



Particle Tracking Model (PTM): II. Overview of Features and Capabilities

PURPOSE: This Dredging Operations and Engineering Research (DOER) Technical Note (TN) is the second in a series. It describes the features and capabilities of a new Particle Tracking Model (PTM) for analysis of sediment transport and sediment pathways in coastal waters, estuaries, rivers, and waterways. This note is applicable to Version 1.0 of PTM. The PTM graphical user interface is described in the first TN (Demirbilek et al. 2005a) in this series. A tutorial with examples is described in the third TN (Demirbilek et al. 2005b). PTM has been designed to meet the needs of two U.S. Army Corps of Engineers (USACE) research programs, the Coastal Inlets Research Program (CIRP) and the DOER Program. Examples are presented that illustrate key features of the PTM's application in coastal and estuarine environments.

APPLICATION: Accurate prediction of the fate of sediments and other waterborne particulates is a key element in coastal engineering and dredging operations. The PTM simulates sediment movement in a flow field, including erosion, transport, settling, and deposition. In addition to predicting sediment transport pathways and sediment fate, the model produces maps of sediment transport processes, such as sediment mobility, which can be useful in understanding sediment behavior. The reader is referred to MacDonald and Davies (2005) for a comprehensive description of the theoretical formulation and numerical implementation aspects of the PTM.

The PTM is designed to address the following processes and project needs:

- Sediment mobility.
- Fate of mobilized sediment.
- Source or origin location of material in areas experiencing sedimentation.
- Effects of anthropogenic activity on sediment pathways.
- Fate of material released during a dredging and placement operation.
- Stability and fate of in-place sediment, including dredged-material mounds, sediment caps, and contaminated sediment deposits.

Hydrodynamic and wave conditions are generated for PTM application using wave and circulation models. PTM input files include an unstructured grid and time-series for the wave and hydrodynamic conditions. The input grid file is identical to the ADCIRC grid (Luettich et al. 1992). The input hydrodynamic files can be either in ADCIRC or XMDF (Jones et al. 2004) formats. The input wave file is identical to STWAVE wave model files (Smith et al. 2001). As illustrated in Figure 1, the model operates in the Surface-water Modeling System (SMS) Version 9 (Zundel 1998), which allows considerable flexibility in converting hydrodynamic model results from one format to another. Figure 1 shows both the model bathymetry input and a snapshot of the flow field in an estuary. The PTM can read and write XMDF binary file format supported by SMS, which greatly reduces file sizes and file access times.

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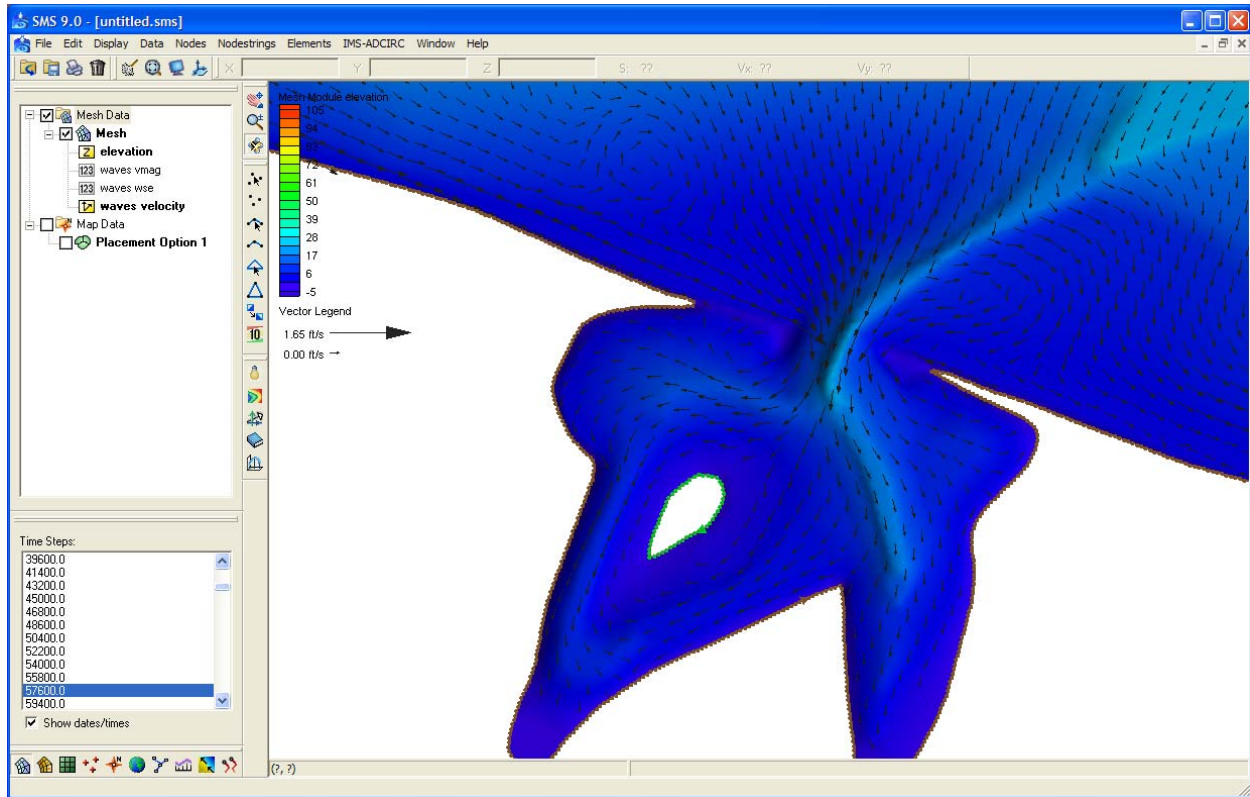


