UTILIZING SEDIMENT TRACER STUDIES TO EVALAUTE TRANSPORT PATHWAYS AT THE MOUTH OF THE COLUMBIA RIVER, USA

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Abstract: During 2006 to 2009, two sediment tracer studies were implemented at the mouth of the Columbia River (MCR) to improve our understanding of littoral sediment transport pathways along the ocean margins of the inlet. Science-based data from these tracer studies is being integrated with other analysis methods to evaluate if dredged material can be preferentially placed within the coastal near shore to augment the sediment budget of the inlet and adjacent coastal margin. This paper summarizes the MCR tracer study methodology and results, with specific emphasis of how the general limitations for tracer studies were addressed and overcome. Results from these studies conclusively show that tracer particles released along the coastal margin of the MCR (at water depth of 13-14 meters) were transported into the active littoral zone of Oregon and Washington, with tracer deposition occurring on beaches. The results indicate that the sand-sized sediment at MCR is dispersed differently along the northern side of the inlet as compared to the southern side.

Introduction and Study Motivation

The Mouth of the Columbia River (MCR) is located on the Pacific Northwest Coast of the USA, at Long-Lat 124W-45 N, between the states of Oregon and Washington (figure 1). Vigorous wave-current interaction at the MCR inlet is motivated by the confluence of large ocean waves interacting with a prominent & spatially variable ebb-tidal delta, a 2.5 meter estuarine tidal range, and the riverine flow regime of the Columbia River; making the MCR inlet one of the most energetic and dangerous coastal inlets in the world. Littoral sediment transport rates near the MCR are expressed in terms of millions of cubic meters per year and can be highly variable in space and time. The adjacent coastal margins north and south of the MCR have been accreting in a spatially-variable manner for many decades, in response to jetty construction during 1885-1939. However, the post jetty construction accretion rate is slowing, and has reversed in several areas close to the MCR inlet leading to recession of the coastal zone over the foreseeable future. The morphology recession rate near the inlet appears to be increasing and the areal extent of shoreface recession is expanding. In additional to compromising the stability of the jetties and the MCR

inlet & navigation channel, progressive loss of shoreface morphology degrades the benthic substrate for nearshore ecology. Regional sediment management (RSM) is being implemented at MCR to maximize the beneficial use of dredged sediment to sustain the littoral budget of the inlet and adjacent coastal zone.

Approximately 3 million cubic meters of sand per year is dredged at the MCR by the US Army Corps of Engineers to maintain the deep-draft federal navigation channel though the inlet. The dredged sand is placed within three permitted openwater sites (figure 1a). Approximately 55% of the dredged sand is placed within two nearshore sites, the Shallow Water site (SWS) and North Jetty site (NJS), which are believed to supplement the adjacent littoral budget. The term "nearshore" represents the coastal region within a water depth range of 12-19 meters. Although the two existing neashore placement sites are highly dispersive, these sites transport capacity limited: Overusing the nearshore sites can create a hazard to navigation though excessive mounding of placed dredged material. Approximately 45% of MCR dredged material (1.3 million cub meters per year) is placed within the Deepwater Site (DWS) which is located offshore of the inlet's littoral zone. Placing MCR dredged material within the DWS is a wasting operation and represents a lost opportunity for utilizing dredged sand to augment the littoral budget of MCR.

The primary RSM objective at MCR is to reduce or eliminate the amount of dredged sand presently being placed within the DWS, and instead, place this sediment resource within the nearshore area of MCR where it can augment the inlet's littoral sediment budget. Because existing permitted nearshore sites are capacity limited, additional dredged material placement site(s) are required to achieve the primary RSM objective at MCR. A secondary RSM opportunity is to verify and improve the littoral budget augmentation associated with existing nearshore sites. A holistic understanding of sediment transport pathways is required to achieve the above RSM objectives at an inlet where morphological response is non-symmetric in space and non-stationary in time. To meet this need, the Portland District Corps of Engineers has initiated two separate sediment tracer studies to identify littoral sediment transport pathways along the coastal margins of the MCR inlet. The first sediment tracer study was initiated in October 2006 and focused on assessing sediment transport pathways at the Shallow Water Site (SWS), an active ocean dredged material disposal site located along the north side of the MCR inlet. The second tracer study was implemented in October 2008 to investigate sediment transport pathways along the south side of the MCR inlet at the South Jetty Site (SJS), a proposed nearshore location for dredged material placement. The overall objective for both tracer studies was two-fold: A) Obtain the stand-along results from each tracer study to conceptually demonstrate sediment transport dispersion pathways to stakeholders and resource agencies, and B) Integrate the tracer study results with other types of analyses to improve methods of sediment transport estimation at MCR.

