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Numerical Modelling of Sediment Particle Transportation on a Navigation Inlet Using the Particle Tracking Model (PTM)

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Abstract

This paper investigates particle transportation using a numerical model application approach to understand the final fate of suspended sediment particle masses due to a dredging operation in a navigational harbor inlet using PTM (Particle Tracking Model). The investigation applied PTM and simulated particle transportation at a navigational harbor called St Jerome Creek Inlet in Chesapeake Bay in Maryland. The United States Army Corps of Engineers (USACE), Maryland District, designed jetties for the inlet, which, when constructed, would minimize dredging requirements from once in a two-year period to once in a ten-year period. In the meantime, due to the frequent dredging requirements of the inlet, there exists a need to understand the fate of the suspended sediments from the dredging operations to assess the environmental impact on the aquatic environment and the coastal community. This study used PTM to simulate the transportation of sediments in a 30-day period during a dredging operation. Ten sediment source locations were selected as possible sites from which dredged materials could be introduced into the flow system. The model output was analyzed to draw conclusions. Results showed that most suspended sediment particle masses moved from their initial site locations and settled along the shoreline, whilst the sediments that found their way out of the inlet system towards the ocean migrated southward and settled approximately 6 miles at the tip of the mainland. The objective of the study is to track sediment particles from a dredging operation. This would be significant in tracking possible contaminants in an aquatic environment for future environmental management decisions.

Keywords

PTM, Suspended Sediments, Dredging, Particle Tracking

1. Introduction

This study investigated the final fate of sediment masses from a dredging operation using PTM on the St Jerome Creek navigational inlet. Improving the St Jerome Creek inlet to minimize dredging was studied by the USACE, Maryland District under the Continuing Authorities Program (CAP) of Section 107 of the River and Harbor Act of 1960 [1]. According to the report, the inlet experienced a lot of sedimentation from the longshore currents and as a result, jetties were proposed, and the selected alignment of the jetties would ensure the trapping of sediments and keep the mouth of the channel clear and reduce the dredging need from a 2-year cycle to a 10-year cycle. On most navigational inlets, dredging would be vital to reduce the quantity of sediments as well as contaminants and therefore, the importance of particle tracking cannot be overemphasized. A good example where dredging involves the removal of contaminants is the Hudson River to clean up the polychlorinated biphenyl (PCB) chemical contaminants [2]. According to a report for dredging works by USACE, more than 400 ports and 25,000 miles of navigation channels are dredged throughout the United States [3]. PTM is a numerical model for particle tracking developed by the USACE Engineering Research and Development Council (ERDC). In this study, sediment particle masses were tracked, and the results showed that the sediments would disperse in all directions inside the north and southern bays of the inlets and settle on the shoreline, whilst sediments that escape the inlet into the ocean would migrate southwards towards the inlet of Potomac River 6 miles in the south. This study would pave a good starting point for future environmental investigations by showing the exact areas where water quality tests could concentrate when tracking possible contaminants in an aquatic environment.

2. Literature Review

The PTM model was developed at ERDC several years ago but has been undergoing modernization to transition the model onto a cloud computing environment. Hence, this study was part of test runs done to assess the model's performance on the new cloud computing services. PTM was developed to give a more in-depth and detailed understanding of the movement and final location of suspended dredged particles during a dredging operation. PTM is also used to model the impact of sediments on mounds or designated sites used as storage sites for dredged materials. [4] noted that there are many other models designed to track particles and examples of such models include STFATE, MPFATE and LTFATE. These models were noted to be near field models, meaning that they could only be used to address the effect of placement of dredged material at sites where dredged material was placed and in contrast to that, PTM, however, was designed to model the far-field fate of materials suspended during dredging operations.

2.1. PTM Model

Most sediment transport numerical models use Harmonic series computations and are therefore developed so that the solution to equations is obtained at fixed points in space. However, PTM employs Lagrangian computations for the sediment particles to interpolate the flow and wave conditions. According to [5], two terms, namely, the drift term due to mean flow and a random term due to turbulence normally govern the equations of more recent particle tracking models. In [6], the Lagrangian framework that PTM was built on was described as one in which the sediment masses are modelled by breaking it into discretized particles that move into the flow; hence PTM performs computations that can locate the particles as they move in the flow. The Lagrangian computations are executed faster compared to the Eulerian computations of the other models.

Each sediment particle representing a mass must be defined by its properties, such as specific gravity, grain size, and the initial point of entry or location into the system. PTM employs some mesh-based computations to model particle interactions with the surrounding environment in which they are being simulated. Hence, PTM performs two types of computations. These are the Eulerian computations which are mesh based to determine the characteristics of the environment and then the Lagrangian computations which are particle based to determine the particle behavior. The operation and design of the PTM model are discussed in the model operation sub section.

2.2. Model Operation

PTM requires input data which includes bathymetric information in the form of a mesh that makes up the domain geometry. Further to this, [6] reiterated that that's why PTM was designed to use a 2D ADCIRC mesh which would provide the bathymetry, currents and water levels and STWAVE input data which will contain the wave data. Any hydrodynamic input data that can only be used in PTM is first converted into the ADCIRC + STWAVE data output. Since the hydrodynamic conditions will be imported from an ADCIRC + STWAVE model, the model inputs for ADCIRC are usually in the form of a grid file that has nodes and each node contains information on location coordinates and water levels at that point in the grid system [7].

The components of an ADCIRC simulation start by creating a simulation with specified parameters. An unstructured grid is used in the simulation to model tides and currents that occur in the study area. To accurately predict water level and circulation conditions on any day in the inlet, forcing from tides, wind, rivers, and waves is used into an ADCIRC model onto the unstructured grid (finite elements). Multiple boundary conditions can be specified including periodic wetting and drying. Model parameters are specified including tidal constituents which are then applied to the ADCIRC simulation in an SMS interface.