Figure 1. Example PTM simulation within the SMS 9.0 modeling environment

LAGRANGIAN MODELING OF PARTICLE TRANSPORT: In general terms, a Lagrangian modeling framework is one that moves with the flow, whereas an Eulerian modeling framework is one in which the solution is obtained at fixed points in space. In a Lagrangian framework, the waterborne constituent being modeled is represented as a finite number of discrete particles that are tracked as they are transported by the flow. Each particle represents a specified mass of the constituent (sediment, for example) and has the same properties of the represented constituent (settling speed, density, etc.). Major advantages of a Lagrangian approach over the more traditional Eulerian approach are computational efficiency and the visualization. One hydrodynamic simulation can serve as input for multiple variations of transport because the Lagrangian model is not coupled with the hydrodynamic model. In addition, for monitoring specific sediment sources, the Lagrangian approach may be more appropriate because it does not have to track other sediments in the domain. The Lagrangian approach in PTM includes the following features:

- Diffusion and advection processes are accurately and efficiently modeled.
- Particle distributions (grain size, sediment type) are simulated by specifying different characteristics for each particle type.
- Natural variability in particle characteristics and response are represented.
- Processes such as particle sorting are simulated.
- Particle pathways can be identified, so that sources and destinations of sediments are identified.

- A Lagrangian simulation is significantly less computationally intensive compared to an Eulerian transport simulation, thus permitting evaluation of numerous alternatives. However, users must supply the hydrodynamic forcing.

MODEL STRUCTURE: In addition to hydrodynamic/wave time series, particle data are also required by the PTM. Sediment or particle input includes the number of particles, the mass and density of sediment in each particle, and the grain size distribution of particles. The SMS interface (Demirbilek et al. 2005a) guides the user to needed information. The user can also specify the fall velocity and critical shear stresses for erosion and deposition. This feature is necessary for modeling fine sediments. The user also specifies sediment sources that will be tracked. In addition, native bed sediment characteristics are user-specified. Sediment particles can be distributed across an area of the bed or injected into the flow as a vertical line, horizontal line, or point source. To enable realistic simulation of dredging operations, multiple sources can be simulated simultaneously. Source terms can vary both spatially and temporally.

As previously stated, the flow field is prescribed as input to the PTM. The PTM spatially and temporally interpolates flow conditions to resolve particle movements at finer scales than the input flow mesh. In most applications, the input flow field will be two-dimensional and depth-averaged. Support for three-dimensional (3D) flow fields is under development and will be available in the next release of the PTM.

Hydrodynamic and particle transport parameters are calculated at each time-step across the entire mesh. These Eulerian parameters characterize the environment through which the Lagrangian particles move. In addition, the PTM quantifies particle parameters such as the release, entrainment, advection, dispersion, settling, and deposition at each time-step. PTM calculations are divided into Eulerian and Lagrangian categories, as described below.

Eulerian Calculations. These are carried out for the entire domain (mesh) at each time-step to determine the behavior of the native bed sediments and include:

- Bedform calculations to predict the sub-grid scale bedforms over the domain, including their growth and decay over time.
- Shear and mobility calculations to predict the influence of the flow field on the particles in the domain.
- Transport potential calculations to predict the mode of transport and the potential sediment transport rates of the bed materials in the domain.
- Transport gradient calculations for the potential transport rates, and the local instantaneous rate of erosion and deposition of the native bed materials, which are expressed as the time rate of bed change (dz/dt). This rate of bed change is used to characterize the local sediment transport environment at a particle location and to determine the likelihood of burial of a particle.

Lagrangian Calculations. These are carried out for each particle active in the domain and include:

- Flow calculations – interpolation of the local flow and wave conditions at the particle's location.

- Mobility calculations – determination of the mobility of a particle and, if presently deposited, the likelihood of its entrainment in the flow using the flow and wave conditions at the particle's location.
- Trajectory calculations – determine the position of a particle at the end of the time step using an advection – diffusion equation with representation of settling, deposition, and erosion.
- Boundary condition checks – ensure that the particle predicted path does not violate boundary conditions.

MODES OF OPERATION: The PTM includes three modes of operation: two-dimensional (2D), quasi three-dimensional (quasi-3D), and full three-dimensional (3D). It should be noted that at present, the 3D mode includes three-dimensional particle movement capabilities, but not 3D hydrodynamic capabilities. Three-dimensional hydrodynamic capabilities will be incorporated in a subsequent version of the PTM. Main features of each mode are described below.

2D Mode. This is the simplest mode of operation of the PTM. An analogy of this technique is sand grains moving on a concrete bed. The 2D mode assesses transport processes and pathways and the maximum likely particle excursions. Figure 2 is a schematic representation of the 2D mode viewed in plan (top panel) and from the side (lower two panels). In Figure 2, the panels to the left show the fluid velocity profile (logarithmic) used to determine particle velocities. The sediment mobility M is simply the ratio of the skin shear stress acting on the bed τ to the critical shear stress τ_{cr} . Some key features of the 2D mode are:

- Sediment particles are independent of each other.
- Erosion and deposition are controlled by a transport threshold (Shields curve or user-defined).
- Local flow conditions at the particle location are interpolated both spatially and temporally from the input hydrodynamics.
- Advection velocity is based on estimated advection velocities of the bedload and suspended load (potential rates).
- Sediments are assumed to be entrained instantaneously from the bed once the critical shear stress is exceeded. There is no particle mixing; the native sediments are not modeled.
- There is no vertical advection or settling. The vertical elevation of each particle is at the elevation of the centroid of the local particle's transport distribution z_c (computed from the integral of the concentration and velocity distributions).
- Sediment advection is based on a depth-integrated interpretation of the particle transport distribution. Particles move at velocity U_p , which is equal to the fluid velocity $U(z_c)$ estimated from the local depth-averaged fluid velocity $\bar{U}$.