Tracer Study Objectives and Requirements

A sediment tracer study is a method to evaluate the in-situ dispersal patterns affecting a specific sediment type within a targeted area of interest. For the MCR studies, a specific mass of tracer particles were manufactured to mimic characteristics of sediment native to the study area; in terms of the sediment size gradation, density, hardness, shape, and fall speed within the water column (ETS 2007). The sediment tracer is deployed at a specific drop zone (DZ) and repeated sediment in-situ sampling is performed at the DZ and surrounding area to "track" the dispersal of the released tracer material. Because of the way the particles are manufactured and analyzed, it is possible to detect very low levels of tracer in each sediment sample (1 part per billion), enabling tracking of the tracer after significant "dispersion" by waves and currents. Analysis of the spatial and temporal distribution of recovered tracer indicates the spatial extent of tracer sediment transport during the data collection time-frame.

In both MCR tracer studies, the intent was to design and deploy a sediment tracer which would 'behave' in the same way (in terms of sediment transport) as the dredged material to be placed within the disposal sites, *after* the dredge material has reached the seabed. The tracer would be moved (or became suspended) by waves and currents in manner consistent with the dredged material in a post-disposal setting. The goal for these tracer studies was to provide direct identification of the transport pathways and evaluate if MCR dredged sediment placed at nearshore disposal sites (water depth 13 -15 meters) become part of the littoral budget.

Tracer studies can be perceived as unscientific endeavors that produce ambiguous results. This unsatisfactory result will be realized if three important considerations are not fully addressed: 1) The sediment tracer must properly emulate the sediment physics of interest, 2) A sufficient mass of tracer must be deployed to allow detection to far-field dispersion points, and 3) Proper post-deployment sampling must be performed to capture the dispersion of trace over time. Each of these elements has a direct bearing on study cost and performance (success vs. failure). The MCR tracer studies addressed the above considerations though detailed experimental design and execution protocols and considerable effort was given to optimize tracer study design prior to execution. Adaptive management was essential to realize study success during the post-tracer deployment phase. A complete description of the studies is available in contract study reports that were provided to US Army Corps of Engineers-Portland District (ETS-EHI 2007 and 2010).

Shallow Water Site (SWS) Tracer Study – North Side of MCR Inlet

The SWS is highly dispersive and has been actively used for dredged material placement since 1997. Approximately 25 million cubic meters of dredged sand have

been placed within the SWS during 1997-2009, with less than 2 million cubic meters of cumulative net deposition. The following question was to be addressed by deploying a sand-sized sediment tracer within the SWS: Does MCR dredged material placed at the SWS move northward onto Peacock Spit and ultimately onto Benson Beach, offshore toward deeper water, southward toward the MCR navigation channel, or inshore toward the interior of the MCR inlet?

South Jetty Site (SJS) Tracer Study–South Side of MCR Inlet

The SJS has not been used for operational placement of MCR dredged sand. However, this site is being proposed for active use. The goal of the SJS study was to evaluate how dredged material would behave after being placed within the SJS. The following questions were to be addressed by deploying two sand-sized particle tracers at two drop zones (DZ) within the SJS. If MCR dredged material was to be placed at the SJS (as emulated by the tracer placed at DZ-A and DZ-B), would the placed dredged material move shoreward and ultimately onto Clatsop Plains, offshore toward deeper water and possibly into the MCR inlet, southward, or northward toward the south jetty? Would the placed dredged material move preferentially in a cross-ore direction, or in a alongshore direction? Is there a tendency for sediment placed closer to the MCR south jetty to be transported offshore? During the intervening time period between tracer sampling events, what are the relative proportions of released tracer that would end up within each of the above general trending locations?

Procedure

The MCR sediment tracer studies were executed in 2 planning phases and 4 operational phases. First, the physical properties of the sediment of interest were identified. This data defined the specifications to create the sediment tracer. Second, the areal aspects of the site of interest, environmental forces that affect sediment transport at the site, and expected far-field sediment dispersion aspects were estimated. This data was used to define the location and method for tracer deployment, areal extent for post-deployment tracer sampling, the frequency of sampling events needed and sampling density for each event, and mass of tracer needed to be manufactured & deployed to satisfy detection limits over the expected dispersal area. Third, the tracer was manufactured according to the gradation, shape, & density of the MCR dredged material and shipped to the project site. Fourth, the tracer was prepped for deployment and placed at pre-determined release points within the drop zone (DZ). Fifth, a series of position-controlled sediment sampling events were performed periodically within and beyond the DZ to capture tracer as it is progressively dispersed within the project area. Tracer dispersal results from each sampling event describe the spatial aspects of the sediment tracer at a given point in time, integrated from the date of tracer deployment. The sixth and final step of the

tracer study procedure was to test each sediment sample for tracer content. Sample testing was performed subsequent to each sampling event, and results are used to inform the following sampling event.

