APPLICATION OF THE PARTICLE TRACKING MODEL TO PREDICT THE FATE OF DREDGED SUSPENDED SEDIMENT AT THE WILLAMETTE RIVER

Tahirih Lackey[1] and Jarrell Smith[2]

ABSTRACT

The US Army Corps of Engineers, Portland District is evaluating the fate of sediments associated with proposed dredging operations in the Lower Willamette River, near the confluence of the Willamette and Columbia Rivers in Oregon. The Lower Willamette was last dredged in 1997 to an authorized depth of -12.2 m (-40 ft) MLLW. Plans are to increase the navigable depth to -13.1 m (-43 ft) MLLW. The proposed dredging will include removal of both maintenance and new work materials through hopper and clamshell dredging. The primary objectives of this study are to define the fate of sediments in the Lower Willamette and Columbia River suspended due to dredging and placement, and to characterize sediment mixing in the water column near the dredging operations. The Particle Tracking Model (PTM) was utilized to address these issues. PTM is a US Army Engineer Research and Development Center developed Lagrangian particle tracker which models sediment parcels through a supplied hydrodynamic flow field. In this project, PTM worked in combination with several dredging source models, which provided predictions of dredging resuspension rates as sediment sources in the model. Estuarine Fluid Dynamics Code (EFDC) hydrodynamics were used for particle forcing. PTM results were evaluated to compare resuspension and fate of sediments by clamshell and hopper dredging alternatives. Results indicate an overall tendency of dredged sediment movement north towards the Columbia River or into Multnomah channel. Settling and burial of sediment occurred quickly in the region for both clamshell and hopper operations, which minimized transport south of the dredging region.

INTRODUCTION

The Engineering Research and Development Center (ERDC) of the US Army Corp of Engineers (USACE) at the request of the USACE Portland District (NWP) numerically simulated the transport of sediment suspended due to intended dredging operations in the Willamette River. The purpose of this study was to determine the fate of the suspended sediment based on dredge type and placement site. The Lower Willamette was last dredged in 1997 to an authorized depth of -12.2 m (-40ft) MLLW. Proposed dredging occurs according to the Willamette River Dredged Material Management Plan (Figure 1). Currently the two main focus areas are River miles 2-3 (Region 1) and 8-10 (Region 2). As seen in the map legend, the areas to be dredged are shown in yellow and/or red contours. Also shown utilizing a bold magenta line is the main channel within the river. The dredging region of mile 2-3 (yellow boxed region) is much smaller than that of mile 8-10. Therefore this work which is focused on mile 2-3 will be utilized as a simplified version of the more extensive dredging operation that will take place in mile 8-10. Maintenance dredging in region 2 will be simulated by NWP. Placement for dredging in the mile 2-3 region is expected to occur at an open water site in the Columbia River not visible in the figure.

The Lower Willamette currently serves as a navigation access to a host of industrial facilities. As seen in figure 1, this area is located at the confluence of the Willamette and Columbia River. Also visible in the figure is the Multnomah channel, located on the northern west bank of the Willamette. Historically the Willamette River system in the Portland area was an extremely integrated and ecologically active region. However in the early 1900's industrialization and modifications to improve navigation reduced the amount and quality of open slack water areas,

[1] Research Hydraulic Engineer, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, ATTN: CEERD-HC-C; 3909 Halls Ferry Road; Vicksburg, MS 39180 phone: 601.634.3552 email: Tahirih.C.Lackey@erdc.usace.army.mil

[2] Research Hydraulic Engineer, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, ATTN: CEERD-HC-C; 3909 Halls Ferry Road; Vicksburg, MS 39180 phone: 601.634.4310 email: Jarrell.Smith@erdc.usace.army.mil

off-water channels, and wetland habitats. With the aid of these events, pollution and urban waste water discharge resulted in the river being declared almost biologically dead by the 1930's. With a change in focus and the recognition of environmental ramifications of industrial activities, in the 1960s interagency groups through focused efforts began to ascertain ways to increase the health of the river while at the same time accomplishing industrial goals such as maintaining navigation pathways. Eventually in 2000 portions of the river bed were officially identified as containing contaminated sediment and several of these areas were listed as national priorities through the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or Superfund. Although the specific area in question for this project is not likely CERCLA, the sediment to be dredged from the channel does include some of the Contaminants of Concern. Therefore, efforts must be made to predict and quantify exposure for assessment of effects, and risks of the proposed dredging operations. Ultimately this screening level assessment will be used to determine if further risk assessment is needed.

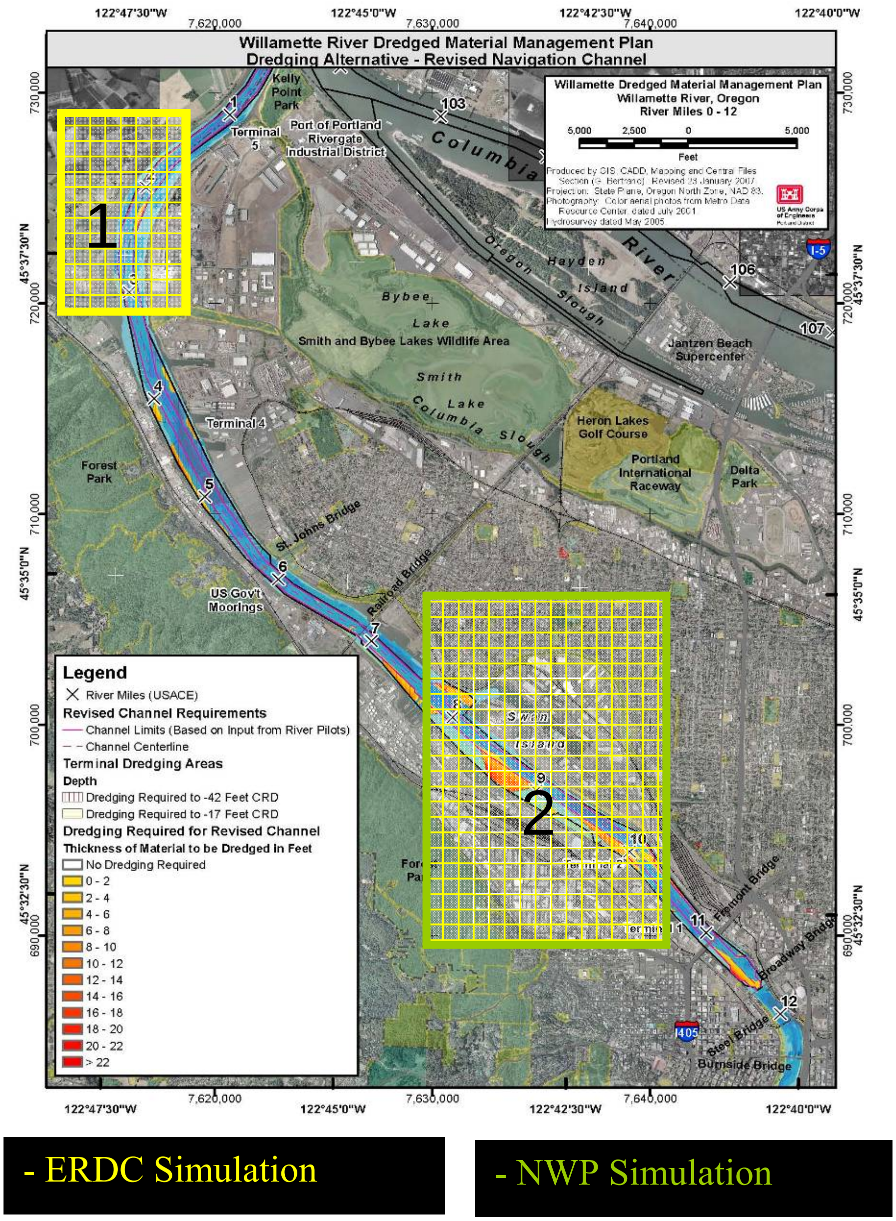


Figure 1. Willamette River Dredged Material Management Plan. Yellow boxed region is the focus area for this work (Region 1). The green boxed area is where additional simulations by the Portland district will be performed.

To address the issue of the far-field fate of suspended sediment due to dredging and placement, the Particle Tracking Model (PTM) is utilized. One major motivation to use the model is that PTM has been designed to focus on sediment sources specifically indicated by the user. In situations for which the sources of contamination or sediment resuspension are known, PTM works optimally and can simulate multiple scenarios much more rapidly than Eulerian sediment transport models.

The exposure characterization of dredging operations in Region 1 required analysis of sediment deposition and mixing within the water column. Hypothetical two week dredging operations were simulated with a start date of July 15, 2001. Operational characteristics of dredge types, dredging schedules, etc were determined based on previous NWP dredging operations. Production rates, mass of sediment suspended, and other relevant quantities were calculated based on sediment and operational characteristics as well as ambient conditions. The operational goal was to dredge 38,230 cubic meters (50,000 cubic yards) of material with both a hopper and clamshell dredge. This paper presents a concise description of the particle tracking model, a detailed accounting of model input information utilized in the project, and results and analysis of the simulations.

THE PARTICLE TRACKING MODEL

Model Description

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, estuarine, and riverine applications, PTM is specifically designed to predict the fate of material suspended 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 current interface for PTM is the Surface-water modeling system.

PTM models such processes as settling, deposition, resuspension, and particle-bed interactions to simulate the transport of both fine and coarse sediment. PTM requires the input of hydrodynamics (i.e. water surface elevation and velocities), mesh and bathymetry information, and sediment characterization of both the native or bed sediment and the sediment sources (Figure 2). These sources may initiate from sediment resuspended during dredging and/or placement. Instead of undertaking the impossible task of modeling every grain of sand, silt, and clay, PTM instead discretizes the sediment into "parcels". Each parcel is representative of a specific mass of sediment. These parcels preserve the overall size distribution of the sediment source. The model then steps through time tracking the position of each parcel. PTM outputs time-accurate horizontal and vertical positions of sediment parcels. Various other attributes such as mass, density, and suspension status are also assigned to each of the output parcels.

