THE PARTICLE TRACKING MODEL: DESCRIPTION AND PROCESSES

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ABSTRACT

Accurate prediction of the fate of sediments and other water-borne particulates is a key element in coastal engineering and dredged material management. These predictions are used to assess the impact of dredging and placement operations on contaminant transport, sensitive habitat, endangered species, rehandling, and beneficial use activity. The Particle Tracking Model (PTM), a Lagrangian particle tracker, addresses these needs by simulating sediment movement of multiple sediment types in a flow field. Although a versatile model currently utilized in various coastal and river applications, PTM is specifically designed to predict the fate of material released during dredging and placement operations, and to address the stability and fate of in-place sediment including dredged-material mounds, sediment caps, and contaminated sediment deposits. PTM combines accurate and efficient transport computations with effective visualization tools, making it useful for assessment of dredging practices and proposed dredging operations. The model operates in the Surface-water Modeling System (SMS) Version 9 and contains algorithms that appropriately represent transport, settling, deposition, mixing, and resuspension processes in nearshore wave/current conditions.

Keywords: Dredging, numerical methods, sediment transport, Lagrangian, far-field fate

INTRODUCTION

The effect of dredging operations is a major area of focus in navigational and sediment transport research. This is largely due to a much more rigorous and perhaps conscientious approach to obtaining accurate predictive information concerning the consequences of dredging and placement by all interested parties. Negative effects such as contamination and environmental disturbances are deterrents to dredging in certain regions. In addition, the range of applications for beneficial use of dredged material has increased in recent years. Exciting areas such as beach nourishment and the creation of environmental habitats have become prevalent. Weighing the costs and benefits of dredging operations is, therefore, a constant battle for the dredging community. This task is difficult if not impossible to accomplish without accurate information from predictive models which can be used to determine the fate of dredged material, both during dredging as well as placement.

In an effort to address these issues, the Engineering Research and Development Center of the Army Corp of Engineers on behalf of the Dredging Operations and Environmental Research program is developing and perfecting a suite of models which, working together, can predict sediment transport during dredging operations (Moritz et al 2000, MacDonald et al 2006). The near field fate models such as STFATE, MPFATE, and LTFATE address the effect of placement of dredged sediment at dredged mounds (figure 1). The Particle Tracking Model (PTM), however, has been designed specifically to address the needs of the dredging community to understand and predict the far-field fate of material suspended during dredging operations. As our understanding of sediment transport processes improves, so do the predictive capabilities of the model.

PTM is a Lagrangian particle tracking model which simulates sediment movement of multiple sediment types in a flow field, while including processes such as erosion, transport, settling, deposition, and resuspension. Given the time dependent hydrodynamics of a system, PTM tracks particles through the flow field. The particle movement is a function of not only the velocity components of the flow, but also other additional characteristics that effect sediment transport such as particle-bed interactions, particle settling rates, and a multitude of other influences. Sediment being modeled is discretized into a finite number of particles that are followed as they are transported by the flow. Sufficient particles are modeled such that transport patterns are representative of all particle movement from the sources.

