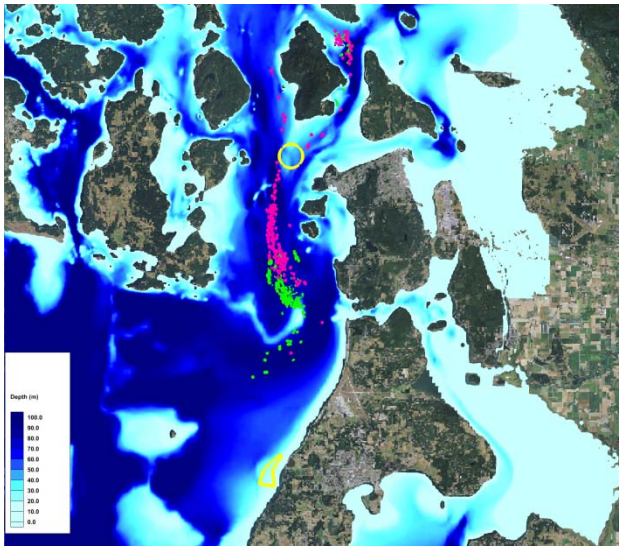
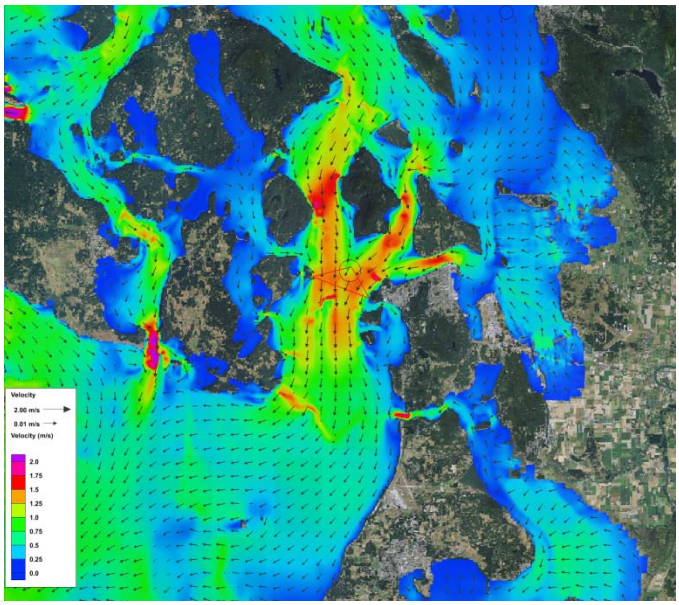
US Army Corps of Engineers ®
Seattle District

WASHINGTON STATE DEPARTMENT OF
Natural Resources

Dredged Material Management Program

Dispersive Disposal Site Fate and Transport Analysis for Puget Sound, Washington





September 2012

Executive Summary

The Dredged Material Management Program (DMMP) agencies manage eight open-water dredged material disposal sites in Puget Sound and the Strait of Juan de Fuca. Three of these (Port Angeles, Port Townsend and Rosario Strait) are dispersive sites. As the name implies, dredged material placed at these sites does not remain on site, but is widely dispersed. Because post-disposal monitoring is not possible at these sites, the dredged-material evaluation guidelines used for dispersive sites are more stringent than those used at the non-dispersive sites. Only the cleanest material may be placed there.

In 2007 the DMMP agencies began an intensive public process to revise the evaluation guidelines for dredged material containing dioxin. The Lower Elwha Klallam Tribe submitted a comment letter expressing concern over the fate of dredged material placed at the dispersive sites. Specifically, the Tribe was concerned that dredged material containing dioxin could impact shellfish beds in the area. The DMMP agencies agreed to evaluate this possibility by conducting a fate and transport study for material placed at the dispersive sites.

The first step in the study was development of a hydrodynamic model of Puget Sound by the Corps of Engineers. Then, in August 2011, the Department of Natural Resources funded a field survey of tidal currents in the vicinity of the disposal sites. Data from this survey were used by the Corps to validate and calibrate the hydrodynamic model. In the final step, the calibrated hydrodynamic model was combined with a particle tracking model to simulate – over a 72-hour period – the fate and transport of dredged material placed at the disposal sites.

The modeling results indicated that material placed at these three sites is indeed dispersed, with the Port Angeles and Rosario Strait sites being the most highly dispersive. The Port Townsend site is less dispersive, but material placed there is still widely scattered in the vicinity of the site. Fine-grained material, with which dioxin and other hydrophobic organics tend to sorb, remains in the water column longer than sand and is therefore the most widely dispersed. These particles tend to be transported to the west - parallel to the Strait of Juan de Fuca - at the Port Angeles and Port Townsend sites. The results are more mixed at the Rosario Strait site, with the majority of the material transported to the south or southwest, but small fractions of the material also being transported to the northeast into Bellingham Channel, and to the east through Guemes Channel and Deception Pass.

Despite the dispersive nature of these sites, a key finding was that none of the modeled dredged material entered any of the shellfish areas identified by the Lower Elwha Klallam Tribe. While fine-grained material does stay in the water column for an extended period of time, transport paths were largely confined to deeper water, away from the shorelines where shellfish beds are found. The fine-grained material does eventually settle lower into the water column as well. At the Port Angeles and Port Townsend sites, no more than ten percent remained in the top 20 meters of the water column after 24 hours, putting the majority of the fine-grained material below the depth range of commercial geoduck tracts. In summary, the modeling results indicate that dredged material disposal at the Port Angeles, Port Townsend and Rosario Strait sites is unlikely to impact shellfish resources in the vicinity of the sites.

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1 Introduction

1.1 Purpose and Scope

The Dredged Material Management Program (DMMP) agencies manage the open water dredged material disposal sites established by the Puget Sound Dredged Disposal Analysis (PSDDA) study in the 1980s. The DMMP sought to investigate the fate and transport of dredged material placed at the dispersive dredged material placement sites within the Strait of Juan de Fuca and Puget Sound using site specific sediment data and a recent numerical model developed for the Puget Sound Basin. The purpose of the study is to determine if hydrodynamic conditions indicate the potential for dredged materials to be transported in the vicinity of critical shellfish habitat identified by the Lower Elwha Klallam Tribe (LEKT) near Port Angeles, Sequim, and Port Townsend, Washington. Measured current profile data and numerical modeling are utilized to provide additional insight on this question. This report describes the data collection and numerical modeling analysis. A tidal circulation hydrodynamic model is validated with measured data and is then used to force a particle tracking model (PTM) to investigate short term fate of dredge material placed at three dispersive PSDDA sites.

1.2 Project Description

The Dredged Material Management Program (DMMP) consists of four agencies that work collaboratively to manage and regulate the disposal of dredged material from dredging projects in Washington State. These agencies include the U.S. Army Corps of Engineers, Seattle District (USACE); the U.S. Environmental Protection Agency, Region 10 (USEPA); the Washington State Department of Ecology (Ecology); and the Washington State Department of Natural Resources (DNR).

Dredged material determined to be suitable for open water placement may be placed at one of the eight PSDDA dredged material sites. Of the eight sites, five are classified as non-dispersive and three are classified as dispersive sites (PSDDA 1989). The three dispersive sites are identified as the Port Angeles, Port Townsend, and Rosario Strait sites shown in Figures 1-3. The guidelines used to initially determine the dispersive site locations were the following:

- Maximum dispersion of the material is desired; therefore the site should be in an area of high current (i.e., average current speed > 25 cm/sec).
- The site should be buffered by a minimum of 1 nautical mile from shorelines and human use areas as measured from the edge of the disposal zone
- The site should be located at a minimum depth of 180 feet to avoid sensitive biological resources. It was advisable to increase the depth to provide additional protection for natural resources concentrated near shore at shallower depths.
- The sites should be located so that the ultimate fate of dispersed material will not have a significant adverse impact on natural resources.

1.3 Historical Studies

Site Selection

During original PSDDA site selection the dispersive sites were all situated in areas subject to mean currents greater than 25 cm/sec. Table 1 lists measured mean and calculated 99th percentile currents based on regression analysis near each dispersive site (EHI 1987). The flow types were also identified; flow types refer to the variation in current direction and magnitude with depth. Both the Port Angeles and Port Townsend sites are classified as two-layer flow with the net surface layer currents moving seaward (west) and flow below 165 feet landward (east). The Rosario Strait site is classified as single layered with a net southerly direction. Most of the current measurements were derived from historic current meter deployments from 1950-1978 by USEPA, NOS, NOAA, and UW in the area and were not specifically tailored to measuring currents within the final disposal site boundaries themselves. Rather, these data combined with the numerical modeling (Crean 1983) were used to identify Zones of Siting Feasibility (ZSF's).

