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DISTRIBUTION AND MOVEMENT OF SUSPENDED SEDIMENT IN THE GULF OF MEXICO OFF THE TEXAS COAST*

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ABSTRACT

ERTS-1 imagery has proven very useful in studies of the distribution of suspended sediment in the Gulf of Mexico off the Texas coast. Moreover, by using suspended-matter concentrations as tags on water masses, much information on water movement can be obtained. The utility of suspended sediment as a tracer is dependent on the sediment remaining in suspension long enough to travel an appreciable distance or to be visible on successive images. Although the evidence is not conclusive, it seems likely that much of the suspended sediment in Gulf of Mexico nearshore waters during normal sea-state conditions has remained in suspension since the time of its entry into the Gulf of Mexico through rivers and tidal inlets.

Superimposed on the general offshore decrease in turbidity are more complex concentrations of turbid water which may be classified as plumes or bands. A plume is attached to its source river or inlet during its growth, but at the end of an ebb tidal cycle, the plume from a tidal inlet becomes detached and drifts passively. Most bands are aligned either parallel or obliquely to shore. Water movement in some oblique bands is known to be toward shore, whereas in others it is away from shore. The bands may originate in several ways: by drift along streamlines from localized sources, such as river mouths, where suspended sediment is being continuously supplied; by the deformation of ebb-tide plumes after they have been detached from their source at a tidal inlet; or by the concentration of suspended sediment in the convergence or divergence zones between water masses, especially in the convergence or divergence zones associated with helical circulation cells.

1. INTRODUCTION

The movement of suspended fine-grained sediment, which is one facet of the sedimentological cycle involving the erosion, transport, and deposition of earth materials, is a geologic problem particularly accessible to study by repetitive remote-sensing techniques. ERTS-1 imagery has proven suitable for such studies; the imagery reveals differences of as little as 0.7 mg/l in the concentration of suspended particulate matter in surface waters of the Gulf of Mexico.

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Suspended sediment is environmentally important from several standpoints. Its entry into suspension may constitute erosional damage, and its deposition may be damaging to channels, harbors, and biologically productive wetlands or sea floors. It may be considered a pollutant because of its detrimental effects on certain organisms; moreover, it may contain adsorbed metallic and organic compounds that are pollutants.

Under certain conditions the remote sensing of suspended particulate matter may be used as a tool for investigating physical oceanographic problems. One condition is that water masses must differ distinguishably in their content of suspended matter. If this condition is fulfilled, certain aspects of the flow system, especially current directions, may be deducible from the pattern of turbidity contrasts visible in an image; however, the capability of measuring current velocities is severely limited. A further condition is that the concentrations of suspended matter in distinct water masses must remain sufficiently close to constant long enough for the water masses to be recognizable in successive images. If this condition is fulfilled, the suspended-matter concentrations can be used as tags on water masses, by which their movement can be traced. Under favorable conditions, the Lagrangian field of motion can be determined in much greater detail by this method than is practicable by using discrete drift objects such as drogues or bottles. The first condition has usually been fulfilled in ERTS-1 imagery of the Texas coast, and the second condition has sometimes been fulfilled in the overlap areas of ERTS-1 images taken on successive days but has so far not been fulfilled in images taken during successive 18-day ERTS-1 cycles.

2. SOURCES OF SUSPENDED SEDIMENT

Most of the suspended particulate matter so abundant in coastal parts of the northwestern Gulf of Mexico is fine-grained terrigenous sediment (Manheim, Hathaway, and Uchupi, 1972). This sediment enters the Gulf of Mexico in three known ways: through river mouths, by flow of turbid bay and lagoon waters through tidal inlets, and by resuspension of sea-floor sediments during times of strong waves. The relative importances of the three sources of suspended sediment in the Gulf of Mexico are not known.

It was suspected, from the occasionally poor correlation between wave activity and nearshore turbidity, that resuspension of sea-floor sediments might not be the most important source of suspended sediment in coastal waters of the Gulf of Mexico. The ERTS-1 imagery supports this hypothesis and suggests that much of the suspended sediment in the nearshore waters at any one time has remained in suspension since the time of its entry into the Gulf of Mexico through rivers and tidal inlets. Although resuspension of shelf sediments may be significant during major storms, some evidence suggests that even during hurricanes,

resuspension may not be the most important source of suspended sediment (Hayes, 1967, p. 33-42).

