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PTM: Particle Tracking Model

Report 1: Model Theory, Implementation, and Example Applications

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Abstract: This report introduces a Lagrangian-based Particle Tracking Model (PTM) developed by the Coastal Inlets Research Program (CIRP) and the Dredging Operations and Environmental Research Program (DOER) being conducted at the U.S. Army Engineer Research and Development Center. The PTM's Lagrangian framework is one in which the sediment being modeled is discretized into a finite number of particles that are followed as they are transported by the flow. Lagrangian modeling is insightful for modeling transport from specified sources. Many particles are modeled such that transport patterns are representative of all particle movement from the sources. The model operates in the Surface-water Modeling System (SMS) interface and allows the user to simulate particle transport processes to determine particle fate and pathways. Waves and currents used in the PTM as forcing functions are developed through other models and input directly to the PTM. PTM Version 1.0 input files are from the ADCIRC or M2-D depth-averaged hydrodynamic models and STWAVE and WABED wave models. Other models can be used as input by first converting their output to ADCIRC, M2-D, or STWAVE and WABED formats.

The general features, formulation, and capabilities of PTM Version 1.0 are described in this report, including the basic components of the model, model input and output, and application guidelines. Other chapters of this report provide detailed information about the PTM's theory, numerical implementation, and examples that demonstrate the model's potential usage in practical applications. Sediment pathways are readily identified within the Lagrangian modeling framework of the PTM for conditions with sharp gradients in suspended solids (plumes, for example), where numerical diffusion in Eulerian models would require very small grid spacing to provide reliable solutions. The Lagrangian framework of the PTM is computationally advantageous, and the model can be run with a fraction of the computer execution time required by Eulerian models. Each particle in the PTM represents a given mass of sediment (not an individual sediment particle or grain), and each particle has its own unique set of characteristics. As a minimum, a particle must be defined with certain physical properties (e.g., grain size and specific gravity) and an initial position. The particles can also be given other characteristics that may be independent of the solution, and particles can be static or dynamic. Particles from sources being modeled (as opposed to the local, or native, bed sediment) are introduced, or released, into the domain from specified source locations. These sources are designed to permit modeling of a wide range of natural or anthropogenic processes in coastal and environmental studies.

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Preface

This report describes a modeling system being developed by the Coastal Inlets Research Program (CIRP) and the Dredging Operations and Environmental Research (DOER) Program. A corresponding interface in the Surface-water Modeling System (SMS) is also being developed. The PTM has application to dredging and coastal projects, including dredged material dispersion and fate, sediment pathway and fate, and constituent transport. This technical report describes theory and numerical implementation aspects of the PTM and includes five examples that demonstrate application of the PTM in engineering studies. Subsequent reports in the PTM series will provide model validation with field data from various U.S. Army Corps of Engineers (USACE) dredging-related studies.

The CIRP and DOER Programs are administered by Headquarters, USACE. Research and Development activities of the PTM are being conducted at the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS. The CHL Technical Director for CIRP and DOER was James E. Clausner. Program Managers for CIRP and DOER were Dr. Nicholas C. Kraus and Dr. Todd S. Bridges, respectively.

Model development was performed by Drs. Neil J. MacDonald and Michael H. Davies, of Pacific International (PI) Engineering, Ottawa, Canada, under contract to CHL. Interface development was performed by Dr. Alan K. Zundel and John D. Howlett. Principal Investigators and contract monitors for this work were Dr. Zeki Demirbilek, Coastal Entrances and Structures Branch (HN-HH), and Dr. Joseph Z. Gailani, Coastal Processes Branch (HF-CT), CHL. They were responsible for providing direction for and assembling, editing and reviewing this report. Drs. Zeki Demirbilek and Tahirih C. Lackey, and Jarrell Smith, HF-CT, provided examples for this report.

Work at CHL was performed under the general supervision of Jose E. Sanchez, Chief of Coastal Entrances and Structures Branch(HN-H); Dr. Rose M. Kress, Chief of Navigation Division; Ty V. Wamsley, Chief of Coastal Processes Branch (HF-C); Bruce A. Ebersole, Chief Flood and

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COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

List of Symbols

A_s, A_{ss}, A_{sb}	Coefficients
c_Δ	Velocity deficit coefficient
C	Concentration
C_0	Reference concentration
C''	Dimensionless Chézy coefficient
C_D	Drag coefficient
dt	Time-step
D	Characteristic grain size
\bar{D}	Mean grain size
D_{35}	Thirty-fifth-percentile surficial grain size (35% finer)
D_{50}	Median surficial sediment grain size
D_{90}	Ninetieth-percentile surficial grain size (90% finer)
D_{gr}	Dimensionless grain size
E_t	Turbulent diffusion coefficient
E_v	Vertical diffusion coefficient
$E_{t_{\min}}$	Minimum turbulent diffusion coefficient
f_e	Frequency of particle entrainment
f_p	Frequency of particle pickup
g	Gravitational acceleration
h	Flow depth
h_{active}	Thickness of the active transport layer of the bed
h_{burial}	Depth of burial of a particle
k'_s	Skin (or grain) roughness height
k''_s	Bed form roughness height
K_{burial}	Reduction factor to account for the possible burial of the particle
K_{E_t}	Scale factor for the turbulent diffusion coefficient
K_{E_v}	Scale factor for the vertical diffusion coefficient
K_{mixing}	Reduction factor to account for mixing within the active sediment transport layer

M	Mobility
M_b	Mixing enhancement coefficient for wave breaking
n	Sediment porosity
P_e	Probability of particle entrainment
P_p	Probability of particle pickup
q_p	Transport pickup or entrainment rate
q_s	Suspended transport rate
q_t	Total transport rate
s	Relative density ratio ($= \rho_s / \rho$)
t	Time
t_f	Fall time of a particle
t_p	Time required to pick up one full layer of material of particle grain size
t_w	Expected wait time between entrainment events for a particle on the bed
T	Transport parameter ($= M - 1$)
u_A	Horizontal advection velocity for particles
u'_A	Advection velocity for particles at time-step $n + \frac{1}{2}$
u_b	Advection velocity in the bed load layer
u_c	Advection velocity of the total load (i.e., centroid)
u_s	Advection velocity for suspended particles
u_D	Dispersion velocity for particles
u'_D	Dispersion velocity for particles at time-step $n + \frac{1}{2}$
u_*	Shear velocity
u'_*	Shear velocity associated with skin friction only
u''_*	Shear velocity associated with form drag only
u_{z_c}	Particle velocity when entrained at the centroid height
\bar{U}	Depth-averaged velocity
U_{cr}	Critical velocity
w_s	Particle fall velocity
w_A	Vertical advection velocity
w_D	Vertical diffusion velocity
x	Coordinate dimension

x_n	x position of particle at time-step n
x_{n+1}	x position of particle at time-step $n + 1$
x'	x position of particle at time-step $n + \frac{1}{2}$
z	Vertical coordinate
z_b	Thickness of the bed load transport layer
z_c	Height of the centroid of the total load transport distribution above the bed
z_p	Particle height above the bed
z_s	Height of the centroid of the suspended load transport distribution above the bed
z_0	Reference elevation
β	Dimensionless scale factor for Rouse concentration profiles
γ	Ratio of turbulent shear stress standard deviation to its mean
ζ	Free-surface elevation
η	Bed form height
η_b	Equilibrium bed form height
κ	Von Karman constant (≈ 0.4)
μ_τ	Mean of the turbulent shear stress
θ	Shields parameter
θ_{cr}	Critical Shields parameter
$\dot{\theta}_{cr}$	Critical Shields parameter adjusted for hiding/exposure effects
ν	Kinematic viscosity of the fluid
ξ	Hiding and exposure correction factor
Π	Random number uniformly distributed between 0 and 1
ρ	Fluid density
ρ_s	Sediment density
σ	Relative height above the bed ($= z/h$)
σ_o	Dimensionless reference height above the bed ($= z_0/h$)
σ_τ	Standard deviation of the turbulent shear stress
τ'	Combined wave-current shear due to skin friction
τ''	Combined wave-current shear due to form drag
τ'_c	Current-induced shear stress due to skin friction

τ_c''	Current-induced shear stress due to form drag
τ_{cr}	Critical shear stress
τ_t	Instantaneous turbulent shear stress
τ_w'	Wave-induced shear stress due to skin friction
τ_w''	Wave-induced shear stress due to form drag
ϕ	Mobilized angle of bed shear resistance
Ψ	Random number between 0 and 1 distributed according to a Rouse sediment concentration profile

1 Introduction

Pacific International (PI) Engineering has been contracted by the U.S. Army Engineer Research and Development Center (ERDC) to develop a Lagrangian-based particle transport model. This model, the Particle Tracking Model (PTM), is funded through two ERDC research programs, the Coastal Inlets Research Program (CIRP) and the Dredging Operations and Environmental Research (DOER) Program. The model operates in the Surface-water Modeling System (SMS) interface and allows the user to simulate particle transport processes to determine particle fate and pathways. The model uses waves and currents as forcing functions. Forcing functions are developed through other models and input directly to the PTM. PTM Version 1.0 input files are from the ADCIRC or M2-D depth-averaged hydrodynamic models and STWAVE and WABED wave models. Other models can be used as input by first converting their output to ADCIRC, M2-D, or to STWAVE and WABED formats.

The present report describes the general features, formulation, and capabilities of PTM Version 1.0. It identifies the basic components of the model, model input and output, and provides application guidelines.

Most sediment transport modeling techniques are developed in an Eulerian framework, i.e., one in which the solution is obtained at a fixed point in space. Such models compute sediment transport rates over the modeling domain and, based on gradients in these rates, can also compute the morphological evolution of the bed. Eulerian modeling tools are a key component of the engineers' analysis toolbox. A second, less frequently used but equally powerful tool is the Lagrangian modeling technique. The PTM is based upon the Lagrangian technique.

In general terms, a Lagrangian modeling framework is one that moves with the flow. The PTM's Lagrangian framework is one in which the sediment being modeled is discretized into a finite number of particles that are followed as they are transported by the flow. In a strict sense, particles and sediments are different quantities in the context of a particle tracking model. Henceforth, we shall refer to particles in this report, and reserve the nomenclature of sediments for Eulerian models. Lagrangian modeling is especially appropriate for modeling transport from specified

sources. Sufficient particles are modeled such that transport patterns are representative of all particle movement from the sources. In addition, sediment pathways are readily identified within the Lagrangian modeling framework. This modeling framework is appropriate for conditions with sharp gradients in suspended solids (plumes, for example), where numerical diffusion in Eulerian models would require very small grid spacing to provide reasonable solutions. Another advantage to Lagrangian frameworks is computational. Lagrangian models can be run with a fraction of the computer execution time required by Eulerian models although the circulation and wave fields must be precalculated. This makes them appropriate for simulating multiple alternatives.

Each particle in a Lagrangian transport model represents a given mass of sediment (not an individual sediment particle or grain), and each particle has its own unique set of characteristics. As a minimum, a particle must be defined with certain physical properties (e.g., grain size and specific gravity) and an initial position. The particles can also be given other characteristics that may be independent of the solution, and particles can be initially static or dynamic.

Particles from sources being modeled (as opposed to the local, or native, bed sediment) are introduced, or released, into the domain from specified source locations. These sources are designed to permit modeling of a wide range of natural or anthropogenic processes.

All particles are subjected to the hydrodynamic forcing. The complexity of the particle behavior within the flow is defined by the user. It can range from highly complex, where each particle is subjected to the same forces and exhibit the same kinematics as a single sediment particle, to simple cases where the particles are subjected to spatially-averaged forces and react more like the total mass of sediment in the water column. The material properties of the particles can also affect particle behavior.

The flow field must be prescribed as an input to the model. It can be complex or simple in resolution and dimensionality. In most applications, the input flow field will be two-dimensional (2-D) and depth-averaged, requiring approximation of the vertical structure of the flow. Waves can have a significant effect on particle transport, and these should be specified as appropriate.

Because the sediment particles being modeled interact with the surrounding environment, Lagrangian models must also perform some Eulerian, or mesh-based, calculations in order to estimate various quantities for native sediments. Examples of these are mobility and transport of native sediments and bed form development.

2 Model Design

Basic structure

The basic structure of the PTM is simple; a region (geometry) with bathymetric and sediment data is defined. Flow and, if applicable, wave data are supplied to the model, and particles are released into the flow. The computations then proceed through time, modeling the behavior (entrainment, advection, diffusion, settling, deposition, burial, etc.) of the released particles. There are two types of calculations performed at each time-step of PTM. Eulerian (mesh-based) calculations are required to determine the local characteristics of the environment, and Lagrangian (particle-based) calculations are required to determine the behavior of each particle. This procedure is represented in the flow diagram shown in Appendix A.

SMS interface

The PTM interface is operated in the SMS graphical user interface (Zundel 2005). The SMS interface gathers the required input file names and values, and it creates (or modifies) the program control file (.pcf), which contains all information necessary for a simulation. Program execution is initiated from the interface. A technical note describing use of the PTM within SMS (Demirbilek et al. 2005a) is included in Appendix B.

Two other technical notes have been published that describe the PTM's general features and capabilities (Davies et al. 2005) and give tutorials in its operation (Demirbilek et al. 2005b). These are included in Appendix C and D, respectively.

Bathymetric, hydrodynamic, and wave data

The PTM has been designed to accept two-dimensional (2-D) ADCIRC (Luettich et al. 1992) files for the domain geometry, bathymetry, currents, and water levels, and STWAVE (Smith et al. 2001) files for waves. Both these models are also operated within the SMS interface. Other hydrodynamic or wave output can be used if it is first converted to ADCIRC or STWAVE file format, respectively. The hydrodynamic and wave files must be finalized prior to the start of a PTM simulation.

The present version of the PTM requires that the mesh geometry and bathymetry file be in standard ADCIRC format (.14 or .grd). This mesh forms the solution domain. The PTM requires that these files be in the Cartesian coordinate system. Input files in geographic coordinates can be converted to Cartesian coordinates using the SMS interface. For directions on converting coordinates, one can use the Help command within SMS and review the topic: General Tools/Coordinates/Coordinate Conversions.

The PTM supports the **Extensible Model Data Format (XMDF)** hydrodynamic binary data format for currents and water levels in preference to the standard ADCIRC .63 and .64 format. The XMDF (.h5) format is random access and can significantly reduce run time. The SMS interface will automatically convert ADCIRC files to this file format when the user opens the files in the SMS interface.

The vertical distribution of the horizontal flow velocity is assumed to follow a logarithmic distribution with the near-bed velocity gradients being controlled by bed roughness (Yalin 1977).

The PTM accepts standard STWAVE files (.wav and .brk) for wave data input. Wave data are interpolated onto the finite element mesh by the PTM. The model can accommodate one layer of nesting, with the nested (inner) grid data used in preference to the outer grid data.

The PTM uses a calendar and clock-based time system to synchronize hydrodynamic, wave, sediment source, and simulation times. Each time-step in an ADCIRC output file includes a time stamp, but this time (in seconds) is relative to an arbitrary reference point that must be supplied to the PTM by the user. The time-steps in an STWAVE output file do not contain reference time information, so both the start time and duration between steps must be supplied to the PTM. Care should be taken in supplying these times, as well as the times for sources and simulation start and finish times.

Eulerian calculations

Various mesh-based quantities must be computed from the input flow and wave data and native sediment distribution. These Eulerian calculations are carried out over the domain defined by the finite-element mesh. Computed values include:

1. Framework calculations – establish background data such as water depth, flow velocities, frictional information, native (bed) sediment characteristics.
2. Bed form calculations – predict sub-grid scale bed forms over the domain.
3. Shear and mobility calculations – predict the influence of the flow field on the bed sediments over the domain.
4. Transport calculations – predict the potential sediment transport fluxes over the domain.
5. Bed change calculations – predict the local instantaneous rates of erosion and deposition of bed materials (expressed as the time rate of bed change, dz/dt) using the potential transport fluxes. These values characterize the local sediment transport environment of the bed material to determine the likelihood of burial of a particle.

Source releases

The material which is to be modeled in the PTM is released from sources. The amount of material released from each source is specified as a mass, either as an instantaneously released total mass or as a mass release rate over a given time period. The PTM represents this mass by a finite number of particles.

Particles can be introduced into the system via three different types of sources as point sources, line sources and area sources. There can be any number of any source type used in a simulation, and different source types can be specified in the same simulation.

There are two types of point sources: instantaneous and varying-release. If the material to be modeled is to be released at a single point in time, then an instantaneous should be specified. An example of this type of release is an accidental spill from a vessel. This type of release occurs at a fixed location, and the full release of material occurs at the time given and with the properties specified. If the release of material occurs over a period of time, then a varying-release point source should be specified. An example of this type of release is a leak from a pipeline. The characteristics of release point sources can vary with time (e.g., release rate, three dimensional positions, etc.). Varying-release point sources can be started, stopped, re-started, moved, etc., as directed in a source release schedule, which is developed through the SMS interface. The horizontal and vertical radii of both types of point sources can be specified in the source release schedule. If either radius is greater than zero, then the initial locations of

the individual particles are varied so as to produce a two- or three-dimensional Gaussian-distributed cloud.

Line sources must either be vertical or horizontal and are varying-release. Particles released from a line source will have a uniform distribution along the line and a two-dimensional Gaussian distribution in the plane perpendicular to the line. Line sources are specified by their end points. Line sources may move or change length, position, or discharge properties with time. Linear interpolation in time is used for most properties in a line source, but the characteristics of the release do not vary along the line source (e.g., the release rate of particles can vary with time for a line, but the rate will be the same over the length of that line). To model a line source with varying characteristics along the line, one could use a series of lines positioned end to end, each with different characteristics.

Area sources must lie on a vertical or horizontal plane and are varying-release. Area sources are polygons and are specified by the locations of their vertices. The vertices must be ordered with a counter-clockwise convention. Particles are released from an area source such that there is a uniform distribution over the area and a Gaussian distribution perpendicular to the source. Source properties within an area source are uniform across the polygon.

Lagrangian calculations

Lagrangian calculations are carried out for each particle active in the domain and include:

1. Flow calculations – interpolate the local flow and wave conditions at the particle's location. (Vertical flow velocity is estimated using the continuity equation if the input hydrodynamics are two-dimensional. Externally computed vertical flow velocity will be included when fully-3-D hydrodynamic input is incorporated into the PTM.)
2. Mobility calculations – determine the mobility of the particle and, if deposited, the likelihood of its entrainment in the flow using the flow and wave conditions at the particle's location.
3. Trajectory calculation – determine the position of the particle at the end of the time-step using an advection-diffusion routine with consideration of settling, deposition, and erosion. Particle inertia is not considered.
4. Boundary condition check – check that the particle's predicted path does not violate boundary conditions.

5. Sediment trap check – check whether the particle's destination falls within a sediment trap.

Modes of operation

The Lagrangian calculations identified in the above list are general. The PTM offers three options for determining how these calculations are performed: 2-D, quasi-three-dimensional (Q3-D), and 3-D. At present, the 3-D mode includes 3-D particle movement capabilities based on 2-D depth-averaged hydrodynamics. Three-dimensional hydrodynamic capabilities will be incorporated in a subsequent version of the PTM. The choice of model mode may have a significant effect on the results of a simulation.

The 2-D representation of particle motion is the simplest. It provides a preliminary assessment of particle motions and pathways. A 3-D approach is required for applications where interaction with the native bed is significant, or where the vertical movement and settling of sediment particles are concerned. The PTM offers Q3-D and 3-D approaches for modeling such conditions. The Q3-D mode involves a combination of empirical particle transport functions and a 3-D advection, settling, and dispersion routine to mimic some of the key 3-D transport processes. The 3-D mode performs more comprehensive 3-D particle entrainment, deposition, and re-suspension routines. The Q3-D mode requires less execution time than 3-D, because larger time-steps can be used. Unless the vertical location of the particles is important, in which case fully 3-D mode should be used, the decision as to which 3-D mode to use depends on properties and processes influencing the transport, and requires some judgment. Test cases using 3-D and Q3-D modes can be compared to determine if the more computationally efficient Q3-D mode is sufficient for a specific application.

Although these three modes differ in some of their transport algorithms, they are fairly similar in the computational time required to execute a single time-step. They differ significantly, however, in the size of time-step required to obtain a realistic simulation of transport processes. Because the 2-D mode does not perform vertical advection computations, it can tolerate relatively large time-steps. The 3-D mode simulates vertical trajectories of particles in detail and, therefore, requires a small time-step. The Q3-D mode was developed to simulate key 3-D 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 movements that a particle takes during a single time-step are not out of proportion to the scale of the transport processes of interest. Table 1 provides guidelines for maximum time-steps that may be specified in each mode of operation and for different particle grain sizes.

A maximum time-step of 300 sec is provided in Table 1 for 2-D mode. This value has been demonstrated as a reasonable upper bound for many open-water coastal and fluvial applications where trajectory is not expected to deviate significantly during the time-step. For Q3-D and 3-D modes, the limiting time-step is computed as the travel time for a sediment particle with the grain size D , and particle fall velocity, w_s , to cover the vertical resolution distance shown in the table. For Q3-D mode, a resolution of between 1 and 0.1 m is typically sufficient, whereas for 3-D mode, the resolution required depends greatly on the specific physical processes being simulated. Time-step requirements for vertical resolutions of 0.1 and 0.01 m for 3-D mode are provided in Table 1 for illustration. Time-steps Δt as short as 0.1 sec may be necessary when dealing with coarse-grained particles in cases where vertical resolution of the order of 1 mm is required. Note that these are guidelines, and actual time-step requirements need to be evaluated on a case-by-case basis. This can be done by simulating transport for a test case at several different time-steps and choosing the largest time-step that still reasonably represents the small time-step solution.

Table 1. Guidelines for selecting maximum time-step for various grain sizes.

Mode			2-D	Q3-D	3-D	
Vertical resolution required (m)			N/A	1	0.1	0.01
Sediment	D (mm)	w_s (m/sec)	Δt (sec)	Δt (sec)	Δt (sec)	Δt (sec)
Silts	0.01 - 0.06	0.00005 - 0.0024	300	300	45 - 300	4 - 200
Fine sand	0.07 - 0.12	0.0032 - 0.009	300	120 - 300	10 - 30	1 - 3
Med sand	0.13 - 0.5	0.01 - 0.07	300	15 - 100	1.5 - 10	0.15 - 1
Coarse sand	0.5 - 1	0.07 - 0.12	300	8 - 15	1 - 1.5	0.1 - 0.15

The 2-D, Q3-D, and 3-D modes of operation of the PTM are described in the following subsections. Also discussed is a neutrally-buoyant option that can be run in conjunction with the 3-D mode. Neutrally buoyant

particles represent dissolved constituents or fine particles or loose flocs in cases where total settling is negligible compared to simulation duration.

2-D 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 2-D mode gives an assessment of transport processes and pathways, and the maximum particle excursions.

In the 2-D mode, the sediment particles are independent of each other and do not interact with the native sediment. Erosion and deposition are controlled by the transport threshold (Shields curve or user-defined). This method neglects bed-particle interactions. Particles are considered to be mobile and are advected if the particle mobility, $M > 1$. If $M < 1$, the particle does not move. The mobility assessment includes a turbulent shear stress component, τ_t (see turbulent bed shear stress formulation in Chapter 3, “Model physical processes”). Advection velocity is based on the estimated advection velocities of bed load and suspended load (potential rates). Particles are assumed to be entrained from the bed instantaneously once the critical shear stress is exceeded. There is no vertical advection or settling; the vertical elevation of each particle is taken as the elevation of the centroid of the local sediment particle distribution. (The centroid height is unique to each particle size in the simulation, with finer particles tending to be entrained higher above the bed.) Horizontal particle advection is based on a depth-integrated interpretation of the sediment particle load.

Because there are no vertical trajectory calculations, longer time-steps can be specified in this mode than are required for the 3-D modes. This mode provides a fast and efficient model for identifying sediment pathways and zones of potential erosion or accretion. Zones of potential erosion can be identified by specification of an area source with similar characteristics to the bed sediments.

Q3-D mode

The Q3-D mode of the PTM involves more sophisticated transport processes than the 2-D mode. Stochastic characteristics of particle transport are considered.

In the Q3-D mode, the horizontal movement of particles is determined by the elevation of the particle above the bed, and it is reduced to represent sub-grid scale processes (e.g., frequency of pickup, frequency of entrainment, burial, and mixing with bed sediments). This reduction represents the possible interaction of the particle with the bed and has the effect of slowing the net horizontal transport. The vertical velocity of the particle is comprised of the vertical flow velocity, a random dispersion component and a fall velocity component that is directed towards the transport centroid. Hence, the vertical position of a particle in Q3-D mode is used primarily to influence its horizontal movement, rather than as a true measure of the vertical distribution of the source material. In depositional areas, the particle will settle toward the bed at the fall velocity calculated from characteristic grain size and fluid conditions (temperature, salinity, etc.). Particles depositing on the bed are re-entrained into the flow by means of a probabilistic technique. The frequency of entrainment is computed considering the particle pickup rate, the mixing depth of native sediment in the active transport layer, and the likelihood of burial by native sediments.

3-D mode

Particle behavior in 3-D mode is treated as behavior of an individual sediment grain (or floc) subject to gravitational and hydrodynamic forces. If the vertical elevation of the particles is important, then fully 3-D mode should be used.

The horizontal velocity of each particle is equal to the fluid velocity at the vertical elevation of that particle. The vertical velocity consists of the vertical flow velocity, a fall velocity component and a random dispersion component. (Vertical flow velocities are estimated using continuity if the input hydrodynamics are two-dimensional. Externally-computed vertical flow velocity will be included when fully 3-D hydrodynamic input is incorporated into the PTM.) Particles depositing on the bed are re-entrained into the flow using a probabilistic technique. The frequency of entrainment is computed considering the particle pickup rate, the mixing depth of native sediment in the active transport layer, and the likelihood of burial by native sediments.

Neutrally-buoyant option

This mode of operation of the PTM is designed to simulate particles with no fall velocity. As such, the model results should be interpreted only as representing very fine sediments or dissolved constituents. This mode can also be used to determine resident times (the cumulative amount of time that a particle spends within a given region). Neutrally-buoyant particles will be utilized more fully as the PTM is expanded to simulate dissolved contaminant transport.

Neutrally-buoyant particles are assumed to have no fall velocity and to be independent of each other. Horizontal advection velocity is based on the horizontal flow velocity at the position of the particle. There is no vertical fall velocity, but vertical position of the particle will vary because vertical flow and dispersion. (Vertical flow velocities are estimated using continuity if the input hydrodynamics are two-dimensional. Externally-computed vertical flow velocity will be included when fully 3-D hydrodynamic input is incorporated into the PTM.) Because there is less vertical movement, longer time-steps can be specified for this option than are required for the standard 3-D mode. The time-step values listed in Table 1 can be taken as a guide, but higher values might be specified.

Neutrally-buoyant particles are available only in 3-D mode, and these provide a useful tool for visualizing the behavior of flow fields generated by 2-D depth-averaged hydrodynamic models.

3 Model Physical Processes

This chapter describes the various PTM components and is divided into two sections. The first section, “Eulerian transport calculations,” describes processes that affect the native bed sediments (e.g., sediment mobility, bed form development, etc.). The second section, “Lagrangian transport calculations,” addresses processes that determine particle motions (e.g., mobility, entrainment, advection, dispersion and settling).

Eulerian transport calculations

Regardless of the calculations performed by the PTM for sediment particle advection, erosion, and deposition, there are several basic sediment transport parameters that must be defined for the study domain. These include near-bed flow conditions, bed shear, bed forms, and sediment particle mobility.

The Eulerian calculations can be performed using more than one technique. The choice between algorithms is user-defined and is controlled in the SMS interface through the *Eulerian Method* control (as demonstrated in Chapters 4 and 5, “Model Operation” and “Model Application,” respectively). This selection controls a number of Eulerian calculation techniques, including bed form growth and native sediment transport rates.

Roughness characterization

Bed roughness calculations in the model are based on the surficial sediment grain size. The median, or D_{50} , sediment grain size is used in the computation of bed forms, which produce form roughness. The ninetieth-percentile, or D_{90} , sediment grain size is used in the computation of skin roughness. These values are input and assigned to each node in the domain and may vary across the domain. Non-erodible areas (e.g., rock outcroppings) can be specified with an effective skin roughness height, k'_s , in place of a grain size. This data is specified on the *Hydro, Sediment, and Source Input* page of the model control within the SMS interface.

Shear stress

Shear stress is a function of the flow and sediment bed conditions. Four shear stress components are calculated in the PTM:

1. Current-induced shear stress due to skin friction, τ'_c .
2. Current-induced shear stress due to form drag, τ''_c .
3. Wave-induced shear stress due to skin friction, τ'_w .
4. Wave-induced shear stress due to form drag, τ''_w .

For the current-induced shear stress due to form drag, τ''_c , the form roughness height, k''_s , is estimated using a combination of the bed form length and steepness. The PTM implements methods described in van Rijn (1993) to calculate shear stress. An overview of these methods follows. The bed shear stress (Pa) can be calculated from the depth-averaged velocity, \bar{U} , as:

$$\tau''_c = \frac{\rho \bar{U}^2}{C''^2} \quad (1)$$

Here ρ is the water density, and C'' is the dimensionless Chézy coefficient, which for rough turbulent flow is approximated by:

$$C'' = 2.5 \ln \left[11 \frac{h}{k''_s} \right] \quad (2)$$

where h = flow depth (m).

The bed shear velocity, u_* (m/sec), is computed from:

$$u_* = \sqrt{\frac{\tau''_c}{\rho}} = \frac{\bar{U}}{C''} \quad (3)$$

For rough turbulent flows, the bed shear velocity, u_* , is dependent upon the flow depth, h , the characteristic roughness of the flow, k''_s and \bar{U} :

$$u_* = \frac{\bar{U}}{2.5 \ln \left(11 \frac{h}{k''_s} \right)} \quad (4)$$

For the current-induced shear stress due to skin friction, τ'_c , a roughness height, k'_s representative of the skin, or grain-size, roughness of the bed is used. In the PTM, skin roughness is taken as 3 times the D_{90} of the bed material for erodible beds, where D_{90} is the grain size that 90 percent of the sediment is finer (by weight). The model interface can override this value with a user-specified value.

The situation becomes more complicated in the case of combined wave and current flows. Quantifying frictional effects in flows with combined waves and currents cannot be regarded as independent tasks, but should take into account the influence of the interaction of the two flows. Near-bed wave-current interaction effects have been shown by numerous authors to modify energy dissipation and bed shear stresses significantly (e.g., Bijker 1966; Kemp and Simons 1982; O'Connor and Yoo 1988). For example, detailed near bed measurements show that there is a reduction of the near-bed current velocity due to the increase in eddy viscosity resulting from the presence of waves.

The PTM incorporates two different algorithms to compute the combined wave-current shears, τ' and τ'' . These are the algorithms of O'Connor and Yoo (1988) and van Rijn (1993). The techniques are complex, and the reader is referred to the original texts for a detailed description. The user selects the algorithms to use from the SMS interface through the *Eulerian Method* control. This selection controls a number of Eulerian calculation techniques, including growth of bed forms and native sediment transport rates. The O'Connor and Yoo (1988) technique is obtained by setting the *Eulerian Method* control option to "PTM," whereas the van Rijn (1993) technique is obtained by setting it to "Van Rijn." It should be noted that the group of techniques that comprise the "PTM" approach offer substantial computational advantages over the van Rijn techniques, especially in terms of solution speed. These techniques were assembled by members of the PTM development team at PI Engineering during the development of PTM and over the course of several studies on wave and tidally-driven transport processes including the St. Lawrence River (Davies and Watson 1997) and the North Sea (MacDonald 1998).

Threshold for initiation of motion

The threshold of motion for bed sediments and particles resting on the bed is commonly defined by the Shields curve (see Chapter 4 of Yalin (1977) for discussion), which is given by the dimensionless Shields parameter, θ as:

$$\theta = \frac{\tau'}{\rho g (s-1) D} \quad (5)$$

Here g is the gravitational acceleration, s is the relative density ratio of the particles, and D is the characteristic grain size. The dimensionless critical Shields parameter, θ_{cr} , is that value of θ at which the inception of sediment transport occurs and is given as:

$$\theta_{cr} = \frac{\tau_{cr}}{\rho g (s-1) D} \quad (6)$$

The shear stress at this point is the critical shear stress, τ_{cr} , corresponding to the inception of transport.

Soulsby and Whitehouse (1997) reexamined the Shields curve for predicting the inception of sediment transport as a function of the sediment dimensionless grain size, D_{gr} , defined as:

$$D_{gr} = D_{50} \sqrt[3]{\frac{(s-1)g}{\nu^2}} \quad (7)$$

Here D_{50} is the grain size at which 50 percent of the sediment is finer (by weight), and ν is the kinematic viscosity (sq m/sec) of the fluid.

Soulsby and Whitehouse (1997) presented the following analytic expression for θ_{cr} as a function of D_{gr} :

$$\theta_{cr} = \frac{0.30}{1 + 1.2 D_{gr}} + 0.055 \left[1 - e^{-0.02 D_{gr}} \right] \quad (8)$$

The solution to Equation 8 is shown in Figure 1.

Soulsby and Whitehouse (1997) also demonstrated that the same Shields criterion is applicable for wave action provided the shear stress is the peak orbital near-bed shear stress. Although Stive et al. (2005) suggested that the use of the Shields parameter for wave-induced transport is somewhat limited by its lack of inclusion of acceleration terms, this is a shortcoming that would be most significant for coarse materials, which are affected by relatively short waves. For sand-sized materials under a wide range of

wave conditions, the Shields curve approach provides a reasonable estimate of particle transport mobility.

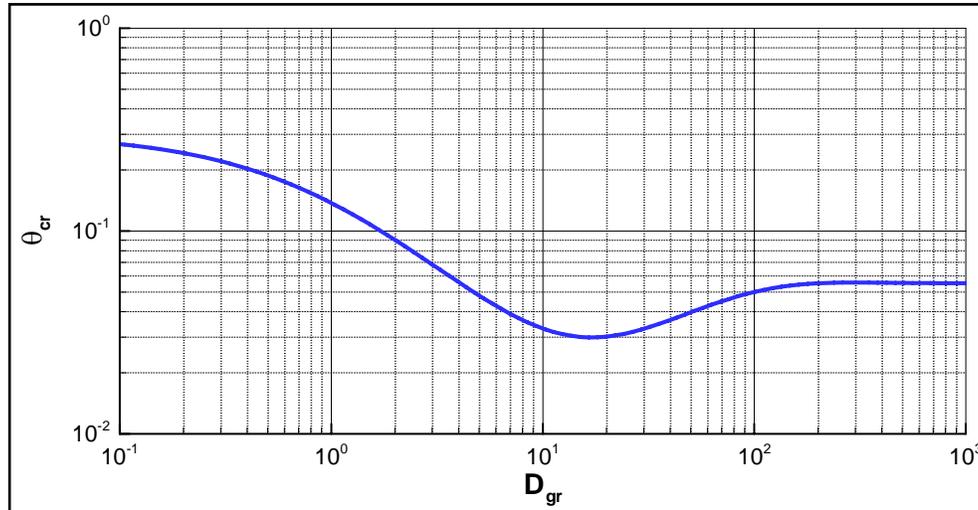


Figure 1. Sediment transport threshold under currents.

Transport mobility

The dimensionless mobility, M , is the ratio of the skin shear stress acting on the bed, τ' , to the critical shear stress, τ_{cr} , and is defined as:

$$M = \frac{\tau'}{\tau_{cr}} = \frac{\theta}{\theta_{cr}} \quad (9)$$

The critical shear, τ_{cr} (Pa), can be determined from:

$$\tau_{cr} = \theta_{cr} \rho (s - 1) g D \quad (10)$$

The dimensionless transport parameter, T , is also commonly used to assess sediment mobility. It is defined as:

$$T = \frac{\tau' - \tau_{cr}}{\tau_{cr}} = M - 1 \quad (11)$$

From the known distributions of the native (bed surface) sediments and the flow conditions over the domain, the mobility of the bed sediments (and particles on the bed) may be determined. Spatial and temporal maps of mobility can be useful engineering tools, and the SMS interface of the

PTM supports a user-selected option to allow these maps to be saved for viewing.

Bed form calculation

Estimating bed form geometry is necessary to calculate the shear stress due to form drag, τ'' , and the overall flow resistance offered by the bed. The equilibrium dimensions of bed forms under waves and currents are computed using the technique of van Rijn (1984c) for currents and the technique of Mogridge et al. (1994) for combined current and wave conditions.

Van Rijn's (1984c) bed form and roughness calculation methodology is as follows. The equilibrium bed form height, η_b , is determined on the basis of mobility, flow depth, and grain size:

$$\begin{aligned} \eta_b &= 0 & M &\leq 1 \\ \eta_b &= 0.11 h \left(\frac{D_{50}}{h} \right)^{0.3} [1 - e^{-0.5(M-1)}] (24 - M) & 1 < M \leq 24 & \quad (12) \\ \eta_b &= 0 & M &> 24 \end{aligned}$$

These are steady-state equations, predicting no bed forms for conditions where the mobility, M , is less than unity (no transport) and for high flow conditions where bed forms would be washed out ($M > 24$). Equation 12 is shown graphically in Figure 2.

Bed forms do not develop for very fine materials ($D_{50} < 0.05$ mm). In the PTM, it is assumed that if $D_{50} < 0.05$ mm, bed roughness is defined solely by skin friction and is as follows:

$$k'_s = 3 D_{90} \quad (13)$$

The model interface can override this value with a user-specified value, if desired.

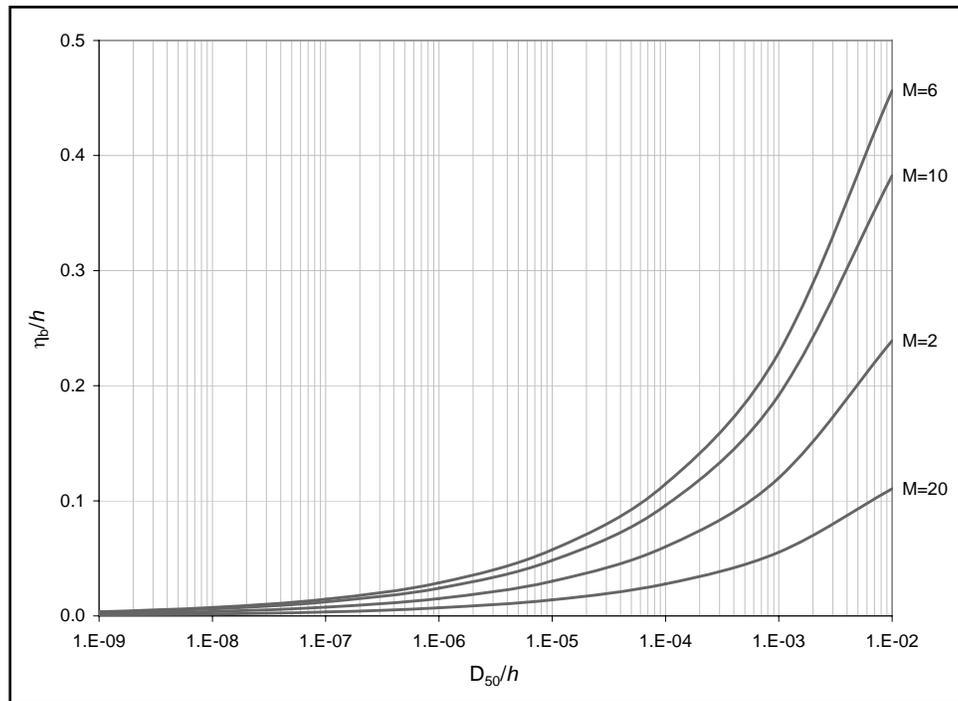


Figure 2. Van Rijn (1984c) prediction of bed form height as a function of relative depth for several mobility levels.

The above equations compute the equilibrium bed form height. In nature, bed forms continually adjust to changing flow conditions. The rate of change of bed forms is related to the local bed load transport rate (van Rijn 1984a; Nielsen 1992). In the PTM, a simple algorithm has been implemented to allow bed forms to gradually adjust from their present height to their new equilibrium height. The rate of change of bed form height is related to the overall transport rate. In this case, the PTM uses the transport pickup rate, q_p (m/sec), to estimate the maximum temporal rate of change of the bed. (See “Probabilistic particle-bed interactions” section for a description of sediment pickup rate.) At time t in a simulation, the bed form height, η , existing on the bed is compared to the equilibrium bed form height, η_b , from the predictive equations. If η is less than η_b , then the bed forms are growing; if η is greater than η_b , then the bed forms are decaying. The time rate of change of bed form height is then calculated as:

$$\begin{aligned} \frac{\partial \eta}{\partial t} &= -q_p & \eta > \eta_b \\ \frac{\partial \eta}{\partial t} &= q_p & \eta < \eta_b \end{aligned} \quad (14)$$

The bed form length is assumed to respond instantly to changes in flow conditions.

Potential transport rate

The PTM requires potential transport rates over the model domain to compute gradients in transport to estimate the potential for erosion and deposition of the native bed materials. These rates are used to determine the likelihood of burial of a sediment particle once deposited. This information, which can be output and mapped, is useful in its own right as an indicator of sediment transport conditions in the domain.

The PTM offers a choice of two techniques, Soulsby-van Rijn (Soulsby 1997) and van Rijn (1993), for the potential total load transport rate under combined wave-current conditions. The choice between algorithms is selectable in the SMS interface through the *Eulerian Method* control. The Soulsby-van Rijn technique is obtained by setting the *Eulerian Method* control to “PTM,” whereas the van Rijn technique is obtained by setting the control to “Van Rijn.” The group of techniques that comprise the PTM approach (developed by PI Engineering) offers substantial computational speed advantages over the van Rijn techniques.