The 2D mode of the PTM provides a fast and efficient method for identifying sediment particle pathways and zones of potential erosion (sources) and potential accretion (sinks). However, because the 2D mode does not include mixing and other pertinent transport processes, it cannot identify the rate of transport. It is not possible to assess the fate of nearshore placement without quantifying transport rates. Because the 2D mode does not quantify transport rates, it is limited to examining potential transport pathways for sediments placed at a location.

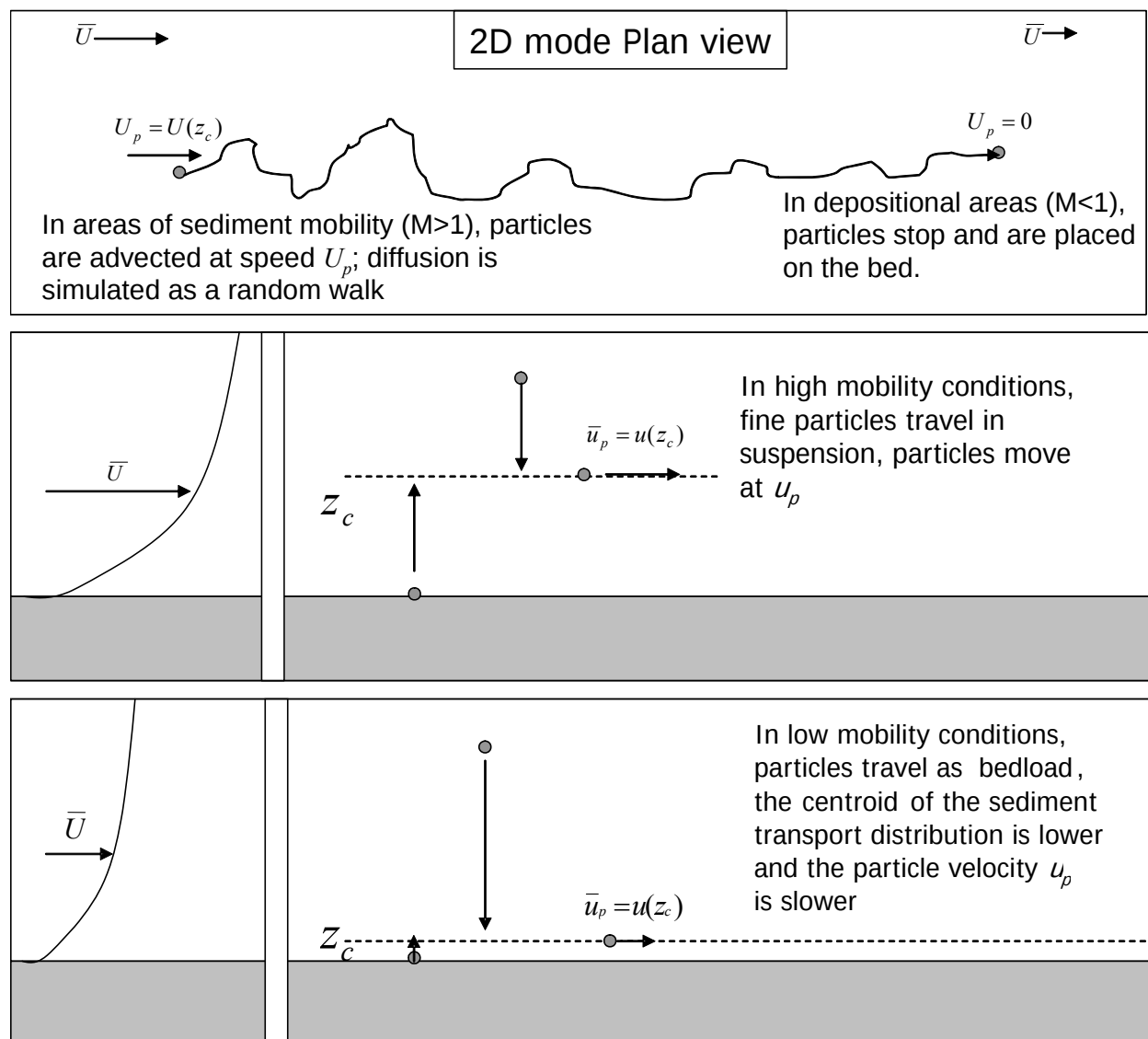


Figure 2. Schematic of 2D mode

Quasi-3D Mode. This PTM mode employs a different transport method than the 2D mode with an emphasis on the stochastic characteristics of transport. Figure 3 is a schematic of the quasi-3D mode. The top panel shows particle paths in energetic conditions, where suspended sediment transport dominates. Here the particle's equilibrium height is high in the water column, representing a suspended-load dominated transport condition. The lower panel shows a less-energetic, combined bedload-suspended load condition. Here, the particle's equilibrium elevation is much closer to the bed. In this latter case, the sediment advection velocities are much smaller than in the suspended sediment transport case. The panels to the left show the fluid velocity profile (logarithmic) and the velocity deficit function determining particle velocity.

In the quasi-3D mode, the particles follow a vertical trajectory toward their centroid elevation z_c at a speed equal to the particle fall velocity w . This is in contrast to the 2D mode where particles do not advect vertically, but are located at the centroid height z_c . The particle velocity U_p is

computed on the basis of the local flow velocity distribution $U(z)$, which is reduced by a velocity deficit function to represent the effects of particle-bed interactions.