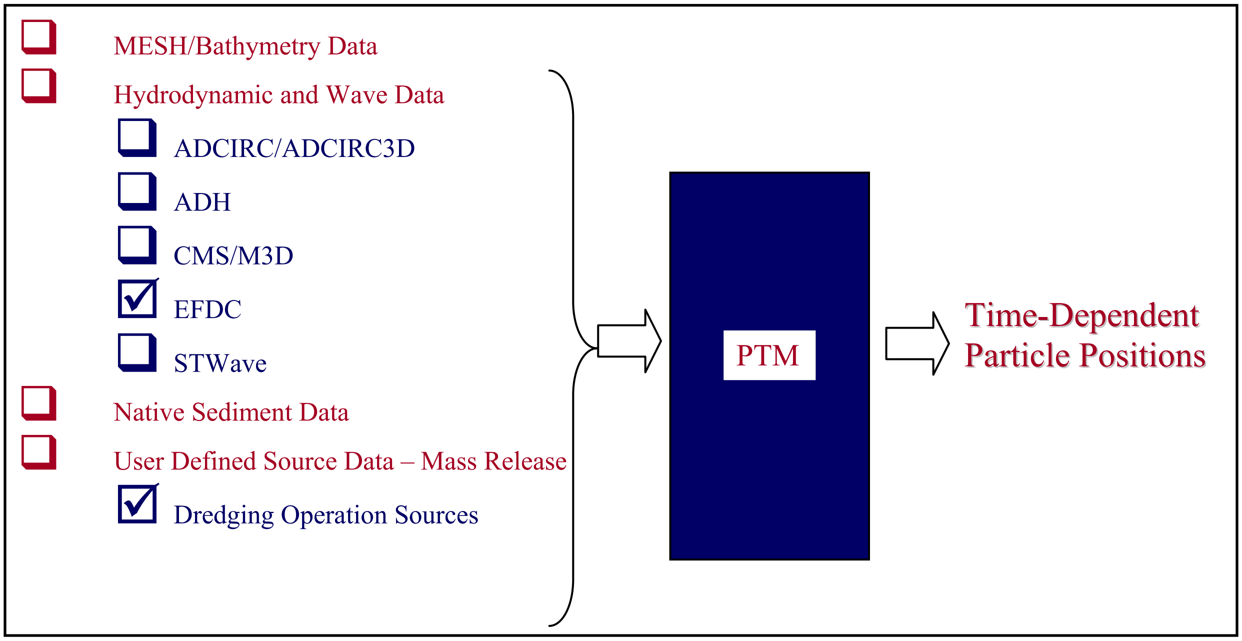


Figure 2. PTM model input and output schematic

Particle Model Input

Mesh and Bathymetry

An Estuarine Fluid Dynamics Code (EFDC) grid has been provided for the purpose of hydrodynamic input to PTM. EFDC is a finite difference model which utilizes a series of quads and triangle cells. Bathymetry and hydrodynamic output are specified at EFDC cell centers. The current grid encompasses the region of the Willamette River from its confluence with the Columbia River at the north most end down southward to river mile 20. Figure 3 shows a PTM mesh with bathymetry contours. The zoomed in area focuses on mile 2 through 3, which is the dredging region of interest for PTM simulations described in this report. An important characteristic of this area is the Multnomah channel which serves as a distributary to the Willamette on the west bank of the river. In this figure, elevation contours demonstrate both the channel down the middle of the river where the depth is approximately fifteen meters and shallower regions along the inside bend where the channel is to be dredged.

For this application, the mesh was developed by converting the EFDC grid to a format compatible with PTM. Similar to finite element hydrodynamic models such as ADCIRC and ADH, PTM mesh format consists of triangular elements. Values for bathymetry and hydrodynamics are given at the nodes. The conversion was accomplished by first converting the EFDC to an RMA10 .geo grid with an ERDC-developed FORTRAN code (EFDC2ADH.f). EFDC internally develops a file which contains the corner nodes of every cell. This conversion code interpolated the elevation values from the cell center to those nodes using bilinear interpolation. This new grid was then loaded into SMS, converted from quads to triangles, and exported to PTM style format.

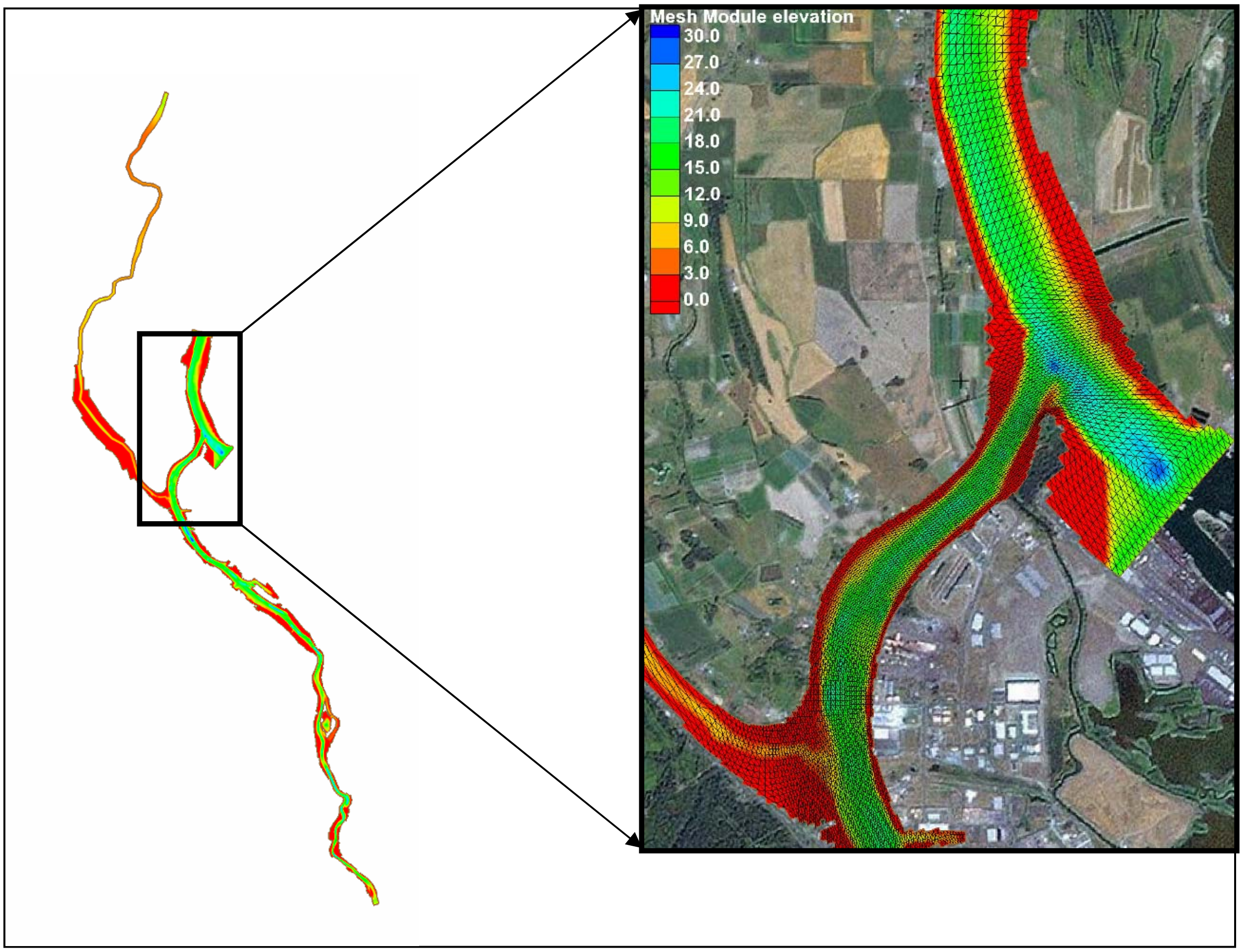


Figure 3. Left: PTM mesh. Right: Zoom in to focus area with elevation contours.

Hydrodynamics

EFDC hydrodynamic results were provided based on the aforementioned EFDC grid. Water surface elevation and velocity components are given at cell centers. These data were interpolated onto PTM grid nodes utilizing a FORTRAN code. The time-accurate hydrodynamics cover a 30-day period from July 15 to August 14. Figures 4a thru 4c compare the hydrodynamics obtained by the EFDC code with the interpolated PTM hydrodynamics. Contours of velocity magnitude show increased velocity (m/s) as the flow enters Multnomah channel. The EFDC hydrodynamic solution is driven by a boundary condition imposed at the end of Multnomah channel as represented in the EFDC grid. The current boundary condition suggests that flow is primarily unidirectional directed towards the Columbia River. Therefore fluid and sediment move only into the channel without the possibility of return. Within the Willamette River, flow is tidal as seen in the time progressive snapshots of Figure 4. Velocity patterns produced by the flow conditions can be complex. In Figure 4a (July 15 at 10am) the flow leading from the south towards Multnomah channel shows a general parabolic profile with slower velocities near the river banks. However in the same figure, flow approaching from the north is in the process of reversal. Figure 4b (July 17 at 2am) shows that the main flow direction is southward. Figure 4c (July 20 at 6am) shows the flow once again reversing, but the profiles are much more complex than the general parabolic profiles depicted in Figure 4a.

These hydrodynamic patterns are extremely important to suspended sediment simulations, as PTM relies on accurate hydrodynamics to determine the motion and displacement of sediment. Because the EFDC hydrodynamic solution is interpolated to PTM format, care was taken to verify that the hydrodynamic results were appropriately and accurately transformed. Visual and numerical comparisons between the two data sets indicate that the data appear to be well within the order of accuracy of the depth-averaged hydrodynamics.

