ANALYSIS OF FLUORESCENT SEDIMENT TRACER FOR EVALUATING NEARSHORE PLACEMENT OF DREDGED MATERIAL

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ABSTRACT

Nearshore placement of sand dredged from coastal navigation channels is a continuing and growing interest for coastal zone managers, scientists, and residents. The long-standing practice of placing sandy dredged material offshore as the least-cost, project-specific alternative in the U.S. is being replaced with a more holistic, regional sediment management approach that frequently calls for placement of dredged material in the nearshore environment. Several studies have been conducted to monitor dredged material mounds in depths of 10-20 m, but few if any have monitored mounds in depths less than 6 m.

Nearshore placement of sandy dredged material has been approved by state regulatory agencies for sediments dredged from the Brunswick Federal Entrance Channel on the Atlantic coast of Georgia. The placement of dredged material in 2-8 m water depth presented an ideal opportunity to evaluate the performance of the selected nearshore placement sites and practices. As part of this monitoring and modeling study, fluorescent tracers representing silt- and sand-sized particles were deployed at two nearshore placement sites and monitored over a period of 7 months. Sampling and analysis of the tracer data presented difficulties associated with the spatial and temporal variability of sediment transport processes and scales of interest. However, valuable insights into the sediment transport processes operating at the nearshore mounds were possible through the sediment tracer application. Combined with other observations, the sediment tracer study provided key information regarding: winnowing and fate of fine-grained silt from the mound, transport directions and deposition of sandy sediment from the mound, morphological feedbacks between the mound and hydrodynamics, and factors limiting tracer studies for evaluation of long-term sediment transport processes. The sediment tracer study, combined with other monitoring components and numerical modeling are leading to improved design of nearshore placement methods in the coastal environment.

Keywords: Dredging, beneficial uses, Brunswick, sediment transport, numerical analysis.

INTRODUCTION

Nearshore placement of sand dredged from coastal navigation channels is a continuing and growing interest for coastal zone managers, scientists, and coastal residents. In the U.S., sandy sediments dredged from navigation channels have been historically placed in offshore placement sites as a least cost alternative. It is widely recognized that this practice potentially produces negative impacts (erosion) to downdrift beaches (Bruun, 1996; Dean and Dalrymple 2002). The magnitude of such impacts likely varies with site conditions and is frequently a subject of debate. Fortunately, the long-standing practice of placing sandy dredged material offshore as the least-cost, project-specific alternative is being replaced with a more holistic, regional sediment management approach that frequently calls for placement of dredged material in the nearshore environment.

Bypassing of sandy sediments from coastal inlet navigation channels may be accomplished through a variety of methods, including direct placement of sand on beaches and placement in subaqueous sites within the littoral zone. In many situations, subaqueous placement can reduce costs of dredging operations or is warranted because the dredged sediments have sufficiently large fine sediment content to be considered unsuitable for direct beach placement. Generally, effectiveness of subaqueous, nearshore placement in delivering sand to beaches decreases with increasing distance from shore. Therefore, understanding is sought in the physical processes of sediment transport from nearshore placed dredged material to best optimize subaqueous nearshore placement. Several studies

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have been conducted to monitor dredged material mounds in depths of 6-20 m (Hands and Allison, 1991; Bodge, 1994; Douglass, 1996), but few if any have monitored mounds in depths less than 6 m.

Nearshore Placement at Savannah and Brunswick, Georgia

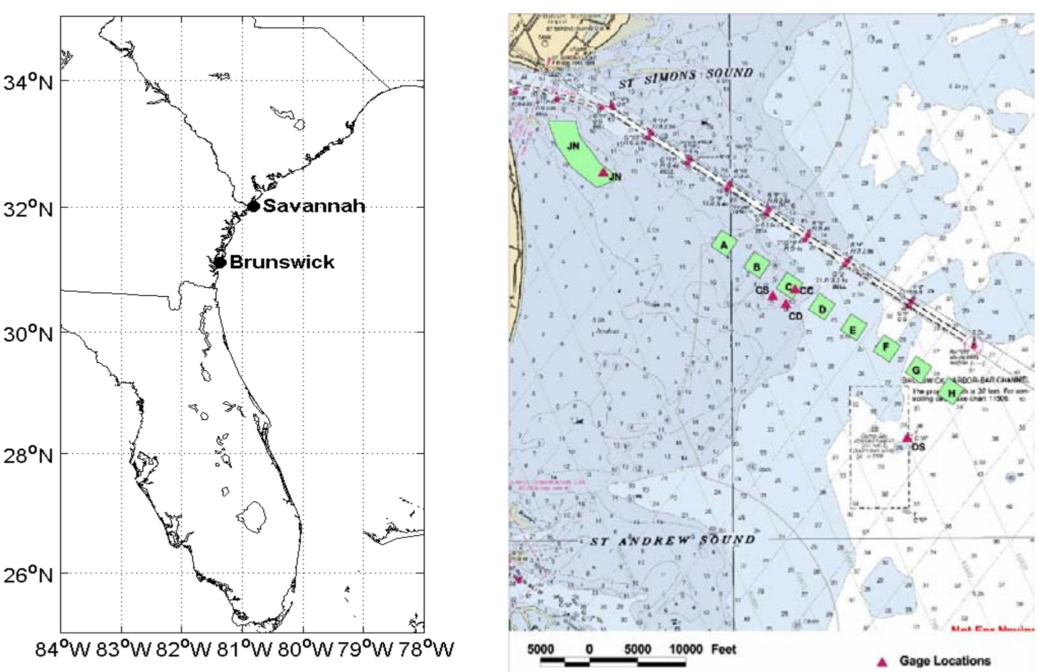
To return sand dredged from federal navigation channels near Savannah and Brunswick, Georgia (Figure 1A) to the littoral system, the U.S. Army Engineer District, Savannah had supported studies of nearshore placement practices at the two sites. At Brunswick, Savannah District gained regulatory approval for nearshore placement in nine channel-adjacent sites (Figure 1B) and began placement in late 2000. Savannah District proposes similar nearshore placement for the Savannah River channel, but seeks better understanding of sediment behavior in these environments to identify the best placement locations and practices.