The Soulsby-van Rijn total load sediment transport equation (Soulsby 1997) is:

$$q_t = A_s \bar{U} \left[\left(\bar{U}^2 + \frac{0.018}{C_D} \bar{U}_{rms}^2 \right)^{1/2} - U_{cr} \right]^{2.4} \quad (15)$$

where

$$A_s = A_{sb} + A_{ss} \quad (16)$$

$$A_{sb} = \frac{0.005h \left(\frac{D_{50}}{h} \right)^{1.2}}{[g(s-1)D_{50}]^{1.2}} \quad (17)$$

$$A_{ss} = \frac{0.012D_{50}D_{gr}^{-0.6}}{[g(s-1)D_{50}]^{1.2}} \quad (18)$$

$$C_D = \frac{0.4}{\left[\ln\left(\frac{h}{z_0}\right) - 1 \right]^2} \quad (19)$$

U_{cr} is the critical velocity, which is given as:

$$U_{cr} = \begin{cases} 0.19D_{50}^{0.1} \log_{10}\left(\frac{4h}{D_{90}}\right) & D_{50} < 0.5 \text{ mm} \\ 8.5D_{50}^{0.6} \log_{10}\left(\frac{4h}{D_{90}}\right) & D_{50} \geq 0.5 \text{ mm} \end{cases} \quad (20)$$

Particle transport calculations

In this section, the basic information necessary to enable the model to predict a particle's transport is introduced and discussed.

Certain calculations are performed differently for each mode of operation of the model. For example, advection velocity calculations in the 2-D and Q3-D modes require computation of the suspended and bed load sediment concentration profiles, whereas the 3-D mode computes advection velocity solely from the particle's position, independent of the local transport. Other calculations, such as for sediment fall velocity, are independent of the model's mode of operation.

Particle position

The PTM uses a second-order predictor-corrector technique to solve for particle position at time $t + dt$ for each of the three orthogonal dimensions x , y , and z . This is illustrated in the following example for the x dimension. The first stage of the scheme uses information at the particle's present position and time to predict the particle's position one-half time-step into the future, x' , as:

$$x' = x_n + \frac{1}{2}(u_A \ dt + u_D \ dt) \quad (21)$$

where u_A and u_D are the advection and diffusion velocities, respectively, at location x and time-step n . The second stage of the scheme uses information from this location over the full time-step:

$$x_{n+1} = x_n + u'_A dt + u'_D dt \quad (22)$$

where u'_A and u'_D are the advection and diffusion velocities, respectively, at location x' and time-step $n + \frac{1}{2}$. The computation of these velocities is dependent upon the mode of operation:

1. 2-D mode – uses the local horizontal velocity at the elevation of the centroid of the sediment transport distribution for sediment with the characteristics of the particle.
2. Q3-D mode – uses the local horizontal velocity at the elevation of the particle, which may be adjusted to account for bed-interaction (see the section Advection velocity).
3. 3-D mode – uses the local horizontal velocity at the elevation of the particle.

The calculation of the advection velocity for each mode of operation is described in the following sections.

Advection velocity

2-D mode

The 2-D and Q3-D modes require knowledge of the elevation of the centroid of the sediment transport distribution to compute horizontal advection velocities.

The particle load or concentration within the water column is the integral of the concentration, C (kg/m³), over depth:

$$C = \int_{z_0}^h C(z) dz \quad (23)$$

The transport rate is the product of concentration and velocity, and is given by:

$$\bar{q}_s = \int_{z_0}^h C(z) \bar{u}(z) dz \quad (24)$$

The mean particle advection velocity, \bar{u}_A , is determined from potential transport rate divided by the sediment load as:

$$\bar{u}_A = \frac{\int_{z_0}^h C(z) \bar{u}(z) dz}{\int_{z_0}^h C(z) dz} \quad (25)$$

This advection velocity can also be viewed as the velocity of the flow at the centroid of the particle transport rate distribution. Direct solution of this equation is too time-consuming to be implemented in the PTM. Therefore, a simpler approach has been adopted and as outlined next.

Suspended particle concentration profiles can be assumed to follow the form proposed by Rouse (1939) as:

$$\frac{C}{C_0} = \left(\frac{\frac{1}{\sigma} - 1}{\frac{1}{\sigma_0} - 1} \right)^{\frac{w_s}{\kappa\beta u_*}} \quad (26)$$

where σ is the relative height above the bed ($= z/h$), $\kappa = 0.4$, $\beta = 1$, and C_0 is the reference bed concentration at elevation σ_0 .

Rouse concentration profile shapes are considered to characterize the relative effects of particle size and shear stress on suspended concentration profile (Figure 3).

The product of the above concentration curves and assumed logarithmic velocity distribution have been integrated to determine the height of the centroid of the suspended load transport distribution, z_s , for values of $w_s/\kappa u_*$. Regression of the centroid height results in an expression for the centroid height of the suspended particle load, z_s , as a function of $w_s/\kappa u_*$ (Figure 4).

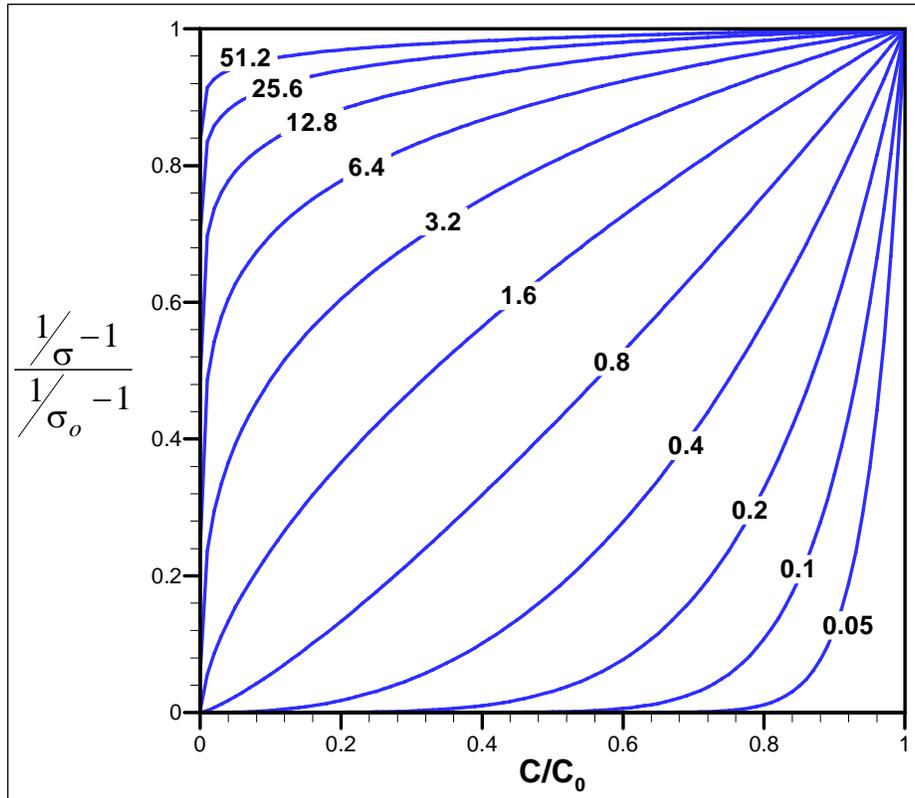


Figure 3. Rouse concentration distribution after Yalin (1977).
Lines are labeled by $w_s/\kappa U^*$ value.

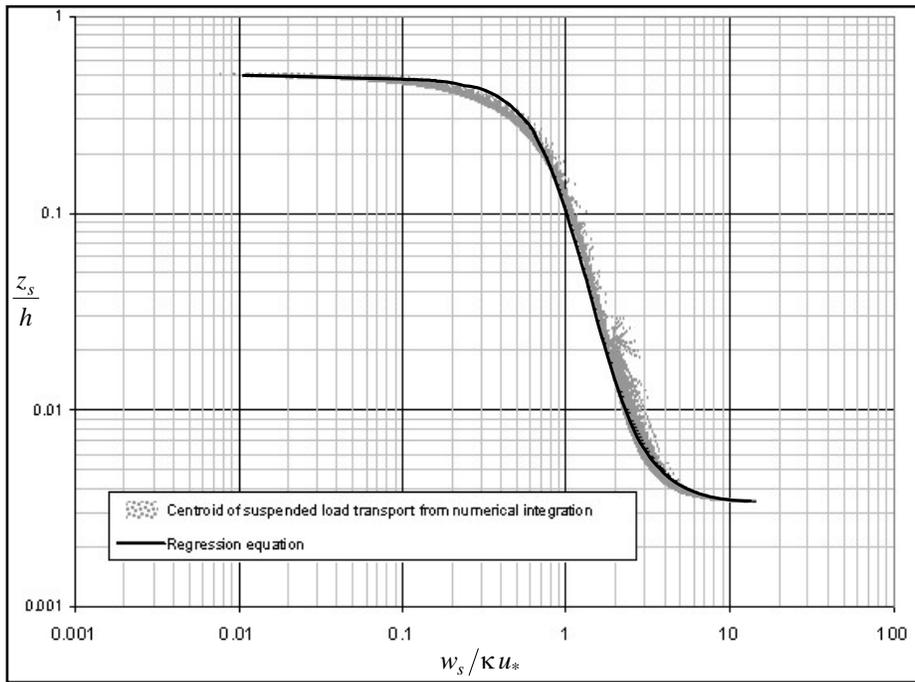


Figure 4. Relationship used to determine height of centroid of suspended particle load transport.

The resulting equation for the height of the centroid of the suspended load, z_s , is:

$$\frac{z_s}{h} = 0.0398 \cdot 10^{-1.08 \tanh \left[1.2 \ln \left(\frac{w_s}{\kappa u_*} \right) - 0.4 \right]} \quad (27)$$

Particle fall velocity (Figure 5), w_s (m/sec), is defined as a function of the dimensionless grain size, D_{gr} , and can be approximated by the following equations proposed by Soulsby (1997), which have been adapted for extremely fine grain sizes ($D_{gr} < 0.0672$) in the present work:

$$\frac{w_s D}{\nu} = \begin{cases} \sqrt{107.33 + 1.049 D_{gr}^3} - 10.36 & D_{gr} \geq 0.672 \\ 0.0077 D_{gr}^2 & D_{gr} < 0.672 \end{cases} \quad (28)$$

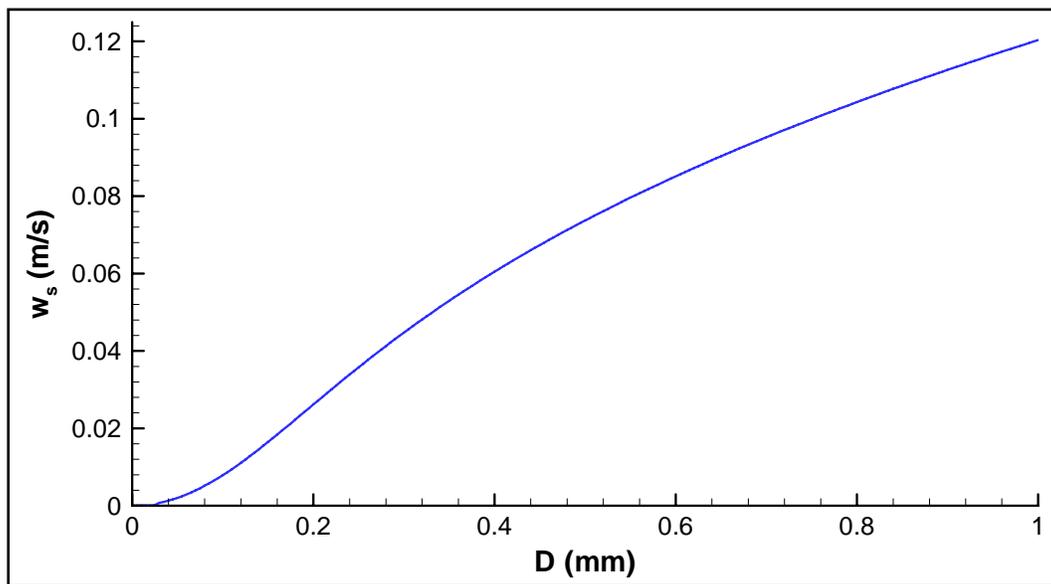


Figure 5. Fall velocity for sediments.

The speed of advection of the suspended load is u_s (m/sec), which is the velocity at elevation z_s (m) in a logarithmic profile.

$$u_s = 2.5 u_*'' \ln \left(30 \frac{z_s}{k_s''} \right) \quad (29)$$

Bed load is represented by a uniform layer of thickness propagating at speed, u_b (m/sec). Estimates of bed load velocity have been suggested by Yalin (1977), van Rijn (1984a), and Engelund and Fredsoe (1976). In the PTM, the bed load velocity is estimated using the relationship of Engelund and Fredsoe (1976).

$$u_b = u_*' \left(10 - \frac{7}{\sqrt{M}} \right) \quad (30)$$

The weighted average velocity of the total load is computed from the ratio of suspended load to total load, q_s/q_t . This ratio can be determined through integration of a predicted vertical profile of transport. However, a simpler relationship is shown as the curve superimposed on the following figure.

Figure 6 is adapted from van Rijn (1984b) and the data set of Guy et al. (1966). This curve has the following form:

$$\frac{q_s}{q_t} = 0.5 \tanh \left\{ 1.3 \left[\ln \left(\frac{u_*''}{w_s} \right) - 0.3 \right] \right\} + 0.5 \quad (31)$$

The advection velocity of a sediment particle is computed on the basis of the elevations of the bed load and suspended load components. The weighted advection velocity of the total load, u_c (m/sec), is obtained by the ratio of the suspended load to bed load as:

$$u_c = \frac{q_s}{q_t} u_s + \left(1 - \frac{q_s}{q_t} \right) u_b \quad (32)$$

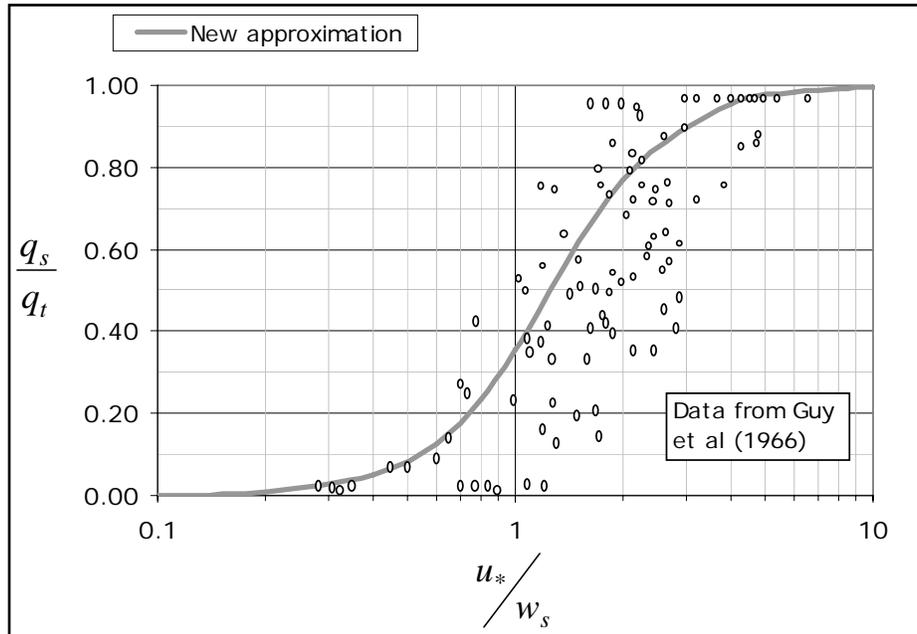


Figure 6. Ratio of suspended to total load.

The height above the bed at which the velocity occurs is computed assuming a logarithmic flow distribution of the form:

$$u(z) = u_*'' \left[5.75 \log_{10} \left(\frac{z}{k_s''} \right) + 8.5 \right] \quad (33)$$

This height is the transport centroid elevation, z_c (m), which can be given as:

$$z_c = k_s'' \cdot 10^{\left[0.1739(u_c/u_*'') - 1.47826 \right]} \quad (34)$$

The horizontal particle advection, \bar{u}_A , velocity for the 2-D mode is thus:

$$\bar{u}_A = u_*'' \left[5.75 \log_{10} \left(\frac{z_c}{k_s''} \right) + 8.5 \right] \frac{\bar{U}}{|U|} \quad (35)$$

This horizontal advection velocity is solved as a vector quantity in the model.

In 2-D mode, all particles travel at the elevation of the local instantaneous sediment transport centroid for their grain size, so there is no vertical velocity component to the advection velocity. Particles may move in the

vertical, however, because the centroid elevation above the bed will vary with changes in hydrodynamics.

Q3-D mode

In nature, a particle grain may be entrained upward into the flow by a burst of turbulence and then may settle back toward the bed where it may rest for some period of time before being re-entrained. This process results in net horizontal particle advection speeds that are slower than that of a continuously entrained particle. Explicit simulation of this advection retardation process is reproduced by determining the frequency of entrainment of a particle from the bed and computing the proportion of time a particle would be expected to be entrained by the flow. The advection retardation process is illustrated schematically in Figure 7.

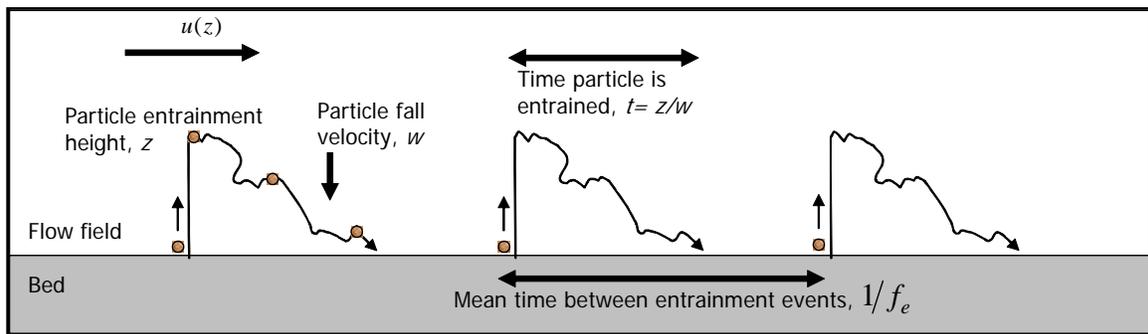


Figure 7. Advection paths for conditions for bed-particle interaction.

In Q3-D mode, the effect of particles settling to the bed and waiting to be re-entrained is represented implicitly by computing the relative proportion of time that the particle is expected to be entrained. Particles are assumed to be continuously drawn to the bed at the fall velocity, w_s .

The mean fall time, t_f of a particle from the transport centroid elevation z_c (a particle's expected vertical position) is estimated by:

$$t_f = \frac{z_c}{w_s} \quad (36)$$

The expected wait time between entrainments for a particle on the bed is t_w :

$$t_w = \frac{1}{f_e} \quad (37)$$

where f_e is the frequency of entrainment. A detailed description of the methodology for the computation of f_e is presented in the section “Probabilistic particle-bed interactions.”

The proportion of the time that a particle would, therefore, be expected to be entrained in the flow is:

$$\frac{t_f}{t_w} = \frac{z_c / w_s}{1 / f_e} = \frac{z_c f_e}{w_s} \quad (38)$$

A first-order approximation of the average advection velocity of a particle at elevation z_p can be expressed as the product of the entrained particle advection velocity, $u(z_p)$, and the proportion of the time it is entrained. In this approach, highly mobile particles ($z_c f_e > w_s$) will remain in motion and move at their expected advection velocity, u_{z_c} . In other words, particles are being re-entrained before they have time to fall to the bed. Particles that have lower mobility or relatively high fall velocity are expected to spend more time on the bed prior to re-entrainment; the average advection velocity of these particles is, therefore, reduced by a velocity deficit coefficient, c_Δ .

$$c_\Delta = \begin{cases} 1 & z_c f_e \geq w_s \\ \frac{z_c f_e}{w_s} & z_c f_e < w_s \end{cases} \quad (39)$$

That is, if $z_c f_e$ is greater than or equal to w_s , the particle stays entrained in the flow and does not interact with the bed. However, if $z_c f_e$ is less than w_s , the particle regularly settles to the bed and gets re-entrained, thereby reducing the horizontal particle advection velocity. This difference is represented computationally by:

$$\bar{u}_A = \begin{cases} c_\Delta \bar{u}(z_p) & 0 < z_p \leq z_c \\ c_\Delta \bar{u}(z_p) + \frac{z_p - z_c}{0.4z_c} (\bar{u}(1.4z_c) - c_\Delta \bar{u}(z_p)) & z_c < z_p \leq 1.4z_c \\ \bar{u}(z_p) & 1.4z_c < z_p \end{cases} \quad (40)$$

The horizontal advection velocity given by Equation 40 is shown graphically in Figure 8. The fluid velocity follows the vertical profile indicated by the dashed line in Figure 8. The near-bed zone starts at elevation $1.4z_c$ above the bed. A simple bilinear velocity deficit function is applied to decrease the velocity from $1.4z_c$ at the top of this near-bed zone to its value at the centroid height and zero at the bed. This horizontal advection velocity is solved as a vector quantity in the model.

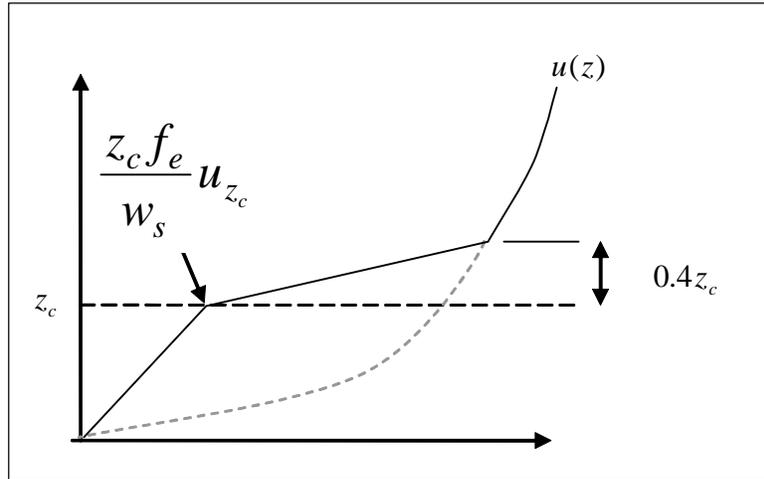


Figure 8. Velocity deficit model for horizontal particle advection.

Particles in the Q3-D mode are free to move in the vertical, but there is a tendency imposed on movement towards the local centroid elevation. The vertical advection velocity in the Q3-D mode is given by:

$$w_A = \begin{cases} w(z_p) - w_s & z_p > z_c \\ w(z_p) & z_p = z_c \\ w(z_p) + w_s & z_p < z_c \end{cases} \quad (41)$$

The local vertical flow velocity, $w(z_p)$, is estimated using continuity if the input hydrodynamics are two-dimensional:

$$w(z_p) = \left(\frac{1}{h} \frac{\partial \zeta}{\partial t} + \nabla U \right) (h - z_p) \quad (42)$$

where ζ is the free-surface elevation. Externally computed vertical flow velocity will be included when fully 3-D hydrodynamic input is incorporated into the PTM.

3-D mode

Particle behavior in fully 3-D mode is treated as behavior of an individual sediment grain (or floc), subject to gravitational and hydrodynamic forces. If the vertical location of the particles is important, then fully 3-D mode should be used.

The horizontal advection velocity of each particle in 3-D mode is equal to the fluid velocity at the vertical elevation of that particle.

$$\bar{u}_A = \bar{u}(z_p) \quad (43)$$

The vertical advection velocity in fully 3-D mode is:

$$w_A = w(z_p) - w_s \quad (44)$$

Vertical flow velocities are estimated using continuity if the input hydrodynamics are two-dimensional. Externally-computed vertical flow velocity will be included when fully 3-D hydrodynamic input is incorporated into the PTM.

Diffusion velocity

Horizontal diffusion

In the absence of more detailed information on eddy diffusivity from the hydrodynamic model, the PTM estimates lateral diffusivity independently of the hydrodynamic model. As presented in Fischer et al. (1979) and as applied by Shen et al. (1993) amongst others, the turbulent diffusion coefficient, E_t , is estimated to be:

$$E_t = K_{E_t} h u_*'' \quad (45)$$

The empirical coefficient K_{E_t} relates the turbulent diffusion to the local shear velocity and water depth. Typically, K_{E_t} ranges from 0.15 to 0.6.

Two modifications are made to the method given by Equation 45 for use in the PTM. First, a coefficient, M_b , which accounts for enhanced mixing due to wave breaking is included.

$$E_t = M_b K_{E_t} h u_*'' \quad (46)$$

This wave breaking coefficient is defined as:

$$M_b = \begin{cases} 1 & \text{outside surf zone} \\ 1 + K_{E_w} H_s & \text{inside surf zone} \end{cases} \quad (47)$$

where K_{E_w} is an empirical coefficient that relates the enhanced diffusion to the local significant wave height, H_s . Typically, K_{E_w} is set at 5. The location of the surf zone is taken as any non-zero area in the STWAVE *brk* file.

Second, the formulation presented in Equation 45 produces a diffusion coefficient E_t that increases proportionally with depth and shear velocity. In coastal applications, the shear velocity drops off rapidly as depth increases. Consequently, as particles are advected into deeper and quiescent water (e.g., toward the offshore limit of an ebb shoal), the eddy diffusion drops to near zero. A user-supplied minimum value of the eddy diffusion coefficient ($E_{t_{\min}}$) can be specified as a lower limit on diffusivity.

$$E_t = \max(E_{t_{\min}}, M_b K_{E_t} h u_*'') \quad (48)$$

The default value of $E_{t_{\min}}$ is taken as 0.02 m²/sec in the PTM.

Vertical diffusion. The vertical diffusion coefficient, E_v , is modeled using a parabolic-shaped distribution:

$$E_v = M_b K_{E_v} U \left[\frac{z_p (h - z_p)^2}{h^3} \right] \quad (49)$$

This equation is similar to Pritchard's method (Fischer et al. 1979) if the Richardson number is taken as 0. As was done with the horizontal diffusion, the vertical diffusion is limited as:

$$E_v = \max \left\{ E_{v_{\min}}, M_b K_{E_v} U \left[\frac{z_p (h - z_p)^2}{h^3} \right] \right\} \quad (50)$$

The default value of $E_{v_{\min}}$ is taken as 0 in the PTM.

Random walk model. This estimate of the turbulent diffusion coefficient is used to drive a random walk diffusion model. The random walk representation of the horizontal dispersive velocities u_D (and u'_D) are computed as:

$$u_D = 2(\Pi - 0.5) \sqrt{\frac{6E_t}{dt}} \quad (51)$$

where Π is a random number uniformly distributed between 0 and 1. Note that the horizontal dispersive velocities are isotropic. The vertical turbulent diffusion coefficient is taken as:

$$w_D = 2(\Pi - 0.5) \sqrt{\frac{6E_v}{dt}} \quad (52)$$

for a uniformly-distributed random number generator. If a Gaussian random number generator were to be used in Equations 51 and 52, the value 6 should be reduced to 4 to achieve the same dispersion.

Turbulent bed shear stress formulation

A probabilistic shear stress distribution is used to reflect the influence of turbulence on the shear stress imposed by the flow. The probability, p_τ , of a given instantaneous (turbulent) shear stress is given as:

$$p_\tau = \frac{\tau}{\sigma_\tau \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\tau - \mu_t}{\sigma_t} \right)^2 \right] \quad (53)$$

Equation 53 is used to quantify an instantaneous shear, τ_t , that follows a Gaussian distribution with a mean of μ_τ and a standard deviation of σ_τ .

The standard deviation of the shear stress fluctuation is:

$$\sigma_\tau = \gamma \mu_\tau \quad (54)$$

De Ruiter and van Mierlo (1980) and Bridge and Bennett (1992) found a value of $\gamma = 0.4$ from experimental flume work. In order to implement this feature in PTM, the time-step is included by setting $\gamma = 0.05 dt$. Figure 9 shows the shear stress range for calculated applied shear stress from 0 to 2 Pa.

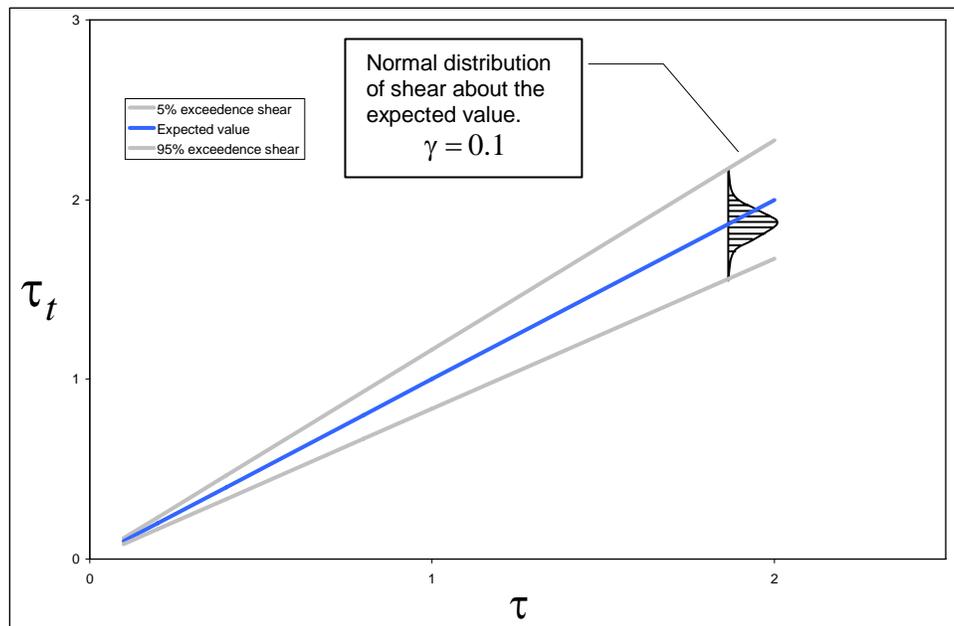


Figure 9. Variation in range of instantaneous (turbulent) shear stress with expected shear stress.

Hiding and exposure function

On a mixed bed with mean sediment size D_{50} , smaller particles hide behind larger particles and require a larger shear stress for the onset of mobility. Similarly, particles larger than D_{50} are more exposed and require a smaller shear stress for mobility. This is treated in the PTM by means of a hiding and exposure function (Egiazaroff 1965; Kleinhans and van Rijn 2002). The function is a correction factor, and it is applied to the critical shear stress for inception of motion as:

$$\dot{\theta}_{cr} = \xi \theta_{cr} \quad (55)$$

where ξ is a dimensionless hiding and exposure correction factor. The critical Shields parameter is a dimensionless representation of the shear stress acting on the particle and is computed using the approximation of Soulsby and Whitehouse (1997) (see the “Threshold for initiation of motion” section for discussion of the technique.) The hiding and exposure function is given by (Egiazaroff 1965):

$$\xi = \frac{5}{3} \left[\log \left(19 \frac{D}{D_{50}} \right) \right]^{-2} \quad (56)$$

This function is valid for $0.3 < D/D_{50} < 10$, and limits the particle’s mobility threshold to be no greater than 3 times and no less than one-third of the critical Shields parameter of that particle. Note that the hiding and exposure function is only applied to particles that are deposited on the bed.

Figures 10 through 12 illustrate how the hiding and exposure function affects θ_{cr} for beds of $D_{50} = 0.1, 1,$ and 10 mm.

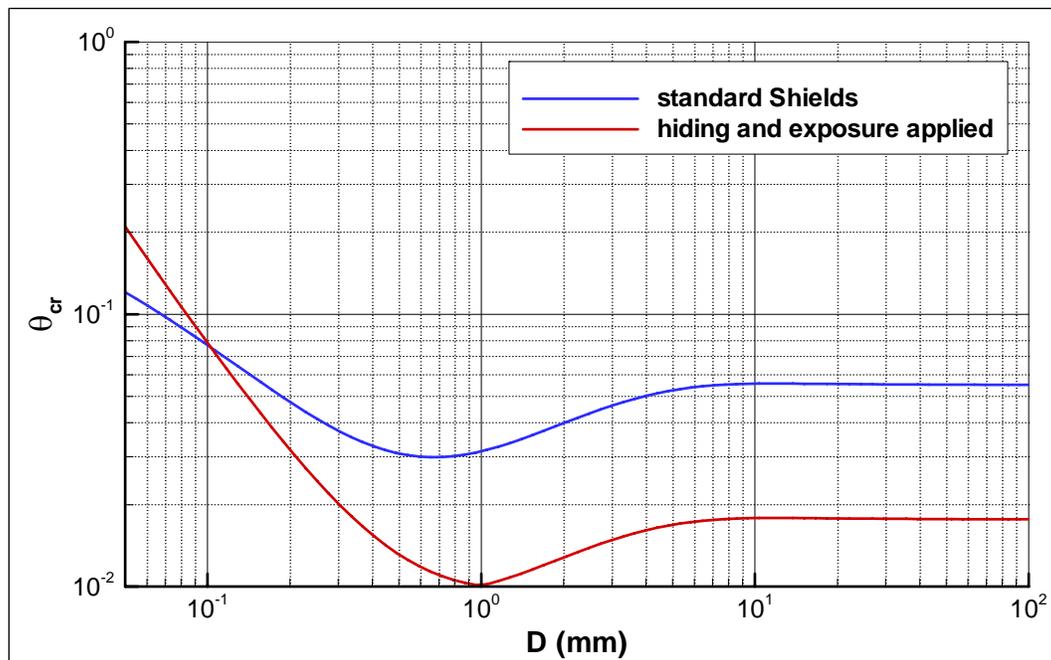


Figure 10. Comparison of Shields and hiding and exposure functions for $D_{50} = 0.1$ mm bed material.

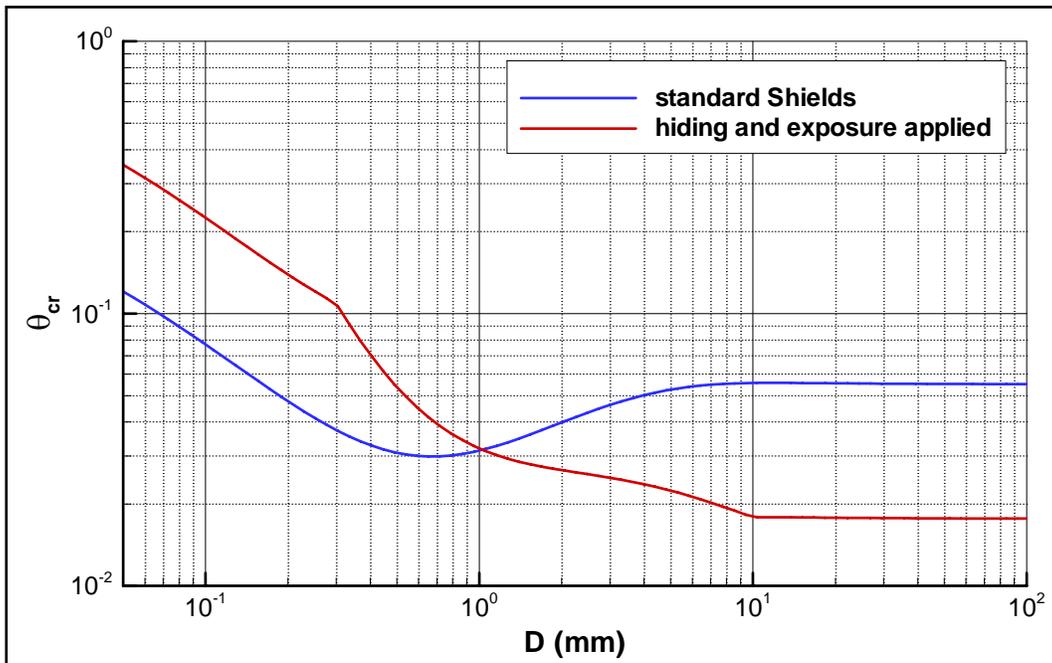


Figure 11. Comparison of Shields and hiding and exposure functions for $D_{50} = 1$ mm bed material.

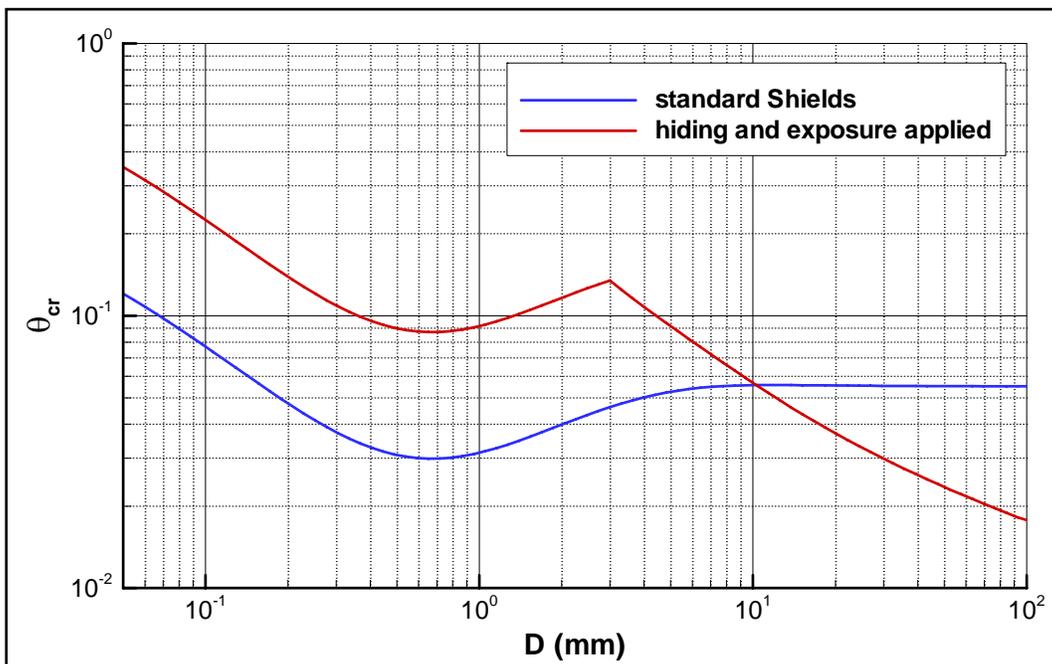


Figure 12. Comparison of Shields and hiding and exposure functions for $D_{50} = 10$ mm bed material.

Probabilistic particle-bed interactions

One of the challenges in a Lagrangian model is how to address interactions between a deposited particle and the bed on which it deposits and mixes. Unlike Eulerian models, sediment bed dynamics are not explicitly simulated in the PTM. To include this interaction within the PTM, a probabilistic approach is used. The frequency of entrainment of a particle from the bed is computed as a function of the potential transport rate for the particle. This is combined with other factors that account for the likelihood of mixing of the particle within an active transport layer and the likelihood of burial of the particle by ambient transport processes.

Frequency of entrainment

In the PTM, particle entrainment is based on the mean shear stress and the critical shear stress for erosion as defined by the Shields curve, as well as by the following five supplemental considerations:

1. The turbulent fluctuations in the instantaneous shear stress.
2. Modifications to the critical shear stress to account for hiding and exposure effects of graded sediment beds.
3. The transport pickup rate from the bed, q_p .
4. The ambient transport conditions on the bed (erosion/deposition), leading to an estimate of the depth of burial of the particle, h_{burial} .
5. Mixing of the particles within the active transport layer, which is based on the thickness of the active transport layer, h_{active} .

These have been implemented in a manner such that the frequency that a particle is picked up from the bed, f_e is determined as:

$$f_e = K_{burial} K_{mixing} f_p \quad (57)$$

In this equation, f_p is the frequency of pickup based on the estimated particle transport pickup rate for the particle. K_{mixing} is a reduction factor to account for the fact that the particle may lie anywhere within the thickness of the active sediment transport layer at the particle location. K_{burial} is a reduction factor to account for the possible burial of the particle by ambient sediments. The units of f_e are sec^{-1} or Hz. These processes are discussed in the following sections.

Pickup rate

The pickup function of van Rijn (1984b) is used to predict q_p , the particle entrainment rate, as:

$$q_p = 0.00033 \left(\frac{\theta_t - \theta_{cr}}{\theta_{cr}} \right)^{1.5} \left(\frac{(s-1)gD^3}{\nu^2} \right)^{0.1} \sqrt{(s-1)gD} \quad (58)$$

The units of q_p are m/sec. This estimate of q_p is based on the mobility and grain size of the particle. Note that Equation 58 is modified to use the turbulent Shields parameter, θ_t , which is computed using the turbulent estimate of the shear stress, τ_t , as:

$$\theta_t = \frac{\tau_t}{\rho g (s-1) D} \quad (59)$$

The time required to pick up one full layer of material of particle grain size, D , from the bed is t_p , which is given by:

$$t_p = \frac{D}{q_p} \quad (60)$$

The frequency that a particle will be picked up from the bed in any given time interval is calculated by:

$$f_p = \frac{q_p}{D} \quad (61)$$

This frequency, for various values of grain size diameter and mobility function, M (see Equation 9), is illustrated in Figure 13.

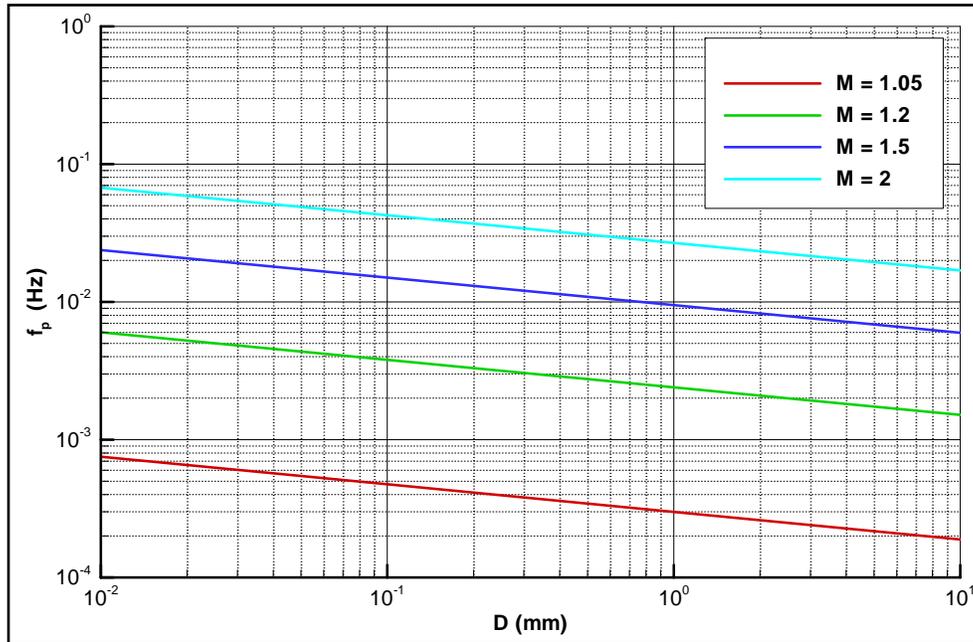


Figure 13. Variation of frequency of pickup with grain size and mobility.