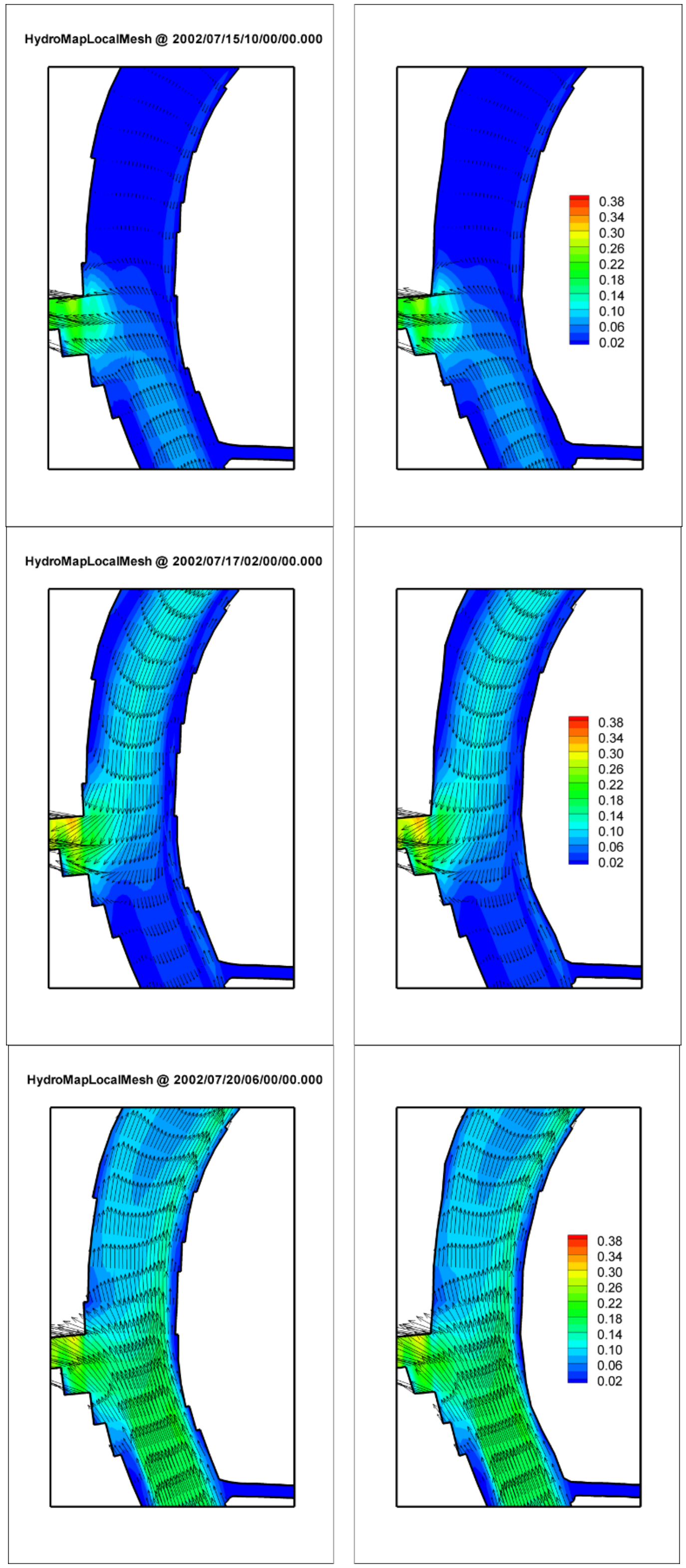


Figure 4. Hydrodynamic Comparison of depth-averaged velocity fields between PTM (left) and EFDC (right) at three times: a) July 15 at 10am, b) July 17 at 2am, and c) July 20 at 6am. Contours indicate velocity magnitude (m/s), vectors indicate magnitude and direction of the depth-averaged velocities.

Bed Shear Stress

Shear stress is a measure of the tangential force per unit area induced by fluid flow over the sediment bed. Bed stress is a function of the flow velocity, water properties, and sediment bed conditions. Sediment bed conditions were derived from the native sediment characterization which will be described in detail in the following section. PTM implements methods described in van Rijn (1993) to calculate bed shear stress. The bed shear stress (units: Pa) is calculated from the depth-averaged velocity, $\overline{U}$, as:

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

where ρ is 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 = 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.

The bed shear stresses seen in the following figures represent two of the hydrodynamic conditions from Figure 4. Figure 5 shows the high shear stress region in red and low shear stress regions contoured blue. As parcel suspension and deposition are dependent on bed shear stress, this figure suggests a tendency for parcels within the channel region to become suspended and deposited as the flow changes direction.

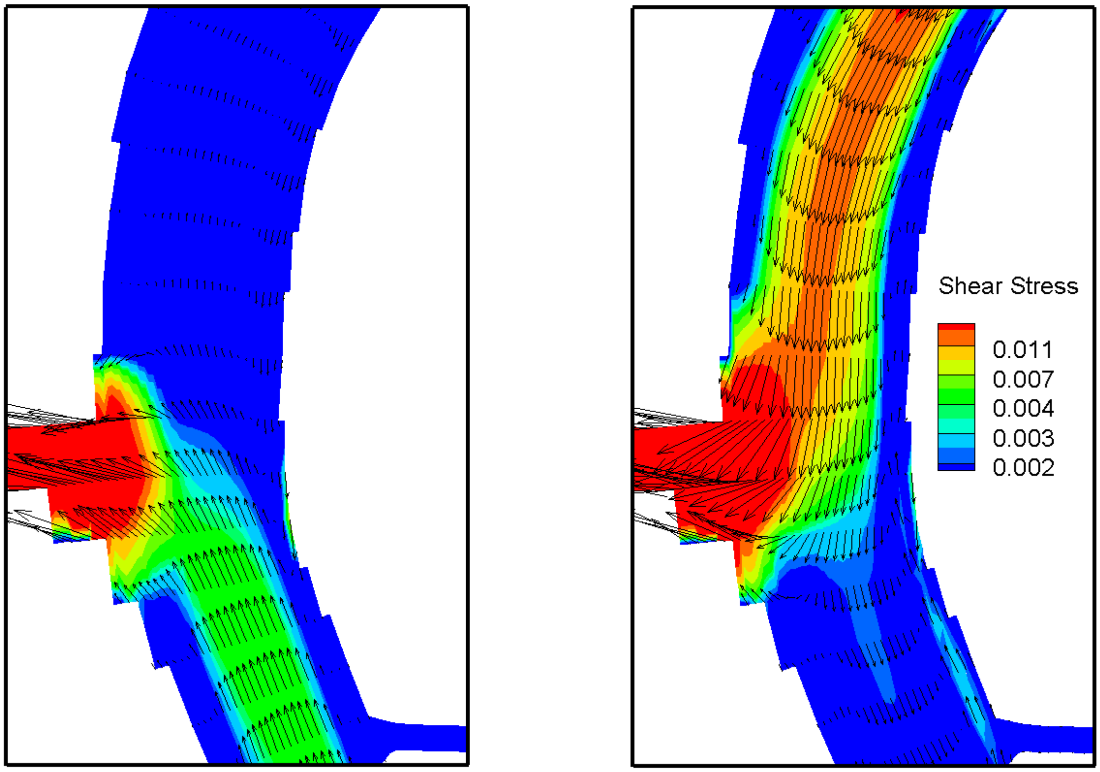


Figure 5. Bed shear stress (Pa) for July 15 at 10am and July 17 at 2am.

Critical shear stress represents the bed stress at which a particle is in a state of impending motion. The critical shear, τ_{cr} (Pa), for non-cohesive sediments can be estimated by:

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

where θ_{cr} is the dimensionless critical Shield's parameter. Here g is gravitational acceleration, s is specific gravity of the particles, and D is the characteristic grain size.

Native Sediment Data

Native sediment data was provided in the form of grain size distributions for surface sediment samples at numerous points within the area. Figure 6a shows the PTM mesh (red) overlain with the positions for which native sediment data was supplied (black). Values of D_{35}, D_{50}, and D_{90} were inferred from the size distributions and mapped to the PTM mesh nodes using nearest-neighbor association. Nearest-neighbor association was determined to be a more realistic procedure that would not diffuse the features of the original sediment map. Figures 6b through 6c show the characteristic native-bed grain sizes as applied to the PTM mesh. One important fact obtained from figure 6 is that sediment is composed primarily fines in the dredging region. However in the placement area in the Columbia River the bed sediment is coarser. This becomes important in the case of particle bed interactions which incorporate algorithms for probability of resuspension based not only on the critical shear but also on the burial and hiding that goes on at the bed.