The following points summarize the main features of the quasi-3D mode:

- Particles can move vertically in the water column. Settling processes are modeled. The direction of vertical motion is controlled by the position of the centroid of the local sediment transport distribution (i.e., particles suspend or settle toward the centroid).
- Mass of particles in transport and their advection rates are controlled by the potential transport rate. Particles travel at some elevation representative of the centroid of transport distribution.
- Transporting particles move toward the centroid, but they do not default to this level as in the 2D mode. For example, a particle released at the top of the water column will transport, for some time, in the upper part of the water column until settling velocity brings it down to the centroid. It will remain at or near this location until shear stress falls below critical, upon which it can deposit.
- The rate of entrainment of deposited sediment is determined probabilistically. A probability of entrainment is computed considering the sediment transport pickup rate, the mixing depth of sediments in the active transport layer, and the likelihood of burial by ambient sediments.

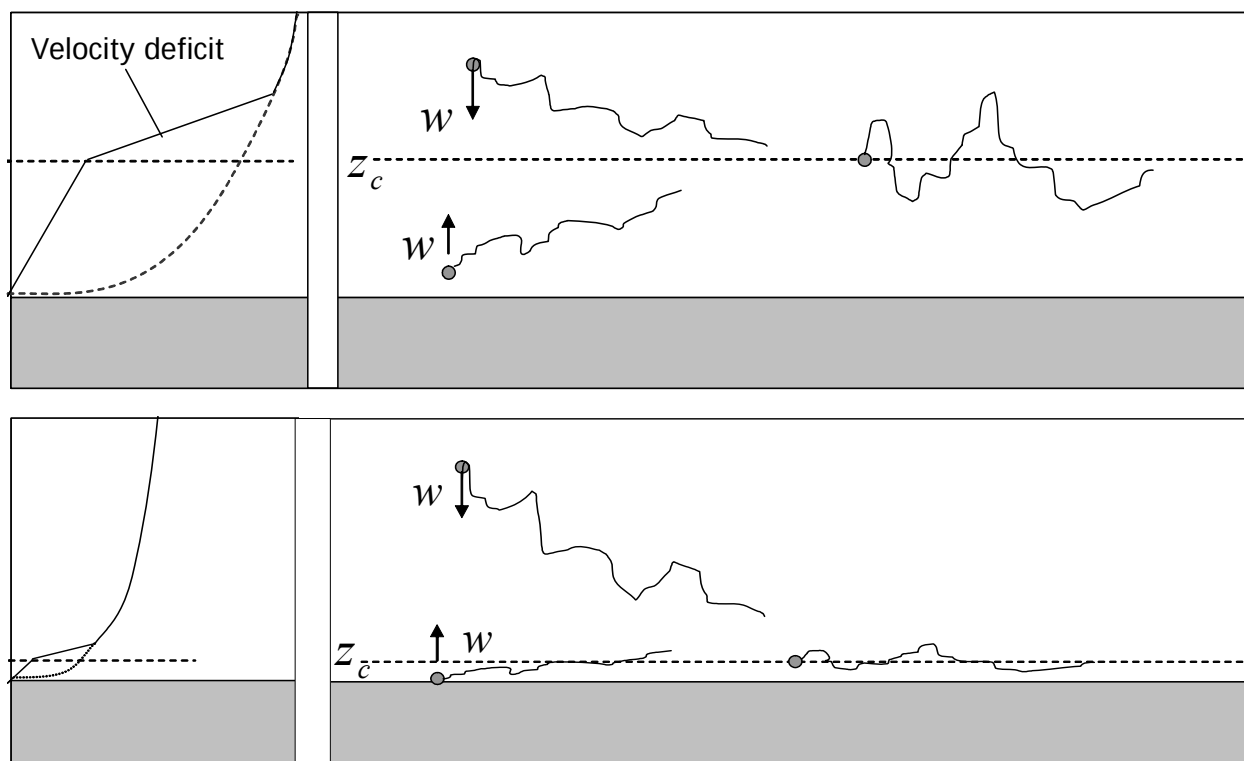


Figure 3. Schematic of Quasi-3D mode

Full 3D Mode. This mode of the PTM does not require the assumption that particles of a particular sediment property advect vertically to a specified centroid. Each particle settles, entrains, and advects independent of the centroid concept utilized in 2D and quasi-3D modes. In

the 3D mode (Figure 4), the entrainment and settling of sediment parcels are based on the properties of the individual sediment grains represented by that parcel.

The following points summarize the main features of the 3D mode at present:

- Each particle has the transport characteristics of individual sediment grains within that particle.
- Both horizontal and vertical advection consider modeling the dynamics of individual particles (i.e., the centroid concept is not employed).
- Probability of resuspension of deposited particles is based on mixing depth.

This mode is a more sophisticated and a more computationally intensive sediment particle transport technique. The 3D mode provides the most detailed representation of sediment transport and is well-suited for simulations where particle vertical trajectories are most critical (for example, for dredging-related issues). Future development of the PTM will refine the 3D mode and will include testing in field projects and linking to 3D hydrodynamic models.

