TRANSPORT OF RESUSPENDED DREDGED SEDIMENT NEAR CORAL REEFS AT APRA HARBOR, GUAM

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Model studies have been conducted to investigate the potential coral reef exposure from proposed dredging associated with development of a new deepwater wharf in outer Apra Harbor, Guam. The Particle Tracking Model (PTM) was applied to quantify the exposure of coral reefs to material suspended by the dredging operations at proposed sites. Key PTM features include the flexible capability of continuous multiple releases of sediment parcels, control of parcel/substrate interaction, and the ability to track vast numbers of parcels efficiently. This flexibility has allowed for model simulation of the combined effects of sediment release from clamshell dredging, of chiseling to fracture limestone blocks, of silt curtains, and of flocculation. Because the rate of material released into the water column by some of the processes is not well understood or *a priori* known, the modeling protocol was to bracket parameters within reasonable ranges to produce a suite of potential results from multiple model runs. Data analysis results include mapping the time histories and the maximum values of suspended sediment concentration and deposition rate. Following exposure modeling, the next phase of the analysis has been an ecological assessment to translate the PTM exposure level predictions into predicted amounts of coral reef damage. The level of potential coral reef impact will be an important component of the final selection process for the new deepwater berthing site.

INTRODUCTION

Determining the fate of sediment introduced to the water column due to manmade sources (construction, dredging, etc), near environmentally sensitive receptors (habitat, species, etc) is an engineering problem that has become increasingly relevant. Environmental resource agencies need to understand before projects are approved, the impact exposure to the resuspended sediment will have on the receptors. In this study, alternatives for the construction of a new deep water wharf at Apra Harbor, Guam (Figure 1) to provide a berthing site for transient nuclear powered aircraft carriers (CVN) are investigated. Development of a site would involve dredging at the wharf location and additional dredging to provide a turning basin and access fairway. A major concern is the fate of the sediment resuspended during dredging. Two of the sites that are under consideration for construction are Polaris Point (Figure 2) and Ship Repair Facility (Figure 3). These sites are adjacent to large, diverse coral reefs, and there are concerns about the impacts of dredging upon the coral. Figures 2 and 3 show the navigation footprints for the Polaris Point and Ship Repair Facility options respectively. For each option, the region in green shows major areas of adjacent shallow, highly diverse coral reefs. Hashed areas depict regions that must be dredged to a depth of -51.5ft.

The Naval Facilities and Engineering Command Pacific (NAVFAC PAC) has requested ERDC assistance with determining the fate of resuspended dredged sediment during dredging operations for the Apra Harbor port development. This resuspended material may temporarily increase turbidity during and after the dredging operation. In addition, this material is transported by currents and will eventually deposit. Suspended solids-induced turbidity and sedimentation have the potential to adversely impact the diverse coral formations in Apra Harbor. ERDC is using the Particle Tracking Model (PTM) to quantify the fate of dredged material released during the harbor expansion project to accommodate CVN. The results of this modeling effort will quantify exposure of the nearby coral reefs to turbidity and sedimentation. These exposure assessments are a critical component in risk analysis.

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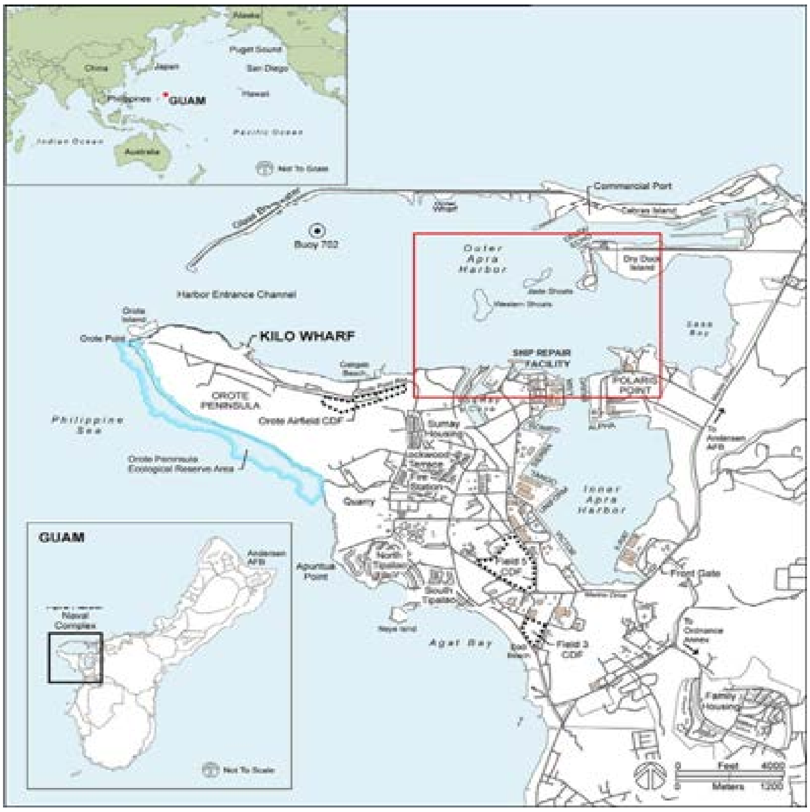

Figure 1 Site Location map.

Key features of PTM are the ability to simulate dredge sources and dredge controls. These features support risk evaluation for dredging operations and risk reduction introduced through controls. Control measures simulated using PTM include silt curtains and dredging rates.