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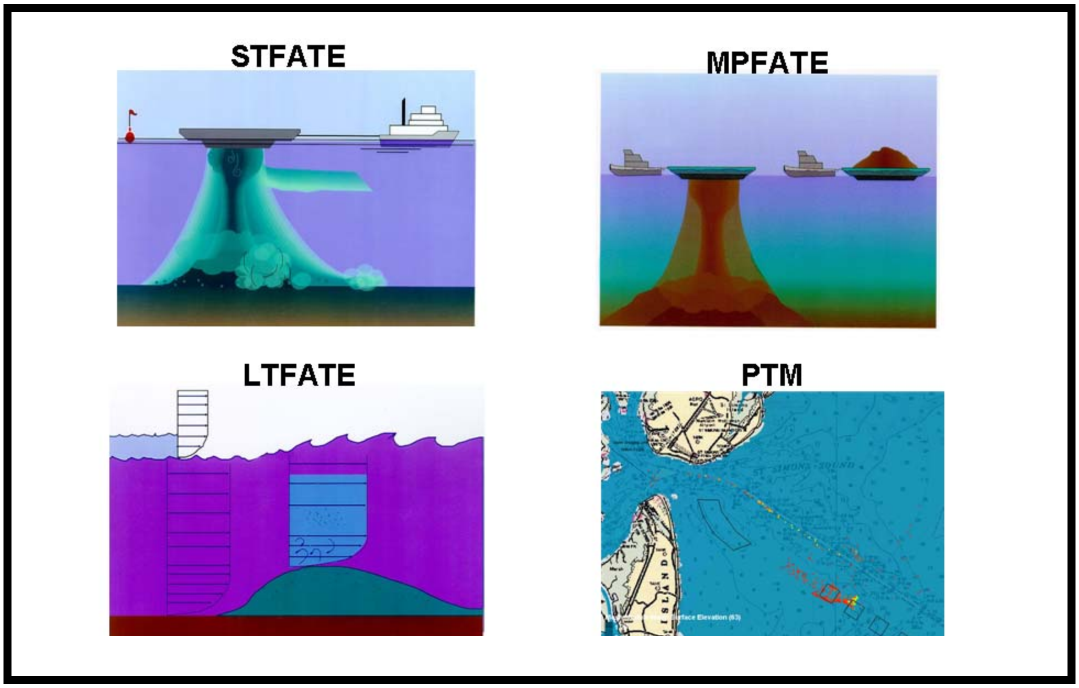


Figure 1. Suite of USACE predictive dredging models.

In general, a Lagrangian reference frame is one which moves with the flow. A Lagrangian method was chosen because it is extremely beneficial to the task of modeling the far-field fate of dredged sediment, giving both qualitative and quantitative information about the position of sediment in a time accurate manner. Within the Lagrangian framework, sediment pathways are readily identified. In addition, this method 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. Also, Lagrangian models tend to be much more efficient than their Eulerian counter-parts. It should also be mentioned that, although for this paper the focus of PTM will be primarily on sediment transport applications, the model is extremely versatile and can be adapted to simulate a wide range of Lagrangian-type particles such as fish and other biological transport.

The chosen model interface of PTM is the Surface-water Modeling System (SMS) (Zundel et al. 2005). This allows PTM to combine accurate and efficient transport computations with effective visualization tools, making it user friendly and therefore practical for the assessment of dredging practices and proposed dredging operations. Currently PTM v1.0 is accessible through the SMS v9.2 interface. The input requirements and model output will be discussed in detail in subsequent sections of this paper and can be further referenced in Demirbilek et al (2005a), Demirbilek et al (2005b), Demirbilek et al (2005c) ,and MacDonald et al. (2006).

In this paper, we first give an overview of the model design. Then we describe some of the processes and assumptions used in the model. Next we discuss model input and give a general summary of model output and visualization techniques. Finally, we address future plans for PTM development and make concluding remarks. As this paper is focused on processes and model development, a detailed PTM application is not shown in this work but can be found in Gailani et al (2007) and MacDonald et al (2006).

MODEL OVERVIEW

PTM employs three modes of operation: 2D, Quasi-3D, and 3D. The differences in these three modes are determined by the algorithms that are utilized for the calculations. The 2D representation of particle motion is the simplest. It provides a preliminary assessment of particle motions and pathways. A 3D 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 Quasi-3D mode involves a combination of empirical particle transport functions and a 3D advection, settling, and dispersion routine to mimic some of the key 3D transport processes. The 3D mode performs more comprehensive 3D particle entrainment, deposition, and re-suspension routines, but takes longer computational time due to the requirement of smaller time-steps.

Figure 2 is a schematic that describes the general internal procedure for PTM. First initial particle positions are determined for a time step. This is accomplished either by user source input or (after the first time-step) through output from the previous time-step. The code then goes through a series of mesh based Eulerian Calculations. Framework calculations establish background data such as water depth, flow velocities, frictional information, native (bed) sediment characteristics. Bed form calculations are performed to predict sub-grid scale bed forms over the domain. Shear and mobility calculations predict the influence of the flow field on the bed sediments over the domain. Transport calculations approximate the potential sediment transport fluxes over the domain and bed change calculations estimate 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. The frequency of updating shears, bedfoms, and mobility are determined by the user.