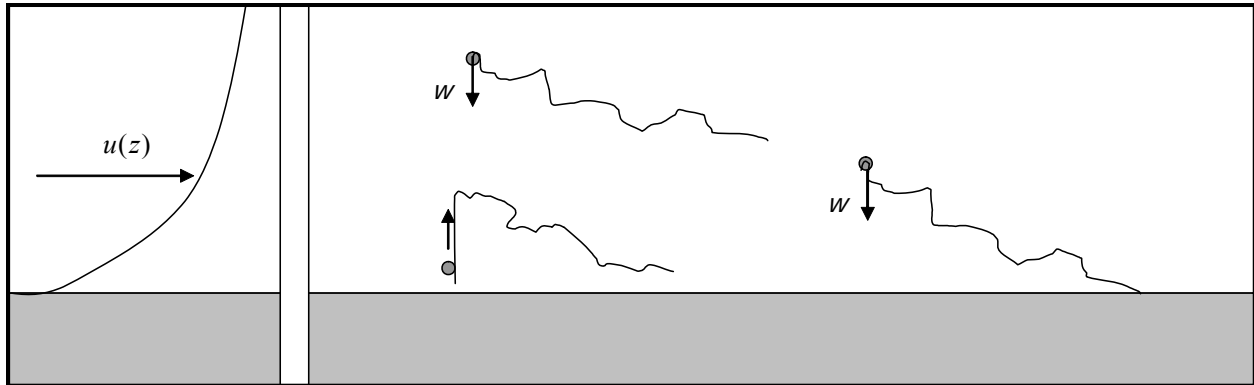


Figure 4. Schematic of fully 3D mode

EXAMPLES OF PTM CAPABILITIES: This section provides illustrative examples that demonstrate applications of the PTM to 1) evaluation of dredged material placement sites, and 2) the assessment of sediment pathways in complex coastal inlets with temporally and spatially varying tides and waves. These examples are based on a hypothetical estuary as shown in Figure 5. The input data files used to generate these examples, as well as the PTM solutions, can be downloaded from: <http://el.erdc.usace.army.mil/dots/doer>.

A coupled wave-tidal current hydrodynamic data set was created by applying the Inlet Modeling System (IMS) models developed in the CIRP (<http://www.cirp.army.mil/>). The IMS Steering Module in SMS linked the simulation of tides and waves. The IMS-ADCIRC model provides the tidal elevation and currents, and STWAVE provides the waves required for this PTM application. The simulations presented here use a 2-m semidiurnal tidal range, and waves are from the NNW with a significant wave height of 2 m and a peak period of 7 sec. The seabed is composed of sand with a median grain diameter d_{50} of 0.2 mm. The following two examples illustrate features and capabilities of the PTM for modeling of nearshore sediment transport at the inlet entrance, and for dredging operations in the inner estuary.

Example 1 – Nearshore Sediment Transport. The PTM is applied here to identify transport pathways of sediments placed in the nearshore of an idealized estuary (Figure 5). In this example, the ocean is to the north. A tidal inlet cutting through a large ebb shoal connects to the eastern arm of the estuary. The quasi-3D PTM mode was selected for this simulation.

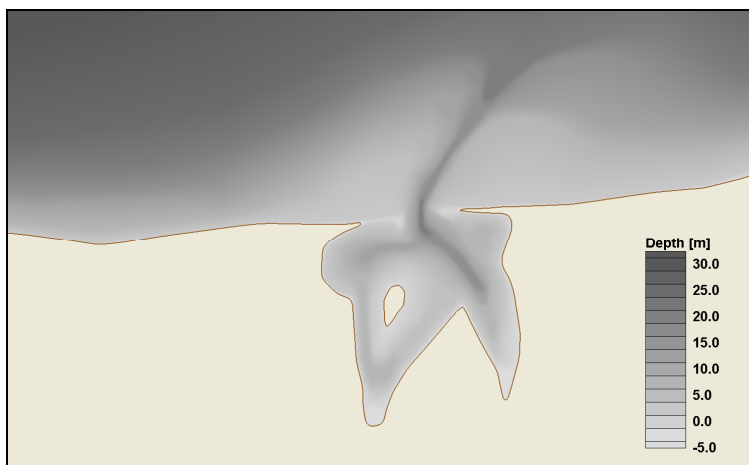


Figure 5. Idealized inlet

The PTM allows evaluation of sediment mobility and transport pathways for specific sediment sources. This PTM application identifies possible transport pathways for sediments carried into the inlet by wave-generated currents.

Figures 6 through 9 show spatial snapshots of some of the underlying processes that control sediment behavior in the PTM. These include currents, sediment mobility, bedforms, and erosion and deposition (net morphology change). These snapshots show conditions 1/2 hr into the PTM simulation. Figure 6 shows the ebb currents in the main channel and at the entrance to the estuary and the eastward longshore current creating a flood current at the western edge of the inlet. Figure 7 is a plot of sediment mobility for 0.2 mm sand resulting from the combined

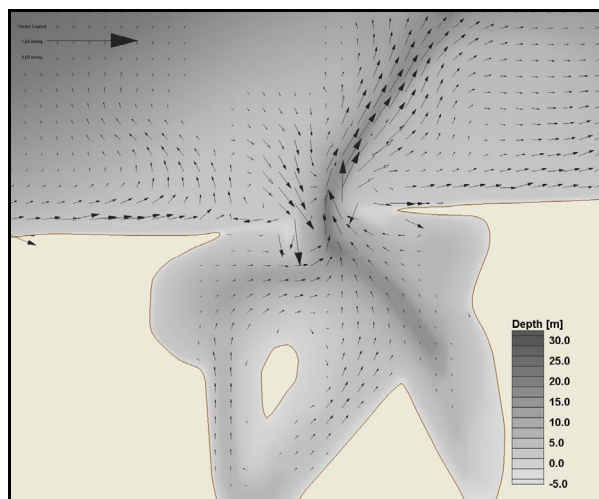


Figure 6. Snapshot of currents at idealized inlet (t=0.5 hr)

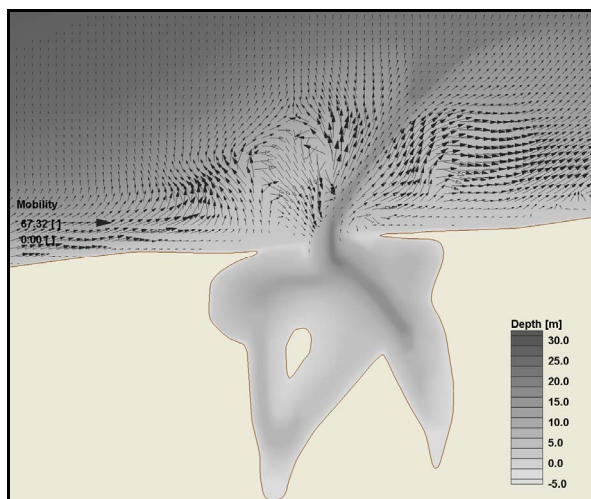


Figure 7. Snapshot of sediment mobility under waves and currents 0.5 hr into simulation