With planned dredging and nearshore placement activities at the Brunswick Bar Channel in the fall of 2002, Savannah District utilized the opportunity to gather data for assessment the nearshore placement practices at Brunswick and improved understanding of proposed nearshore placement activities at the Savannah River Entrance Channel. Specific issues to be addressed by this study include:

1. Do sandy sediments in the dredged material re-enter the littoral zone and provide a benefit to adjacent barrier islands? If so, at what timescale are the benefits realized?
2. Does nearshore placement of dredged material cause significant deposition of fine-grained sediments in the nearshore region?
3. Will nearshore placement result in a significant increase in maintenance dredging requirements through rehandling of sediments placed near the channel?

The study of sediment and hydrodynamic processes at Brunswick was extensive and comprehensive covering a one-year period following placement of dredged material. Data collected include: hydrodynamic and wave conditions at five locations, high-resolution bathymetry, extensive collection of sediment samples (both surface and cores), and deployment and sampling of physical sediment tracer.

The conclusions of this study will assist Savannah District in developing a Dredged Material Management Plan (DMMP) for the Brunswick Harbor and Savannah Harbor and River Federal Navigation channels and will assist the district in developing methods for utilizing dredged material beneficially within the context of a Regional Sediment Management (RSM) plans for the coast of Georgia.



(A) (B)

Figure 1. (A) Southeastern coast of U.S. with location of Savannah and Brunswick navigation channels indicated. (B) Channel-adjacent nearshore placement sites at Brunswick, Georgia.

This paper's objectives include assessment of quantitative and qualitative analyses of the tracer study directed towards addressing nearshore placement at Brunswick and similar shallow-water environments. Tracer deployment, sampling, and analysis are presented in the methods section, followed by presentation of results, discussion of the results, and conclusions.

METHODS

A key component of the nearshore placement study at Brunswick involved the deployment, sampling, and analysis of physical tracer at two nearshore placement sites adjacent to the Brunswick navigation channel. In this section, general descriptions of tracer deployment and sampling are given as background information, but the focus is description of analytical techniques applied to the sampled tracer.

Tracer Deployment

Tracer deployment includes such tasks as selecting the characteristics and quantities of tracer to be deployed, selecting appropriate locations for tracer seeding, and developing appropriate deployment methods. Sediment tracing methods have long been used to evaluate the mobilization and transport of sediments. Traditional methods have included the use of coated particles, radionuclides, sediment mineralogy, among others. Recent developments in sediment tracer methods include the application of fluorescent plastics manufactured at sediment densities and mechanically ground to represent specific native particle distributions (Marsh, 2001). As multiple sediment types and seeding locations were to be assessed in the study, fluorescent tracers were selected as a convenient and appropriate tracing technology. By manufacturing tracer particles with distinct fluorescent wavelengths, each tracer seeding location and sediment type is identified in subsequent laboratory sample analysis.

Site Selection

Ambient depths of nearshore placement sites at Brunswick range between 1 and 10 m Mean Lower Low Water (MLLW). Additionally, the dominant hydrodynamics (and sediment transport forcing) cover a wide range of conditions. With increasing distance from the inlet between Jekyll and St. Simons Islands, tidal currents generally decrease. Additionally, wave breaking occurs rarely at the offshore sites, with much higher frequency along the outer margins of the ebb shoal, and with much lower frequency and intensity at protected locations in the interior of the ebb shoal. Consequently, Site JN is characterized by flood-dominant currents with relatively small waves, Site C is characterized by ebb-dominant tidal currents with frequent wave breaking, and Site H is characterized by weak tidal currents, and bottom stresses from non-breaking waves. As deeper-water sites were of less interest for this study, Sites C and JN, were selected to cover the range of wave/current conditions in the energetic nearshore environment.

Tracer Characteristics and Quantities

The manufacturing process for the tracer deployed in this study involves production of plastic pellets impregnated with fluorescent dyes (to distinguish particles during laboratory analysis) and heavy mineral content (to control particle density). The plastic pellets are then ground to a specified target size and sieved if necessary to remove particles outside the specified size range.

As two seeding locations (Sites C and JN) and two sediment types (sand and silt) were selected for this study, four fluorescent colors were manufactured for deployment. Two sediment size classes, fine to medium sand and silt, were sought for this study. Sand tracer was ground to a size distribution with median diameter, d_{50} of approximately 250 μm and minimum and maximum sizes of 100 and 550 μm. Silt tracer was produced with a target median diameter of 50 μm and size limits of 10 to 100 μm. Target particle density was to match that of quartz, 2.65 g cm^{-3}. The resulting characteristics of the four tracer particles manufactured are presented in Table 1. Based on the long duration of tracer sampling (up to one year), the energetic nearshore environment, and associated uncertainties, 500 kg of each silt tracer and 1000 kg of each sand tracer were manufactured and deployed.

Deployment

Native sediments were collected from each deployment location and tracers were mixed at 1:1 dry weight tracer to sediment ratio. The sediment-tracer mixture was transferred in 13 to 15-kg batches to water soluble bags then released to fall through the water column and deposit on the bed. The soluble bags dissolve in 60-90 seconds, leaving the sediment-tracer mixture on the surface of the seabed. Deployment occurred 31 January 2003 at Site JN with the tracer placed on a low, broad remnant feature from the nearshore placement in 2000. On 5 February 2003

Table 1. Characteristics of manufactured tracers.

Sediment Type	Deployment Location	Color	Tracer Density, (g cm^{-3})	d_{50} (µm)	Mass (kg)	Particles Released	Average Particle Mass (g)
Sand	Site C	Violet	2.72	240	1000	8.27×10^{10}	1.2×10^{-5}
Sand	Site JN	Magenta	2.71	270	1000	7.83×10^{10}	1.3×10^{-5}
Silt	Site C	Yellow	2.62	65	500	6.26×10^{14}	8.0×10^{-10}
Silt	Site JN	UV Blue	2.64	45	500	1.28×10^{15}	4.0×10^{-10}

tracer was placed at Site C on the shoreward crest of the torus-shaped mound completed in January 2003. Placement of the tracer was localized and for both sites all tracer was placed within a 12-m radius.

Sampling and Laboratory Analysis

Immediately following tracer deployment, surface samples were collected from surrounding areas, indicating no inadvertent tracer dispersal during deployment. Subsequently, surface grab samples were collected 17-20 February and 3-5 April. These surface samples indicated few positive counts of tracer. Subsequently, sediment coring was performed to sample sediment tracer that presumably had been buried. On 23-25 June collection of 7 vibracores and 112 pushcores indicated that much of the Site C sand tracer had been buried along the margins of the mound. A final coring campaign during 25-29 August 2003, in which 338 pushcores were collected, provided the most comprehensive view of tracer movement and deposition and is the subject of the analysis presented in this paper.