Active layer depth

The mechanics of the active layer of particle transport at the bed are modeled after the shear-sliding model of Wilson (1987). Once the critical shear stress for the inception of particle transport is exceeded, the shear stress applied to the bed mobilizes a thickness of particles. Frictional resistance to sliding is provided by the internal shearing resistance of the soil. The thickness of the active layer, h_{active} , is the depth of bed mobilized to resist the excess shear applied at the top of the bed.

$$h_{active} = \frac{\tau_t - \tilde{\tau}_{cr}}{\rho(s-1)(1-n)g \tan \phi} \quad (62)$$

Here, $\tilde{\tau}_{cr}$ is the critical shear stress of the bed particles, n is the sediment porosity, s is the relative density of the sediment, and ϕ is the mobilized angle of shear resistance. The latter quantity is assumed to be equal to the dynamic angle of repose of Bagnold (1966) and is set to 18 deg, based on laboratory studies. Using standard values for the quantities in Equation 62, this can be approximated as:

$$h_{active} \approx 5(\theta_t - \tilde{\theta}_{cr})D \quad (63)$$

This mixing depth affects the frequency of particle entrainment; the thicker the mixing depth, the higher the number of candidate particles for removal and, hence, the lower the probability of any individual particle being removed. This relationship is expressed as the mixing factor, K_{mixing} as follows:

$$K_{mixing} = \begin{cases} \frac{D}{h_{active}} & h_{active} > D \\ 1 & h_{active} \leq D \end{cases} \quad (64)$$

Influence of bed level change on entrainment

Total load transport under waves and currents is computed over the Eulerian mesh with the van Rijn – Soulsby technique (Soulsby 1997). Erosion and deposition potential, which is expressed as the rate of bed change, is computed from the gradients in total load. These calculations are done on an elemental scale (i.e., computed on the input finite-element mesh).

The rate of bed level change allows estimation of the erosion or deposition occurring at the bed location of any deposited particle. If a particle is resting on the bed, the rate of erosion or deposition at the particle location is integrated over time starting from the instant the particle lands on the bed. The likelihood of particle entrainment diminishes as the particle is covered by local deposition. Once the particle is below the mixing depth, the likelihood of entrainment goes to zero. If conditions at the particle location become erosional, this process is reversed: the likelihood of entrainment increases linearly from zero (when the particle is at the mixing depth or lower) to one (when the particle is exposed on the upper surface of the bed).

The erosion or deposition rate, dz/dt , is used to compute the elevation of the bed within the active layer (or below it).

$$h_{burial} = \int_{t_0}^t \frac{dz}{dt} dt \quad (65)$$

From Equation 65, the position of the particle within the active layer can be determined and the frequency of entrainment, f_e , modified accordingly. If the value of dz/dt is negative, the particle is assumed to stay at the top of the bed with no reduction in the likelihood of entrainment. However, if the value of dz/dt is positive, the particle becomes buried, and the likelihood of entrainment diminishes with burial depth into bed. The likelihood of entrainment becomes zero if the depth of burial is equal to, or greater than, the active layer depth.

$$K_{burial} = 1 - \frac{h_{burial}}{h_{active}} \quad 0 \leq K_{burial} \leq 1 \quad (66)$$

Particle deposition

In 2-D mode, particles are deposited if the local mobility falls below critical for that particle. In Q3-D and 3-D modes, particles are deposited on the bed once they pass below one-quarter of the skin roughness height.

$$\text{if } z_p \begin{cases} < \frac{k'_s}{4} & \text{particle deposits} \\ \geq \frac{k'_s}{4} & \text{particle remains active} \end{cases} \quad (67)$$

If a particle becomes deposited, it will cease to move until it is re-entrained.

Particle re-entrainment

Particles that deposit on the bed can be re-entrained into the flow under certain circumstances. The PTM performs a series of checks on each deposited particle each time-step to determine whether that particle should be re-entrained. This section outlines the methods used to determine re-entrainment for each mode of operation.

2-D mode

Deposited particles are re-entrained if the local mobility is greater than critical. Particle vertical position increases in the water column with the increase in elevation of the sediment transport centroid.

Q3-D mode

Particles deposited on the bed in the Q3-D mode are re-entrained into the flow using a probabilistic technique. The frequency of entrainment, f_e , is computed considering the particle pickup rate, the mixing depth of native sediment in the active transport layer, and the likelihood of burial by native sediments. Details of the computation of f_e are presented in the “Probabilistic particle-bed interactions” section.

If the PTM is run with particle-bed interactions active, then a test is performed each time-step on each deposited particle to determine whether the particle should be re-entrained.

$$\text{if } \Pi \begin{cases} < f_e \cdot dt & \text{particle re-entrained} \\ \geq f_e \cdot dt & \text{particle remains deposited} \end{cases} \quad (68)$$

The entrainment elevation is set to the centroid elevation, i.e., $z_p = z_c$.

If the PTM is run with particle-bed interactions inactive, then deposited particles are assumed to be instantaneously re-entrained to the centroid elevation, if their mobility is greater than unity.

3-D mode

Particles depositing on the bed in the 3-D mode are re-entrained into the flow using a probabilistic technique. The frequency of entrainment, f_e , is computed considering the particle pickup rate, the mixing depth of native sediment in the active transport layer, and the likelihood of burial by native sediments. Details of the computation of f_e are presented in the “Probabilistic particle-bed interactions” section.

If the PTM is run with particle-bed interactions active, then the test given in Equation 68 is performed each time-step on each deposited particle.

The entrainment elevation is computed using a Rouse-type random number generator. This generator will produce random numbers that are distributed according to a Rouse sediment concentration profile for the specific sediment and flow conditions (see Equation 26). As a result, the random numbers will be biased towards 0 (taken as the bed) rather than 1

(taken as the surface). An example of the distribution of random numbers produced by this technique is shown in Figure 14.

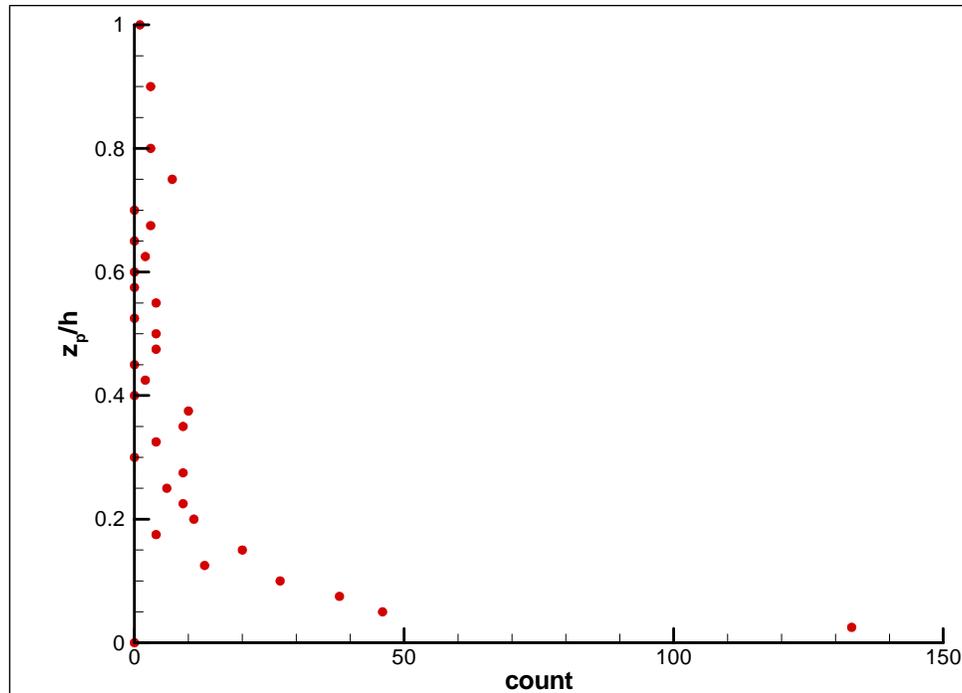


Figure 14. Example of Rouse-type random number generator output.

The new elevation of a re-entrained particle is taken as:

$$z_p = \Psi h \quad (69)$$

where Ψ is a random number between 0 and 1 distributed according to a Rouse sediment concentration profile.

If the PTM is run with particle-bed interactions inactive, deposited particles are assumed to be instantaneously re-entrained, and the test in Equation 68 is not performed. The elevation of entrainment is given by Equation 69.

The influence of particle-bed interaction is shown in Figure 15. This plot shows the average sediment advection velocity as a function of mean flow velocity for two simulations using the 3-D advection mode. The depth of flow is 10 m, and the particles were released 1 m above the bed. The released particles have uniform diameter of 0.1 mm. The bed is mobile and $D_{50} = 0.2$ mm. The simulation with particle-bed interaction turned off has an average sediment advection nearly equal to the flow velocity, which is

to be expected for a particle of this size. With particle-bed interaction turned on, particle advection rates are decreased because the particles mix with the bed sediments.

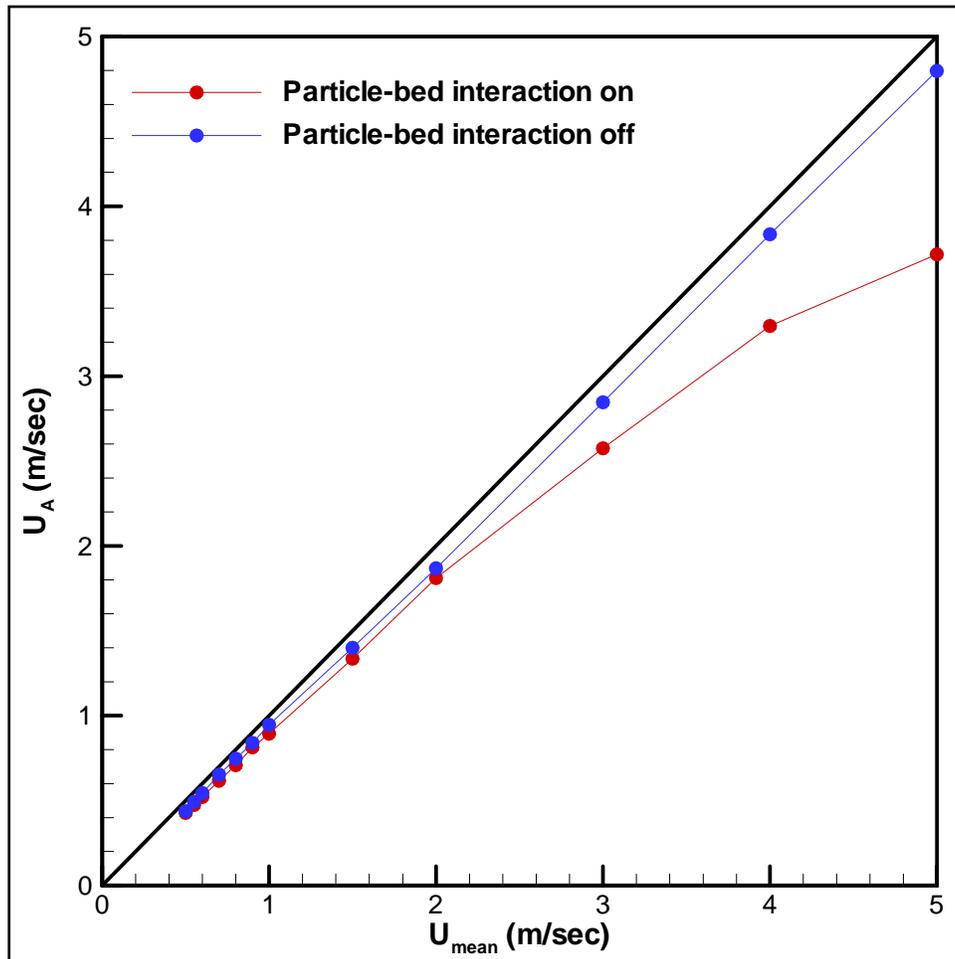


Figure 15. Influence of particle-bed interaction on sediment advection.

Figure 16 compares sediment advection velocities for four particle sizes. All simulations have particle-bed interaction turned on; other test parameters are as described above. Larger diameter particles are advected more slowly. The reduction in transport near $\bar{U} = 2.0$ m/sec is due to the change in bed form height and its impact on flow shear.

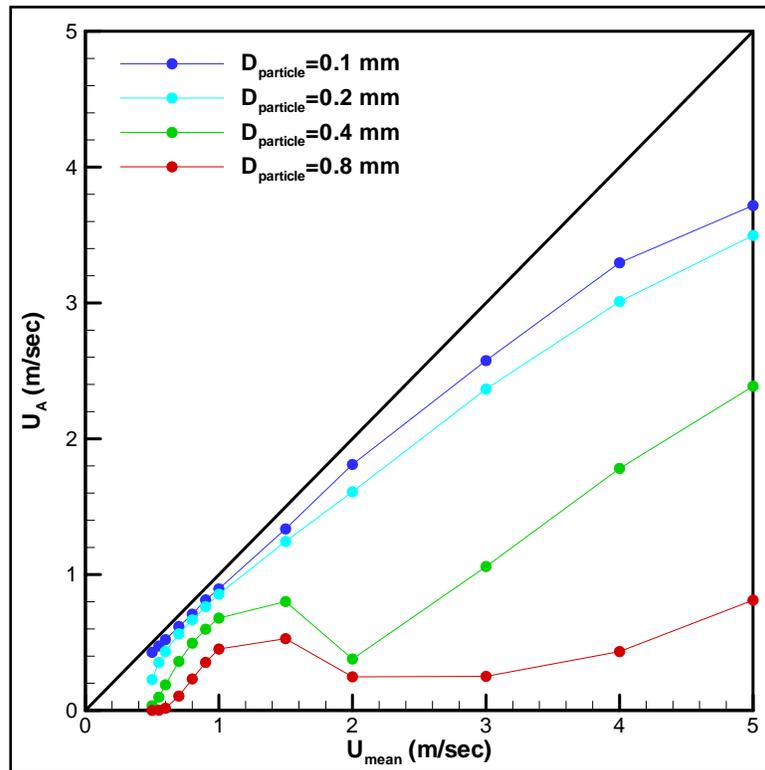


Figure 16. Comparison of sediment advection for a range of grain sizes.

Boundary conditions

The PTM uses the land and open boundaries given in the ADCIRC mesh file. Particles may pass through an open boundary. If a particle passes through an open boundary, it ceases to be included in the computation.

A particle may not pass through a land boundary. The ADCIRC flow patterns should not cause particles to be directed across solid boundaries. However, if because of large time-steps, the advection-diffusion routines do predict a particle trajectory that intersects a land boundary, it should be caught by one of a number of tests performed. The particle will be placed alongside the boundary in question. The meaning of boundary in this section is mesh boundary (element on a boundary). If a particle is driven onto a dry point, it becomes stranded. Wetting and drying are included, if the original hydrodynamic model was run with this capability.

4 Model Operation

The PTM is operated through the SMS graphical user interface (Zundel 2005). The SMS interface gathers the required run-time information and file names, and creates or modifies the various input files. Program execution is initiated from within the interface. In this section, the basics of the PTM control dialogue are presented, together with the information required for each of these files. This is done to assist in their construction within the SMS. A separate technical note describing use of the PTM within the SMS (Demirbilek et al. 2005a) is included in Appendix B.

Model setup and input files

The PTM requires a number of input files depending upon the characteristics of the simulation, although all simulations must have a minimum set of files. This minimum set of files includes:

1. A program control file (.pcf) that contains run-time instructions for the model. The construction of this file constitutes the majority of the work in setting up a PTM simulation. This file is written by the SMS interface and is described in the following section.
2. A geometry file containing the bathymetry and boundary information for the model. This file must be an ADCIRC compatible three-noded triangular finite element mesh (i.e., a .14 or .grd file) in Cartesian coordinates and S.I. units.
3. An element neighbor file. The model writes this file at the time of first execution on a new mesh file. This file only needs to be regenerated if the node or element structure (e.g., number of nodes or elements, or connectivity) changes. The generation of this file can be time-consuming for very large meshes, so it is read from disk in subsequent simulations.
4. Hydrodynamic input files containing the time-varying free-surface elevation and depth-averaged velocities.
5. A native (bed) sediment file containing information about the native sediments over the domain defined by the mesh file. This file can be written by SMS if required.
6. A sediment-source file containing information about the sediment sources. This file is created in the SMS interface's Map module.

Additional files may also be used.

1. Wave files containing information about the wave field. At present, only STWAVE and WABED files are supported.
2. A trap file detailing information about locations where information about the simulation should be extracted. These perform in a manner analogous to a sediment trap in a physical model or field study – capturing or noting the sediments that either pass through or are deposited within a user-defined area.

Program control file

The program control file contains all the necessary control data and input/output file information for a PTM simulation.

A PTM simulation is started by selecting [*PTM / New Simulation*] (Figure 17). This will establish a particle data set and enable the selection of PTM model control by selecting [*PTM / Model Control*] (Figure 18). This will open a blank PTM simulation dialogue window (Figure 19). All simulation setup (with the exception of the sediment sources and traps, if specified) is done by filling in the fields on the pages of the PTM model control.

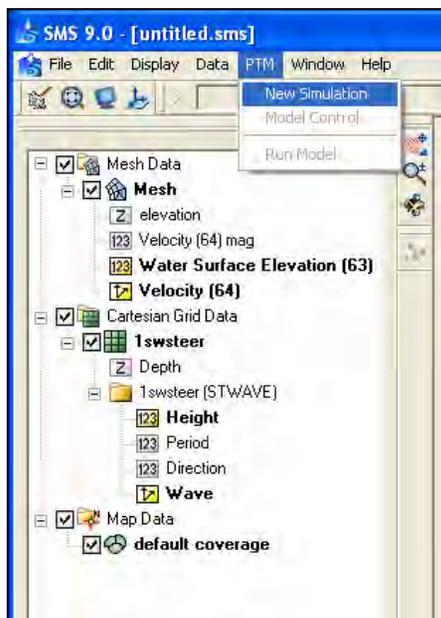


Figure 17. Initiating a PTM simulation.

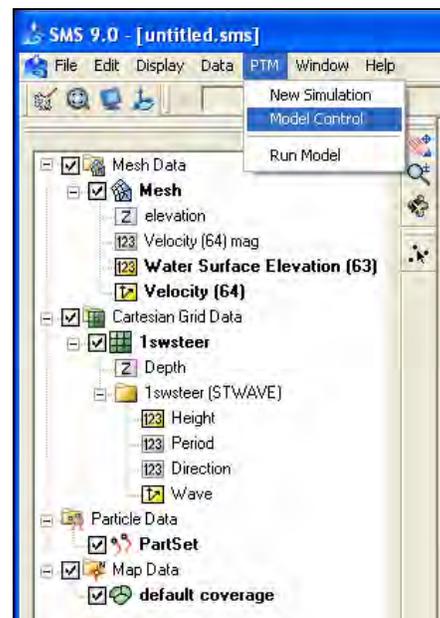


Figure 18. Selecting the PTM model control.

The program control file (with extension .pcf) is saved to disk by SMS prior to execution or by selecting [*File | Save PTM*] from the menu.

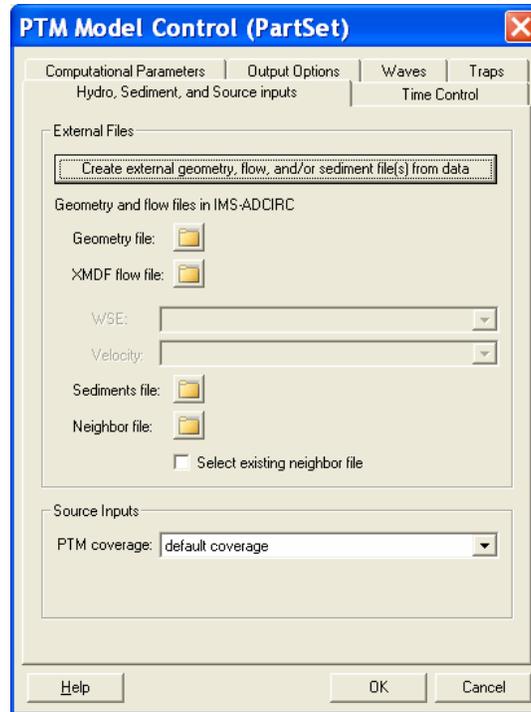


Figure 19. PTM model control window at initialization.

The main input files (geometry, hydrodynamics, and sediments) are identified on the *Hydro, Sediment, and Source Input* page. The native bed sediments file can be generated if one is required. Files are input by selecting the file browser button (). The initial page is shown in Figure 19 and a completed page is shown in Figure 20.

The source coverage (i.e., the location and schedule of the sediment sources) is also identified on this page. A source coverage must be created in the Map module before it can be identified on this page. The ADCIRC mesh and results file and, if required, the STWAVE input files, should be opened in the SMS environment prior to starting a PTM simulation, so that sources can be specified.

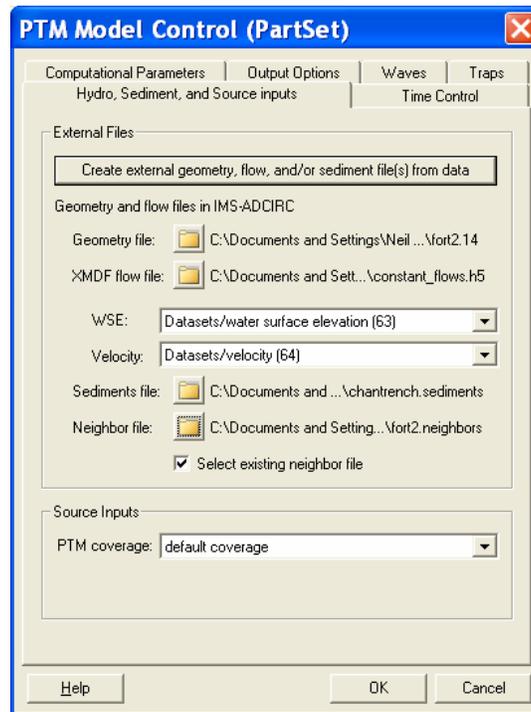


Figure 20. Example completed *Hydro, Sediment, and Source Input* page.

The *Time Control* page (Figure 21) is used to input the start time, stop time, and time-step of the simulation. It is also used to input the start time of the input ADCIRC hydrodynamics file. This time is required because the PTM uses UTC time, whereas time-steps in an ADCIRC file are relative to an arbitrary reference time that was identified when the ADCIRC run was created. It is anticipated that future developments of the ADCIRC – SMS interface will support the specification of UTC times throughout the development and analysis of ADCIRC simulations.

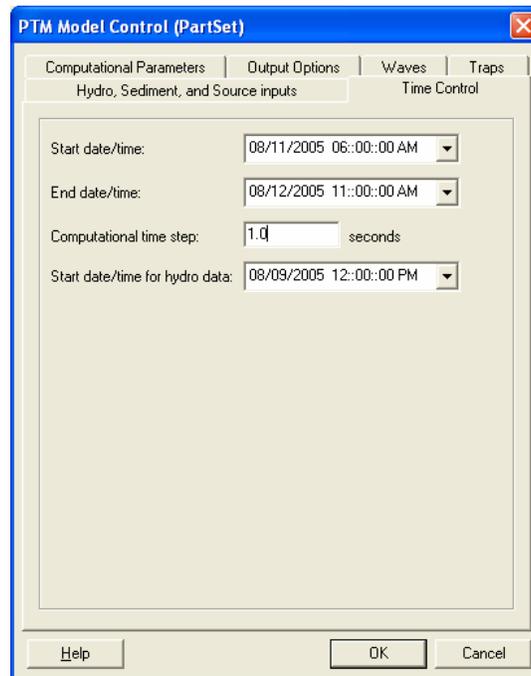


Figure 21. Example completed *Time Control* page.

The *Computational Parameters* page controls how the model performs the simulation. The *Computational Methods* panel controls four run-time flags:

1. The *Distribution* box controls whether the model synthesizes sediment particles to match the given particle size distribution by weight or by diameter (preferred). The particle size distribution characteristics are unique for each stage of each source and are given in the source file, which is created in the Map module.
2. The *Centroid* box controls whether the model computes the sediment transport centroid height above the bed using equations from van Rijn or from Rouse (preferred).
3. The *Eulerian* box controls whether the model computes a number of sediment-based parameters using equations from van Rijn or various techniques selected for PTM (preferred, see “Eulerian transport calculations” in Chapter 3 for details). These parameters are subsequently output to generate temporal and spatial maps of transport conditions.
4. The *Advection* box controls whether the model uses a 2-D, Q3-D or 3-D advection technique (see “Modes of operation,” Chapter 2 for details).

The *Computational Parameters* panel (Figure 22) controls various coefficients and three routines that influence particle interactions (see

“Particle transport calculations,” Chapter 3 for details). The bottom box on the page controls how often the Eulerian calculations are performed on the bed. This value has a significant effect on the model speed and should not be set too small. A reasonable update period for cases with tidal flows that are primarily semi-diurnal is 30 min.

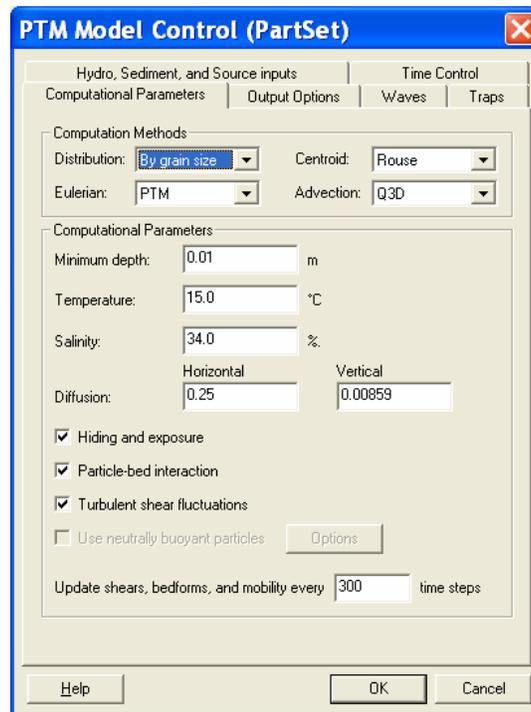


Figure 22. Example completed *Computational Parameters* page.

The *Output Options* page controls which data are stored to disk for later analysis and visualization (Figure 23). These values can have a significant effect on the model run time. If a large number of particles are used or if the mesh is very large, too much output data may substantially increase run time and disk storage requirements. The mapping output increment should be at least as large as the updating increment set on the *Computational Parameters* page.

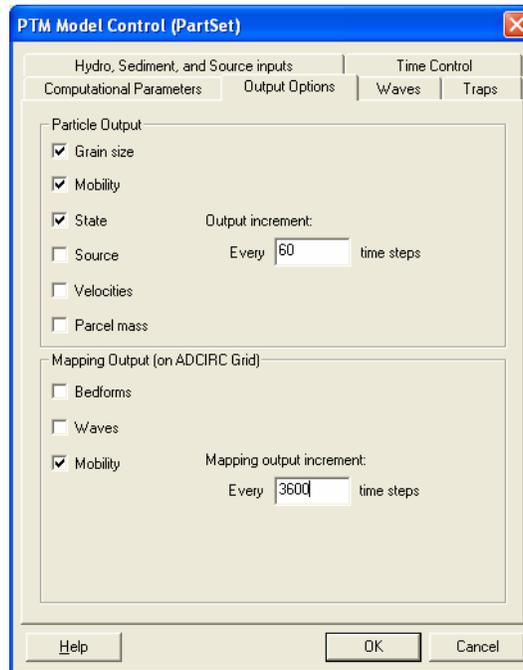


Figure 23. Example completed *Output Options* page.

If waves are used, the *Waves* page needs to be completed. Wave model geometry can be obtained automatically by pressing the From STWAVE/WABED Grid button (Figure 24). The wave grid file must already be open.

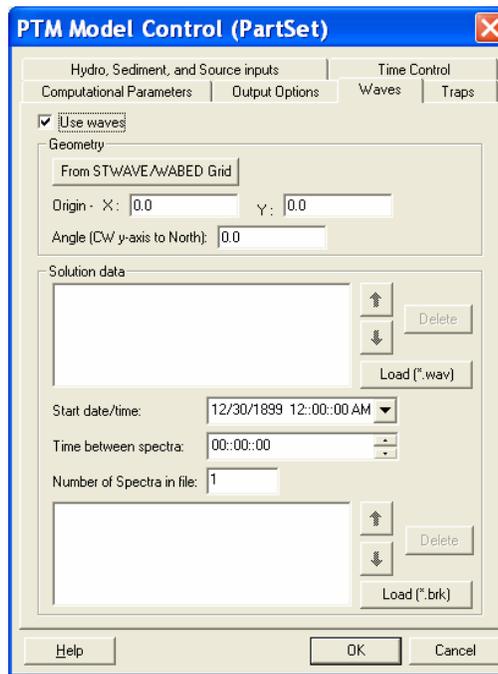


Figure 24. Example completed *Waves* page.

Since output steps in an STWAVE/WABED output file do not contain any time information, both the start time and duration between steps must be supplied to the PTM.

If traps are in the simulation, the *Traps* page must be completed (Figure 25). Traps are created as closed polygons in the Map module. The SMS interface will automatically identify any active polygon coverage as the trap. If traps are not to be used, then this page can be left with its default settings, because the default dates should be outside the simulation period.

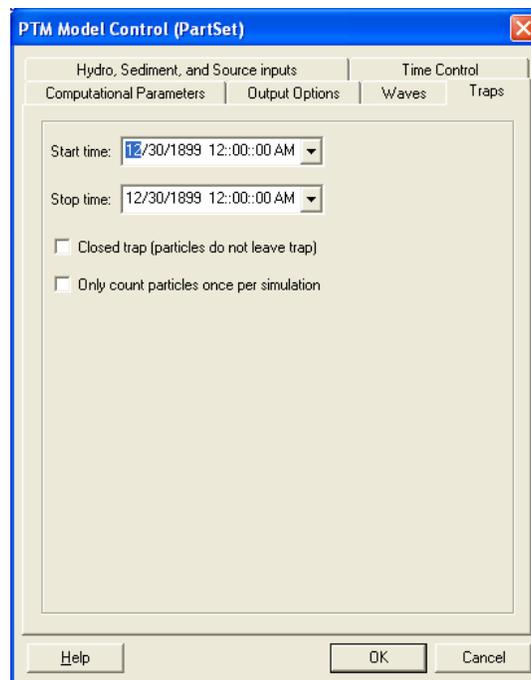


Figure 25. Example *Traps* page showing default values (i.e., traps not active).

Sediment source file

The sediments modeled in a PTM simulation are introduced to the model via a source file, which is generated through the Map module in the SMS. Point sources (both instantaneous and varying-release) and line sources are first created as simple point or line coverages, respectively. These coverages must have their *Type* set to PTM. This is performed by highlighting the coverage and following the menus available using a right-mouse click on the coverage, as is illustrated in Figure 26.

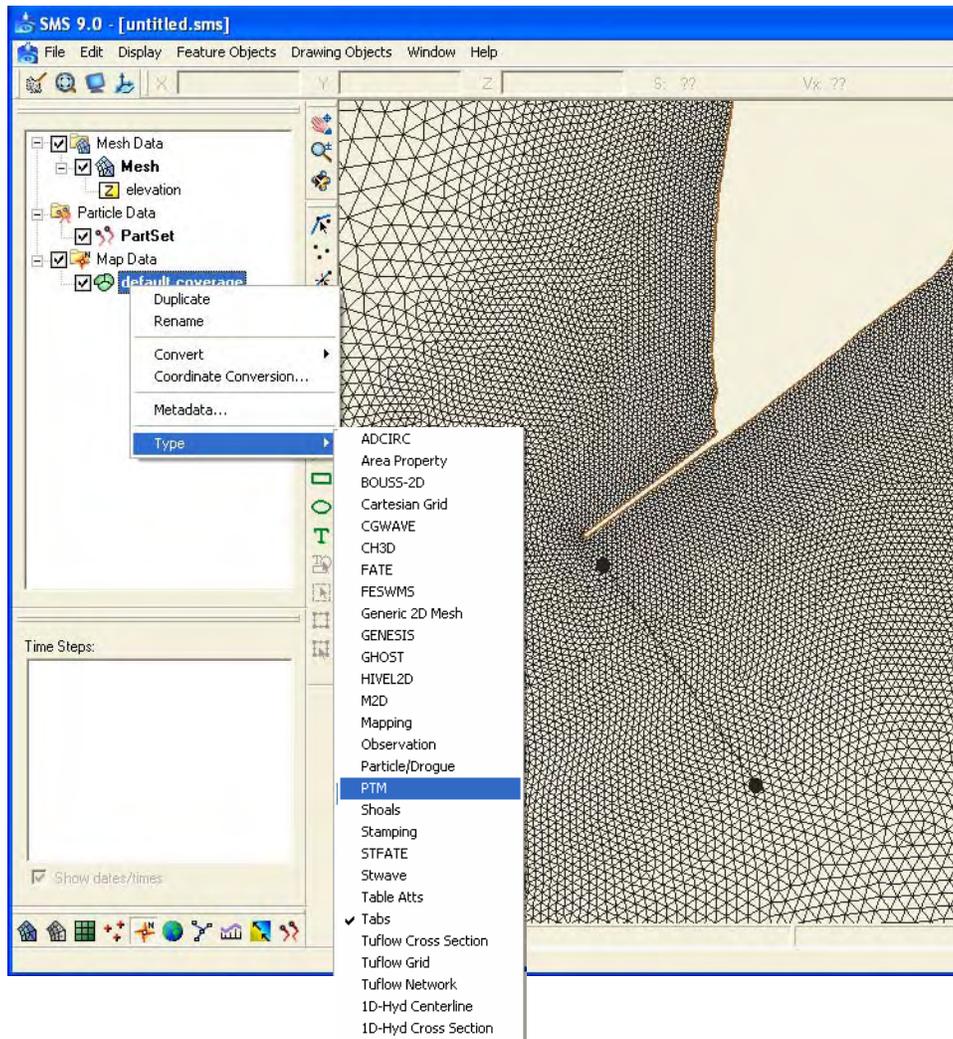


Figure 26. Conversion of source coverage type to PTM.

After conversion to PTM type, double-clicking on the coverage will open the source's control box (Figure 27). This box is used to enter data to specify the source's characteristics and location data. Any number of instructions can be added to the source file (new lines are added automatically). Each instruction is identified by a unique UTC time. These instructions can be separated by any duration (minimum 1 sec). The final instruction must be beyond the end of the simulation (a zero sediment discharge rate is acceptable). In this way, complicated release schedules (e.g., dredge movement, changes in discharge rate, changes in properties of material released, intermittent releases) can be reproduced by the model.

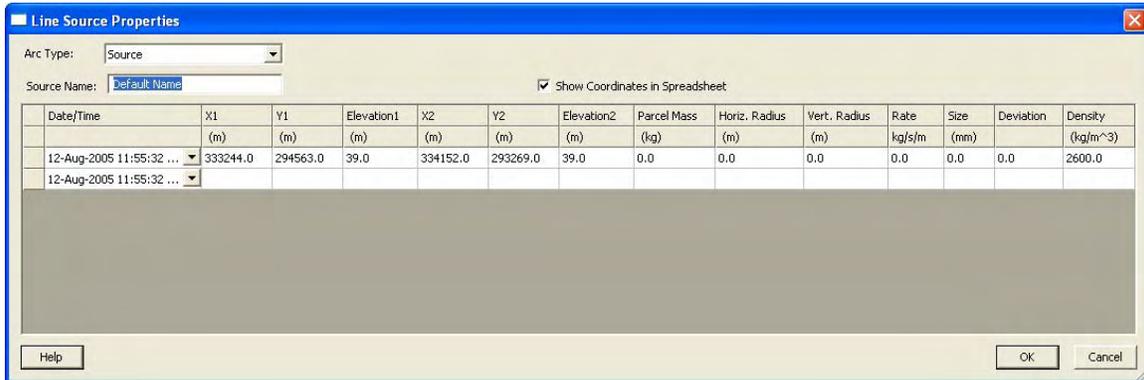


Figure 27. Example source control box.

Source file structure

An important point to remember about source files is that PTM will interpolate between each instruction for all data in the file. One can use this structure to build up complicated source functions.

An example source release is shown in Figure 28. Nine lines of data (instructions) would be required in the source file to enable PTM to reproduce this release schedule:

1. Time 1 is the start of the source discharge. It can be any time later than or equal to the start time of the simulation.
2. Between Time 2 and Time 3, the sediment discharge rate is to decrease. Because the model interpolates, the initial discharge (i.e., that at Time 1) is repeated at Time 2, so that the discharge is constant over the period between Time 1 and Time 2.
3. A short time later (e.g., 1 sec) the discharge is decreased to a new value (Time 3).
4. The discharge is kept constant until Time 4. Therefore, the instruction at Time 4 is a repeat of Time 3, but at a later time.
5. The next instruction is at Time 5. It has a zero discharge rate; therefore the model will linearly vary the discharge between Time 4 and Time 5.
6. A second release of sediment is desired, but at a slightly later time. Time 6 is specified to identify the start of the release, which will almost immediately increase to the rate at Time 7. If the value at Time 7 had been specified as Time 6, the model would have linearly increased the rate from zero at Time 5, rather than the step-function release desired.
7. The discharge is kept constant until Time 8. Therefore, the instruction at Time 8 is a repeat of Time 7, but at a later time.

8. The next instruction is at Time 9. It has a zero discharge rate and is shortly after Time 8 (minimum 1 sec).
9. Note that the final instruction (Time 10) must occur after the end of the run – again, because the model will interpolate between the second-last and the last instruction. The discharge at Time 10 is zero, as was the case at Time 9. Therefore, there will be no discharge over the time period between Time 9 and Time 10.

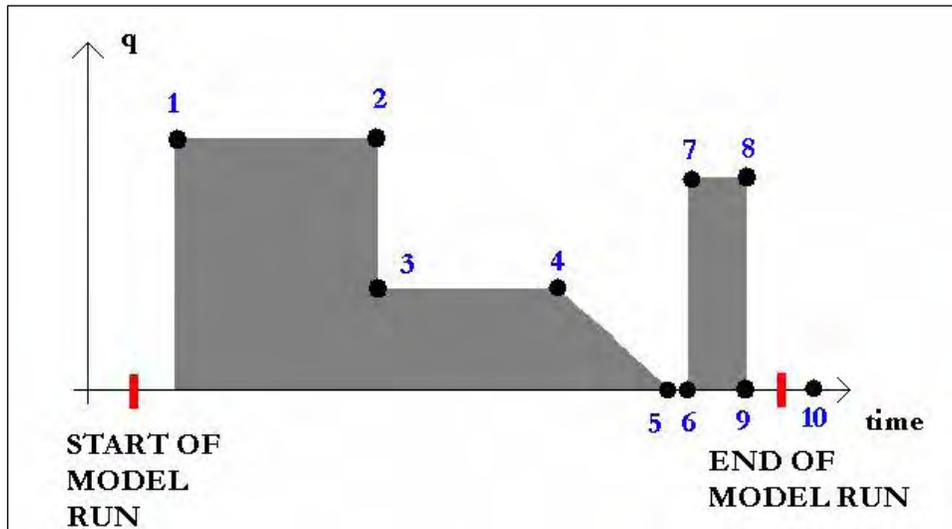


Figure 28. Example source release schedule.

The source control box for this example is shown in Figure 29.

Point Source Properties

Source Type: Point Mass Rate Source

Point Name: Default Name

Date/Time	X (m)	Y (m)	Elevation (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Rate (kg/s)	Mean Grain Size (mm)	Standard Deviation (Phi-units)	Density (kg/m ³)
13-Jul-2004 8:30:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	5.0	0.2	0.4	2650.0
13-Jul-2004 8:55:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	5.0	0.2	0.4	2650.0
13-Jul-2004 8:55:01 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	3.0	0.2	0.4	2650.0
13-Jul-2004 9:20:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	3.0	0.2	0.4	2650.0
13-Jul-2004 9:30:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	0.0	0.2	0.4	2650.0
13-Jul-2004 9:32:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	0.0	0.2	0.4	2650.0
13-Jul-2004 9:32:01 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	4.0	0.2	0.4	2650.0
13-Jul-2004 9:38:00 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	4.0	0.2	0.4	2650.0
13-Jul-2004 9:38:01 AM	535300.0	300250.0	0.0	1.0	10.0	0.2	0.0	0.2	0.4	2650.0
13-Jul-2004 11:00:00 PM	535300.0	300250.0	0.0	1.0	10.0	0.2	0.0	0.2	0.4	2650.0
13-Jul-2006 2:44:45 PM										

Buttons: Help, OK, Cancel

Figure 29. Example source release properties window.

Note that although the previous example only dealt with discharge rate, most quantities are interpolated between instructions (e.g., grain size, source location, etc.).

The particle mass can be used to control the number of particles that are generated to represent a mass release.

Instantaneous sources

These are used for instantaneous releases of sediment. These are point sources that are not interpolated; the full release of sediment occurs at the time given and with the properties specified.

Point sources

These are point sources that are interpolated. The release of sediment is variable and occurs at the times given and with the properties specified. Linear interpolation is used for most properties. A stationary, continuous point source can be specified by using two point sources with identical characteristics separated in time.

Line sources

Line sources must either be vertical or horizontal. Linear interpolation is used for most properties in the line source. Line sources may move, change length, and change discharge properties.

Area sources

The area sources are polygons. The points must be ordered using a standard counter-clockwise convention. Source properties within an area source are uniform across the polygon.

Selection of sediment sorting

The grain size associated with each particle released from a sediment source is selected by the model such that the mass of sediment released in a single instruction reproduces a user-defined particle size distribution. The form of the distribution is Gaussian and is specified by a mean grain size and a standard deviation. In order to simplify the selection, two sets of units are used; the mean grain size \bar{D} is specified in millimeters, and the standard deviation σ is specified in phi-units (ϕ). The phi-unit is the

negative logarithm to the base 2 of the sediment diameter in millimeters, such that the mean phi-unit grain size is:

$$\bar{\phi} = -\log_2(\bar{D}) \quad (70)$$

By specifying the standard deviation in phi-units, the degree of sorting of the sediment becomes independent of the mean grain size. The generally-accepted ranges are as follows:

$$\begin{aligned} \sigma < 0.5\bar{\phi} & \quad \text{well sorted} \\ 0.5\bar{\phi} \leq \sigma < 1.0\bar{\phi} & \quad \text{moderately sorted} \\ 1.0\bar{\phi} \leq \sigma < 2.0\bar{\phi} & \quad \text{poorly sorted} \\ 2.0\bar{\phi} \leq \sigma & \quad \text{very poorly sorted} \end{aligned} \quad (71)$$

After a source is created, it will become available to the model through the *Source Input* box on the *Hydro, Sediment, and Source Input* page (Figure 30).