Fate and Transport

Numerical modeling (Crean 1983) investigated water particle movement in the Port Townsend and Port Angeles sites during neap and spring tides. At the Port Townsend Site the water particle trajectory was shown to oscillate in an east-west direction with a net westerly movement without leaving the ZSF over a 25 hour tidal cycle during a neap tide. During a spring tide the particle left the ZSF within 9 hours. Similarly the model results indicate an entirely east-west tidal circulation at the Port Angeles ZSF over a 25 hour tide cycle and indicated particle movement outside of the ZSF with a slightly northwest net movement. Fate of suspended sediments is of particular interest as contaminants are typically bound to the solid phase of sediment, notably the fine grained fractions. Available drifter data were utilized to estimate far field dispersion from the placement sites. The exact trajectory of far field dispersion is strongly influenced by surface winds and their influence on surface currents. These data comprised of drift cards, drift sheets, and drogues. Drift cards were placed near the Port Townsend site in 1976 and 1980 and were observed to reach beaches within the inner Strait of Juan de Fuca (EHI 1987). It was speculated dredge material residing in the surface microlayer (i.e. the top 0.1 millimeter of the water column) following release is expected to do the same. The surface layer is generally defined as the top 1 meter of the water column. It was assumed a maximum of 5% of the original dredge volume could be suspended within the surface layer. Suspended particles measured within the upper water column following disposal by scow (bottom dump barge) at the Elliott Bay non-dispersive site were observed to be 2 to 4% of the initial disposal volume (Truitt 1986) by performing a mass balance with samples collected through the water column.

Table 1. Current characteristics at dispersive PSDDA sites (from EHI 1987)

PSDDA Site	Mean Current (cm/s)	99th Percentile (cm/sec)	Flow Type
Port Angeles	45	121.4	Two layer
Port Townsend	40	108.0	Two layer
Rosario Strait	50	134.7	Single Layer

1.4 PSDDA Disposal Site Use

Dredged material placed at the PSDDA sites comprise of clays, silts, sands, and gravels. Table 2 lists the dredging year and cumulative volume disposed at each dispersive site from 1989-2011. The Rosario Strait site is the most actively used site with an average annual disposal volume of 95,000 cy/year. The Port Townsend site has been used on six occasions with an average annual disposal volume of 2,600 cy/year. The Port Angeles site is the least utilized, having been used only once, in 1996.

Table 2: PSDDA Dispersive Placement Areas Site Use (1989-2011)

Disposal Site	Dredging Year Usage (1989-2011)[1]	Cumulative Volume (CY)	Dredging Source(s)
Rosario Strait	91, 92, 93, 94, 95, 96, 98, 99, 02, 03, 04, 05, 06, 07, 09,11	1,978,623	USACE Swinomish Channel O&M; BP Oil Refinery Deepening; Anchor Cove Marina; USACE Bellingham O&M; Squalicum Waterway; Shell Oil Pier (Anacortes); La Conner Marina; Port of Blaine Marina; Port of Anacortes (Cap Sante Marina); Anchor Cove Marina; Dakota Creek Shipyard;
Port Townsend	93, 98, 99, 07, 09,10	54,777	USACE Keystone O&M; USACE Port Townsend O&M; Point Hudson Marina; Driftwood Key Community Club;
Port Angeles	96	22,344	Holnam Inc. / Ideal Cement

[1] Dredging year: June 16 through June 15 of ensuing year. A dredging year overlaps two calendar years