Laboratory analysis of the sediment cores was undertaken by first cutting the cores into sections according to visible tracer or sedimentological boundaries. The sections were then weighed prior to drying and analyzed by fluorescent microscopy and magnifying UV lamp to determine tracer counts per dry weight of sediment-tracer sample. Ten percent of the samples were selected at random for replicate analysis and were compared for consistency.

Analysis of Results

Scientific analysis of results was performed to extract information related to the movement of dredged material from the two tracer deployment sites. The analysis included both quantitative and qualitative measures of tracer transport. Specific analyses include: tracer mass conservation assessment, distribution and migration of tracers sampled, and tracer burial.

Average Mass of Tracer Particles

The quantitative assessments presented in this analysis attempt to verify mass conservation and determine migration of the sediment tracers deployed at Sites C and JN. Laboratory analysis of sediment samples during this study quantify the number of tracer particles detected in a given mass of sediment. To convert the count concentration to mass concentration, mean tracer particle mass was estimated by passing a subsample of tracer material with known mass through a particle counter and dividing the subsample mass by number of particles counted. The estimated number of particles deployed and mean mass of tracer particles ($\overline{m_p}$) are given in Table 1.

Note that the mean particle masses presented in Table 1 do not imply that all particles or even most particles have the assigned mean mass. Assuming spherical particles (particle mass increases with d^3) suggests that doubling particle size increases particle mass by a factor of 8. For example, violet sand tracer has mean particle mass of 1.2×10^{-5} g particle^{-1}. The size distribution in Figure 2 indicates that the size range of violet tracer is approximately 100-500 µm, which results in an estimated range of particle masses between 1.4×10^{-6} and 1.8×10^{-4} g particle^{-1}, indicating that the coarsest particles have 125 times more mass than the smallest particles. Subsequent analyses inherently assume that segregation of particles during transport is negligible and distribution of tracer particle sizes within any sample is similar to the deployed size distribution. These assumptions are questionable considering numerical tracer modeling at Brunswick (Gailani and Lackey, 2007), general observations of particle sorting in coastal environments, and results presented later in this paper.

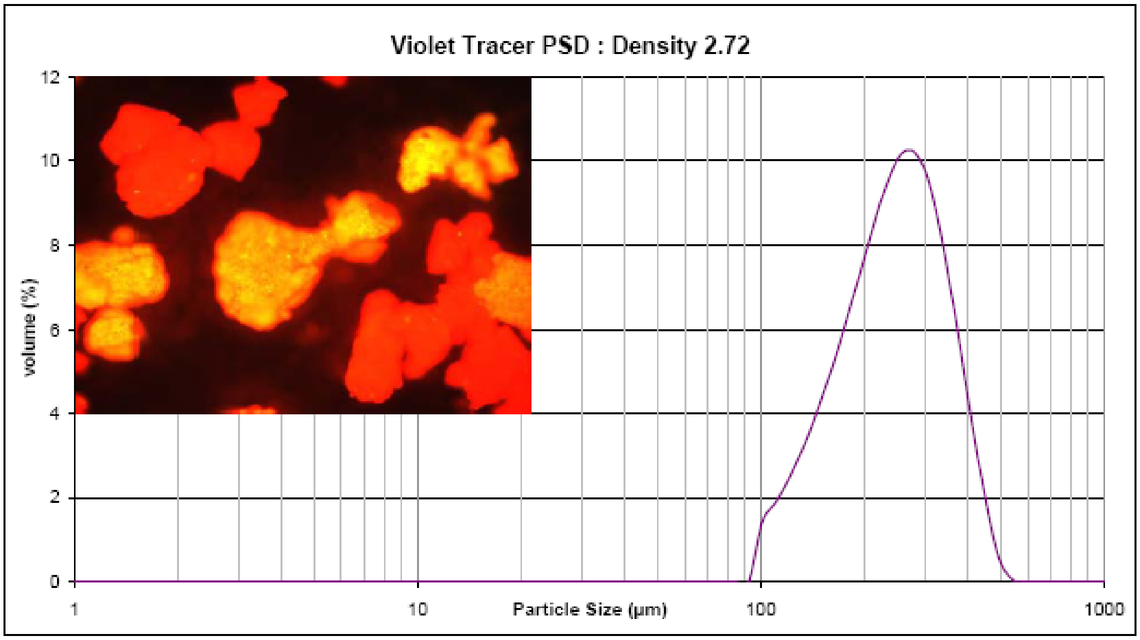


Figure 2. Grain-size distribution and fluorescent micrograph of violet tracer particles.

Mass Conservation

A fundamental check in quantitative tracer analysis is conservation of either particles or mass. As the interest here is mass transport, the approach described here will focus on mass conservation using the previously estimated mean particle masses for each tracer. Adequacy of the sampling density and distribution is verified by comparing the mass of tracer inferred from post-placement sampling to the mass of tracer deployed. For the sampled distribution to adequately represent the true distribution of tracer material, mass inferred from post-placement sampling must nearly equal mass introduced during deployment. The mass-conservation analysis is a necessary but insufficient check on the adequacy of the sampling distribution, as a few strategically placed samples could result in a favorable mass-conservation check, while misrepresenting the true distribution of the tracer.

The data resulting from the sampling campaign is composed of geo-referenced sediment coring positions and tracer counts from core subsamples positioned by depth from the sediment-water interface. To estimate total tracer mass from these discrete samples, vertical and horizontal integration of the sampled quantities is performed. The data are integrated first vertically, then horizontally to produce the total mass estimate.

As previously stated, each core was vertically subsampled resulting in a vertical distribution of tracer counts as shown in Figure 3. (Note: in some locations such as those presented in Figure 3, replicate cores were taken.) In most cases, the first subsampled position in a core was 10-15 cm below the core surface. The following expression was used to integrate and convert the tracer count concentration to mass per unit area (horizontal) of sediment bed:

$$C_z = \overline{m}_p \, \rho_s \, (1-n) \int_0^h C(z) \, dz \tag{1}$$

where C_z = mass of tracer per unit area, $\overline{m}_p$ = mean tracer particle, ρ_s = density of sediment (2.65 g cm^{-3}), n = bed porosity (typical value for sandy bed is 0.4), h = depth of core, and C = count concentration of tracer (particles per gram dry sediment). The expression ρ_s *(1-n)* represents the conversion of bed volume to dry sediment mass.