The unstructured mesh used in an ADCIRC simulation is a grid file called a fort. 14 file which contains the model geometry. This file carries the nodal information which will be the x, y, z coordinate location of each individual node. Data of these nodes can be obtained from the NOAA data viewer website and is continuously updated from time to time. Wind parameters simulated on any day can be obtained from a piece of recorded storm information on the Coastal Hazard Systems (CHS) website and loaded onto the mesh nodes dataset. In the SMS interface, this input data is defined in the fort.13 file and assigned in the model control before running the simulation. Tidal constituents are usually mapped to ocean nodes and are specified during the model control phase.

Data can be linked into the ADCIRC simulation model directly by linking the model to links to the recording stations to input velocity, water elevation and meteorological information. When the ADCIRC+STWAVE model is run, a series of harmonic analysis equations will be performed in the background to calculate and solve for water levels and wave conditions at any given time. The output of an ADCIRC + STWAVE model is a very accurate time series of water circulation. To validate the results obtained from an ADCIRC simulation, measured data can be obtained from NOAA Tides and Currents which is collected from buoys and stations at or near the area of study. This data can be used to compare and validate the ADCIRC output data [4]. It shows an outline of the operation of a particle tracking model as demonstrated [5] (**Figure 1**).

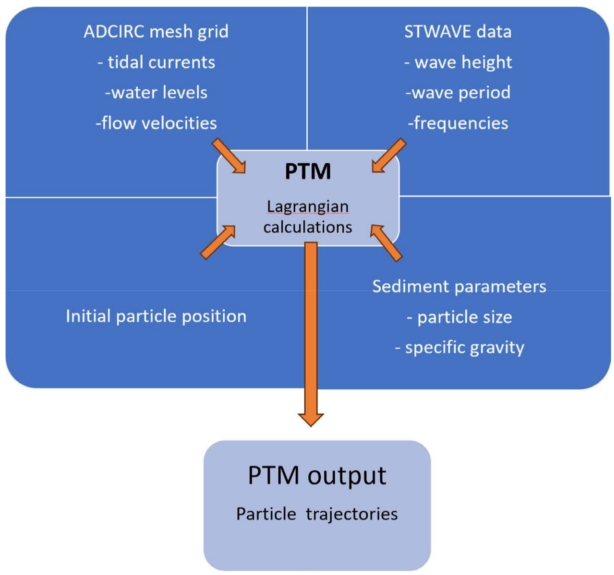

Figure 1. PTM model workflow showing inputs and outputs of the model.

The PTM model is usually run using the Surface Water Modeling System (SMS) developed by Aquaveo. SMS provides the computing environment and a 3D representation of the numerical model and visualization tools of the results. In SMS, the mesh grid can be visualized, and the coordinate projections can be changed depending on the needs of the user. And again, there will be efforts to transition the model into a cloud environment and bolster its capabilities through high performance computing. In the following section, an effort was made to run a PTM model simulation on St Jerome Creek. The simulation was done assuming that the jetties were constructed and installed in place. As a result, the effect of the jetties on the movement of suspended sediments was carefully studied.

3. Methodology

To model the movement and transportation of sediments in St Jerome Creek inlet, input data was prepared, and the location of the particle source was identified. The first step was to have the geometric domain which is the mesh grid from the ADCIRC simulation. Figure 2 below shows the schematic diagram of the steps followed in the simulation exercise.

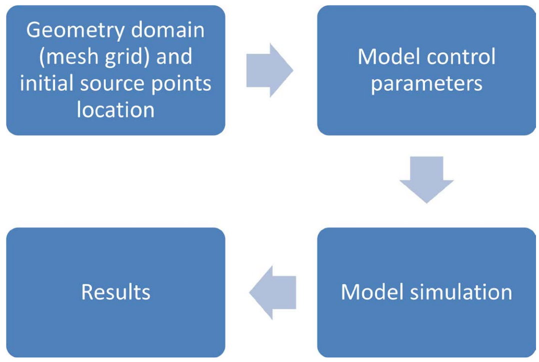

Figure 2. Steps in modelling with PTM.

3.1. Study Area Overview

St Jerome Creek is in St Mary's County in Maryland along the western shore of the Chesapeake Bay between St Jerome Neck and Fresh Pond Neck. The channel at the inlet shoals two years after dredging and this causes problems for navigation vessels through the channel. As a result, during periods of low water levels, the movement of vessels is negatively impacted, leading to economic losses for local boat operators and watermen [8]. According to [9], dredging for maintenance purposes has been conducted once every 10 years due to funding issues. The depth inside the channel must be controlled and the minimum controlling depth is 2ft or less, therefore restricting navigation operations in the channel. To minimize shoaling, two batter pile/vinyl sheet pile jetties held in place by vinyl covered piles at the entrance to St Jerome Creek were proposed [10]. The alignment of the jetties was chosen so that there would be a minimum shoaling rate. Feasibility reports have been prepared and the project is still in the feasibility study phase. Hence, in addition to technical, financial, operational, and environmental studies already done during the planning of the project, this review will investigate how numerical modelling using PTM. Figure 3 shows the details of the study area.