The sediment tracer was manufactured to emulate sand-sized sediment dredged from the MCR navigation channel navigation. Although the sediment within the MCR is classified as fine-medium sand (average D50 = 0.2 mm), having less than 3% fines content, the modal grain size can vary by 40% throughout the entire 8 km-long x 0,7 km-wide channel. The specific gravity of MCR sediment varies from 2.70-2.75. Figure 2a shows the gradation range for MCR sediment and the achieved gradation for the sediment tracer. It is noted that 80% of the sand dredged at MCR has gradation which is finer than what is shown for the "inner" channel samples in figure 2a. The specific gravity for the sediment tracer material was 2.72. Fall velocity tests were performed on the tracer particles and the corresponding MCR sand to compare the tracer and sediment to ensure they behaved in a similar manner. The percentage difference of sediment grain fall speed between the two particle types was between 3–8%, which was not considered to be significant. The tracer material is synthetic, fluorescent-labeled, inert, durable/resistant to abrasion, and environmentally benign. Three "colors" of tracers were manufactured: magenta tracer was deployed at the SWS DZ, yellow tracer was deployed at the SJS DZ-A, and blue tracer was deployed at SJS DZ-B. The detection limit for this type of sediment tracer is 1 part per billion (1 sediment grain per kg of sampling mass) and each tracer color can be discriminated. Approximately 124,000 particles were contained within each per dry gram of manufactured tracer. For the SWS tracer, approximately 1.5 $x10^{11}$ magenta particles were contained within 1200 kg of tracer material. For each of the SJS tracers, approximately 4.4 $x10^{10}$ particles were contained within 350 kg of yellow and blue tracer material.

Prior to tracer deployment at water depth of ~13.5 m, the respective study area was sampled widely to determine if there was any background fluorescence that would interfere with tracer detection, and to verify native sediment size and density profiles. To deploy the tracer, it was mixed 1:1 with native sediment and placed in dissolving starch bags weighing ~ 20 kg each. Each bag of tracer:sediment mix was placed within a 50-75 m radius of the DZ, with the XY coordinate recorded for each bag release point via DGPS. The starch bags dissolved within 4 minutes of making contact with water. Within two days after deployment, the DZ was sampled widely to determine the initial distribution of tracer. Deployment of a magenta tracer at the SWS DZ occurred during 2-4 October 2006, ~1.5 km offshore of the MCR north jetty in water depth of 13 meters. Post-deployment sampling at the SWS occurred 2, 6, 12, and 35 months later. Two sediment tracers were deployed within the SJS during 22-24 October 2008 at DZs along the northern (DZ-A=yellow tracer) and south areas (DZ-B=blue tracer) of the SJS. Post-deployment sampling for the SJS tracers occurred 3

and 11 months later. Sampling can continue as long as detectable levels of tracer are recovered.

In-situ grab samples were obtained using a Shipek sampler having sample volume capacity of 3000 ml. In situ grab sample size (mass per gab) varied from 0.4 to 1.0 kg and penetration depth of the sampler was estimated to b 5-10 cm into the seabed. The XY coordinate for all collected grab samples was recorded via DGPS and each grab sample was assigned unique control numbers. All samples were prepped and shipped to the ETS ISO 9001 accredited laboratory in Scotland by EHI. Each sample was weighed and then examined for tracer particles on non-fluorescing paper using a magnifying fluorescent lamp. The total number of tracer particles (>0.125 mm) present in each sample was counted and expressed as tracer counts (particles) per 100 grams of dry sediment. Repeat analyses were performed to ensure tracer count reliability (ETS-EHI 2007 and 2010). Grain size analyses were performed (for a finite number of grab samples) for the recovered tracer particles using a fluorescence microscope (figure 2b).

The results for each tracer sampling event at time (t) were expressed as location of sediment sample (XY) and tracer concentration (counts/100 gram sample dry weight). Tracer results are being used in conjunction with morphology change assessments (differencing of bathymetry surveys) to correlate spatial variations in sediment transport with respect to the spatially variable morphology at the MCR inlet. Tracer studies are also providing invaluable geo-referenced data for verifying-calibrating computer model simulations for sediment transport at MCR (see the CS 2011 paper by Gelfenbaum et al). Other correlative uses of the MCR tracer studies are ongoing. The ultimate goal of our work is to improve understanding of the likely long-term consequences of management decisions on the sediment budget of the MCR inlet and the adjacent coastal margins.

SWS (Magenta) Tracer Study Results and Discussion

The SWS tracer results summarized in figures 3a-3c clearly show that the tracer particles released in SWS did move northward onto Peacock Spit and as far as Benson Beach (3 km) within 2 months (OCT06-DEC06). The northward migration of the magenta tracer continued over time with concentrations increasing into far-filed area and presence of tracer particles becoming more widespread up to Month 6 (figure 3d, integrating tracer movement during OCT06-MAY07). The fact the tracer was detected along the shoreface of Benson beach within 2 months of deployment is very interesting and supports that dredged sediment placed at the SWS is likely to nourish the beaches to the north along the Washington coastline. The sediment tracers proved the existence of a pathway from the SWS to Peacock Spit, to Benson Beach. The majority of positive beach samples were found along the MHHW line versus the MLLW line of the beach and suggests active building of the beach.

