Journal of Coastal Research	6	4	789-799	Fort Lauderdale, Florida	Fall 1990

Estuarine-Shelf Exchange Using Landsat Images of Discharge Plumes

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ABSTRACT

DINNEL, S.P.; SCHROEDER, W.W., and WISEMAN, W.J., Jr., 1990. Estuarine-shelf exchange using landsat images of discharge plumes. *Journal of Coastal Research,* 6(4), 789-799. Fort Lauderdale (Florida). ISSN 0749-0208.

Landsat satellite data can provide descriptions of discharge plume morphology, as well as estimates of estuarine-shelf suspended sediment exchange. Thirty-three images, collected over an 11-year period, of the Mobile Bay, Alabama, discharge plume were analyzed in conjunction with environmental data. Plume size was principally controlled by river discharge but modified by the tides. Suspended sediment transport estimates based on plume size suggest that the annual suspended sediment load from Mobile Bay to the adjacent shelf can be exchanged during an average five-month cold front season and an average spring flood. Wind-wave resuspension of Mobile Bay sediments during frontal passage and direct river borne suspended sediments are the two major sources of suspended sediment transported to the shelf.

ADDITIONAL INDEX WORDS: *Estuarine-shelf water exchange, river discharge, estuarine exchange, estuarine discharge plume, Landsat data, plume morphology, suspended sediment transport.*

INTRODUCTION

Remotely-sensed suspended sediment data in coastal regions is a useful tracer for studies of estuarine circulation and estuarine-shelf exchange. Landsat imagery has been used to describe Chesapeake Bay plume dynamics (MUNDAY and FEDOSH, 1981), estuarine-shelf response to cold-air outbreak conditions (SCHROEDER *et al.*, 1985), effluent pathways in Lake Erie (LeDREW and FRANKLIN, 1987), Mobile Bay discharge plume morphology (ABSTON *et al.*, 1987), and to document river-discharged suspended sediment transport in Chesapeake Bay (STUMPF, 1988). Regional estuarine-shelf exchange is important to an understanding of the general physical circulation and, consequently, larval recruitment and transport of pollutants and suspended sediment (SHAW *et al.*, 1985; SCHROEDER and WISEMAN, 1986; WISEMAN, 1986; ABSTON *et al.*, 1987; WISEMAN *et al.*, 1988).

ABSTON *et al.* (1987) discussed the relationships between environmental forcing parameters and discharge plume morphology in a descriptive format. Briefly, higher river discharge was related to an increase in plume size. River discharges of less than 4500 m^3/s were associated with plume areas from 100 to 500 km^2, while river discharges greater than 4500 m^3/s were associated with plume areas that ranged from less than 100 to over 1700 km^2. Comparative analyses indicated that other environmental parameters, the tide range and phase, could modify the effect of river discharge and alter plume size.

We have quantified the relationships discussed in ABSTON *et al.* (1987) using correlation and regression analyses to determine statistical relationships between plume morphology and environmental forcing. In the absence of theoretical justification for more complex relationships we used linear regression to determine direct relationships. We redefined ABSTON *et al.* (1987) suspended sediment estimates for the discharge plumes and the shelfward transport of suspended sediment. We have based suspended sediment transport esti-

89032 received 26 May 1989; accepted in revision 19 March 1990.

mates on three concentrations associated with different plume volumes. Plume volume was estimated as the product of the measured plume areas and a characteristic plume thickness. The annual volume of suspended sediment transported to the inner shelf by Mobile Bay discharge was estimated by coupling these plume volumes with characteristic suspended sediment concentrations.

Mobile Bay is located on the northeastern coast of the Gulf of Mexico (Figure 1). The Bay, 50 km in length along its north-south axis, 17 km wide in the north and 38 km in the south, has an area of 985 km^2. It is relatively shallow (average depth 3 m) yet has a 12 m dredged ship channel running along its longitudinal axis. SCHROEDER (1978) estimates that, on average, Main Pass accommodates approximately 85% of Mobile Bay's volume exchange with the Gulf of Mexico; the other 15% is exchanged via Pass-aux-Herons with Mississippi Sound to the west.

Discharge plumes result from direct forcing of the estuarine gravitational circulation by river flow, tidal exchange, and sub-tidal wind-driven flow. River input to Mobile Bay discharges predominantly into the northern Bay; the average annual mean discharge of the Mobile River System from 1929 to 1983 is 1848 m^3/s (SCHROEDER and WISEMAN, 1986). Daily discharge can vary from 250 to over 15000 m^3/s. Low flow is considered to be less than 500 m^3/s and flood discharge to be greater than 7000 m^3/s (SCHROEDER, 1979; SCHROEDER and LYSINGER, 1979).