The purpose of this paper is to describe the methods used to simulate sediment transport near coral reefs as well as the strategy developed to assess the impact of resuspended dredged sediment to the area of interest. To this end, data analysis results are shown in the form of total accumulation, deposition rate, and suspended sediment concentration due to the proposed dredging operations.

The exposure estimated due to the sediment transport is the first part of the overall goal of the project. The outcome of this analysis are utilized by coral reef biologists who then add effects assessments to help determine overall risk to the coral due to the dredging operations. This assessment will provide additional support to NAVFAC PAC in choosing a berthing site.

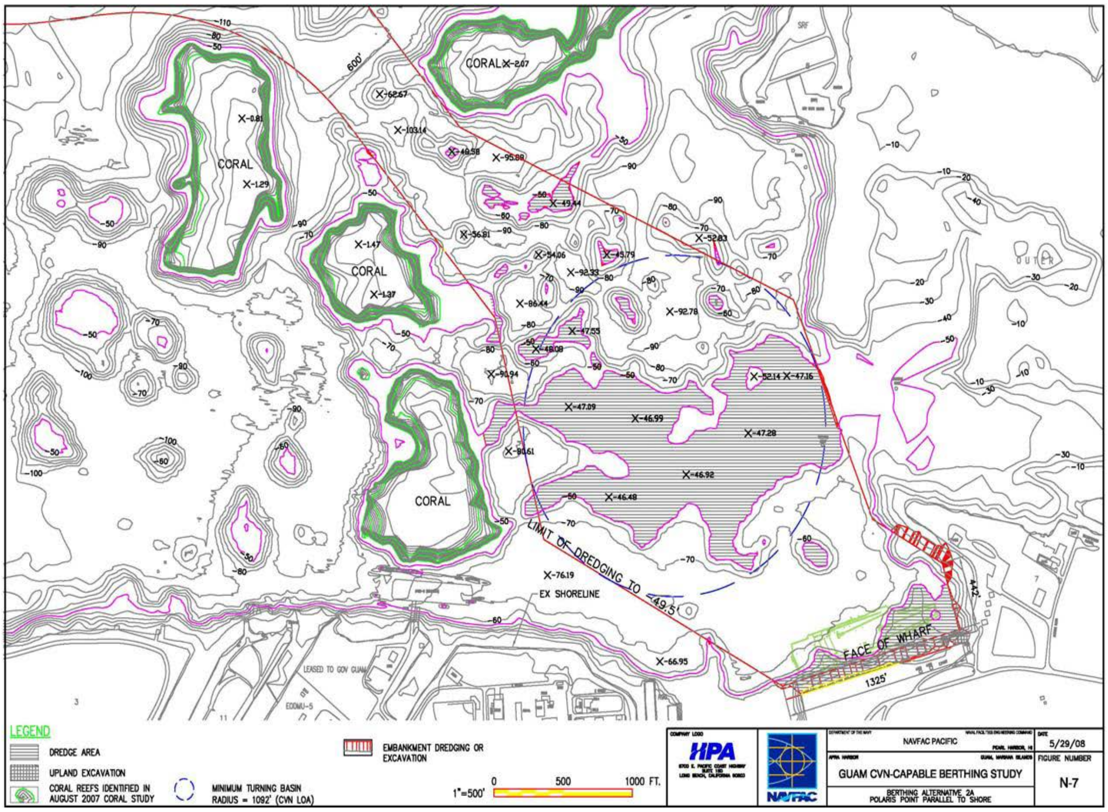

Figure 2. Polaris Point Navigation Footprint.

