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Remote Sensing of Suspended Sediment Discharge into the Western Gulf of Maine during the April 1987 100-Year Flood

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ABSTRACT

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In early April 1987, heavy rainfall produced record floods in several Maine rivers. The suspended sediment discharge into the western Gulf of Maine during this event was identified using NOAA-9 and NOAA-10 Advanced Very High Resolution Radiometer (AVHRR) data from March 29 to April 14. The satellite images were processed to obtain water reflectances corrected for atmospheric interference. Sediment concentrations were estimated from the reflectances using relationships previously calibrated for other estuaries, owing to the lack of *in situ* data on such episodic events in Maine. The sediment plumes showed a westward movement upon reaching the Gulf of Maine. The remotely sensed observations indicate that 10^6 metric tons of fine-grained sediments were carried onto the continental shelf in the largest plume, that from the Kennebec-Androscoggin river system.

ADDITIONAL INDEX WORDS: *AVHRR, continental shelf, sediment transport, plume.*

INTRODUCTION

The estuaries along the Gulf of Maine are small, comparable in cross-section to their respective rivers, thereby allowing sediment loads carried by the rivers to pass directly onto the continental shelf. As a result, the discharge of sediment during high flow may have a strong effect on the quantity and patterns of sedimentation on the shelf, especially for fine-grained sediments. The resultant deposits can be studied using shipboard measurements; however, the episodic supply of material can be studied only with difficulty. Some information on the quantity of sediment carried by the river may be available from freshwater gaging stations. However, the transport and dispersal of sediment offshore cannot be readily detected or monitored from ship owing to the logistical difficulties of planning for such sudden events.

One solution to these problems is the application of satellite-derived imagery. Sensors on board such satellites as Landsat, SPOT, and the NOAA polar orbiters can provide synoptic data on coastal areas. Information from these satellites has been proven suitable for estimating suspended sediment concentrations in coastal waters (KLEMAS *et al.*, 1974; MUNDAY and ALFOLDI, 1979; STUMPF, 1988; PRANGSMA and ROOZEKRANS, 1989), and atmospheric correction techniques permit quantitative comparisons of images collected at different times (STUMPF and PENNOCK, 1989). Of the available sensors, Landsat and SPOT generally provide an image of a given area every few weeks, limiting their utility in examining episodic events, although evaluation of large numbers of images can permit determination of general patterns of the suspended sediment plumes (*e.g.*, GRIGGS and HEIN, 1980; DINNELL *et al.*, 1990). The Advanced Very High Resolution Radiometer (AVHRR) provides imagery almost daily, making it well suited for such a task.

In early April 1987, heavy rainfall and melting snowpack produced severe floods in the rivers of southern Maine. On several of the rivers, 100-year and greater floods were reported (FONTAINE, 1987). The suddenness and severity of the floods precluded most shipboard observations of sediment transport. However, data collected from the AVHRR permitted assessment of the suspended sediment dispersal patterns for this event, and

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demonstrates the capability of this instrument for documenting the transport of suspended sediment into coastal waters.

METHODS

The AVHRR is described in detail in KIDWELL (1986) and PLANET (1988). The sensor provides data on red (0.58–0.68 μm) and near-infrared (0.72–1.0 μm) spectral bands, as well as thermal-infrared radiances that are used to calculate sea surface temperatures. The sensor has a 1.1 km pixel width at nadir. In 1987 the sensor was operating from two NOAA polar orbiting satellites: NOAA-9 and NOAA-10, each providing nearly daily coverage.

The AVHRR data sets were acquired in Level 1B digital format (KIDWELL, 1986). The encoded location information (latitude and longitude) was processed to map each pixel in the image to the nearest neighbor of a Mercator projection. The unmapped pixels were filled with an average of a 3 × 3 block of the surrounding filled pixels. A secondary correction fitted the image shoreline to a database shoreline to within 1 pixel. Clouds were identified using both the derived temperature and reflectance data (STUMPF, 1987); essentially low temperature and high reflectance indicated clouds. To estimate suspended sediment concentrations, we determined water reflectances (R_D) using the corrections for solar zenith angle and atmospheric interference described in STUMPF and PENNOCK (1989). The total reflectance (R_*) in each of the two reflected-light bands was determined by the equation:

$$R_*(\lambda) = \frac{A_*(\lambda)r^2}{T_0(\lambda)T_1(\lambda)\cos\theta_0} \qquad (1)$$

where λ is the band (1 or 2); A_* is the raw "albedo" measured at the satellite as defined by sensor calibrations (PLANET, 1988); T_0 and T_1 are the transmission losses caused by the atmosphere from the sun to the earth and from the earth to the sensor, respectively; r is the distance from the earth to the sun normalized to the mean radius of the earth orbit; and θ_0 is the solar zenith angle ($90° - \theta_0$ is the sun's elevation). STUMPF and PENNOCK (1989) discuss this technique in greater detail.