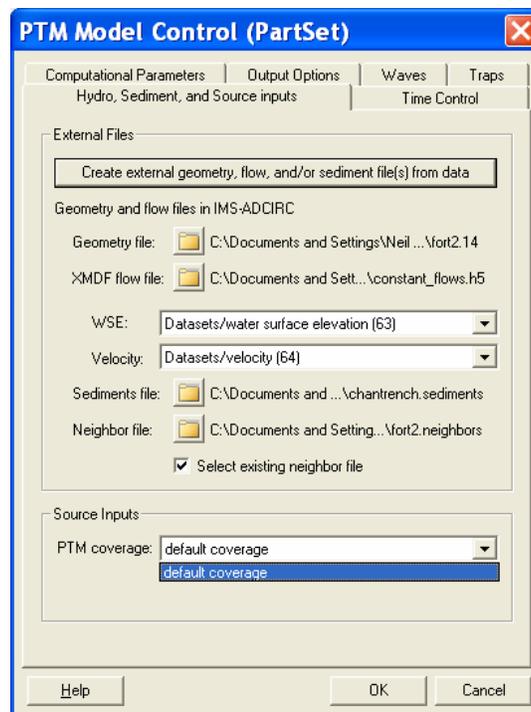
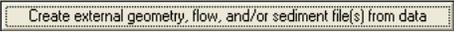


Figure 30. Selection of source coverage in PTM model control box.

Native sediments file

This file contains the spatially-varying grain size information for the native sediments in terms of D_{35} , D_{50} , and D_{90} . Frictional characteristics of the bed are computed with D_{90} . The D_{50} value is used in the prediction of bed forms, in the determination of sediment mixing routines that influence re-entrainment of deposited particles, and in the hiding and exposure routines that influence the critical shear stress of deposited particles. The D_{35} value is used in the determination of the suspended sediment transport if the van Rijn approach is selected for the centroid method.

Non-erodible areas (e.g., rock outcroppings) can be identified by a negative input grain size. This absolute value of the grain size is treated as an effective roughness height, k'_s and k''_s .

The native sediments file is specified on the *Hydro, Sediment, and Source Input* page of the PTM control box (Figure 30). A native bed sediments file can be generated by the SMS interface, if one is required, by pressing the  button. This will open the *Create PTM External Input Files* widow. After the geometry is selected and the native sediments option selected, the window will appear as is shown in Figure 31. A file name must be specified at this point.

Geometry file

The geometry file is used to specify the bathymetry of the domain and the boundary conditions. This is a standard ADCIRC mesh file, usually given the extension *.14* or *.grd*. The coordinates must be in metric (or S.I.) units and must be in Cartesian coordinates. The SMS interface can convert ADCIRC files that are in curvilinear geographic coordinates (e.g., lat-long) into a plane Cartesian system (e.g., state plane).

The geometry file is specified on the *Hydro, Sediment, and Source Input* page of the PTM control box (Figure 20). Although the PTM can be run with this file only identified in the *Hydro, Sediment, and Source Input* page, it should be opened separately in the SMS interface to allow source terms to be specified graphically.

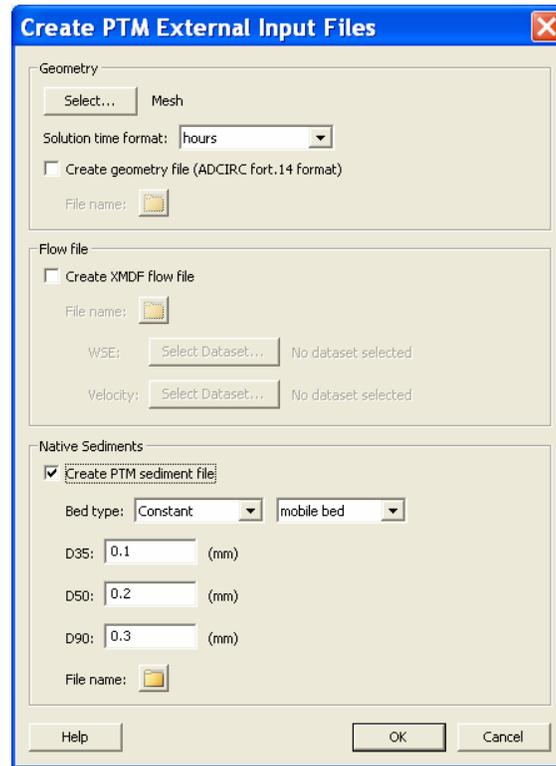


Figure 31. Create PTM External Input Files page.

Neighbor data files

To reduce model run time, the PTM uses a list of the numbers of all neighboring elements of each element. This information can be time-consuming to obtain for large meshes, so creation of the neighbor data file is performed only once for each mesh; once computed, this additional information is written to a neighbor file (extension *.neighbors*). On subsequent simulations, the information is read from the neighbor file. If no neighbor file exists, the model will create one using the provided name. The neighbor file is specified on the *Hydro, Sediment, and Source Input* page of the PTM control box (Figure 30). This file only needs to be regenerated if there are changes to the element-node structure (e.g., addition of new nodes, changes in connectivity). Changes in node depths or locations, for example, will not necessitate a new neighbor file.

Hydrodynamic data files

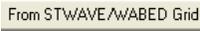
At present, these files must be ADCIRC-compatible, three-noded triangular finite element mesh files in XMDF file (*.h5*) format. XMDF files require much less disk space than the ASCII standard ADCIRC format and, because they are random-access, can be read more quickly by the

PTM. This can provide a significant time saving, especially if the PTM simulation starts some time after the start of the ADCIRC simulation.

The SMS interface automatically converts standard ADCIRC files (.63 and .64) to X MDF format when they are opened. The hydrodynamic file is specified on the *Hydro, Sediment, and Source Input* page of the PTM control box (Figure 20).

It is important to note that ADCIRC output files do not have a time stamp to identify their start. The start time must be supplied to the PTM to allow the ADCIRC flows to be converted to UTC time, so that they can be synchronized with the other input data (sources, flows, waves, etc.). This is done in the *Time Control* page of the program control box (Figure 21).

Wave input files

These are standard STWAVE output files. They have the extension .wav. If the steering module is used to generate the files, then each file will contain a single frame of data or snapshot of the wave field. If STWAVE is run in a stand-alone mode, then a single file will be generated with a number of frames of wave data in a single file. The wave data are supplied to the PTM in the *Waves* page of the program control box (Figure 24). Opening the STWAVE simulation first allows the interface to automatically obtain the grid data. This is done by pressing the  button (Figure 24).

STWAVE output files do not have a time stamp to identify their start. The start time must be supplied to the PTM in the *Waves* page of the program control box (Figure 24).

Trap file structures

A trap is defined as an area into which particles enter and are counted. The trap may be open (particles are free to leave) or closed. A flag can also be set to control whether particles are counted once per simulation or every time they re-enter an open trap. Time limits can also be specified on the trap's operation.

The PTM uses polygon coverages to catalogue particle activity. These coverages must be constructed in the Map module prior to their identification in the PTM model control pages. The trap data are supplied to PTM in the *Traps* page of the program control box (Figure 25).

Output files

The PTM produces a number of output files depending upon the characteristics of the simulation. There are four main output files:

1. Echo file – giving a synopsis of the input for the simulation (e.g., input parameters set, default values used by PTM, mesh dimensions). This is an ASCII text file with the extension *input*.
2. Particle file – giving particle-based information about the source sediments introduced to the domain (e.g., particle position, user-selected properties and user-selected attributes). The default format is binary XMDF with the extension *_particles.h5*.
3. Map file – giving mesh-based information about the native sediments in the domain (e.g., sediment mobility, bed forms, sediment transport rate). The default format is binary XMDF with the extension *_maps.h5*.
4. Error file – giving run-time error information for debugging a failed simulation. It is only produced if errors are encountered in the simulation. This is an ASCII text file with the extension *err*.

An additional output file(s) may be produced if traps are required:

1. Count file – giving information about any particles caught in a trap while the trap is active. This file is only produced if traps are in use. This is an ASCII file with the extension *_count.out*.
2. Residency file – giving information about the residency times of particles in designated areas (i.e., traps). This is an ASCII file with the extension *_residency.out*.
3. Bin file – giving information about any particles in a trap at the end of the simulation. This file is only produced if traps are in use. This is an ASCII file with the extension *_bin.out*.

If errors are produced, then an error file is generated:

1. Error file - giving run-time error information for debugging a failed simulation. It is only produced if errors are encountered in the simulation. This is an ASCII text file with the extension *err*.

Particle file

As discussed in Chapter 1, each sediment particle can have a unique set of attributes and certain other properties. Properties refer to quantities that

are invariant in a simulation (e.g., grain size), whereas attributes may vary (e.g., particle position, particle state). Certain physical attributes (e.g., particle position) are required for the solution to proceed, whereas others simply extend the capabilities of the model to provide output information. The following is a list of particle attributes in this first version of the PTM:

- position (x, y, z)
- state (i.e. mobile, inactive or deposited)
- mass
- mobility
- velocity
- initial source

The desired values for output are selected on the *Output Options* page of the PTM model control box (Figure 23). The user must also specify the output increment. This value should be carefully selected, because it can have a significant effect on the model speed and disk storage requirements. If a large number of particles are used, a small value for this increment may result in a long run time or large disk storage requirements.

The particle file can be used for animating the movement of the particles during a simulation. Particle files give, as a minimum, the position of each particle and its ID number at a selected output frequency. Additional information (i.e., particle properties and attributes) can be written to the files if desired.

It should be noted, however, that the path of a particle taken from the particle file will always be an approximation of its actual path, unless the output increment is 1. In general, these approximations are acceptable. However, in some instances the path may appear to violate boundaries, as is shown in Figure 32. In this figure, the hollow circles represent a particle's position at each time-step. The filled red circles represent those time-steps when the particle's position is recorded to disk. In certain circumstances with large output increments, the model output can give the false impression that particles have crossed through boundaries. In this example, the particle has traveled around the end of the jetty, whereas the path inferred from the positions file (and the one that will appear in the paths file) implies that it passed through the jetty.

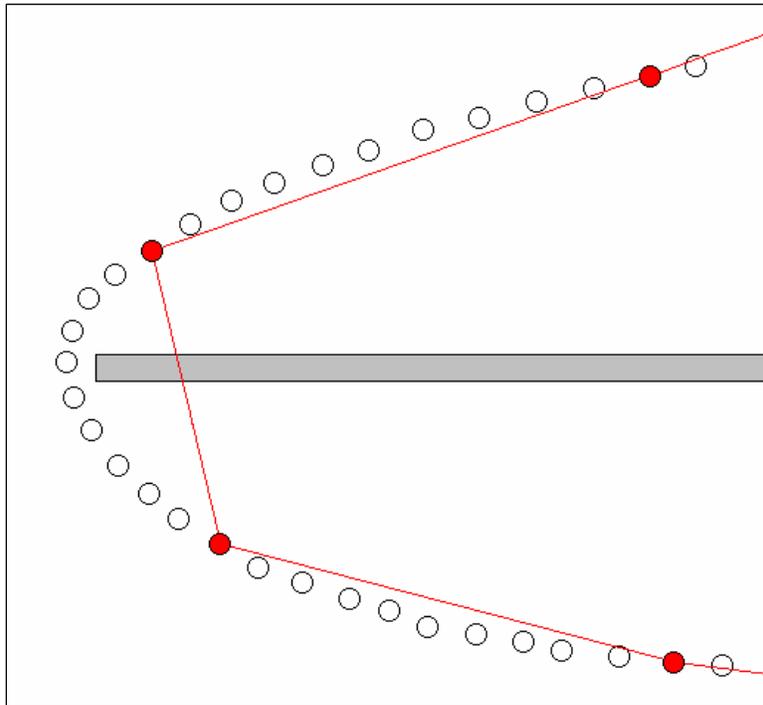


Figure 32. Apparent path of particle (red line) from particle file with output every 10 steps.

Map file

The mapping output file presents data on the nodes of the Eulerian mesh. All data are in S.I. units, with lengths expressed in meters with the exception of grain sizes, which are specified in millimeters. The available output values in Release 1 are:

- bed forms
- waves
- mobility

The desired values for output are selected on the *Output Options* page of the PTM model control box (Figure 23). This value should be carefully selected, because it can have a significant effect on the model speed and disk storage requirements. If the mesh is very large, a small value for this increment may result in a long run time or large disk storage requirements.

Model execution

Once all the input preparation is complete, a PTM model simulation can be executed by selecting [*PTM / Run Model*] from the pull-down menu (Figure 33).

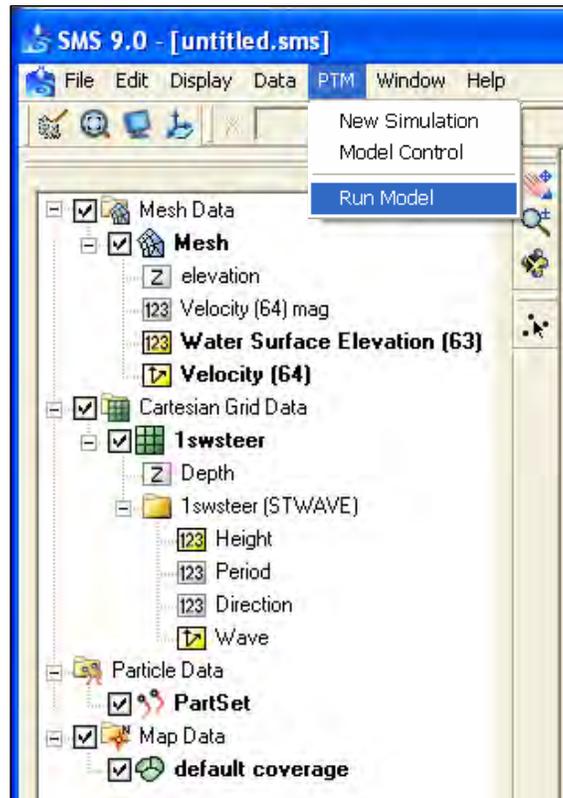


Figure 33. Executing a PTM simulation.

Three technical notes have been published that describe the PTM's general features and capabilities and give tutorials in its operation (Demirbilek et al. 2005a, Davies et al. 2005 and Demirbilek et al. 2005b). These should be referenced for additional information and guidance on the operation of the PTM. These technical notes are included in the Appendices B through D of this report.

Output window

An output window will be opened at the start of a PTM simulation (Figure 34). The window will show the run time information including the model version number, the run time, number of particles in the simulation and number of time-steps. After a certain number of time-steps an

estimate of the run time will be given. If desired, the simulation can be aborted during its execution from this window.

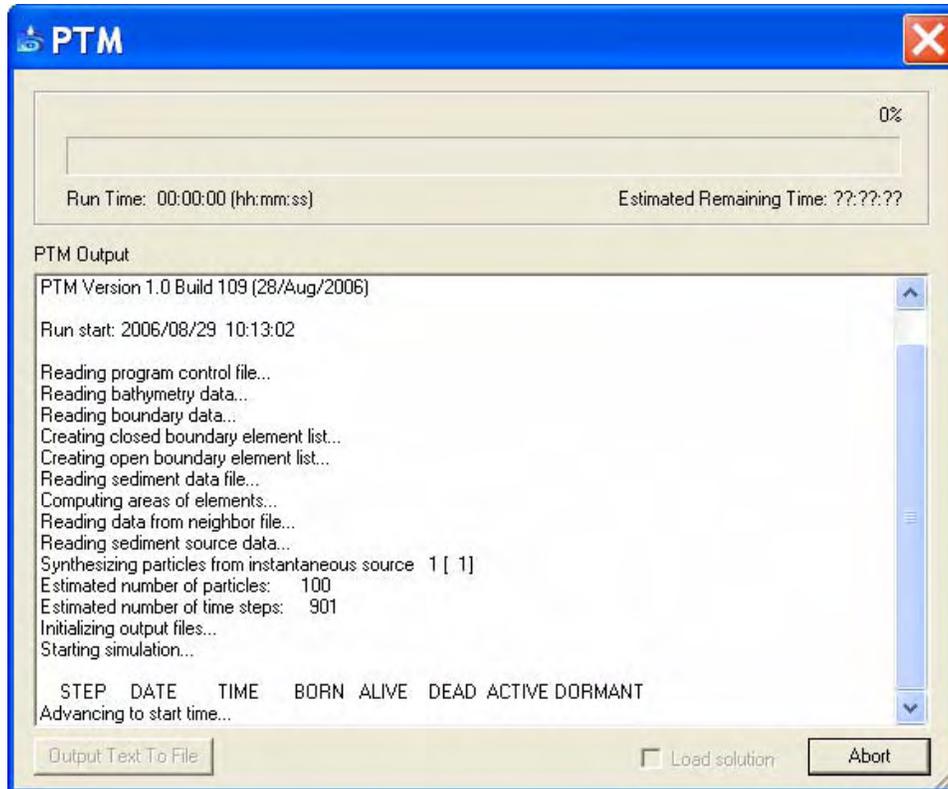


Figure 34. Output window at the start of a PTM simulation.

An update of the simulation status is given at increments of 100 time-steps (Figure 35). This includes time-step number and corresponding date and time in the simulation, and number of particles in various categories.

These are as follows:

1. BORN is the number of particles that have been generated up to this point in the simulation.
2. ALIVE is the number of particles that are still within the model domain and are available for transport.
3. DEAD is the number of particles that have left the domain and are unavailable for transport.
4. ACTIVE is the number of particles that are in motion at that time-step.
5. DORMANT is the number of particles that are inactive or deposited at this time-step.

The symbols “=>P” or “=>M” indicate that the model is outputting data to the particle or map file, respectively.

Figure 35 shows the output window at the completion of a simulation. The solution can be loaded automatically when the window is closed if the box is checked. Pressing will close the simulation window.

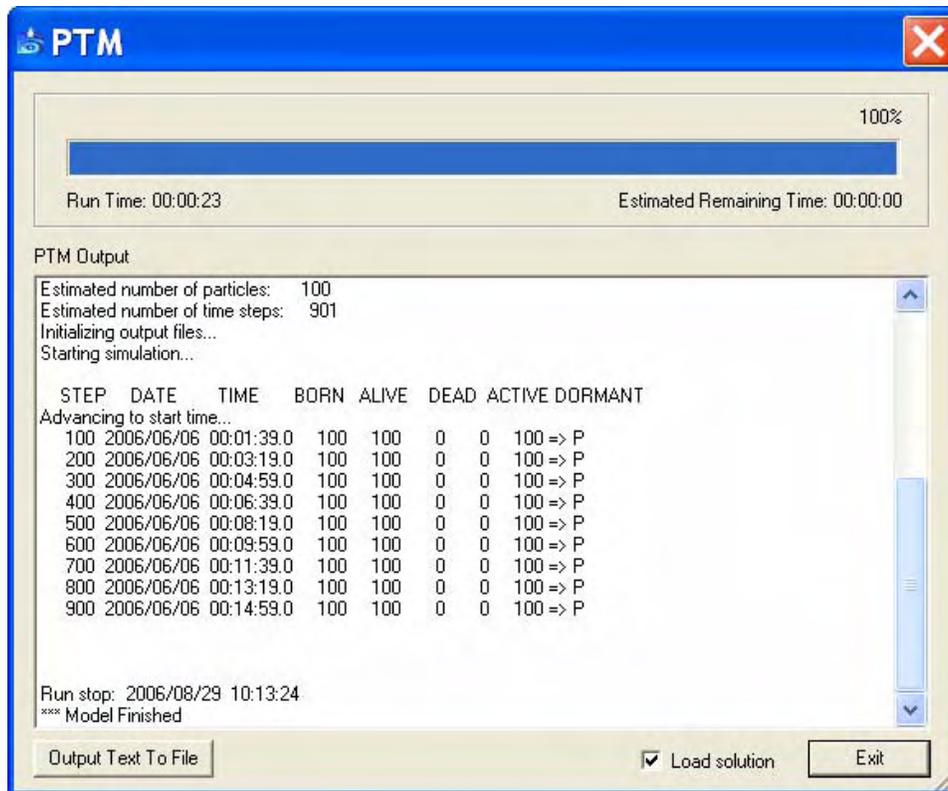


Figure 35. Output window at the end of a PTM simulation.

Number of particles

The number of particles should be checked to ensure that a reasonable number of particles will be included in the simulation. This value is given at the start of a simulation (Figure 34). If too few particles are used, there may not be enough to provide the resolution required for an accurate solution, whereas too many particles may result in a simulation that takes too long to run. The simplest way to control this number is by adjusting the particle mass in the source coverage. Using a very large number of particles may result in a failure of the model to execute.

It is advised that, for new cases, a preliminary simulation be conducted with a small number of particles (e.g. a few hundred) so that the input

values can be checked. The optimum number of particles to use in a production run requires a judgment call on the part of the user and will depend upon a number of factors, including number of sources, temporal and spatial extent of sources, duration of the simulation, required resolution of the solution, computational speed and memory size of processor and desired run time.

Output visualization

Once the simulation is complete and has been loaded, the results can be visualized. Options for visualization are set using the *Particles* page of the *Display Options* window (Figure 36).

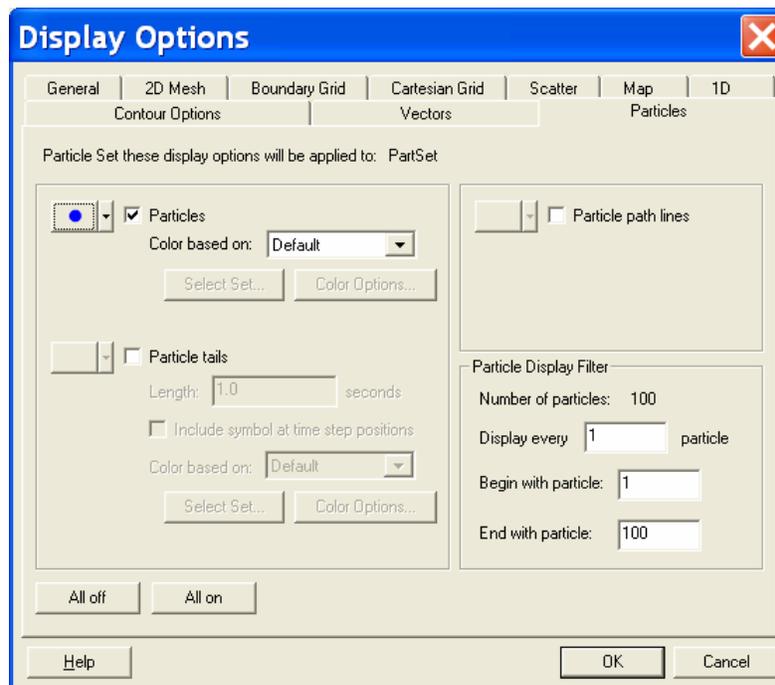


Figure 36. Display options page for particle visualization.

The options include controls for particle path lines, particle tails and various particle settings, such as color and size. The particle visualization capabilities of the SMS interface are described in detail in (Demirbilek et al. 2005a), which is included in Appendix B.

5 Model Application

PTM applications are presented in this chapter. Perhaps one of the most important concepts to gain from this chapter is the capability of the PTM to aid in a wide range of coastal and hydraulics projects. The applications are intended to serve as sample problems for users in their practical applications of the model. Although each case addresses the validity of results and usefulness of PTM, the applications demonstrates a specific set of processes which include: advection and diffusion, mixing within the water column, slope effects, deposition and resuspension, and the successful use of data (hydrodynamic and wave) obtained from other models. Applications are validated through both an understanding of sediment transport processes and by comparison to measurements.

Example applications considered in this chapter are:

1. Fluctuating flow through a straight flume of constant depth.
2. Uniform flow over a channel.
3. Concentration plume in a flume.
4. Combined wave and current flow in an idealized coastal inlet.
5. Wave-current co-existing flows at two field sites.
6. The effect on sediment transport of recent and proposed coastal modifications.

Although the first three applications represent hypothetical situations, these serve to validate known sediment transport processes. The idealized inlet case is for a laboratory experiment performed by CIRP. The two field applications are for projects near Anchorage, AK, and Brunswick, GA.

Each section of this chapter focuses on one example and includes PTM application objectives. Next, PTM setup and input are discussed, including the mesh used, hydrodynamic and wave data, source information, as well as basic computational characteristics such as time-step. Finally, model results are presented. Chapter 4 is specifically dedicated to the explanation of input files. Therefore, the present chapter addresses pertinent details of input in a more general way. In the case of field applications and the idealized inlet, the project's background is provided.

Example 1: Straight flume

Objective

The first example demonstrates entrainment of sediment moving down a straight channel within a uniform flow. The distinguishing characteristic in this example is particle deposition and resuspension. One of the major goals of sediment transport models is to accurately simulate these processes, based on critical shear calculations discussed in Chapter 3.

PTM setup

A simple mesh was developed for this test case consisting of four nodes and two cells. The length of the flume is 100 m, and the width is 25 m (Figure 37). Although the depth remains constant at 1 m, the velocity is time dependent, changing in a sinusoidal manner.

The velocity in the x (horizontal) direction is constant across the domain (no slip boundary condition at the $y = 0$ m and $y = 25$ m) and cycles between 0 and 0.5 m/sec over a period of 2 min. The transverse velocity stays constant at 0 m/sec (Figure 37).

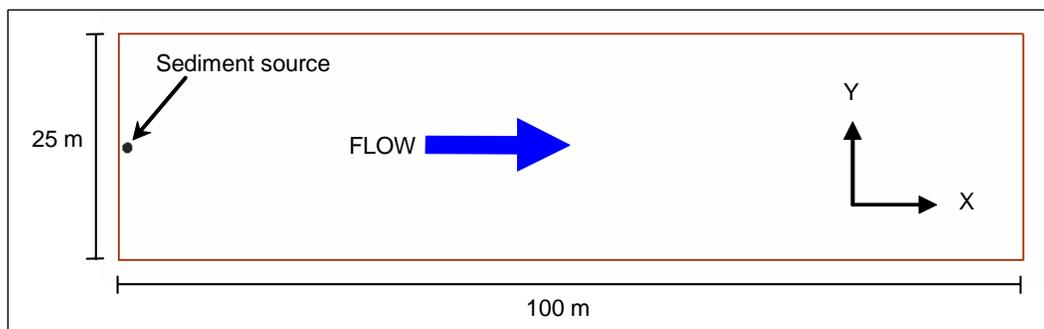


Figure 37. Example 1 geometry.

The sediment source for this case is a mass rate point located at $x = 1.0$ m and $y = 12.5$ m (Figure 38). Particles are released 0.5 m above the bed (Figure 38) at a rate of 0.01 kg/sec with a particle mass of 0.1 kg (1 particle every 10 sec). The mean particle size is $64 \mu\text{m}$ and standard deviation of 0.4ϕ . Particles are released for 15 min. In this simulation the 3-D mode was used with a time-step of 2 sec.

Date/Time	X (m)	Y (m)	Elevation (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Rate (kg/s)	Mean Grain Size (mm)	Standard Deviation (Phi-units)	Density (kg/m ³)
06-Jun-2006 12:01:...	1.0	12.5	0.5	0.1	0.01	0.01	0.01	0.064	0.4	2600.0
06-Jun-2006 12:15:...	1.0	12.5	0.5	0.1	0.01	0.01	0.01	0.064	0.4	2600.0
06-Jun-2006 12:15:...	1.0	12.5	0.5	0.1	0.01	0.01	0.01	0.064	0.4	2600.0
11-Jun-2006 1:18:5...							0.0			

Figure 38. Sediment source description for Example 1.

PTM results

Figure 39 shows an elevation view of the bed, water column, and particles. Particles are released 0.5 m above the bed and are advected by the flow. In the figure, blue-colored particles are active and red-colored particles are deposited.

Particles start to deposit just prior to 4 min into the simulation. More particles deposit and resuspend along the flume bed as the simulation progresses. At 7 min and 9 min, all particles have been entrained back into the flow. This example application clearly demonstrates that the PTM is capable of representing the process of sediment deposition and resuspension. Figure 40 shows the elevation view of the path of a single particle. A number of resuspension events are identified in the figure.

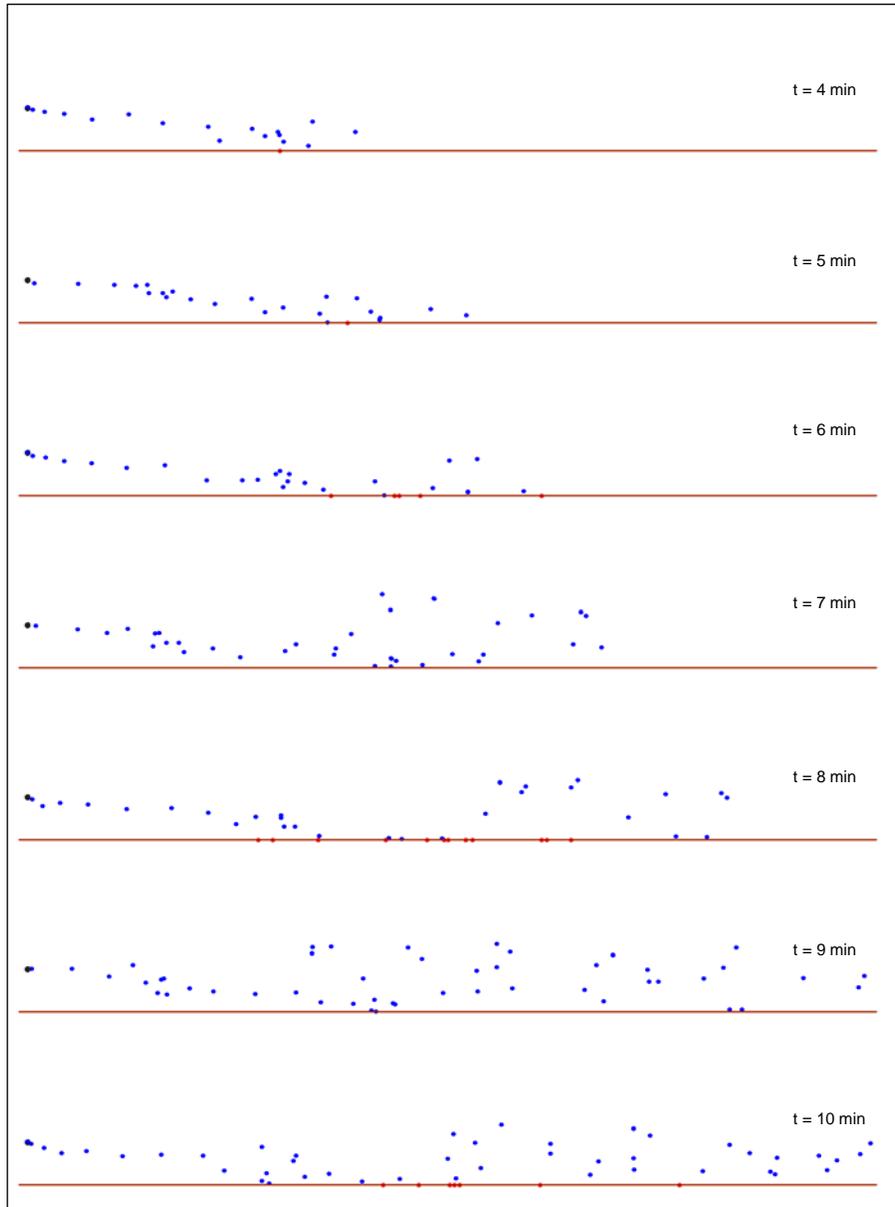


Figure 39. Particles released in a straight channel at 1-min intervals (elevation view). Red particles are deposited. Blue particles are active.

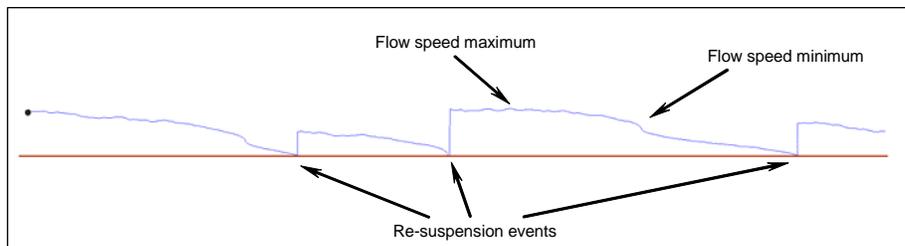


Figure 40. Path of a single particle (elevation view).

Example 2: Flow over a trench

Objective

The next application concerns flow over a trench. The objective of this example is to verify the capability of the PTM to correctly simulate the effect of vertical velocity change on particle movement. Presently, the PTM uses hydrodynamic input from 2-D models. A characteristic of the model is its capability to simulate the 3-D effects of particle transport given such 2-D input (see Chapter 3). This is important because the majority of hydrodynamic model data are 2-D, vertically averaged flow. Also, addressed here is the effect of slope side geometries.

PTM setup

Figure 41 shows channel geometry. The top plot is a plan view that shows the finite element mesh, the bottom plot is an elevation view (distorted vertically by a factor of 50) showing the location of the trench. The ambient depth is 2 m at the channel edge. The channel is 4 m deep and 400 m wide. The locations of the two sources are also shown. The flow moves from right to left.

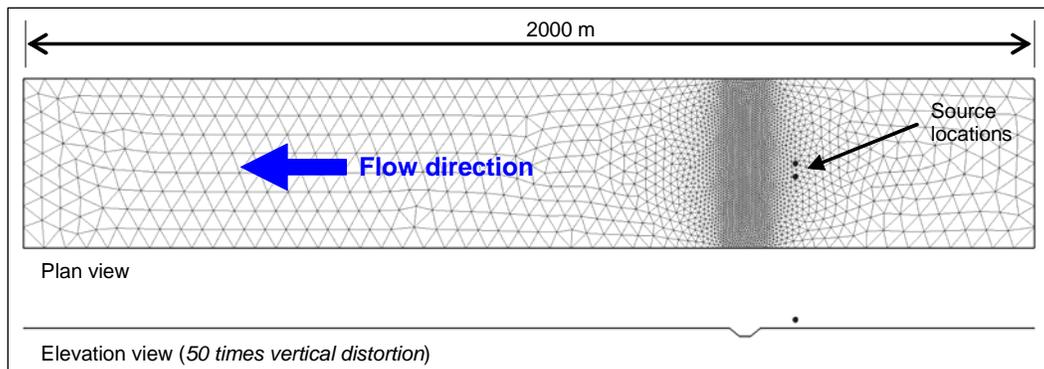


Figure 41. Example 2 geometry.

Two instantaneous sources are used in this example. The property pages showing the source settings for this simulation can be seen in Figure 42. As shown in the source property pages, the first set of particles is released instantaneously on 12 August 2004 at 6:30 p.m., and the second set at 7:00 p.m. The specific positions of release points are $x = 9,158$ m and $y = 900$ m for the first and $x = 9,158$ m and $y = 1,000$ m for the second. The release point elevation for both cases is 1 m above the bed. The mass

of each parcel is 0.1 kg, and the total mass of sediment is 3 kg. The mean particle size is 10 μm , and the standard deviation is 0.4 ϕ .

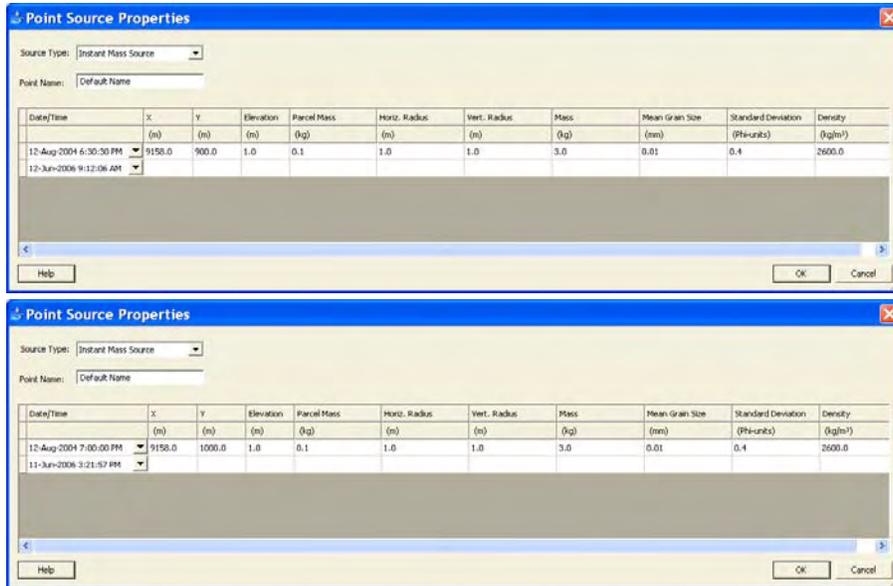


Figure 42. Source property pages for Example 2.

The time control portion of the PTM Model Control input window (see Chapter 5) is shown in Figure 43. This simulation begins at 6:30 p.m. on 12 August 2004 and ends at 8:00 p.m. on the same day. The computational time-step is 1.0 sec. The hydrodynamic data also begin at 6:30 p.m. on 12 August 2004.

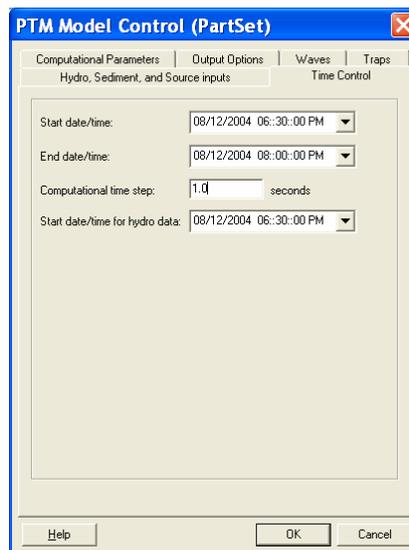


Figure 43. PTM Time Control.

Figure 44 shows the Computational Parameter page of the PTM Model Control for this case. The 3-D advection modeling algorithm is chosen. This algorithm is generally most appropriate for simulation of fine-grained sediment transport. Also considered in this run are particle-bed interactions.

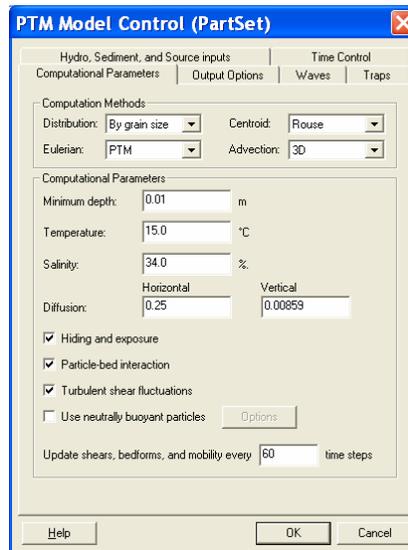


Figure 44. PTM Computational Parameters.

PTM results

As the particles are propelled down the channel by the flow field and then cross the channel, the expected outcome is that particles will follow the streamlines of the flow. That is, they should separate vertically as the cross-sectional area increases.

A single frame of output for the simulation is shown in Figure 45. The particles are colored according to their source. These fine particles follow the streamlines.

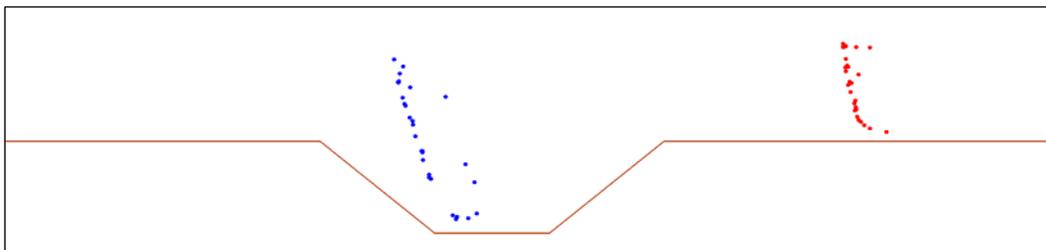


Figure 45. Snapshot of particles passing over trench.

Streamlines for a number of the particles are shown in Figure 46. As particles pass across the trench, the impact of the vertical velocity distribution is obvious. The particles closer to the bed lag behind the particles higher in the water column. There is a distinct vertical separation at the higher particles also, whereas the particles close to the bed appear to cluster closer together.

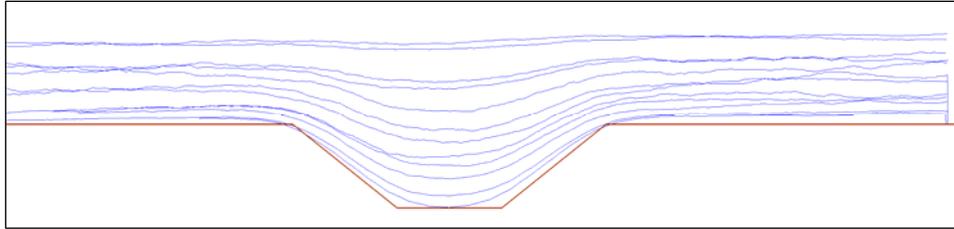


Figure 46. Streamlines of selected particles passing over trench.

PTM results at 10 min intervals are presented in Figure 47.

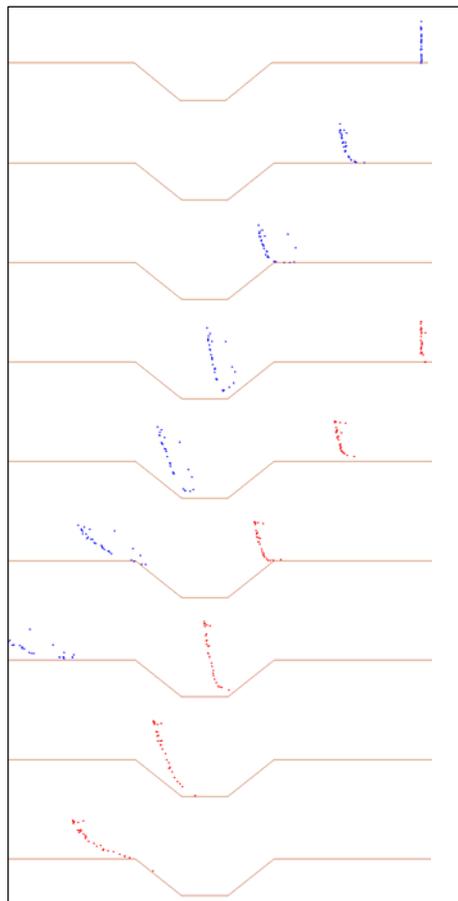


Figure 47. Particles crossing trench. Particles are colored according to their source. Each frame is separated by 10 min.