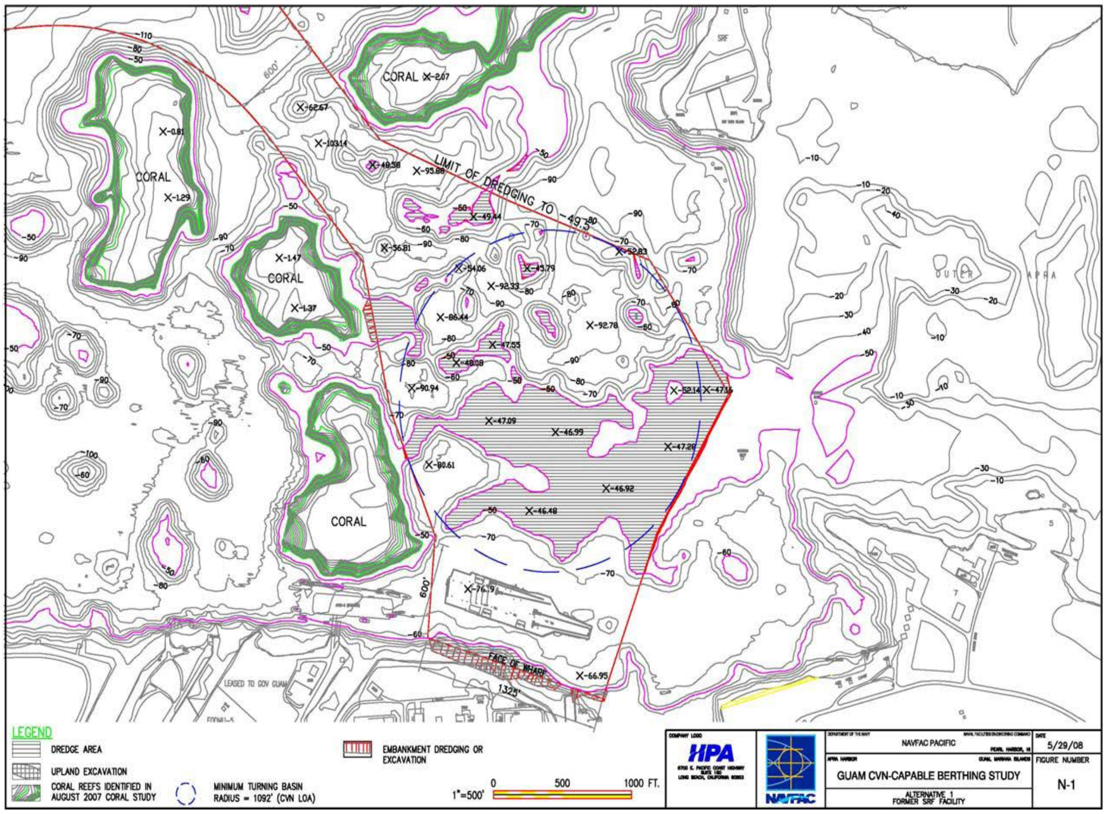

Figure 3. Ship Repair Facility Navigation Footprint.

METHOD

The Particle Tracking Model (PTM) is a US Army Corps of Engineers-developed, Lagrangian model designed specifically to track the fate of suspended sediments and other constituents released from specific sources such as dredges, placement sites, outfalls, etc. in complex hydrodynamic and wave environments. Though the most common application has been for dredging activities, the model has also been successfully applied in other ways, such as tracking the dispersion of fish larva, dissolved contaminants, etc. This paper describes the application in a tropical coral reef environment.

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. 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, sediment is discretized into “parcels”. Each parcel is representative of a specific mass of sediment. These parcels preserve the overall size distribution and total mass of the sediment source. The model then steps through time tracking the position of each parcel. PTM output includes 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.

Particle settling parameters may be user-defined or determined by algorithms based on verified theoretical and empirical relationships. For this application, particle size and density are used to define settling. PTM also includes particle interaction with native sediments and the potential for resuspension. Resuspension potential is based on known parcel sediment characteristics, native bed sediment characteristics, and water column processes (McDonald et al., 2006). PTM includes probabilistic methods to account for burial, hiding, etc. Resuspension of sediment deposited on complex coral reefs is poorly understood. Coral reefs include craggy surfaces with numerous crevices to trap sediment. For this reason and because of the low current velocities at this site, for this application, the model assumes that all particles which fall below a pre-defined level (2 cm away from the bed) are deposited and are not allowed to resuspend. This provides a conservative estimate of sedimentation and is considered a reasonable assumption in the absence of additional process data.

PTM employs both Eulerian and Lagrangian frameworks. Eulerian calculations are carried out over the entire domain and thus dependent on the grid sizes. Eulerian calculations are mostly at sediment-water interface through bedform, bed shear and mobility, transport potential, and transport rates. In the Lagrangian framework, the waterborne constituent being modeled is represented as a finite number of discrete particles that are tracked as they are transported by the flow. Major advantages of a Lagrangian approach over the traditional Eulerian approach are computational efficiency and the visualization. The Lagrangian calculations include local flows, mobility of a particle, and trajectory calculations. Thus the Lagrangian approach provides diffusion and advection processes accurately and efficiently calculates particle pathways so that sources and destinations of particles are easily identified.

Like most Lagrangian particle trackers, all transport is in the reference frame of the particle, ultimately solving a classic system of equations:

$$\frac{d\vec{\mathbf{x}}}{dt} = \vec{\mathbf{u}} \qquad (1)$$

In this system, x is the particle position vector x=(x,y,z) and u is the flow field velocity vector u=(u,v,w). Numerically this system of equations can be discretely solved as:

$$\mathbf{x}^{n+1} = \mathbf{x}^{n} + \Delta t \vec{\mathbf{u}}^{n} \qquad (2)$$

where n is the timestep.

For sediment transport performed utilizing PTM, the equation becomes more complex:

$$\mathbf{x}^{n+1} = \mathbf{x}^{n} + \Delta t \mathbf{F}^{n} \qquad (3)$$

where F is a function of the flow field velocity, diffusion, settling, and multiple other sediment transport processes (McDonald et al 2006). Integration of particles forward in time is performed using a Runge-Kutta scheme. Users are given the choice between 2nd or 4th order Runge-Kutta schemes. PTM estimates diffusion through turbulent diffusion coefficient, E_t,

$$E_t = K_{E_t} h u_*^n \qquad (4)$$

Here, K_{Et} is an empirical coefficient which relates E_t to water depth, h, and shear velocity, u*. Diffusive transport velocity, $u_{D,}$ is determined from

$$u_D = 2(\Pi - 0.5)\sqrt{\frac{6E_t}{dt}} \qquad (5)$$

Here, $\prod$ is a random number between -1 and 1.

MODEL INPUT

Release Protocols

The rate at which dredge-induced suspended material will be introduced into the water column at Apra Harbor is a function of many parameters, several of which are the still being studied. To model this quantity, reasonable estimates had to be made for the dredging production rate, the suspended sediment loss rate, and the distribution of the losses within the water column and the effects of a silt curtain. Based upon the assumption that a clamshell dredge would be employed that was similar to previous recent dredging activities within Apra Harbor, two dredging production rates, 1800 cubic yards per day and 1110 cubic yards per day (assuming 24 hours of dredging per day) were chosen. The higher value was based upon typical maximum production rates from dredging events in the vicinity of Alpha and Bravo wharfs (Mr. Donald Murata, personal communication, 2010), at Kilo Wharf (Sea Engineering 2010), and from previously modeled values (Sea Engineering 2009). While dredging logs show that this production value can be frequently reached on some days, entire dredging operation production rates are typically much lower, due to “down-time” events. However, using this production rate for the entire simulation was expected to produce the maximum sediment concentrations in sensitive areas. For a production rate of 1800 cubic yards per day, the Polaris Point dredging footprint could be dredged in slightly longer than 11 months, assuming constant dredging. It would take approximately 18 months for the Polaris Point dredging footprint to be completely dredged at a production rate of 1,110 cubic yard per day. The lower production rate is a more likely achievable long-term production rate.