Next Lagrangian computations are performed for each particle. Because hydrodynamic data is most likely available less frequently than that required by Lagrangian calculations, values are interpolated in time. Flow algorithms are performed which interpolate the local flow and wave conditions spatially at the particle's location. 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. The trajectory integration determines 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. Particle positions are then checked for violation of boundary conditions. And finally sediment traps are checked to determine if a particle's destination falls within a sediment trap. These newly calculated positions are the input for the next iteration.

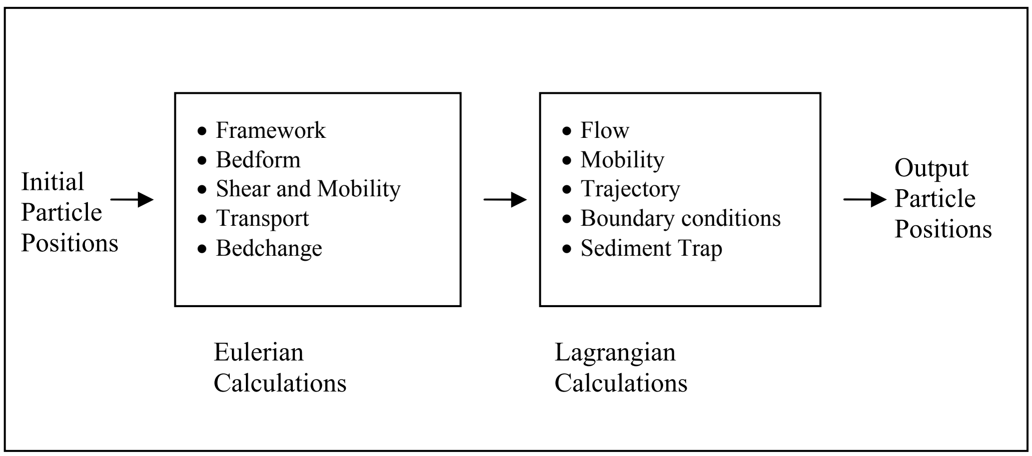


Figure 2. Schematic of PTM internal procedure.

MODEL PHYSICAL PROCESSES

PTM contains algorithms that appropriately represent initiation of motion, transport, settling, deposition, mixing, and resuspension processes in nearshore wave/current conditions. In this section we discuss the algorithms for both the mesh based Eulerian calculations and the Lagrangian particle transport calculations. As mentioned in the previous section, PTM operates in three different modes (2D, Quasi-3D, and 3D). For simplicity we discuss here only those algorithms which pertain to fully 3D calculations. More detailed information about the other two modes can be found in MacDonald et al (2006).

Eulerian Transport Calculations

Shear Stress

Shear stress is a function of both the flow and sediment bed conditions. As it plays a major role in many of the subsequent calculations, we will begin by describing the methods used to calculate these quantities. First it should be mentioned that there are actually four types of shear stresses calculated in PTM. They are the shear stress due to skin friction and the shear stress due to form drag for both current-induced and wave-induced stresses. In this document we will denote these variables as follows:

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'' .

PTM implements methods described in van Rijn (1993) to calculate shear stress. The bed shear stress (Pa) can be calculated from the depth-averaged velocity, $\overline{U}$, as:

$$T_c'' = \frac{\rho \overline{U}^2}{(C'')^2} \tag{1}$$

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

$$C'' = 2.5 \ln\left[11 \frac{h}{k_s''}\right] \tag{2}$$

where h = flow depth (m). 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 bed shear velocity, u_* (m/sec), is computed from:

$$u_* = \sqrt{\frac{T_c''}{\rho}} = \frac{\overline{U}}{C''} \tag{3}$$

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 $\overline{U}$:

$$u_* = \frac{\overline{U}}{2.5 \ln\left(11 \frac{h}{k_s''}\right)} \tag{4}$$

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 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. It should also be noted that the calculations becomes more complicated in the case of combined wave and current flows. Details of these calculations can be found in the technical report (MacDonald et al 2006).