The evidence from the ERTS-1 imagery concerns the behavior of river-mouth plumes and plumes from tidal inlets. When a plume from the Rio Grande is well developed, it can be traced continuously for distances of at least 75 km downdrift (south during the fall and winter of 1972-73) along the coast (Fig. 1). Ebb-tide plumes generated at tidal inlets become detached at slack water and drift with the coast-wise current (Fig. 2). As many as four detached ebb-tide plumes have been seen downdrift (south during the fall and winter of 1972-73) of Aransas Pass, the most distant one having traveled about 85 km in 4 days of relatively calm weather. Evidently, suspended sediment introduced into the Gulf of Mexico through tidal inlets can remain in suspension for several days, even during relatively calm conditions, and can account for much of the turbidity in coastal waters, even at points far removed from river mouths and tidal inlets.

3. DISTRIBUTION OF SUSPENDED SEDIMENT

In general, the concentration of suspended matter in the north-west Gulf of Mexico decreases offshore (Manheim, Hathaway, and Uchupi, 1972). Superimposed on this gradient are more complex local variations in turbidity, most of which may be classified as plumes or bands.

Plumes are formed by jet flow from river mouths and tidal inlets. As the intracoastal bays and lagoons are presently less saline than sea water, plumes from the tidal inlets form surface layers like those from rivers. Coastal currents affect both types of plumes, causing their distal ends to bend in the direction of the current. The development of the two types of plumes differs, however, because river discharge continues for indefinite periods, whereas the discharge from a tidal inlet is restricted to periods of ebbing tidal currents.

If river discharge and coastal currents are steady enough, a river-mouth plume approaches a steady-state form so that its distal end drifts passively with the coastal current while the sediment disperses and settles in the water column. The Rio Grande plume has been seen to extend southward 65 km, hugging the convex shoreline, then becoming detached at a point of increased curvature and extending at least another 10 km along its previous line of movement (Fig. 1). The plume, or at least its surface part, is evidently kept pressed against the shoreline by an onshore component of surface drift. The suspended sediment may disperse seaward in a near-bottom layer as the river water mixes with sea water or as the suspended sediment falls from the less dense surface layer into an underlying layer of sea water. The plume from the Brazos River commonly extended obliquely offshore to the southwest during the winter of 1972-73, giving evidence of offshore surface

drift. Because of the lack of confinement, the offshore-drifting plume disperses rather rapidly and has not been traceable more than 40 km from its source.

Plumes from tidal inlets never attain a steady-state form because of their pulsing character. During or very shortly after its detachment at slack water, an ebb-tide plume is deformed in such a manner that its nearshore end lags behind its offshore end (Fig. 2). Its sharply defined updrift edge thus becomes oriented obliquely offshore in the direction of drift. The flow pattern by which an ebb-tide plume is deformed during and immediately after detachment is not yet fully understood. Later, during its drift along the coast, the direction of obliquity of the updrift edge of a plume is sometimes reversed (Fig. 2), indicating that the edge has been sheared because of a shoreward increase in longshore-current velocity. This phenomenon is restricted to a nearshore zone no more than 10 km wide and is evidently a result of the wave-driven circulation.

Most bands of turbid water are fairly straight and are oriented either parallel or obliquely to shore (Figs. 3 and 4). Occasionally, however, bands are incorporated into vortices having diameters of from 10 to 20 km; such vortices have been seen only during periods of relatively calm weather, when previously generated flow systems are presumably moving largely by inertia. The bands detectible on ERTS-1 imagery are on the order of 1 to 10 km wide and occur either singly or in series.

One of these bands was sampled at sea and photographed by a NASA aircraft from an altitude of 18,000 m coincidentally with an ERTS-1 overpass in late August 1972. The band was about 5 km wide, was centered along a line about 8 km from shore, and extended for a distance of about 120 km from Aransas Pass southward. Measured concentrations of suspended matter at the water surface were 1.0 to 1.8 mg/l within the band, compared with 0.2 to 0.8 mg/l on either side; the concentrations generally increased with depth. Horizontal and vertical salinity and temperature gradients were slight. Drift-bottle recoveries, plume orientations, and the orientations of linear slicks, which are visible in the aerial photographs are of the type produced by Langmuir circulation (Langmuir, 1938; Asaf, Gerard, and Gordon, 1971), indicated that the average current direction was southward, parallel to the axis of the band. At its southern end, the band gradually impinged against the concave shoreline. At the point of impingement, the aerial photographs showed an abundance of turbid rip-current plumes.