Following vertical integration, horizontal integration is performed by multiplying the result of (1) by the representative area, A, of each core, such that the total tracer mass inferred from the samples is:

$$M = \sum_{i=1}^{K} A_i \, C_{zi} \tag{2}$$

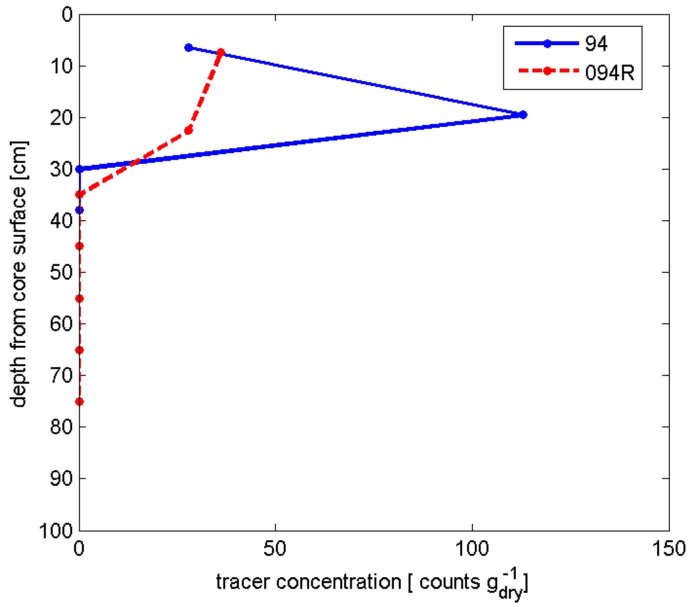


Figure 3. Vertical distribution of tracer counts from JN core 94 (and its replicate core 94R).

where representative area, A_i, for each core is determined from the distribution of pushcore locations. First, a convex hull and triangulated network are developed for the distribution of points. Then Voronoi polygons (or Thiessen polygons) are developed to represent the region of influence for each sample. (Voronoi polygons bound the region for which a particular core is closer than any other core. In other words, the polygon edges define points equidistant from two adjacent cores.) The area of each Voronoi polygon is the area of influence applied in (2).

Centroid of Mass

Displacement of the mass centroid of the tracer is a way of quantifying tracer movement over a given period of time. The centroid of tracer mass is computed by principles of first moments:

$$x_c = \frac{\sum_{i=1}^{K} A_i C_{z\,i} x_i}{\sum_{i=1}^{K} A_i C_{z\,i}} \tag{3}$$

where x_i = position of core i and the summations are performed over all cores. The centroid position, y_c, is performed similarly, with substitution of y_i for x_i in (3).

RESULTS

Analysis of the data resulting from the 25-29 August 2003 pushcore samples was performed by the methods outlined in the previous section. Figures 4 and 5 present vertically integrated sand tracer count concentrations from each of the core samples collected at Sites C and JN. Note that the horizontal scales in the two figures are different to cover the range of sample positions at each site. Bathymetric contours in the two figures are from a February 2003 survey, and contours are indicated in 0.25-m intervals with darker shading indicating deeper depths.

Patterns of sediment tracer distribution are noticeably different at the two sites. Site C is characterized by locally high tracer concentrations along the margins of the mound with low or zero concentrations in many adjacent samples. Additionally, tracer counts were largest deeper in the cores sampled, with much of the tracer material buried by 15-30 cm of tracer-free sediment as shown in vertical distributions of sediment tracer presented in Figure 6. The horizontal and vertical distributions of tracer at Site C suggest that the violet sand tracer recovered was transported from the deployment location (indicated by * in Figure 4) on the mound crest, deposited along the deeper margins of the mound, and subsequently buried by additional sediment transported from the mound crest.

Tracer deposition patterns from samples collected at Site JN are distributed in a more regular pattern. Highest tracer concentrations are grouped in a central zone, with tracer concentrations generally decreasing radially in all directions to zones of low or zero concentration. Figure 7 presents vertical distributions of tracer concentration for a subset of six cores taken longitudinally through the deposit indicated in Figure 5. Like the tracer at Site C, tracer was buried (up to 30-cm depth) in the cores, but unlike Site C, tracer particles were generally detected in the near-surface sections of the core. In one instance (Core 80) the lowest section in the core indicates high counts of tracer, therefore the tracer deposit is not fully quantified. This was a rare occurrence in the dataset for both Site C and JN. The horizontal and vertical distribution patterns at Site JN suggest that the magenta sand tracer was transported from the deployment location (* in Figure 5), mixed with transporting native sediments, and deposited in slightly deeper water in the flood-current direction 10-100 m away from the deployment location. The depth of tracer burial suggests that the locations where tracer was found is net depositional and is characterized by a significant degree of bed mixing or that the tracer was transported there by a gradual process, perhaps by alternating ebb and flood currents.

Mass Conservation

Mass conservation of sand tracer was estimated from the distribution of vertically integrated tracer counts presented in Figures 4 and 5 by the previously described mass integration method. Voronoi polygons were developed for each sampling distribution and are indicated in Figures 4 and 5 by yellow lines. Recall that the Voronoi polygons represent each sample's area for numerical integration. Notice in Figure 4 that three nodes have positive tracer counts, but no associated Voronoi polygon. For this situation, representative areas of adjacent cores were applied. Results of the mass conservation estimates are summarized in Table 2.

Table 2. Results of mass conservation estimates for sand tracer at Sites C and JN.

Site/tracer	Mass Deployed (kg)	Mass sampled (kg)	Percent Recovered
C / violet	1000	39	3.9 %
JN / magenta	1000	152	15 %

Both tracer deployment sites indicate relatively low tracer recovery near the dredged material mounds. This suggests that once sediment is eroded from the mounds, most of the sediment is transported outside the site boundaries. Site C is more exposed to wave energy than Site JN, which likely contributes to larger sediment transport rates and lower recovery of tracer material. In addition to the sampling locations indicated in Figures 4 and 5, 26 pushcores were collected along the navigation channel, Jekyll Island shoreface, and just inside the inlet between Jekyll and St. Simons Islands. Only one sample indicated recovery of violet sand tracer (from Site C) at very low concentration just inside the inlet. Gailani and Lackey (2007) performed numerical modeling of the tracer releases at Sites C and JN which suggest possible fate of the tracer material unaccounted for in the mass conservation assessment.