To correct for distortions caused by haze and thin clouds we determined a corrected reflectance, R_D,

$$R_D = R_*(1) - R_*(2) - R_{bias} \qquad (2)$$

where 1 and 2 denote the two channels, and R_{bias} represents a residual bias due to Rayleigh scattering. This bias for the scene was determined so that $R_D = 0$ over clear water. This solution is suitable for small areas (<200 km across). Typically, uncorrectable and unmasked haze may produce errors in R_D of 0.003 (about 5 mg L^{-1} in sediment concentration).

The suspended sediment concentrations were determined using the equation and coefficients presented by STUMPF and PENNOCK (1989):

$$n_s = \frac{a_x}{0.18(b_{bs}^*/R_D) - S^*} \qquad (3)$$

where n_s is the suspended sediment concentration; a_x is an absorption coefficient; b_{bs}^* is the specific backscatter coefficient for sediment; and s^* is the specific coefficient for absorption and backscatter for the sediment. The coefficients were obtained from calibration data collected in Delaware and Chesapeake Bays, with a_x, b_{bs}^*, and s^* equal to 1.83 m^{-1}, 0.022 m^2 mg^{-1}, and 0.110 m^2 mg^{-1}, respectively, resulting in n_s in mg L^{-1}. The coefficient a_x will remain relatively constant in most waters except during severe algal blooms (>30 μg L^{-1}). The sediment coefficients, b_{bs}^* and s^*, may change with the optical grain size of the sediment. As a result, the appropriate values of these coefficients and, therefore, those for n_s for the Maine floodwaters may differ from the calculated ones by as much as a factor of 2 (*e.g.*, STUMPF, 1988). The importance of this potential error in n_s will be considered in the discussion.

Streamflow records for selected stations in the Kennebec-Androscoggin river system, which had the greatest outflow and the largest plume, were obtained from the U.S. Geological Survey, Water Resources Division.

Information on wind direction was collected from the NOAA Weekly Weather summaries (NOAA, 1987), and the output of the NOAA Limited-Fine Mesh numerical model (REEVES and PYTLOWANY, 1985).

RESULTS

In late March, warm weather began melting the snow pack in Northern New England. On March 30, a low pressure system developed off the Virginia coast, then moved slowly to the northeast, producing two days of strong (>10 m/sec), southeasterly (onshore) winds. These winds enhanced