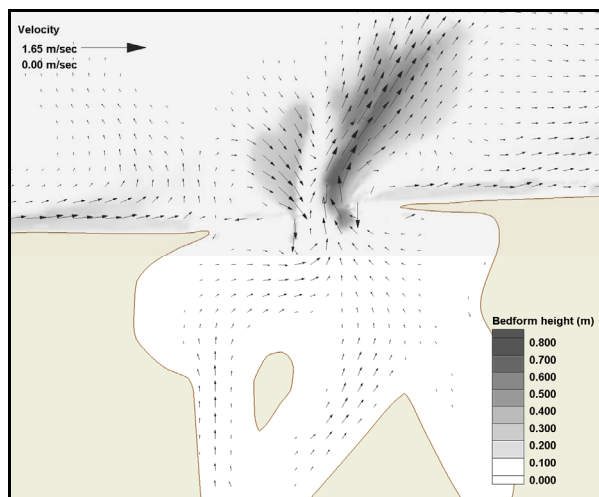


Figure 8. Snapshot of bedforms at the inlet, where vectors indicate mean currents

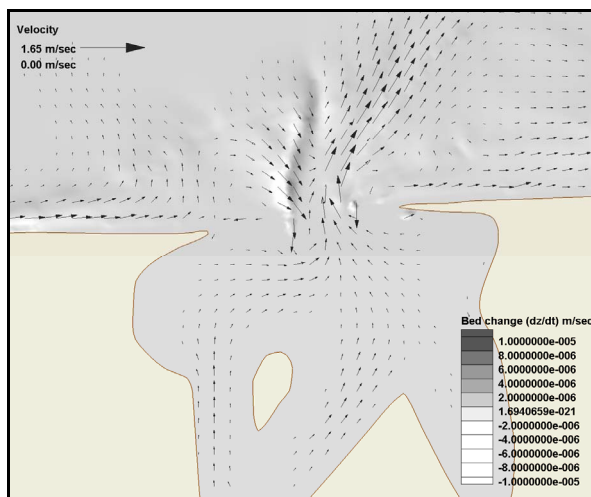


Figure 9. Snapshot of instantaneous erosion/deposition patterns at the inlet, with vectors showing mean currents

effects of waves and currents. Wave action results in high sediment mobility along the shore both east and west of the inlet, and currents cause high mobility near the inlet approach and inside the main channel. Figure 8 is a plot of bedform heights, showing maximum bedform heights to occur in the main channel of the inlet. Figure 9 is a snapshot of instantaneous bed change in the study area. Here, the shading represents morphological change, with zones of erosion and accretion denoted respectively by lighter and darker shades. This plot shows erosion in the offshore areas of the beaches and accretion in the nearshore. In Figure 9, both erosion and accretion patterns occur throughout the entrance to the estuary.

Figures 10 through 12 show the transport of sediment placed in the nearshore area across the inlet entrance at various times through the simulation. The black dots indicate parcel locations. Figure 10 shows particle locations near the start of the simulation. These particles represent a $d_{50} = 0.2$ mm sand placement simulated as a line source releasing 7,400 kg of sediment in the first minute of the simulation. These figures show that the particles are transported eastward by the wave-generated longshore current at the start of the simulation. A small percentage of the sediment is moved offshore to the ebb shoal by the tidal current. As the simulation progresses, the longshore current generated by waves from the northwest carries sediments eastward to within the surf zone. Sediments are moved (distributed) both out to the edge of the ebb shoal and carried into the flood shoal area. By the end of the simulation, the particles have been carried both offshore to the ebb shoal and inshore to the flood shoal. The combination of waves and wave-generated current has resulted in a steady eastward transport of particles alongshore.