Samples collected in month 12 (figure 3d, integrating tracer movement during OCT06-SEP07) and 35 further confirm continued presence, and possibly further accumulation of tracer particles, even though the concentrations on the beach were low compared with the adjacent seabed samples. Based on these results, it is clear that sediment from the SWS does become part of the littoral budget. Presence of particles on the southern end of Long Beach in Month 12 confirms migration north in line with longshore transport.

The 6-month sample results (integrating tracer movement during OCT06-MAY07) show some tracer migrates west into deeper water. However, it appears that this pattern did not continue indefinitely with the distribution of tracer particles appearing to migrate north around the ebb shoal and in line with the longshore transport. The results from the tracer study suggested a widespread dispersion of the dredged material from the SWS, supporting the hypothesis that the SWS is a dispersive site overall and suggesting that placing dredged sand within the SWS 'nourishes' the entire ebb shoal and beyond. The pattern of distribution of tracer particles tends to suggest a dual transport processes of tidal-driven (and possibly estuarine) and longshore transport with a net result of almost exclusively northerly/northwesterly movement. Virtually no southerly/easterly movement of the SWS was observed toward the inlet channel, during any of the sampling events.. This is assuming that widespread zero counts are not a function of burial. However, given the distribution of zero counts over a range of different water depths and topography it is assumed the lack of tracer particles in these areas is a function of no transport pathways existing towards the south and east. This suggests that the transport direction from the SWS is consistent though the year. The presence of the ebb shoal is clearly significant and distribution tends to be a function of this feature excluding material that travels due north from SWS and enters the nearshore littoral zone. Deposition on the Washington beaches is probably a by-product of this migration. The results clearly show that sand tracer dispersal from SWS was widespread throughout the ebb shoal area.

Table 1 summarizes a mass budget analysis for the SWS tracer, which provides an indication of the relative volume of tracer accounted for in each sampling event. Values were determined by calculating the area around each individual sampling position using a Voronoi polygon method (polygon defined by equidistance to nearest neighboring sample) and multiplying the tracer count per 100 g of dry sediment by the estimated mass of dry sediment within this area to a depth of 0.05 m. Assumptions are that there has been minimal burial and that the tracer particles are uniformly distributed throughout each polygon. Based on the bedform activity observed at the SWS and SJS, a 0.05 m burial depth may underestimate the effect of bedform burial (figure 2c).

SJS (Yellow and Blue) Tracer Study Results and Discussion

Figures 4a & 4b indicate that within 3 months after deployment (OCT 08–JAN 09), he initial northward dispersion of the sediment tracer placed at DZ-A (yellow) and DZ-B (blue) is correlated. The correlation in tracer movement at DZ-A and DZ-B diminishes by Month 11(JAN 09-SEP 09), as shown in figures Ac & 4d. Figure 4d indicates widespread dispersal and movement of sand-sized particles from release site DZ-B (Blue) toward the north and northwest suggesting that DZ-B is located within an area that is affected by a net residual longshore tidal flow towards the northwest (see figure 1c). It is likely that such circulation is created by or is a result of the South Jetty, which protrudes 5 km offshore into the general south to north longshore flow of the region. Figure 4d results correspond with the current regime shown in figure 1c. Figure 4c indicates that northward and westward dispersal from DZ-A (yellow) is much more limited than at DZ-B, with a large proportion of the particles remaining close to the release site. Figure 4c indicates that the primary (bottom) transport direction at DZ-A is northward toward the MCR South Jetty, at which point the tracer was transported east and deposited alongshore, possibly within an alongshore littoral cell. Based on this scenario, the bottom current regime at DZ-A (and locations between DZ-A and the south jetty) would not correspond to figure 1c. If true, this is a remarkable difference in bottom circulation and transport process for coastal nearshore locations separated by less than 1.5 km (distance between DZ-A and current data collection point (see figure 1a). The SJS tracer data suggest that DZ-A is probably located within a return gyre or circulation where flow runs opposite to the net south-north results longshore tidal flow leading to transport into shallower water towards South Jetty and ultimately back to the south along the shoreline of Clatsop Plains.

It is clear that tracer material from the two SJS DZs have different transport processes affecting them, despite being at the same depth contour (14 meters) and approximately 2.4 km apart. These differences may be manifested during different times of the year. Yellow tracer results indicate that sand-sized material released at DZ-A moves shoreward and ultimately onto Clatsop Plains. It appears that sand-sized material released at DZ-B ultimately is spread more widely and moves north and west towards the navigable channel and the MCR inlet. Both tracers appear to move in a longshore direction rather than a cross-shore direction, although once the particles became close to the South Jetty this influences the transport and deposition patterns.