The direction of water movement in a band may be either toward or away from the point at which the band touches shore. Along the Texas coast north of Aransas Pass during the fall and winter of 1972-73, the bands were usually oriented obliquely to shore, diverging from

the shoreline in a southwestward direction. The direction of water movement in this area was southwestward and away from shore, though not necessarily exactly parallel to the bands.

The bands may originate in several ways. Some are simply long, relatively narrow plumes from river mouths. These bands are necessarily oriented along streamlines of the flow system. Some bands originate by the detachment and deformation of plumes from tidal inlets. In these bands, which are oriented obliquely to shore, the water movement is not necessarily parallel to the bands and may be more nearly parallel to shore.

Converging and diverging currents are probably important in shaping bands that originate from river-mouth or tidal-inlet plumes and may be solely responsible for the formation of other bands. Although direct evidence is lacking, the great lengths and uniform widths of some bands suggest that the currents are commonly organized into paired helical circulation cells of Langmuir type but much larger in scale than typical Langmuir cells. The axes of such cells, if they exist, are probably parallel to the primary or average current direction.

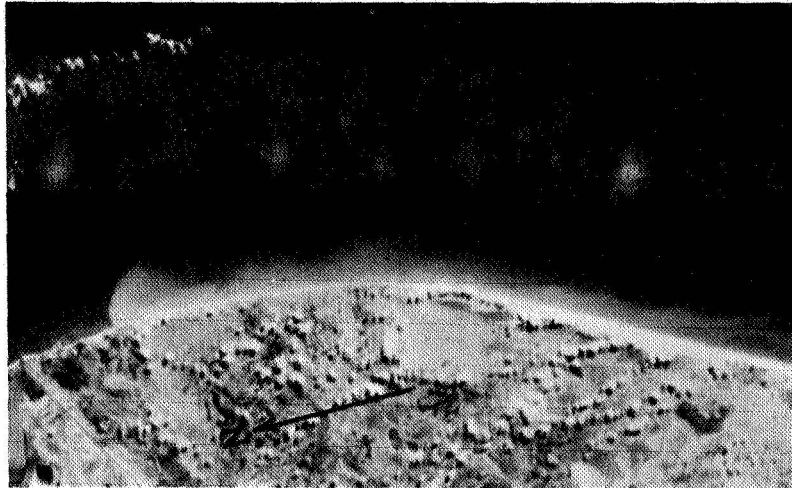
It is conceivable that suspended sediment could be concentrated in either the zones of surface convergence and downwelling or in the zones of surface divergence and upwelling of a system of helical circulation cells. The former distribution could occur if the suspended sediment were concentrated in a less dense water mass trapped in the zone of surface convergence between two circulation cells of denser, less turbid water. The latter distribution could occur if the concentration of suspended matter increased downward, and such a distribution could reach a steady state if the settling velocities of the particles were equaled by the velocity of upwelling. The turbid band sampled at sea during late August 1972 was probably of this latter type.

4. CONCLUSIONS

ERTS-1 imagery has furnished valuable information on the sources, distribution, and movement of suspended sediment in the northwestern Gulf of Mexico; much of this information could hardly be obtained in any other way and could certainly not be obtained over such large areas at such frequent intervals other than by satellites. Measurements of current velocity from single images have proven possible where the place and time of origin of detached plumes from tidal inlets could be inferred, and measurements by time-lapse methods have proven possible in the areas of overlap between images taken on successive days. In addition, the patterns of turbidity variation in the imagery reveal a wealth of detail on current directions and relative velocities.