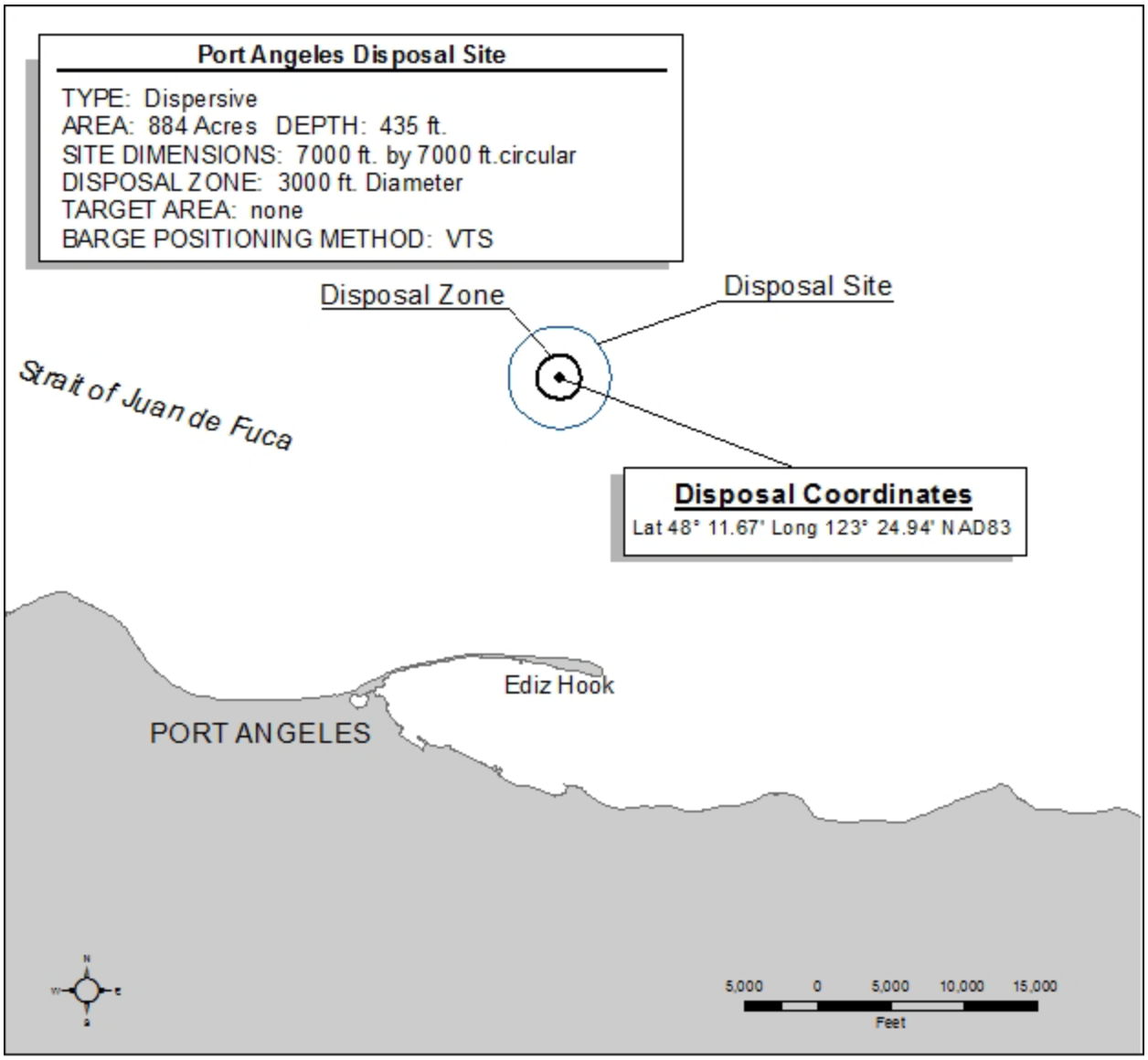

Figure 1: Port Angeles Disposal Site Location

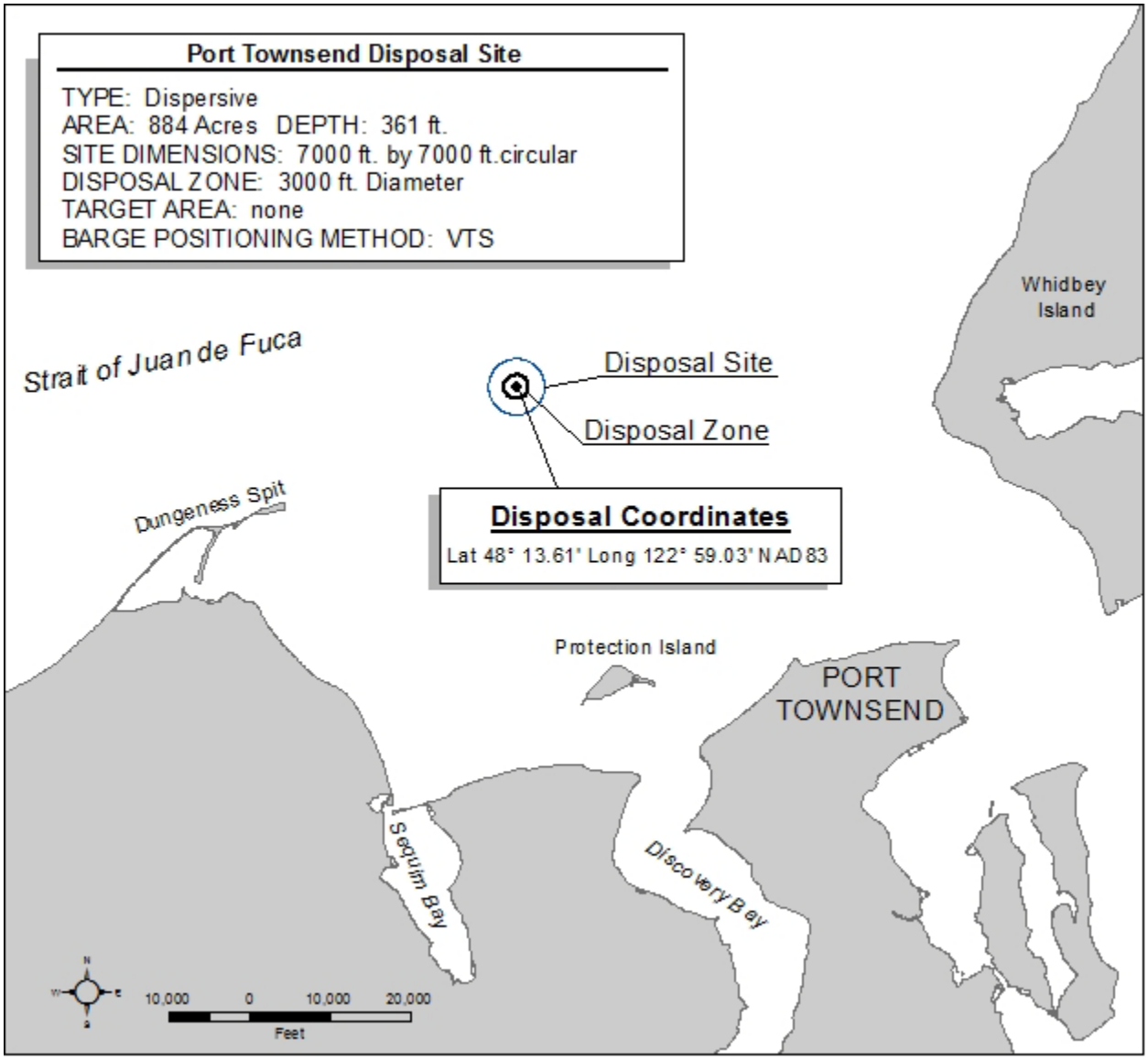

Figure 2: Port Townsend Disposal Site Location

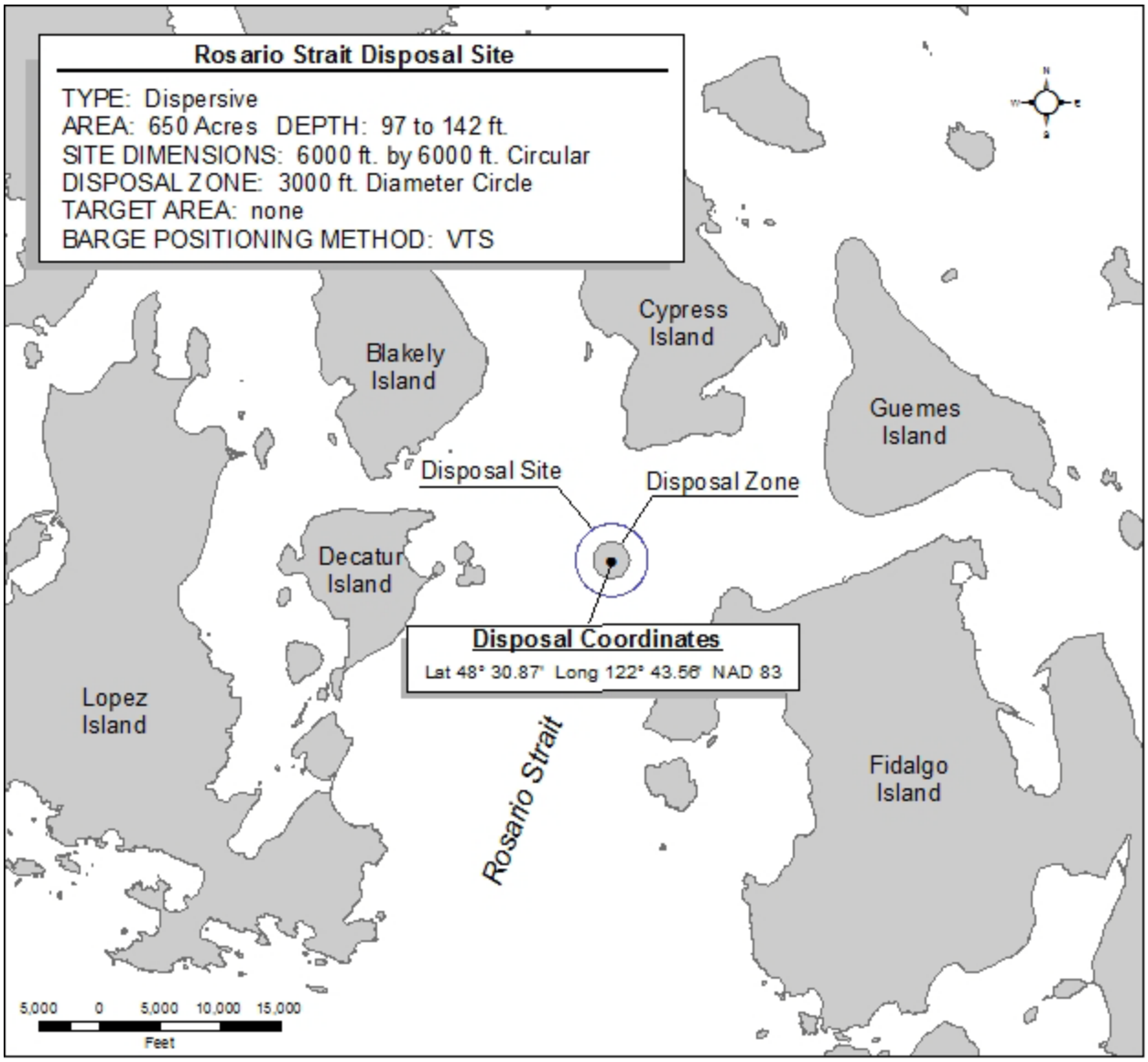

Figure 3: Rosario Strait Disposal Site Location

2 Numerical Modeling

2.1 Model background

The Coastal Modeling System (CMS) FLOW numerical model is utilized to analyze tidally generated current patterns throughout the Puget Sound Basin over various tidal cycles. The particle tracking model (PTM) simulates sediment fate and transport for a finite number of particles placed in a current flow field. The CMS-FLOW version 4.00 and PTM version 2.0.55 have been incorporated into the U.S. Army Corps of Engineers supported Surface Modeling System (SMS) graphical user interface. Model grid generation and model setup are performed within SMS version 11.0.

2.1.1 CMS-FLOW

CMS-FLOW solves the two-dimensional, depth-integrated continuity and momentum equations by applying a finite-volume method (Militello et al. 2004; Sanchez et al. 2011). These equations are solved numerically using an implicit finite differencing method. In the present application, The CMS-FLOW model domain encompasses the entire Puget Sound Basin as shown in Figure 4. The western boundary is specified in the Strait of Juan de Fuca just east of Neah Bay, WA. The northern boundary is specified near Cherry Point north of Bellingham, WA. Tidal currents are forced in the model by specifying a time varying water surface elevation at the open water boundaries. These boundary conditions in the model are forced using observed water levels at the National Oceanic and Atmospheric Administration (NOAA) Neah Bay, WA and Cherry Point, WA water level stations respectively.