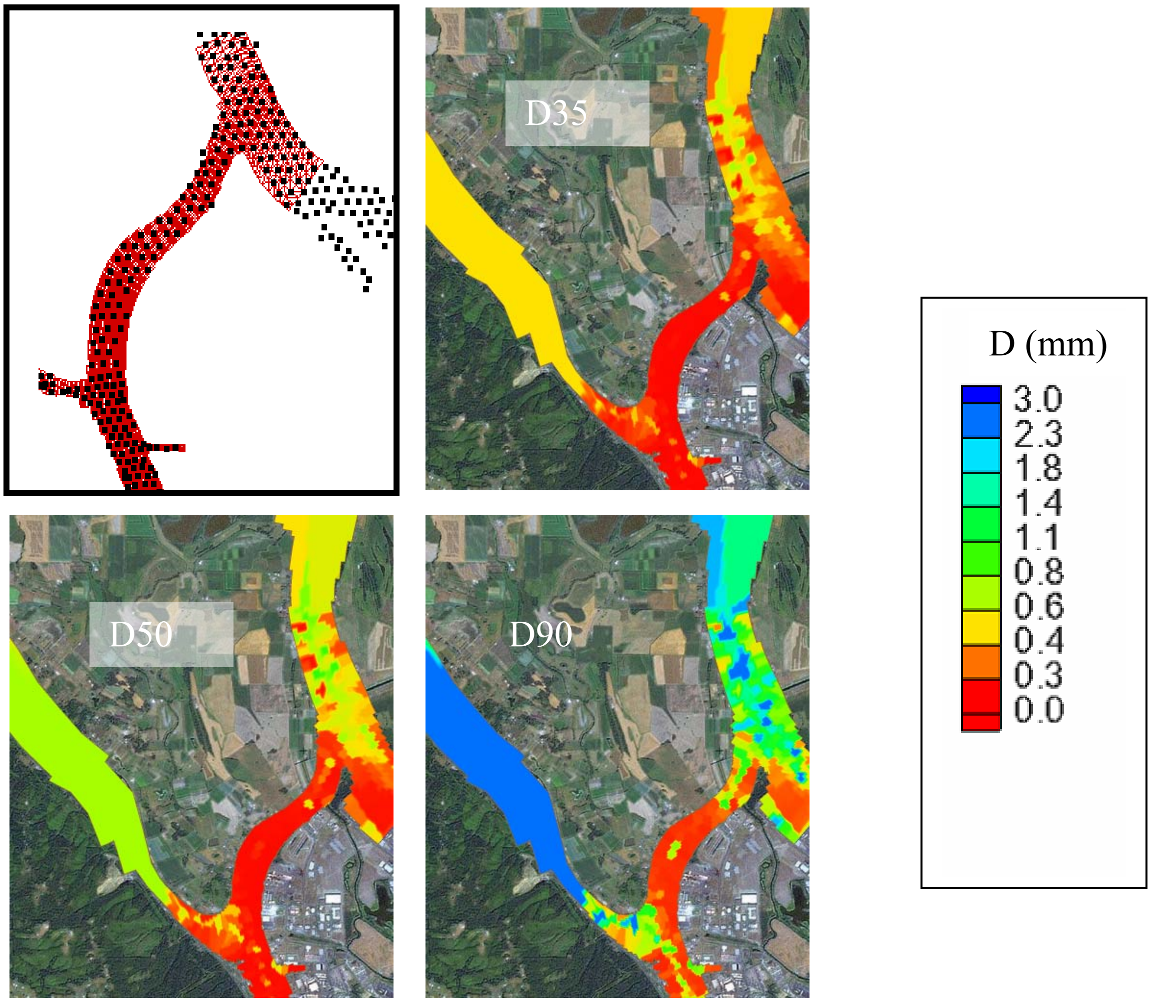


Figure 6: a) Mesh with locations (black points) where native sediment data was provided. Native sediment distribution values for b) d35, c) d50, and d) d90 in millimeters.

PTM Source Development

In this study, two dredge types are simulated: 1) Clamshell Dredge and 2) Hopper Dredge. Each dredge produces specific types of losses during dredging and placement that result in suspended sediment entering the water column. This report addresses only sediment suspended associated with dredging. To simulate the sources of a dredging operation, PTM requires the following data:

- Date/Time of dredging operation
- Positions (x,y,z) of sediment introduced into the water column
- Rate of sediment introduction
- Size distribution of suspended sediment
- Sediment density

Sediment settling rate and critical shear stress due to erosion and deposition can be either calculated by the model or input by the user. The specific equations for those processes are discussed in detail by McDonald et al (2006). In this project, the settling and critical shear stresses are calculated by PTM for sands and specified for fines (clay and silt). Based on the sediment grain size data at the dredging site, approximately 73.6% of the dredged material is clay/silt and 26.9% is sand.

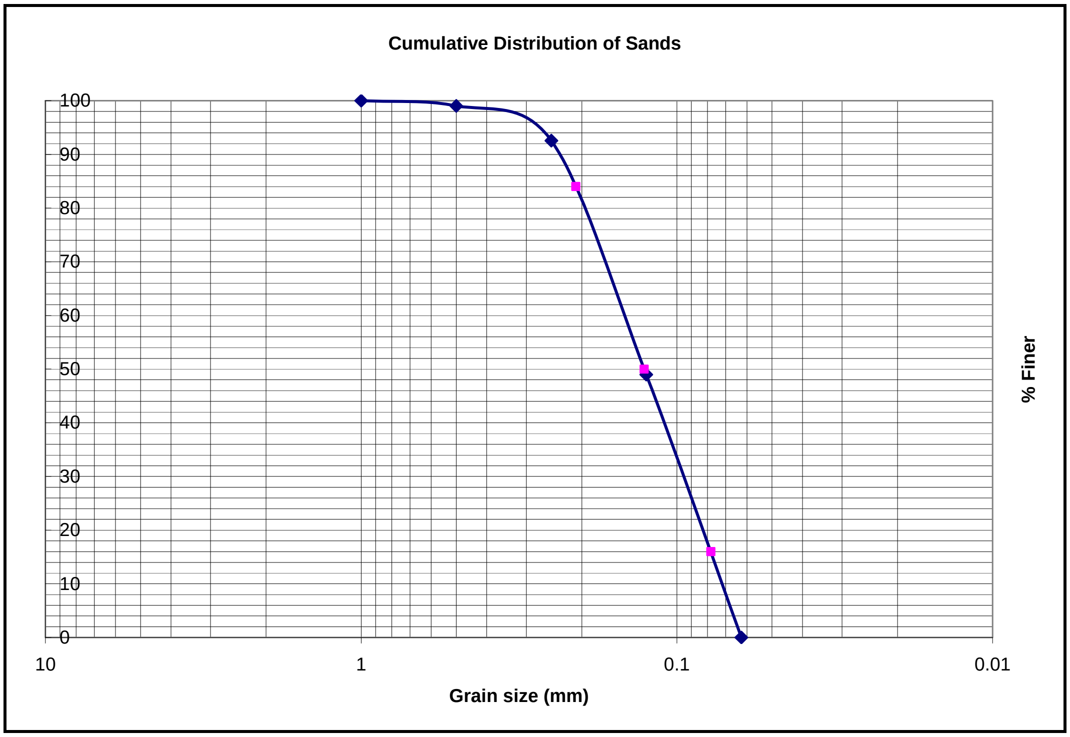


Figure 7. Cumulative Distribution of Sands calculated using NWP field data.

Values of the cumulative distribution of sands were determined by provided sediment data. The standard deviation for the sand was then calculated as follows:

$$SD = \sqrt{\frac{D_{84}}{D_{16}}} \qquad (6)$$

Diameter(mm)	% Finer
0.209	84
0.127	50
0.078	16
Standard Deviation	1.64

The specified value of settling for fines is 0.0005m/s. The critical shear for initiation is 0.1N/m^2 and the critical shear for deposition is 0.075N/m^2. These values were determined based on previous fine-grained sediment transport studies.

Clamshell Dredge

The clamshell dredge is a mechanical dredge which scoops or grabs the material from the bottom and then lifts it through the water column before placing it into barges. There are several sources of suspended sediment, each associated with a specific phase of the dredging operation. Two primary sources of sediment suspension come from ascent and descent phases. During ascent, sediment is washed from the bucket exterior and also released from the mounded sediment surface within the bucket. A third source of suspension is the sediment entrained by surge currents and bed disturbance as the bucket approaches and impacts the sediment bed. Finally sediment is released by surface drainage and leaking during slewing. A schematic of a mechanical dredge and suspension mechanisms related to impact, cut, and initial ascent are illustrated in Figure 8.

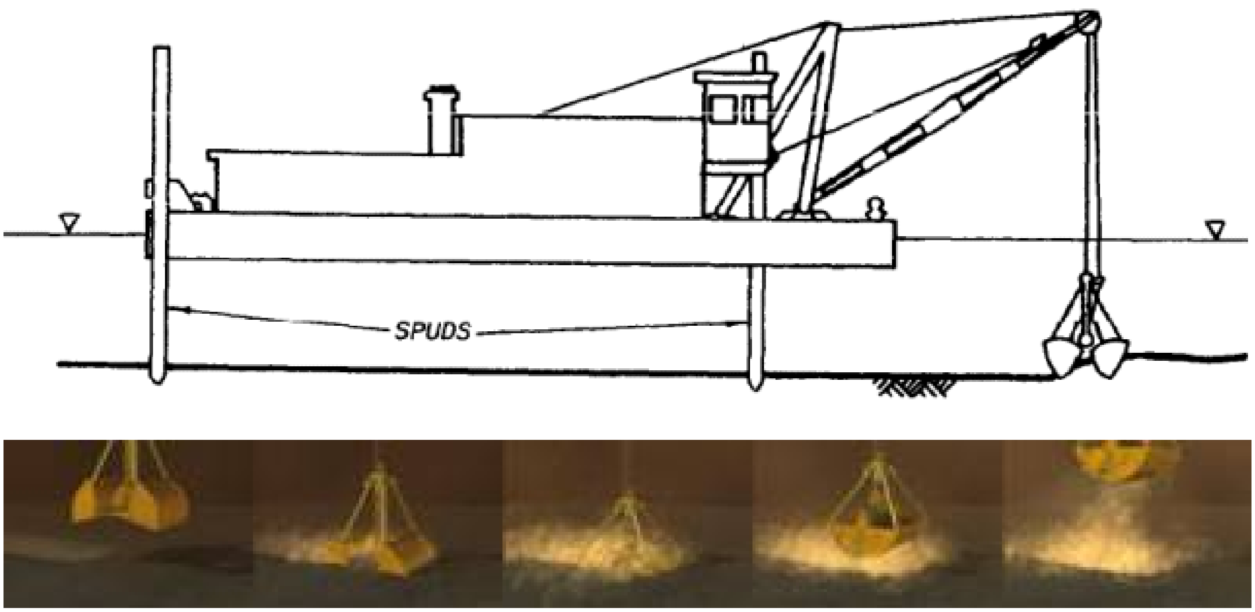


Figure 8. Schematic of a clamshell dredge with images of sediment suspended due to dredging. Courtesy of USACE