The astronomical tide in this region is primarily influenced by the declination of the moon. Tropic tides occur when the declina-

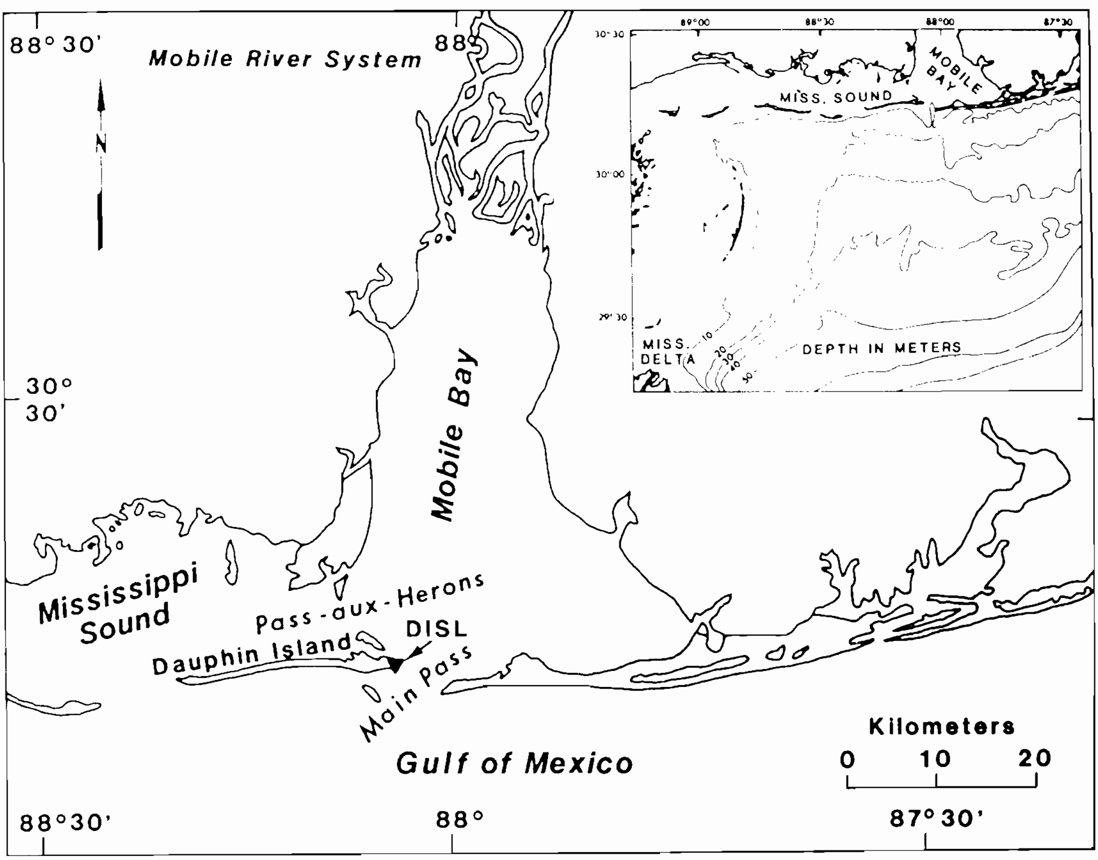

Figure 1. Map of Mobile Bay, Alabama. Inset shows Mobile Bay in relation to northeast Gulf of Mexico.

tion angle is high. They are strongly diurnal and have the highest tide range, 0.9 m, and strongest predicted surface currents, 1.7 m/s, at Main Pass. Equatorial tides occur when the declination angle is low. These tides have low ranges, 0.05–0.2 m, and weak, variable and sometimes unpredictable surface currents, 0.1–0.3 m/s, at Main Pass (MARMER, 1959; U.S. DEPARTMENT OF COMMERCE, 1973-1983a,b; SCHROEDER, 1976; SEIM *et al.*, 1987).

Climatology of the local winds is discussed in SCHROEDER and WISEMAN (1985). Prevailing winds in the late fall and early winter are from a northern quadrant. Cold fronts associated with convergent air masses interrupt the prevailing winds with energetic episodic winds from the southwest and northwest (HUH *et al.*, 1984). The strengthening of the Bermuda high pressure system in the spring switches the prevailing wind direction to the southeast. By summer the winds are weak and predominantly from a southern quadrant.