The percent of the dredge material lost or released during the clamshell dredging process was also required. Loss rates typically average less than 1% (Hayes and Wu 2001; Hayes et al. 2007; Bridges et al. 2008). A 2% loss rate was chosen as a maximum loss rate value, and a 1% rate was also modeled to conservatively represent a more average value.

This material is introduced into the water column at the bottom as the clamshell bucket picks up a load, while the bucket is ascending to the surface, and at the surface while the material is being transferred to a barge or other holding facility. A conservative estimate is that 40% is introduced near the bottom, 30% within the water column, and 30% near the surface.

A silt curtain is expected to be used during dredging operations to reduce the suspended sediment load. Silt curtains are typically deployed with a gap at the bottom to reduce the current drag. A 3 meter bottom gap was conservatively chosen for modeling purposes. Curtains are typically porous to reduce drag. Therefore, the curtain permits some water and possibly a small portion of the finest sediments to pass through. Two silt curtain conditions were modeled, one that was 90% effective in stopping the finest material from passing (along with all of the coarser material), and a curtain that was 100% effective at stopping sediment passage (USACE 2005).

The anticipated total dredge volume is approximately 608,000 yds^3 for the Polaris Point alternative and 479,000 yds^3 for the Ship Repair Facility alternative. For modeling purposes it is assumed that when dredging was completed at a site, it began immediately at the next site. Dredge site modeling generally proceeded from north to south.

Dredging Scenarios

Multiple dredging scenarios were modeled in this study for each of the two sites (Polaris Point and Ship Repair Facility). Presented in Table 1 are cases 1 through 4. Case 1 represents the “maximum” case. This case provides the higher production rate and the larger loss term. Case 4 represents a “minimum” case. The remaining cases are some combination of the parameters that fall in the middle.

Table 1. Case Descriptions.

Case	Production Rate (yd^3/day)	Dredge Time (months)	% Loss	Silt Curtain Efficiency
1	1800	12	2	90%
2	1110	18	2	90%
3	1800	12	1	100%
4	1110	18	1	100%

Bathymetry

For this study, a curvilinear grid in the horizontal plane was generated for the CH3D-Z model. In the horizontal domain, 167 by 97 quadrilateral grid cells were generated. The resolution varies between approximately 30 m in the vicinity of the navigation channel (including the coral reefs defined in Figures 2 and 3 and 200 m west of the area of interest. The vertical grid is in the z-plane and has increments of 2 m. The maximum depth was set as 56 m, corresponding to 28 layers. Figure 4 shows the extent of the grid. The colors represent depths. Bathymetric data from various sources were gridded at 2 m, 10 m, and 20 m resolutions to compile a final, comprehensive bathymetry for the site. In addition, NOAA ENC (electronic nautical chart) digital sounding data were utilized. The available data for each grid cell were averaged. The elevation values were then rounded to the nearest 2 m (resolution of the z-grid). The distribution of corals was also considered.

The simulation covers a three month period between 11/1/2007 and 1/31/2008. This 3-month period coincides with the ADCP deployment period by TEC, Inc. (Sea Engineering, 2009) when field data could be used for model calibration. The major driving forces are the water surface elevations at the entrance of the harbor and surface wind. The source of the water level information is the NOAA tide gage at Apra Harbor (ID 1630000) (Latitude: 13° 26.3' N Longitude: 144° 39.2' E). The tide has both diurnal and semi-diurnal constituents. For wind forcing, the first 2 months between 11/1/2007 and 12/31/2007 is from Apra Harbor and the 1 month period in 2008 January is from the Guam Airport. The dominant wind direction is westerly (180°). The model time step was 10s.