As mentioned previously, PTM discretizes sediment mass into sediment “parcels”. Once introduced into the flow, these parcels are then tracked over time. The sources introducing parcels to the water column can take various forms, enabling the user to adequately represent the specific characteristics and spatial distributions of the actual source. That is, sources introduced based on sediment being released at a placement site would differ from a more continuous process such as dredged sediment flow from a pipeline dredging operation. PTM allows for instantaneous point releases, horizontal and vertical mass rate line releases, and area releases. The clamshell dredge sources are represented by mass rates releases over vertical line segments. This allows representation of the losses at different sections of water column.

i. Descent + Ascent | uniformly distributed over the water column
ii. Impact | ½ bucket diameter from the bottom
iii. Slewing | uniformly distributed over upper 3m

The specific rate of the source released is dependent on the rate coefficients determined by the Clamshell Dredging Source Terms model (Hayes et al 2007). This method requires numerous pieces of information that may affect the rate of suspended particulate release. The information can be separated into three categories: equipment, dredging operation, and the physical properties of sediment. Once these coefficients are obtained, they are factored into the overall production rate to determine the losses due to each of the previously mentioned effects. The mass production rate of transportable particles P_{Mass} is determined based on the equation

$$P_{Mass} = f_t * P * C_s$$

where f_t is the percent of particles subject to transport from the dredging site, P is the production rate, and C_s is the in situ sediment concentration.

In this simulation, the clamshell size was specified by NWP as 15.3 cm (20 cy). The clamshell digs (lifts load through the water column) every 45 seconds. Once every approximately 2 hours, the operation stops for 10 minutes while the scows, which have reached capacity 1147 cm (1500 cy), are changed. At this point the filled scows place sediment at the specified disposal site (Figure 9). Once every 7 hours, the operation stops for 60 minutes for a break/crew change. This goes on for 24 hours a day. To complete one pass across the dredged region (see Figure 1), a full day of dredging is required. For model input simplicity it is assumed that there are 7 full hours of dredging and one hour halted.

The operation continues until all dredging is completed. For the river mile 2-3 work; there is at most 38,230 cubic meters (50,000 cubic yards) of dredging. In this operation, it is assumed that 10,276 cubic meters per day (13,440 cubic yards per day) are dredged. Therefore the dredging operation itself requires 4 days for completion. The simulation continues for another 17 days after completion to obtain a total of 21 simulated days to determine the ultimate fate of the dredged sediment.

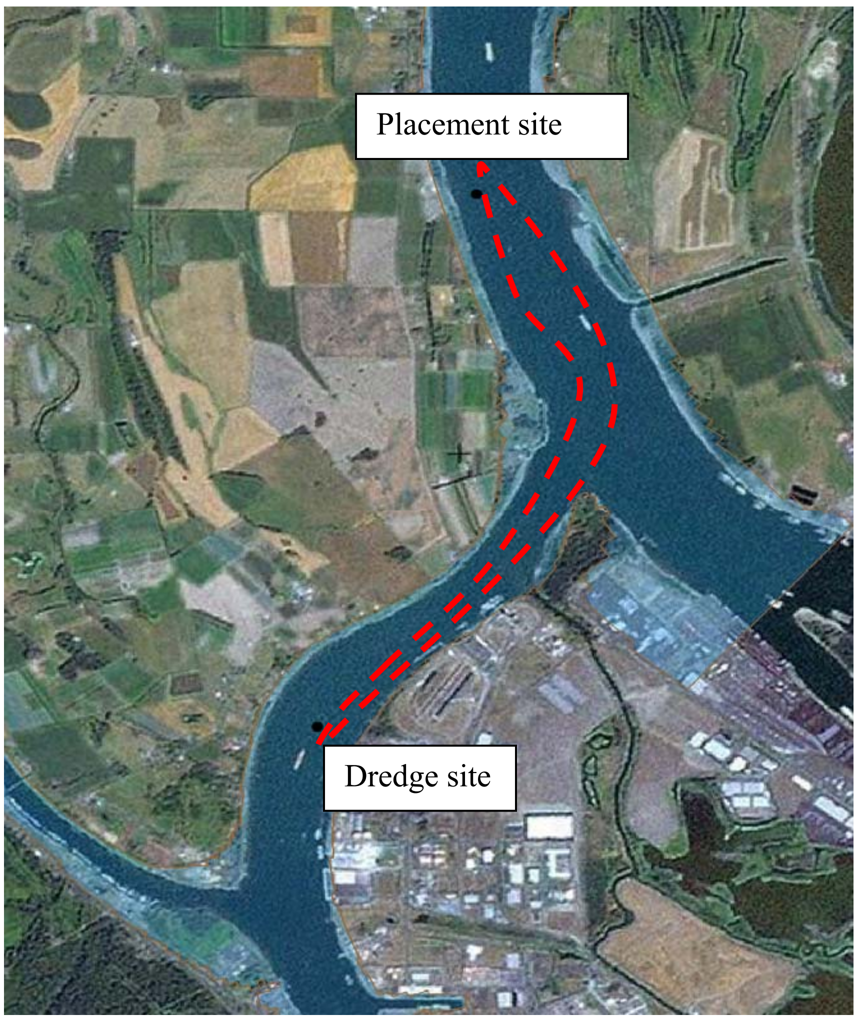


Figure 9. Dredging operation and placement path shown by red dashed line.

For the clamshell dredging operation described in this work, the following dredge source terms are determined:

Source	Rate kg/m/s	Position in Water column
Ascent & Descent	.015	Distributed over water column
Impact	.034	1/2 bucket diameter from bottom
Slewing	.042	Upper 3m

The water column length is assumed to be approximately 15 m based on the bathymetry and water surface elevation information provided.

The overall loss rate for each type has been further divided into sands (26.1 %) and fines (73.9%). The clamshell dredge source is therefore separated into six segments for PTM as indicated in Figure 10. It should be noted that mechanical dredging releases in practice are periodic associated with each bucket cycle. The dredging source in PTM is represented as continuous. This approximation is considered acceptable in this case because the periodic plumes merge in short distances and the focus of this work is far-field assessment of the plume, not within a few hundred meters of the dredge.

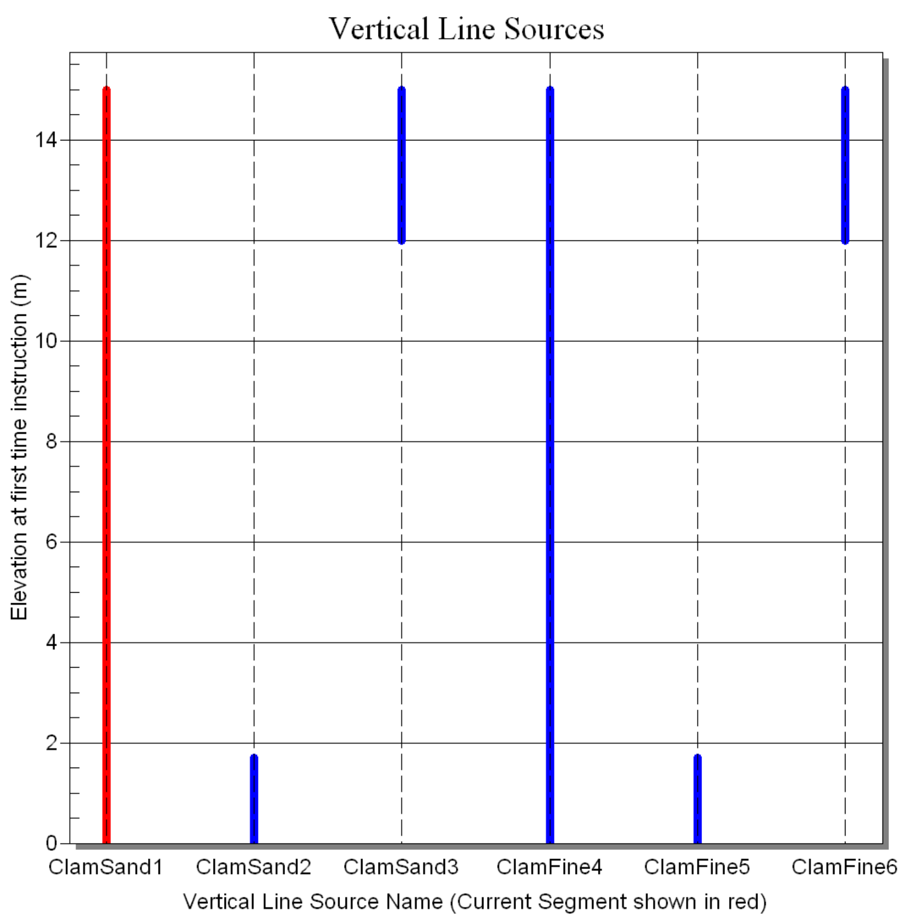


Figure 10. Graph of clamshell source.

Hopper Dredge

The hopper dredge (Figure 11) is a form of hydraulic dredge which removes the sediment from the bed through suction and stores the hydraulically transported slurry in hoppers fabricated within the hull of the dredge vessel. Suspended sediment sources from this process are quite different from the clamshell dredge operation. Some losses during dredging may result from the suction process itself as well as overproduction. However, losses much larger than those occurring at the draghead may result if the hopper is permitted to overflow. During overflow operations, hydraulic loading of the hopper continues after the hoppers are full of slurry. During this process, more rapidly settling sediment particles deposits within the hopper while water and slower settling particles are returned to the water column. During overflow, sands and coarser bed aggregates removed from the bed are preferentially stored in the hopper. Consequently, fine-grained sediments are primarily released to the water column.