Initiation of Motion

The initiation of motion for PTM particles located at the bed is dependent on the critical shear stress τ_{cr} . This value is utilized in the critical Shield's parameter. Defined by the Shield's curve, the dimensionless parameter θ (Sheild's parameter) gives the threshold of motion for particles at the bed (see Yalin (1977) for complete discussion).

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

In this equation, D is the characteristic grain size, ρ is the density, g is the gravitational acceleration, and s is the relative density ratio of the particles. The value of θ at which the inception of sediment transport occurs is then called the critical Shield's parameter θ_{cr} and is given by:

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

PTM uses a analytical representation of this equation based on later work performed by Soulsby and Whitehouse (1997) who developed a relationship based on the dimensionless grain size, D_{gr}.

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

Here D_{50} is the grain size at which 50 percent of the sediment is finer (by weight) and ν is the kinematic viscosity of the fluid. The resulting new equation determined by Soulsby and Whites for θ_{cr} is:

$$\theta_{cr} = \frac{0.30}{1+1.2D_{gr}} + 0.55\left[1-e^{-0.020D_{gr}}\right] \tag{8}$$

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:

$$M = \frac{T'}{T_{cr}} = \frac{\theta}{\theta_{cr}} \tag{9}$$

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

$$\tau_{cr} = \theta_{cr}\rho(s-1)gD \tag{10}$$

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

$$T = \frac{\tau' - \tau_{cr}}{\tau_{cr}} = M - 1 \tag{11}$$

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.

Bedform 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 as follows:

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

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 ($M > 24$). Bed forms do not develop for very fine materials ($D_{50} < 0.05$ mm). In PTM, it is assumed that if $D_{50} < 0.05$ mm, bed roughness is defined solely by skin friction and is:

$$k_s' = 3D_{90} \tag{13}$$

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 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, PTM uses the transport pickup rate, q_p (m/sec), to estimate the maximum temporal rate of change of the bed. 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:

$$\begin{aligned} \frac{\partial \eta}{\partial t} &= -q_p \qquad \eta > \eta_b \\ \frac{\partial \eta}{\partial t} &= q_p \qquad \eta < \eta_b \end{aligned} \tag{14}$$

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

Potential Transport Rate

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. 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.

Lagrangian Transport Calculations

Transport of particles in PTM is accomplished by three basic steps: 1) Particle location, 2) Particle interpolation, and 3) Particle integration. That is, first particle positions are located within the mesh. Then the Eulerian forcings are interpolated from the surrounding mesh to the particle position. Finally a new particle position is calculated by solving the basic equation

$$\frac{d\vec{X}}{dt} = \vec{V} \tag{15}$$

This simple differential equation states that the change in the position ($\vec{X}$) over time dt is equal to the velocity ($\vec{V}$). Therefore the most basic solution to these equations determine that

$$\vec{X}^{n+1} = \vec{X}^{n} + \vec{V}dt \tag{16}$$

By thus solving this equation, the new particle position $\vec{X}^{n+1}$ can be calculated at each time t. The main difficulties come in calculating the value of $\vec{V}$ which is a function of several quantities that will describe later.

Particle Position Integration

The basic Euler scheme shown in equation 16 is the simplest algorithm to the above differential equation. The scheme is first order accurate and often requires very small time steps as flows become very complex or when dealing with intricate sediment transport such as near bed particle behavior. Therefore a more accurate method must be used to allow for greater accuracy and larger time steps. Testing focused on determining effects of accuracy and efficiency for the PTM integration scheme is currently being performed.

As a first step in this direction, PTM v1.0 utilizes a two step predicator corrector scheme. This scheme is by nature second order accurate. In step 1 of the scheme, the particle position is integrated one half time steps. Then in step 2 this value and the initial particle position are used to calculate the new particle position, $\vec{X}^{n+1}$. In the following equations $\vec{X}'$ is the half time step particle position and $\vec{V}'$ is the velocity of the particle at this time.