3.2. ADCIRC Mesh Grid

An unstructured mesh grid for the North Atlantic coast was used as the input source of the bathymetry, geometrical domain and the water elevations of

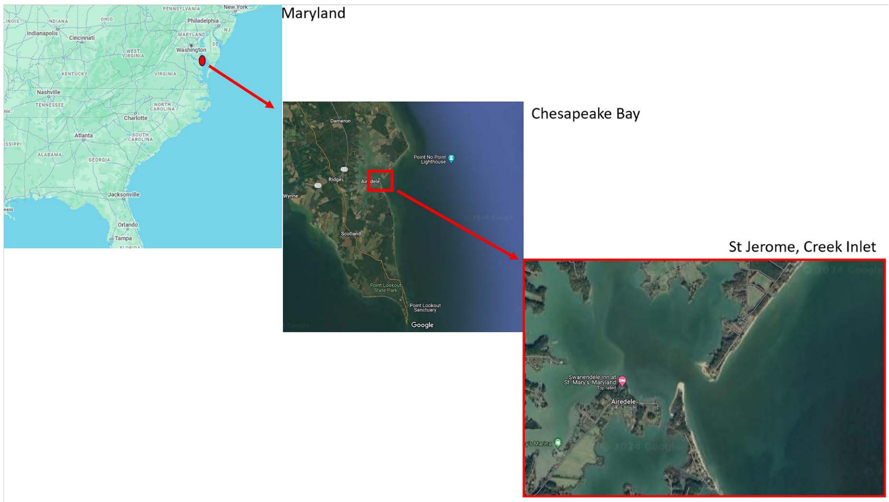

Figure 3. St Jerome Creek in Chesapeake Bay, Maryland [11].

Chesapeake Bay for the period of May 2023. The mesh was edited to reduce the size and create a domain around the study area thus reducing computation time needed for mesh-based calculations. Figure 4 below shows the domain of the ADCIRC mesh for Chesapeake Bay.

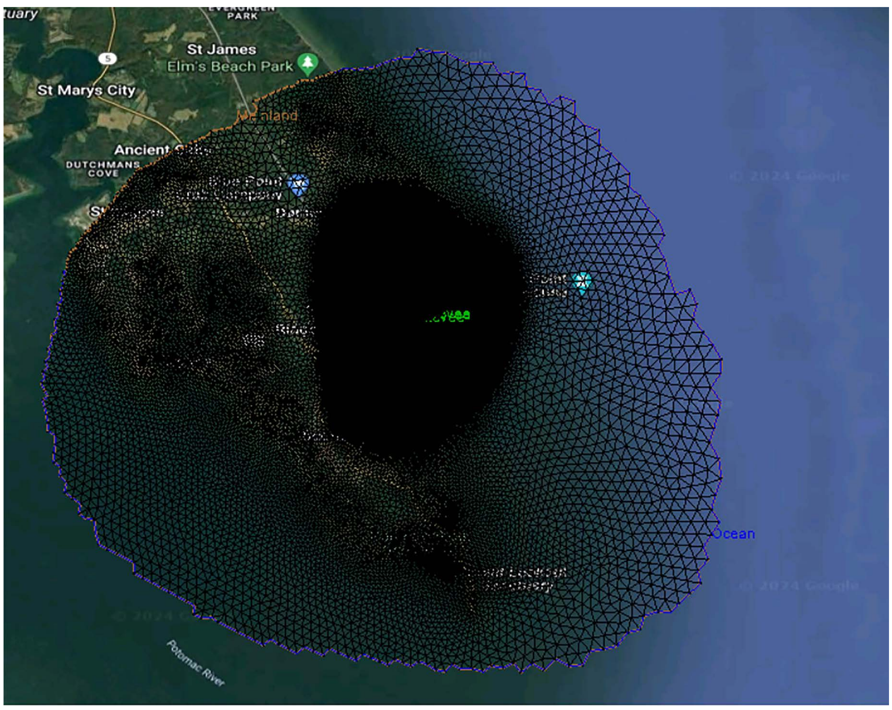

Figure 4. Mesh grid for boundary conditions, water elevations and bathymetry data for the study area [12].

Figure 5 shows the magnified view of the mesh. The outline of the inlet has a better resolution whilst the levees representing the proposed jetties are shown in green lines.

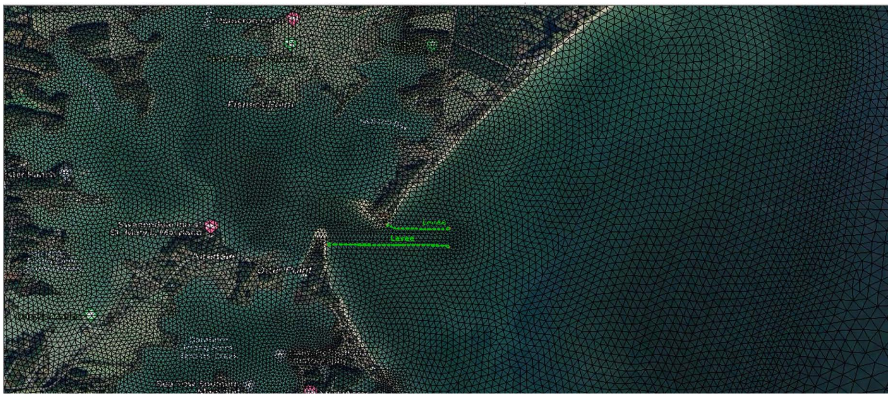

Figure 5. St Jerome Creek mesh grid and levees for the proposed jettiues.

3.3. ADCIRC + STWAVE Data and Boundary Conditions

An ADCIRC model control was prepared by specifying various hydrodynamic conditions and parameters. The simulation was run from the date of 1st of May 2013 to 31st of May 2013. The data was averaged at 30-minute intervals for a simulation period of 30 days. Boundary conditions to the ADCIRC mesh were applied to the simulation as well as the global major tidal constituents. The boundary conditions included the levees that were internal to the domain. After the boundary conditions were assigned to the simulation, an ADCIRC + STWAVE model was run. Figure 6 shows predicted water currents from the ADCIRC + STWAVE model. To introduce sediment sources, 10 location points were selected which represented dredging sites in the north bay and the south bay closer to the navigation inlet.