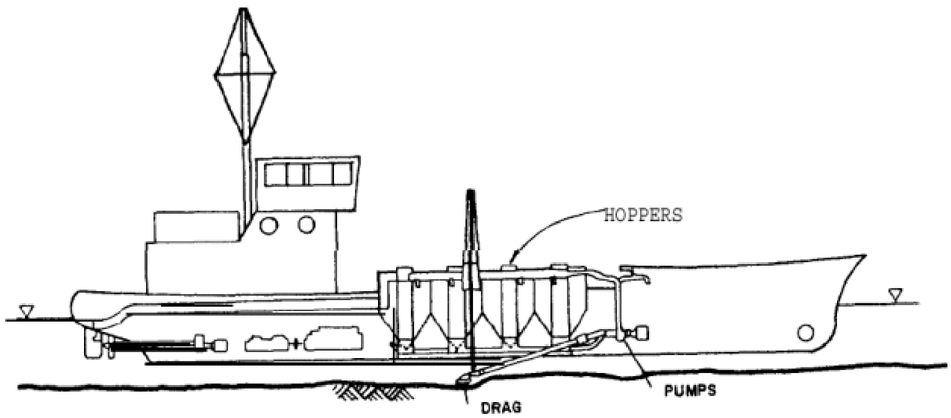


Figure 11. Schematic of hopper dredge. Courtesy of USACE.

The hopper dredge in this simulation is assumed to behave like the Essayons (2,800 cy of solids per full load, for Willamette River dredging). For simplicity, it is assumed that the hopper dredge transits the "dredge reach" within a single load. The hopper digs for 60 minutes per load and contains two drag-heads which remain at the bed. Overflow is released back into the river during the last 45 minutes of each hopper load. After filling the hopper dredge (60 minutes), the hopper travels to the open water disposal site, places its material, and then returns. The roundtrip disposal process requires thirty minutes.

For this study, the suspension rate associated with overflow was estimated by the Hopper Overflow Model. The draghead source was determined based on the Hayes Hopper Model (1997). Utilizing sediment grain size information as well as equipment and operation information, the models produce the following source rates:

Source	Rate	Position in Water column
Overflow	0.48kg/m/s	Distributed over water column
Draghead	0.18kg/m/s	Distributed over width of the draghead

Placement

Placement occurs at an open water disposal site on the Columbia River (Figure 9). Placement sources were modeled using STFATE. STFATE is an USACE sponsored model for representing sediment and/or constituent transport processes during open-water placement from a single scow or hopper dredge. The behavior of the material during placement is assumed to be separated into three phases: convective descent, during which the disposal cloud falls under the influence of gravity and its initial momentum imparted by gravity; dynamic collapse, occurring when the descending cloud either impacts the bottom or arrives at a level of neutral buoyancy where descent is retarded and horizontal spreading dominates; and passive transport-dispersion, commencing when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation. Output from STFATE was formatted into a series of instantaneous releases which PTM utilized as input. Figure 12a shows the placement schedule for both the hopper and clamshell simulations. Noteworthy is the increased length of days for the clamshell case due to lower production rate.

Figure 12b shows the mass distribution of sediment for the Hopper and Clamshell/Scow placement. The amount of sediment in the water column decreases closer to the water surface. After placement impact, a sediment cloud forms near the bed as indicated in the figure. As a large percentage of the sediment is initially close to the bed, under low flow conditions, deposition occurs easily.

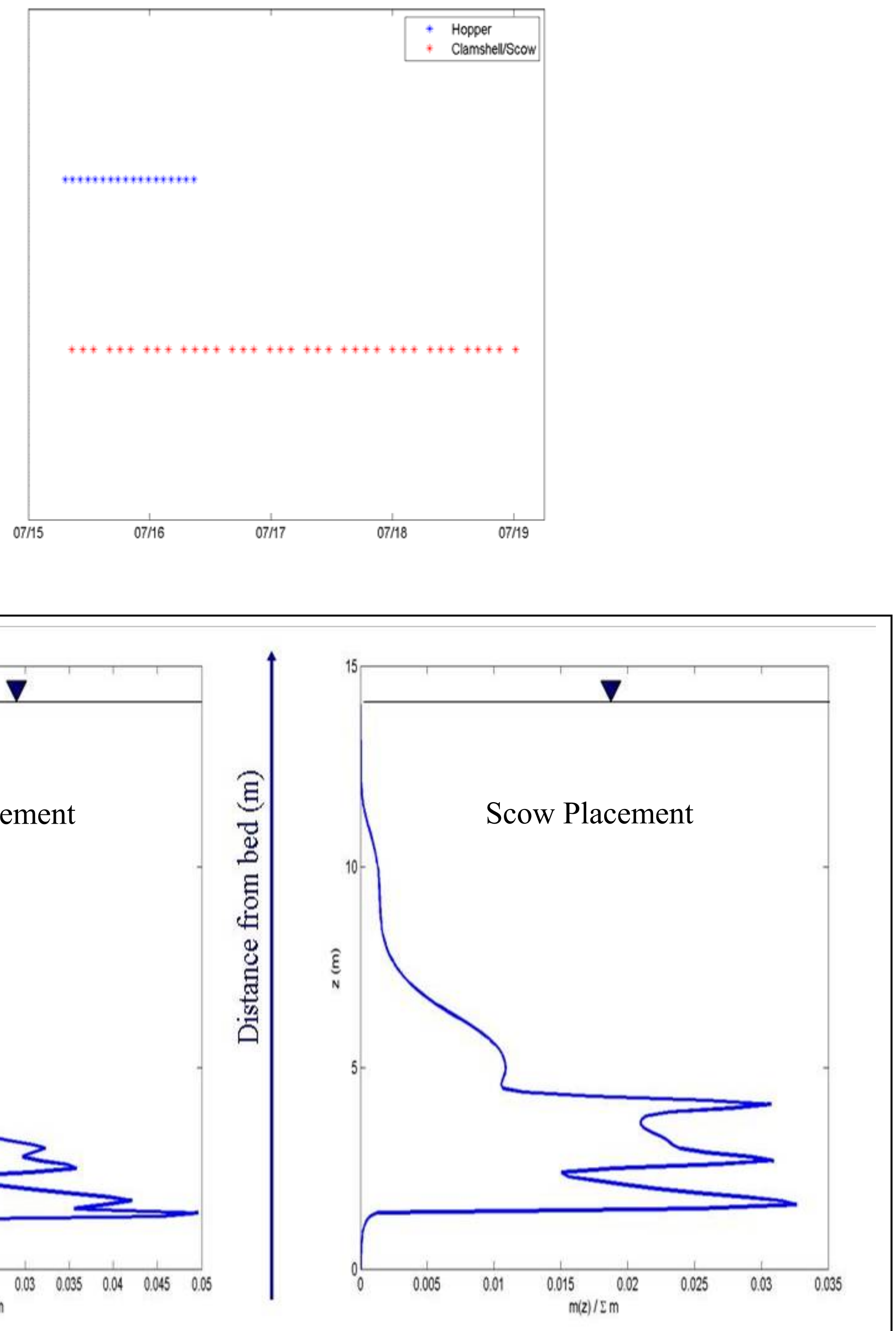
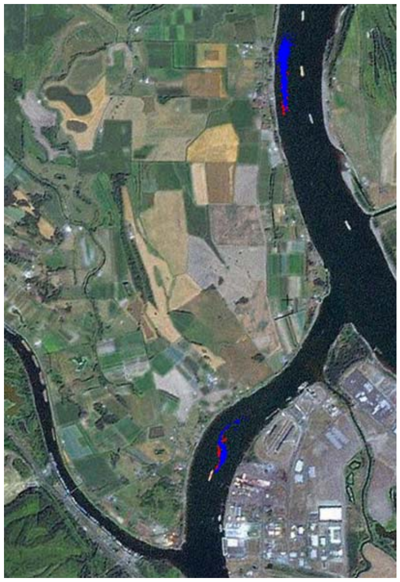


Figure 12. a) Placement schedule for hopper and clamshell/scow b) Mass distribution of sediment over the water column after placement.

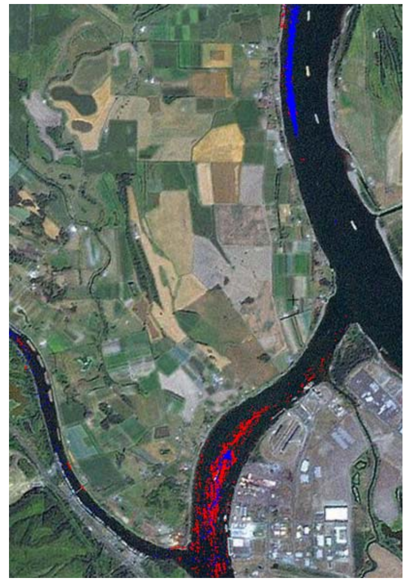
Simulation Results

In Figure 13 the particle positions are shown 3 hrs, 24 hrs, 4 days and 10 days after commencement of dredging. Red particles are resting on the bed and blue particles are actively transporting in suspension. Initially the parcels are transported along the channel in a relatively concentrated streak. Visible also is the initial placement of sediment at the Columbia River. A portion of the sediment quickly deposits. Within 24 hrs, the sediment begins to spread across the channel, and a small percentage of dredged sediment has transported into Multnomah Channel. A large portion of previously suspended sediment has deposited at the dredge site. At this time, sediment is still being introduced into the water column at the dredge site, so a concentration of suspended particles is visible near mile marker two. A thin stream of particles remains suspended at the placement site suggesting that advection due to strong currents is overcoming diffusion in that region. After four days, dredging has almost stopped and almost all of the sediment in the dredging region has deposited within the mile 2-3 region of Willamette or in the Multnomah channel. Most of the sediment placed in the Columbia River has been transported outside of the computational domain. The remaining sediment in the placement region comes from the most recent pass of the scow. After ten days the dredged sediment is primarily resting on the bed. This suggests that the critical shear for erosion has not been maintained long enough for transport out of the area. This is also an indication that some of the sediment has undergone burial. All sediment in the placement area has been transported out of the computational domain in the Columbia River. Due to high velocity flows in that area, shear stress increases accordingly, preventing deposition of sediment. The parcel position visualization indicates an overall tendency of the dredged sediment to move northward towards the Columbia or into Multnomah channel as opposed to further down the Willamette River.