$$\text{STEP 1: } \vec{X}' = \vec{X}_n + \frac{1}{2}(\vec{V}dt) \tag{17}$$

$$\text{STEP 2: } \vec{X}^{n+1} = \vec{X}_n + (\vec{V}'dt) \tag{18}$$

Velocity Calculations

As seen in the previous section, the velocity calculations play an important role in determining the particle position at each time step. The particle velocity term V in the previous equations is actually a mixture of various forcing elements. To understand this better, first we separate the particle velocity into the horizontal (U) and vertical (W) components. Within these components we can further compartmentalize the velocity as follows:

In the horizontal directions:

$$U = U_A + U_D \tag{19}$$

where A indicates advective forcing and D indicates diffusion. In the vertical direction we get similar terms

$$W = W_A - W_S + W_D \tag{20}$$

The horizontal velocity of each particle is equal to the fluid velocity at the vertical elevation of the particle added to the velocity due to diffusion. The vertical velocity however is determined by the vertical velocity component of the fluid at the point z_p minus the settling velocity, W_s of the particle. The vertical velocity component due to advection from the flow W_A can be determined by an assumed velocity profile if the hydrodynamic input is two-dimensional or obtained exactly from three-dimensional hydrodynamic input. The particle fall velocity, 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). They have been adapted for extremely fine grain sizes (D_{gr} < 0.0672) for PTM.

$$\frac{W_S D}{\nu} = \begin{cases} \sqrt{107.33 + 1.049 D_{gr}^3} - 10.36 & D_{gr} \geq 0.672 \\ 0.0077 D_{gr}^2 & D_{gr} < 0.672 \end{cases} \tag{21}$$

PTM uses a random walk diffusion model to calculate the velocity due to diffusion. The random walk representation of the horizontal dispersive velocity U_D is computed as:

$$U_D = 2(\Pi - 0.5)\sqrt{\frac{6E_t}{dt}} \tag{22}$$

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

$$W_D = 2(\Pi - 0.5)\sqrt{\frac{6E_v}{dt}} \tag{23}$$

The turbulent diffusion coefficients in the previous equations are estimated 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:

$$E_t = K_{E_t} h u_*'' \tag{24}$$

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. The variable u''_* is the shear velocity associate with form drag only. Slight modifications have been made to this equation in PTM to account for enhanced mixing due to wave breaking. The vertical diffusion coefficient is modeled using a parabolic-shaped distribution,

$$E_v = M_b K_{E_t} U_x \left[\frac{z_p \left(h - z_p\right)^2}{h^3} \right] \tag{25}$$

where M_b is a wave breaking coefficient and h is the flow depth and z_p is the vertical particle location.

Particle-bed Interactions

This section describes the series of algorithms developed to simulate the behavior of particles near the bed. It includes a hiding and exposure function, frequency of entrainment calculations, as well as deposition and re-entrainment algorithms.

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 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:

$$\dot{\theta}_{cr} = \xi \theta_{cr} \tag{26}$$

where ξ is a dimensionless hiding and exposure correction factor. The hiding and exposure function is given by (Egiazaroff 1965):

$$\xi = \frac{5}{3}\left[\log\left(19 \frac{D}{D_{50}} \right) \right]^{-2} \tag{27}$$

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. The hiding and exposure function is only applied to particles that are deposited on the bed.

Frequency of Entrainment

In nature, the behavior of a particle at the bed can be extremely complex. Particles deposit at the bed and can be re-entrained right away or can perhaps mix with the active sediment transport layer and then become entrained some time later (see figure 3). To include this interaction within 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.

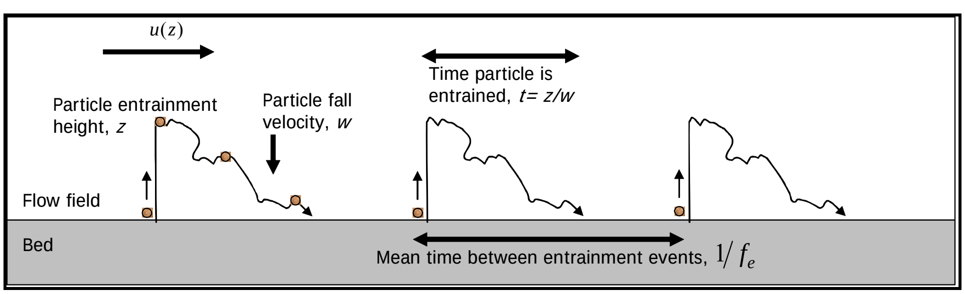


Figure 3. Advection paths for conditions for bed-particle interaction.