Site C

It is worthwhile at this point to further explore the tracer data from the 25-29 August 2003 surveys. Apparent from the distribution of tracer concentration in Figure 4, the tracer was transported from the mound crest and a small portion of this tracer deposited locally along the inner and outer flanks of the mound. With exception of one core, no tracer was found along the mound crest, where the tracer was initially deployed. Also noted in Figure 4 is the large variation in tracer concentration between sample locations, suggestive of large horizontal gradients in tracer content near the depositional area.

Figure 6 shows vertical tracer concentration profiles from four core locations along the southeastern margin of the mound at Site C. From these profiles it is evident that much of the tracer is buried between 30-70 cm below the sediment surface, with increasing concentration in cores 444 and 345. In fact, core 345 represents nearly 80 percent of the estimated tracer mass recovered at Site C. The vertical concentration profiles have one (or at most two) sub-sections with significantly higher concentration than the bounding sediments. This suggests that the tracer was deposited in a relatively thin horizon and buried by tracer-free sediment. In this example, it is clear that the horizontal sampling intervals are inadequate (from a numerical perspective) to assess mass conservation with a high degree of certainty.

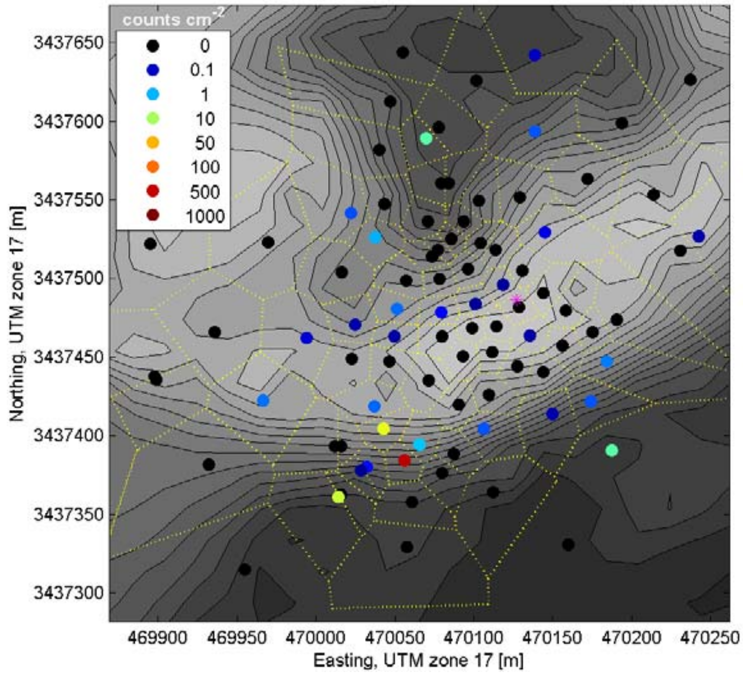


Figure 4. Locations of pushcore collection at Site C and associated vertically integrated tracer count density. Voronoi polygons are indicated by yellow lines. Tracer deployment location is indicated by the magenta (*). Bathymetric contours (0.25 m intervals) are from a February 2003 survey.

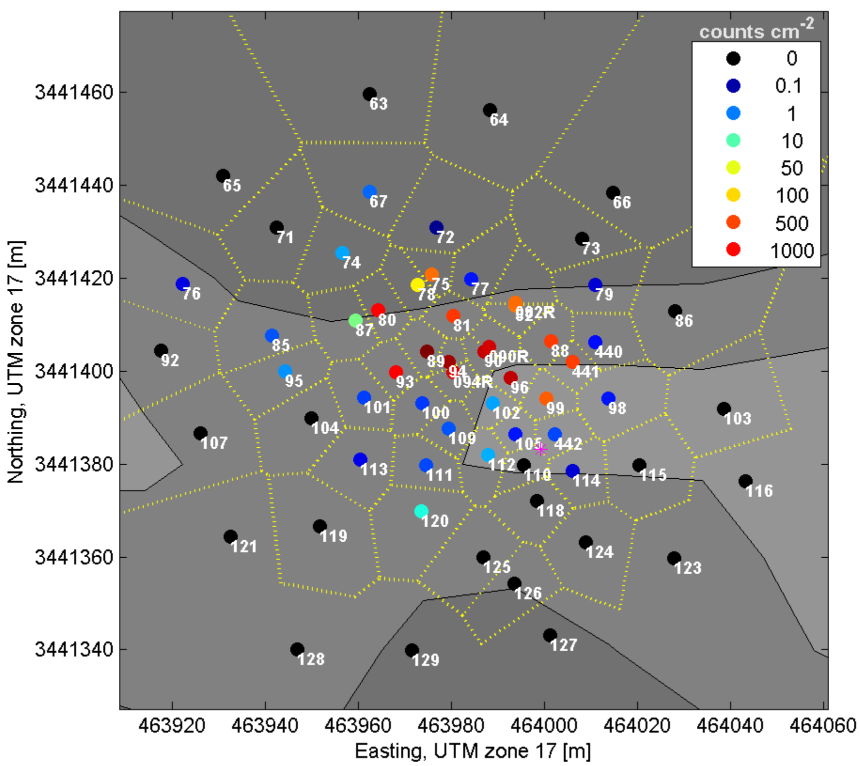


Figure 5. Locations of pushcore collection at Site JN and associated vertically integrated tracer count density. Voronoi polygons are indicated by yellow lines. Numeric labels indicate core number. Tracer deployment location is indicated by the magenta (*). Bathymetric contours (0.25 m intervals) are from a February 2003 survey.