A telescoping grid feature is utilized to resolve bathymetric features such as sills, narrow channels, and embayments while providing less resolution in deeper open water conditions, resulting in greater numerical efficiency. Additionally, an implicit numerical solver is utilized to simulate longer time durations. A maximum time step of dt = 600 sec is used in the simulation. Water level and velocity observation cells are specified at all NOAA water level stations and each of the 3 open water dispersive PSDDA sites for model validation.

2.1.2 PTM

The Particle Tracking Model (PTM) computes fate and pathways of sediments and other waterborne particulates in coastal engineering and dredging applications in a Lagrangian modeling framework (MacDonald et al. 2006; Demirbilek et al. 2008; Li et al. 2011). In general terms, a Lagrangian modeling framework is one that moves with the flow; thus each particle is followed in time and space within the model. The PTM's Lagrangian framework is one in which the sediment being modeled is discretized into a finite number of particles that are followed as they are transported by the flow. Each particle in the PTM represents a given mass of sediment (not an individual sediment particle or grain), and each particle has its own unique set of characteristics. As a minimum, a particle must be defined with certain physical properties (e.g., grain size and specific gravity) and an initial position.

In this application, dredged material characteristics obtained from dredged material suitability reports from the DMMP are used to identify the physical sediment particle properties. Sediment release points are specified within each disposal site boundary and sediment is released at a specified source rate (mass per unit time). The model then computes the particle fate and transport over multiple tide cycles using the current flow field computed in the CMS-FLOW model. The PTM tracks each particle's horizontal location, vertical height in the water column and particle state (active or dead) as a function of time. An "active" or "dead" state refers to whether the particle is in motion and actively being transported or one that has reached the seabed and is no longer suspended. It is important to note, however, that "dead" particles can later be resuspended by currents and once again become active and subject to transport; the CMS-FLOW model does include this resuspension process.

2.2 Modeling Strategy

CMS-FLOW water levels and current velocities were validated using measured velocity data. A one-month simulation was performed to generate tidal statistics at the active NOAA water level stations within Puget Sound. Tidally-generated currents were validated with an acoustic Doppler Current Profiler (ADCP) survey performed during a spring tide cycle from 12-16 August 2011 (Integral Consulting Inc. 2011). Wind-generated surface currents were not considered in the model, nor was vertical circulation generated from freshwater plumes generated from the Elwha or Dungeness Rivers. Once the CMS-FLOW model was validated the model was then employed to force PTM to investigate short-term fate and transport of dredged material released at the three dispersive PSDDA sites.

2.3 Hydrodynamic Modeling

2.3.1 Model Setup

A combination of the NOAA Port Townsend 1/3 arc-second tsunami inundation digital elevation model (Lim et al 2011), 2005 Puget Sound Lidar Consortium topographic survey (PSLC 2005), and the NOAA Coastal Relief Model (Divins and Metzger 2008) were integrated to develop the model bathymetry. All data was converted to the Washington State Plane North Meters horizontal projection, and the NAVD88 vertical datum. The model bathymetry scatter set was interpolated to the telescoping Cartesian grid shown in Figure 4. The telescoping grid allowed for resolution of the narrow channels and islands throughout the domain providing better detail of the hydrodynamics. The regions with the highest grid resolution are located at the various sills (i.e. Deception Pass, Admiralty Inlet, and Tacoma Narrows) in addition to each PSDDA site. A total of 252,435 computation cells are included in the model domain with cell sizes ranging from 120 meters to 480 meters.

Water levels used to force the open water boundaries in CMS-FLOW were extracted for Station 9443090 (Neah Bay, WA) and 9449424 (Cherry Point, WA) from NOAA's Tides and Currents website (http://tidesandcurrents.noaa.gov). A 24 hour model spin up time is specified within CMS-FLOW to prevent numerical instabilities as the model reaches steady state.

2.3.2 Model validation – water levels

The CMS–FLOW model was validated by computing the tidal harmonics from computed water levels over a one month period from August 1-31, 2011. In general, model calibration consisted of refining and smoothing model bathymetry and increasing resolution in areas of high relief. Water levels were validated at NOAA water level stations 9444090 (Port Angeles, WA), 9444900 (Port Townsend, WA) and 9449880 (Friday Harbor, WA). Modeled water levels were analyzed using the T_Tide harmonic analysis Matlab script (Pawlowicz et. al, 2002). The S2, P1, O1, M2, and K1 tidal constituents[1] amount to 96.3% of the amplitude within Puget Sound. Figures 5 through 10 compare the measured versus modeled tidal constituents and water surface elevation time series. Note in Figures 6, 8, and 10 the first 24 hours of the modeled water levels include the model spin-up period. This accounts for the discrepancy between measured and modeled water surface elevations in the first 12 hours of these figures.

[1] S2 – Principal solar semidiurnal constituent; P1 – Solar diurnal constituent; O1 – Lunar diurnal constituent; M2 – Principal lunar semidiurnal constituent; K1 – Lunar diurnal constituent;
(source: http://tidesandcurrents.noaa.gov/harmonic_cons_defs. html)

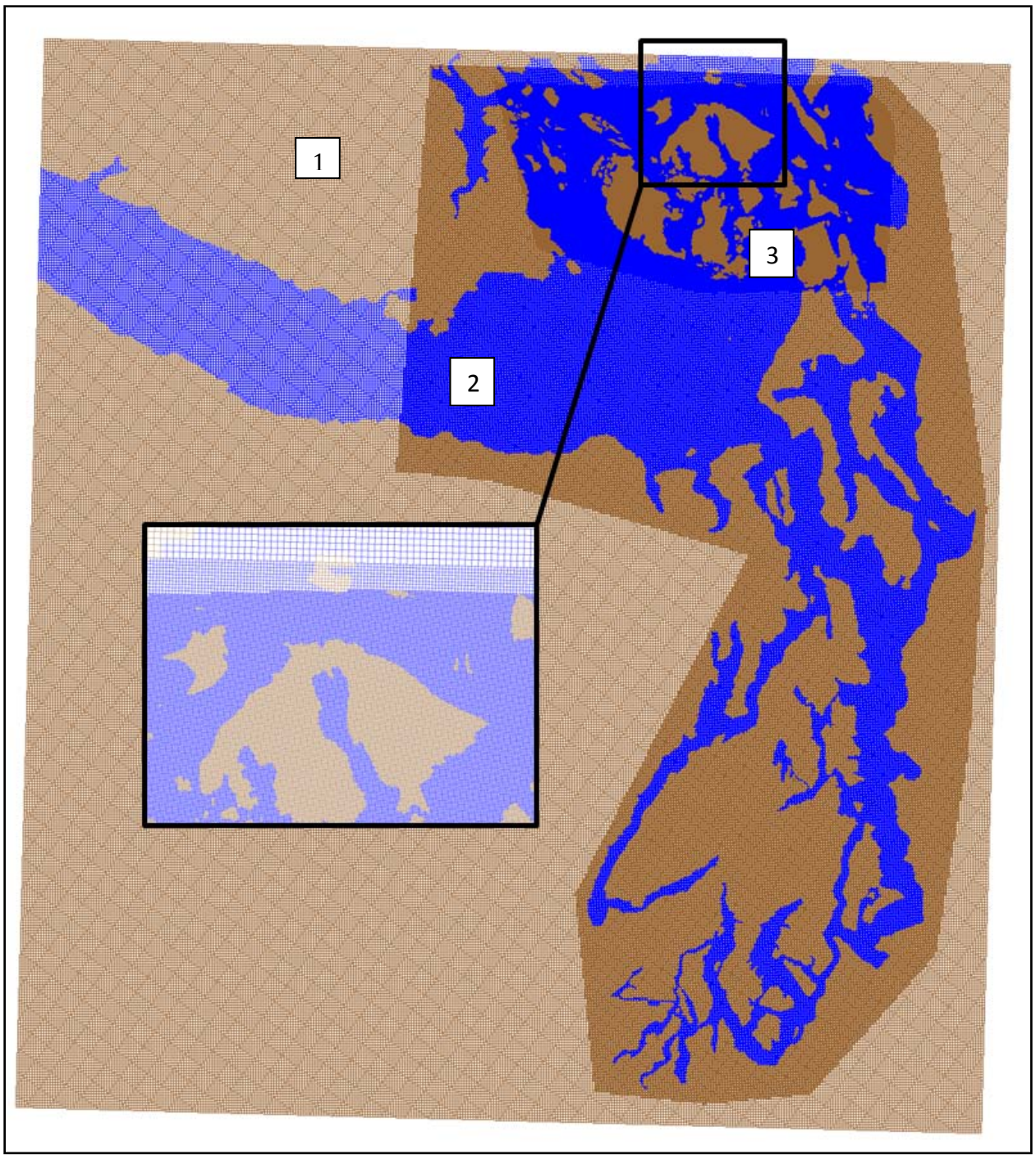

Figure 4: CMS-FLOW Model Grid Showing One Example of the Three Refinement Layers (Cell Sizes: 480, 240 and 120 Meters in Areas 1, 2 and 3 respectively.)