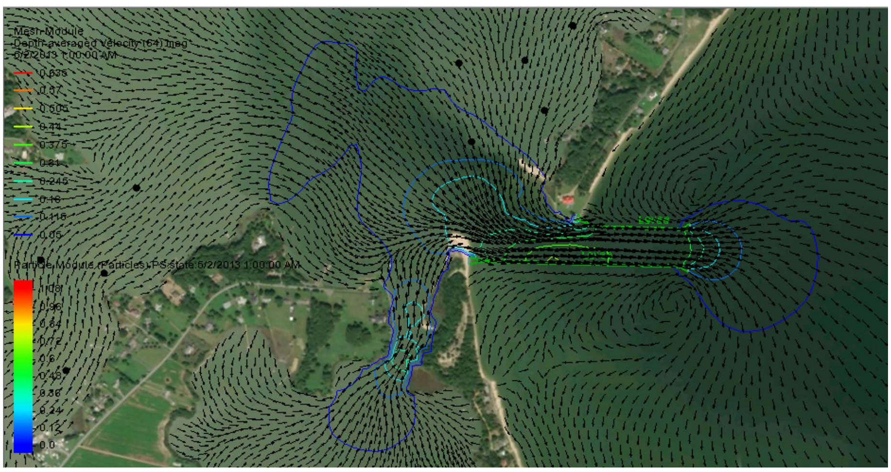

Figure 6. Water curents and sediment source initial location points. The vector contours in colour indicate high velocities inside the levees and lower velocities outside the levees. The black dotted points are the dredging locations and these are the initial location sites for the model from which the sediment masses are introduced into the flow.

3.4. Sediment Parameters

Five locations were selected on the north and on the south bays inside the navigation inlet. These were the locations from which sediments were introduced into the system. For each location, sediment attributes were assigned as shown in Figure 7 below.

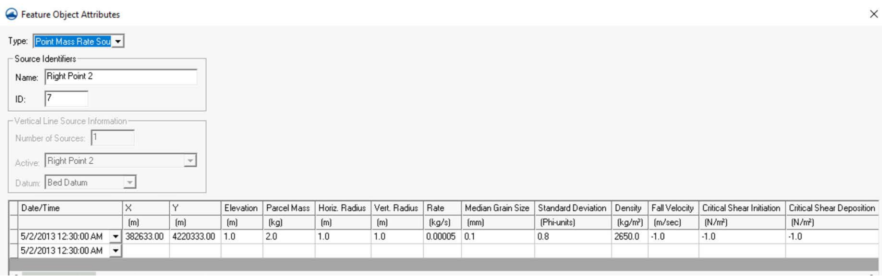

Figure 7. Point source attributes of the sediment mass at each location point.

A median grain size of 0.1 mm was assigned to the sediments with a density of 2650 kg/m^3. The PTM model is based on LaGrangian computations and the parameters for the equations are as shown in Figure 8 below. Eulerian computations would be performed based on the mesh grid data and the model parameters used in the investigation are shown below.

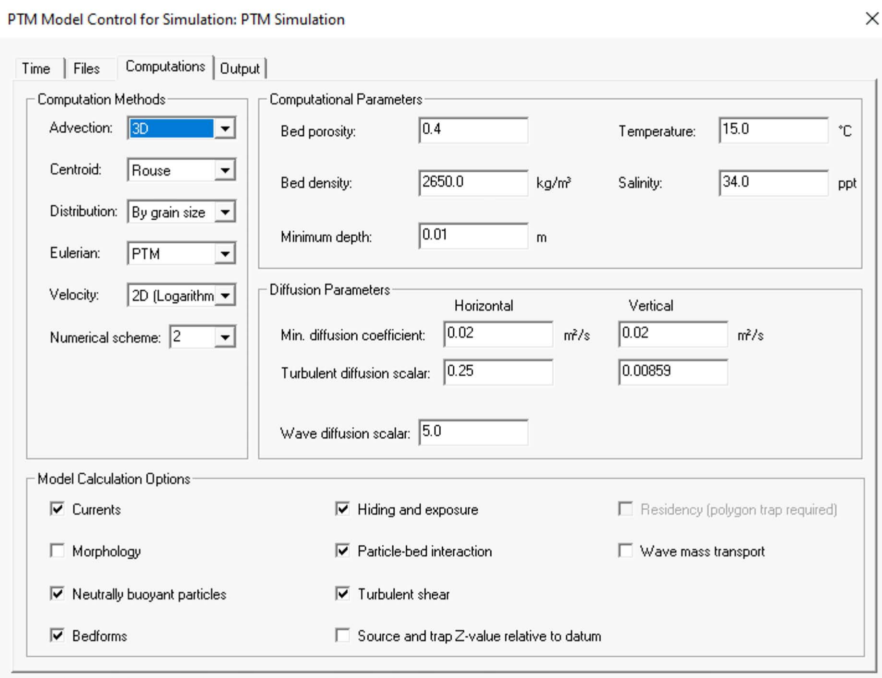

Figure 8. Eulerian and Lagrangian parameter inputs for the model.

The hydrodynamic conditions start time selected was the 1st May 2013 whilst the simulation start time was the 2nd May 2013 so that the simulation could run within the hydrodynamic condition period. The model was set so that every 30 timestep, a particle mass location was tracked and registered in the output. Figure 9 details the timing settings that were used in the model.

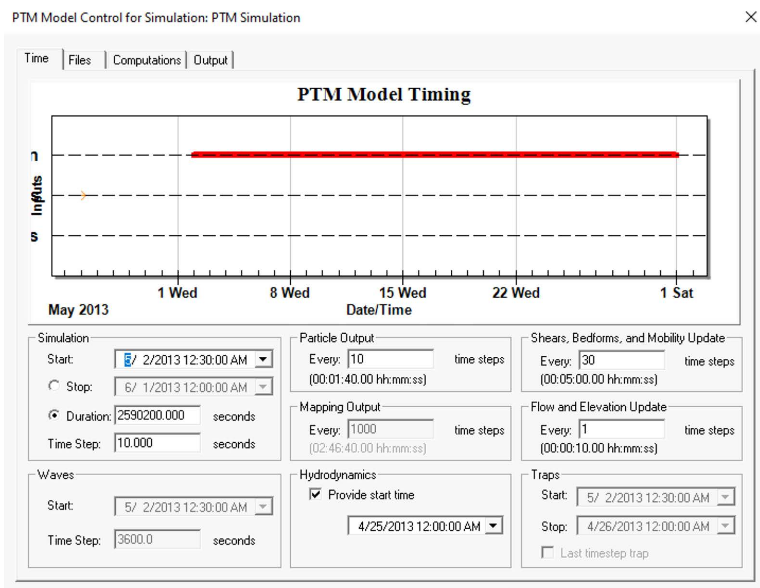

Figure 9. Model simulation timing settings show the simulation start period and particle output timestep.