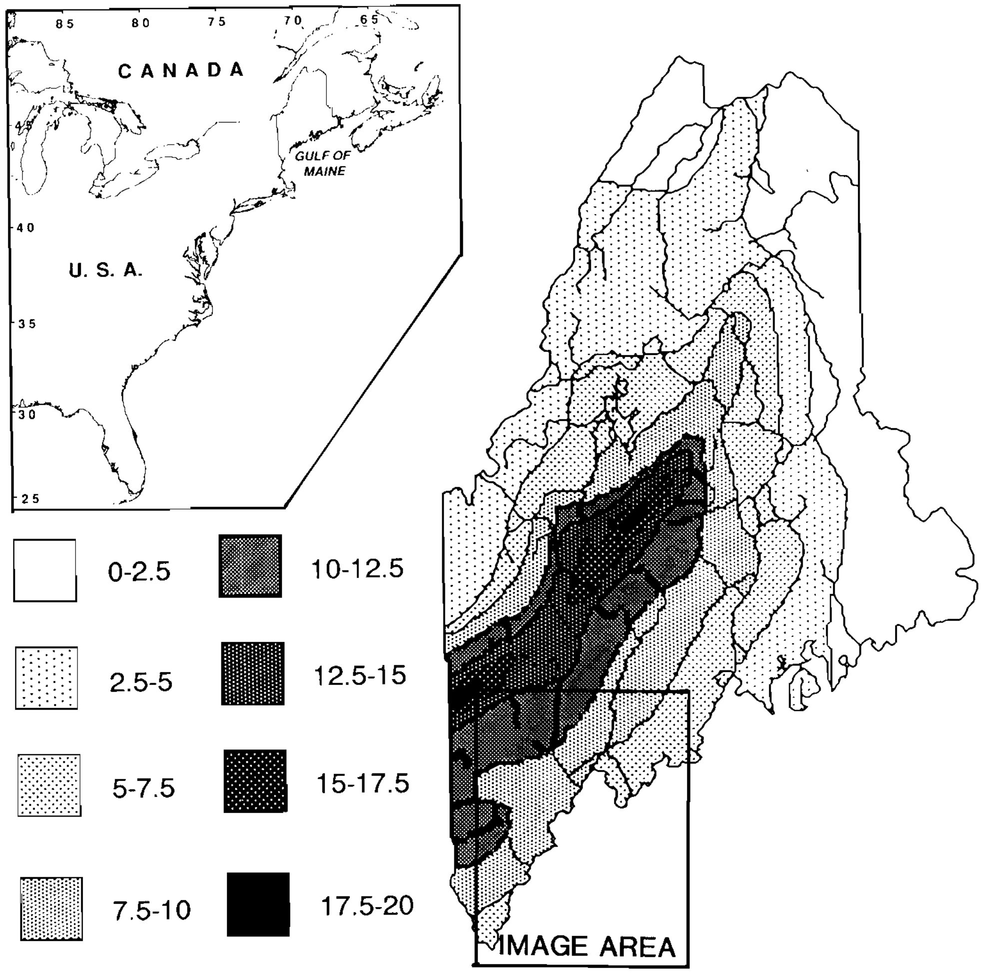

Figure 1. Location map of the Gulf of Maine and rainfall distribution in centimeters over Maine from March 30 to April 2, 1987. Area of satellite images shown in box.

the rainfall along the southeast flank of the southwest-northeast trending mountain ranges in Maine and New Hampshire. As a result, most of the area received >5 cm (2″) of rain, with up to 18 cm (7″) falling in some areas (Figure 1). Because the ground was saturated by melting snowpack, much of the rain ran directly into the streams (FONTAINE, 1987).

From April 1–3, severe floods occurred through New Hampshire and western Maine (Table 1), including record discharges in the Penobscot, Kennebec, and Androscoggin Rivers. Because these rivers have narrow estuaries, we should expect most of their suspended sediment load to be discharged into the Gulf of Maine.

On March 29, just prior to the flood, slightly turbid water appeared off the Kennebec (K) River (Figure 2). Estimated sediment concentrations were 4–8 mg L^{-1} in this plume and less than 2 mg L^{-1} in most of the remaining Gulf, typical conditions for these areas (SCHNITKER, 1974). The Saco (S) River did not show a sediment plume at this time.

The heavy overcast associated with the storm prevented any remote observations until April 2. On April 2, even while the rivers crested inland