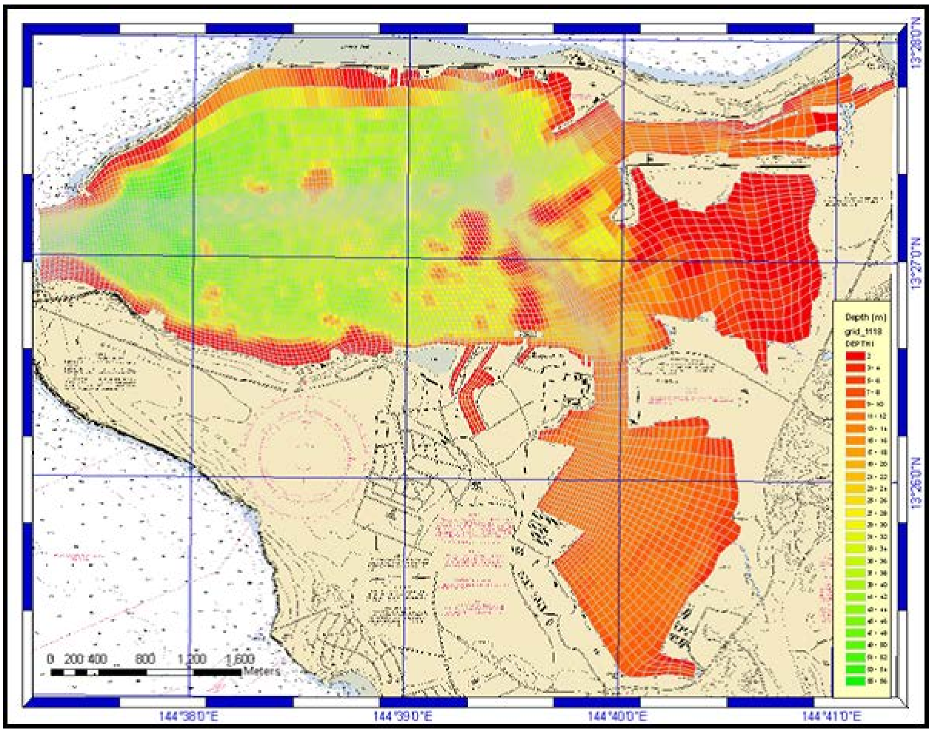

Figure 4. Model grid shown with water depths.

Sediment Characteristics

Four sets of sediment samples have been collected in the vicinity of the project area. These have been analyzed to determine their sediment size distributions. To appropriately model the behavior of the fine material, the average curves were then separated into sand, silt, and clay fractions. The median and standard deviation values were then calculated for these three subsets. These values were used as inputs to the PTM model. Grain sizes for the silt and clay fractions closely bracket the measured suspended sediment grain size values observed during the recent dredging at Kilo Wharf (Sea Engineering, 2010).

The majority of sediment in Apra Harbor is biologically derived carbonate material. These sands exhibit a wide range of densities, depending on conditions. For this study, a typical value found in the literature (King and Galvin, 2002) of 2800 kg/m^3 was used for all simulations.

Table 2. Percent Sediment Size Fractions.

Sediment	Turning Basin	Polaris Point	Ship Repair
% sand	65.1	75.6	72.3
% silt	23.8	14.5	13.7
% clay	11.1	9.9	14.1
% fines	34.9	24.4	27.7

RESULTS

The PTM provides time dependent particle positions as output. These data were used to determine particle pathways and study general sediment movement. This paper presents three types of maps which were developed for data analysis. For this project, it was determined that Concentration Maps, Accumulation Maps, and Rate of Deposition Maps could be utilized to provide useful information to help determine exposure. Data analysis tables were created to summarize results from the maps.

Cartesian Grid Mapping Technique

Grid mapping was performed using the Surface Water Modeling System (Zundel, 2005). Grid mapping was used to quantify accumulation (sedimentation), concentration (total suspended solids), and rate of deposition maps. As stated previously, PTM utilizes a finite element mesh (Figure 5, black) for particle tracking of the sediment. Output includes time dependent particle positions. Each particle is representative of a designated mass of sediment. The particles retain relevant data, including grain size, mass, density, etc. The data is post-processed to create maps contour maps of relevant data, such as concentration. A Cartesian grid (Figure 5, shown in blue) is placed within the area of interest. At every timestep, particles located within a grid cell are used to calculate deposition, concentration, and accumulation for that grid cell. The resulting values within the grid can be used to create contoured maps of the properties. For this work each grid cell is 60m X 60m and the total area of the grid is approximately 2.5 million meters squared.

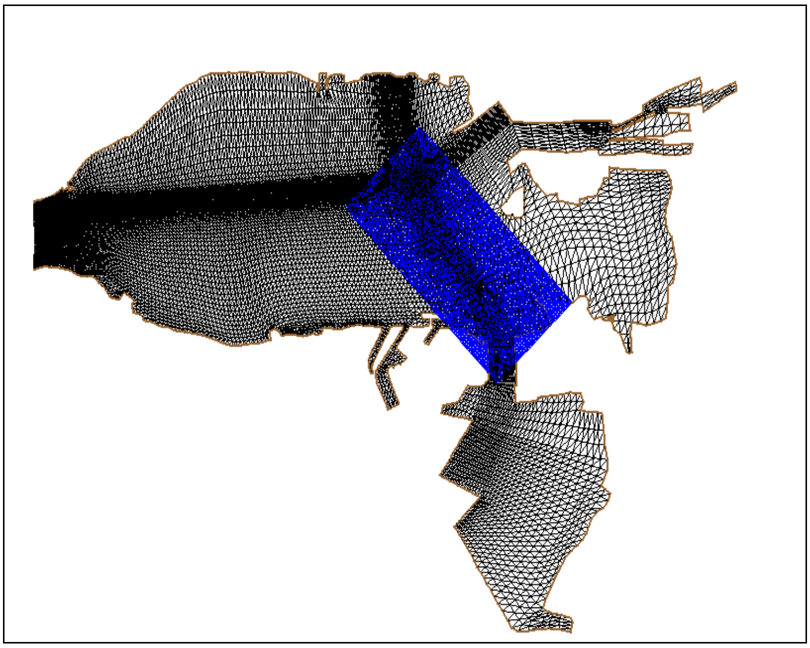

Figure 5. PTM finite element mesh (black) with Data analysis Cartesian grid (blue).

Total Accumulation

Figure 6 shows the total accumulation from the Polaris Point and Ship Repair Facility dredge footprints for the Case 1 conditions. These maps represent the total accumulation of sediment within an area due to deposition of resuspended dredged material at the end of the dredging project. In Case 1, this means the accumulation is over an approximately one year period. The values shown on the map range from 5g/cm^2 (red) to 0.05g/cm^2 (blue). The greatest sedimentation is found close to Polaris Point and the

Ship Repair Facility, respectively. This is expected because the largest amount of material is dredged in those areas. Also, the majority of the sediment accumulates within the navigation channel footprint. There are a few regions such as the south western portion of the footprint where sediment deposits outside of the footprint (solid black line). Values there generally remain less than 0.6g/cm^2. Within the ship repair facility map there is one small region in which the contours that exist outside of the footprint area are cyan (0.60-1.15 g/ cm^2). It should be noted that dredging controls can be used to reduce sedimentation outside of the channel footprint. For example, dredging near the edge of the footprint can be confined to time periods when tidal currents would move the material back toward the channel. This type of dredging control will reduce volumes deposited outside the channel footprint. Dredge control measures were not used in these simulations.