In PTM, particle entrainment is based on the mean shear stress, critical shear stress for erosion as defined by the Shields curve, and 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.
4. The ambient transport conditions on the bed (erosion/deposition), leading to an estimate of the depth of burial of the particle.
5. Mixing of the particles within the active transport layer, which is based on the thickness of the active transport layer.

The details of these calculations are lengthy and can be found in MacDonald et al 2006. Once calculated, these processes have then been implemented in a manner such that the frequency that a particle is picked up from the bed, f_e is determined as:

$$f_e = K_{burial} K_{mixing} f_p \tag{28}$$

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.

Particle Deposition and Re-entrainment

Particles are deposited on the bed once they pass below one-quarter of the skin roughness height, k_s'.

$$\text{if} \quad z_p \begin{cases} < \dfrac{k_s'}{4} & \textit{deposits} \\ \geq \dfrac{k_s'}{4} & \textit{active} \end{cases} \tag{29}$$

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

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. As a result, the random numbers will be biased towards 0 (taken as the bed) rather than 1 (taken as the surface). The new elevation of a re-entrained particle is taken as:

$$z_p = \Psi h \tag{30}$$

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

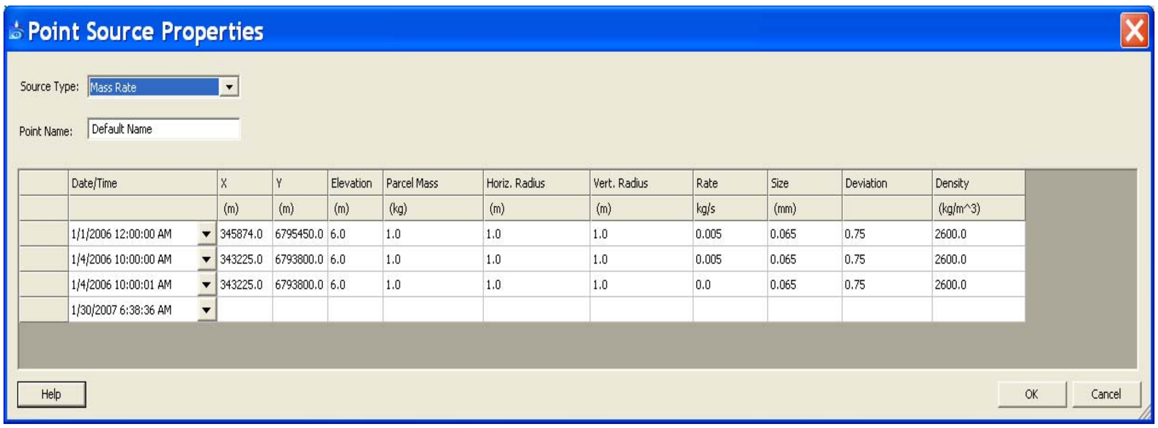
Boundary Conditions

PTM uses the land and open boundaries given in the 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. However, a particle may not pass through a land boundary. The particle will be placed alongside the boundary in question. 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.

PTM MODEL REQUIREMENTS AND VISUALIZATION

Model Input

Effectively modeling sediment transport by PTM requires three major components of user input: source input, bathymetry and native sediment information, and hydrodynamic input. Source information describes the sediment that will be transported during the simulation. Currently this input is given as an instantaneous source or a mass rate. Figure 4, shows an example PTM interface window for source input within SMS. In PTM, sources can occur as points, lines (both horizontal and vertical), and areas. In this particular example, a point source with a mass rate is shown. The user defines the time dependent positional information for sources which includes x, y, and elevation coordinates as well as the horizontal and vertical radius of the source. Based on the user input of the total amount of sediment that will be modeled and the "parcel" mass which describes the amount of sediment represented by each particle, the model then discretizes the source in space and time, determining the number of particles that will be modeled. It should be emphasized that each particle in the model represents a given mass of sediment (not an individual sediment particle or grain).