General Conclusions and Ongoing Work

The physical characteristics of the tracer particles were well matched with the natural dredged sediment dredged at MCR. Based on the pattern of observed tracer distribution compared with the general understanding of the oceanographic processes at MCR and aspects sediment transport, the tracer particles appear to have continued

to behave in the same way as the natural dredged sediment. The tracer particles remained detectable for at up to 3 years in an extremely high energy environment. Post-deployment results conclusively show that tracer particles released at the SWS and SJS in water depth of 13-14 meters were transported into the active littoral zone of Oregon and Washington, with tracer deposition occurring on beaches. The results indicate that the sand-sized sediment at MCR is dispersed differently along the northern side of the inlet as compared to the southern side. The rate of SWS tracer dispersion was much higher and more directionally coherent than at either of SJS DZs. The differences in tracer dispersion trends are consistent with the differences observed in bottom current data for the SWS and the SJS (figures 1b & 1c).

One uncertainty surrounding the pattern of deposition is the fact that samples were collected using a grab sampler in an area with active sand waves (figure 2c), and, consequently, a significant amount of the tracer may be at a depth greater than that sampled. To evaluate the effect of bed-form roll-over on sediment tracer behavior, vibracoring was performed within the SJS during SEP10 to obtain 48 samples to depth of 0.6 m. These cores samples will be analyzed for tracer content.

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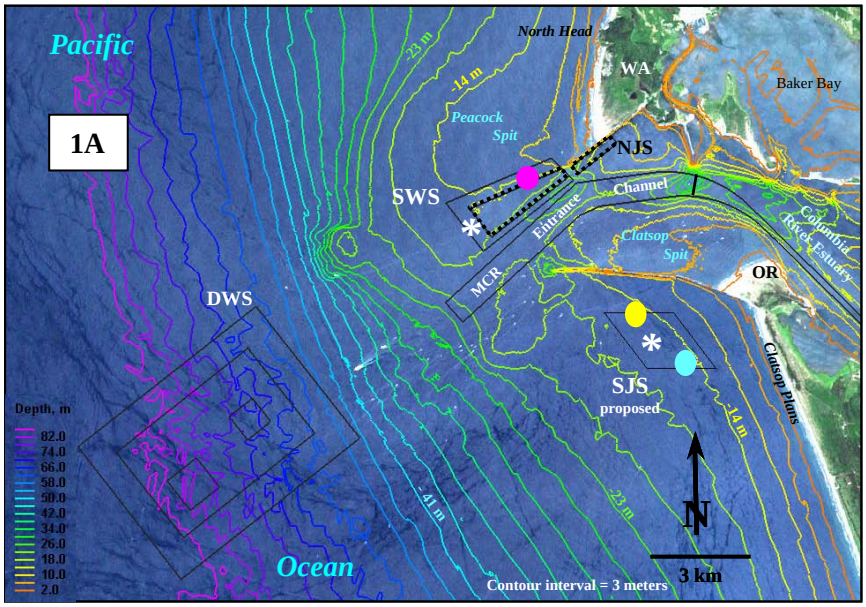
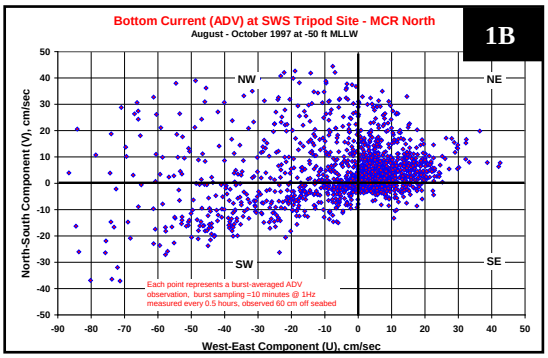