Example 3: Concentration plume

Objective

The objective of this example is to compare the diffusion predicted by the PTM and an exact analytical solution for diffusion (Roberts and Webster 2002).

PTM setup

The analytical solution presented in this example is based on a point release of 0.5 kg into an infinitely-wide, 2-D uniform flow of 1.0 m/sec. The diffusion coefficient is 0.25 m²/sec.

The flow and diffusion coefficients used in PTM are 3-D and unique for each particle at each time-step. In addition to vertical and horizontal diffusion coefficients, the computations take into account proximity to boundaries and depth of flow. As such, for the purposes of comparison with the analytical solution, the PTM code was modified to override these computations and use a uniform velocity field and diffusion coefficient to produce the results presented in this section.

PTM results

Figure 48 shows a comparison between the analytical and PTM predictions 50 m downstream of a continuous point source. In this example, the PTM was run with time-steps of 1 and 5 sec. Figure 49 shows the results at 250 and 500 m. The agreement between the PTM calculation and the analytical solution is excellent. By contrast, Eulerian schemes typically have difficulty obtaining an accurate diffusion solution due to inherent numerical diffusion (Vreugdenhill 1989).

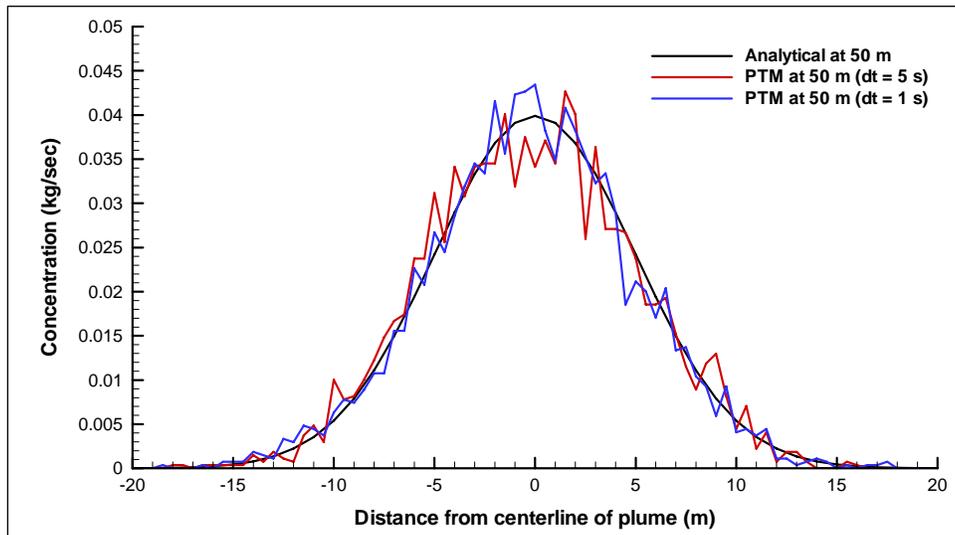


Figure 48. Diffusion modeled by PTM compared to analytic solution.

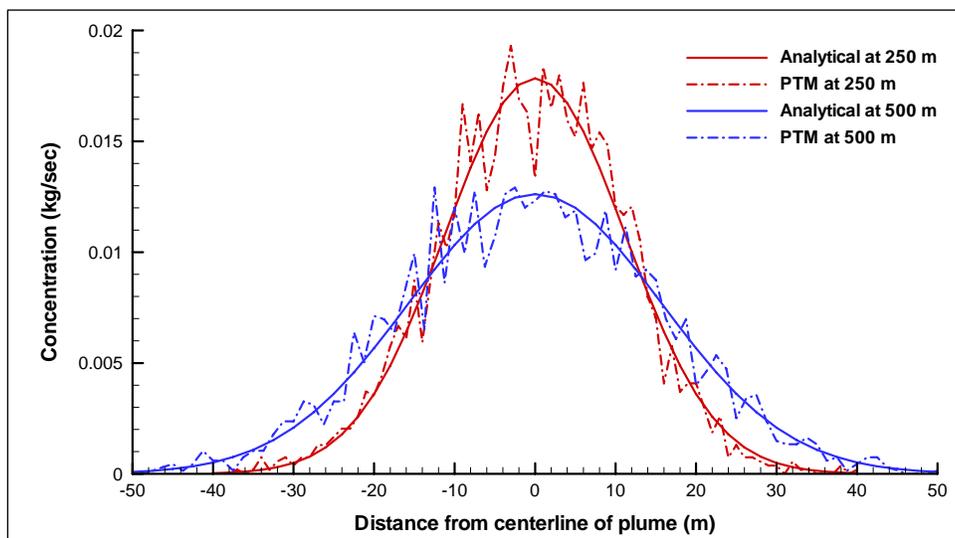


Figure 49. Comparison of pure diffusion at two distances from point source.

Example 4: Flow in an idealized inlet

Objective

In most coastal inlet applications of the PTM, coexisting flow conditions require proper handling of wave-current interactions and shear stresses that affect the movement of sediment particles. The overall capabilities of the PTM are examined in this example in the presence of waves and currents, where wave shoaling, refraction, diffraction, reflection, and breaking processes occur around an inlet protected by two jetties. This example examines the wave-current interaction at an idealized inlet to test

the basic processes of sediment transport. Note that this is an idealized inlet; the flow conditions are wave-dominated, and there is no tidally-induced flow through the inlet. As well, no flood or ebb delta features are represented in the bathymetry.

Wave input for this PTM simulation is obtained with STWAVE (Smith et al. 2001). The user provides the PTM with an STWAVE grid and the associated wave field file. If necessary, one can also use the SMS to convert result files from other hydrodynamic or wave models and configure necessary inputs in required formats prior to using them in a PTM application. This is illustrated in Example 3 where hydrodynamic input is obtained from M2-D (Militello et al. 2004), a 2-D finite-difference coastal circulation model. M2-D input was manually converted to ADCIRC file formats using the SMS. In a future release of SMS, this process will be automated to facilitate the usage of the PTM and its coupling with other hydrodynamic models.

Background

The CIRP conducted two laboratory experiments to investigate wave behavior and wave-induced currents around jetties of an idealized inlet (Seabergh et al. 2006). The first experiment examined refraction and diffraction at an offshore breakwater and dogleg jetty. Wave diffraction into the bay behind the inlet with and without flood currents was also studied. The second experiment involved testing two types of jetty structure, an absorbing and a reflective jetty. The highly absorbing jetty resembles a fairly porous rock rubble structure, whereas the fully reflective jetty represents a vertical sheet pile or a caisson breakwater. The laboratory model is constructed according to a 1:50 scale to replicate a medium-sized U.S. Atlantic Coast inlet. The laboratory schematic is shown in Figure 50.

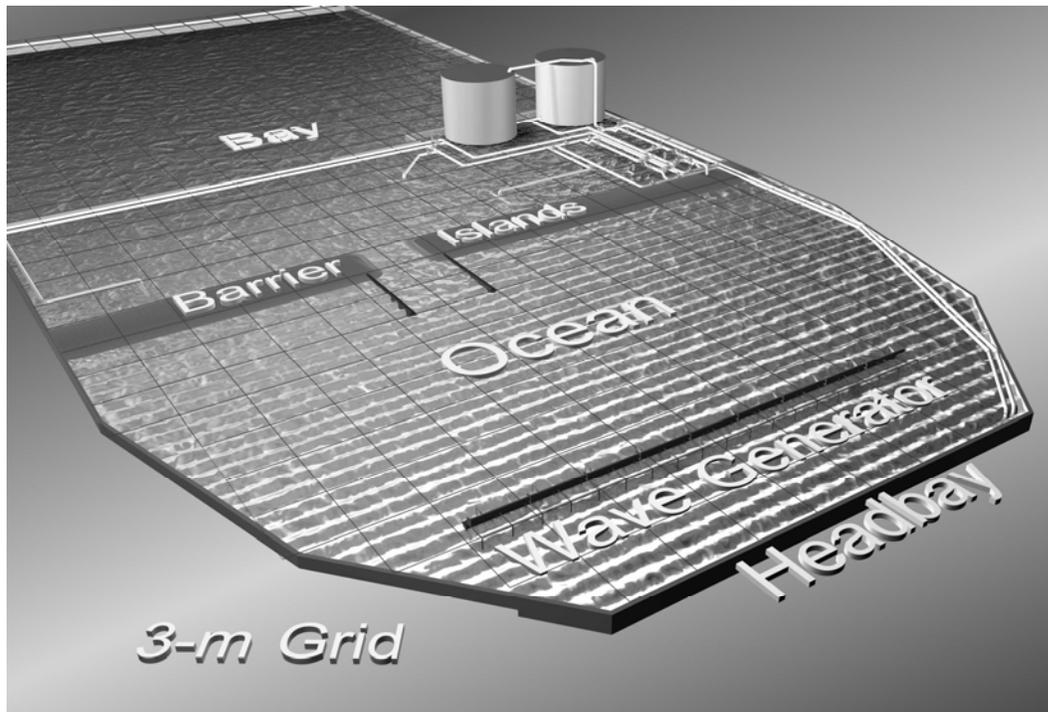


Figure 50. Schematic of laboratory experiment for idealized inlet.

Experimental conditions include both regular and irregular unidirectional waves generated at the model's offshore boundary representing mild to moderate and high sea states. Incident wave direction was either 0 (shore-normal) or 20 deg (oblique) to shoreline. Wave and current measurements were made on a grid consisting of cross-shore and along-shore transects on the up-wave side and bay side of jetties for easy application in numerical model calibration. Wave direction was measured for some experiments by a remote-sensing video-camera system as well as analyzed from the current vector data. Wave and current measurements were also conducted within the inlet on three transects parallel to the jetties. A photograph of the model arrangement can be seen in Figure 51.



Figure 51. Laboratory arrangement for idealized inlet tests.

For this application, data from these experiments served as input to the PTM. The PTM was then run to analyze sediment transport.

PTM input

The mesh for the idealized inlet is shown in Figure 52. As flow moves through the inlet, wave diffraction occurs, developing intricate flow patterns. An example of this can be seen in Figure 53, where calculated flow recirculation regions are developed throughout the idealized inlet.

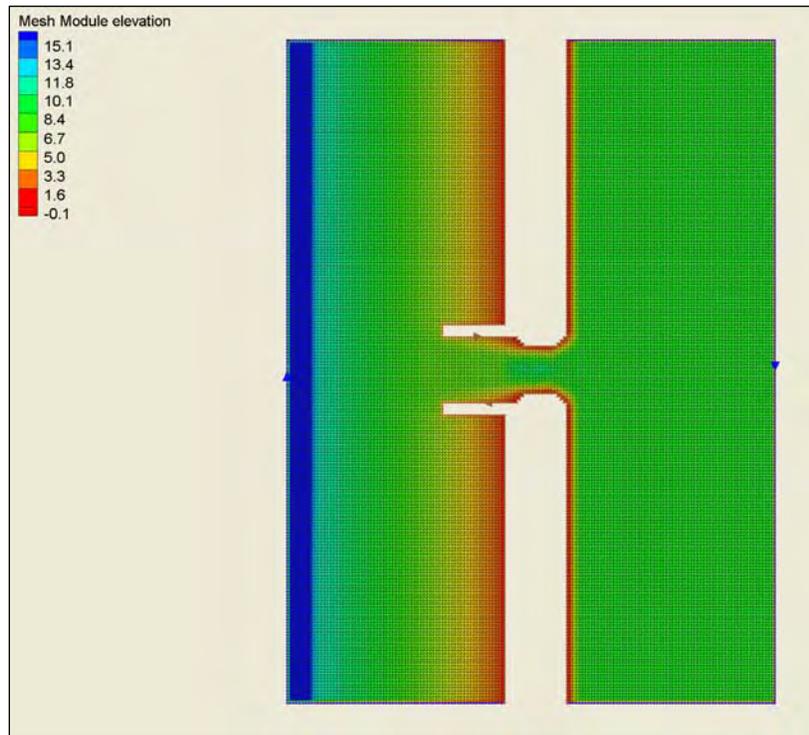


Figure 52. Example 4 mesh and bathymetry.

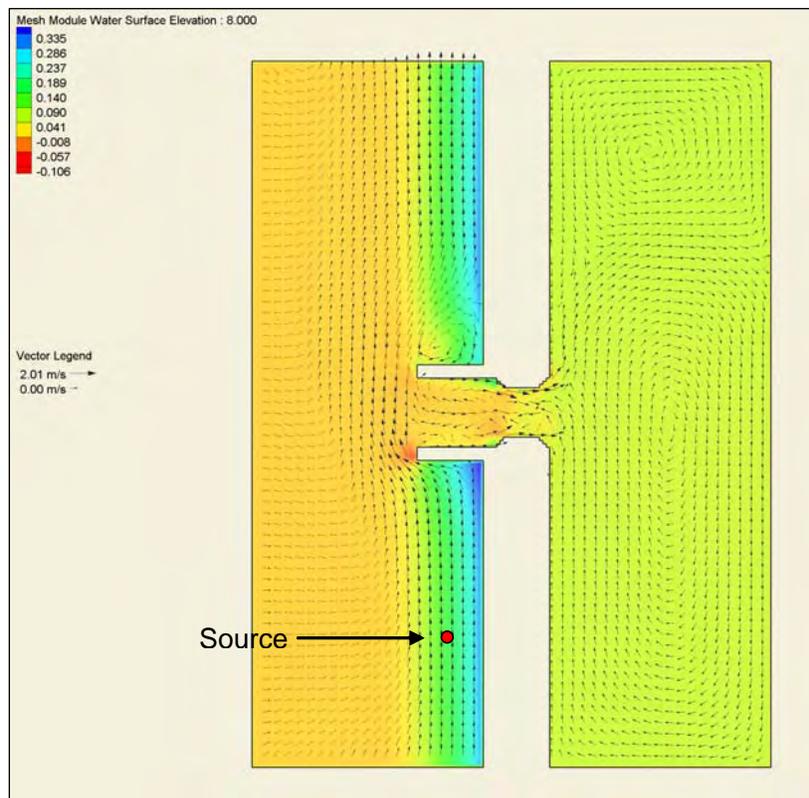


Figure 53. Flow field at $t = 8$ sec.

The source specified was a continuous mass point source (see Figure 53) at a rate of 10 kg/sec. The sediment size is medium sand, with median size 0.2 mm. Each particle represents 1 kg of sand (one particle released every 10 sec). The setup of the source is shown in Figure 54.

Date/Time	X	Y	Elevation	Parcel Mass	Horiz. Radius	Vert. Radius	Rate	Size	Deviation	Density
	(m)	(m)	(m)	(kg)	(m)	(m)	kg/s	(mm)		(kg/m ³)
01-Jan-2006 10:00:00 AM	1157.6	625.9	1.0	1.0	5.0	0.25	10.0	0.2	0.4	2650.0
01-Jan-2006 11:30:00 AM	1157.6	625.9	1.0	1.0	5.0	0.25	10.0	0.2	0.4	2650.0
23-Dec-2005 12:37:03 PM	1157.6	625.9	1.0	1.0	5.0	0.25	10.0	0.2	0.4	2650.0

Figure 54. Source input property page.

For this case a native sediments file was created using the Create PTM External Input Files option. The D_{35} , D_{50} , and D_{90} are 0.1, 0.2, and 0.5 mm, respectively (Figure 55). A beneficial feature of the interface is that once this file is created, it can be used for other simulations with this grid.

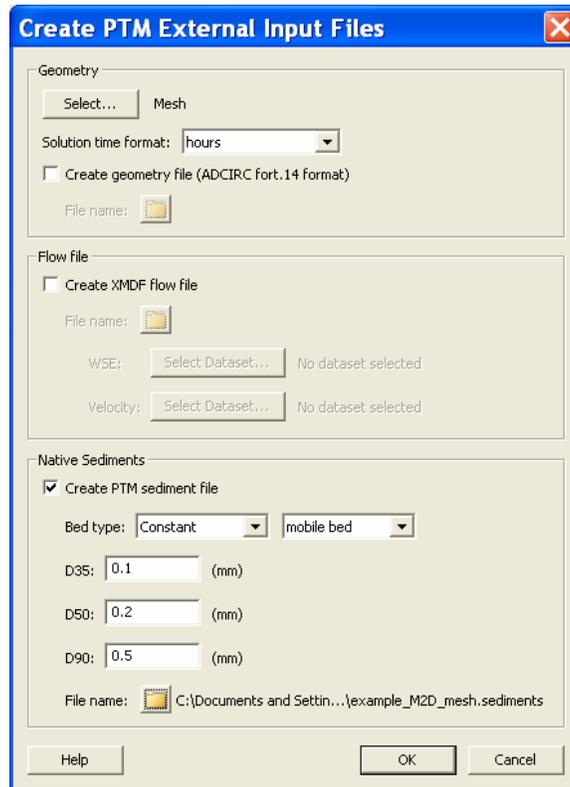


Figure 55. Create PTM External Input Files SMS dialogue box.

The simulation is set to run for 1 hr with a time-step of 1.0 sec using the Q3-D mode. As mentioned in Chapter 4, the wave option is given under the waves tab in the PTM Model Control (Figure 56). The details of the STWAVE solutions (start time, grid origin, etc.) are input into the model control.

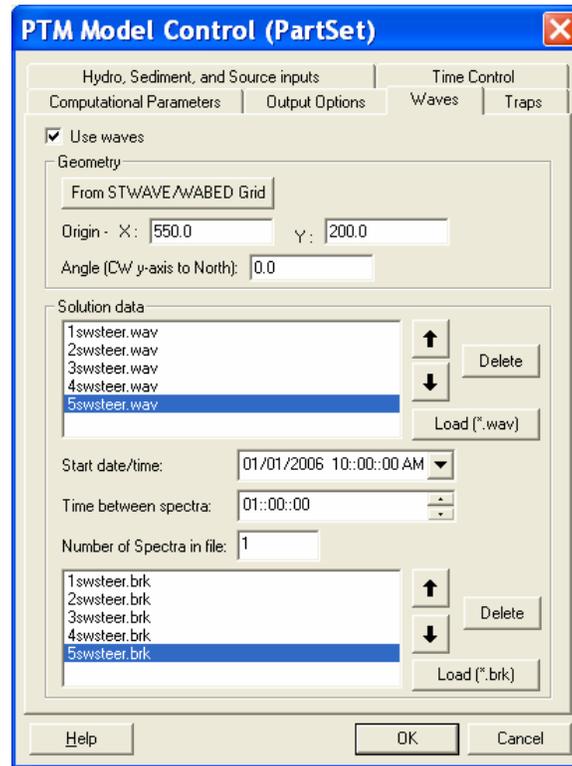


Figure 56. PTM Wave Model Control in SMS.

PTM results

The particle positions after 1 sec can be seen in Figure 57. Blue particles represent suspended particles, and the red particles represent currently deposited particles. The particles are transported towards the channel by the longshore currents, they then move longitudinally towards the channel due to the specified longshore boundary condition. However, they are soon forced into the channel by the tide during this portion of the simulation. Sixty seconds after the start of the simulation, particles move through the channel and deposit due to decreased wave action (Figure 58). For real applications, this information can be valuable to establish the effect of a channel configuration. As sediment enters into the channel, deposition potential is required for assessing navigation issues and dredging requirements.

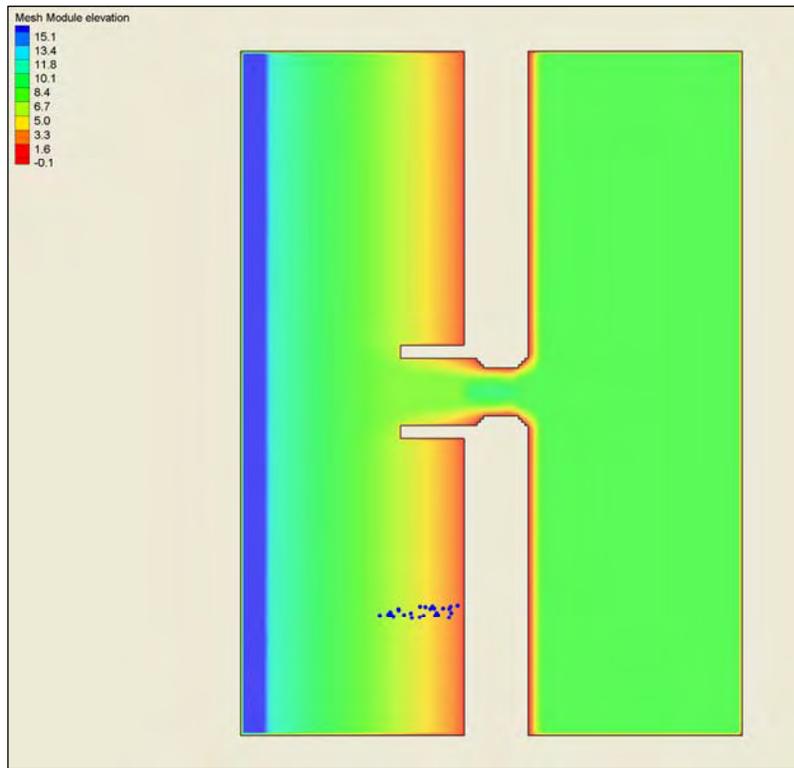


Figure 57. Particle positions at $t = 1$ sec.

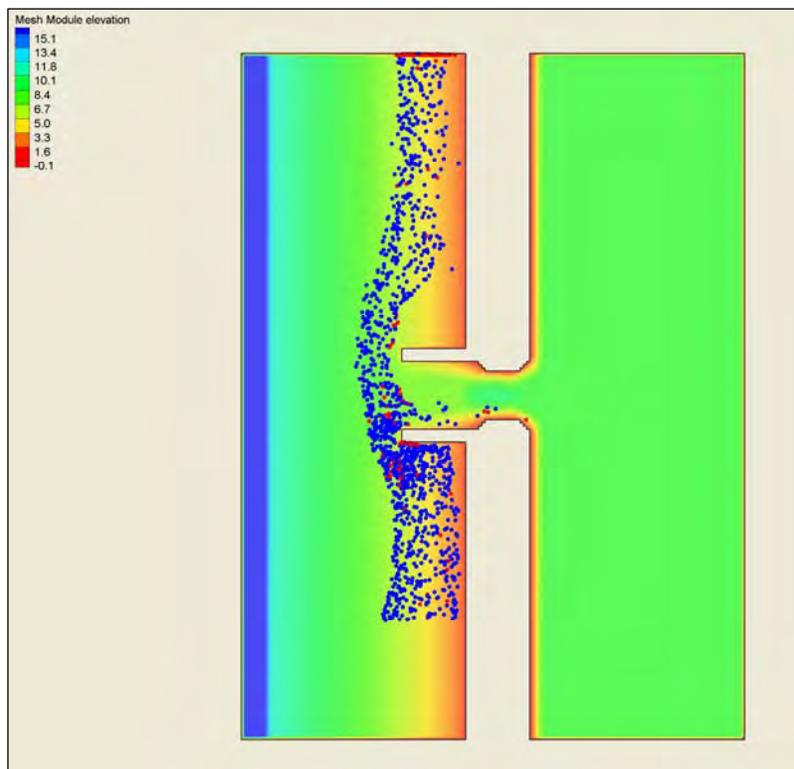


Figure 58. Particle positions at $t = 60$ sec.

Example 5: Dredging application, Brunswick, GA

Objective

This example demonstrates application of the PTM for evaluation of nearshore placement of dredged material. These PTM simulations are part of a larger study to develop a Dredged Material Management Plan that includes optimization of nearshore dredged material placement for littoral zone nourishment. Another component of the study placed fluorescent sediment tracer in the nearshore environment and monitored tracer migration over a 6-month period. The PTM simulations described here pertain to transport of sand and silt from two existing dredged material placement locations. The objective is to demonstrate a PTM application for nearshore placement of dredged material and to compare model results to fluorescent tracer study observations.

Background

The ERDC is supporting the USACE Savannah District in conducting a multi-year study to evaluate and validate numerical models for predicting dredged material transport at nearshore and open-water sites (Evans Hamilton, Inc. 2004). Nearshore transport predictions are required to address natural resource, beneficial use, and site capacity issues. Accurate predictive models are necessary for selecting and managing nearshore placement sites. PTM is applied at the Brunswick, GA, site as a diagnostic tool to judge the combined capabilities of other models, including hydrodynamic and wave models. PTM takes the results of these other models as drivers to determine fate and pathways of sediment in the modeling area and provides both qualitative and quantitative assessment of the consequences of dredging activities near Brunswick, GA.

Dredged material from the Brunswick Harbor Entrance Channel has recently been placed in a series of channel-adjacent, open-water dredged material placement sites approximately 1,200 m south of the shipping channel (Figure 59). Dredged material removed from the entrance channel is composed of approximately 80 percent sand and 20 percent silt and clay. The dredged material does not meet guidelines for direct beach placement (less than 12 percent fines). Therefore, nearshore placement is considered a promising alternative to direct beach placement for which winnowing by wave action will naturally separate sand and silt fractions. The coarser sand fraction is likely to remain in the nearshore, while fine-

grained sediment will be suspended by high wave energy in the nearshore and transported offshore by currents.

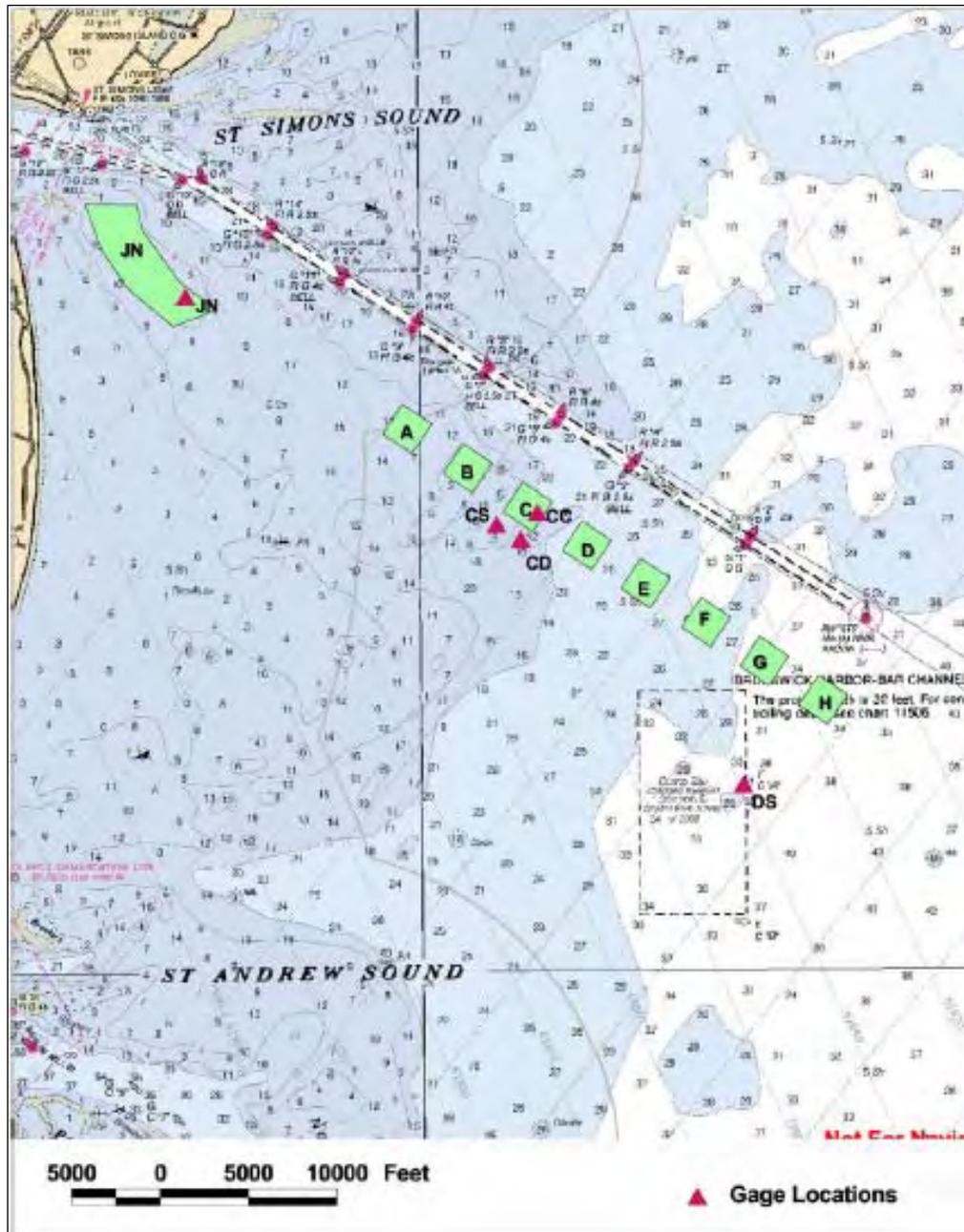


Figure 59. Map of Brunswick dredge material mound region.

Fluorescent tracer study

Fluorescent tracer field experiments were performed in 2003 to study the transport and fate of dredge material placed at Sites C and JN (Figure 55). Fluorescent tracer was manufactured to represent silt and sand-sized

particles characteristic of the dredged material (Table 2). Four tracer colors were manufactured (two sand-sized and two silt-sized) to distinguish particles during analysis by both sediment class (silt or sand) and initial location (C or JN). In late January 2003, fluorescent tracer was mixed with equal quantities of dredged material and placed on the mound crests at Sites C and JN. A sampling scheme was developed over the region to sample for tracer particles at 15, 60, 140, and 205 days following tracer release. The first two sampling events were performed with surface grabs, resulting in little recovery of sand tracer. The final two rounds of sampling were collected with shallow vibracore and pushcore, resulting in much higher rates of tracer recovery and indicating burial of sand tracer by as much as 0.3-0.5 m at the edge of mound C.

Table 2. Tracer characteristics.

Tracer Color	Sediment Type	Deployment Site	D_{50} (mm)	Standard Deviation
Violet	Sand	C	0.235	0.525
Yellow	Silt	C	0.065	0.724
UVblue	Silt	JN	0.045	0.898
Magenta	Sand	JN	0.272	0.554

Mass conservation analysis of the recovered tracer at Site C indicates that the extremely fine (10-20 μ m) spatial resolution of sampling was insufficient to resolve spatial variability in the tracer deposition and burial along the margins of the mound. The spatial variation at site JN was much more gradual, but mass conservation analysis indicated that only 20 percent of the particles released were recovered, suggesting that a large fraction (of particles, not necessarily mass) of sand tracer at JN was transported outside the sampling area. Analysis of silt-sized tracers deployed at C and JN indicates rapid winnowing from the deployment site, transport in suspension, and wide dispersal of tracer within and presumably beyond the study boundaries.

PTM setup

The PTM was applied for the period of tracer monitoring between 31 January and 21 February 2003. Numerical particles were specified with statistical distributions similar to each fluorescent tracer (D_{50} and standard deviation, see Table 2). Numerical particles were introduced as point sources on the sediment bed and made available for erosion and transport at the times and locations of the fluorescent tracer deployment.

Hydrodynamic and wave conditions were provided from calibrated and verified ADCIRC and STWAVE simulations for the period of monitoring. Figure 60 gives the ADCIRC mesh, site bathymetry, and particle source positions at Sites C and JN. Grid resolution in the Jekyll Island nearshore region and channel was nominally 50 m.

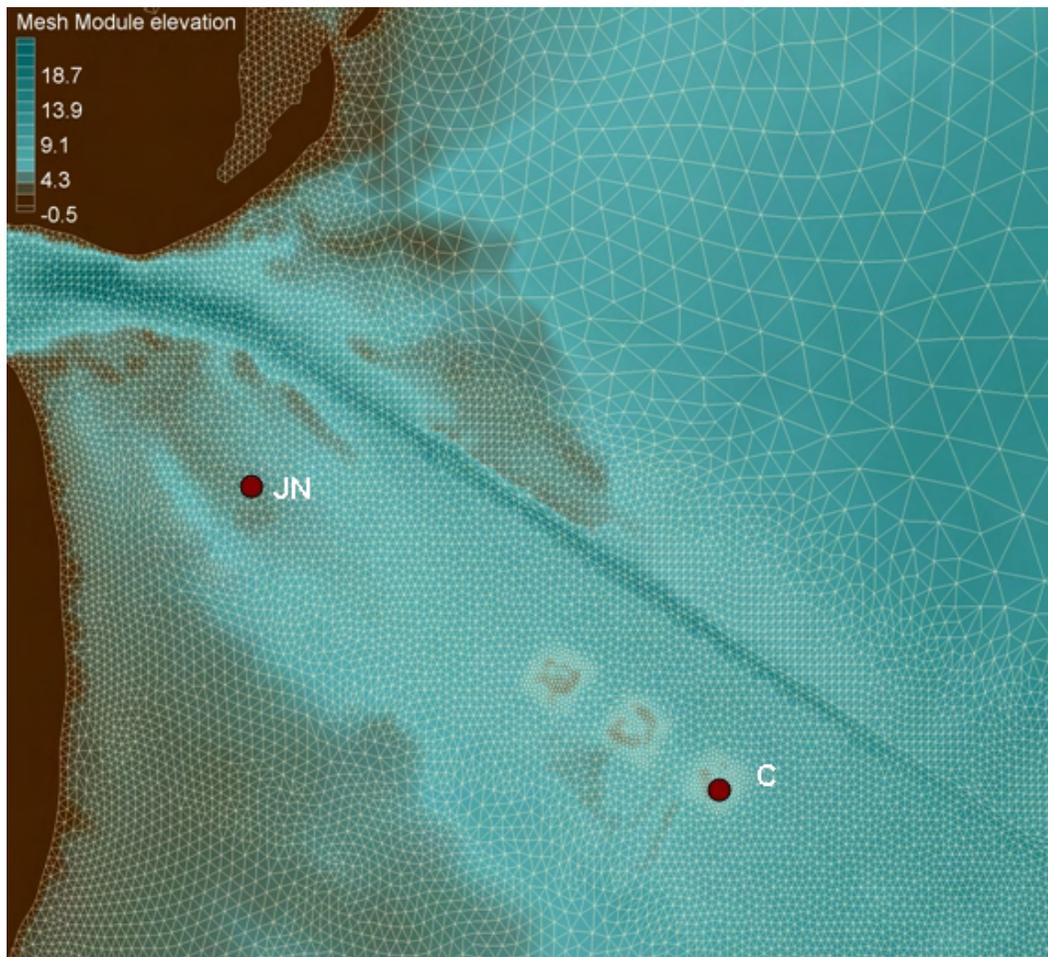


Figure 60. ADCIRC and PTM computational mesh, bathymetry (depth in meters relative to mean tide level), and position of Sites C and JN.

Figure 61 shows the SMS dialogue box for sediment source input for silt sediment at site JN. The PTM's 3-D mode was required to accurately predict the movement of this fine sediment. (It should be noted that the ADCIRC hydrodynamics were 2-D.) A 2-sec time-step was used in the 3-D model option for modeling both sand and silt in the same simulation. (This allowed PTM to reasonably simulate sand movement given its large settling speed.) Unlike previous simulations, where source release rates were user-defined, the source release rate for this simulation was model-estimated through a bed erosion algorithm (Chapter 3). Through this

method, particle introduction to the water column representative of bed erosion is possible. Time varying wave-current conditions were used to estimate bed shear stress and erosion (source strength) to the water column. This PTM option is described in Chapter 3.

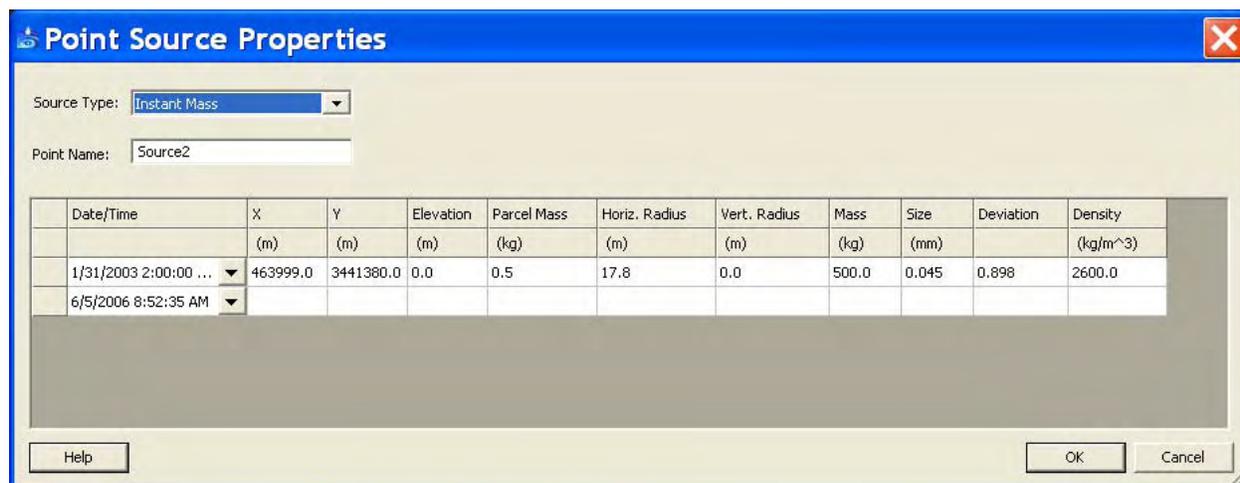


Figure 61. Properties of sediment sources.

PTM results

The PTM simulations were performed for the tracer analysis period. In this section, results for transport of each tracer are compared to the equivalent PTM source transport.

Silt at Site JN

Similar to the fluorescent tracer study, the PTM results indicate that silt is rapidly winnowed from the site. The PTM results also indicate that the much of the silt is transported to the channel and deposited in the channel and on the channel side slopes. Although direct tracer assessment was not possible for the channel, several indicators in the tracer study support the PTM results. These include tracer detection on the sound-side of Jekyll Island and on the side slopes of the navigation channel. PTM indicates that a small fraction of silt initially moves into the Jekyll Island nearshore region and is subsequently resuspended and transported offshore by increased wave energy. The ephemeral nearshore deposition of JN silts was also observed in the tracer study. A snapshot of the PTM output after the 21-day simulation is provided in Figure 62.

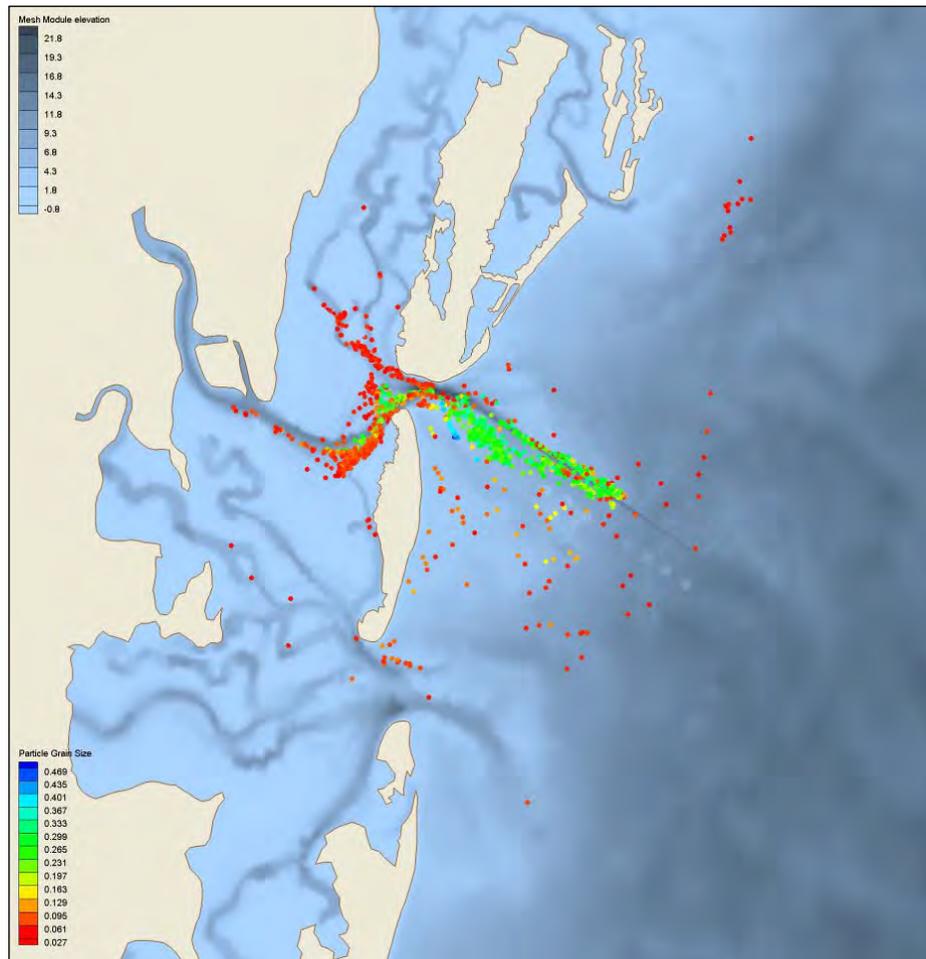


Figure 62. PTM predictions for sediment at Site JN after 21 days. Particles are colored according to grain size.

Sand at Site JN

Model data indicate that coarser sand (~0.35 mm) remains close (within 100 m) of the deployment site. Tracer data indicate that approximately 20 percent of the sand tracer remained within 100 m of the deployment site. Interestingly, if winnowing of particles is the dominant process (as indicated by the PTM simulation), 20 percent of the tracer particles are coarser than 0.250 mm, which is not greatly different from the sorting of particles in the PTM simulation. The PTM results indicate that finer sand (<0.30 mm) is transported northwest from the site, into the channel, and then transported bi-directionally by tidal currents with a net drift in the ebb direction (Figure 62). The PTM also predicts only small quantities of the sand moving from Site JN to the Jekyll Island littoral system, a similar conclusion from the tracer study.