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)
1/1/2006 12:00:00 AM	345874.0	6795450.0	6.0	1.0	1.0	1.0	0.005	0.065	0.75	2600.0
1/4/2006 10:00:00 AM	343225.0	6793800.0	6.0	1.0	1.0	1.0	0.005	0.065	0.75	2600.0
1/4/2006 10:00:01 AM	343225.0	6793800.0	6.0	1.0	1.0	1.0	0.0	0.065	0.75	2600.0
1/30/2007 6:38:36 AM										

Figure 4. PTM point source properties window within SMS interface.

In addition to position information, the source input also includes physical particle properties such as grain-size and density input. Each particle has its own unique set of characteristics. As the model is run it calculates and outputs particle specific information such as mobility, velocity, and the particles state of deposition or suspension. The particles can also be given other characteristics that may be independent of the solution.

Native sediment information must be developed by the user for PTM. This feeds the model details about the grain-size distribution of the sediment which will interact with the source particles in the active bed layer. Native sediment becomes important when characterizing such processes as probability or entrainment and burial.

Bathymetry information is passed to PTM from various models. Internally PTM converts the grids to a triangular finite element mesh. Currently the 2D mesh geometries associated with PTM are from ADCIRC, ADH, and M2D. However, any model with similar formatting can be converted to work within PTM. Present interface development will soon make this process effortless for the user. It should also be noted that several 3D models geometries can be read into the most recent developed version of PTM (ADCIRC3D, CH3D, M3D), however the current released version PTM v1.0 allows for only 2D meshes.

Similar to bathymetry information, hydrodynamic input to PTM can be obtained from various models. To date the majority of the PTM applications focus on results obtained using 2D hydrodynamic models. In such cases PTM performs 3D computations for particle transport using the input from the 2D hydrodynamic models. The 2D hydrodynamics are primarily the solution of the depth-averaged shallow water equations. Vertical flow velocities are approximated based on assumptions such as logarithmic velocity profiles. Although these are accepted assumptions for many coastal projects, there is a growing need within this field to perform fully three-dimensional hydrodynamic computations where secondary vortical flow regimes and vertical velocities become more important. General examples of such cases are flows near some placement sites, near structures, and most coastal flows that coincide with rivers. Currently available in development form is a version of PTM which utilizes three-dimensional hydrodynamic input.

Because waves can have a significant effect on particle transport, wave model input is also accepted into PTM. PTM contains several algorithms which predict sediment transport due to wave/current interactions. The format for wave data utilized in PTM is specific to the STWAVE Model (Smith et al 2001).

Model Output and Visualization

PTM provides time accurate output of particle positions which can then be visualized or quantified for other calculations. Figure 5 shows a sample of PTM output obtained from the SMS interface. Based on user selection, particles are tagged for characteristics such as grain size, particle ID, source information, and state of deposition or suspension. This provides an opportunity for the user to characterize particles based on his or her specific needs. Grain-size visualization may help determine the fate of certain fine sediments; however source visualization may easily establish origins of major contaminate areas.

Other abilities such as the creation of particle pathlines and particle traps are also key visualization options that can be utilized through the interface. Particle pathlines permit the user to trace the exact path of each particle. A trap is defined as an area in which particles enter and are counted. Traps were developed to allow a user to determine when particles enter a particular mesh region. The trap may be open (allowing particles to exit after entering) or closed.

Because time is synchronized between hydrodynamic data and PTM output, users can visualize through animations the movement of hydrodynamic data such as contours of water surface elevation or velocity vectors with the movement of the particles. This is an extremely powerful tool which visualizes the effect of flow qualities on a particle. A more detailed example of the PTM interface is shown in Gailani and Lackey (2007), MacDonald et al (2006), and Demirbilek et al (2005c)