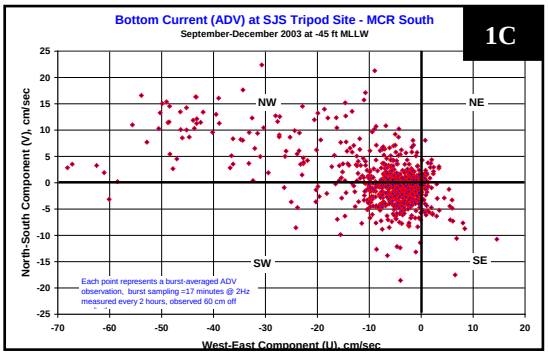
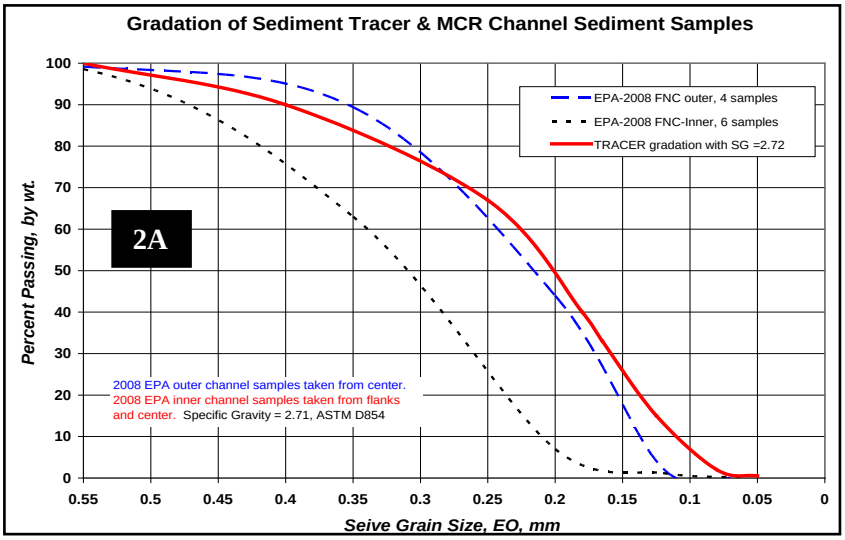


Figure 1 a. Spans 12km x 20 km at the Mouth of the Columbia River. Sediment tracer material was released at three locations; shown as magenta, yellow, and blue circles. White * show where bottom currents were observed at the SWS and SJS locations.

Figure 1b.shows bottom currents observed at the SWS location during Fall 1997.

Figure 1c.shows bottom currents observed at the SJS location during Fall 2003.



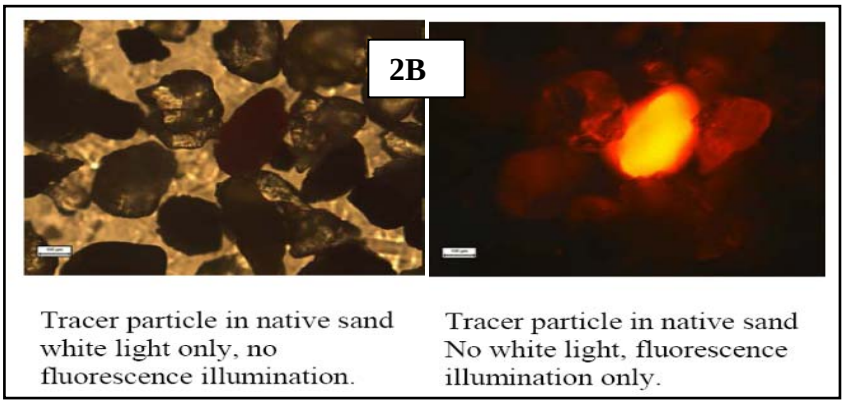
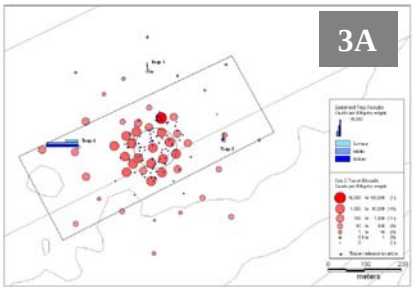
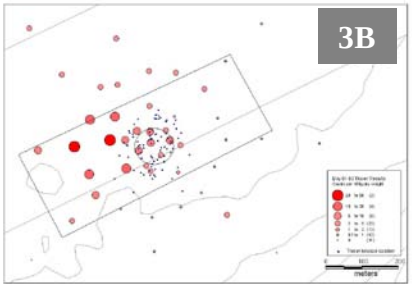


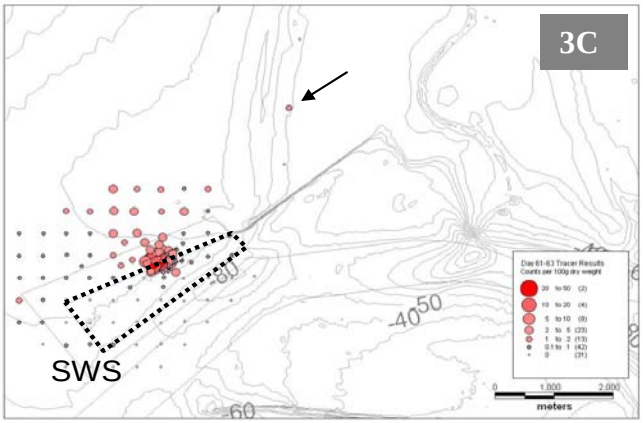
Figure 2 a. Two gradation curves describing the sediment within the inner and outer channel at MCR. 80% of the sediment dredged at MCR comes from inner channel areas. The third curve applies to the TRACER that was manufactured to emulate MCR dredged material.

