Change of Particle Composition from Fluvial into an Estuarine Environment: Rappahannock River, Virginia

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ABSTRACT


SEM analysis of suspended material from the Rappahannock River estuary reveals changes in particle composition and the nature of particle association between fluvial and estuarine environments. Fluvial suspensions supplied by river flooding are enriched in single grains and very small flocs whereas estuarine suspensions are enriched in aggregates mixed with single coated grains. Fluvial material is significantly modified as it passes into the estuarine environment by association with organic material and biota to form complex aggregates.

ADDITIONAL INDEX WORDS: Aggregates, estuarine, flocs, fluvial, Rappahannock River, suspended particles.

INTRODUCTION

Changes occurring in the composition and association of fine particles during transport from a fluvial into an estuarine environment are of fundamental importance. Knowledge of these changes is important in reconstructing past transport processes, in distinguishing fluvial and estuarine sediments, and in determination of partitioning of fluvial sediment transported toward the ocean during dispersal studies. Most of the annual sediment discharge from terrestrial sources occurs during periods of high water discharge following storms or snow melt. Variations in particle size, mineralogy and concentration have been detected by a variety of techniques: e.g. electronic particle sizing (KRANCK, 1979); X-ray diffraction mineralogy (EDZWALD and O’MELIA, 1975); laser holography (GIBBS and HELTZEL, 1982) and optical microscopy (GIBBS et al., 1983). The changes that occur in particle composition and association as fluvial material passes into contiguous estuarine environments are not sufficiently documented as yet. Micrographs from scanning electron microscope (SEM) studies of samples of suspensate populations can show associations of biota, organic material, and mineral grains although only a few studies have attempted to document these changes across a salinity gradient by use of SEM (PIERCE and SIEGEL, 1979; SYVITSKI and MURRAY, 1981; EISMA et al., 1982, 1983). Each of these deal with a specific set of conditions in the watershed and the estuary.

This paper describes the type of particles and nature of particle association observed after a river flood in the Rappahannock River and Estuary, Virginia. The samples were collected almost simultaneously in fluvial and estuarine zones as part of a multidisciplinary field experiment, HIFLO, organized by the Chesapeake Research Consortium.
(NICHOLS et al., 1981). The broad aim was to learn how estuarine processes respond to high river inflow and influx of sediment.

The suspended sediment load of the Rappahannock Estuary consists of silt and clay, derived from a Piedmont metamorphic terrain. The bulk of the fluvial load is supplied during short periods of high runoff, like that occurring during the HIFLO experiment when water discharge was up to 358 m$^3$s$^{-1}$, a flow occurring once every year on the average (annual storm). About 21,000 tonnes, or 30 percent of the annual, average fluvial input, was supplied during four days, March 26-29, 1978.

The Rappahannock is a microtidal, partially-mixed estuary having a mean tide range of about 0.5 m at Tappahannock (Figure 1). At normal river inflow, salt water intrudes 68 km landward to the vicinity of Tappahannock, but the tide penetrates 166 km landward into freshwater reaches. Tidal currents vary with time from nearly zero to more than 0.4 m s$^{-1}$ and hence, suspended sediment goes through repeated cycles of tidal scour and settling to the bed with concentrations varying from around 20 to 150 mg l$^{-1}$ at 0.3 m above the bed. A background population less than 30 mg l$^{-1}$ remains in the water column near slack tide. Suspended sediment is also derived from shorelines, lateral tributaries, biological production within the estuary and from Chesapeake Bay via landward flow.

**OBSERVATIONS AND METHODS**

Water samples for particle analyses were obtained in freshwater fluvial reaches (93 to 111 km landward), seaward across the fresh and salt water transition, (between 74 to 66 km), to a surface salinity of about 8 in the main estuary (46 km, Figure 1). Samples were taken at six stations spaced at about 9 km intervals along the channel (Figure 1). Samples were obtained at one or more sampling depths at each station. Each station was occupied once close to slack water before ebb tide (±1 hour), on 1 April 1978. Horizontal positions were determined by ranging and compass bearings on buoys and landmarks; water depths were determined by shipboard fathometer and sampling depths with a standard meter wheel. Water samples were obtained from the water column with horizontally mounted Van Dorn bottles; those at 0.3 m above the bottom were obtained with a tripod-mounted Van Dorn bottle. Small aliquots (<1 ml) of eleven water samples were taken immediately after recovery of the Niskin bottles. The aliquots were immediately filtered through 13-mm diameter, 0.45 μm nominal pore size membrane filters, using a hypodermic syringe and a Swinnex filter holder. The filters were placed in a desiccator and dried upon return to the laboratory (same day). After drying, the entire filter was mounted on SEM stubs and coated with platinum-palladium in vacuum. SEM micrograph images were made of all particles along transects across the filter at magnifications between 0.5 k and 3 k. From the 546 micrographs, microtextural particle types were identified and projected diameters measured. For non-circular particles, elliptical shapes were assumed and the major and minor axes measured. Individual particles down to 0.5 μm could be resolved on the filter surface. Magnifications up to 20 k were used to determine interparticle contacts. For some samples, two magnifications were used to discriminate both very small and very large particles. Particle statistics were calculated using both frequency and projected area of individual particles.