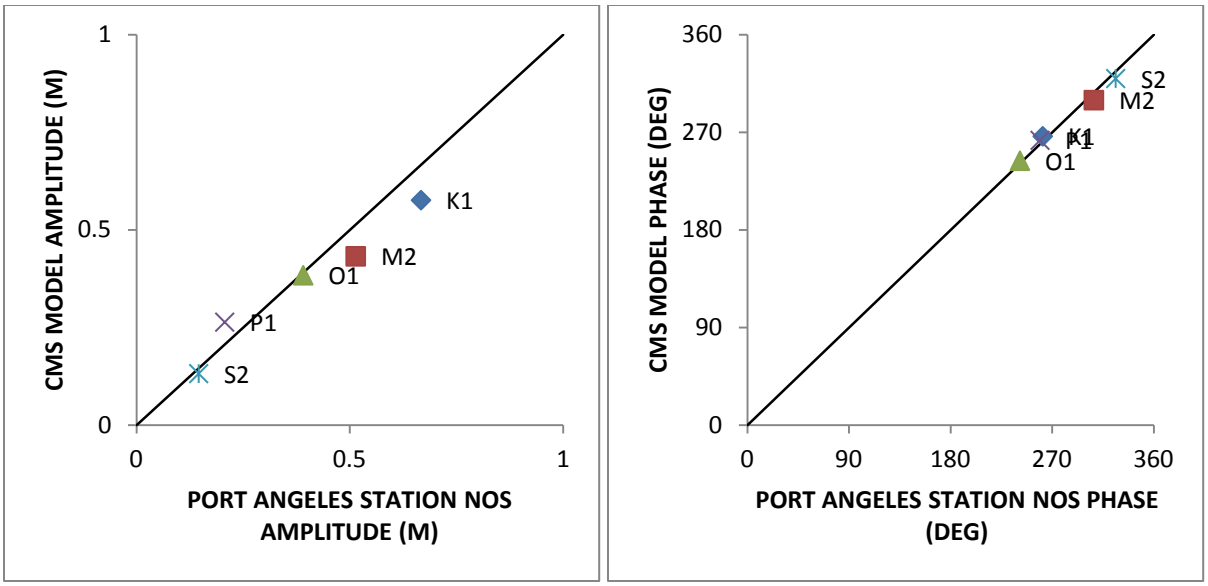

Figure 5: Tidal Constituent Comparison at Port Angeles Tide Station

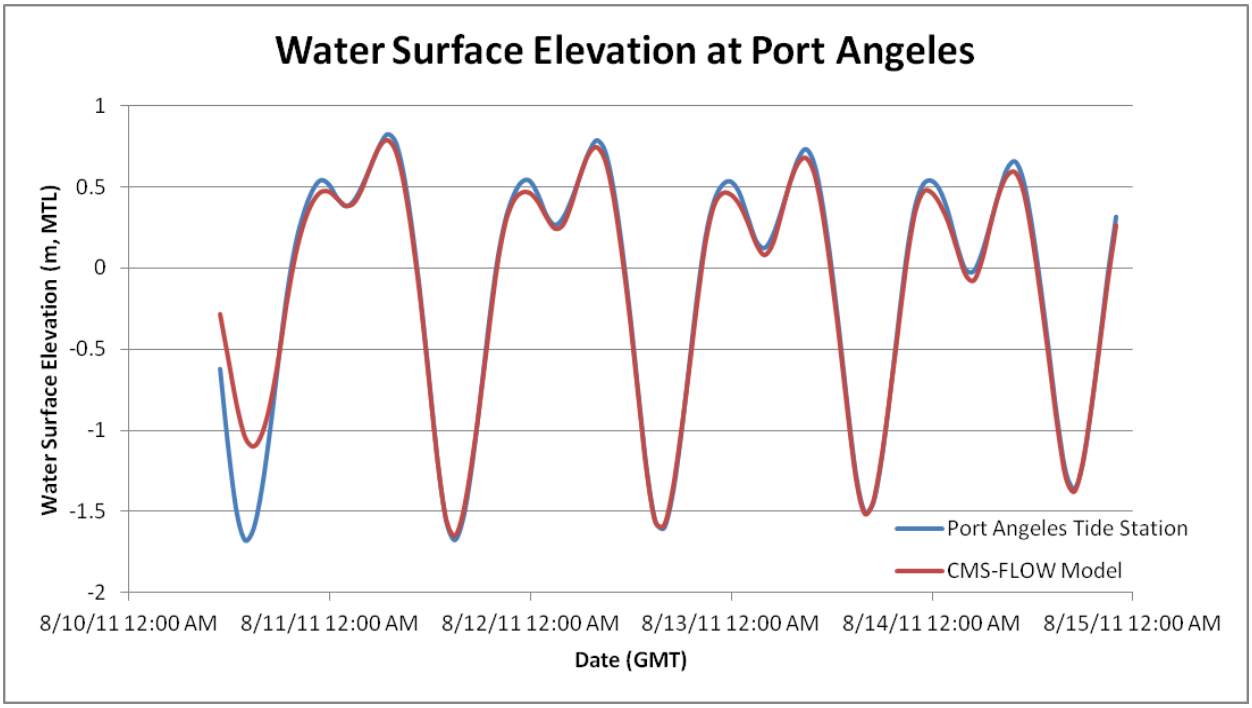

Figure 6: Water Surface Elevation at Port Angeles Station vs. CMS-FLOW Model

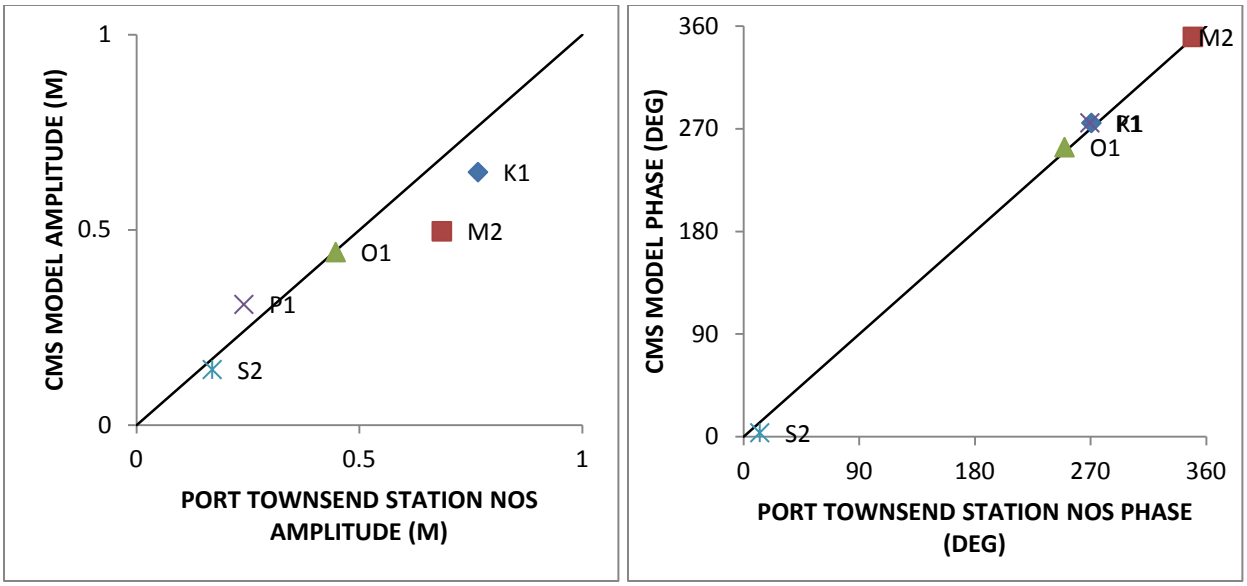

Figure 7: Tidal Constituent Comparison at Port Townsend Station

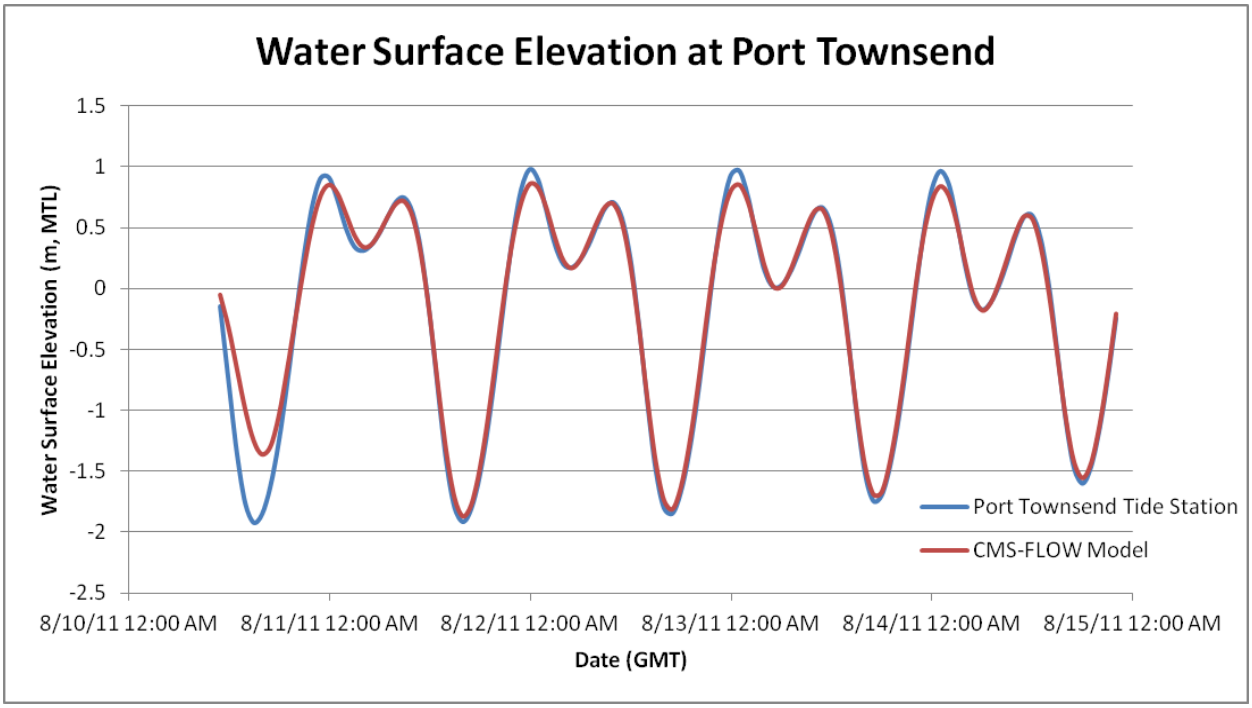

Figure 8: Water Surface Elevation at Port Townsend Tide Station vs. CMS-FLOW Model

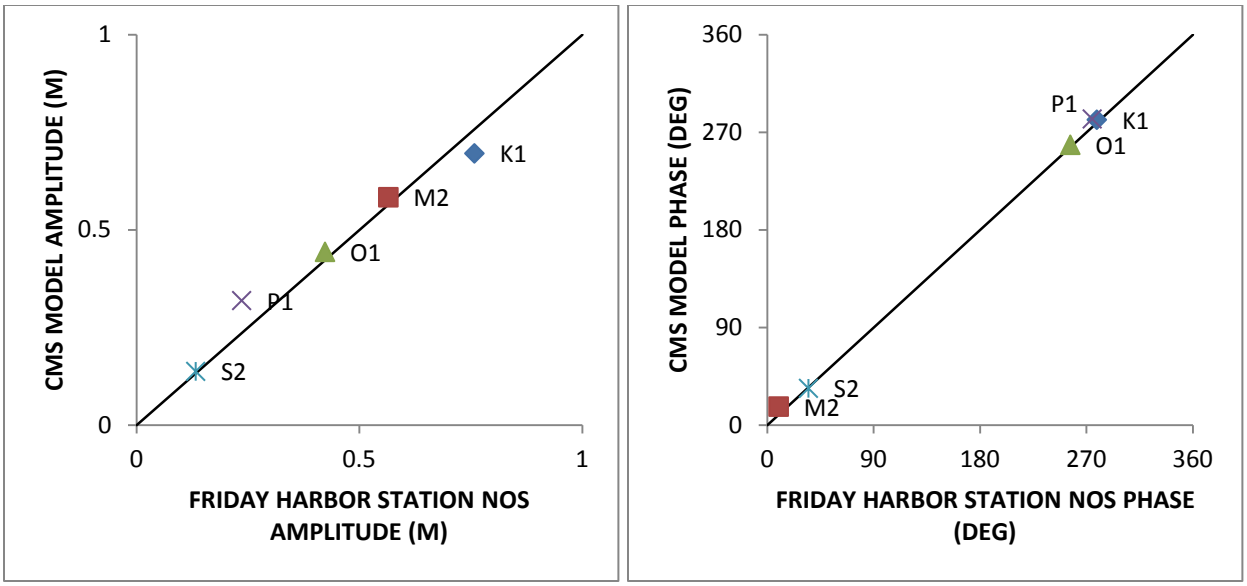

Figure 9: Tidal Constituent Comparison at Friday Harbor Station

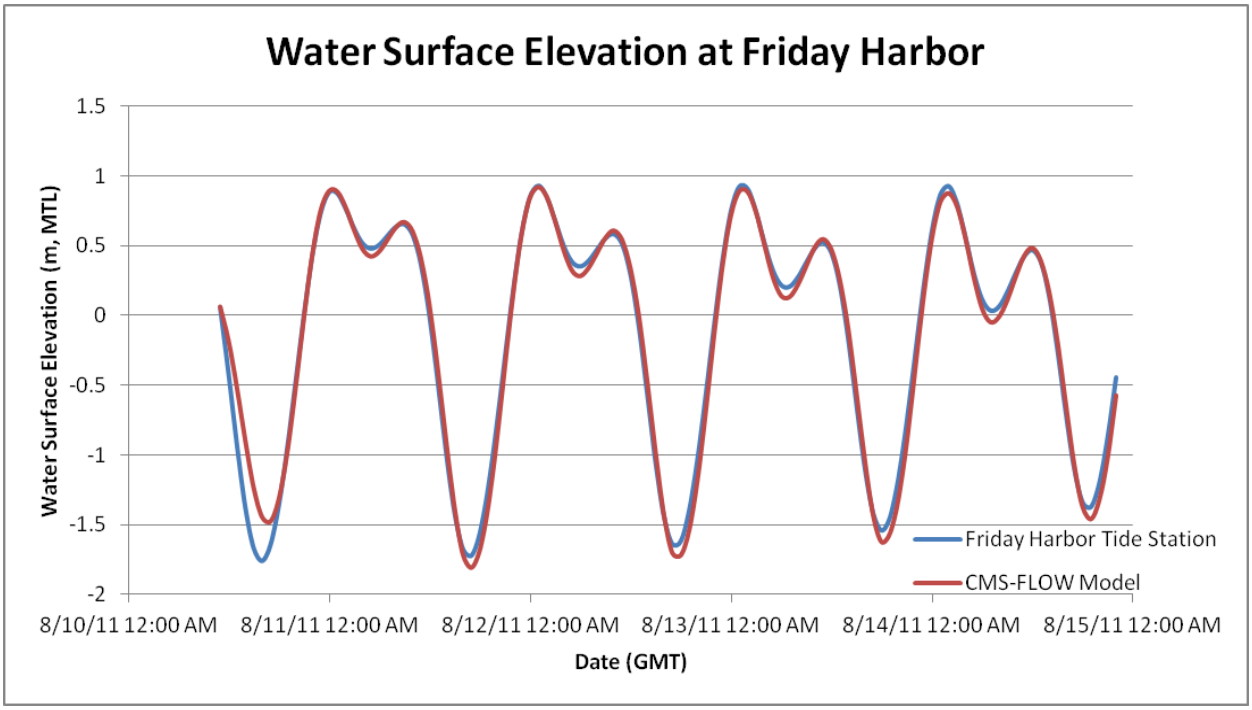

Figure 10: Water Surface Elevation at Friday Harbor Station vs. CMS-FLOW Model

2.3.3 Model validation – currents

A principle component analysis[2] of the velocity vector time series was used to compute the primary direction of the tidal currents. Figure 11 shows the tidal ellipses derived from the modeled current velocities in CMS-FLOW at each PSDDA site over a 120 hour simulation. Both the Port Angeles and Port Townsend major ellipse axes show a predominately east-west orientation (93.2 and 91.2° true north respectively) indicating that currents move primarily east and west. The Rosario Strait site shows a northeast-southwest orientation (199° true north) which is expected based on the orientation of the Strait.