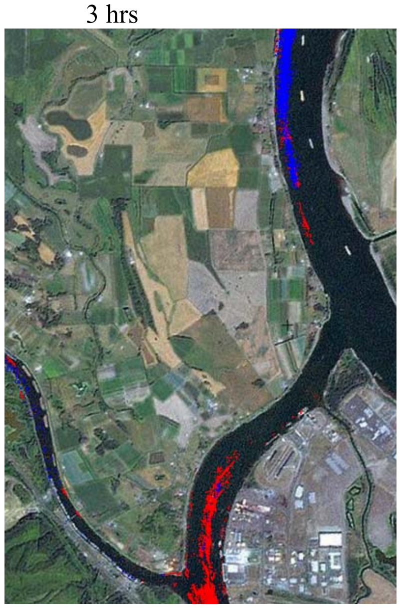
The natural presentation of PTM results are sediment parcel positions (as presented earlier). However, it is also possible to express these results as concentrations. Suspended sediment concentration is estimated by developing a grid (the concentration grid), summing the parcel masses found within a grid cell and dividing by the volume of the cell. Concentration contours are presented in Figure 14 for the 12-hr, 2-day, and 5-day conditions. Concentration is measured in kilograms per meter cubed. Values range from 0 to 0.1. Due to large differentials between the dredging region and the placement region, the maximum values at the placement site are not shown. As the parcels initially enter the water column, the level of sediment concentration is relatively large and focused within a small area. Diffusion and advection processes, combined with settling quickly reduce the concentration levels. The largest concentration values can be seen in placement region. By day five, the sediment concentration is reduced to near zero except along the channel centerline in the dredging area. Sediment in the placement region has been transported outside the computational domain. This region maintains zero concentration after five days.



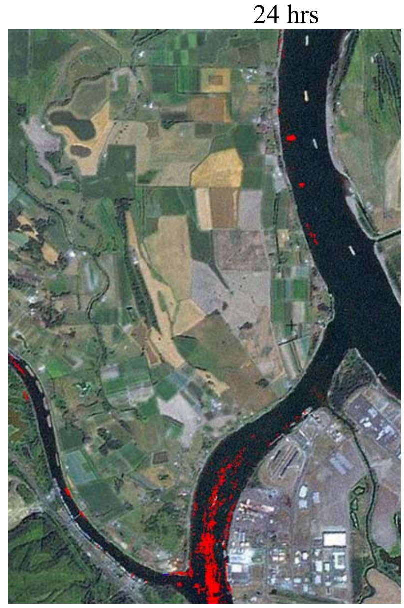
3 hrs



24 hrs

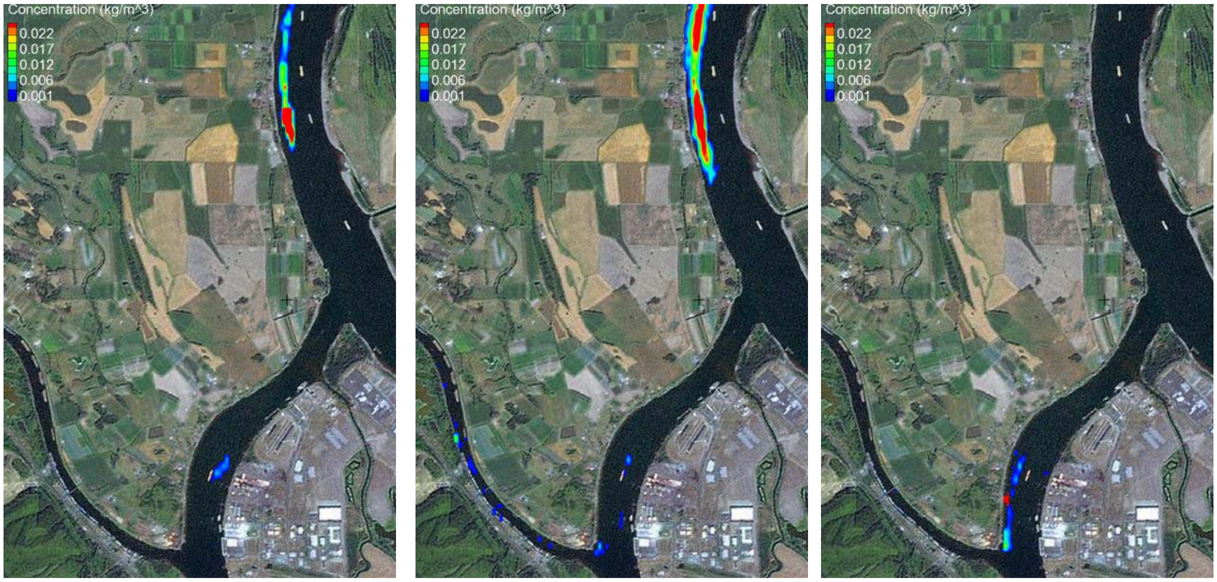


4 days



10 days

Figure 13. Particle positions from clamshell simulation. Blue indicates suspended sediment. Red represents deposited sediment. The yellow square is the initial dredging position.



12 hr 2 days 5 days

Figure 14. Concentration contours for clamshell simulation.

Hopper Dredge

Figure 15a shows a snap shot of the resuspended sediment after three hours. Noticeable is the difference in the parcel positions here as opposed to what is seen in the clamshell dredge simulation. Because the suspended sediment source rates are larger in the hopper case, there is more sediment both in the dredging region and in the placement area. In addition, it can be seen that because the hopper has made two placement trips there are two distinct groupings of sediment suspended in the placement area, whereas the clamshell operation has only made one trip at that time. Figures 15b through 15d display results for the remaining dredging period. These figures are similar to that seen by the clamshell dredge, except a larger amount of sediment is in suspension. Figure 15c shows that dredging and placement are complete by day four, so most of the sediment placed in the Colombia River has been transported downstream. Also interesting is the suspended sediment visible in the dredging region during day five. Since the sediment in the area has initially deposited, it becomes evident that this is sediment that resuspended from the bed due to large currents that flow through the Willamette. Determination of the length of time during which sediment may resuspend is an important factor.

The previous results are supported by the concentration maps seen in Figure 16a and 16b. It is clearly shown that although initially the placement area contained the highest concentrations, within two days the concentration of suspended sediment in the Colombia River has decreased to nothing. Also the concentrations in the dredging area are larger than that of the clamshell simulation as expected.

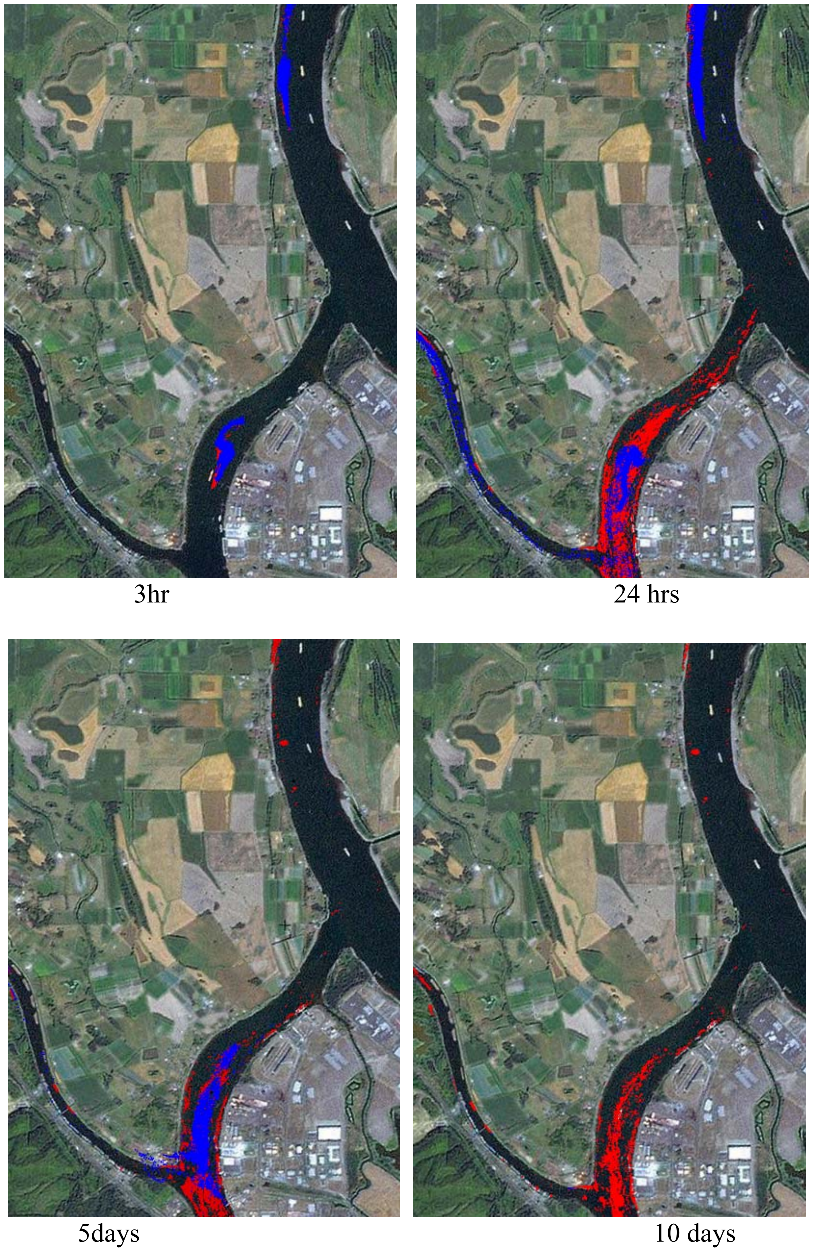
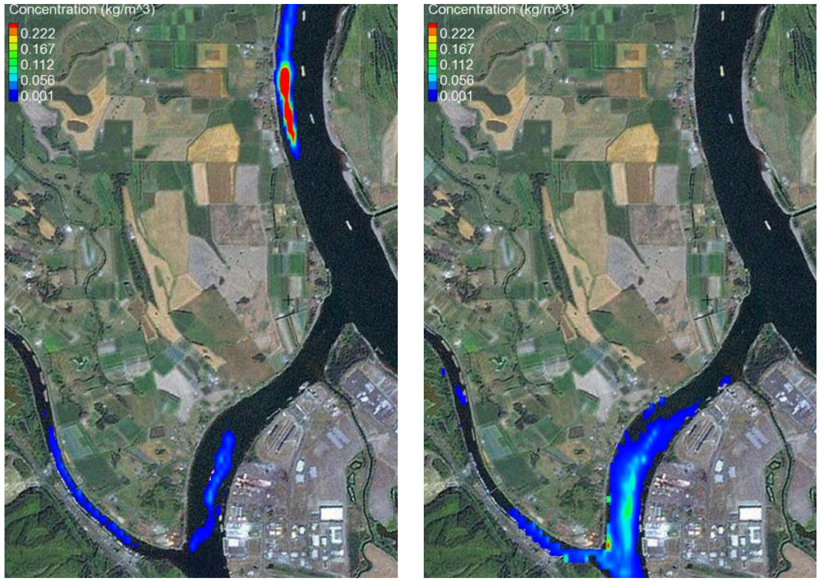