Salinity was determined in situ from an Inter-ocean induction conductivity unit. Total suspended sediment concentrations were determined by filtration using 0.80 μm Millipore membrane filters.

Stations R25, R30, and R35 are located in the estuarine zone having slightly salty water (1.0 to 9.0 salinity) and a two-way net flow through upper and lower layers. Conductivity at stations R45, R50, and R60 were below detection limits of our instruments, although historical data, for comparable river discharges, suggest that stations R50 and R60 are in the fluvial zone and station R45 is transitional from fluvial to estuarine.

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**Figure 1. Configuration and location of the Rappahannock River estuary, Virginia. Station locations, R25, R60, etc. in relation to fluvial and estuarine zones.**
RESULTS

Particle Types

Analysis of the SEM micrographs reveals five major types of particles. (1) *Clean grains* are single mineral grains having surface microtextures and laminae readily visible. This does not preclude that a thin coating may exist on the surface of the grains but it is insufficient to mask the surface texture. (2) *Coated grains* are single mineral grains having indistinct microtexture and blurred laminae, cleavage faces, and fracture surfaces. The coatings could be weathering products, organic material (PIERCE and SIEGEL, 1979; EISMA et al., 1983) or iron oxhydroxides (SHOLKOVITZ, 1976). (3) *Biogenic particles* are mainly living microbiota or fragments of tests. (4) *Flocs* are composite particles composed of individual mineral grains. They have a friable appearance with little or no matrix (Figures 2A, 2B). (5) *Aggregates* are complex assemblages of coated mineral
grains in a matrix, which exhibits no ordered structure, granularity, fracture, or cleavage (Figure 2C). The matrix is assumed to be organic material. Some particles identified as aggregates may be fragments of pellets.

Additionally, SEM analysis reveals three minor types of particles, including two sub-types of biogenic particles: (1) Pellets are cylindrical or ovoid masses of grains, with the long axis several times the short, consisting of individual grains (Figure 2D). They are similar in appearance to pelleted particles illustrated by ZABAWA (1978), which may be pseudofeces (SCHUBEL, 1982). (2) Organic material consisting of a mass of apparently soft matter with no ordered structure and no included biogenic particles or mineral grains. Although flattened on the filter into ovate and circular patterns, these particles were probably spherical while in suspension. (3) Small spherical particles, about 2 µm in projected diameter, were observed at station R30. They are similar in appearance and size to authigenic particles found by EISMA and KALF (1980) in the Rhine. They are also similar in appearance to fly ash (EMEIS and STOFFERS, 1982) but smaller.

We use the term aggregate instead of agglomerate, because of its wider usage in sedimentology (McCave, 1984; EISMA et al., 1982; HONJO et al., 1984), oceanography (KARL and KNAUER, 1984), biology (SILVER and ALLDREDGE, 1981), soil science (BREWER, 1964), and clay mineralogy (MOON, 1972). Composite particles called agglomerates by SCHUBEL (1971, 1982), ZABAWA (1978), and SYVITSKI and MURRAY (1981), would be aggregates by our terminology.

### DISTRIBUTION OF PARTICLE TYPES

Particle-frequency statistics provide information on the number of different particle types and on the average size of each type and of the total sample. Such statistics, on the other hand, provide little information on the distribution of mass among particle types, inasmuch as composite particles consist of numerous individual grains (Figure 2) which, if counted separately, would outnumber the single particles. Area-weighted statistics (used in this article because volume measurements cannot be obtained from the SEM photographs) provide more information on the mass distribution than do number statistics.

Single grains are the most numerous particles in the fluvial zone (Stations R50, R60) but are subordinate to flocs in projected area (Figure 3). Flocs at station R60 are small and consist of 2 or 3 individual grains, loosely bound together. At R50, the flocs are made up of a very large number of individual grains, loosely bound together either as “rafts” (Figure 2B) or long “strands” (Figure 2A), with no apparent matrix. Most of the single grains are clean.