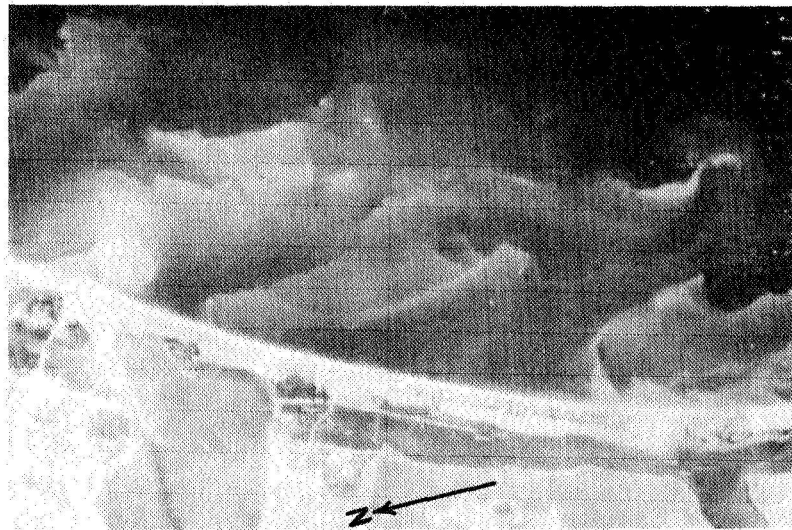
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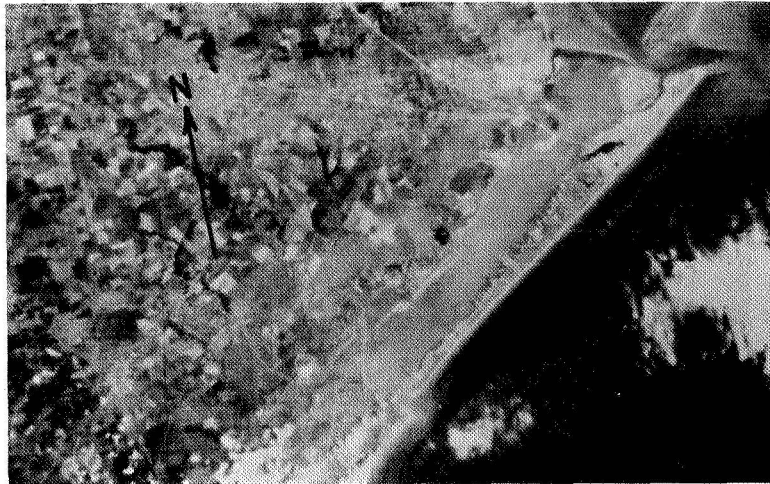
0 20 40 km

Fig. 1. - Plume of turbid water from the mouth of the Rio Grande on October 4, 1972; part of image 1073-16260, band 4.



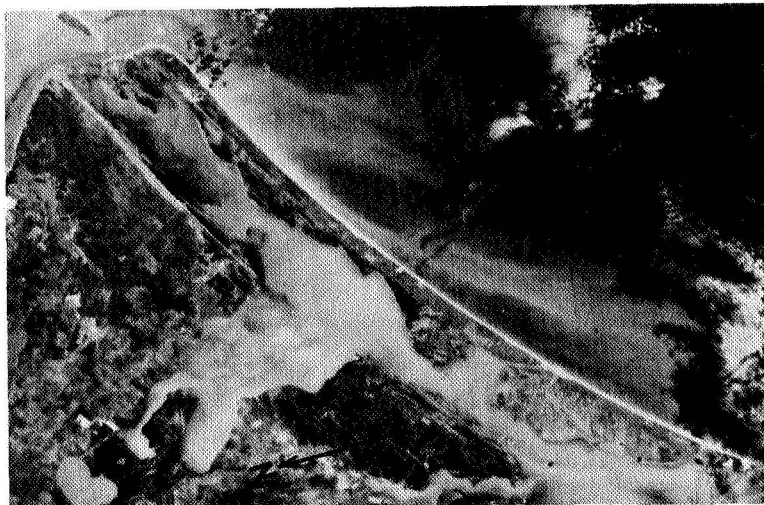
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Fig. 2. - Active and detached ebb-tide plumes of turbid water from Aransas Pass, Texas, on October 23, 1972; part of image 1092-16314, band 4.



0 20 40 km

Fig. 3. - Band of turbid water oriented parallel to the shoreline of Galveston Island, Texas, on August 29, 1972; part of image 1037-16251, band 5.



0 20 40 km

Fig. 4. - Bands of turbid water oriented obliquely to the shoreline of Matagorda Island, Texas, on November 10, 1972; part of image 1110-16313, band 5.