In order to better understand the horizontal and vertical variability of currents near each site, an Acoustic Doppler Current Profiler (ADCP) survey was performed across each site during a spring tide, or when tidal currents were expected to be fairly strong. Integral Consulting Inc. outfitted the *R/V Gen III*, a 54-foot catamaran, with a 300-kHz Teledyne RD Instruments' Workshorse Sentinel ADCP to profile currents in a 6 to 8 nautical mile loop through each site, over a 24-hour tide cycle. The survey was conducted from 12-16 August, 2011. The transects shown in Figure 12 were designed to resolve flows through the dominant bathymetric features and dominant directions. At the Port Angeles and Rosario Strait sites, transects were run in a counter-clockwise direction. Transects were run clockwise at the Port Townsend site. The ADCP surveys confirmed currents stronger than 1 meter per second (100 cm/s) at each of the dispersive sites. The transects also demonstrate significant stratification both in magnitude and direction. Stratification was most pronounced during slack tide conditions at the Port Angeles and Port Townsend sites, which agrees with historical studies discussed in Section 1.3.

Peak measured ebb tide conditions are shown in Figure 13. For the Port Angeles and Port Townsend sites, the figure shows only those transects that cross through the disposal sites (a double-legged transect in the case of Port Townsend). For the Rosario Strait site, the figure shows the southwest transect, which is oriented perpendicular to the currents at the disposal site. While this transect does not actually cross through the site, the approximate location of the site is shown as if projected on the transect by currents moving through the site perpendicular to the transect. During the maximum ebb tide conditions, the strongest currents at the Port Angeles and Port Townsend sites were measured above 1.2 m/s in the top 20 to 40 meters of the water column as shown in Figure 13. Below this depth, velocities were on the order of half as fast as those observed on the surface. At the Rosario Strait site, currents were measured up to 1.8 m/s; however the velocity was more uniform with depth. During slack tide conditions, velocity directions varied more with depth, most significantly at the Port Townsend site as shown in Figure 14. Bottom velocity was still measured to be fairly strong at the Port Angeles site at 0.6 m/s during slack conditions even while surface currents were approximately half as strong.

Typical modeled ebb and slack tide velocities are shown in the vicinity of the disposal sites in Figure 15. The depth-averaged velocities shown in the figure compare favorably to the measured velocities shown in Figures 13 and 14. Higher-resolution versions of figures 13-15 can be found in Appendix A.

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[2] Principle Component Analysis (PCA) is a mathematical procedure developed in the early 1900's as a means of extracting the dominant patterns from datasets that on the surface appeared random.

Figures 16-18 compare the measured depth-averaged ADCP currents with the computed CMS-FLOW depth-averaged currents for selected transects representing periods of peak ebb and peak flood velocities around the disposal sites. Further information regarding transect locations and times can be found in the ADCP data report (Integral Consulting Inc., 2011). Overall the current magnitude and directions measured by the ADCP compare reasonably well with those values from the CMS-FLOW simulation. Much of the error can be attributed to differences in velocity and direction with depth due to stratified flow, which is not represented in the CMS-FLOW model. Root Mean Square Error (RMSE) was computed between modeled and observed velocities at each ADCP transect passing through the disposal site and is included in Figures 16-18. RMSE ranged from 5 to 16 centimeters per second (cm/s) between the 3 sites. In general, the model predicted current magnitudes with lower RMSE at the Port Angeles and Port Angeles site than at the Rosario Strait site.

Given the resolution of the model grid and the complexity of the bathymetric features, the overall agreement in spatial and temporal trends between the model results and the measured data was considered adequate, and it was determined that the model was acceptable to use as the forcing for the PTM model.

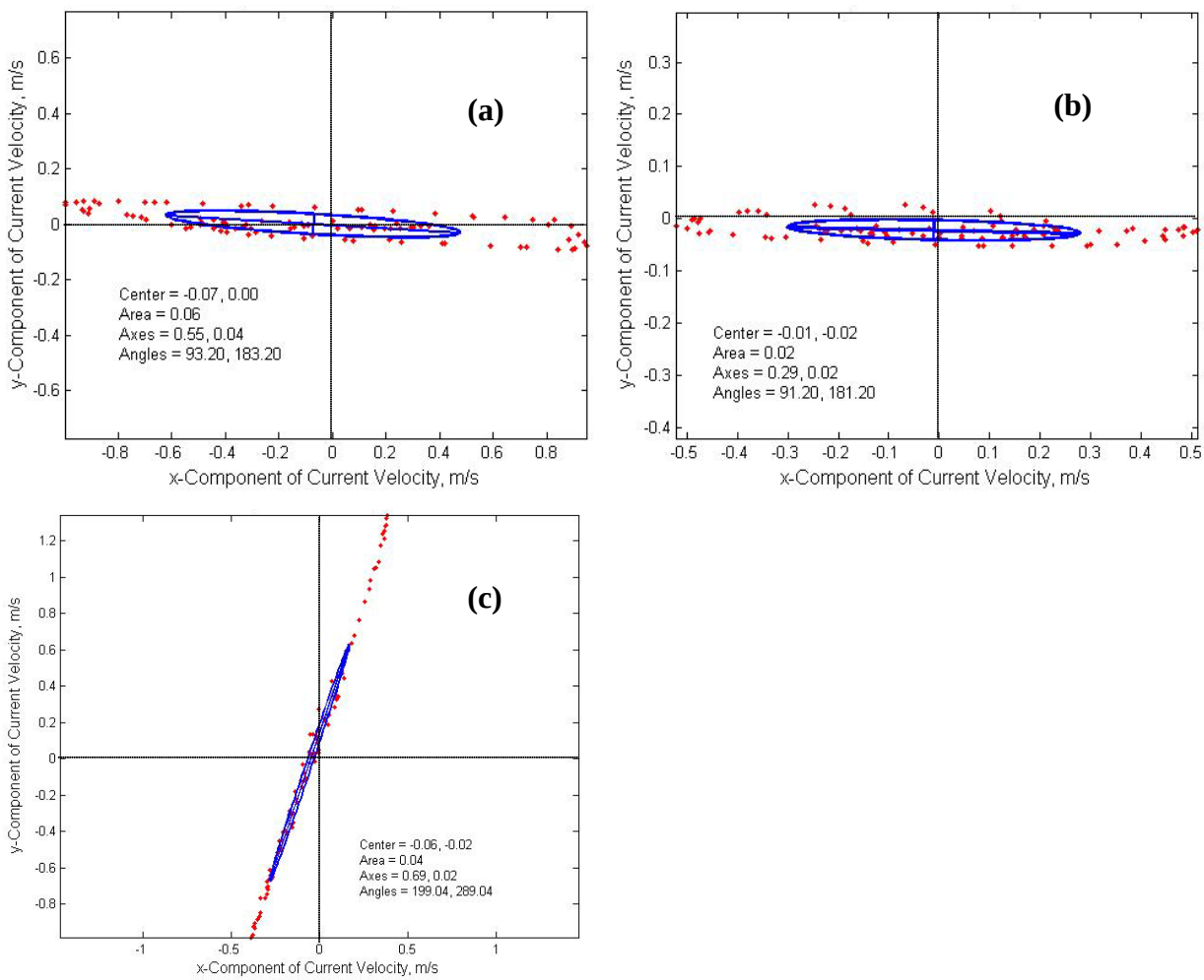

Figure 11: Modeled tidal ellipses at (a) Port Angeles (b) Port Townsend and (c) Rosario Strait Disposal Site