In contrast, samples from the estuarine zone (R25-R35) contain mixtures of individual coated grains and aggregates, with the individual grains being slightly more numerous than the aggregates (Figure 3). On an area-weighted basis, aggregates
are the dominant particle type in the estuarine zone, averaging 71% of the total projected area. Aggregates from the estuarine zone are bound predominantly by a matrix although a substantial number (up to 20%) are flocs. Samples from the fresh-salt transition (R45) are slightly more enriched in aggregates than samples from the estuarine stations. Of specific note, clean grains dominate the fluvial zone but are nearly absent from samples from the estuarine zone while aggregates are the dominant particle type in the estuarine zone (on an area-weighted basis) but are absent from the fluvial zone.

The trend of particle size based on total particle number and projected area varies within narrow limits, except for one sample at station R50 (Figures 4A and 4B). The arithmetic number-weighted mean size of all samples is less than 7 \( \mu m \) (Figure 4A), the mean being influenced by the large number of small grains, which far outnumber the larger composite particles. The area-weighted mean size of particles in the samples ranged from 10 to 151 \( \mu m \) (Figure 4B). The sample from station R60 has a significantly smaller number-weighted mean diameter (t-test of sample means) than all other samples and near-bottom samples have larger mean diameters than those samples from higher in the water column at the two stations where multiple samples were taken (R30, R45). With these exceptions, there is no systematic trend of mean diameters with location or with depth. Abundant and large composite particles, such as found in near-bottom samples (e.g. R50, R30), contribute to the large area-weighted mean size (Figure 4B). In general, the area-weighted mean size in samples from the estuarine zone (R25-R35) is larger than that of samples from the transitional and fluvial zones. The larger mean size of the estuarine samples is attributed to the number of aggregates present.

The minor particle types, pellets, organic material, and small spherical particles, were found only in samples from the estuarine zone.

**DISCUSSION**

**Interpretation of Results**

The particle population in the upper fresh-water reach of the river is dominated by single clean grains and very small flocs in contrast to the estuarine zone where aggregates and coated grains dominate. This contrast is undoubtedly enhanced by flooding with a supply of "new" fluvial sediment from the uplands, stream banks, and/or resuspension of channel fill. The small flocs are either derived from the soils or channel fill or are formed during transport in fresh water. Work by others (SYVITSKI and MURRAY, 1981; GIBBS et al., 1983) indicate that much of the suspended material in fluvial reaches is relatively fine-grained and probably consists of single particles.

The fragile appearance of the flocs at station R50 would suggest that they have not been transported any distance. These very large composite particles appear similar in form and size to those reported in Delaware Bay by GIBBS et al. (1983) at salinities of 0.3.

In passing from the fluvial into the estuarine zone, clean grains disappear and the population of flocs is drastically reduced. Instead, the particle population is enhanced in coated grains and organic-bound aggregates. The contrast between the two populations in the Rappahannock is marked.

The average particle size in the estuarine zone, based on projected area, is considerably smaller than that of the large flocs at R50 but larger than that of the sample population farther landward.
and considerably more complex than the floes at either of these stations. This would agree with the size and particle type changes found by Eisma et al. (1982) and Gibbs et al. (1983) where large floes disappear, being replaced by other composite particles in a seaward direction. Eisma et al. (1983) found that a large part of the population of suspensates in the Ems Estuary was associated with macroaggregates, so fragile that normal sampling procedure caused them to break, a problem also encountered when sampling oceanic marine snow (Hamner et al., 1975; Honjo et al., 1984). The macroaggregates in the Ems Estuary consisted of building blocks of single grains and of smaller aggregates, which resisted dispersion.

CONCLUDING COMMENTARY

Many changes occur as fluvial material passes into the estuarine environment, but the SEM analysis shows that modification in the form of coatings and aggregation are the most important. The findings indicate that the changes are sufficiently distinct to distinguish fluvial and estuarine suspensates in modern environments but differences may not be preserved in the bottom sediments. Size analyses of cohesize bottom sediments would generate data that would do little toward interpretation of the physical conditions under which these sediments were deposited. It remains to develop methods to determine the process (or processes) that bring about these changes and to predict the degree of sediment aggregation, both in time and space. More information is needed on the change of particle types occurring on both the rising and falling river inflow in contrast to those changes at normal inflow. Meade (1972) points out that flocculation, organic aggregation, and biologic processing are, or could be, important processes but the relative importance of each is not known.

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LITERATURE CITED