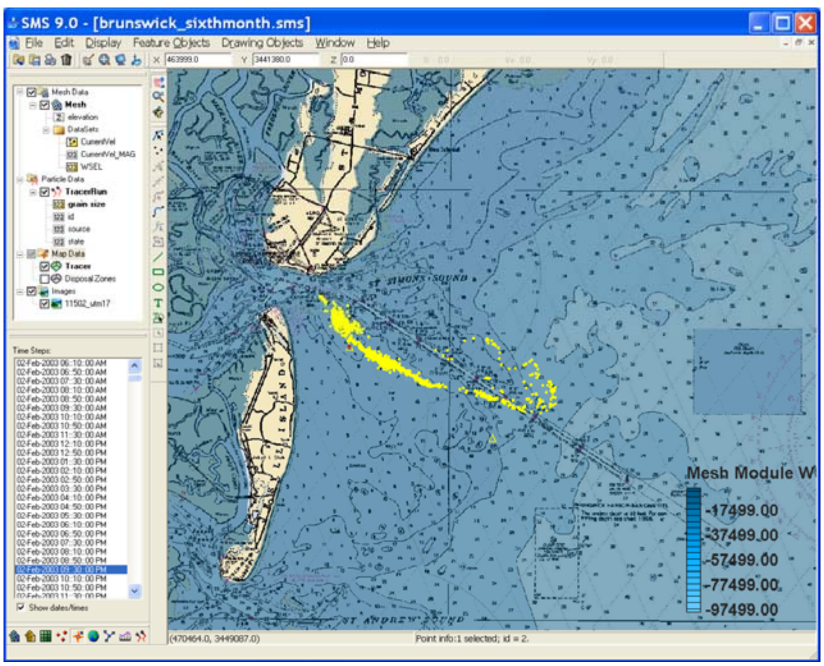


Figure 5. Sample PTM output from SMS interface.

SUMMARY AND FUTURE WORK

The Particle Tracking Model is a Lagrangian particle tracker designed specifically for dredging operations. The model contains algorithms which calculate sediment transport processes including settling, deposition, resuspension, and mixing. It combines these accurate and efficient transport computations with extremely effective visualization tools, making it useful for assessment of dredging operations. Hydrodynamic input from a number of models, both two-dimensional and three-dimensional, can be used as input. Both current and wave data can be utilized. The model operates in three different modes, allowing the user choices with regards to computing time.

PTM processes for transport can be separated into Eulerian and Lagrangian calculations. Eulerian calculations first take place at the mesh level and are interpolated to particle positions. The algorithms include bedform calculations as well as shear and mobility computations. Lagrangian calculations transport the particle at each time step, utilizing the values obtained by the Eulerian calculations for forcing. Velocity components for both advective and diffusive processes are computed. Particle-bed interactions are modeled such that burial and re-entrainment are possible.

PTM has been modularized effectively for development purposes. Therefore, as our understanding of sediment transport processes improve, new algorithms can easily be added to PTM. PTM is currently being designed to accept source terms from near-field dredging models (Dredge Source Term, LTFATE, STFATE, MDFATE, DCORMIX, etc) as well as to incorporate WQ and contaminant transport processes. Cohesive sediment algorithms to accurately describe processes such as flocculation are in present development.

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NOMENCLATURE

C''	Dimensionless Chézy coefficient
dt	Time-step
D	Characteristic grain size
$\overline{D}$	Mean grain size
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
f_e	Frequency of particle entrainment
f_p	Frequency of particle pickup
g	Gravitational acceleration
h	Flow depth
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
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	Total horizontal velocity for particles
U_A	Horizontal advection velocity for particles
U_D	Dispersion velocity for particles
u_*	Shear velocity
u'_*	Shear velocity associated with skin friction only
u''_*	Shear velocity associated with form drag only
$\overline{U}$	Depth-averaged velocity
U_{cr}	Critical velocity
V	Total vertical velocity for particles
V'	velocity for particles at time-step $n + ½$
W_s	Particle fall velocity
W_A	Vertical advection velocity
W_D	Vertical diffusion velocity
X_n	position of particle at time-step n
X_{n+1}	position of particle at time-step $n+1$
X'	x position of particle at time-step $n + ½$
z	Vertical coordinate
z_p	Particle height 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
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
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'_w	Wave-induced shear stress due to skin friction
τ''_w	Wave-induced shear stress due to form drag
Ψ	Random number between 0 and 1 distributed according to a Rouse sediment concentration profile