3.5. Model Calibration and Validation

Validating the model using a fluorescent tracer in Brunswick was detailed in research work by [4]. Four different colors to represent four sediment types were placed at various locations after a dredging operation. The sample tests were repeated four times, and samples were collected and analyzed using a sampling scheme. The objective of the scheme was to determine the fate of the sand or silt which was placed at the top of dredged sand materials stored at various locations during a dredging operation. By collecting samples and analyzing for the presence of the color tracers from different locations in the water system, the findings were compared to the model results in order to validate the model results. The validation process and results indicated that the Particle Tracking Model was appropriate for this application in this review study.

As for the ADCIRC model, it has been used in multiple applications and together with the existence of a mesh for the US east coast on the Atlantic Ocean, this permits an accurate prediction of storm surges. A NOAA tides and currents database exists which contains measured data for tides and currents and water levels as measured by buoys and stations monitored by NOAA [12].

4. Results

Visualizing the results in SMS, trends of sediment mass movement were observed, and this pattern was observed over periods of timesteps of the 1st day, the 5th day, the 10th day, the 20th day and then the 30th day. These were discussed as follows:

Timestep after the first 24hrs.

After a timestep of approximately 24 hrs., the initial movement of the sediment masses would be expected to be observed to commence at depths at the seabed. The model showed dispersion of blue colored particles indicating movement of particle masses at seabed depths. The sediment masses dispersed in all directions from their initial location. Some sediment masses though a few quantities began moving through the channel pf the levees and into the ocean. **Figure 10** shows results observed at a timestep of 24 hrs. of the model results.

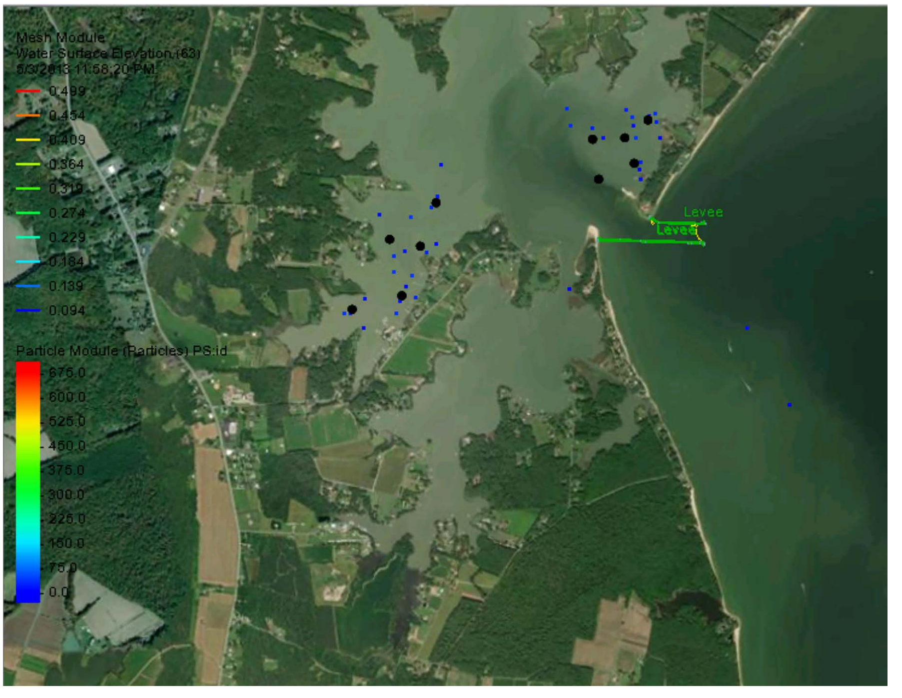

Figure 10. Model results at a timestep on 5/3/2013 at 11:58 pm of the model simulation. Sediment masses have a blue color code showing that movement would occur beginning at the sea bed depths where the dredged materials lies. Agitation of sediments would be caused by the bucket of the dredging equipment.

Timesteps between 2nd *day to* 5th *day*

The model results for timesteps from the 2nd day to the 5th day showed the same pattern of sediment mass movements at the seabed with some noticeable movement of sediment masses up the water depths towards the surface. Most noticeable was the increase in sediment mass movement in all directions from their initial location sites. Movement was still restricted to the bottom depths whilst movement was in different directions. More sediment masses leave the inlet towards the ocean. At the ocean side, the direction of flow of the sediment masses was south ward. **Figure 11** shows the sediment masses distribution between the timesteps.