DATA AND METHODS

Thirty-three cloud-free Landsat Multispectral Scanner (MSS) images collected over an 11-year period from 1973 to 1983 were used to characterize the discharge plume from Mobile Bay. Standard enhancements of MSS band 5 images at scales of 1:1,000,000 and 1:500,000 covering 10 months of the year were reviewed for this analysis. No images from July or August were used. Discharge plumes were defined visually based on the higher relative reflectance of the discharge plume than that of the inner shelf waters. Descriptive plume parameters, *i.e. area, length, width* and *azimuth,* were measured. *Area* was determined by planimeter. A curvi-linear axis was subjectively drawn from the center of Main Pass, through the center of the plume, to the leading edge of the plume. Plume *length* is simply the length of this axis. Plume widths, normal to this axis, were measured at 2 km intervals along the axis. The average of these widths is the plume *width.* The compass bearing each of the 2 km intervals along the axis was averaged. This average is the *azimuth* and is considered the general orientation of the plume. Environmental parameters, *i.e.*, Q, HS, ER, WU1, WV1, WU3 and WV3, refer to the lagged river discharge, the phase of the tide, specifically the time from the last high slack water to the time of the image, the ebb tide range, and the east-west and north-south, one- and three-day average winds, respectively.

River discharge, (U.S. DEPARTMENT OF INTERIOR, 1973-1983) was lagged to account for travel time from the upriver gauging stations to the Bay. A five-day lag for discharges greater than 6000 m^3/s, and seven days for discharges less than 6000 m^3/s was used. These lags fall within the 4- to 8-day phase lag between river discharge and Mobile Bay water level found by SCHROEDER and WISEMAN (1986). Plume size has been related to tide range and phase (ABSTON *et al.*, 1987). Although the tidal range is small, the large Bay area allows development of a large tidal prism, which can be up to 16% of the Bay volume. Plumes imaged during the ebb cycle were smaller than those observed at the end of the ebb cycle. These, in turn, were smaller than plumes residing on the shelf some period of time after the completion of the ebb tide. All the tidal information used in this study consisted entirely of predicted values for Main Pass from National Ocean Survey (NOS) tables (U.S. DEPARTMENT OF COMMERCE, 1973-1983a,b). Although *in situ* water level data was available for Main Pass, this data was not used because it contained a signal due to wind effects (SCHROEDER and WISEMAN, 1985; DINNEL and SCHROEDER, 1989).

Plumes are expected to change in size and orientation because of shelf currents. We estimated the mean local winds, which contribute to nearshore currents and affect the subtidal shelf-estuarine exchange (SCHROEDER and WISEMAN, 1985, 1986; DINNEL, 1988; WISEMAN *et al.*, 1988). Winds recorded at Dauphin Island Sea Lab (DISL), on the east side of Main Pass (Figure 1), were resolved into vector components with oceanographic orientation. East-west (positive to the east) and north-south (positive to the north) components were low-pass filtered with a cutoff at 40 hours to describe the mean winds. Raw winds were averaged over a one-day period, and filtered winds averaged over a three-day period, immediately preceding the time of each plume image. The one-day winds are representative of the average local wind over the time period concurrent with the plume formation. These winds contribute to local mixing and transfer momentum to the plume. The three-day winds represent the sustained winds which are thought to affect the subtidal shelf-estuarine exchange (SCHROEDER and WISEMAN, 1985, 1986; WISEMAN *et al.*, 1988) and contribute momentum to the innershelf currents (DINNEL, 1988). Some effects, though, can not be readily estimated from available data: the loss of plume area because of entrainment into Mobile Bay during the flood tide, effects of tidal currents on the shelf, and effects of pressure gradients set up by the buoyant plume itself.

Plume volume, V_A, was estimated by multiplying measured plume area by a characteristic plume thickness. One- and two-meter thicknesses represent upper and lower bounds for average plume thickness. These bounds were estimated from limited, unpublished, *in situ* hydrographic data sampled from 13 discharge plumes resulting from high river flow conditions during the spring of 1979. These quasi-longitudinal plume transects also indicated a sharp reduction in suspended sediment concentrations between the 10 and 15 ppt surface isohalines. The 10 ppt isohaline was conservatively considered to delineate the horizontal as well as vertical plume boundary.

Plume volume, V_{CR}, was determined by an independent method using environmental parameters and was used to corroborate V_A. V_{CR} is the sum of the ebb tidal volume and the river volume discharged into the Bay during the preceding ebb and flood tides. The river volume, was simply the lagged daily discharge, multiplied by the duration of the preceding flood and ebb tide and assumed river input at the Bay head to be balanced by a simultaneous output to the Gulf. The ebb tidal volume was calculated by assuming a sinusoidal tidal-current velocity at the surface at Main Pass. Tidal velocity increases from zero at the time of last high slack water, to the maximum velocity at the time of predicted maximum ebb flow, then decreases to zero at the time of low slack water. This assumption was reasonable in light of the measured Main Pass tidal current data presented by SCHROEDER (1976). We assumed that half the surface velocity, at any time, was the average cross-sectional velocity. This average cross-sectional velocity, sinusoidally varying with time, was integrated over the duration of the ebb tide that preceded the image and then multiplied by the cross-sectional area of Main Pass, to produce the volume of water that passed through Main Pass on that particular ebb tide.