Silt at Site C

The PTM predictions indicate that soon after particle seeding, silt particles rapidly winnow from the mound and are initially transported southward and deposited over the inner shelf. Later in the simulation, some of the silt particles are resuspended and transported northward, further scattering the silt-sized particles. Wide dispersal of silt particles from Site C is supported by the tracer study, but significant quantities of the yellow “silt” tracer deployed at Site C were also found in the Jekyll nearshore. This behavior may be explained by the fact that the manufactured tracer meant to represent silt at Site C also contained a large fraction of particles (by weight) in the range of 60-100 μm , or fine sand. If numerical particles in this size range are considered in this analysis, the PTM results are consistent with observations from the tracer study.

Sand at Site C

The PTM transport predictions for sandy sediments at Site C are not supported by tracer data. The suspected reason for the disagreement between tracer and numerical particle transport is the morphological behavior of the dredged material mound, by which sand tracer was transported from the mound crest and buried primarily along the southeast margin of the mound. The morphological processes involved rollover migrations are not represented in the PTM. As a result, the PTM estimated that fine and coarse sand migrated much further than actually observed.

Example 6: Suspended sediment transport in Northern Cook Inlet and Knik Arm, AK

Objective

The PTM is a versatile tool for representing sediment transport in a wide variety of aquatic systems. The primary objective of this example is to quickly and interactively investigate transport of suspended sediments in northern Cook Inlet and Knik Arm, AK.

Background

Knik Arm is a 45-km-long extension of Cook Inlet from Point Woronzof near Anchorage, to the confluence of Knik and Matanuska Rivers (Figure 63). The Port of Anchorage (POA) is situated on the southeast

shore of Knik Arm near the entrance to Cook Inlet (Figure 64). Near Cook Inlet, Knik Arm features include a deep, central channel and large, intertidal mud flats along the shoreline, and a 12-m spring tide range. Knik Arm and upper Cook Inlet are fed by numerous glacially fed rivers such as the Matanuska, Knik, and Susitna, which contribute large sediment loads during periods of snow and glacial meltwater (predominantly during summer months). Lower Knik Arm is characterized by many headland points that constrict the strong tidal currents and produce large gyres during both flood and ebb flows that strongly influence sedimentation on the intertidal mud flats and at the POA.

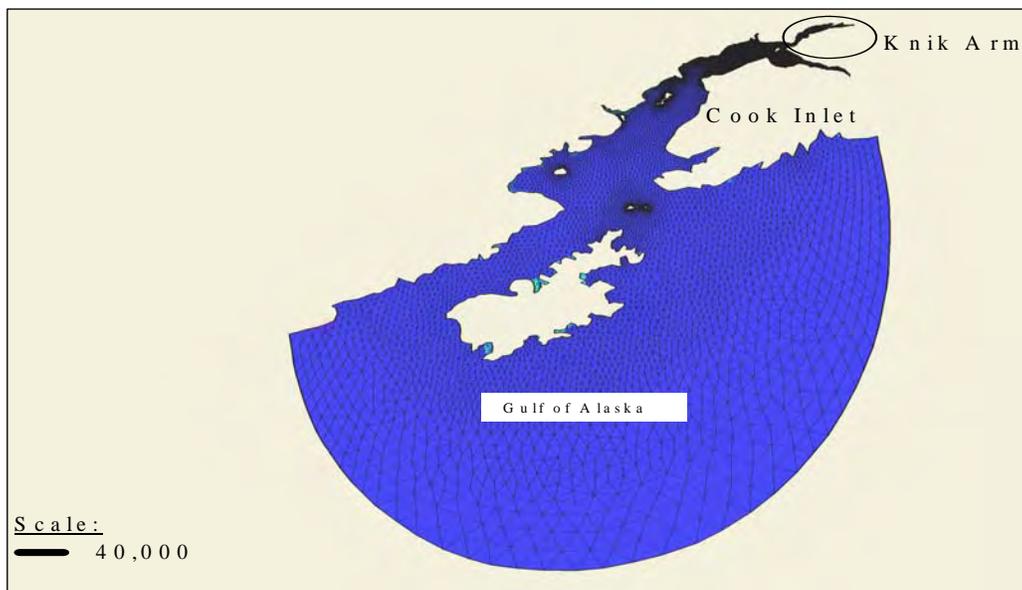


Figure 63. ADCIRC and PTM grid for Cook Inlet. Horizontal scale indicated in meters.

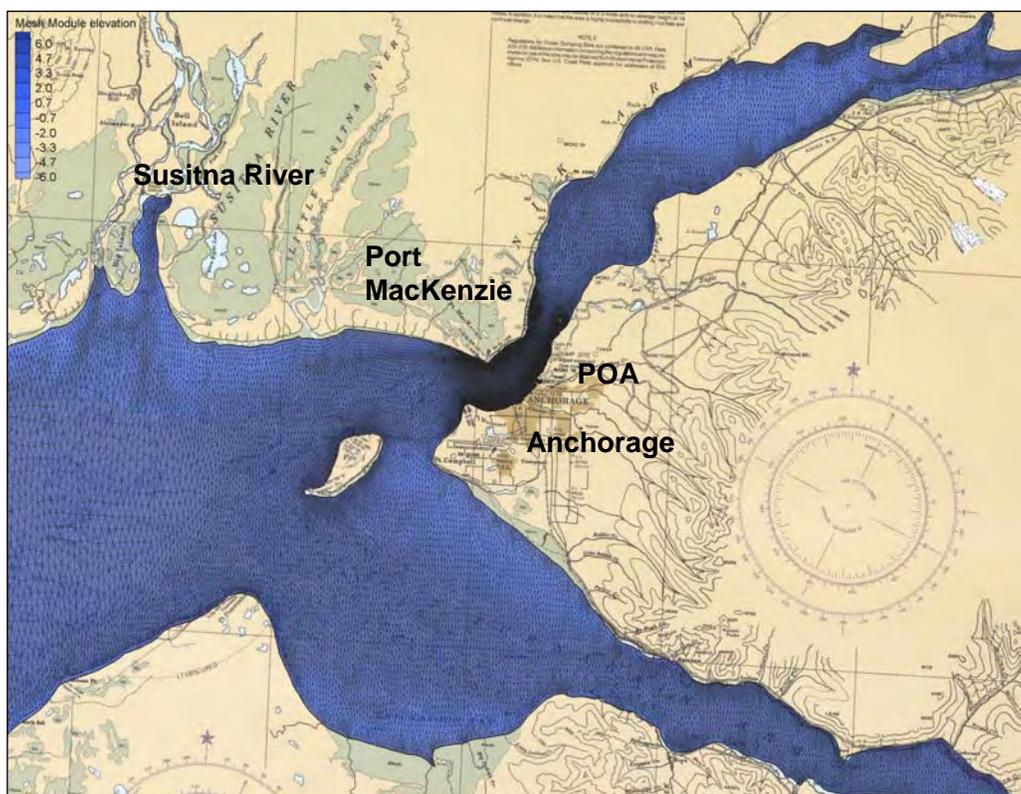


Figure 64. Knik Arm and POA, including ADCIRC mesh. Note fine mesh spacing near POA.

Initial studies indicate that the Knik Arm Crossing may alter flow conditions and infilling at the POA, which is a Federally maintained for navigation. Due to the large riverine sediment input and sediment storage in adjacent intertidal mud flats, the POA presently requires considerable annual maintenance dredging and has, in recent years, experienced even larger shoaling rates. Consequently, the PTM was applied in upper Knik Arm to better understand sediment transport patterns in this highly dynamic system.

PTM input

A 2-D ADCIRC grid was created for the entire Cook Inlet system (Figure 63), with increasing mesh resolution provided in areas of interest (including the POA) (Figure 64 and Figure 65). Finest resolution in the ADCIRC/PTM mesh is provided near the POA with approximately 10-m node spacing (Figure 64 and Figure 65). Field-measured tidal-elevation and current data were used to validate the hydrodynamic model. Wave-generated bed stresses in Knik Arm are negligible, and the influence of waves on sediment transport is neglected in this study.

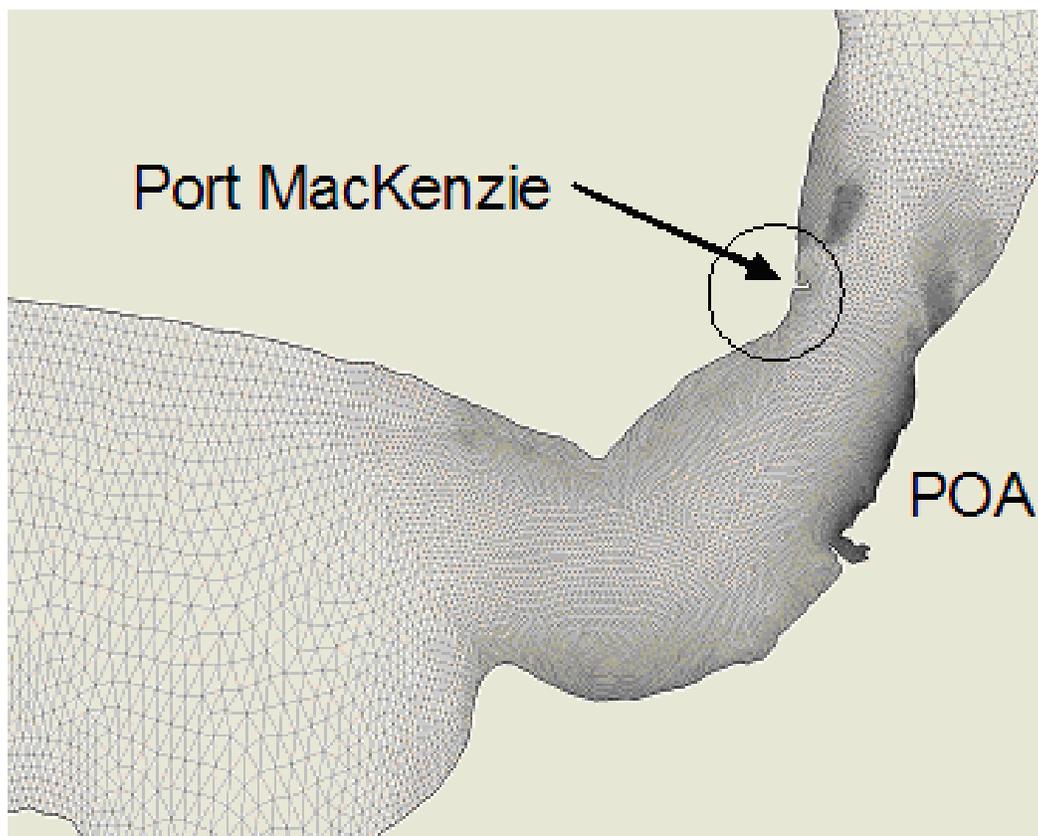


Figure 65. ADCIRC/PTM hydrodynamic mesh of upper Cook Inlet and lower Knik Arm near Anchorage, Alaska. Locations of Port MacKenzie and Port of Anchorage are indicated.

A period of 6 days between 19-25 July 2005, during spring tide, was simulated. Only tides were included in these simulations (no waves or river inflows). Two sediment sources were specified for this simulation (Figure 66): the first source is located approximately 5000 m north of the POA, and the second source is located near the Susitna River mouth.

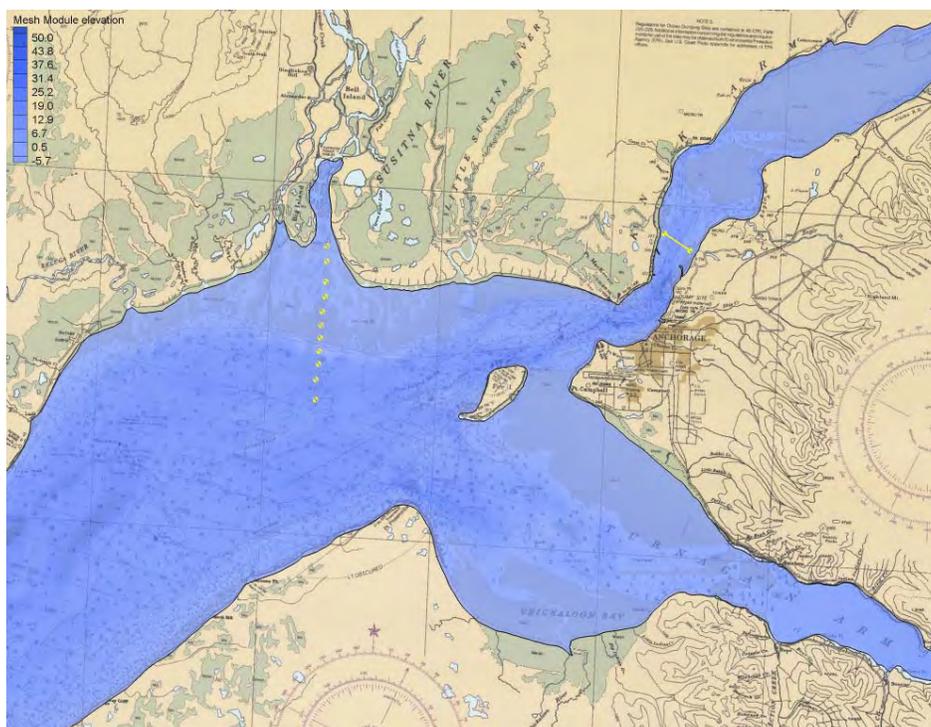


Figure 66. Location of two particle release sources in Cook Inlet/Knik Arm model. A line source is indicated approximately 5,000 m north of POA. A series of point sources is indicated south of Susitna River mouth.

For the first sediment source, north of the POA, sediment particles were introduced into the system for 10 hr at a mass rate of 1×10^{-4} kg/sec using a horizontal line source (see Chapter 2 for types of sediment sources available in the PTM). This source extended across the width of Knik Arm and was vertically positioned at 2-m water depth. Figure 67a shows the SMS dialogue box that provides specifics for this line source. A series of point (vertical line) sources were used for the second sediment source located near the Susitna River mouth (see Chapter 2 for details on vertical line sources). Each of the vertical line sources were configured for a uniform vertical distribution of particles released at a rate of 0.05 kg/sec. Figure 67b shows the SMS dialogue box for one of the eleven point sources. Although individual point source positions vary, the release rates and particle characteristics are identical for all 11 points. Particle characteristics for all sources are representative of coarse silt and fine sand ($d_{50} = 0.065$ mm), characteristic of suspended sediments in the study area. The 3-D PTM model option was used in this example because this example deals essentially with fine-grained sediments. Similar to Example 4, the ADCIRC simulations used here were 2-D. The PTM time-step was set to 15 sec, and the model was run for 7 days. For this example, a larger time-step than Example 4 is justified due to the slower settling velocity of silt.

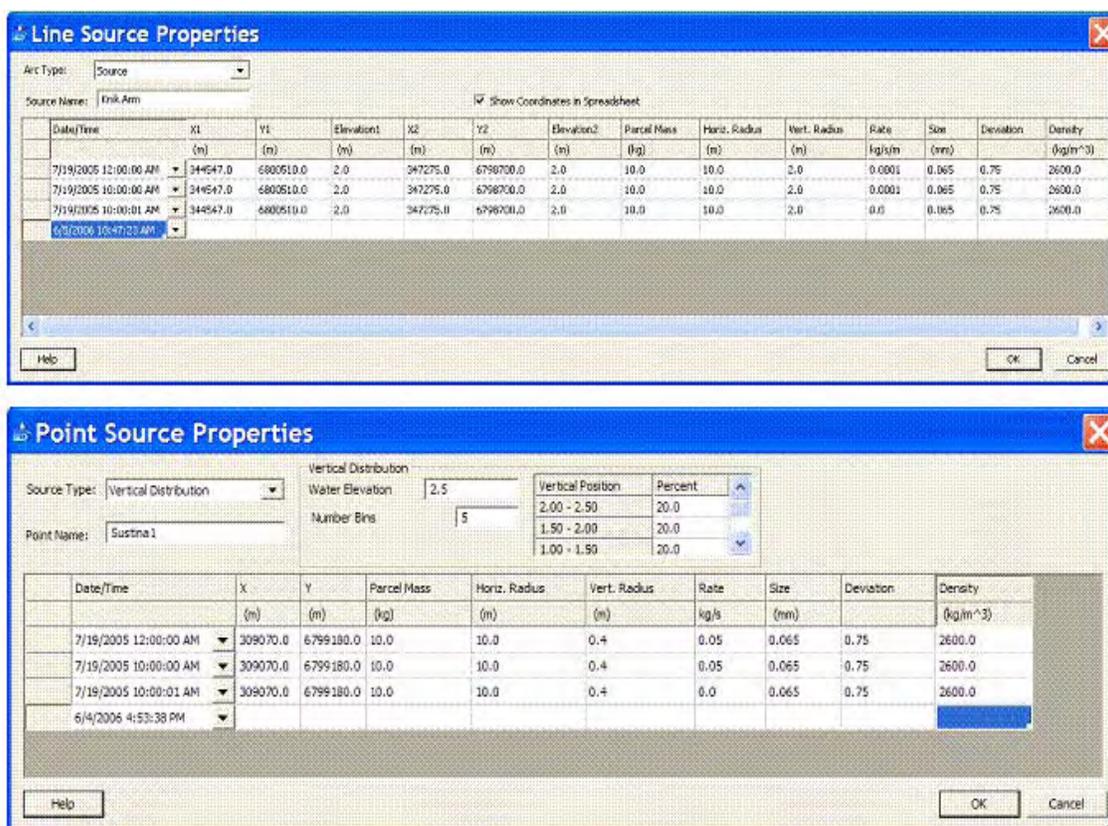


Figure 67. (a) Knik Arm horizontal line source and (b) sample Susitna River vertical line source.

PTM results

Figure 68 shows the PTM particle locations from both sources at the end of the 7-day simulation. Red particles indicate deposited sediments, and blue particles indicate sediment in suspension. Similar to observations in the natural system, deposition of silt particles is limited predominantly to the areas adjacent to the intertidal mud flats. Strong tidal flows in the main channel produce sufficiently large bed shear stresses to limit fine-sediment deposition, and more quiescent conditions in gyres shed by the numerous points in the system produce weaker bed stresses and conditions more favorable to fine-sediment deposition. Near sharp changes in geometry and bedslope, field measurements have identified 3-D hydrodynamic features. The presently applied ADCIRC 2-D hydrodynamics do not represent these hydrodynamic secondary flow features. 3-D flow characteristics would more accurately represent actual hydrodynamic conditions in the study area, and 3-D hydrodynamic modeling is planned for future applications and final analysis.

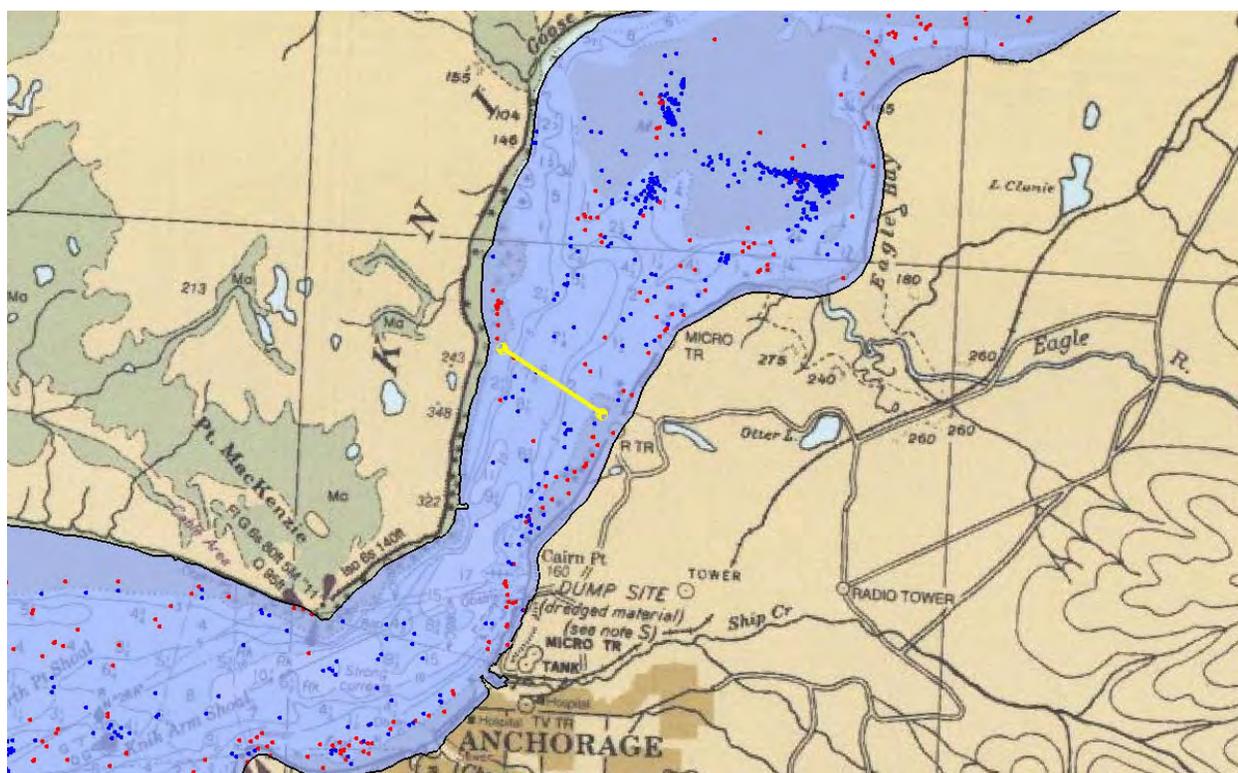


Figure 68. Particle positions in Knik Arm region at 23 July 2005 (12 p.m.). Blue particles indicate suspended sediment and red particles indicate sediment resting on bed.

The PTM indicates that much of the sediment introduced near the Susitna River mouth deposits on the large intertidal mudflat/delta (Figure 69). No known data (other than the presence of the mudflat itself) are available to verify the modeled result. One objective of the PTM application was to assess the potential role of sediment discharge from the Susitna River as a source of sediment to lower Knik Arm. Preliminary simulations with the PTM indicate that sediments introduced near the Susitna River mouth either deposit on the surrounding mud flats or are transported with a net southward direction in upper Cook Inlet. Therefore, the Susitna River is not a significant source of sediment to lower Knik Arm.

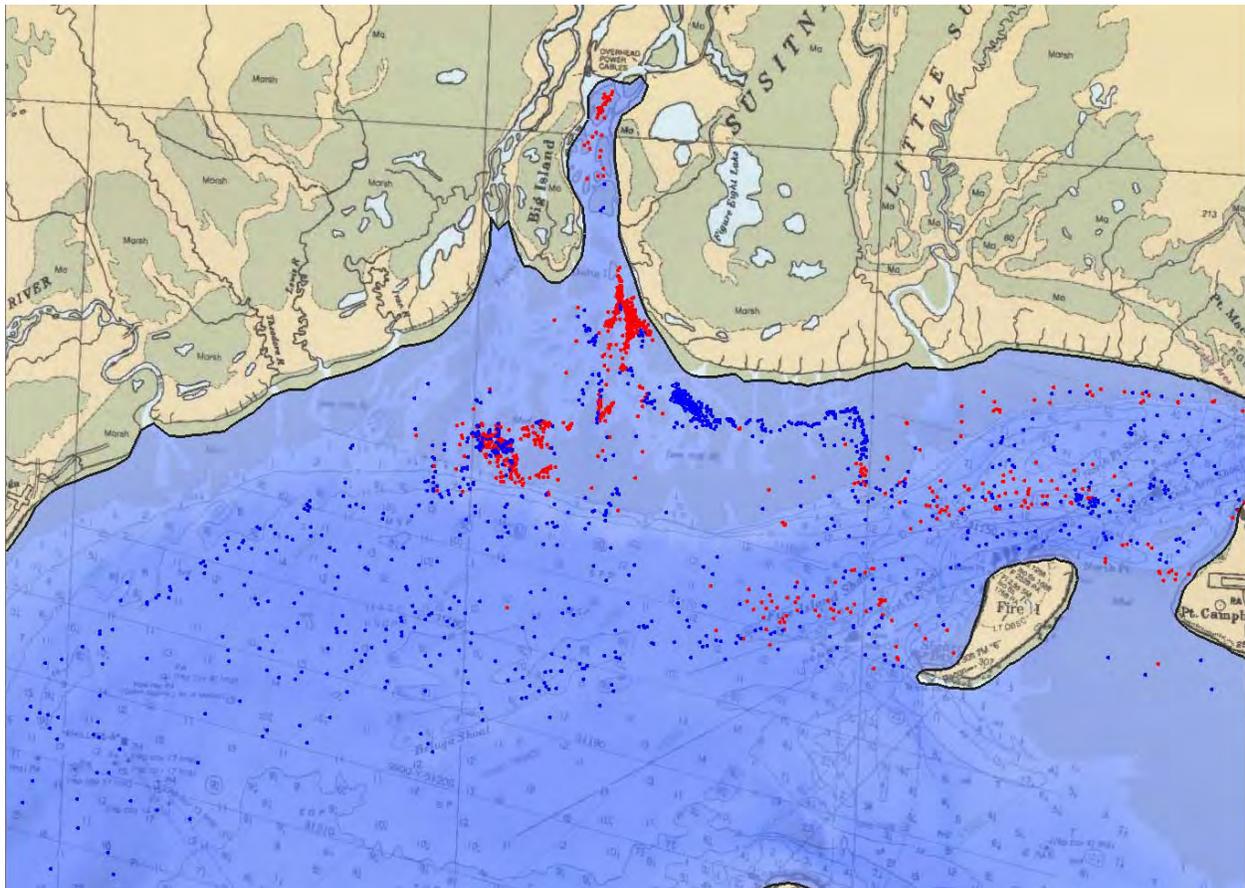


Figure 69. Particle positions in Susitna River region. Blue represents suspended particles and red represents deposited particles.

6 Concluding Remarks

A new Lagrangian modeling tool, the PTM, has been developed for tracking the fate of sediments and neutrally-buoyant particles in coastal, ocean, and fluvial waters. The model requires pre-calculated hydrodynamic model results such as those from the ADCIRC circulation model and the STWAVE wave model. Operating within the SMS modeling environment, the PTM allows the user to specify detailed information about sediment sources such as sediment release locations, rates of sediment release, and grain-size characteristics.

Ongoing development of the model will further validate the algorithms employed against field and laboratory data sets and extend model applicability to other hydrodynamic models including those representing 3-D processes. Refinements to the usability of both the model and its interface are ongoing. The model is designed to provide engineers with insight into sediment transport conditions and sediment pathways.

The quality and accuracy of particle fate simulations depends directly upon the input flow conditions. It is important that the flow model results input to the PTM be an accurate representation of the site. As with any computer modeling tool, careful analysis and interpretation of the model results and comparisons to field conditions are essential to achieving accurate and meaningful simulations.

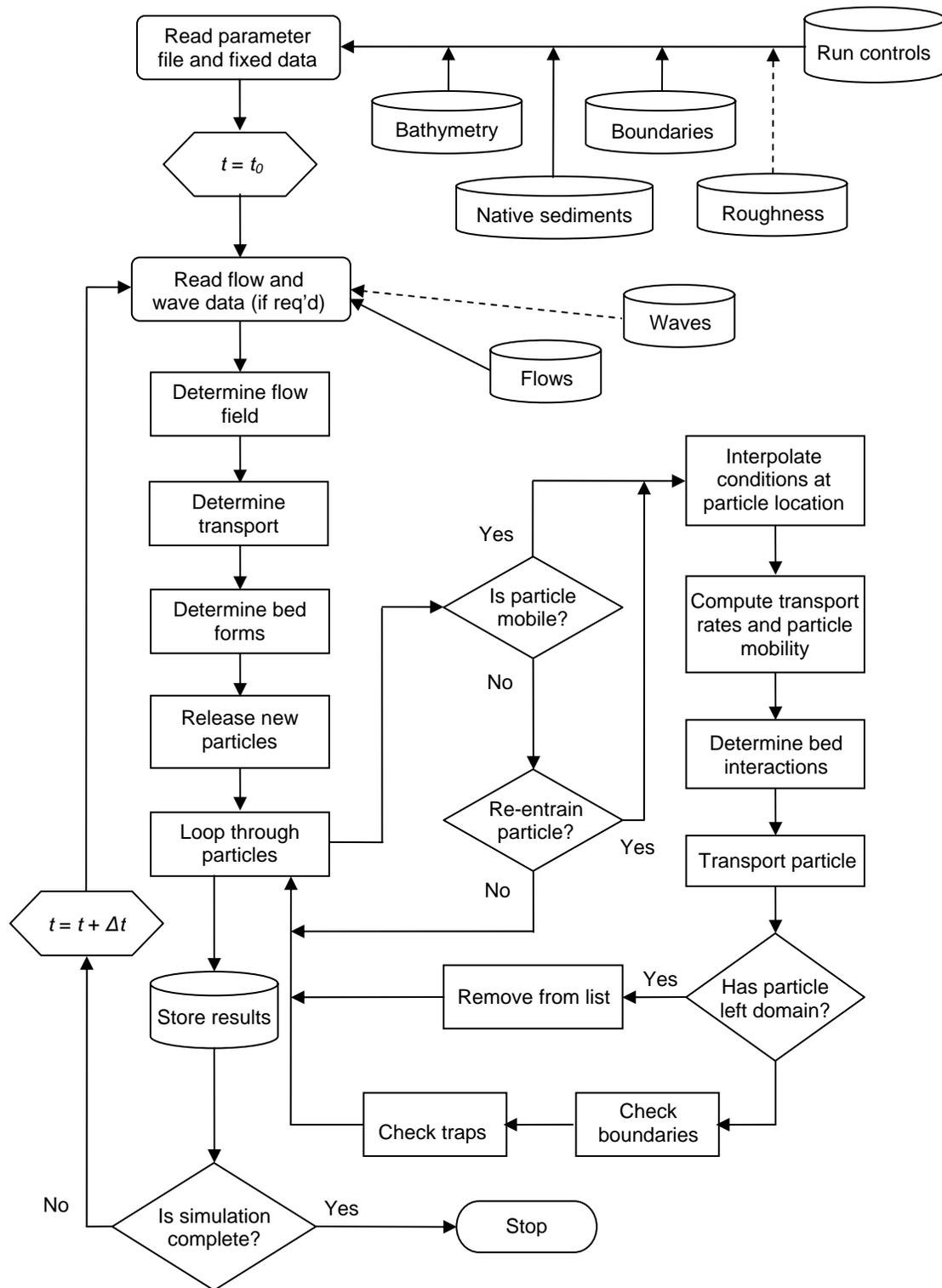
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Appendix A: Model Flow Diagram



Appendix B: Particle Tracking Model (PTM) in the SMS: I. Graphical Interface



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Particle Tracking Model (PTM) in the SMS: I. Graphical Interface

PURPOSE: This Dredging Operations and Environmental Research (DOER) Technical Note (TN) describes the graphical interface for the Particle Tracking Model (PTM). The Coastal Inlets Research Program (CIRP) and the DOER Program are jointly developing the PTM. The PTM is described in a series of three technical notes. This technical note, Part I, describes the graphical user interface of Version 1.0 of PTM. Part II (Demirbilek et al. 2005a) provides an overview of general features and capabilities of PTM. Part III (Demirbilek et al. 2005b) is a tutorial with examples. The PTM has been developed for application to dredging and coastal projects, including dredged material dispersion and fate, sediment pathway and fate, and constituent transport. A technical report (MacDonald and Davies, in preparation) provides details about the theory and implementation aspects of the PTM.

INTRODUCTION: PTM methodology is based on a parcel calculation technique, in which parcels represent a given mass of sediment subjected to the same forces and exhibiting the same kinematics as a single sediment particle. Each parcel has its own set of attributes (e.g., grain diameter, specific gravity), which influence parcel behavior (entrainment, transport, settling). The PTM employs a Lagrangian particle tracking technique to estimate migration of sediment particles as influenced by the hydrodynamic forcing inputs, including current velocity and wave fields. This approach compliments the Eulerian sediment transport and morphological models, and can provide information about a specified subset of sediment processes. This information may be applied in projects without the more resource-intensive application of a Eulerian sediment transport model.

PTM inputs are unstructured grid bathymetry, and time series of both water surface elevation, current velocity fields, and waves at each point in the modeling domain. The grid bathymetry is read from the standard IMS-ADCIRC (ADvanced CIRCulation model; see Luetlich et al. (1992)) mesh file. The water surface elevation and current velocity fields are read from files written using the Generic Model Data Format standard (XMDF; see Jones et al. (2004)). Optionally, PTM also supports wave model or field data at grid points from a separate (Cartesian) grid. Wave input files to PTM are the standard STWAVE (Steady-state WAVE transformation model) output files (Smith et al. 2001). In addition to the hydrodynamic and wave input, the user specifies sediment sources, sediment properties, and model parameters to run PTM. The SMS interface of the PTM includes commands for layout of the model inputs including sediment sources, specification of the numerical parameters, and management of the Eulerian data (grids and solutions of ADCIRC and STWAVE). Both hydrodynamic and wave inputs are mapped to the PTM-specific computational grid. The velocity and wave fields must be computed or approximated (if desired) prior to constructing a PTM simulation in SMS. Result files for these fields are then used as input to a PTM simulation.

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PTM I/O FILES: PTM requires five input files (Figure 1). These are the model parameters file (*.pcf), the particle source file (*.source), the native sediments file (*.sediments), the ADCIRC Eulerian grid file (*.grd or *.14), and the flow data in XMDF format (*.h5). Two other optional file types containing wave data and particle trap definitions may also be specified. The model may be launched from inside SMS, in which case the parameter file can be built through interface prompts. All other input file names and their locations are specified in the *.pcf file, along with the names and locations of model output files. Alternatively, the model can also be run outside of SMS using the parameter file as a command line argument. In this case, all input files must already exist.

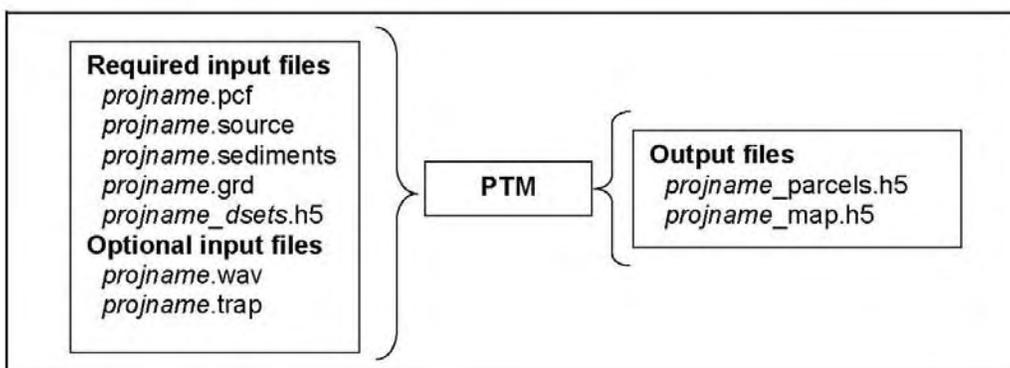


Figure 1. Files involved in a PTM simulation

The model creates two types of output files, the particle and Eulerian mapped output files. The particle output file (*.parcel.h5) contains the paths and locations of individual parcels at each output time, along with attributes of those parcels such as their characteristic size, speed, source, and index. Parcel attributes that may be saved are briefly described in Table 1. Eulerian mapped data are output to the *_map.h5 file at each grid location. The Eulerian output includes wave parameters, flow values, bedforms, and computed mobility.

Attribute	Type	Description
Grain size	Static – floating point	Size of a characteristic particle
Mobility	Transient – floating point	Tendency of the particle to move
Elevation	Transient – floating point	Elevation of the particle above the sediment bed
State	Transient – integer	=0 for dormant particle, =1 for moving particle
ID	Static – integer	Particle ID
Source	Static – integer	Particle source identifier
Parcel mass	Static – floating point	The total mass of particle

The PTM output files are in binary format, and written as hdf5 files in XMDF standard (<http://www.wes.army.mil/ITL/XMDF>). These files allow for storing large simulations in a compressed form to speed up data processing and viewing, and ensuring portability of the

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compressed data across different computing platforms. The binary file format also allows users to run the PTM on one computing platform and perform post-processing on a different computing platform. The default computing platform for the PTM simulations is a PC, and all of these tasks can be performed on a PC.

PTM INTERFACE: The PTM interface in SMS is accessed through the *Particle Module*  of SMS. User assistance for SMS is available through the “Help” icon within SMS and the SMS users guide (Zundel 2005). A general description of the interface follows. A simulation can be initiated by choosing the *New Simulation* command in the PTM menu, or by opening an existing simulation using either an SMS project (.spr) file or a PTM program control file (.pcf). The PTM uses the *Map Module*  to define the source terms for particles, and may use the *Mesh Module*  to visualize, select, and possibly convert the current data. PTM also utilizes the *Cartesian Grid Module*  to convert, visualize, and select wave input data.

The PTM interface primarily consists of the PTM menu and various sub-menus in the *Particle Module*, and the PTM coverage in the *Map Module*. The *Particle Module* is used to specify user input and create the *.pcf file and the *Map Module* is used to define the particle source terms. This document describes the standard components of the PTM interface. It is recommended that the user become familiar with other modules of SMS to fully exploit the many intricacies and features of the PTM interface.

PTM menu. The PTM menu and commands are listed and described in Figure 2 and Table 2, respectively.

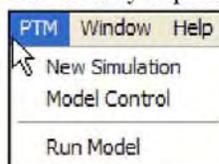


Figure 2. PTM Menu

Command	Functionality
New Simulation	Creates a new PTM simulation. A simulation includes a set of particle sources, sediment conditions, run parameters, and the corresponding particle paths computed by PTM once the model has been executed.
Model Control	Brings up the Model Control dialog to specify model simulation parameters for the present simulation.
Run Model	Brings up a dialog to allow users to select the executable of PTM to run with the present simulation. As the model runs, a dialog monitors progress of the model and gives the user status messages. After the run is complete, the spatial solutions are read in for analysis and visualization.

Specifying simulation parameters. The PTM simulation dialogue stores all the model parameters and input files used in a simulation. To specify these parameters the user selects the *Model Control* command from the PTM menu, which invokes the PTM *Model Control Dialog*. This dialogue consists of six separate pages (Figure 3-9), discussed below:

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- Computational parameters dialog page* (Figure 3). This page allows the user to select computational methods and parameters from the available list of capabilities. Computational methods include choosing whether particles will be distributed by weight or by grain size, whether Eulerian interpolation will use the van Rijn (1984 and 1993) or PTM method, whether the particle centroid will be computed by the Rouse (1939) or van Rijn method and whether advection will use the 2D or quasi-3D method. User-specified computational parameters in the Model Control dialogue box include the specification of a minimum cut-off depth, water temperature, salinity, transport factor, and diffusion parameters. The minimum cut-off depth refers to the minimum water depth for which a particle will be tracked. The minimum depth is used to limit calculations at near-zero depths; typically this is set to 0.01 m, but may need to be set lower if working on very fine scale or laboratory problems. If a particle moves into a region of the domain with a water depth lower than the cutoff depth, the particle is considered inactive until water level rises enough to increase the depth above the cutoff depth. The user also specifies how often the shear, bedforms, and mobility should be recomputed. The user is referred to the technical report (MacDonald and Davies, in preparation) for a description of these methods and appropriate application.

- Hydrodynamic, sediment, and source input dialog page* (Figure 4). This page is used to specify input files for bathymetry, flow (current and water surface elevation), and native sediment parameters. This box is also used to define particle sources. As noted above, the model requires a Eulerian grid to define the bathymetry, native sediments, water surface, and the velocity field. If these files exist in the appropriate format, they can be accessed directly without loading the grid

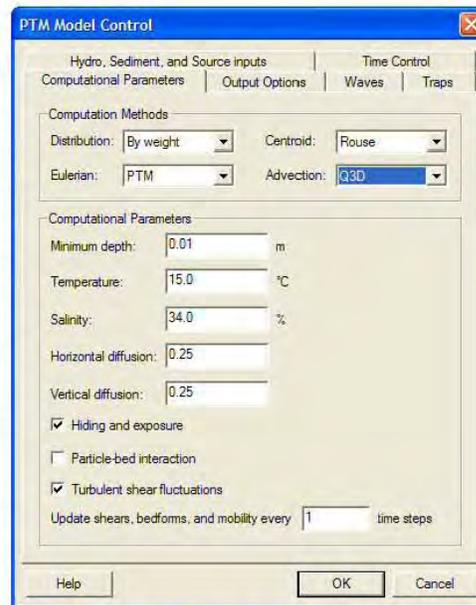


Figure 3. Computational parameters page of PTM Model Control Dialog

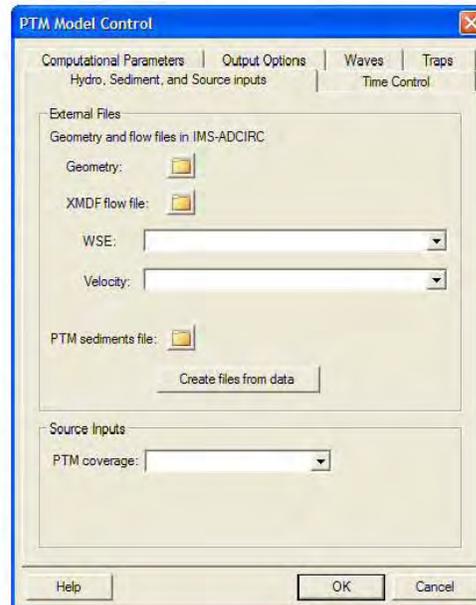


Figure 4. Hydrodynamic, sediment, and source inputs page of PTM Model Control Dialog

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into SMS. If the files do not exist in the appropriate format, SMS can be used to convert existing Eulerian data to the correct format using the *Create Files from Data* button. This button displays the *Create PTM external input files* dialog (Figure 5).