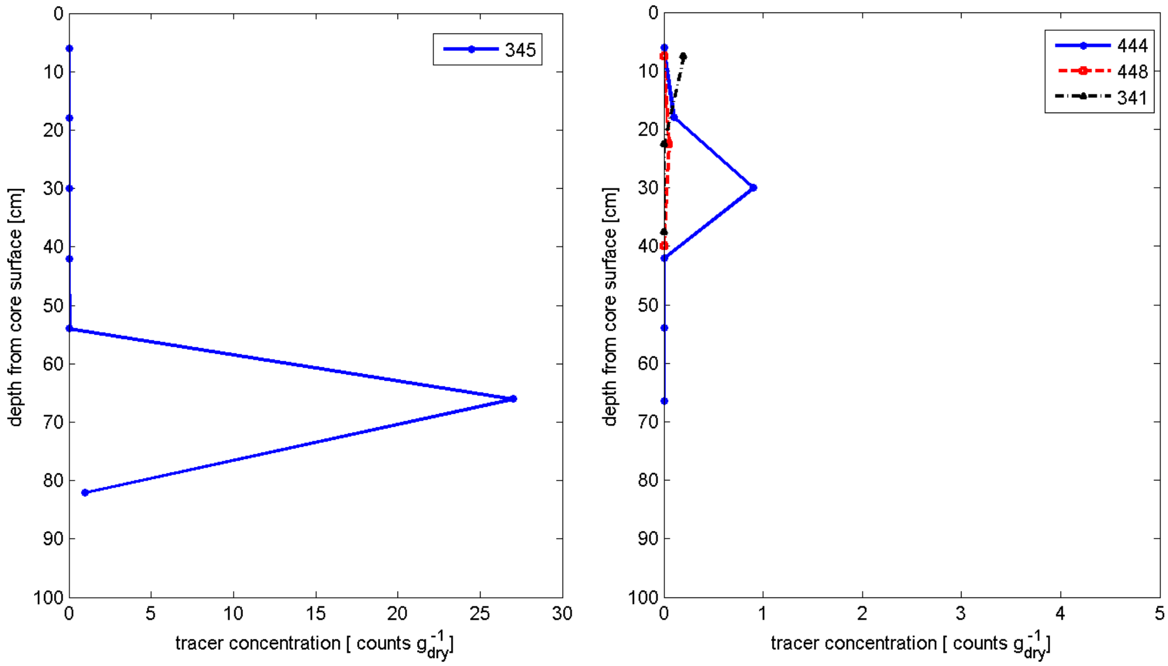


Figure 6. Selected vertical tracer concentration profiles from 25-29 August 2003 sampling campaign from the southeast margin of the mound at Site C.

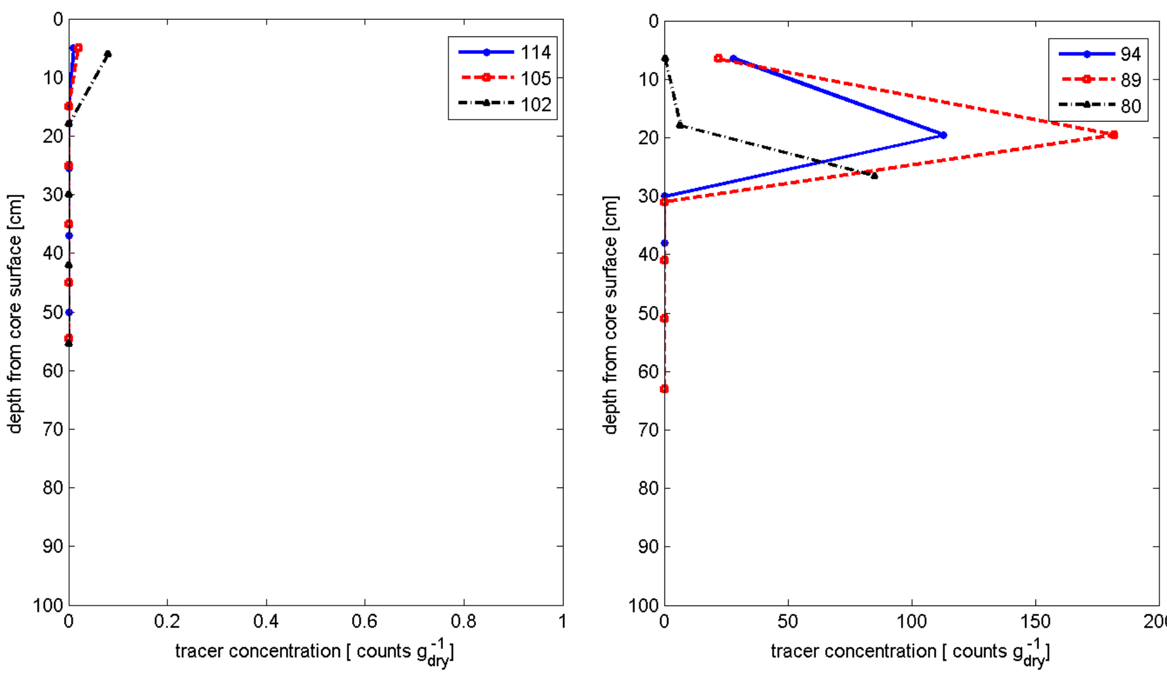


Figure 7. Selected vertical tracer concentration profiles from 25-29 August 2003 sampling campaign near Site JN.

While it is clear that the horizontal sampling resolution at Site C is inadequate for detailed quantitative analysis, it should be recognized that the sampling resolution is exceptionally high for field operations (on the order of 20-30 m spacing in the high sample density region). What should be appreciated here is the extreme level of effort (and expense) required to acquire quantitative estimates from tracer data in complex sedimentary environments such as the mound at Site C.

Site JN

Hydrodynamic and sedimentary environments at Site JN are significantly less complex than those of Site C. In Figure 5, it is seen that the deposition patterns and horizontal gradients of tracer concentrations are fairly well defined by a high-density of core samples (resolution on the order of 10-25 m). However, as the mass conservation exercise points out, only 15 percent of the tracer material deployed is accounted for in the sampling. The following discussion explores potential explanations for the missing tracer mass.

Sampling Resolution. Attention is first given to sampling resolution. At Site C, horizontal gradients in tracer distribution are large relative to the sampling resolution. Horizontal sampling resolution at Site JN is finer than that of Site C, and appears to describe relatively smooth variations in tracer concentration. Figure 7 presents vertical tracer distributions for a transect of cores in the apparent direction of tracer transport. Core 114 is southeast of the deployment location, and Cores 105, 102, 94, 89, and 80 are located progressively farther to the northwest from the sampling location. At Site JN, isolated pockets of extremely high tracer concentration would be required to explain the mass conservation deficit, and is not considered likely after evaluation of horizontal and vertical distribution of tracer in the samples.