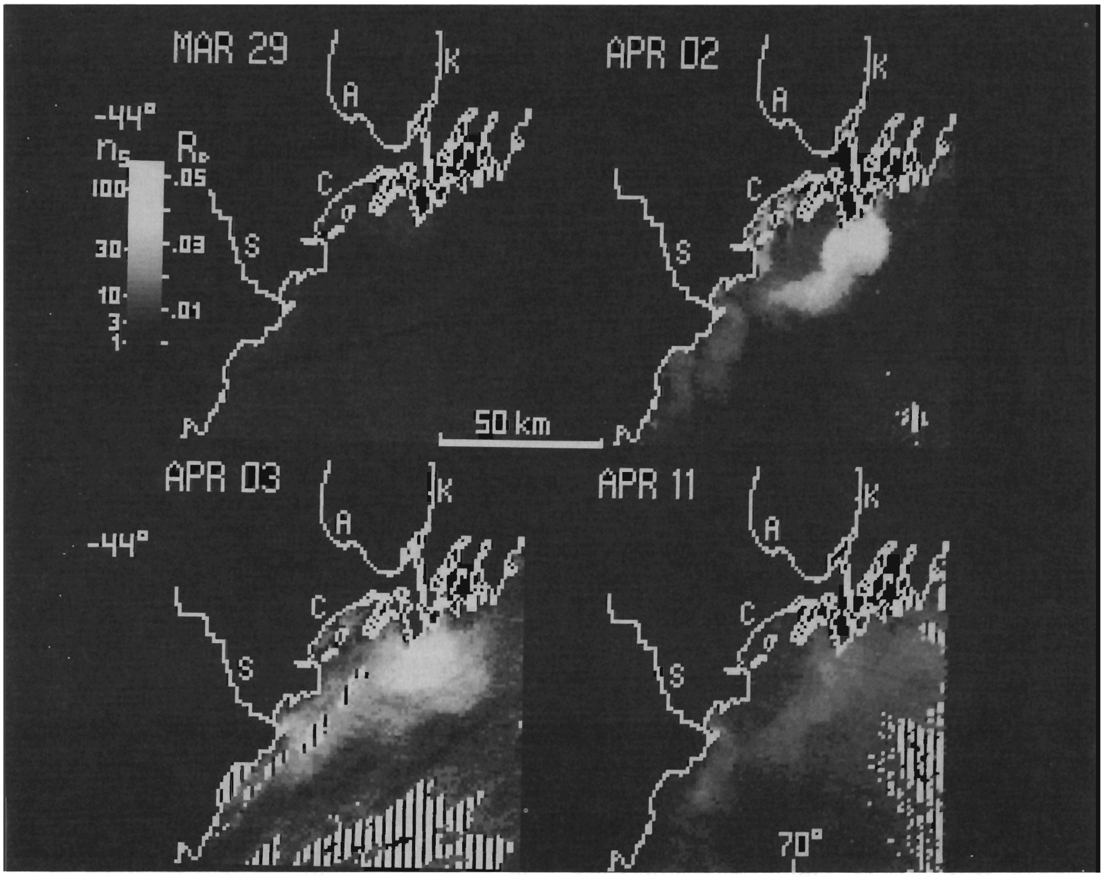

Figure 2. AVHRR images of the western Gulf of Maine showing reflectance (R_D) with the suspended sediment concentration calibration. Clouds are masked in white stripes. S = Saco River, C = Casco Bay, A = Androscoggin River, K = Kennebec River. See text for detailed explanation. March 29, 1987, 1350 EST (NOAA-9) showing conditions prior to the flood. April 2, 1987, 0800 EST (NOAA-10), taken when the rivers were cresting inland, showing plumes from the Kennebec-Androscoggin system, Casco Bay, and the Saco River. April 3, 1987, 0735 EST (NOAA-10) showing some dispersion of the plumes. A band of thick haze and clouds (striking SW-NE) could not be completely removed from the offshore waters in this scene, causing some distortion in the reflectances in these areas. April 11, 1987, 0800 EST (NOAA-10) showing a return to more normal sediment loads one week after the major flood.

(Table 1), they had already produced extensive plumes in the Gulf (Figure 2). Casco Bay (C) showed increased turbidity resulting from the high discharge of the Royal and Presumpscot Rivers. The Kennebec (K) and Saco (S) plumes extended up to 30 km from shore and 50 km westward along the coast.

The estimated sediment concentrations in the plume from the Kennebec-Androscoggin system (the two rivers meet in an estuary about 25 km inland) reached 50–100 mg L^{-1}. Maximum estimated concentrations in the other plumes were 15–30 mg L^{-1} (this includes the Penobscot at about 25 mg L^{-1} in Penobscot Bay, which is not shown).

On April 3, the plumes maintained their intensity (Figure 2). The edge of the Kennebec plume showed evidence of dispersion toward the east. Winds on April 2–3 were light (<5 m/sec) and variable. The reduced winds may have allowed this eastward diffusion to occur, rather than prolonging the strong westward movement.

A second storm system entered the region on April 4 (preventing remote observation) causing flooding in central New Hampshire and Massa-

Table 1. *Maximum flood discharges in April 1987 for rivers entering the western Gulf of Maine.*

River Gaging Station (in Maine)	Discharge (m^3/sec)	Date	Estimated Recurrence (years)
Saco			
Cornish	885	April 3	40
Casco Bay			
Royal River			
Yarmouth	239	April 1	30
Presumpscot			
W. Falmouth	167	April 1	—
Androscoggin			
Auburn	2,890	April 2	100
Kennebec			
N. Sidney	6,230	April 2	>100*
Penobscot			
Eddington	4,330	April 3	75*

