data and modelling analyses.

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□ ZUSAMMENFASSUNG □

Durch die Benutzung der Satellitendaten mit Oberflächenbeobachtungen werden ausführliche Auskünfte über Sedimententransport während schwerer Abführungsperioden der Trichtenmündungen geliefert; es ist durch LANDSAT und AVHRR (Advanced Very High Resolution Radiometer) Reflektierungsdaten des Chesapeake Bay-Gebiets demonstriert. Im März 1979 hätten die Flüssen Susquehanna und Potomac schwere Abführung. Hängende Sedimentensättigungen (5- bis 10-mal als normale) wurden in der Buchtachse von Schiff und Satellit beobachtet. Die Satellitendaten zeigten noch dazu einen Fluss der Oberflächensedimente in der Nebenflüsse hinein. Nach zwei Woche trug das Oberflächengewässer in der Nähe Annapolis 10% der Sedimentlast des Susquehanna-Flusses, und davon 5% ging im Gewässer der nördlichen Nebenflüsse. Satellitenbildwerk des Potomac-Flusses zeigt ein in der niederigen Trichtenmündung entwickelte Verwirrungsmaximum, das Sättigungen, die zu 10- bis 20-mal als normale bewertete sind, hat. Wichtige Masse Sedimenten gingen in der Bucht vom Potomac hinein. Die Satellitendaten zeigen auch Unterschieden der Kerngrösse zwischen Potomac- und oberen Buchtsedimenten. Es gibt nur AVHRR-Satellitendaten und USGS-Abmessungsstationdaten für dem Ereignis des November 1985. Das Bildwerk zeigt die Bewegung und die schwere Sättigungen der hängenden Sedimenten in der oberen Trichtenmündung; die Sättigungen wurden zu dreimal der 1979-Niveaus und 100-mal normale bewertet zu sein. Dieses Ereignis lieferte vielleicht 50% der durchschnittlichen Jahresablagerung in der niedrigen Potomac-Trichtenmündung.--*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*