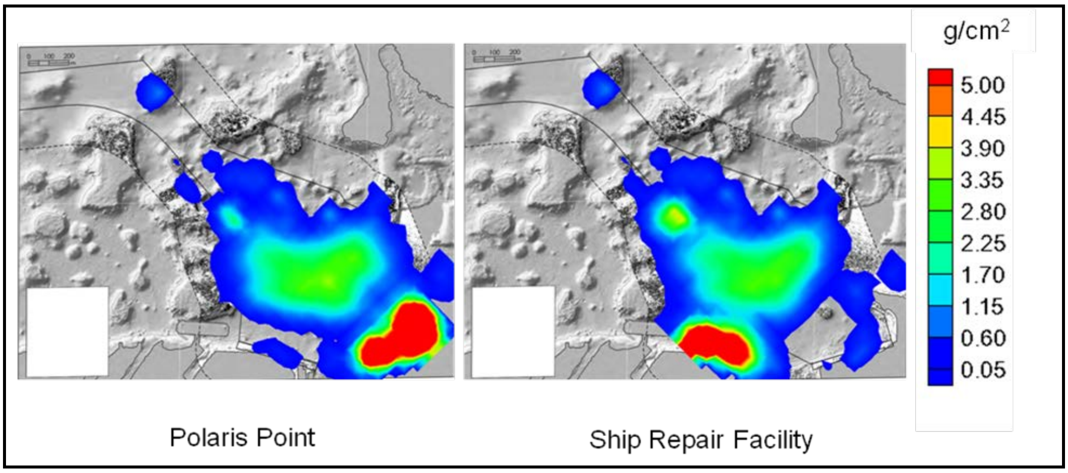

Figure 6. Case 1 accumulation contours for Polaris Point and Ship Repair Facility.

Case 2, which differs from Case 1 only by a lower dredging rate, produces results of total accumulation similar to that of the Case 1 scenario. This is to be expected because the total loss during the dredging operation remains the same. Case 3 and Case 4 have lower values of accumulation. In both these cases the loss is reduced from 2% to 1% and the silt curtain is assumed to be 100% effective. Therefore there is less sediment introduced into the water column and the sediment that is released occurs lower in the water column.

Maximum Deposition Rate

Maximum deposition rate is defined as the greatest daily rate of sedimentation that occurs at each grid cell during any time in the simulation. Therefore, the resulting plot is not indicative of any snapshot in time, but rather are a compilation over time of the maximum sedimentation rate value in the time series at each individual grid cell. The values are given in g/cm^2/day. The time at which the maximum deposition occurs at each grid cell generally corresponds to the time at which dredging occurs in a nearby location. In the figures, maximum deposition rate is primarily less than 0.70 g/cm^2/day. For case 1 (Figure 7), the values outside the footprint (but within the 200m line) remain less than 0.25 g/cm^2/day. For case 2, the values decrease slightly due to the lower dredging rate. In case 2, dredging takes 18 months and in case 1 dredging takes 12 months. Case 2 maximum values are approximately 0.45g/ cm^2/day. Case 3 indicates lower sedimentation rates than either Cases 1 or 2 due to the lower loss rate. Sedimentation rates outside the channel prism are further reduced because all sediment is introduced in the lowest 3 m of the water column. The lowest sedimentation rates are estimated for case 4 which has not only the 18 month dredge period, but also the lower dredging rate and the 100% effective silt curtains. Maximum values in this case are 0.25 g/cm^2/day within the dredging foot print and 0.10 g/cm^2/day within the 200m line.

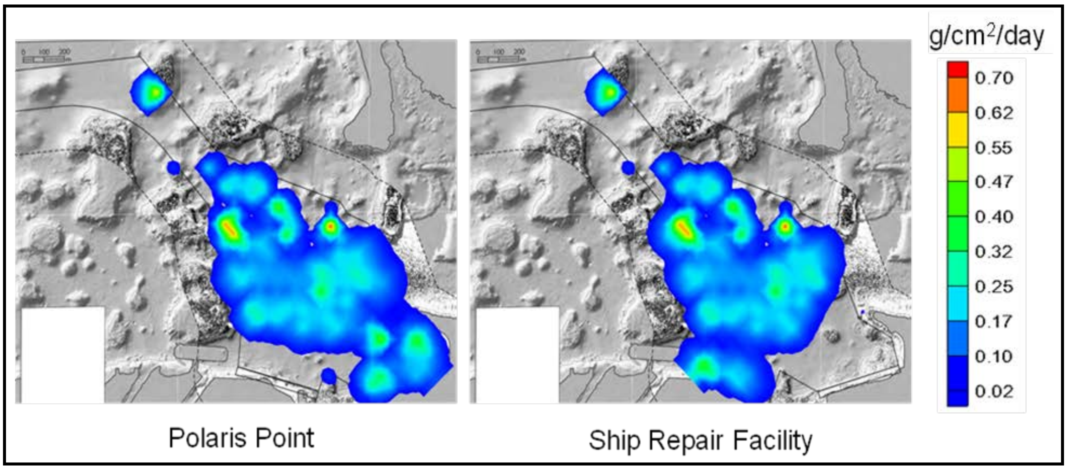

Figure 7. Case 1 maximum deposition rate contours.