Timestep between 5th *day to* 10th *day*

Sediment masses could be observed continuing their escapade from the inlet towards the ocean and then moving southward on the ocean side. The sediment masses that stay in the inlet continue to move in all directions and disperse

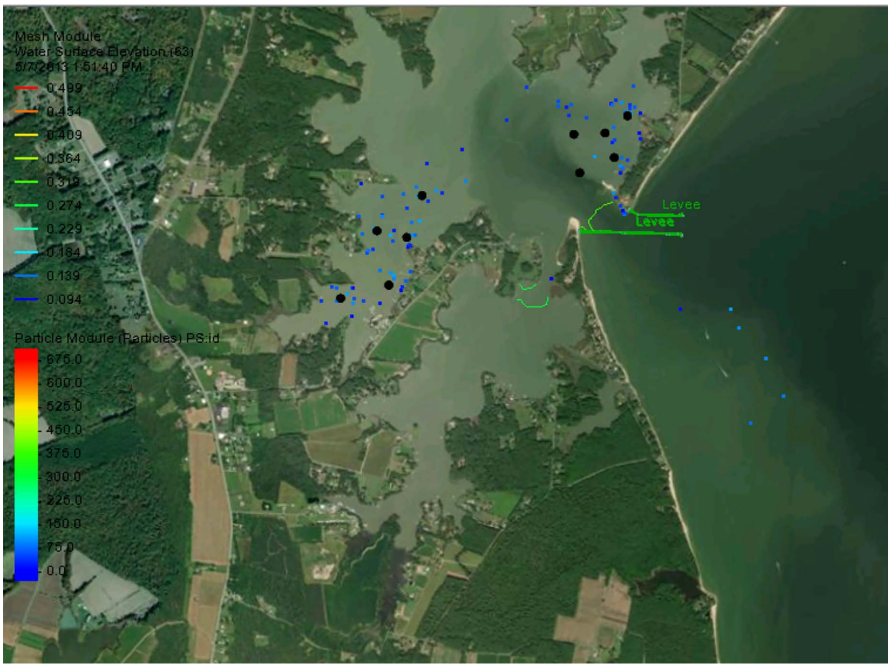

Figure 11. Timestep results after 5 days on 5/7/2013. Sediment masses continue dispersing from their initial location sites in all directions in the inlet. Sediment masses that escape the inlet towards the ocean can be observed to travel in a southward direction. Some sediments begin to flow and rise towards the surface as shown by lighter blue sediment masses.

towards landward of the inlet. More sediment masses show a lighter color code indicating the increased movement of neutrally buoyant sediment masses in the inlet. Most of these sediment masses are transported towards the landward sides of the inlet where they will settle or interact with the ecosystem in those regions. Figure 12 shows the increased movement of the sediment masses at the timestep.

Timestep between 10^{th} *day and* 20^{th} *day*

The model results showed an increased activity in terms of the movement and dispersion of the sediment masses as more and more neutrally buoyant sediment masses flowed at depths closer to the surface thus increasing their mobility. Some sediment masses begin to flow upstream of the inlet towards the estuaries on the north western side of the inlet. In the bay where the sediment masses were agitated during dredging, movement of the sediment in all directions has led to the filing of the bays with sediment masses. On the ocean side, southward movement continues for those sediment masses that escape the inlet. The distribution of the sediment masses is shown in Figure 13.

Timestep between the 20^{th} *and* 30^{th} *day*

Model results at this period showed that sediment masses continued filling the inside bays of the inlet from where they originated, and more sediment masses began to flow on the surface of the water. The final fate of most sediment masses was on the land shoreline as shown by the clustering of sediment masses on the

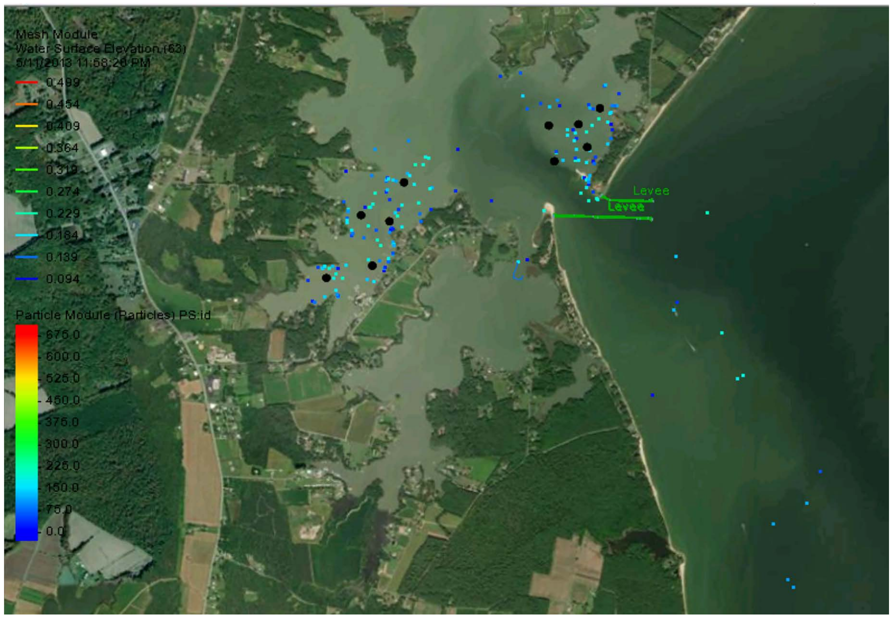

Figure 12. Model results for timestep between 5th day to 10th day. The sediment masses flow and rise from the sea bed towards the surface but they are still restricted to mid depths of the inlet averaged depth. More sediments escape the inlet and travel southward in the ocean.