Figure 2b. Tracer grain embedded within sand, showing how tracer can be identified using fluorescence properties of the tracer

Figure 2c. Ocean floor at the South Jetty Site (SJS). The sand ripples are 5-15cm in height and are indicative of bed load transport caused by waves and current. Imagery taken by USEPA S/V Bold.







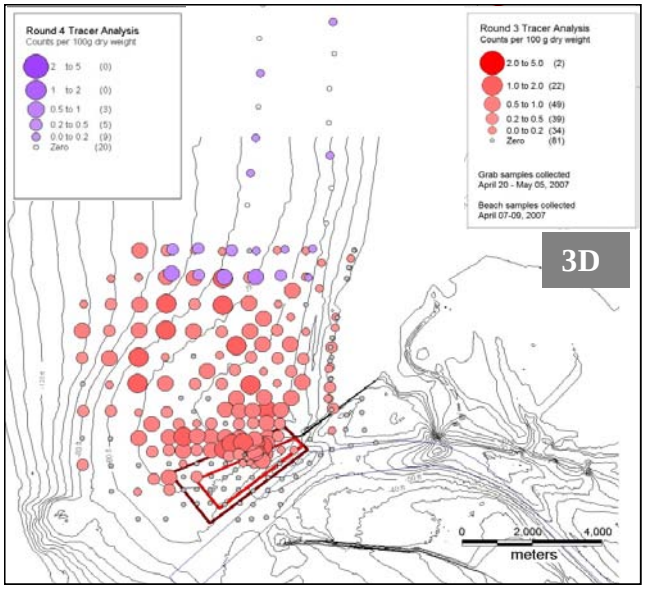
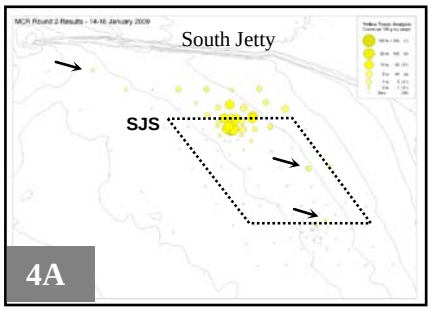


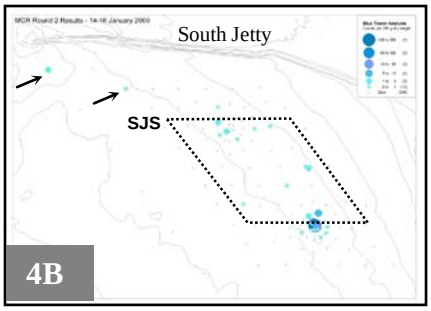
Figure 3 a. Results from the SWS sampling event 1 (2 days after the 4 OCT 2006 deployment), confirming that the tracer was placed as intended within the drop zone (DZ). Tracer concentration was 1-10,000 counts/100 gr of sediment sample.

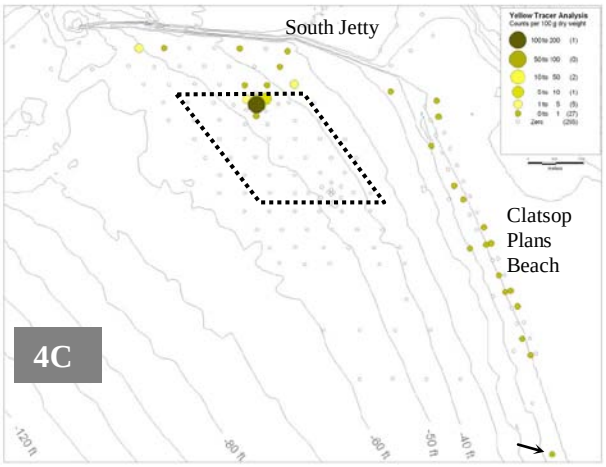
Figure 3b. Near-field results from SWS tracer sampling event 2 (60 days after tracer deployment) showing W-NW dispersal at DZ. Tracer concentration is 2 orders of magnitude less than Figure 3A.

Figure 3c. Far-field results from SWS tracer sampling event 2 (60 days after tracer deployment) showing N-NW dispersal from DZ. Tracer was observed on Benson Beach 3 km to the NE from the SWS DZ (arrow).

Figure 3d. Far-field results from SWS tracer sampling events 3 and 4 (6 months and 1 year after tracer deployment) showing NW and N dispersal from DZ. Tracer was observed on Long Beach 6 km to the N from the SWS DZ 6 months after deployment. Tracer concentration is 3-4 orders of magnitude less than Figure 3A.