Table 1. *Mean tide ranges and associated tidal prisms for Mobile Bay, Alabama.*

	Mean Tide Range (m)	Tidal Prism (km^3)
AUSTIN (1954)	0.46[a]	0.453
McPHEARSON (1970)	0.42	0.414
U.S. DEPT. COMM. (1985)	0.454[a]	0.447
This Study	0.427[b]	0.420

[a] Determined from tidal prism
[b] Range is average of Port of Mobile and Main Pass, Alabama (U.S. DEPARTMENT OF COMMERCE, 1983a)

To determine how well this method estimated the plume volume we calculated the volume of water discharged over the entire ebb cycle, V_E, not just the portion prior to the image. We then compared V_E with the ebb tidal prism, V_P, which we believed to be the best estimate of the ebb tide volume. V_P was 85% of the volume calculated as the average of the predicted tide range at the Port of Mobile and at Main Pass, multiplied by the area of Mobile Bay. Reasonable agreement was found between V_P determined from NOS predicted mean tide range for this study and those in the literature (Table 1). When V_E was regressed against V_P there was good correlation ($R^2 = 0.88$), but the slope of the relationship was not unity. Either V_E was underestimated, *i.e.*, the cross-sectional averaged velocity used for Main Pass was too small; or $V_P$was overestimated. With insufficient *in situ* velocity data to adequately determine an average cross-sectional velocity or the possible flow variation through Main Pass and Pass-aux-Herons, we have to assume some error was contributed from both sources. Despite these difficulties and because of the good relationship between V_E and V_P, we conclude that V_{CR}, calculated using predicted tidal pass currents and river discharge specific to each imaged plume, was a reasonable estimate of the discharge plume volume.

RESULTS

Correlation coefficients between plume morphology parameters and between environmental parameters are presented in Table 2. The

Table 2. *Correlation coefficients, ρ, between plume morphology parameters and between environmental parameters. See text for explanation of variables.*

PLUME PARAMETERS				
	AREA	LENGTH	WIDTH	AZIMUTH
AREA	—			
LENGTH	0.87	—		
WIDTH	0.82	0.57	—	
AZIMUTH	0.36	0.36	0.26	—

ENVIRONMENTAL PARAMETERS							
	Q	HS	ER	WU1	WV1	WU3	WV3
Q	—						
HS	0.46	—					
ER	0.20	0.44	—				
WU1	− 0.08	− 0.08	− 0.09	—			
WV1	0.03	0.11	− 0.37	0.25	—		
WU3	0.03	− 0.02	0.09	0.70	0.08	—	
WV3	0.02	0.07	− 0.39	0.24	0.58	− 0.11	—

Table 3. *Means and ranges of plume morphology parameters and environmental parameters. See text for explanation of variables.*

	MEAN	RANGE
PLUME PARAMETERS		
AREA (km^3)	427	63 − 1722
LENGTH (km)	28.5	12.0 − 60.2
WIDTH (km)	12.1	5.9 − 23.8
AZIMUTH$^+$ (°)	193	148 − 247
ENVIRONMENTAL PARAMETERS		
Q (m^3/s)	3914	278 − 10059
ER (m)	0.34	0.02 − 0.71
HS (hr)	12.03	4.67 − 23.68
WU1 (m/s)	− 0.49	− 4.07 − 4.93
WV1 (m/s)	− 1.56	− 7.34 − 2.55
WU3 (m/s)	0.04	− 3.32 − 3.32
WV3 (m/s)	− 1.64	− 5.57 − 1.50

$^+$ Shore normal is 176°

plume morphology parameters were well correlated with each other, ? ρ ? > 0.5, with the exception of the *azimuth*. The environmental parameters were generally uncorrelated, ? ρ ? < 0.4, and were considered independent. The one- and three-day wind components were well correlated with each other, though. This was expected as the one-day winds contribute information to the three-day winds. During fall, winter and spring the synoptic weather band extends from 2.5 to 5 days (DINNEL, 1988).

Means and ranges of measured plume parameters and environmental parameters at times of Landsat images are presented in Table 3. In general, *area* was positively correlated with *length* and *width*. The *azimuth* varied between − 28° and 71° from shore normal. The mean *azimuth* indicates that the plumes were predominantly oriented to the southwest from Main Pass. River discharge, Q, ranged from low flow to flood conditions. The tide range, ER, encompassed equatorial and tropic tide conditions. Values of HS, the phase of the tide, greater than 12.5 hours indicate that the image was obtained after the ebb tide was completed, *i.e.* during the following flood tide. Low values of the three-day winds, WU3 and WV3, may indicate either low sustained winds or the cancellation of winds from opposite directions.