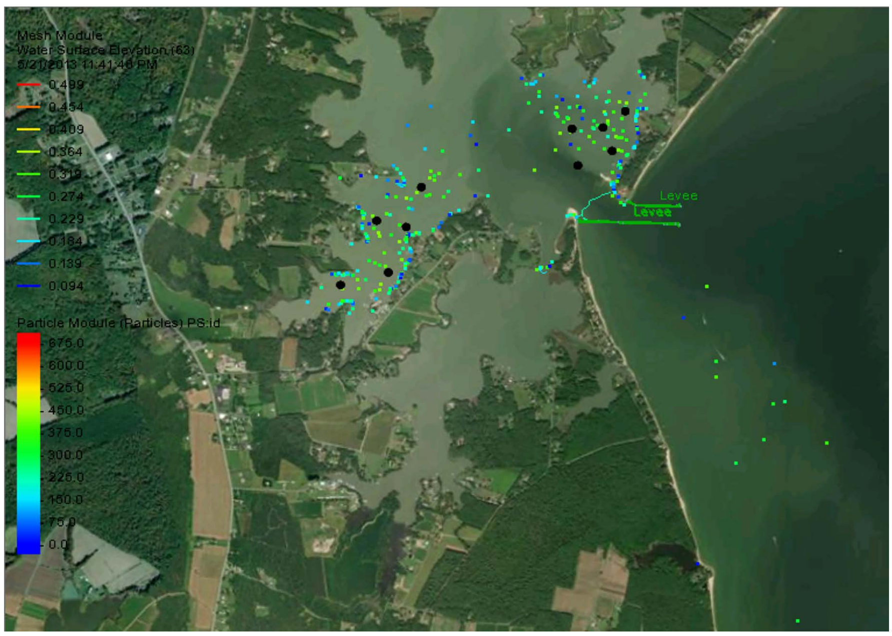

Figure 13. Model results for timesteps between the 10th and the 20th day. Sediment masses continue dispersing and filling the bay whilst the southward movement of sediment masses continues on the ocean side. More sediment masses become neutrally buoyant and are shown in green color indicating flowing in shallower depths compared to the particles in blue color.

land line. The model also showed that most of these sediment masses did not settle to the bottom hence further migration would be possible for periods beyond 30 days. The water quality at this stage would indicate high turbidity as sediment masses occupy almost all levels of the averaged water depth of the inlet. **Figure 14** below shows the model results on the 30th day.

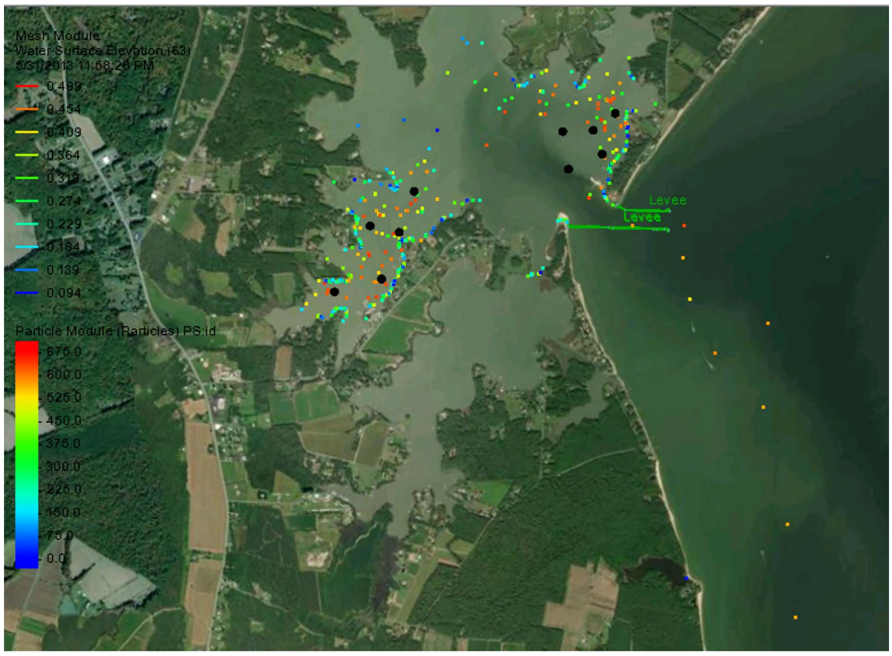

Figure 14. Model results for the timestep on the 30th day of the simulation. Sediment masses with a red color code indicated the flow of sediment at the surface of the water in and around the inlet. Sediment masses could be observed to bind themselves on the shorelines inside the inlet. The southward migration of sediment masses in the ocean side continued as observed in previous steps.

Overall fate of sediment masses after the simulation

The model results showed a pattern of sediment masses transportation in and around the navigation inlet in all directions from the initial location sites. The sediment masses had a tendency to disperse and fill the bay until they reached land shoreline where they were trapped according to the 30-day simulation. A possible explanation for the southward movement of sediment masses on the ocean side could be the attraction of sediment masses to the mouth of Potomac River. The approximate distance travelled by the sediments on the ocean side was 6 miles in the southward direction till the sediment masses reached the mouth of Potomac River. **Figure 15** shows the simulation results at the end of 30 days.

A possible explanation of behavior and characteristics of sediment dispersion and settling towards landward side in the inlet as well as movement in the southward direction could be attributed to the bathymetry of the study area and the hydrodynamics involved. Flood currents could be the reason the sediments were transported towards the landward side. Sediment transport in that region would most likely be caused by waves and tidal currents. As the depth of the water became less and shallower towards the mainland, the currents experienced

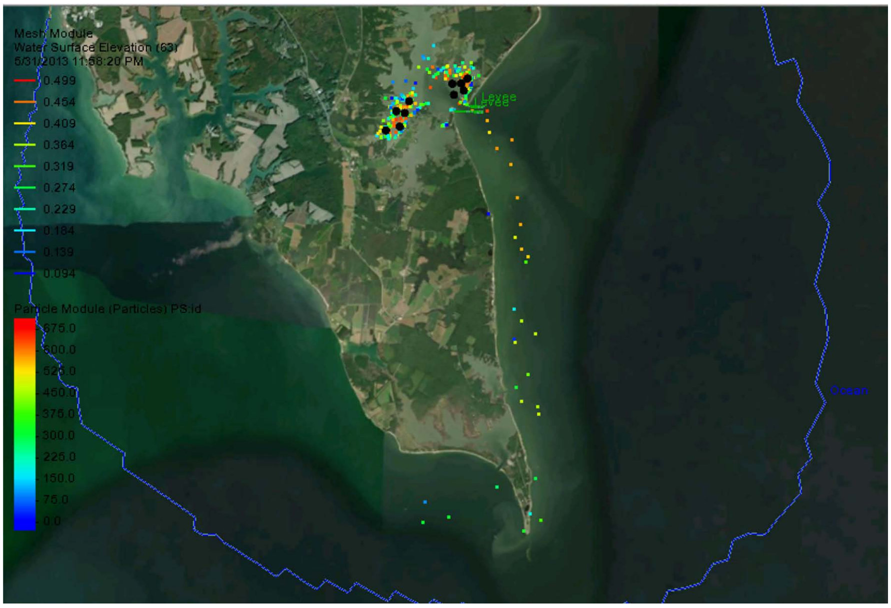

Figure 15. Sedimen masses movement after the 30th day showing migration to the south of sediment masses on the ocean side. When the particle pathlines were activated in the model, the migration to the south could be possibly caused by the flow of currents into Potomac River at the southern tip of the Chesapeake Bay.

bottom friction thus slowing down sediment flow then leading to settling of particle masses. Figure 16 below shows the bathymetry contour lines as well as the currents acting in the inlet.