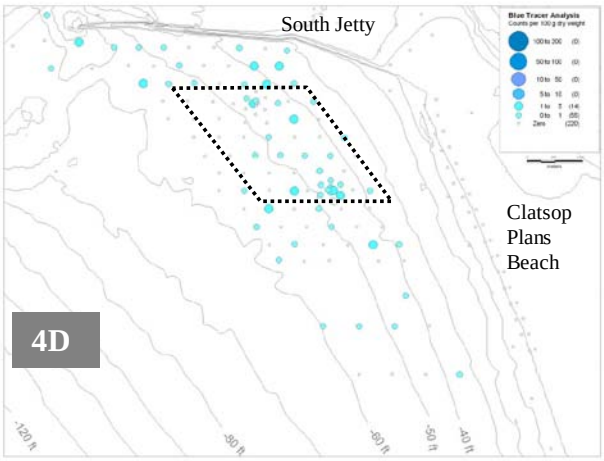


Figure 4a. Near-field results from SJS sampling event 2 for yellow tracer released at DZ-A (3 months after the OCT 2008 deployment) showing northward dispersal from DZ-A, with some South & NW excursions (arrows).

Figure 4b. Near-field results from SJS sampling event 2 for blue tracer released at DZ-B (3 months after the OCT 2008 deployment) showing northward dispersal from DZ-B & some extreme NW excursions (arrows).

Figure 4c. Far-field results from SJS-yellow tracer sampling event 3 (11 months after tracer deployment) showing dispersal toward the north, E-SE, and alongshore toward the south. Yellow racer was dispersed 6-8 km southward along Clatsop Plains Beach. Tracer concentration is 1 order of magnitude less than Figure 4a. DZ-A appears to be located within a littoral cell which retains material within the proximity of the South Jetty and leads to deposition both along the South Jetty and nourishes Clatsop Plains beach.

Figure 4d. Far-field results from SJS-blue tracer sampling event 3 (11 months after tracer release) showing NW and southward dispersal from DZ-B. Tracer concentration is 2 orders of magnitude less than Figure 4b.

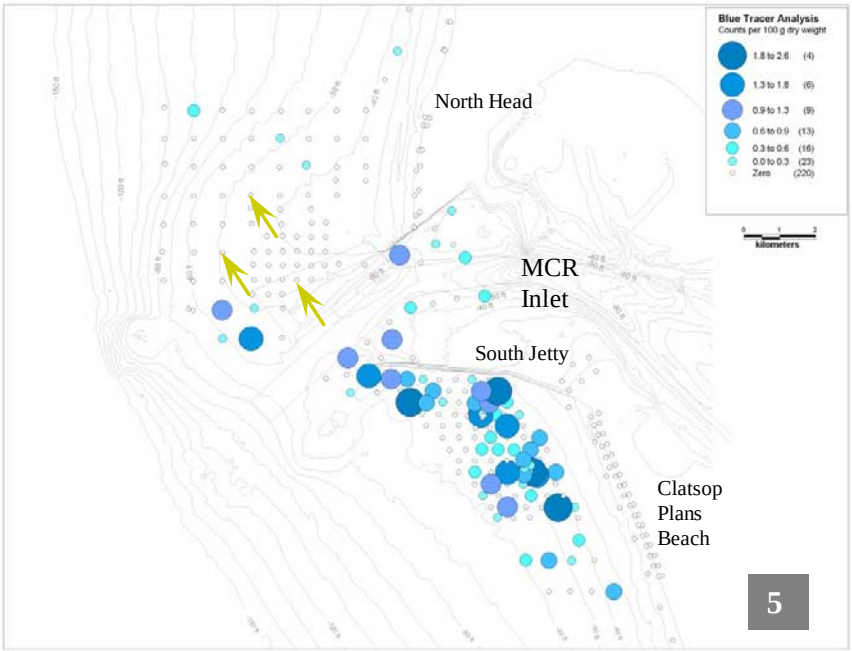


Figure 5. Wide-field of SJS-blue tracer sampling event 3 (11 months after tracer deployment) showing northward bypassing of MCR inlet. Same data as figure 4d, but different scale of view and tracer concentration. Yellow arrows indicate positive detection of yellow tracer on Peacock Spit. Note blue tracer found north of North head

Table 1. Mass budget summary for post-deployment of magenta tracer at SWS (Oct 06 - May 07).

	Day 2	**Day 61-63**	**Month 6**
Area	282,743 m^2	1.16×10^7 m^2	7.09×10^7 m^2
Depth of sediment sampled	0.05 m	0.05 m	0.05m
Volume of sediment	14,137 m^3	582,300 m^3	3,542,559 m^3
Mass of dry sediment in volume	4.5×10^7	1.38×10^9	8.2×10^9
Total tracer particles measured in grabs in Area	1.55×10^{11}	1.16×10^{10}	2.6×10^{10}
Total tracer particles released	1.5×10^{11}	1.5×10^{11}	1.5×10^{11}
Percentage accounted for in Area	**103%**	**7.7%**	**17.2%**
(Assuming 0.3m burial @ 2 & 6 months)	**-**	**(46%)**	**(103%)**