Sampling Depth. If the cores collected were insufficiently deep, unsampled tracer would be neglected in mass integration of the data. There are a few “open” distributions, for which the bottom sample of the core has positive tracer counts (for instance Core 80 in Figure 7). Closing these distributions with hypothetical distributions of shape similar to other closed distributions, or replacing the distribution with the core with maximum tracer counts resulted in an increase of sampled mass by less than 1 percent. The other possibility, that additional tracer was buried deeper than the cores is unlikely. Many cores at JN were collected to a depth of 60-80 cm, and the deepest depth of tracer detection was approximately 50 cm (although at very low concentration). Additionally, the depth of sediment burial at Site JN should be much less than for the mound at Site C, given the lower wave energy and lower bathymetric relief at Site JN. Insufficient coring depth is not likely to explain the large discrepancy in mass conservation.

Transport Outside Sampling Zone. One obvious explanation of the mass deficit in the sampled tracer is transport of a portion of the tracer material beyond the boundaries of tracer sampling. At first glance, the sampled area shows a distinct region of tracer deposition, surrounded by zones of no tracer deposition, suggesting complete accounting of the tracer. However, consider the fact that the JN samples were removed from the lee (referenced to the flood-dominant hydrodynamics at JN) of relict dredged material mounds (see Figures 1 and 5). If this area is a localized area of deposition within an erosional zone, then some tracer could be deposited in the localized depositional area, while the remainder would be transported further from the site, and not be deposited until the next depositional area is encountered. Numerical sediment transport modeling conducted as part of the broader Brunswick nearshore placement study (Smith et al., in prep) indicates that sediment transport at Site JN is flood dominant (like the tidal currents there) and located within a broader area of divergent transport, characteristic of net erosional areas. In this scenario, it is plausible that the tracer not deposited in the local depositional area indicated in Figure 5 was transported farther to the northwest, toward the inlet and navigation channel. Numerical particle tracking modeling (Gailani and Lackey, 2007) suggests transport of tracer from Site JN into the channel near the inlet.

Winnowing Effect. Winnowing describes the preferential transport of material by size or density. If the fine portion of the tracer size distribution were transported away from the deployment site, leaving a coarser fraction to deposit nearby, the estimated mean particle mass would be inappropriately applied in mass conservation estimates. For this explanation to hold, 85 percent of the tracer particles would have been transported from the sampling area, leaving behind 15 percent of the coarser particles in the distribution. From the size distribution of tracer particles, it was estimated that 15 percent of the released particles are larger than 230 μm. If all particles finer than 230 μm were transported out of the sampling area, the remaining coarser particles represent 15 percent of the particles but 65 percent of the tracer mass. (Note here the distinction between particle *number* and *mass*.) If in fact winnowing is the cause of the mass conservation deficit, 15 percent of the particles were deposited in the sampling area, but because the particles are larger and have greater mass, they represent 65 percent of the total tracer mass.

Winnowing is a plausible explanation of the mass conservation deficit. Interestingly, the sediment characterization sampling performed prior to tracer deployment indicates that sediments at the JN deployment site are significantly coarser than adjacent sediments, suggestive of a hydrodynamic environment that is conducive to sediment winnowing.

In summary, sand tracer mass is not conserved at Site JN. The most likely explanation for the non-conservative results is due to transport of tracer outside the sampling area. Additionally, winnowing may have played a role in further reducing the apparent tracer mass determined in the mass conservation analysis. If winnowing played a significant role in tracer transport, then up to 65 percent of the tracer mass may have been accounted in the tracer samples, instead of the 15 percent reported in Table 2.

Tracer Migration

With all concerns of mass conservation and adequate sampling resolution aside, there is information to be gained from the semi-quantitative and qualitative tracer movement evident in the tracer sampling data. At both sites, the fine sediment tracers (yellow and uv blue) were observed to be separated from the sandy tracers (violet and magenta) and fairly rapidly transported from the deployment site and study area. The remaining sand tracers were observed to be transported from the active transport areas of deployment and at least partially trapped in nearby depositional environments.

At Site C, the violet tracer was transported from the mound crest to the seaward and landward flanks of the mound and transported primarily to the southwest along the mound flanks and buried to depths up to 60 cm in depositional areas on the south and southeastern margins of the dredged material mound. This migration and deposition pattern is consistent with morphological migration of the mound feature, where feedbacks between the hydrodynamics and the mound result in some degree of preservation of the mound as a morphological feature. The net migration of the tracer material seems to be to the southwest, which is confirmed through computation of the change in tracer mass centroid (3) by (-71 m,-102 m) which is 124 m with bearing 215º (approximately SW).

At Site JN, magenta tracer was transported to the northwest from the deployment position (near a relict mound crest) to a nearby depositional area as shown in Figure 5. Tracer in this depositional area was mixed to a depth of 20-30 cm, but unlike Site C, tracer was found (at lower concentrations) in the surface sections of the cores. The depositional pattern for the tracer sampled at JN is much less complex than that of the mound at Site C. The smoother depositional patterns at JN and the lower relief of the relict mounds at JN suggest that the morphological feedbacks between the mounds and hydrodynamics are less significant than at Site C. The tracer mass centroid displacement at Site JN was (-16 m, 20 m) from the deployment location or 26 m at a bearing of 322 (approximately NW). As described in the mass conservation discussion, this net movement only applies to the sampled tracer; the movement of the remaining 85 percent of magenta tracer particles is unknown.

DISCUSSION

As shown in the previous section, challenges were encountered in quantifying mass conservation. Site C was characterized by complex depositional patterns with thin lenses of tracer material deposited along the margins of the morphological features of the dredged material mound. Although tracer sampling was extremely dense by field data collection standards, the sampling density was inadequate to quantify mass conservation from a numerical analysis perspective.

Although sampling resolution was high and deposition patterns were much less complex at Site JN, only 15 percent of the deployed tracer particles were represented by samples. Speculation on the potential causes in the discrepancy between deployed and sampled tracer quantities led to a conclusion that tracer must have been transported outside the sampling region. Additionally, winnowing may have played a role in further reducing the apparent mass accounted in the mass conservation estimate. If winnowing occurred during transport of tracer from the deployment to sampling locations (and beyond), up to 65 percent of the tracer mass may have been accounted for in the samples. While it is often difficult to anticipate the transport pathways and ultimate fate of tracer prior to sampling, numerical modeling of a site prior to tracer deployment and sampling may offer insights into depositional areas for sampling plans. Gailani and Lackey (2007) present numerical discrete-particle Lagrangian modeling of the tracer deployment described in this paper. The results of this modeling suggest that the finer portion of sand tracer particles released at Site JN may have been initially transported to the navigation channel side slopes and either buried there or subsequently transported seaward along the channel margins. Unfortunately this modeling was performed after tracer deployment and sampling were complete and was not available during development of sampling schemes.