*Record flood

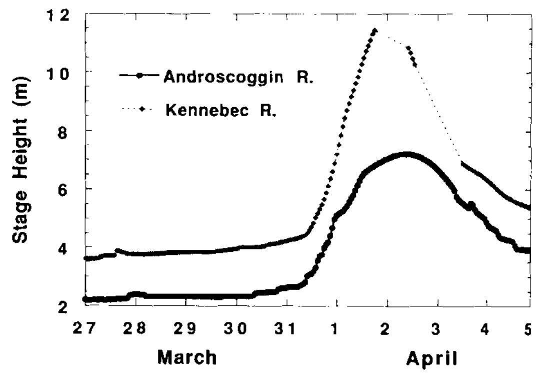

Figure 3. Hourly stage heights for the Kennebec River at North Sidney (95 km upstream from the mouth) and the Androscoggin River at Auburn (80 km upstream).

chusetts. Of the rivers draining into the Gulf of Maine, only the Merrimack in Massachusetts had severe flooding as a result of this storm, cresting on April 7.

The overcast associated with the second storm system finally began to clear on April 11. The plumes had weakened at that time, with the Kennebec and Saco River plumes having estimated concentrations of 10–20 mg L^{-1}. By April 14, the Gulf had returned to the conditions existing prior to the storms.

DISCUSSION

The westward transport of the plumes corresponds to the tendency of the Gulf to have a counter-clockwise gyre in circulation (*e.g.*, BIGELOW, 1927 and BUMPUS, 1960 as summarized in GREENBERG, 1983). This transport could result from wind-induced circulation, or from a combination of Coriolis and gravitational (density-driven) effects. GREENBERG's (1983) numerical model results indicate that wind-induced currents may strongly affect circulation in the Gulf of Maine, even predominating over tidally-induced residual currents. Thus, the gyre may result from the mean wind-driven circulation.

However, the Gulf responds as a semi-enclosed basin, resulting in an extremely complex interaction of the regional wind field with the Gulf waters (WRIGHT *et al.*, 1986). The southeasterly winds acting on both the Gulf and the adjacent shelf may have played a role in the coastal transport in the first two days of April. The weakening of the offshore front between April 2 and April 3 did correspond to a shift to light and southwesterly winds. Coriolis action on the gravitational flow resulting from a freshwater plume would produce the type of curvature westward along the coast that was observed here (GARVINE, 1987). A combination of Coriolis, gravitation, and wind effects probably induced the observed southwestwardly movement of the plumes.

The turbid water seen in Figure 2b and c was produced by the initial pulse of the storm waters. The leading edge of the flood reached the lowest gaging stations on the Kennebec and Androscoggin (80 km upstream of the Gulf) about 1600 EST on March 31 (Figure 3). A speed of 8 km h^{-1} would be reasonable in the river, therefore this leading edge would have reached the Gulf about 0300 EST, April 1. By 0800 EST on April 2, the time of the image (Figure 2b), the leading edge of the plume had moved 40 km from the mouth, indicating a transport speed on the shelf of about 40 cm/sec during that time.

Using the estimated sediment concentration, one can approximate the sediment load discharged into the Gulf. Two techniques are available: an estimate using the plume area, and one using the discharge volume.

In the calculation using the plume area, the quantity of sediment is found from the integrated mass of sediment in the plume. The estimated concentration in each pixel is an average for that area (about 1.18 km^2 at 43.5°N). The depth of the water column producing the signal that reaches

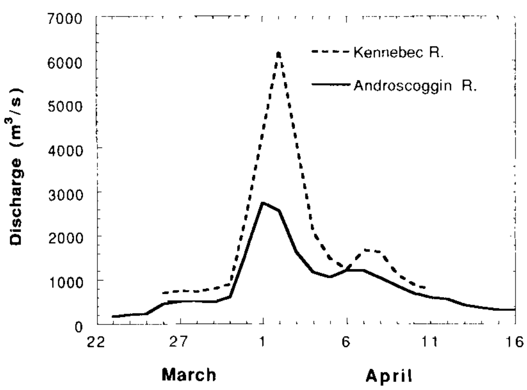

Figure 4. Hydrographs of daily discharge for the Kennebec River at North Sidney and the Androscoggin River at Auburn. The gage at North Sidney failed on April 2 and was not restored until April 4; the peak discharge on April 2 was approximated from the crest height. The total flow from the system is approximately equal to the sum of the discharges of the two rivers.

the satellite varies from about five meters in clear water to a few centimeters in turbid water (>100 mg L^{-1}). This signal is weighted toward the surface concentrations. However, with even slight wave-induced mixing, the concentration will be fairly uniform throughout the plume thickness, so the satellite observation should represent the concentration above the pycnocline.