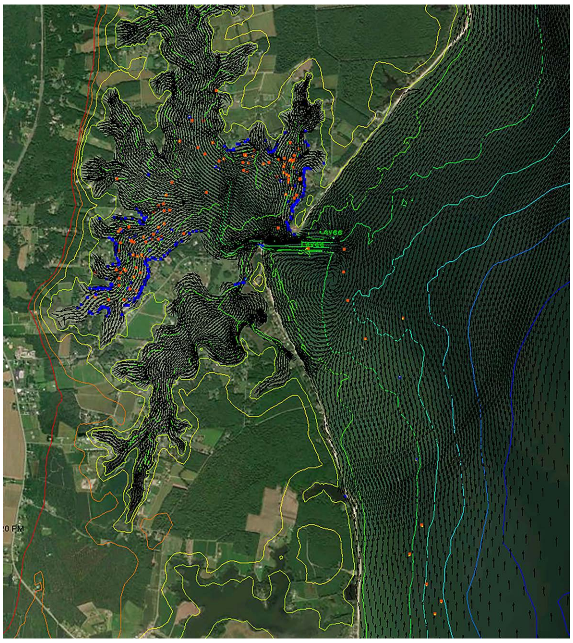

Figure 16. Contour lines showing the general bathymetry landscape of the inlet. The sea bed became shallower towards the land side of the bays in the inlet and more deeper towards the ocean side.

5. Recommendations

The model output shown in the investigation was informative and very significant, showing the predicted fate of suspended sediments due to dredging. This study is enough to give confidence to guide environmentalists during water quality tests by showing hotspots where particles could be trapped and affect the aquatic environments. PTM would reduce costs by directing investigating teams to the exact locations where contaminants could be traced in water in and around any navigational inlet. The accuracy of the bathymetry would need to be continuously updated due to the ever-changing coastal processes. Previous research work by [10] showed that minor differences and errors in ADCIRC could occur if there were inaccuracies in the bathymetry, grid resolution or accuracy of the input wind field. After analyzing the results of this study, PTM can be highly recommended for tracking particles in water and would be a very important tool in saving both the environment and the costs of coastal engineering projects.

Significance of the Study on Navigation Inlets

Particle tracking involves the use of tools either numerical models or physical field measurement techniques to study the transportation of sediments in a flow. Knowing the fate of sediments is very important to managing the aquatic environment, water quality, and the protection of natural habitats. Dredging of navigational channels, rivers and waterways has been an ongoing operation and due to the increased number of inlets, sedimentation rates and sometimes, release of pollutants or contaminants in water systems either in a controlled or by accident, the need for dredging has increased over the years. For instance, the following projects demonstrate the need for particle tracking.

- Scarborough River Inlet

According to Zlatan, approximately over 140,000 cy of sand were removed from the inlet and this project was expected to be completed by mid-March 2024.

- Great Lakes cleanup project in Rouge River near Detroit

Dredging operations for the removal of approximately 70,000 cy of sediments where approximately 35,000 cy of sediments were impacted by polynuclear aromatic hydrocarbons isolated into three engineered caps.

- Hudson River

The Environmental Protection Agency (EPA) has been developing a plan to ensure dredging and management of the Hudson River to clean up the polychlorinated biphenyl (PCB) chemical contaminants in the Hudson River. These contaminants would pose a huge risk to the river environment and everyone in the area if unattended to hence dredging operations would need to be conducted with proper management and monitoring practices in place.

- New Haven Harbor, New England District

Site investigations were reported to be underway for the upcoming improvements to the New Haven Federal Navigation project. As the navigation channel will be widened and deepened, its estimated that 4.32 million cubic yards of material will be dredged from the project.

- Outer Harbor of Holland, Michigan

Hydraulic dredging would be expected to be conducted at a location approximately 1200 feet south of the south breakwater and would be continued for approximately 4500 feet. Approximately 31,000 cy of sediments would be expected to be removed by hydraulic dredging from the inlet [13].

6. Summary and Conclusions

During dredging operations, sediment particles may experience an abrupt large displacement within a short period of time. The perturbations may cause the particles to transition from a very low flow state to an extremely high flow state thus resulting in the movement of the sediments from one location and their deposition to another location.

Sediment particle masses were tracked in a PTM simulation for St Jerome Creek to model and predict the movement and fate of sediment particle masses after a dredging operation. The study assumed that the inlet jetties were fully constructed and completed. Results of the model showed the dispersion of sediments from their initial location towards landward sides where they settled inside the land side. The results also showed southward migration of sediments that left the inlet into the ocean side. These sediments travelled approximately 6 miles and finally settled close to the mouth of the Potomac River south of the inlet. The study concluded that particle tracking provided a very good understanding of the processes and details of sediment transportation during dredging operations so that proper and careful planning can be implemented prior to such activities. However, for the simulation conducted in this study, the recommendation was that validation of results would be highly recommended to compare model results with field measurements. The purpose of the study was to make a simulation using PTM and be able to make a review, having evaluated and analyzed the results and investigated the literature review of the particle tracking model.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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