The level of statistical significance of the linear regressions of individual environmental parameters against the individual plume morphology parameters when these are 90% or greater, as well as the R^2 values, are presented in Table 4. Q, HS, and ER were significantly correlated with *area, length* and *width* at the 94% level or greater. These relationships were suggested in the qualitative analysis of ABSTON *et al.* (1987). Plume *azimuth* was significantly correlated with Q, WU1 and WU3 at the 95% level or greater. As Q increased, the *azimuth* increased toward the west. This may reflect a self-advective process. Large river discharge plumes lower the coastal salinity and the resultant geostrophic flow is westward. The three-day winds, and the correlated one-day winds, are also a possible forcing mechanism

Table 4. *Statistical significance of individual Mobile Bay plume morphology parameters to individual environmental parameters. The significance level (*SL*) is indicated for all the plumes, the high river-discharge plumes,* Q_H ($Q > 4500$ m^3/s)*, and the low river-discharge plumes,* Q_L ($Q < 4500$ m^3/s); ns, *indicates no significance at the 90% level or above. See text for explanation of variables.*

	Area		Length		Width		Azimuth	
	SL	R^2	SL	R^2	SL	R^2	SL	R^2
All Plumes (N = 33)								
Q	99	.37	99	.54	98	.26	98	.19
HS	99	.34	99	.59	98	.21	ns	
ER	97	.16	94	.13	98	.19	ns	
WU1	ns		ns		ns		95	.19
WV1	ns		ns		ns		ns	
WU3	ns		ns		ns		95	.19
WV3	ns		ns		ns		ns	
Q_H Plumes (N = 16)								
Q	ns		ns		95	.36	ns	
HS	ns		99	.49	ns		ns	
ER	94	.25	ns		95	.34	ns	
WU1	ns		ns		ns		ns	
WV1	ns		ns		ns		ns	
WU3	ns		ns		ns		ns	
WV3	ns		ns		ns		ns	
Q_L Plumes (N = 17)								
Q	ns		97	.30	ns		ns	
HS	94	.23	96	.28	95	.29	ns	
ER	ns		94	.27	ns		ns	
WU1	ns		ns		ns		99	.47
WV1	ns		ns		ns		ns	
WU3	95	.29	ns		ns		99	.65
WV3	ns		ns		ns		ns	

for the local inner-shelf circulation, which is normally westward (DINNEL, 1988). Three-day wind values greater than 1 m/s were needed to deflect the plume to the east.

Although these environmental parameters were correlated with the morphology parameters, most of the associated R^2 values were below 0.4, indicating that the relationships had little predictive value. Plume *length*, correlated with Q and HS, had R^2 values slightly greater than 0.55.

We have plotted the three statistically significant environmental parameters (Q, HS and ER) versus *area* (Figure 2). *Area*, of all the plume morphology parameters, is of the most interest in the subsequent discussion. Plume *area* was less than 500 km^2 until river discharge increased to more than 4500 m^3/s (Figure 2A). Although river discharge is significantly correlated with *area*, it appears that the data naturally clusters into plumes associated with low and high river discharge. In the following, Q_H will refer to river discharge greater than 4500 m^3/s and Q_L to river discharge less than 4500 m^3/s. While there appears to be a linear relationship between Q_L and *area*, the slope of the regression line is not statistically different from zero and there is no significant correlation (Table 4). Variability in *area* is so large for values of Q_H, that there is no significant correlation between Q_H and *area* (Table 4), yet the larger values of *area* are only associated with Q_H. The smaller plumes associated with Q_H correspond to uncompleted ebb cycles or were imaged during equatorial tides. Both conditions limited the observed tidal exchange and reduced the volume available to produce the plume.

When Q belonged to Q_L, HS was the primary control on plume *area* (Table 4, Figure 2B). The correlation of WU3 and *area* was also statistically significant under these river discharge conditions. *Area* increased when WU3 blew to the east. Sustained post-front winds to the east interrupt the normal westward flow on the inner shelf and set down the water level at the