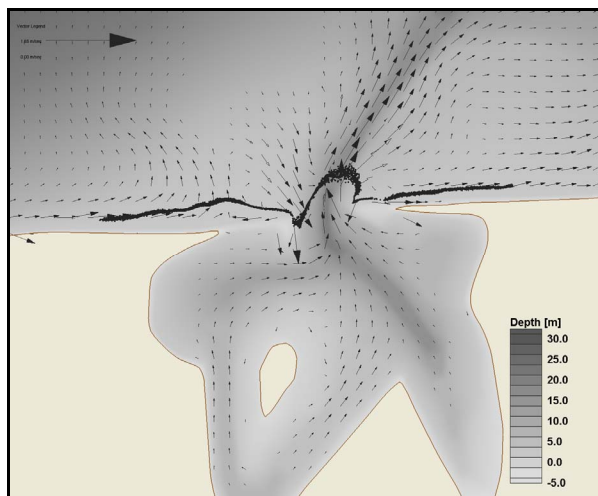


Figure 10. Particle locations and velocity vectors 0.5 hr into simulation

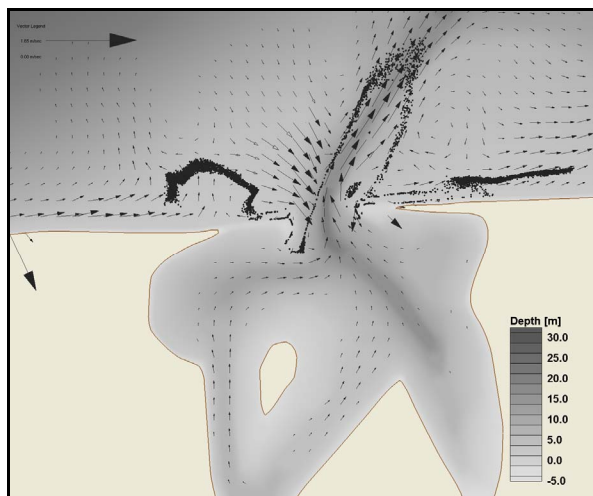


Figure 11. Particle locations after 3 hr

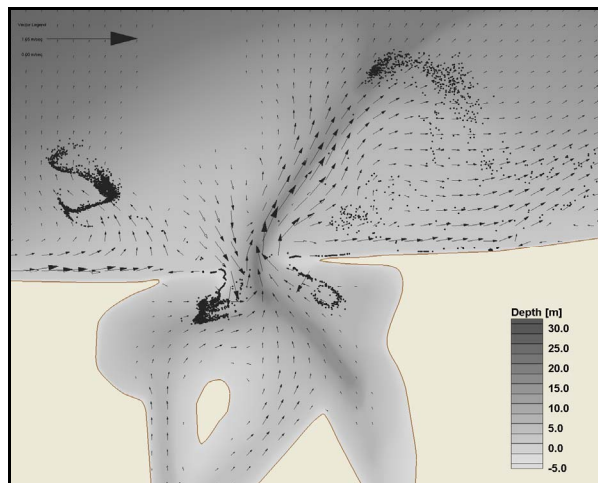


Figure 12. Particle locations after 24 hr

Sediments were initially distributed in a straight line alongshore. After 0.5 hr, the sediments are moving alongshore, where some are drawn into the inlet and some are moved toward the ebb shoal area. After 3 hr, the sediments have migrated further eastward, and sediments in the ebb shoal area have been carried offshore in the ebb channel. A smaller amount of sediment has been carried into the estuary. After 24 hr, the offshore sediments have been moved further offshore and eastward, and a pronounced flood shoal is visible on the west side of the estuary

Example 2. This example is a case study that simulates dredging operations within an idealized estuary. The hydrodynamic environment is tidally dominated; little wave action penetrates into the estuary. In this simple example, dredging operations are treated as a moving vertical line source working back and forth to dredge the channel bed. Optionally, the PTM can simulate dredges with sediment release rates and sediment characteristics varying in time as the dredge moves through the modeling area. The fully 3D transport mode is used in this simulation. The sediment source used here is a vertical column of silt ($d_{50}=2 \mu\text{m}$) with a release rate of 0.012 kg/s/m representing the sediment loss rate from a dredging operation. For the sake of illustration, the dredge source in this example was assumed to be moving at a constant rate of 900 m/hr . Simulation times for sediment sources and hydrodynamics are both referenced to UTC time so that complex temporal sequences of dredging operations can be simulated.

Figures 14 through 17 show a sequence of particles generated by a moving dredge source operating in the estuary. The locations of sediment particles after being transported by the flows

are shown in Figures 15 through 17. The tidal currents carry the sediments away from the dredging area. Some sediments end up in the deep flood channel to the northwest of the dredged area, and others are moved southwest by the currents. Black denotes particles that are in suspension, and white represents particles that have settled to the bed.

The SMS interface is used to map the PTM sediment locations and characteristics (such as grain size) so that the origin and path traveled by any (or all) particles can be determined and illustrated. These techniques are useful if there are concerns about the sources of sedimentation in sensitive areas, e.g., type and amount of sources arriving at a site, the pathways particles take to reach a site, and travel times of different parcels arriving at a site.

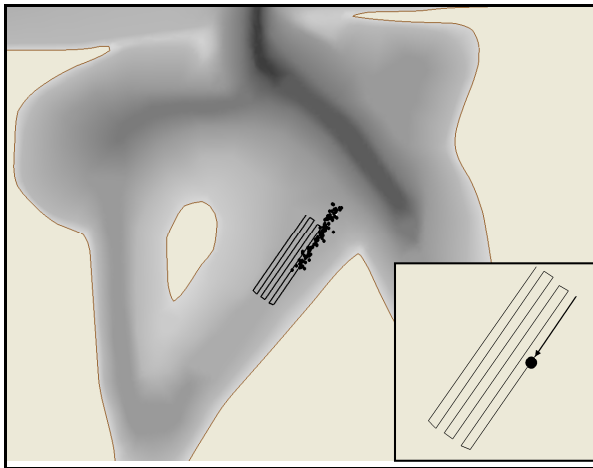


Figure 14. PTM simulation results. The line indicates path taken by the dredge (source), and black dots are suspended sediments released into the flow field 1 hr into the simulation

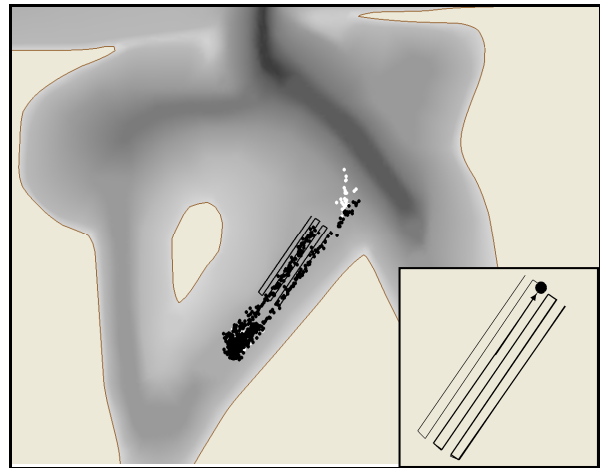


Figure 15. Particles after 8 hr into simulation. Particles that have deposited on the bed are white