Suspended Solids Concentration

The concentration of sediment within the water column is important when determining light attenuation and ultimately the effect of lack of light on the coral. Background TSS are not part of this study. Therefore, only additional TSS introduced by dredging operations is quantified in this study. TSS is not the same as turbidity. However, as part of the ongoing effects study being performed in coordination with the University of Hawaii, dredged sediment TSS will be correlated with turbidity based on multiple samples provided by the Navy. Similar to sedimentation rates, TSS values provided in subsequent figures are maximum values at each grid cell for any time during the simulation. They therefore do not represent a snapshot in time, but rather a compilation of the greatest values over time. TSS values vertically averaged over the water column and units are kg/m^3 ($1kg/m^3$=1g/l=1000mg/l). Figures 8 shows the maximum concentration for Case 1. Maximum concentration is highest near Polaris Point and the Ship Repair Facility where most dredging occurs. The maximum value for Polaris Point is approximately $0.1kg/m^3$. For the Ship Repair Facility values are lower. This is most likely due to the specifics of the bathymetry at the SRF and reduced volume of dredging compared to Polaris Point.

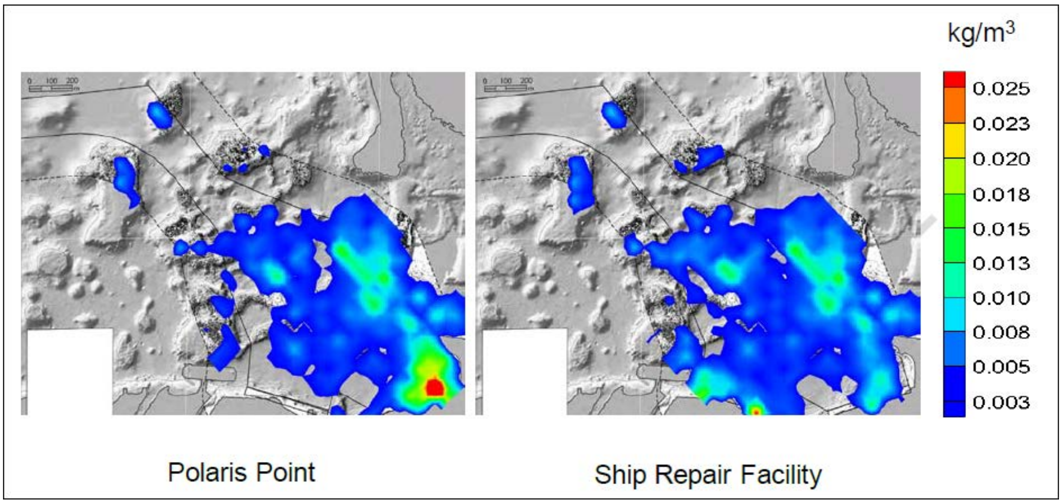

Figure 8. Case 1 maximum concentration contours.

A time series of concentration has been extracted within the area near Polaris Point (Figure 9). At this particular point, maximum concentration is 0.03kg/m^3. As can be seen in the time series concentration values change with time, increasing and decrease as sediment passes through the area due to the tidal hydrodynamics of the system. The greatest concentration values occur between July and December, which is the time frame during which dredging occurs in that area.