We must then estimate the thickness of the plume. Other studies in similar systems can provide a guide. The Connecticut River produces 2 m thick plumes in Long Island Sound during discharges of 2,000 m^3 sec^{-1} (GARVINE, 1974), which are only 20% of the discharge from the Kennebec-Androscoggin system. The Fraser River in British Columbia produces plumes up to 10 m thick where it enters the Strait of Georgia for discharges of 10,000 m^3 sec^{-1} and 3 m thick plumes were observed 15 km from the river mouth (STRONACH, 1981). From these and other observations (*e.g.*, Chesapeake Bay, Schubel, 1974), it appears likely that the plume should be at least 3–4 m thick. Assuming a plume thickness of 3 m, the areal method estimates that the Kennebec-Androscoggin plume contained 0.9×10^5 metric tons (m.tons) of sediment in a given image.

The discharge method offers a partially independent calculation for comparison. It uses the assumption that the discharge of the river system leaving the estuary (Figure 4) carries the highest concentrations observed at point of discharge onto the shelf, however it is not completely independent because both estimates use equation 3 to arrive at the suspended sediment concentration. For April 2, the discharge estimate is 0.77×10^5 m.tons, indicating a total suspended sediment discharge of about 1.5×10^5 m.tons for the event (Table 2). The two estimates are close although the discharge estimate is higher than the areal estimate by about 60%. The difference between the two estimates can be explained by two effects. First, the plume will be deeper than 3 m where the concentration is highest, resulting in an underestimate of sediment load in that area. Second, mixing and settling of sediment into the waters beneath the plume as it moves farther from the source would reduce the sediment found in the plume.

The optical grain size of the sediments observed here may differ from the size of sediments in Delaware and Chesapeake Bays. Due to the paucity of clays in the drainage basins in Maine relative to those in the Piedmont region of the mid-Atlantic (SMITH, 1982), the Maine rivers may carry coarser silts. A two-fold difference in size would double the values of b_{bs}* and s*, thereby doubling the estimated concentrations such that the maximum concentration would be 200 mg L^{-1}. Given the extreme floods involved, concentrations in excess of 100 mg L^{-1} are more reasonable than the much lower ones produced by smaller grain sizes (see, for example, STUMPF, 1988). Accordingly, the Kennebec-Androscoggin system could have supplied well in excess of 10^5 m.tons of sediment.

Table 2. *Sediment Loads for the Kennebec-Androscopggin plume based on areal and discharge estimates.*

Areal Estimate		Discharge Estimate	
Area of plume (A) April 2	811 km^2	Discharge (Q) April 2–3	9,000 m^3 sec^{-1}
Mean sediment concentration in plume (N_s)	36 mg L^{-1}	Approximate n_s at discharge	100 mg L^{-1}
Estimated plume thickness (Z)	3 m	Estimated duration (T)	2 days
Sediment load in plume A × Z × N_s	0.9×10^5 m tons	Sediment load T × Q × n_s	1.5×10^5 m tons

CONCLUSIONS

The AVHRR data revealed the pattern of movement of sediment plumes from the rivers in Maine. Initial transport was to the southwest; this may be explained by a combination of gravitational and Coriolis effects. However, this movement did not persist on the second day, probably as a result of changes in the wind direction. Most sediment was removed from the surface waters after 10 days.

The quantity of sediment in the plume can be estimated. Accuracy of within an order of magnitude appears likely, with the greatest uncertainty owing to variations in grain size (STUMPF and PENNOCK, 1989) and plume thickness. Data from upstream gaging stations may provide some control on the estimated sediment concentrations. Any *in situ* data on the sediment concentration would improve the calibration coefficients. The load estimates in most areas would benefit from field measurements of the plume thickness. AVHRR data can be acquired and processed within 1–2 days of an overpass, thus the imagery can be used to direct *in situ* sampling of sediment plumes during episodic events. Deposition onto the continental shelf is not unique to this coast. Although episodic deposition occurred in this case, other rivers, such as the Mississippi and Amazon Rivers, continually supply some suspended sediment to the shelf. The use of the satellite imagery to determine the direction of transport along the coast can help in identifying the probable areas of deposition from such plumes. Such information may further aid in studies of the benthic characteristics in these areas.

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