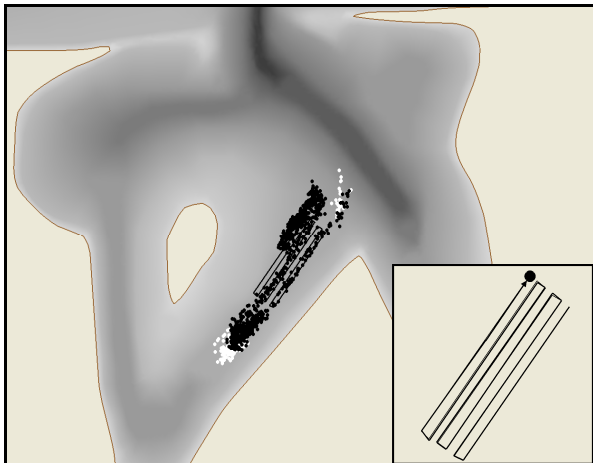


Figure 16. End of dredging operations (12 hr after the start of simulation)

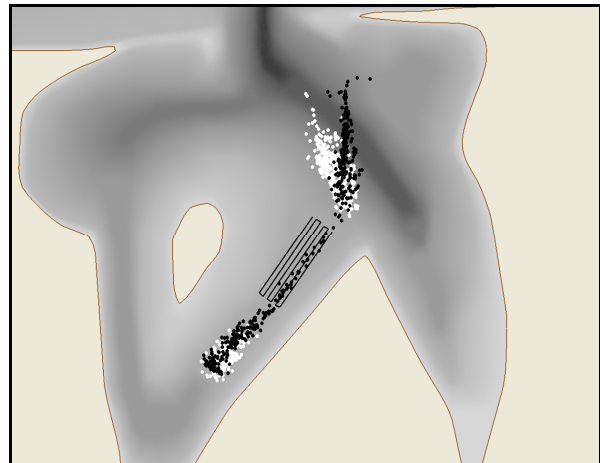


Figure 17. Final location of the particles 48 hr after the start of simulation

SELECTING A TRANSPORT MODE: At present, the user defines the mode of application for the PTM. The 3D approach may be necessary for complex sediment transport conditions, or in areas where the vertical movement and settling of sediments are of concern. The PTM offers both a quasi-3D and a full 3D approach for modeling such conditions. The quasi-3D mode uses a combination of empirical sediment transport functions with 3D advection, settling, and dispersion algorithms to represent key 3D sediment processes. The fully 3D mode performs more comprehensive methods for 3D particle entrainment, deposition, and resuspension.

In general, mode selection is dependent on a number of factors, including the scale of the physical processes of interest, hydrodynamic environment, and sediment properties. Computational effort increases significantly with model complexity. In many situations, a 2D representation of sediment particle motion may suffice (e.g., the study of sediment transport pathways over a large coastal or estuarine area with gradual depth variations).

The three modes of the PTM differ significantly in time-step requirements to obtain a realistic simulation of the particle transport processes. The 2D mode does not perform vertical advection computations and, therefore, can tolerate relatively large time-steps. The full 3D mode simulates vertical trajectories of particles in detail and, therefore, requires a very small time-step. The quasi-3D mode was developed to simulate some 3D processes using larger time-steps.

From a computational perspective, the PTM is unconditionally stable. However, time steps need to be selected carefully to ensure that the vertical and horizontal motions any particle takes during a single time-step are compatible with the scale of the transport processes of interest. Table 1 provides some guidelines for maximum time-steps depending on the PTM mode of operation and particle grain size. These are rough guidelines that have been developed based on experience, and it is recommended that users perform sensitivity runs to determine an appropriate time-step for each PTM application.

Table 1 Guidelines for Selecting Maximum Time-step					
Sediment	d₅₀ mm	Fall velocity, w m/sec	Suggested Minimum Time-step, sec		
			2D Mode¹	Quasi-3D Mode²	Full 3D Mode³
Silts	0.01	7.E-05	300	300	300
Fine sand	0.1	7.E-03	300	150	75
Med sand	0.5	7.E-02	300	14	7
Coarse sand	1	1.E-01	300	8	4
¹ Order of resolution required for vertical processes is N/A. ² Order of resolution required for vertical processes is 1. ³ Order of resolution required for vertical processes is 0.5.					

Model testing indicates that a maximum time-step of 300 sec as suggested in Table 1 is a reasonable upper bound for most coastal and fluvial applications. The limiting time-step is computed as the travel time for a sediment particle with fall velocity w to cover the vertical resolution distance shown in the table. For quasi-3D mode, a resolution of about 1 m is typically sufficient, and for 3D mode, a resolution of the order of 0.5 m is required, necessitating time-steps of the order of 4 sec or less if dealing with coarse material.

The computational effort required to execute a single time-step is not greatly different for the three transport modes. However, computational effort does increase with the size of the model domain (as a result of the grid-based calculations required to determine background transport conditions) and computation time is linearly proportional to the number of parcels being simulated. Therefore, in setting up a simulation, the user must consider the model time-step (a function of both model mode and grain size), the size of the computational grid, and the number of parcels being simulated.

SUMMARY: The PTM is a computationally fast and insightful tool to examine response of sediment particles to complex marine environments. Driven by hydrodynamics from circulation models such as ADCIRC and wave models such as STWAVE, the PTM model can identify areas of sediment mobility and deposition and can predict transport pathways. This technical note is applicable to Version 1.0 of PTM. The next phase of PTM development will enhance the 3D capabilities of the model and couple it with 3D hydrodynamic models for engineering applications. Specifically, the PTM may be used to investigate dredging processes and sediment pathways in coastal projects.

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POINTS OF CONTACT: For technical assistance, contact Dr. Zeki Demirbilek (601-634-2834, Zeki.Demirbilek@erdc.usace.army.mil) the focus area chairman, Dr. Joseph Gailani (601-634-4851, Joe.Z.Gailani@erdc.usace.army.mil) or the manager of the Dredging Operations and Environmental Research Program, Dr. Robert M. Engler (601-634-3624, Robert.M.Engler@erdc.usace.army.mil). This technical note should be cited as follows:

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