The top section of this dialog is used to select the Eulerian grid geometry file. Clicking on the *Choose* button displays a list of the Eulerian objects that have been loaded into SMS. This could be a finite element mesh, or a curvilinear grid, or a scattered triangular mesh from hydrodynamic models. The only limitation is that the object must have bathymetric, water surface, and current data defined in a data set for each computation node in the grid. These data will be converted to the appropriate PTM structure within the SMS interface. The PTM solution/output time units are also specified in the interface. The SMS converts from days, hours, or minutes into seconds as required for PTM calculations. As shown in the top part of the panel (Figure 5), the PTM reads in ADCIRC-format fort.14 file and creates a PTM geometry file in the same format. In the flow files section of the dialog, the user may select ADCIRC-format for current and water elevation files to be saved as PTM input files. The SMS creates the PTM input files when the user clicks the *OK* button. The bottom

Figure 5. Dialog to create input files from Eulerian grid in SMS

panel allows the user to create the native sediments file. This file includes the characteristic grain sizes (in millimeters) of the native bed. A negative value of d_{90} indicates a hard-bottom bed and the value supplied would represent the roughness factor (millimeters). Native sediments are not resuspended in the PTM because they are not a particle source, but they are used to compute roughness, bed forms, and active layer mixing, thereby affecting turbulence and particle mobility.

- *Time control dialog page* (Figure 6). The time control page of the PTM Model Control dialog is used to specify simulation dates and the time-step size. Input parameters are: start date/time, end date/time, computation time-step, output interval, and hydrodynamics start time. The hydrodynamic solution must start at or before the starting PTM simulation date/time, and must contain valid data for the entire PTM simulation period. Guidance for selecting the simulation time-step is provided in the PTM technical report (MacDonald and Davies, in preparation). In

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another dialog box, the user specifies time periods of the particle sources. These time periods must be included in the computational time range defined in the Time Control dialog.

- Output control dialog page* (Figure 7). The *Output Options* page allows the user to specify which model results to save to the output files during the PTM simulation. PTM creates two solution files. One stores the particle data (Lagrangian), and the other stores the mapped Eulerian data. They are named by adding on to the simulation name. The top portion of the page defines which particle-related data sets are saved to the “*SimulationName_particles.h5*” file. The bottom portion of this dialogue allows the user to select data to be mapped back to the Eulerian grid and saved to the “*SimulationName_maps.h5*” file. The user also specifies how often each data type should be saved.
- Wave input dialog page* (Figure 8). This page is similar to the hydrodynamic, sediment, and source inputs page described previously. It allows the user to specify a wave field input file for the PTM simulation. The user specifies the origin and orientation of the grid. If the grid is loaded into SMS, the “*From STWAVE Grid*” button will fill in the origin and angle based upon the grid. In the lower portion of the dialog, the user can input output file name (*.wav) and time stamp for the wave input file.
- Trap control dialog page* (Figure 9). The *trap control* page allows the user to specify the timing control of the polygonal traps defined in the PTM coverage. The user can also specify whether the traps will retain the particles as they arrive, and if they do not retain them, whether to count particles that enter the trap multiple times as a single instance or multiple instances. The PTM technical report provides more detail on using traps in PTM simulations.

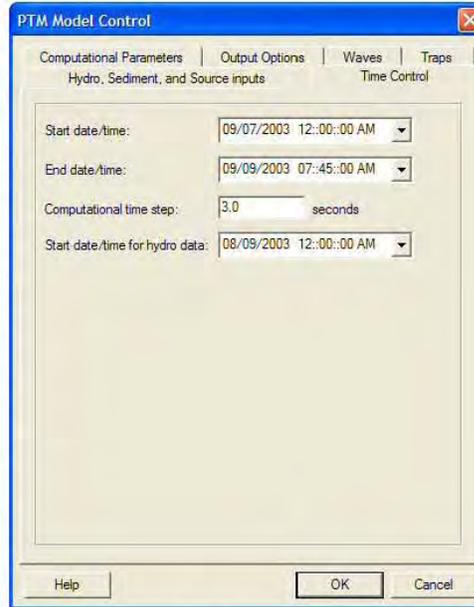


Figure 6. Time Control page of PTM model control dialog

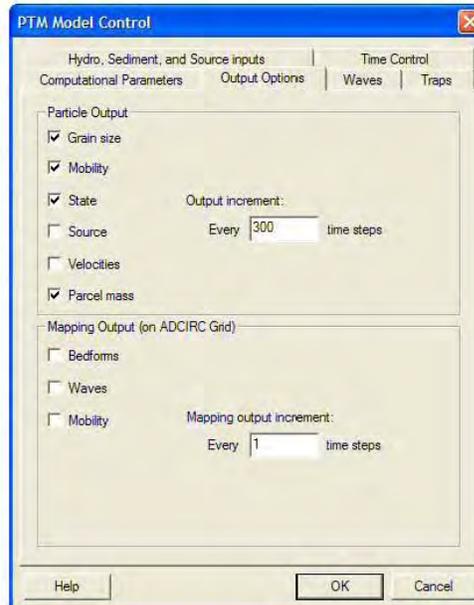


Figure 7. Output control page of PTM model control dialog

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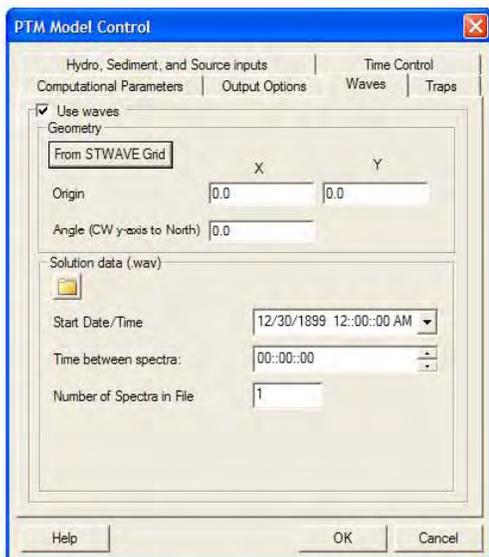


Figure 8. Wave control page of PTM model control dialog

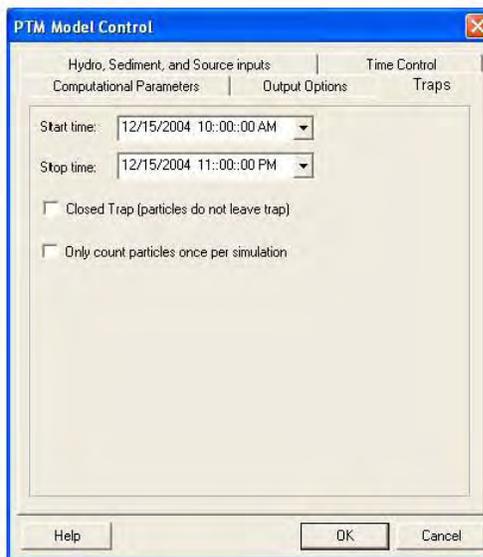


Figure 9. Trap control page of the PTM model control dialog

Specifying particle sources. Particle sources are defined as attributes on nodes and arcs (Zundel et al. 1998; Zundel 2005) in the PTM coverage in the *Map Module*, i.e., PTM sediment sources are defined at a point or along a path. The positions and attributes of each time-varying source are managed in the map module of SMS through the *Feature Objects/Attributes* command. The source attributes can be managed and edited using the *Feature Attributes* command in the map module. The user can create feature points in the map module, and by double-clicking, assign attributes to any feature point to define it as a particle source. Figures 10-13 illustrate the SMS-generated dialogs (tables) for each of the source types. Each row of the table represents a point in time describing the life of the source. For times between rows, each column of data is linearly interpolated from the rows before and after it. The first column of the table includes the date and time. The table also includes a central position (x,y) for the generation of particles, elevation, and characteristic size. The position of each particle generated actually varies across a specified radius (both horizontal and vertical). Further, the size of the characteristic grain of the particle varies according to a specified grain size distribution, characterized by the standard deviation of the sediments. For details, see MacDonald and Davies (2005). Particle source types include:

- *Point source of certain mass rate* (Figure 10). A mass rate point source produces particles at a specified rate over time. Each row in the table defines the point source central location at the time specified in the first column. Point source locations between the times specified in any two adjacent rows are interpolated between the locations specified in each row. The generation rate, characteristic grain size, and other attributes also vary with time. This

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method of particle release can be used, for example, to represent effluent loss from a pipeline that is moved intermittently.

Date/Time	X (m)	Y (m)	Elevation (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Rate (kg/s)	Size (mm)	Deviation	Density (kg/m ³)
10/6/2004 4:00:00 PM	4091.0	3375.0	8.0	2.0	3.0	3.0	0.05	0.05	0.8	2650.0
10/6/2004 5:00:00 PM	4119.0	1966.0	8.0	2.0	3.0	3.0	0.05	0.05	0.8	2650.0
10/6/2004 5:00:01 PM	4091.0	3375.0	8.0	2.0	3.0	3.0	0.0	0.05	0.8	2650.0
11/30/2004 12:35:27 PM										

Figure 10. Mass rate point source attribute table

- Point source with instant mass* (Figure 11). An instant mass source creates an entire group of particles at specific points in time. The times are specified in the first column of each row and the remaining columns control the amount of mass, the mass in each particle, and the other particle attributes. As with mass rate sources, the particle initial positions are distributed randomly around the central location to allow for a natural variability. This method of particle release can be used, for example, to represent release from a split-hull barge during dredged material placement.

Date/Time	X (m)	Y (m)	Elevation (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Mass (kg)	Size (mm)	Deviation	Density (kg/m ³)
10/6/2004 12:00:00 PM	4764.0	2638.0	8.0	2.0	1.0	1.0	180.0	0.2	0.8	2650.0
11/30/2004 12:35:45 PM										

Figure 11. Instant mass point source attribute table

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- Vertical line sources at a planar point* (Figure 12). Point sources may be used to represent a set of vertical line sources. At the top of the dialog, the user specifies the number of bins in the line source and the maximum height above the bottom that particles will be generated. To the right of this information, the user enters the rate of particle generation for each vertical segment as a percentage of the total mass of particles generated. The vertical line is segmented into equal increments (height divided by the number of bins). The table at the bottom again defines the timing of the particle generation (the first column), the central position of the particle generation (second and third columns), and the particle attributes as described above (columns 4-10). Particles are distributed linearly along the line and according to a Gaussian distribution around the line. This source can be used, for example, to simulate vertical distribution of sediment released into the water column from a moving dredge.

Date/Time	X (m)	Y (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Rate (kg/s)	Size (mm)	Deviation	Density (kg/m ³)
10/6/2004 2:00:00 PM	4764.0	1726.0	2.0	1.0	1.0	0.05	0.1	0.8	2600.0
10/6/2004 3:00:00 PM	4764.0	1726.0	2.0	1.0	1.0	0.05	0.1	0.8	2600.0
10/6/2004 3:00:01 PM	4764.0	1726.0	2.0	1.0	1.0	0.0	0.1	0.8	2600.0
11/30/2004 12:35:10 PM									

Figure 12. Vertical line at a point source attribute table

- Horizontal line source* (Figure 13). A horizontal line source is situated along a straight line with two end points having a constant elevation. Particles are generated evenly (uniformly) along this straight line. The line can move over time. Each row defines the position of the line at a particular time, which is specified in the first column. The positions of particles are defined in columns 2-7. The remaining columns define the particle attributes as defined above.

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Date/Time	X1 (m)	Y1 (m)	Elevation1 (m)	X2 (m)	Y2 (m)	Elevation2 (m)	Parcel Mass (kg)	Horiz. Radius (m)	Vert. Radius (m)	Rate (kg/s)	Size (mm)	Deviation	Density (kg/m ³)
10/6/2004 6:00:00 ...	3575.0	3845.0	10.0	3575.0	1570.0	10.0	2.0	1.0	1.0	0.000022	0.025	0.8	2650.0
10/6/2004 7:00:00 ...	3575.0	3845.0	10.0	3575.0	1570.0	10.0	2.0	1.0	1.0	0.000022	0.025	0.8	2650.0
10/6/2004 7:00:01 ...	3575.0	3845.0	10.0	3575.0	1570.0	10.0	2.0	1.0	1.0	0.0	0.025	0.8	2650.0
11/30/2004 12:34:...													

Figure 13. Horizontal line source attribute table

Visualizing PTM solutions. The principal output from PTM is a series of particle locations over time and attributes of those particles at each time (the *_particle.h5 file). The SMS includes tools for visualizing the particle paths. These tools reside in the *Particle Module*. The solution file is read into SMS using the File|Open command. Particle data sets and attributes appear under the name of the simulation in the *Project Explorer* dialog (tree window) in SMS (Zundel 2005) as shown in Figure 14. In this example, PTM output (see Figure 14) consists of particle sources (which stay constant for all times), particle states (active or inactive, i.e., mobile or immobile), and particle velocities. The latter two change from one time-step to another. The user can select an active data set in the upper portion of the tree, and an active time-step to display in the lower portion of the tree.

- *Particle display options (Figures 15 and 16).* The display options in the SMS interface allow users to specify which particles to display and how they should be displayed. Options include displaying the particle at a point in time, the particle path (over the whole particle life), and/or a portion of the path (specified as a time length). These options are depicted in Figures 15 and 16. The display options are shown in Figure 15. The three toggles allow the user to set the display status of the particles, the particle tails (portion of the particle path), and the particle paths. By clicking on the small buttons, the user can change the line thicknesses and colors, and set the symbol to be used for the particle. Particles and particle tails can be color coded to display their attributes by choosing to color particles based on the data sets read from the solution file. In the lower right side of the dialog, the user can choose to filter the number of particles to be displayed.

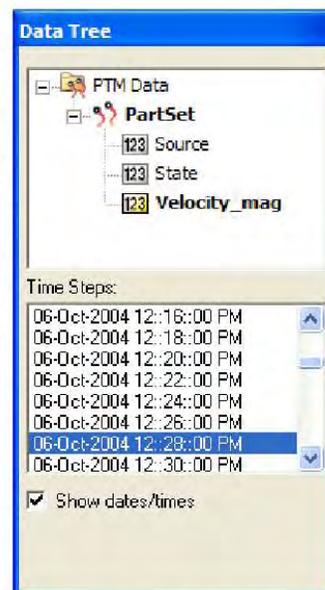


Figure 14. Particle data sets in the project browser and the time-steps

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Figure 15. Particle module display options

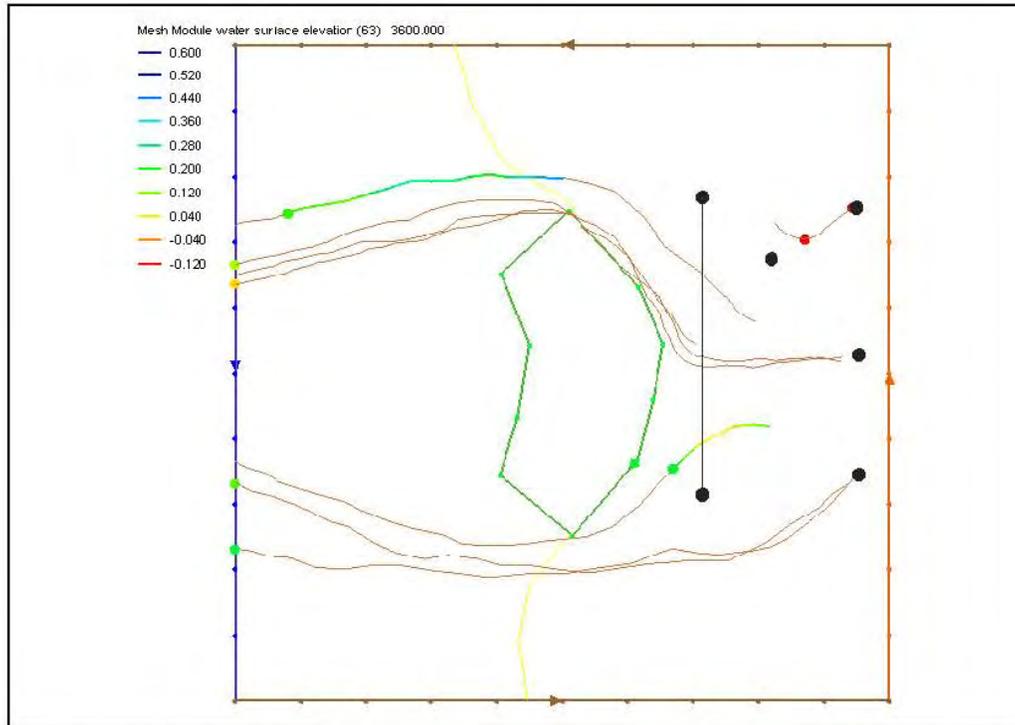
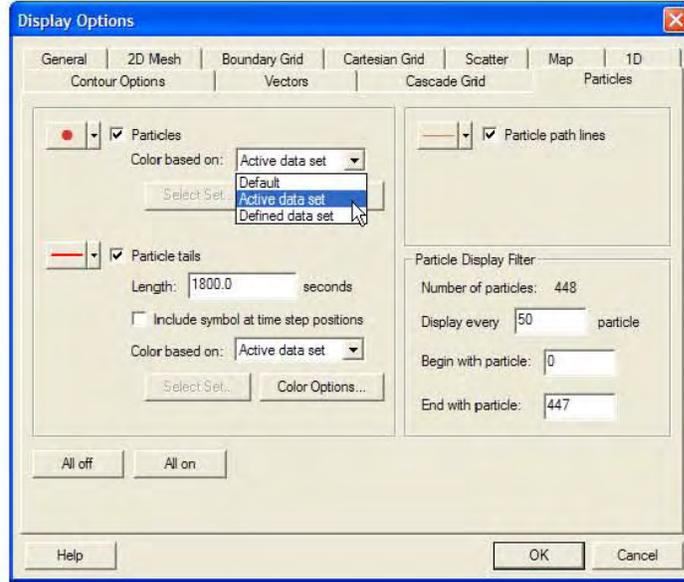


Figure 16. Particle heads, paths, and tails

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Figure 16 is an example display of PTM output. The particles and their tails are colored based on the velocity of the particle. The variation in path color demonstrates the change in velocity over the particle path, and the length of the tail shows how far the particle has traveled in the last half hour. The user specifies this value. The complete paths are shown as thinner, brown lines.

- *Particle selection.* The particle selection tool  can be used to select a specific particle or group of particles. If a single particle is selected, SMS displays the exact value from the current data set or attribute. In other words, if the particle velocity is selected in the Project Explorer, and a user selects a particle, the computed velocity for that particle is displayed. The tool also provides information about the number of particles in a specific area and the average value of the data set for the particles in that area.
- *Data menu.* Several tools that can assist with visualization are available through the SMS particle module data menu shown in Figure 17. These are:
 - o *Create data sets.* This command allows the user to generate additional data sets for each particle throughout the time range of the simulation. The particles and their tails can be colored based on the values in these data sets. Figure 18 illustrates the dialog provided to create these data sets. The user selects which data sets to create, and a name for the computed data set.

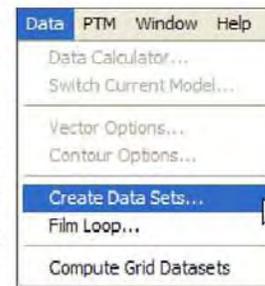


Figure 17. Particle data menu

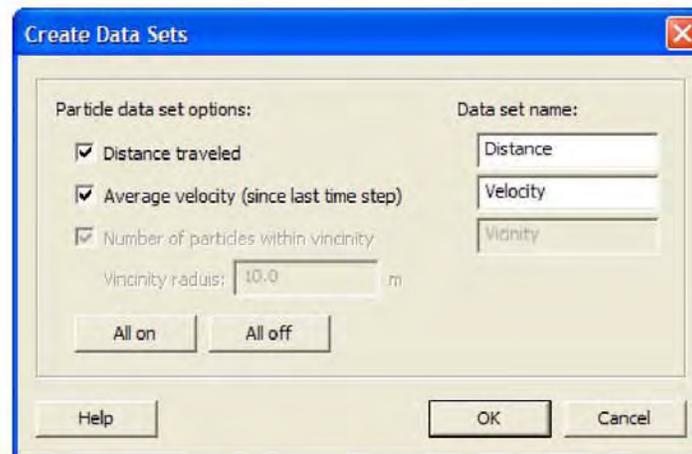


Figure 18. Create Data Set options dialog

- o *Film loop.* This command allows users to animate the progress of the displayed particles through time and saves the output to an avi file.

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- o *Compute grid datasets.* This command allows users to convert the particle data in a region to a set of cells in a Cartesian grid. For example, the user may want to visualize the concentration of suspended particles over a Eulerian domain. By defining a grid in the grid module, the user can select this command, and SMS computes the concentration based on the number of particles in each cell of the grid, and the cumulative particle masses as a ratio with the depth and size of the cell. Additional data sets that are computed include the number of particles from each source in each cell and the average deposition thickness in the cell.

SUMMARY: Various features, tools, and analysis capabilities outlined in this document are designed to enhance the ability of engineers to run the PTM in the SMS. This technical note is applicable to Version 1.0 of PTM, and provides an overview of the main features of the interface necessary for accurate and efficient usage of the model. The PTM and SMS-based interface will evolve as the model is developed and applied in engineering applications. Therefore, the interface of the PTM will undergo revision. Feedback and suggestions from users on design, implementation, and usage of the present version of the PTM interface are welcome.

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Demirbilek, Z., Smith, J., Zundel, A., Jones, R., MacDonald, N., and Davies, M. (2005). "Particle Tracking Model (PTM) in the SMS: I. Graphical Interface," *Dredging Operations and Environmental Research Technical Notes Collection* (ERDC TN-DOER-D4), U.S. Army Engineer Research and Development Center, Vicksburg, MS. An electronic copy of this TN is available from <http://el.erd.usace.army.mil/dots/doer>.

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



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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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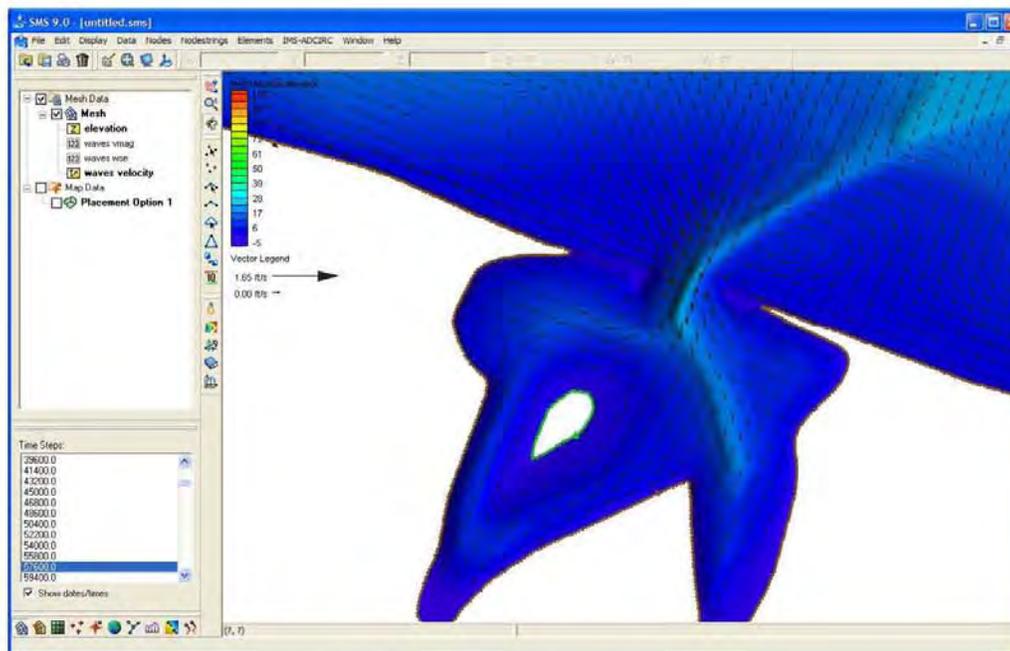


Figure 1. Example PTM simulation within the SMS 9.0 modeling environment

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.

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- 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.

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- 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.

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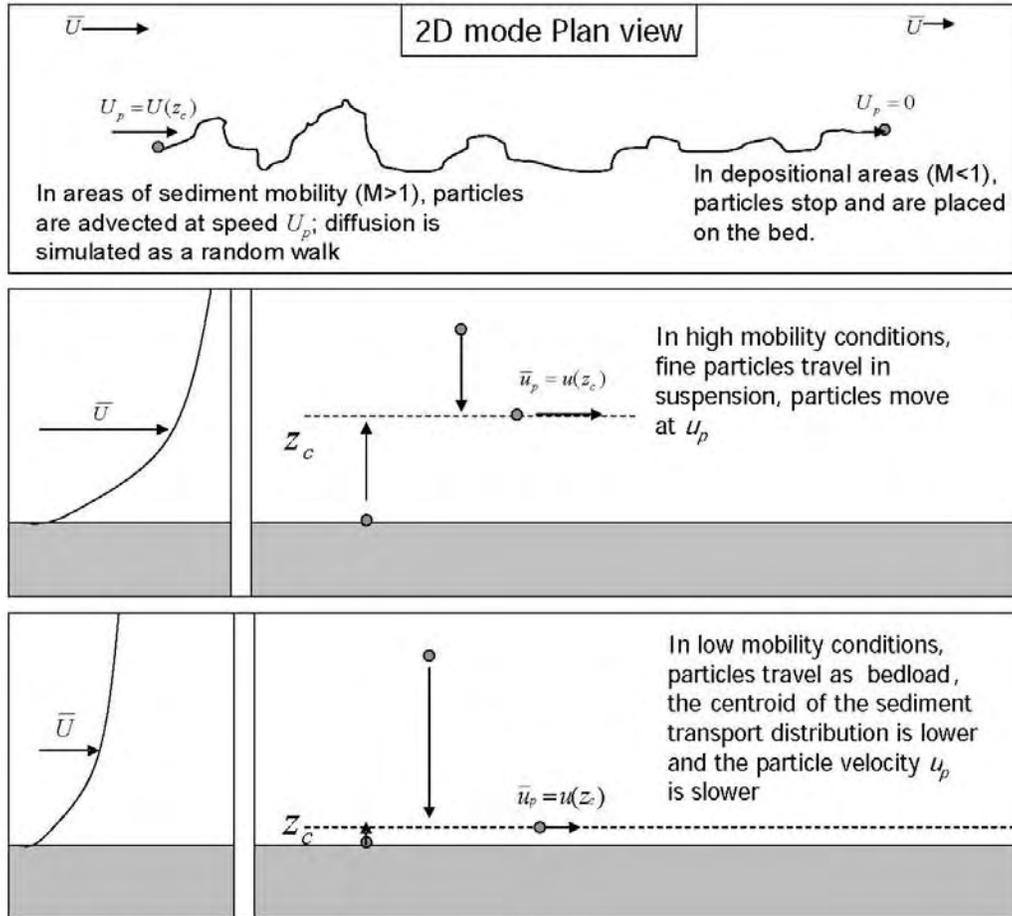


Figure 2. Schematic of 2D mode

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

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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.

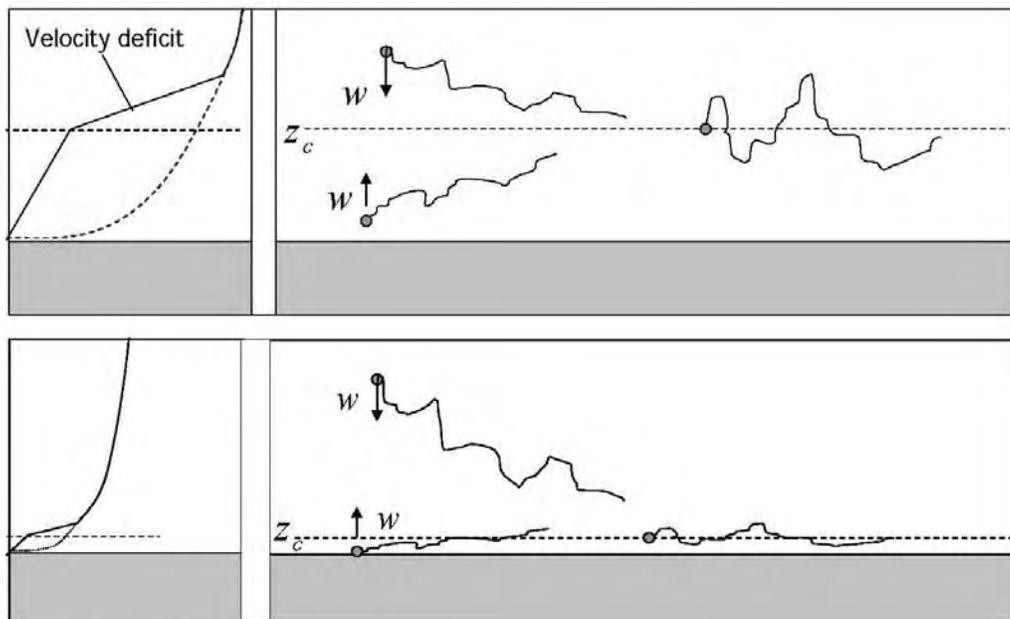


Figure 3. Schematic of Quasi-3D mode

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

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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.

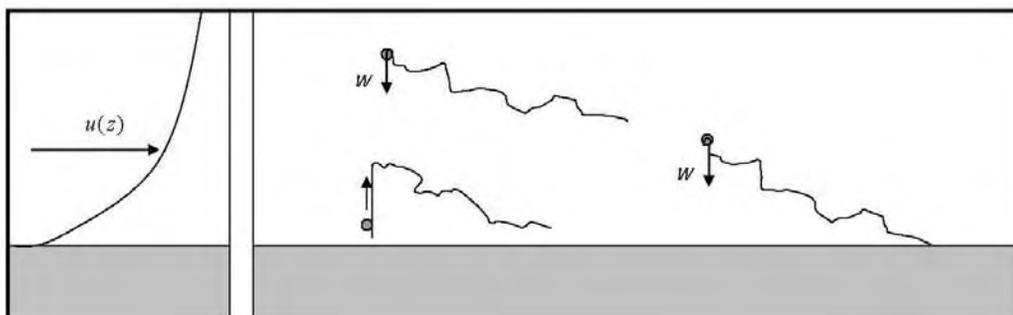


Figure 4. Schematic of fully 3D mode

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.erd.c.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.

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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.

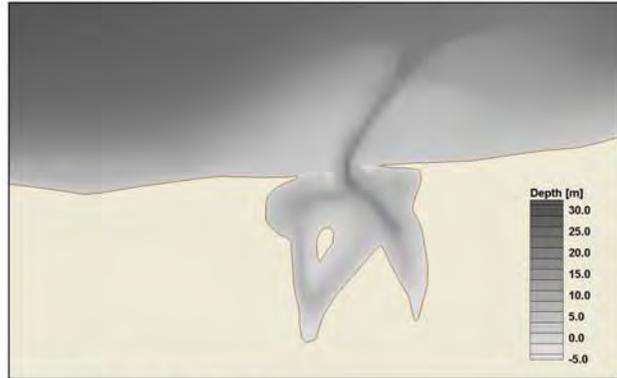


Figure 5. Idealized inlet

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

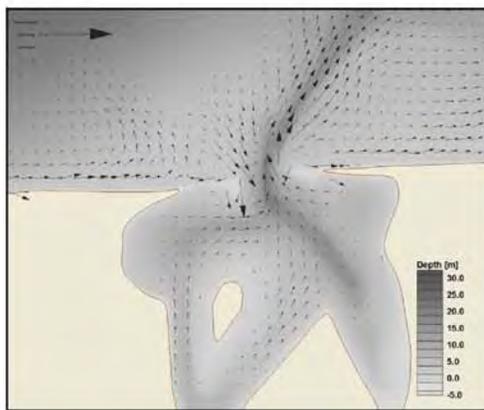


Figure 6. Snapshot of currents at idealized inlet (t=0.5 hr)

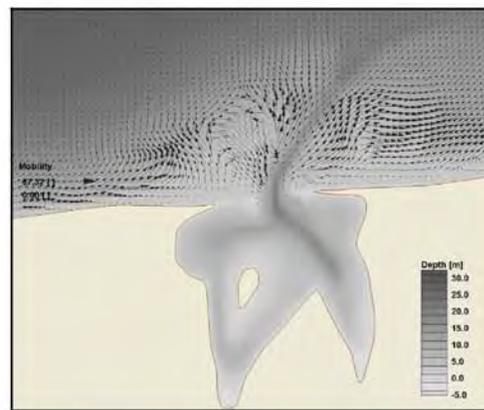


Figure 7. Snapshot of sediment mobility under waves and currents 0.5 hr into simulation

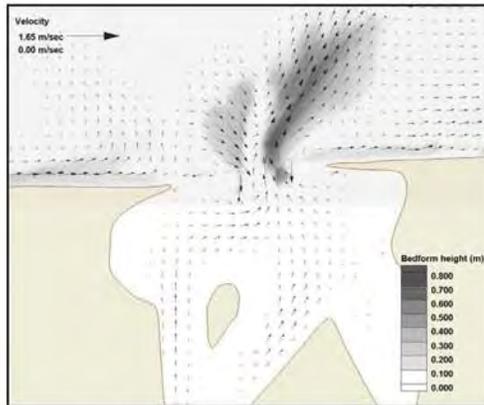
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Figure 8. Snapshot of bedforms at the inlet, where vectors indicate mean currents

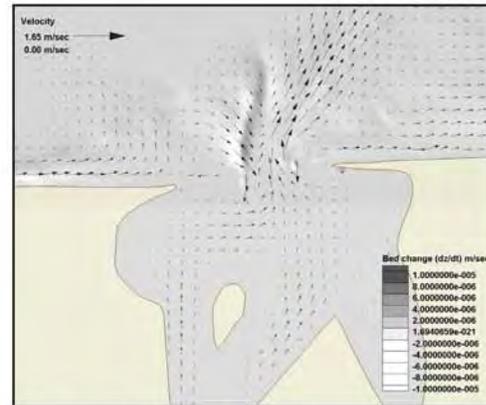


Figure 9. Snapshot of instantaneous erosion/deposition patterns at the inlet, with vectors showing mean currents

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.

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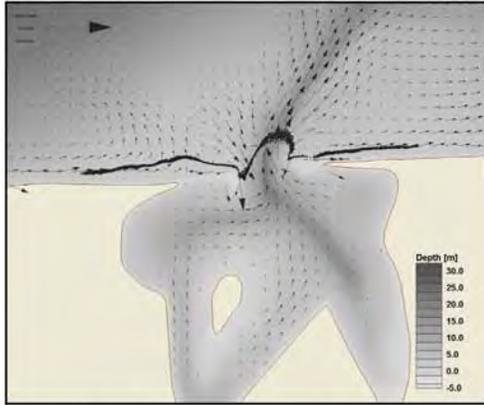


Figure 10. Particle locations and velocity vectors 0.5 hr into simulation

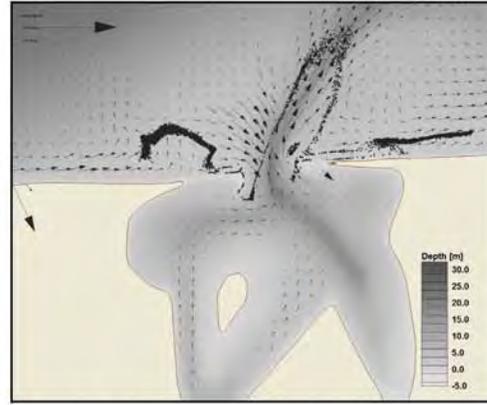


Figure 11. Particle locations after 3 hr

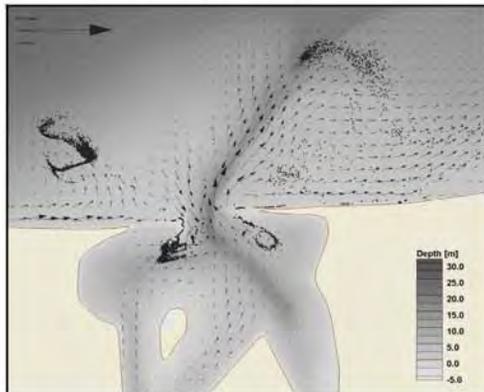


Figure 12. Particle locations after 24 hr

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

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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.

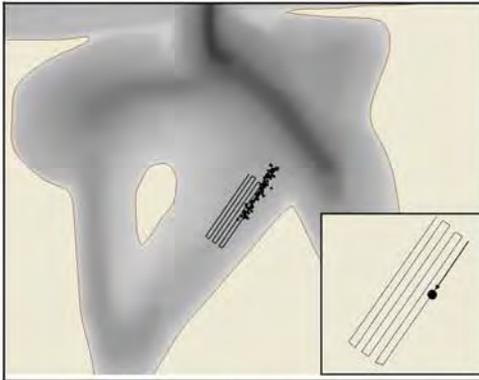


Figure 14. PTM simulation results. The line indicates path taken by the dredge (source), and black dots are suspended sediments released into the flow field 1 hr into the simulation

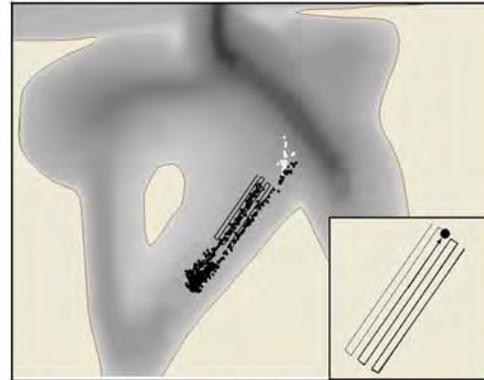


Figure 15. Particles after 8 hr into simulation. Particles that have deposited on the bed are white

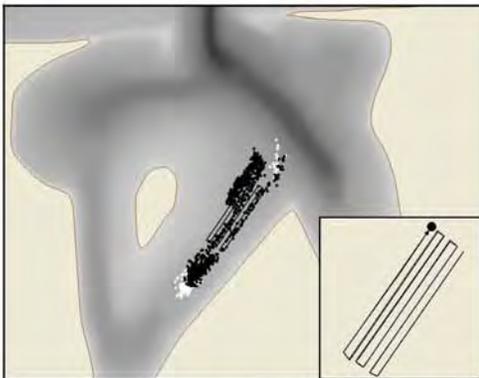


Figure 16. End of dredging operations (12 hr after the start of simulation)

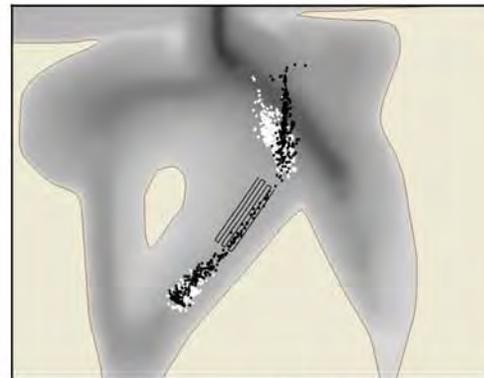


Figure 17. Final location of the particles 48 hr after the start of simulation

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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.

Sediment	d_{50} mm	Fall velocity, w m/sec	Suggested Minimum Time-step, sec		
			2D Mode ¹	Quasi-3D Mode ²	Full 3D Mode ³
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.

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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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Davies, M. H., MacDonald, N. J., Demirbilek, Z., Smith, S. J., Zundel, Z. K., and Jones, R. D. (2005). "Particle Tracking Model (PTM) II: Overview of features and capabilities," *DOER Technical Notes Collection* (ERDC TN-DOER-D5), U.S. Army Engineer Research and Development Center, Vicksburg, MS. <http://el.erd.usace.army.mil/dots/doer>

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Appendix D: Particle Tracking Model (PTM) in the SMS: III. Tutorial with Examples



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Particle Tracking Model (PTM) in the SMS: III. Tutorial with Examples

PURPOSE: This Dredging Operations and Engineering Research (DOER) Technical Note (TN) is a tutorial with examples of the PTM, developed jointly by the Coastal Inlets Research Program (CIRP) and DOER Program. This note is applicable to Version 1.0 of PTM. Demirbilek et al. (2005a) describe the PTM interface, and an overview of features and capabilities of the PTM is presented in Demirbilek et al. (2005b). The theoretical formulation and implementation of the PTM are given in a technical report (MacDonald and Davies, in preparation).

INTRODUCTION: The PTM is a Lagrangian particle-tracking model that is part of the U.S. Army Corps of Engineers (USACE) Surface Water Modeling System, SMS (Zundel 2005, Zundel et al. 1998). It employs a Lagrangian method of tracking particle pathways to estimate migration of sediment particles as influenced by waves and currents. For its input, the PTM requires a geometric surface defining the bottom elevation (depth) over which water level, current velocity vectors, and waves are available at each point in the modeling domain. The user specifies sediment sources and model parameters to perform a PTM simulation within the SMS for a given set of hydrodynamic input (waves, water levels, and currents). The SMS includes commands for layout of the sediment sources, specification of the numerical parameters, and management of the Eulerian quantities (water depth, surface elevation, current velocity).

This document describes typical steps and methodologies users can employ when performing a PTM simulation. The water level, velocity, and wave fields must be simulated or specified prior to constructing a PTM simulation in SMS. This document provides instructions for constructing a PTM simulation, including definition of particle sources, specification of model options and parameters, and coordination of timing for various inputs to the simulation. Commentary is provided to explain the underlying methodologies and reasoning for each step.

LOADING EULERIAN DATA: Eulerian data define the input bathymetry and domain boundary definition as well as input wave and current conditions. The PTM reads these from input files. Wave and hydrodynamic analyses must be performed prior to the PTM simulation. At present, the PTM requires a computation domain defined in the form of an Inlet Modeling System (IMS) -ADCIRC (Luettich et al. 1992) grid file, with an XMDF (Jones et al. 2004) data file containing water surface elevations and currents. If wave input is desired, STWAVE (Smith et al. 2001) is the default wave model, and the user can provide PTM an STWAVE grid and the associated wave field file. The user can also use SMS to convert result files from other hydrodynamic or wave models to these required formats prior to using them in a PTM application.

The example simulation files used in this tutorial come from an analysis performed for a hypothetical generic estuary. Required PTM input files from the IMS-ADCIRC and STWAVE

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simulations are provided as part of the standard tutorials distributed with the SMS (version 9.0) package. These files are also available for downloading at <http://el.ercd.usace.army.mil/dots/doer/doer.html>.

The grid file (estuary.grd in fort.14 format) defines the domain of the PTM simulation. It includes the coordinate location and bathymetric elevation for each node in the grid. The XMDF format hydrodynamic file (estuary_tide.h5) includes water surface elevations and current values for each node at 30-min intervals. These water levels and currents are required input for the PTM. After launching the SMS, the first step in creating a PTM simulation is to select and load the grid file, thus providing a framework for all other Eulerian inputs and outputs. To do this, go to the *File|Open* and select the file “estuary.grd” in SMS. Repeat the command to select “estuary_tide.h5” to load the hydrodynamic solution. The data will be displayed in SMS as shown in Figure 1.