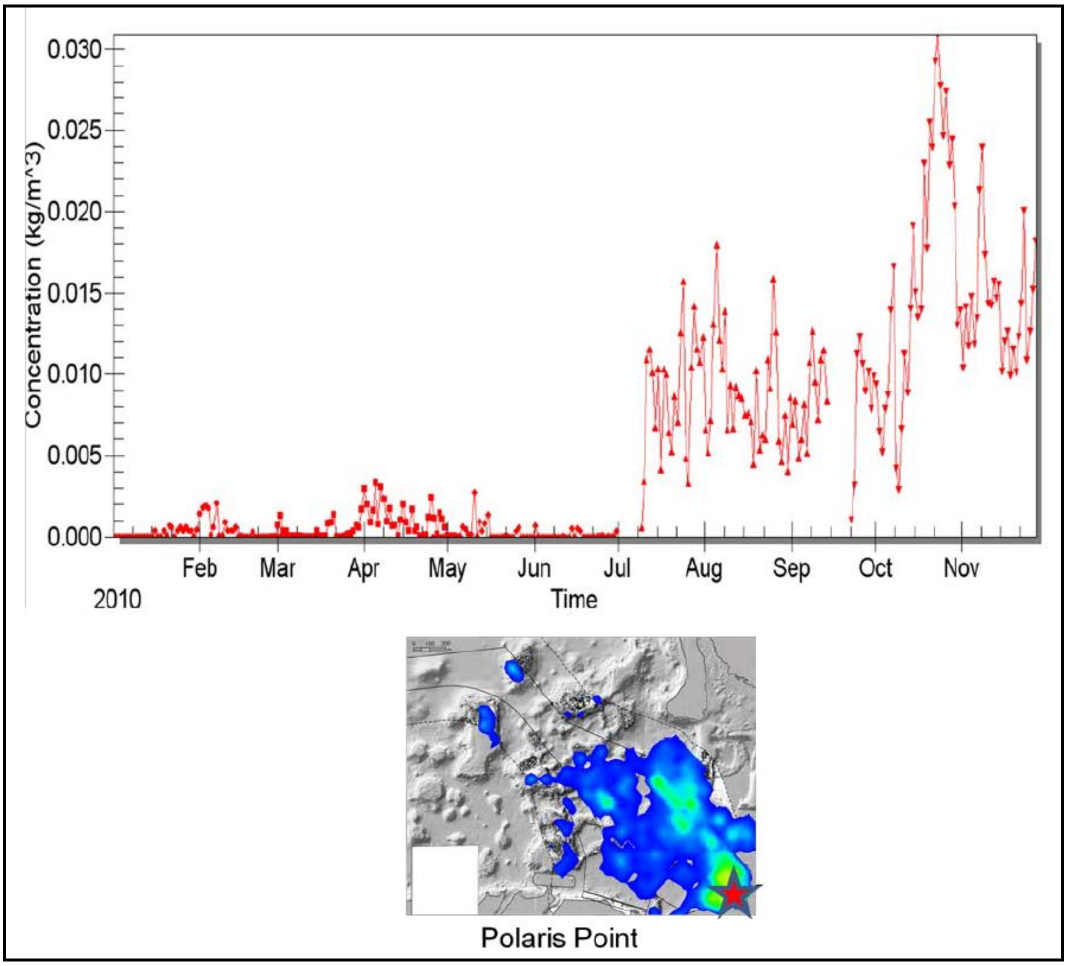

Figure 9. Case 1 concentration time series at a specified point (denoted by red star).

Data Analysis Tables

Tables 3 through 5 show a sample of the results from the previous maximum concentration, maximum deposition rate, and total accumulation maps in table format. The tables present the results for the maximum and minimum exposure cases (Cases 1 and 4. respectively). Each table displays the quantity of area (in meters squared) which has a contour value greater than a specified level. For example, Table 3 shows that for the Polaris Point Case 1 dredging scenario 41,600 m^2 of the study area will have sediment accumulation levels of greater than 1.0 g/cm^2 outside the dredging footprints (Figure 2 and Figure 3), for Polaris Point and Ship Repair Facility, respectively.

Table 3 present total accumulation values. These values reflect the total amount of accumulation that is expected to occur during an entire dredging scenario. Values are calculated as the total number of parcels deposited in each cell throughout the study area. Table 4 presents maximum deposition rate values. These values reflect the greatest daily rate of parcel deposition (sedimentation) that occurs in each grid cell on any date during the dredging scenario. Table 5 shows maximum suspended solids concentration values. These values reflect the maximum number of parcels within the water column at each grid cell on any date during the dredging scenario.

Table 3. Outside Area Accumulation > 1.0 g/cm^2

Case	Total Accumulation	
	Area (m^2) greater than 1.0 g/cm^2	
	Polaris Point	Ship Repair Facility
1	41,600	41,600
4	28,800	28,800

Table 4. Outside Area Max Deposition Rate > 0.1 g/cm^2/day

Case	Maximum Deposition Rate	
	Area (m^2) greater than 0.1 g/cm^2/day	
	Polaris Point	Ship Repair Facility
1	48,000	52,800
4	16,000	14,400

Table 5. Outside Area Max Concentration > 0.01 kg/m^3

Case	Maximum Concentration	
	Area (m^2) greater than 0.01 kg/m^3	
	Polaris Point	Ship Repair Facility
1	76,800	70,400
4	16,000	4,800

CONCLUSIONS

Simulations were performed to model the transport of sediment suspended during dredging operations at Apra Harbor, Guam. The primary concern is the exposure of coral reefs in the area to the resuspended sediment. Sediment source terms were developed for clamshell dredging utilizing silt curtains within two dredging footprints at Polaris Point and the Ship Repair Facility. The z-grid version of Ch3D hydrodynamics was employed to model three-dimensional velocities and water surface elevation for a three month period. For sediment transport simulations longer than three months, the hydrodynamic results were cycled. Multiple scenarios were modeled which varied based on the dredging sources. Clamshell loss terms were varied between 2% and 1%. Silt curtain effectiveness was varied between 90% and 100%. The dredging rate was varied between 1800cyd and 1110cyd. By bracketing multiple parameters and using generously conservative bracket values, the most likely range of results between Case 1 (which produces the maximum exposure) and Case 4 (minimum exposure) has been captured. Further data analysis was performed on the PTM output to produce maps and tables for total accumulation, maximum deposition rate, and maximum suspended sediment concentration.

The modeling results show that for a majority of comparisons the values for Polaris Point and Ship Repair Facility are within 10% of each other, and neither scenario has consistently lower values. In all cases, the differences in the Polaris Point and Ship Repair values are much less than the differences between the Case 1 (maximum exposure) and Case 4 (minimum exposure) values. Therefore, within the defined modeling limits, the most important conclusion that can be drawn from this study is that the modeling indicates that both dredging scenarios (Polaris Point and Ship Repair Facility) would produce roughly the same sediment exposure to the surrounding area. Neither scenario produces clearly better results.

It should be remembered that in designing the cases to be modeled, implicit assumptions were made that best dredging practices would be followed. Conditions such as the chronic spillage of dredge material outside the containment of silt curtains and barge aprons or major accidents such as a catastrophic silt curtain failure were not included within the scope of conditions modeled and could lead to variations in results such as elevated levels of sediment exposure to the adjacent reefs for either scenario.

This paper describes the modeling work that has been done using PTM. These results are currently being used by other researchers to quantitatively relate the effects of the levels of sediment exposure to levels of impact on the coral reef biota. The combined results of these studies will be used within decision support and risk assessment frameworks to support a selection of the optimal CVN berthing site in Apra Harbor.

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