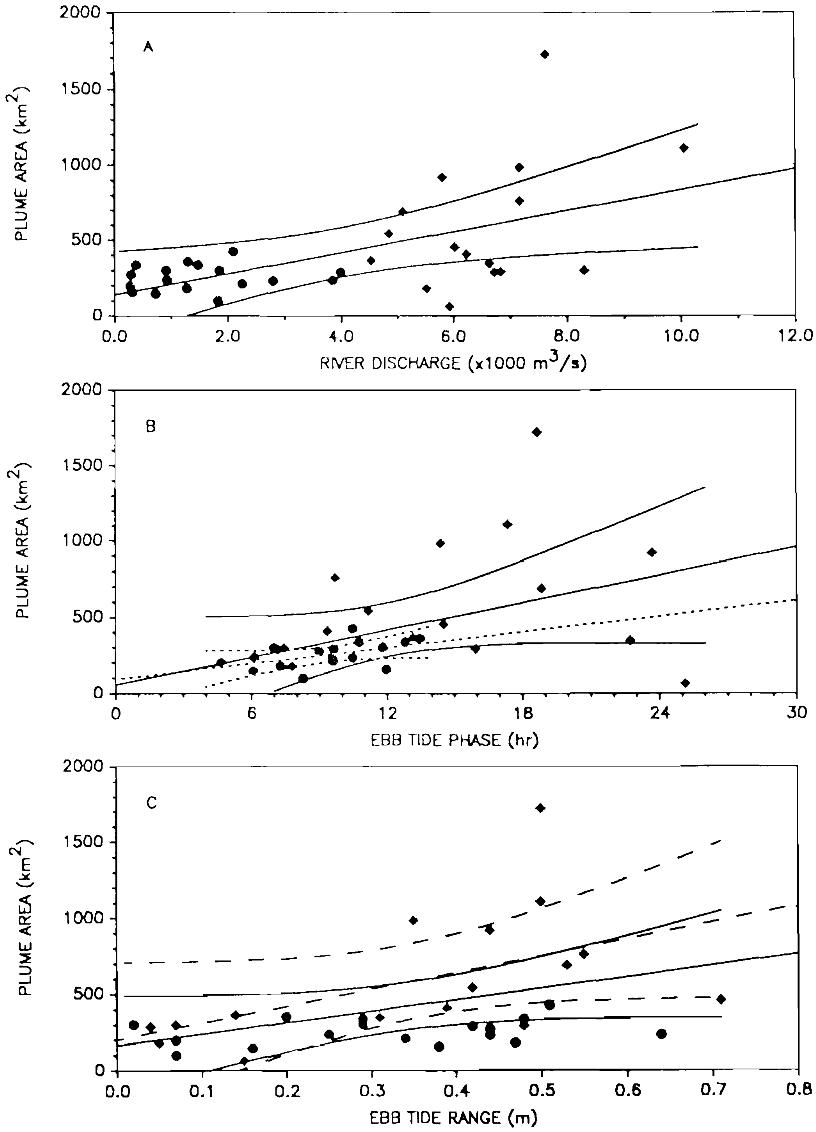

Figure 2. Environmental parameters, (A) river discharge, (B) ebb tide phase, (C) ebb tide range, are plotted versus discharge plume area. High river discharge plumes are indicated by diamonds, low river discharge plumes are indicated by circles. Regression lines, statistically significant at the 90% level or greater, are presented for analyses using all the plumes (solid line), only high river discharge plumes (dashed line), and only low river discharge plumes (dotted line). Confidence limits are determined at associated regression line significance levels (see Table 4).

coast (DINNEL, 1988); increased sub-tidal estuarine-shelf exchange as a result of the alongshore winds contributes to these larger plumes. ER is the primary control on plume *area* when Q belongs to Q_H (Table 4, Figure 2C).

Plume *length,* when Q belongs to Q_H, is significantly correlated with HS; the older the plume the longer it is. Under the same river discharge conditions, plume *width* is significantly correlated with Q and ER; plume width increases with both.

When Q belongs to Q_L, weak but significant

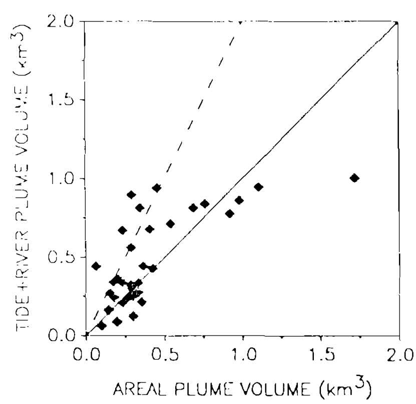

Figure 3. Areal plume volume estimated from Landsat images plotted versus plume volume calculated from tidal currents and river discharge. Solid line represents a 1-meter thick plume, dashed line represents a 2-meter thick plume.

correlations of *length* with Q, HS and ER occur. *Width* is weakly, but significantly correlated with HS. *Azimuth* is more strongly correlated with WU1 and WU3.

Areal plume volumes, V_A, estimated by assuming a plume thickness of one meter, compare well with V_{CR}, plume volumes calculated from predicted tidal information (Figure 3). In only a few instances did V_{CR} approximate a two-meter thick plume volume.

Characteristic suspended sediment concentrations were estimated for three levels of plume areas. Plumes with areas less than 500 km^2 were estimated to have a suspended sediment concentration of 20 mg/l. This smaller plume size is considered to be produced predominantly by tidal processes that discharge wind-wave resuspended sediments. Larger plumes, 500 to 1000 km^2, are considered the direct result of river discharge and carry a riverine suspended sediment load. These discharge plumes are estimated to have a suspended sediment concentration of 40 mg/l. The largest plumes areas, $>$ 1000 km^2, are produced by extreme river discharge, $>$ 10000 m^3/s, and are estimated to have a suspended sediment concentration of 60 mg/l.