Figure 15. Particle positions for hopper dredge simulation. Blue indicates suspended sediment. Red represents deposited sediment.



6hr 2days

Figure 16. Concentration map (kg/m^3) from hopper dredge

The concentration for both cases appears to fluctuate with time. As particles deposit, the concentration decreases. As they are resuspended by the tidal currents, the concentration increases again. A time series of concentration at a position near the confluence of the Multnomah and Willamette shows this behavior. This position was chosen because of the large values of concentration encountered from the previous concentration mapping in that area. Figure 17 shows in blue and green, the time series of concentration for the Hopper and Clamshell dredges respectively. It is clear that the Hopper dredge produces larger concentrations of suspended sediment. As the hopper dredge operation is complete after less than two days and the clamshell operation is complete within five days, it is evident that many of the peaks following the end of the dredging period are due to resuspension. Both concentration time series decay to zero within seven days.

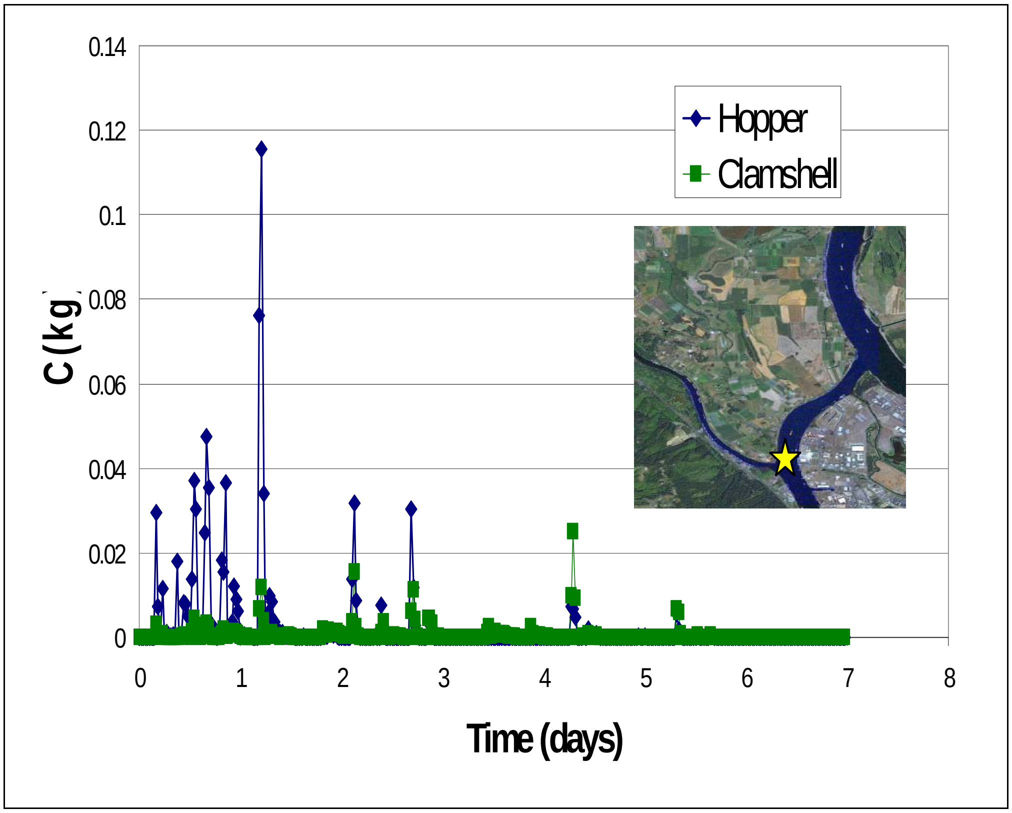


Figure 17. Time series of concentration at a point

Finally, a quantitative comparison of total amount of sediment resuspended due to dredging is shown in the following table. The totally time to dredge 50,000 cy for the clamshell operation is 4 days in comparison to the 1.125 days needed for the hopper simulation. The hopper operation resuspended 2.6% of the total amount of material dredged while the Clamshell only resuspended 0.79%. This suggests that there are some tradeoffs between efficiency and sediment concentration and/or deposition.

	Clamshell	Hopper
Dredging Time	4 days	1.125 days
Total Mass (kg)	15.2 million	15.2 million
Total Resuspended (kg)	40 thousand	120 thousand
% Resuspended	0.79 %	2.6 %

SUMMARY AND CONCLUSIONS

The particle tracking model (PTM) was applied to the study of dredging in the Mile 2-3 region of the Willamette River. Simulations of two dredging operations (clamshell and hopper) to dredge 38,230 cm (50,000 cy) were performed. In this study, placement of dredge material occurs in an open water placement site in the Columbia River. The results indicate that settling and perhaps burial of sediment occurs quickly in the region for both clamshell and hopper dredging, preventing much transport south of river mile 3. Visualization of parcel positions and concentration mapping indicated overall tendency of the sediment to move northward towards the Columbia or into Multnomah channel. Further findings show that in order to dredge the same amount of material, the length of the clamshell operation is significantly longer. However, the hopper dredge with the current rate of overflow provides a larger total mass of resuspended sediment. The largest suspended sediment concentration values occur in the placement region.

Future analysis may include accumulation studies in specific flow regions as well as time series analysis. Dose calculations (the integration of concentration time series) may be useful in future risk assessment work for this project. The next step towards risk assessment of the dredging operation is to determine if the concentration and deposition values are within acceptable levels. Other pertinent information to determine is the cost estimates that result from a longer dredging period. After screening level assessments are complete it is important to discern if additional risk and effects modeling is needed. An assessment of controls such as bucket size, ascent and descent rate, and overflow time will be a key part of the future analysis. Additional future work requires the fate modeling of dissolved particles which have disassociated from the sediment during dredging. The current work focuses on particulate (sediment) transport only. Finally, all of these items must be completed in region 2.

REFERENCES

Demirbilek, Z., Smith, J., Zundel, A., Jones, R., MacDonald, N., and Davies, M. (2004). "Particle Tracking Model (PTM) in the SMS: I. Graphical Interface," *Technical Report DOER-D4*, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, USA.

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," *Technical Report DOER-D5*, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, USA.

Demirbilek, Z., Smith, S. J., Zundel, A. K., Jones, R. D., McDonald, N. J., and Davies, M.E. (2005). "Particle Tracking Model (PTM) in the SMS: III. Tutorial with examples," *Technical Report DOER-D6*, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, USA.

Hayes, D. F., Borrowman, T. D., and Schroeder, P R. (2007) "Process-Based Estimation of Sediment Resuspension Losses During Bucket Dredging" *Proceedings, XVIII World Dredging Congress 2007, WEDA, Lake Buena Vista, Florida, USA.*

Johnson, B. H. 1990. User's Guide for Models of Dredge Material Disposed in Open Water, Technical Report D-90-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lackey, T.C. and MacDonald, N.J. (2007). "The Particle Tracking Model Description and Processes" *Proceedings XVIII World Dredging Congress 2007*, WEDA, Lake Buena Vista, Florida, USA.

MacDonald, N.J., Davies, M.H., Zundel, A.K., Howlett, J.D., Demirbilek, Z., Gailani, J.Z., Lackey, T.C., and Smith, S.J. (2006). "PTM: Particle Tracking Model Report 1: Model Theory, Implementation, and Example Applications" *Technical Report TR-06-02*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi, USA.

ACKNOWLEDGEMENTS

The research presented in this paper was conducted with funding provided by the U.S. Army Engineer District, Portland and the Dredging Operations and Environmental Research Program. Pacific International Engineering is acknowledged for development of PTM.