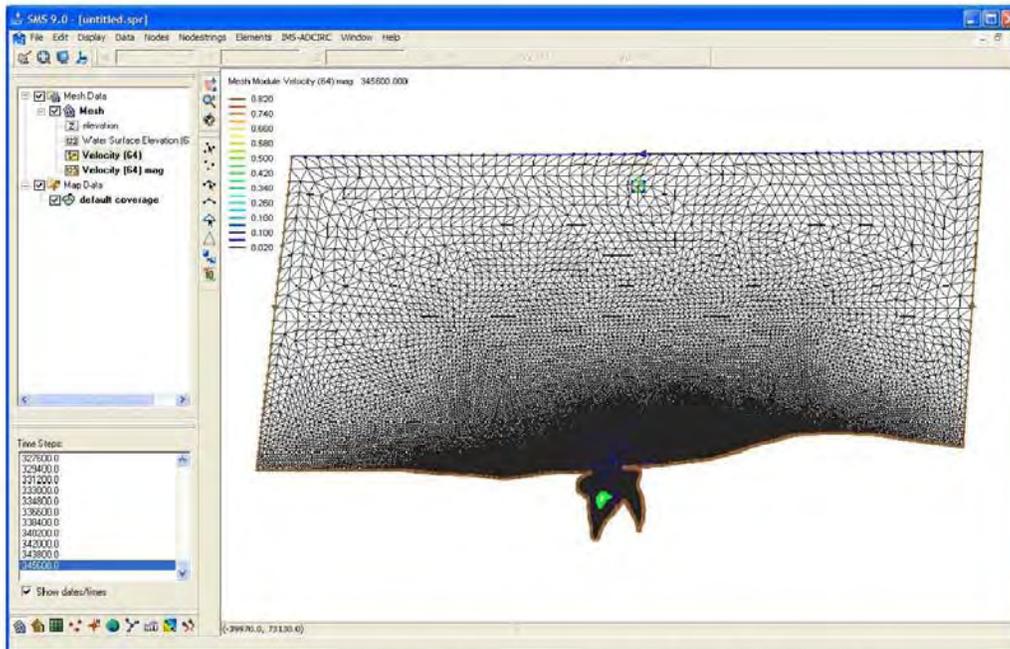


Figure 1. Hydrodynamic mesh and solution data sets visible in the *Project Explorer* window

ADCIRC output files can be large. Therefore, it may be advantageous to trim spatial and temporal range of ADCIRC output to create PTM hydrodynamic input files. This can be performed from within SMS (Zundel 2005). Care must be taken not to spatially trim too much of the grid because once particles reach the edge of the domain, they are lost to the simulation. Therefore, the trimming of ADCIRC output should not result in particles leaving the domain unless the flow patterns could keep the particles from returning to the area of interest.

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The PTM interpolates the hydrodynamic solution data to the Lagrangian particle locations. Therefore, the locations of the ADCIRC nodes are not important for display. In fact, they tend to clutter up the image, so it may be useful to turn them off, by selecting the *Display Options* macro and turning off the *Elements* toggle. Make sure the *Nodes* toggle is also off. Turn on contours (the *Contours* toggle) and the velocity vectors (*Vectors* toggle). Next click on the *Vectors* tab of the *Display Options* dialog and select the option to display vectors on a grid, and click the *OK* button. The vectors that appear on the screen illustrate the nature of the flow field for the selected time-step. Note that at the first time-step, there is little circulation due to the ramping of the forcing condition. Users may also need to adjust the settings for vector display. The image shown in Figure 2 displays vectors on a 20- by 20-pixel grid with minimum and maximum vector lengths of 10 and 80, respectively.

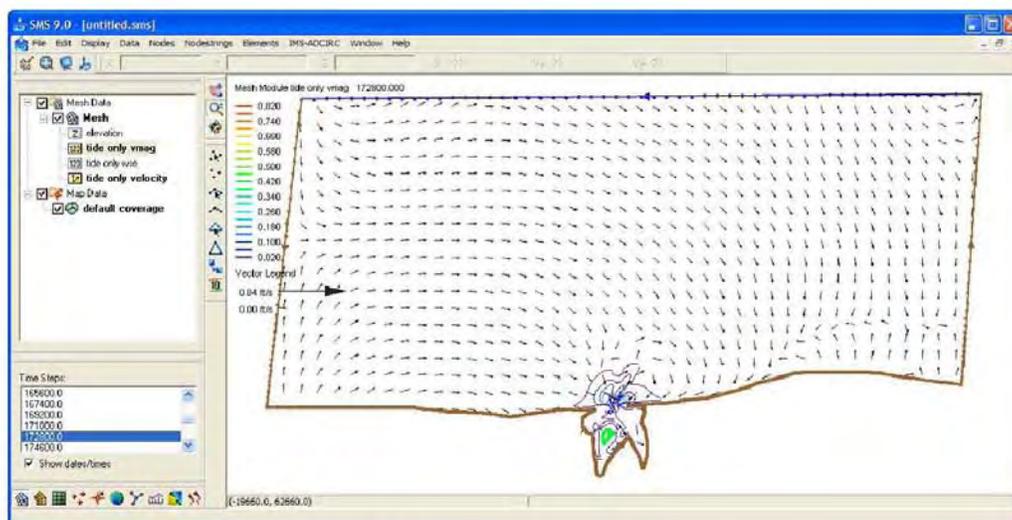


Figure 2. View after hiding ADCIRC grid and showing vectors

If the modeler is not familiar with the hydrodynamics that have been computed for the domain, he/she may want to examine the flow data that are driving the PTM simulation by selecting the data sets from the *Project Explorer* (tree on the left side of the SMS screen). This PTM simulation will use the “tide only velocity” data set, and the simulation will start at the time value 172,800 sec. (explained later). To view currents that will be used by the PTM, click on “tide only velocity” in the *Project Explorer* to select it as the active vector set and click on “tide only vmag” to select it as the active scalar set. Then choose 172,800 as the active time-step (below the tree). Figure 2 shows the view that will result. Note that the names “tide only vmag” and “tide only velocity” in the *Project Explorer* panel on the left are bold. This indicates that they are the data sets displayed in the image.

This simulation will examine particle movement from the coastline just east of the mouth of the estuary. Figure 3 shows a zoomed image of the portion of the domain involved in the Lagrangian calculations. Zoom into this portion of the display using the Zoom tool .

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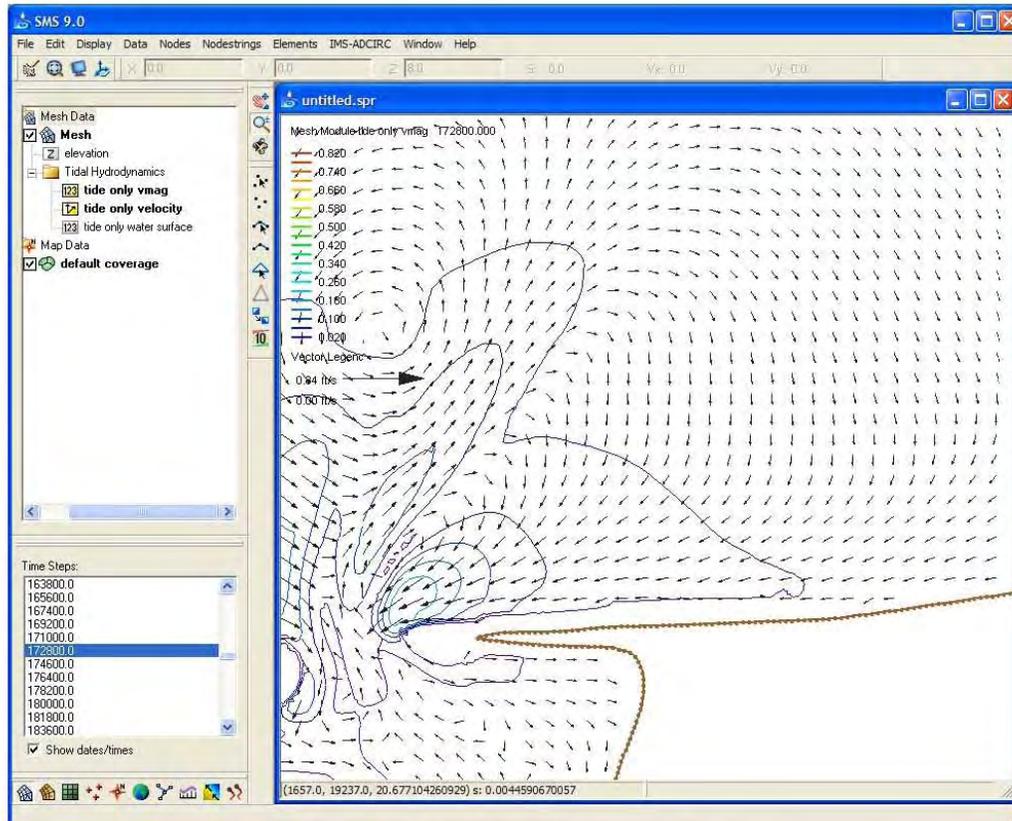


Figure 3. Zoomed view after hiding ADCIRC grid and showing velocity vectors

ADCIRC time series output includes a time stamp (in seconds) for each output interval. These time values are referenced to a starting date, which has been used to reference tidal constituents. Since this example does not represent an actual location, a reference date has been created. Therefore, one can say the time-steps are referenced to 9 February 2004 at midnight (12:00 am). This date corresponds to time zero (0) in the hydrodynamics. The solution file ("*.h5") begins at the time-step value of 1,800 sec. This corresponds to 12:30 am on 9 February 2004. The first 24 hr of solution include the ADCIRC ramp. Over these time-steps, ADCIRC increases the tidal forcing function from zero to the true forcing. For that reason, the first day should not be used in the PTM simulation; the first two days will be skipped and the PTM simulation will start at the time value of 172,800 sec (2 days), which corresponds to midnight on 11 February 2004. Just over two days of the data will be used in this PTM simulation.

A PTM simulation requires specifying the actual date and time values for the simulation. Because ADCIRC data are referenced to a relative start time ($t=0$), it is necessary to specify the hydrodynamic date/time stamp to align it with the PTM time. Table 1 displays the schedule for the events that will be included in the simulation. These include the hydrodynamics, waves, and

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simulated sediment particle sources. The PTM calculations start after the first hydrodynamic output time-step.

Time	Date	Seconds	Event
12:00 am	9 Feb 2004	0	Hydrodynamic reference time (0 sec in ADCIRC)
12:00 am	9 Feb 2004	0	Beginning time for wave simulation data
12:00 am	10 Feb 2004	86,400	End of ramping calculations
12:00 am	11 Feb 2004	172,800	PTM Simulation Starts – Instantaneous Particle Source Emits Particles
12:00 am	13 Feb 2004	345,600	End of PTM and ADCIRC Simulation

DEFINE THE SEDIMENT PARTICLE SOURCES: In this example, a short-duration line source is used to represent nearshore placement of dredged material. An SMS feature arc (or point) is used to define the PTM source location. To create a PTM source using an SMS feature arc, a PTM-type coverage must first be defined as follows:

- In the *Project Explorer* (tree window in the left panel) right-click on the “default coverage.” Select “Rename” and then type “Placement Option 1.”
- Right-click on the coverage again and move the cursor to the “Type” item. A pop-up menu will appear. Select “PTM” as the type.
- Left-click on the coverage to make it active and to activate the Map module.

Create a feature arc by selecting the *Create Arc* tool . This tool bar is on the panel on the left side of the SMS graphics window. Click in the mouth of the estuary (e.g., the southern left point shown in Figure 4) and then double-click at the right point. SMS creates an arc between the two selected points. These steps are illustrated in Figure 4.

The PTM is used in this example to predict pathways and fate of material placed along this line. The exact positions shown are not crucial. It is important to place the source inside the computational domain so that the generated particles are in water. For reference, the coordinates selected in this example were (x=-4,000 m y=11,700 m) and (x=950 m y=12,000 m). The specified line could represent a proposed placement location for material dredged from the mouth of the estuary. In this case, the line varies from the high-velocity inlet to the calmer shore to illustrate the variation in particle activity.

After specifying the location of the source, it is necessary to set the point source attributes. To do this, go to the *Select Feature Arc*  tool, click on the feature arc, and choose the *Feature Objects\Attributes* command. This displays the *Line Source Properties* dialog (Figure 5). Each row of the dialog represents a change over time in the source. Each column defines an attribute of those particles.

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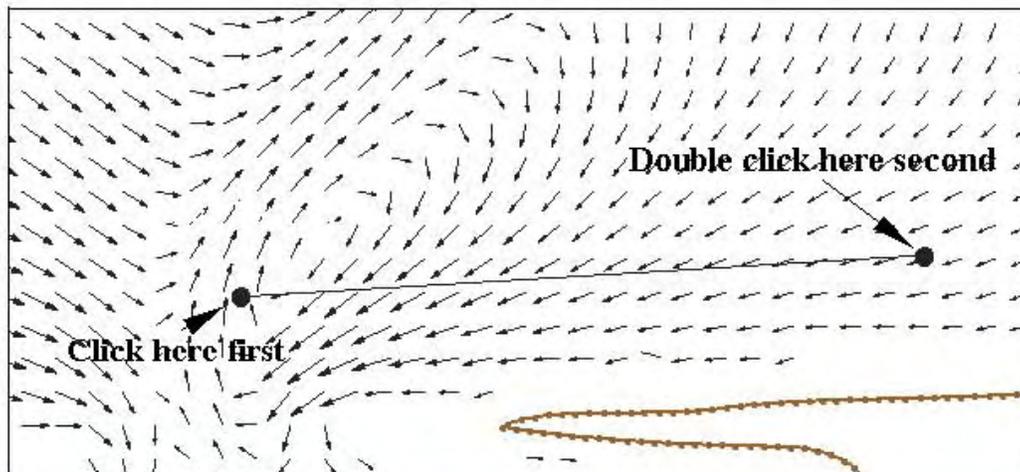


Figure 4. Location of the particle source

Line Source Properties

Alt Type: Source

Source Name: Feature Arc (Auto)

Show Contour Lines (Scale 1:100)

Date/Time	X1 (m)	Y1 (m)	Elevation (m)	X2 (m)	Y2 (m)	Centroid Elevation (m)	Particle Mass (kg)	Particle Radius (m)	Vertical Radius (m)	Rate (kg/s)	Size (mm)	Deviation (mm)	Density (kg/m ³)
2/11/2004 12:00:00 AM	-4000.0	11700.0	1.0	4000.0	12000.0	1.0	1.0	10.0	1.0	0.001	0.14	0.05	2600.0
2/11/2004 12:00:50 AM	-4000.0	11700.0	1.0	0500.0	12000.0	1.0	1.0	10.0	1.0	0.001	0.10	0.05	2600.0
2/11/2004 12:01:50 AM	-4000.0	11700.0	1.0	0500.0	12000.0	1.0	1.0	10.0	1.0	0.0	0.10	0.05	2600.0
2/14/2005 4:00:00 AM													

File OK Cancel

Figure 5. Settings for line source

The first line in Figure 5 defines the time when the source begins to generate particles. Double-clicking on one of the date or time entries and then using the left and right arrow keys in the first column allows the user to enter 2/11/2004 12:00:00 AM as shown in Figure 5. The second, third, fifth, and sixth columns show the coordinates of the segment endpoints. The particles generated are centered around this line. The user can edit these locations, and change the location of the feature arc in this spreadsheet. Enter the values specified above to move the feature arc to the specified location. By changing the location in different rows, the location of the particle source can move over time. The fourth and seventh columns specify the centroidal elevation; enter a value of 1.0 to indicate that material will be released 1.0 m above the bed. The eighth column is the mass of each particle tracked by the PTM. In actuality, this particle is a cluster of particles. Each particle cluster has a characteristic grain size that controls how the particle acts. The mass entered in column 8 helps to account for more material. Enter a value of 1.0 to tell the PTM to create particle clusters of 1.0 kg mass.

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The ninth column specifies the radius (enter 50.0 m) in the horizontal plane to distribute particles, using a Gaussian distribution type. The tenth column specifies the vertical distance (enter 1.0 m) to distribute particles using a linear distribution. The eleventh column controls the number of particles (or particle clusters). It allows the user to specify the rate of mass of the material to be released per meter per second (enter 0.002 kg/m/sec, which yields 0.002*5000 m (length of horizontal line source) or 10.0 particles/sec, each with a mass of 1.0 kg). The twelfth column is the characteristic particle grain size in millimeters, and in this case, $d_{50} = 0.19$ mm. The thirteenth column specifies the standard deviation value of the characteristic grain size by entering a value between 0.0 and 1.0. Enter 0.85 in this example. This allows variation from one particle cluster to the next. Finally, the last column specifies the material density (enter 2,600 kg/m³). This entire line of data defines the start time and conditions for the source.

Select the entire line just created in the *Line Source Property* dialog box. Copy and paste the data to the second line. Change the time of the second line to 11 February 2004 as shown in Figure 5. Note slashes are used in the dialogs for specifying time stamps (i.e., 2/11/2004 12:00:50 AM in place of 11 February 2004). This defines the end time for this source to be 50 sec after it was turned on. By this time, approximately 500 particles (50 sec * 10.0 particles/sec) have been generated. Particle generation can also be designated as time varying by changing the input parameters (such as the rate) in the second line.

Copy the entire line to the third line. Change the time of the third line to 2/11/2004 12:00:51 AM, and change the rate to 0. This turns off the source. Click on the OK button to complete the specification of particle sources. In this example, the first line starts a source, the second line specifies the duration of the source to remain active, and the third line shuts down the source. It is recommended that users follow this standard procedure for specifying sources to the PTM.

SET MODEL PARAMETERS: The user must also specify the model parameters for a PTM simulation. Follow these steps:

- Select the *Particle* module .
- Select the *PTM|New Simulation* command. This will create an empty simulation that shows up in the *Project Explorer* with the name "PartSet."
- Right-click on the new simulation in the *Project Explorer* and select *Rename*. Change the name of the particle set to "Tides."
- Select the *PTM|Model Control* command. This displays the *PTM Model Control* dialog (Figure 6) with the *Hydrodynamic, Sediment, and Source inputs* tab active. Parameters and file names must be provided in several of these tabs for a PTM simulation. These are described below.

In the *Hydrodynamic, Sediment, and Source inputs* tab, specify the existing files that will be used as input for the PTM simulation. Click on the file icon next to *Geometry* and select "estuary.grd." This prompts the PTM to use this grid file to define its Eulerian domain. Click the icon next to *X MDF flow file* and select the file "estuary_tide.h5." This prompts PTM to use this file as a source of hydrodynamic data. In the *WSE* combo box, choose the data set "tide only wse" and in the *Velocity* combo box choose the "tide only velocity."

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At the bottom section of the dialog, select the “Placement Option 1” coverage (just created) as the PTM *Coverage*. This coverage includes the line sources defined above. The SMS will convert the sources defined in that coverage to an input source file for PTM. It will have the same name as the PTM simulation with the extension “.source.”

- In the *Hydro, Sediment, and Source inputs* tab, click on the *Create files from data* button. A dialog will appear (Figure 7). This allows the user to create the input files for the PTM. The geometry and flow files already exist and do not need to be created here. However, a sediment file must be created to define the native sediments. Click on the “Select...” button in the top section and select the ADCIRC mesh that is loaded into SMS. This assures that this grid is the computational domain that will be used for the PTM. Set the *Solution time format* to seconds. Because the grid is already in ADCIRC fort.14 format, and the flow data are already in an XMDF file, do not select the toggles to create geometry and flow files.

Select the *Create PTM sediment file* toggle (near the bottom in Figure 7). The SMS will create a sediments file based on user input. In this example, no spatially varied data sets exist, so choose “Constant” and “mobile bed” and enter the three values of native bed sediment parameters as shown in Figure 7. If data sets defining varied native sediment sizes had existed, the user could set the toggle box to “Varied” and choose the appropriate data sets. The grain size values are used by PTM to compute roughness and entrainment coefficients. Next, specify a name for the sediment file just generated by clicking on the file icon at the bottom of the dialog, assigning the name as “estuary” for the sediment file name (“.sediments” will be added as the extension). Click the OK button to return to the model control dialog.

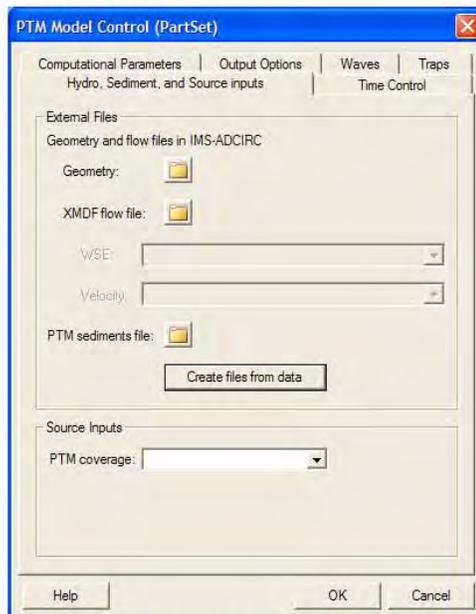


Figure 6. Selection of Hydro, Sediment, and Source inputs for the PTM

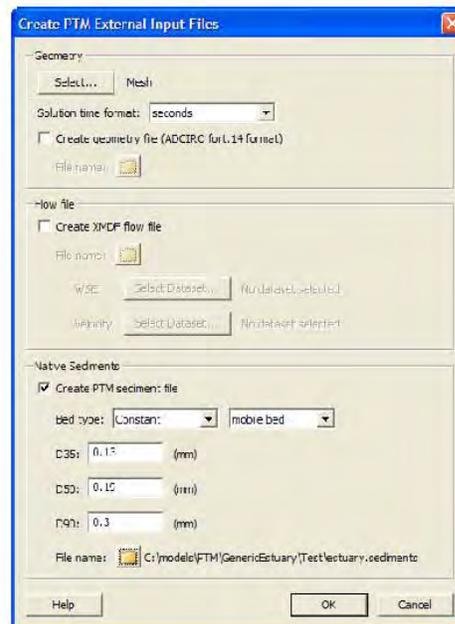


Figure 7. Defining data sources for the PTM

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- Switch to the *Time Control* tab (Figure 8). This dialog allows the user to coordinate the PTM simulation with the hydrodynamics and specify a computational time-step. Enter 2/11/2004 12:00:00 AM for the *Start date/time* as the starting time for the PTM simulation. This is the earliest time any particle source is activated. Next, enter 2/12/2004 07:45:00 AM for the *End date/time*. This is the time that the PTM simulation will end. The PTM will simulate almost 32 hr of particle motion. Set the computation time-step to 3 sec. This tells the PTM to compute particle locations every 3 sec. Enter 2/09/2004 12:00:00 AM for the *Start date/time of the hydro data*. This is the reference time for the ADCIRC simulation.
- Switch to the *Computational Parameters* tab (Figure 9). Change the *Distribution* to *By weight*, and *Advection* to *Q3D* (quasi-3D) (see Demirbilek et al. (2005a) for more information on advection modes). Set the *Update shears, bedforms and mobility every* field to 300 time-steps. This prompts PTM to update the bed every 15 min. More frequent updating can slow down computation. The other values can be left as the defaults, but users can change these as necessary.

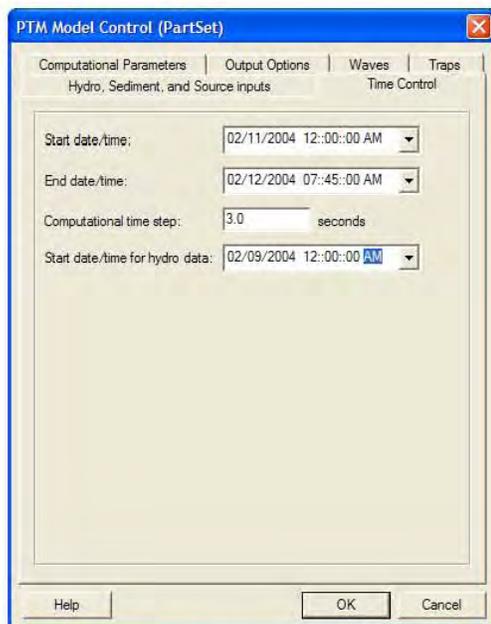


Figure 8. The PTM Time Control Dialog

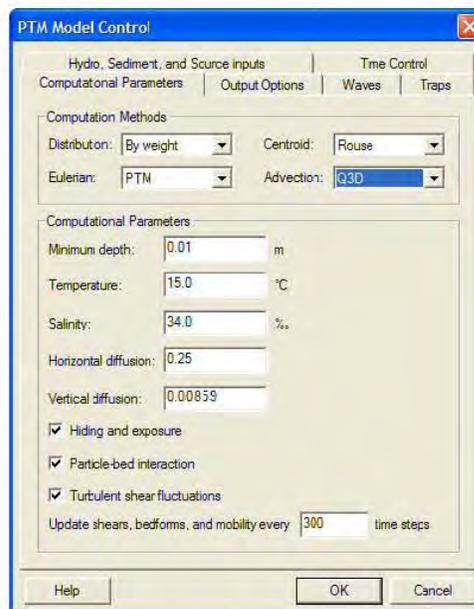


Figure 9. The PTM Computational Parameters Dialog

- Finally, switch to the *Output Options* tab (Figure 10) and set the *Grain Size*, *Mobility*, *State*, and *Parcel Mass* toggles to “on.” This prompts the PTM to output these attributes for the particles that are being traced. The SMS can display PTM output according to any of these settings after the simulation is complete. For example, the particles could be color-coded based on their representative grain size if the *Grain Size* toggle is on. Also enter 10 for the *Output Increment* to save particle locations at every 10 time-steps or 30 sec. This completes the setup of the model parameters for the simulation. Click the *OK* button. The *Traps* and *Waves* tabs will not be used in this example. In an example in the next section, waves will be

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included. The PTM user guides (Demirbilek et al. 2005a, 2005b) provide more details about options that are available for using these tabs.

SAVE THE SIMULATION: The simulation data specified in these dialog boxes must be saved to files before executing the PTM. If the user forgets this step, the SMS will prompt to save the simulation before allowing the simulation to run. To save a simulation, select *File|Save New Project* and enter the name “estuary” as the name of the SMS project file (.sms).

RUN THE PTM: The simulation is ready to be run. This simulation takes approximately 10 to 15 min to compute on a PC. In the first few minutes, the PTM is creating an element neighbor table. During this time, it may appear that the application has stopped, but it is still working. To launch the PTM model, select the *PTM|Run Model* command. If needed, the SMS will bring up a prompt to allow the user to select the directory location of the PTM executable file. Once the model location is defined, select the *OK* button to launch the model. The model location may be set in the preferences, in which case the SMS will launch the model directly after the command is given. A dialog appears that displays a progress bar of the model execution status. When the run is complete, the button at the bottom of the dialog changes from “Abort” to “Exit” and the words “Model Finished” will appear in the output window. Select the *Exit* button to close the model execution.

READ THE SOLUTION: The PTM creates two solution files. The first file stores the particle data (Lagrangian), and the other stores the mapped Eulerian data. These are named by adding file descriptors to the simulation name. For this case, the file “estuary_Tides_particles.h5” includes the particle paths and attributes. If any options for mapping solution data to the Eulerian grid had been selected, the PTM would have written a file named “estuary_Tides_maps.h5.” Both of these files are created in X MDF format (Jones et al. 2004). When the model simulation is completed, the SMS prompts the user to read in the solution files. The solution may also be read in by selecting the *File|Open* command from the menu bar, and by choosing the binary solution file “estuary_Tides_particles.h5.” As the SMS loads this file, data sets appear in the *Project Explorer* (data tree). The SMS will re-draw (frame) the active screen, since new data have been added to the project.

VISUALIZE THE PARTICLES: The SMS supports multiple methods of displaying the particles as demonstrated in this section. To view the options, select the *Display|Display Options* command (Figure 11). The left side of the display options dialog allows the user to

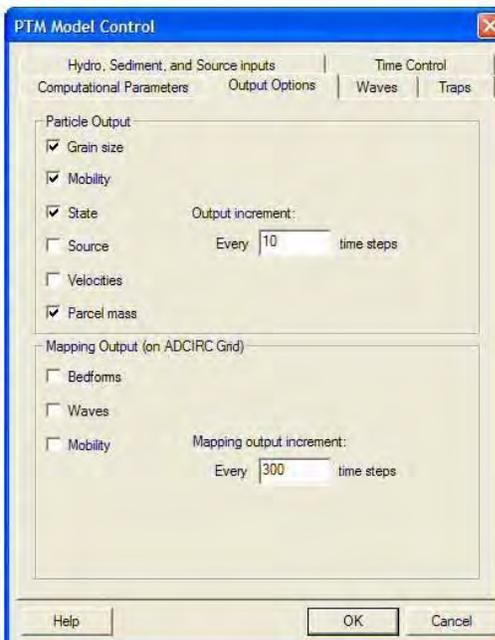


Figure 10. The PTM Output Options Dialog

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control the display of the particle head and tail. Turn both of these on. Click on the symbol next to the *Particles* toggle and change the symbol to a 4-pixel diamond (as shown). The particles and their tails can be color coded. This coding can be based on any of the particle attributes or data sets saved by PTM. For example, the user may want to have the particles colored based on the characteristic grain size of that particle.

If there are multiple sources, the user may want to display particles generated at each source in a different color.

Each of these attributes or data sets is displayed in the project explorer. The “active” data set or attribute is displayed in bold text. For this example, change both the *Particles* and the *Particle tails* to display the “Active data set.” This tells the SMS to color the particles based on whatever attribute/data set is selected. Set the *Particle Tail Length* to 1,800 sec (30 min). This option allows the user to control the length of the particle tail. The tail indicates the speed of the particle. In the upper right corner of the dialog, turn off the toggle to display *Particle pathlines*. This option displays the entire path in a user-selected color. Normally, this option has the tendency to clutter the display, but it is useful in indicating general flow patterns.

The options in the lower right corner of the dialog allow the user to reduce the number of particles displayed. For this case, the default of viewing all the particles is appropriate. Click the *OK* button to exit this dialog.

Stepping Through Time. Select the “grain size” data set in the project explorer. Particles will be displayed in red (smaller characteristic grain size) to yellow, green, and blue (increasingly higher grain size). Click the time-step for 2/11/2004 08:00:00 AM to set the time to about 8 hr into the simulation. Use the down arrow to step through the time-steps and watch the particles move. Note that updating the time in the particle module does not currently update the time in the mesh module, so the vectors will not change. The feature to update the vector field will be added with a future release. The vectors do change when generating an animation as will be shown below. Figure 12 shows the particles approximately 8 hr into simulation time.

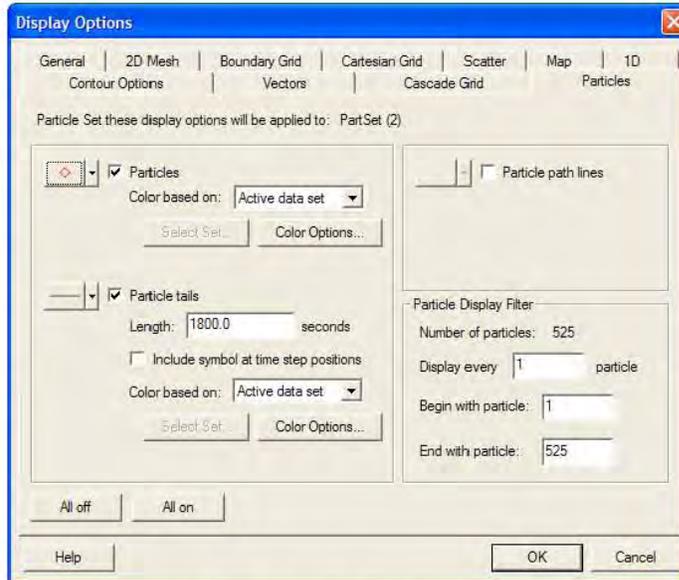


Figure 11. Particle Display Options Dialog

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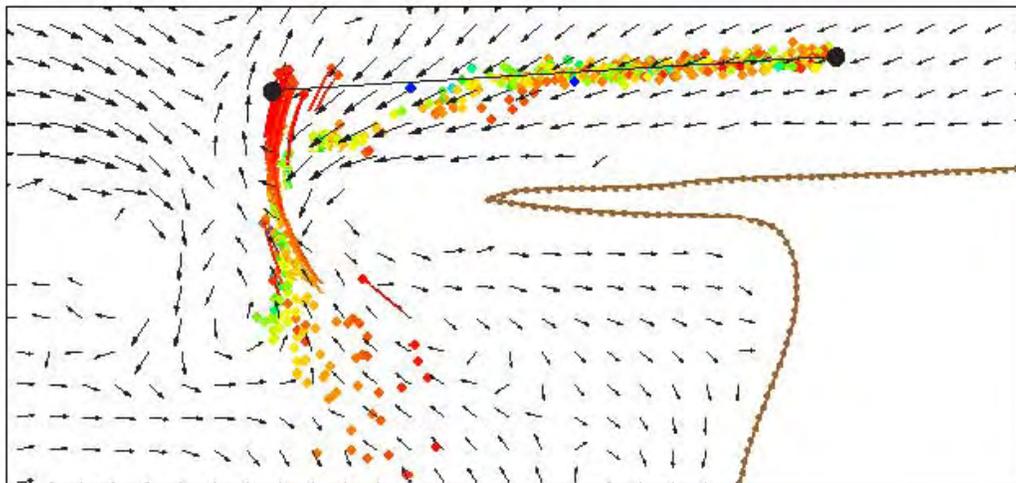


Figure 12. State of particles after 8 hr

Creating an Animation. The SMS includes the tools required to create animations of the particles and flows. When creating an animation, the SMS loops through a time range to create a user-controlled number of snapshots or frames, and saves these images to an “avi” file. The animation sequences are illustrated next:

- Ensure you are viewing the region of the domain you wish to see. Select a region similar to that shown in Figure 12 to see the range of particle motion.
- Select the *Data|Film loop*. command. The dialog that appears allows you to select the type of film loop and the file name to save. Use the defaults and click on the *Next* button.
- The start time and end time should be set to match the entire simulation. To tell the SMS to animate the Eulerian data, be sure to select the *Animate Mesh Data* toggle and enter the reference hydro time as 02/09/2004 12:00:00 AM (the starting hydro time). Select the option to *Specify Number of Frames* and enter 100. Click *Next*.
- Click on the *Clock Options* button. In the dialog that appears, select *Show Progress Bar* and choose the type to be “Horizontal Progress Type.” Set the size to 50 and click *OK*. Click *Finish* in the *Film Loop Setup*.

As the animation is generated, which may take a few minutes, it is also saved to the disk. After the generation is completed, the SMS launches the animation in the viewer PAVIA.exe that is distributed with the SMS. The animation shows that particles in the mouth of the estuary are washed into and then back out of the estuary and distribution of particles varies temporally and spatially. As the velocities decrease in the mouth of the estuary, smaller particles also start settling down. Users should close the animation after viewing and continue with the tutorial.

WAVES: The existing PTM simulation will now be copied and modified to include waves. To include waves, users must have results from a previously run STWAVE simulation, and possibly

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a modified hydrodynamic output that included the wave data. The PTM will then be rerun using both the modified hydrodynamic solution and the wave solution data. The steps to be followed are described below:

- Open the STWAVE simulation by selecting the *File|Open* command and select *estuary_stwave.sim* (also included with SMS version 9.0 tutorials). Click the *OK* button. This provides the basis for wave data that will be included in the PTM simulation. You may need to go into the display options and turn off the cells of the stwave grid.
- Open the ADCIRC solution that was run to include the influence of waves by selecting the *File|Open* command. Select *estuary_waves.h5* (also included with SMS version 9.0 tutorials). Click the *OK* button.
- Right-click on the PTM simulation in the *Project Explorer* (tree) and select “Copy Simulation.” This will create a copy of the simulation just constructed.
- Right-click on this new simulation, which will be named “PartSet (2)” automatically by the SMS, and select the Rename command. Change the name to “Waves.”
- Select this new simulation, by clicking on its name in the *Project Explorer*. Now choose the *PTM|Model Control* menu command to modify simulation input.
- In the *Hydrodynamic, Sediment, and Source inputs* tab (Figure 6), select the ADCIRC solution sets that include the influence of waves on hydrodynamics. Next to the XMDF flow file, click on the icon and choose the file *estuary_waves.h5*. In the WSE combo box, select “waves wse” for water surface elevation. Similarly, select “Datasets/waves velocity” in the *Velocity* combo box. The sediment sources and grid files can remain the same.
- Click on the *Waves* tab (Figure 13). Check the toggle box to use waves, and click on the *From STWAVE Grid* button. This fills in the origin and orientation of the wave simulation based on the *STWAVE* simulation, which was loaded into the SMS in step 1. Click on the icon in the *Solution data* section and select the file “*estuary_waves.wav*.”
- In the lower portion of the dialog, enter the *Start Date/Time* of 2/09/2004 12:00:00 AM. This specifies that the wave data shall start at the same time as the hydrodynamic data.
- Enter the *Time between spectra* as 02:00:00 (i.e., waves are updated every 2 hr) and the *Number of Spectra in File* as 50 (i.e., 50 wave conditions are simulated). Note that this

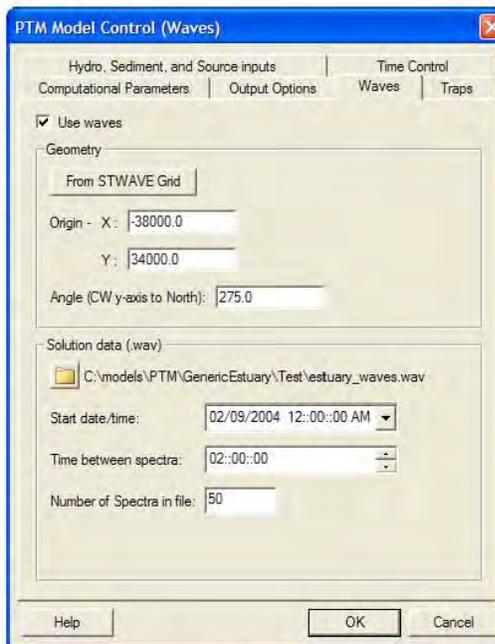


Figure 13. Wave specification in the PTM

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information comes from the STWAVE run. Click the *OK* button to exit the *Model Control* dialog.

SAVE THE SIMULATION: Now resave the simulation before running the PTM. Select *File|Save* to update the estuary.sms project file saved earlier.

RUN THE PTM: The simulation with waves is ready to be run. This simulation takes approximately 15 min to compute on a 3-GHz PC. Read in the solution of this simulation using steps described earlier and view the particle motion as affected by waves. The solution file name is "estuary_Waves_particles.h5." User will note that the wave action greatly influences particle activity near the placement site.

MAP THE PARTICLES TO A GRID: The results of the PTM simulation can also be transferred onto a Cartesian grid for visualization of the Eulerian output. Presently, this methodology only supports the particle counts, and will be enhanced in the future to create data sets for deposition depth, suspended sediment mass, and suspended sediment concentration. To utilize this feature, a Cartesian grid must be created or loaded into the SMS. This example will use the STWAVE grid to visualize the particle counts as follows:

- In the *Particle* module  select the *Data|Compute Grid Data Sets* command. This creates data sets for the Cartesian grid that can now be contoured.
- Switch to the *Cartesian Grid* module . In *Display Options*, turn on Cartesian grid contours. You can now select various time-steps to see the number of particles in each cell in the grid.

SUMMARY: This technical note provides instructions for developing a PTM simulation. A typical project could include many particle sources and wave and velocity fields. In such cases, it would be necessary to perform multiple runs and some variation in the procedure and tools described here would be required. The development of the PTM is ongoing, and the interface is also expected to change. Future technical notes will describe changes to the updated versions of the model and their SMS interface. Feedback and suggestions from users are welcome on the design, implementation, and usage of the PTM and this tutorial.

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14. ABSTRACT This report introduces a Lagrangian-based Particle Tracking Model (PTM) developed by the Coastal Inlets Research Program (CIRP) and the Dredging Operations and Environmental Research Program (DOER) being conducted at the U.S. Army Engineer Research and Development Center. The PTM's Lagrangian framework is one in which the sediment being modeled is discretized into a finite number of particles that are followed as they are transported by the flow. Lagrangian modeling is insightful for modeling transport from specified sources. Many particles are modeled such that transport patterns are representative of all particle movement from the sources. The model operates in the Surface-water Modeling System (SMS) interface and allows the user to simulate particle transport processes to determine particle fate and pathways. Waves and currents used in the PTM as forcing functions are developed through other models and input directly to the PTM. PTM Version 1.0 input files are from the ADCIRC or M2-D depth-averaged hydrodynamic models and STWAVE and WABED wave models. Other models can be used as input by first converting their output to ADCIRC, M2-D, or STWAVE and WABED formats. <div style="text-align: right;">(Continued)</div>					
15. SUBJECT TERMS Coastal Inlets Research Program Dredging Operations and Environmental Research			Particle tracking model Sediment transport Hydrodynamics and waves		
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 168	19a. NAME OF RESPONSIBLE PERSON
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14. ABSTRACT (Concluded)

The general features, formulation, and capabilities of PTM Version 1.0 are described in this report, including the basic components of the model, model input and output, and application guidelines. Other chapters of this report provide detailed information about the PTM's theory, numerical implementation, and examples that demonstrate the model's potential usage in practical applications. Sediment pathways are readily identified within the Lagrangian modeling framework of the PTM for conditions with sharp gradients in suspended solids (plumes, for example), where numerical diffusion in Eulerian models would require very small grid spacing to provide reliable solutions. The Lagrangian framework of the PTM is computationally advantageous, and the model can be run with a fraction of the computer execution time required by Eulerian models. Each particle in the PTM represents a given mass of sediment (not an individual sediment particle or grain), and each particle has its own unique set of characteristics. As a minimum, a particle must be defined with certain physical properties (e.g., grain size and specific gravity) and an initial position. The particles can also be given other characteristics that may be independent of the solution, and particles can be static or dynamic. Particles from sources being modeled (as opposed to the local, or native, bed sediment) are introduced, or released, into the domain from specified source locations. These sources are designed to permit modeling of a wide range of natural or anthropogenic processes in coastal and environmental studies.