The number of sediment-laden plumes can be estimated from the frequency of cold front passages and expected high-magnitude river discharges. There are 30 to 40 cold front passages from November through March (FERNANDEZ-PARTAGAS and MOOERS, 1975; DIMEGO *et al.*, 1976). These frontal passages produce the generally cloud-free skies that enable discharge plumes to be imaged by satellites and produce the wind-wave conditions expected to resuspend the fine sediments in the shallow sounds and bays of the region (SCHROEDER, 1977; SCHROEDER *et al.*, 1985; DINNEL, 1988). We assumed an average of 35 fronts, from November through March, with 2 wind-wave resuspended sediment-laden plumes per front. Plumes not associated with high river discharge had areas of 100 to 500 km^2. Using a midpoint area of 300 km^2, we estimate the average volume of these plumes to be, 300 km^2 $\times$ 1 m or 0.3 km^3. Over the 11-year period of images, the Mobile River system had an annual average of 24 days of flood discharge, $>$ 7000 m^3/s (4 days $>$ 10000 m^3/s). River floods produce plume areas of 500 to 1000 km^2. Using a midpoint area of 750 km^2, we estimate the average volume of these plumes to be, 750 km^2 $\times$ 1 m or 0.75 km^3. We estimate that 70 cold-front plumes with suspended sediment concentrations of 20 mg/l and 20 river-flood plumes with suspended sediment concentrations of 40 mg/l should transport 1.02 $\times$ 10^6 tn of suspended sediment to the shelf. Some of each plume reenters Mobile Bay on the subsequent flood tide. We estimate, conservatively, that 75% of each plume or 0.765 $\times$ 10^6 tn remains on the shelf. Extreme Mobile River floods, $>$ 10000 m^3/s, are associated with large plumes, $>$ 1000 km^2. At very high river discharge, $>$ 10000 m^3/s, flow has been observed out of Main Pass regardless of the tide stage (SCHROEDER and LYSINGER, 1979); we considered these extreme floods not to be modulated by the tides. Four extreme river floods per year with an estimated average suspended sediment concentration of 60 mg/l, again assuming a 1 m thick plume, increases our transport estimates by 0.24 $\times$ 10^6 tn, to 1.005 $\times$ 10^6 tn per year. An average plume thickness of 2 m would increase our annual estimate to 2.01 $\times$ 10^6 tn.

DISCUSSION

We have estimated annual transport of suspended sediment from Mobile Bay to the shelf. Our range of values, 1.005 to 2.01 $\times$ 10^6 tn, brackets the annual estimate of RYAN (1969), 1.3 $\times$ 10^6 tn. We have assumed a five month frontal season, an expected frequency of flood conditions from the Mobile River system, and estimated discharge plume suspended sediment concentrations. Landsat images enabled us to determine Mobile Bay discharge plume area and estimate discharge plume volumes. By assuming suspended sediment concentrations based on plume size, we estimated the suspended sediment load transported to the shelf. Our values do not account for sediment contribution from 10-year floods typically with river discharges of 12000 m^3/s for 10 or more days, or flooding and wave-resuspension due to tropical storms, under which conditions there would be considerably more suspended sediment transported to the shelf. Nor do they account for possible frontal passage concurrent with high river discharge that would increase the transported suspended sediment load. Suspended sediment returned to Mobile Bay on subsequent flood tides may be much less than the 25% we estimated, this would also increase the suspended sediment load transported to the shelf.

Plume volume was estimated from plume area assuming a characteristic plume thickness. This procedure for volume determination compared well to volumes determined from Main Pass tidal currents and Mobile River system discharge. The one-meter thick plumes seemed to be the better estimate, suggesting that the lower value of our suspended sediment range is more reasonable.

We found that plume size is predominantly a function of the Mobile River system discharge, but is modified by tidal conditions. Large plumes occurred only when river discharge exceeded 4500 m^3/s. The phase of the tide and the tide range represented secondary influences on plume size at higher river discharges. Equatorial tide ranges limited discharge plume development because of small tidal prisms. Tropic tide ranges produce a tidal prism that could reach 16% of the Bay's volume and exchange large volumes of Bay water to the shelf. The phase of the tide or the plume age was the major factor influencing plume size at lower river discharge.

SCHROEDER *et al.*, (in press) suggest that Mobile Bay has the capacity to absorb river discharge up to some level, above which the Bay becomes river dominated. Up to this level the Bay as a whole freshens but maintains longitudinal and vertical salinity gradients, above this level the river discharge flushes salt from the Bay. We suggest that the Bay's discharge plume becomes river dominated above a river discharge of 4500 m^3/s, which is less than flood discharge. A 4500 m^3/s flow would discharge 14% of the Bay's volume over a 25-hour diurnal tidal period (used here for comparison), approximately the volume of a tropic tidal prism. An extreme river discharge, > 10000 m^3/s, would discharge 30% of the Bay's volume over a diurnal period.