Additionally, combined tracer particle detection, size, and shape analysis in the laboratory procedures would allow better estimates of tracer particle mass sampled. By associating particle size and shape with particle detection in the laboratory analysis, tracer mass in the mass conservation and centroid movement calculations is improved. Had this been done in the present study, more information regarding the role of winnowing at Sites C and JN would have been possible.

Centroid movement analysis is a potentially powerful way of determining net displacement and direction of transport. Additionally, if sufficient information is available, sediment transport rates may be estimated (Komar and Inman, 1970, Kraus et al., 1983), however this use of tracer in this type of application is likely limited to short-duration deployments in relatively simple geomorphological settings. Centroid-movement assessment of sediment tracer data requires that the mass conservation check be satisfied. If the mass conservation check is not satisfied, but sampling resolution is adequate (as the case for Site JN), a centroid movement assessment may be made for the sampled tracer only, obviously not for the missing tracer.

None-the-less, visual inspection and quantified movement of sampled tracer yielded useful information at both Sites C and JN. Net movement of tracer at Site C was found to be to the southwest, away from the navigation channel. Net movement of the sampled tracer from Site JN was found to be towards the northwest, towards the inlet and navigation channel. In combination with numerical model results (Gailani and Lackey, 2007), the tracer results suggest that Savannah District may choose to favor placement in Sites A-D over Site JN if interest is in keeping sediment in the littoral environment while reducing channel infilling.

Despite several shortcomings in quantitative assessment of the tracer data at this site, much can be gained through qualitative assessment of the results. In the comprehensive study of dredged material placement at Brunswick (Smith et al., in prep), many lines of evidence were used to reach conclusions related to placement locations and practices at the site including: analysis of sediment cores, tracer data, long-term monitoring of waves and currents, suspended sediment sampling, high-resolution bathymetric sampling, and numerical modeling. Although none of these methods provides a complete understanding of the dynamics of sediment transport in nearshore environments, each lends a perspective into the site characteristics. When multiple lines of evidence suggest similar results, confidence is gained in the conclusions. Related to the objectives of the nearshore placement study, the following conclusions were reached:

1. Fine sediments (and tracers) were found to winnow rapidly from the eroded dredged material. Laboratory erosion experiments of sediments from the Savannah River entrance channel suggested that upon erosion nearly all of the fine-grained sediments were separated from sandy sediments and transported in suspension. Further monitoring of dredged material placed at Brunswick (of similar mineralogical composition with fewer fines) confirmed this in the field. Sediments sampled from the margins of Site C were found to have much lower fine-sediment content. Additionally, water column samples collected immediately following tracer deployment indicated silt tracer being transported in suspension.

2. Fine sediments were not found to deposit permanently in the inner shelf environment. In the weeks following tracer deployment, silt tracer was found in isolated surface grab samples in the nearshore environment, but was not found in subsequent surveys. Similarly, numerical modeling of sediment at Sites C and JN (Gailani and Lackey, 2007) indicated that once silt-sized sediments were eroded from the mound crest that they were transported rapidly in suspension, intermittently deposited on the inner shelf, and were subsequently transported to deeper waters or through the inlet into intertidal marshes.

3. Sandy sediments were found to transport much shorter distances than that of the fine-grained sediments and remained in the shallow, nearshore environment. High-resolution, periodic bathymetric surveys at Site C indicated, similar to the tracer experiments, erosion of sediments from the mound crest and deposition along the southern and southeastern margins of the mound. Numerical model simulations (Gailani and Lackey, 2007) also indicate consistent directions of sand transport with the tracer study. At Site JN, numerical simulations of tracer introduced at Site JN suggest that finer sand tracer particles are transported to the northwest and likely entered the channel northwest of the site (supporting the winnowing hypothesis from the tracer study). Simulations of sand tracer at Site C suggest that eventually fine sand tracer becomes widely dispersed to the southwest over the shallow inner shelf and coarser sandy sediments are deposited much closer to the mound, but outside the site boundaries in a flood channel south of Site C.

CONCLUSIONS

Quantitative analysis of sediment tracers placed in the energetic nearshore environment requires careful planning, execution, and analysis. Sediment tracer data collected in the complex environment of an annular-shaped dredged material mound was found to introduce complexities that limited detailed quantitative analysis. Results from a less complex transport environment indicated that approximately 15 percent of the tracer particles remained within the sampling area. Recommendations to improve the quantitative potential of future sediment tracer studies include (1) numerical modeling of the tracer application prior to deployment and sampling and (2) addition of tracer size measurements to the laboratory analysis of samples.

Qualitative and limited quantitative analysis of the tracer indicated primary transport directions of sediment from the dredged material placement sites. When combined with other lines of evidence, consistent conclusions were reached regarding separation of fine-grained sediments and sand, primary directions of sediment transport from the sites, and initial fate of sandy sediments. Additionally, tracer data provided information not obtained by other means such as mixing depth and burial of sediments transported from the site, possible winnowing processes of sandy sediments at Site JN, and transport mechanism and fate of fine sediments eroded from the dredged material placement sites.

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ACKNOWLEDGEMENTS

The research presented in this paper was conducted with funding provided by the U.S. Army Engineer District, Savannah and the Dredging Operations and Environmental Research Program. Evans-Hamilton Inc. and Environmental Tracing Systems, Ltd. are acknowledged for their diligent efforts in field data collection, tracer deployment, sampling, and laboratory analysis. Permission to publish this paper was granted by the Office, Chief of Engineers, U.S. Army Corps of Engineers.

NOMENCLATURE

A	Representative area associated with each sediment core
C	Tracer count concentration (number of particles per gram dry sediment mixture)
C_z	Vertically integrated tracer concentration (tracer counts per unit area)
d	Nominal sediment diameter
d_{50}	Median sediment diameter from particle size distribution
d_{50}	Median sediment diameter for discrete range of particle sizes
h	Length of core
M	Mass of tracer sample
$\bar{m}_p$	Mean particle mass
n	Bed porosity, ratio of pore volume to total volume
x,y,z	Cartesian coordinates
x_c, y_c	Centroid positions of tracer mass
ρ_s	Native sediment mineral density
ρ_t	Tracer material density