CONCLUSIONS

Landsat images provide a mechanism to compare estuarine discharge plumes over long time periods and different environmental conditions. Plume volumes estimated from one- or two-meter thick measured plume areas and estimated suspended sediment concentrations allow a determination of the suspended sediment volume transported to the shelf. Most, if not all, of the annual suspended sediment load transported to the shelf can be accounted for during a five month, November to March, frontal season and an average spring flood. Wind-wave resuspension of fine sediments in the shallow Bay and direct river borne suspended sediment are the two major sources of suspended sediment transported to the shelf.

Plume morphology, described in general by area, length and width, are primarily related to river discharge with modulating effects due to the tides. Up to a certain level of river discharge, 4500 m^3/s, plume size is directly related to tide phase, *i.e.* the longer the tide has ebbed, the larger the plume. Above this level the river discharge dominates the plume size. Yet, even at times of large river discharge, the tidal range and phase modifies the plume size.

Local winds, either across shore or alongshore do not seem to be significantly related to plume size. Yet, the alongshore winds, are well correlated with the orientation of the discharge plume. The direction of the alongshore currents is related to the wind direction, so the orientation of the discharge plumes are thought to be a result of advection by the local current, an indirect result of the alongshore winds, as well as a result of direct momentum transfer from the wind.

ACKNOWLEDGEMENTS

This work is a result of research sponsored in part by NOAA Office of Sea Grant, Department of Commerce under grant number NN85AA-D-SG141 (Project R/EMP-3), the Louisiana State University Sea Grant College Program and grant number NA-85AA-D-SG005 (Project R/ER-16), the Mississippi-Alabama Sea Grant Consortium and The University of Alabama. This publication is contribution No. 115 from the Center for Marine Science, University of Southern Mississippi, contribution No. 138 from the Aquatic Biology Program, The University of Alabama, and contribution No. 172 from the Marine Environmental Sciences Consortium, Dauphin Island, Alabama.

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□ RESUMEN □

Las imágenes del satélite LANDSAT pueden utilizarse para la descripción de morfologías de plumas de descarga, así como para la estimación de intercambio de sedimentos en suspensión en estuarios. El presente artículo analiza 33 imágenes tomadas en un período de 11 años, en la Bahía de Mobile, Alabama, conjuntamente con datos medidos in situ. El tamaño de la pluma es controlado principalmente por la descarga del río pero se ve modificado por las mareas. Las estimaciones del transporte de sedimentos en suspensión basadas en el tamaño de la pluma sugieren que la carga sedimentaria anual aportada por la Bahía de Mobile a la plataforma continental adyacente puede producirse durante un período medio de cinco meses de frente frío y condiciones de avenida. La resuspensión de los sedimentos de la Bahía debido al oleaje y los sedimentos aportados por el río son las dos mayores fuentes de aportación de sedimentos transportados a la plataforma.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ RÉSUMÉ □

A partir des données Landsat, on peut décrire les panaches turbides et estimer les échanges de sédiments en suspension de l'estuaire au plateau continental. Un jeu de 33 images de la Mobile Bay (Alabama), collectées sur 11 ans, ont permis d'analyser le panache turbide en rapport avec les données de l'environnement. La taille du panache dépend essentiellement du débit fluvial mais est modifiée par la marée. Le transport des sédiments en suspension estimé à partir de la taille du panache suggère que la majeure partie de l'apport au plateau continental se fait sur 5 mois de fronts froids en moyenne, et pendant les crues de printemps. La remise en suspension par la mer du vent pendant le passage frontal et l'apport direct de suspensions par la rivière, constituent les deux sources des sédiments transportés vers le plateau continental.—*Catherine Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Mit Hilfe von Landsat-Satellitenaufnahmen können sowohl die Formen von Trübewolken wie auch suspendiertes Material im Flachwasser von Ästuaren abgeschätzt werden. 33 Aufnahmen über eine 11-Jahres-Periode von der Mobile Bay in Alabama wurden in Verbindung mit Umweltdaten im Hinblick auf die Sediment-Trübewolken analysiert. Die Größe dieser Trübewolken wurde prinzipiell kontrolliert durch die Abflußspende, aber durch die Gezeiten modifiziert. Die Abschätzung der Raten der Suspensionsfracht aufgrund der Größe der Trübewolken ergab, daß die jährliche Suspensionsfracht von der Mobile Bay zum angrenzenden Schelf innerhalb einer fünfmonatigen Kaltfrontsaison oder während einer durchschnittlichen Springtide ähnlich sind. Windbedingte Trübesedimente der Mobile Bay während des Durchzugs einer Front und die direkte Anlieferung von Suspensionsfracht durch den Fluß sind die beiden Hauptquellen für Schwebefrachttransport zum Schelf.—*Dieter Kelletat, Essen/FRG.*