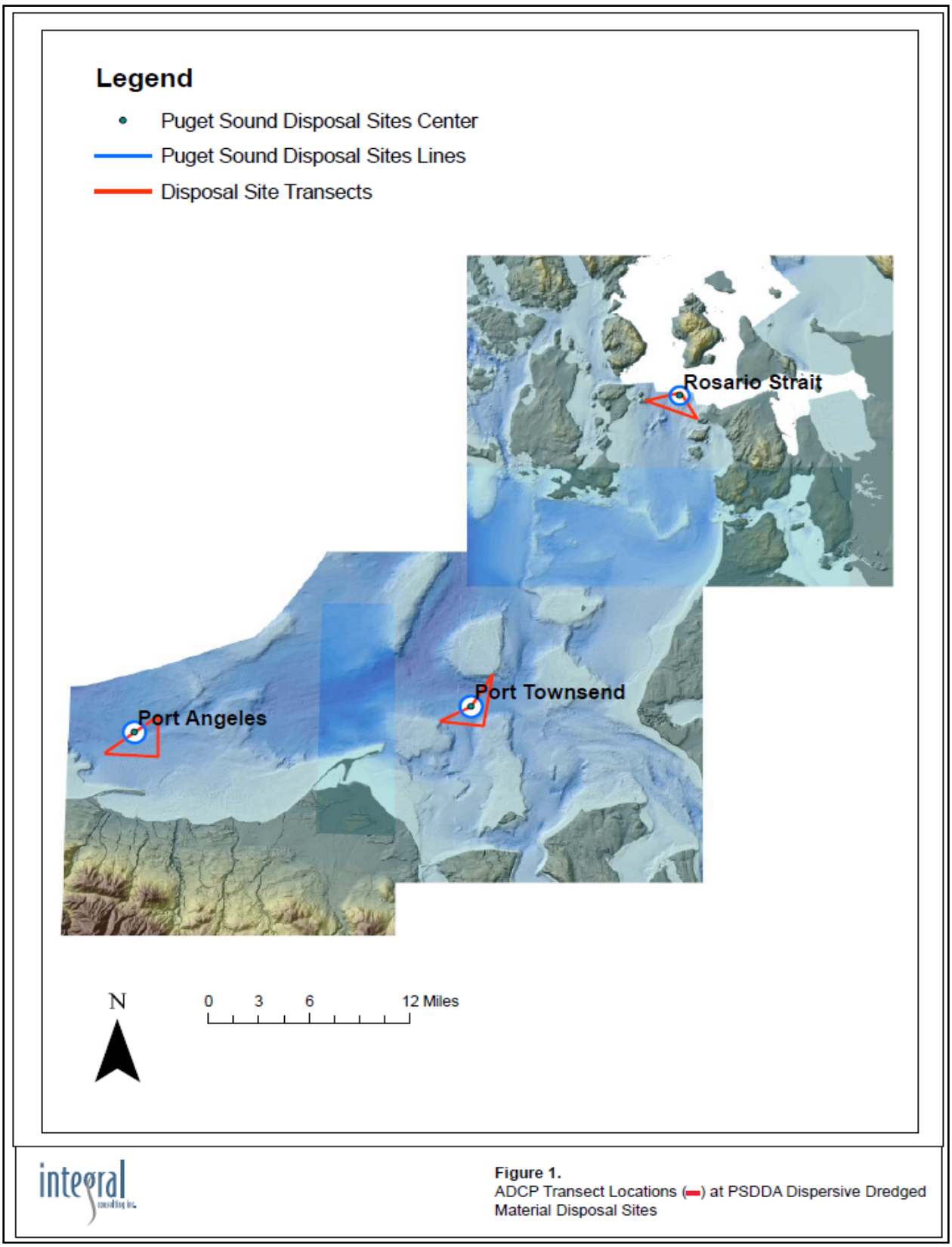

Figure 12: Location of ADCP Transects for Model Validation (from Integral Consulting Inc. 2011)

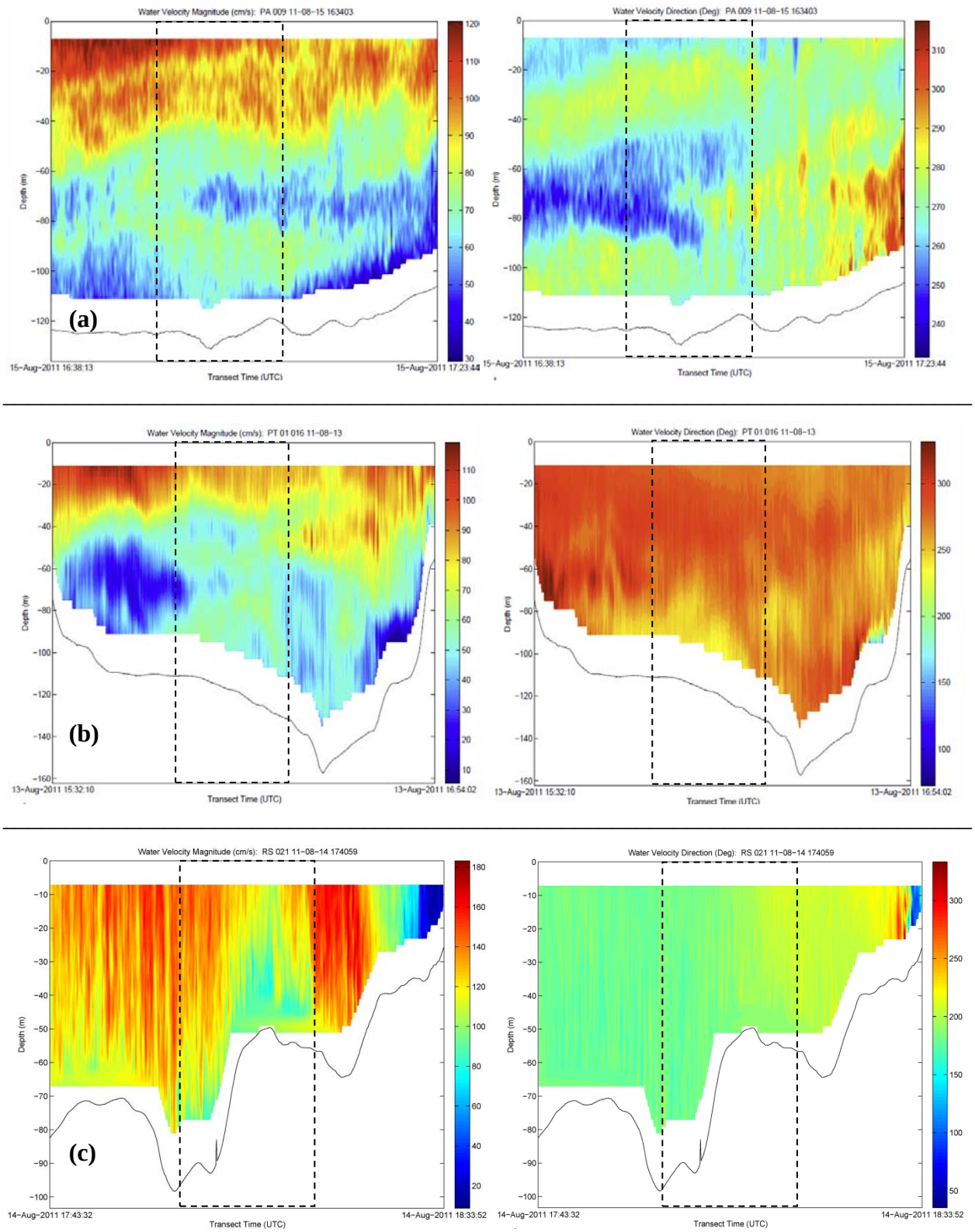

Figure 13. Peak ebb velocity and direction (a) Port Angeles at 15 Aug 2011 1700 UTC (b) Port Townsend at 13 Aug 2011 1600 UTC (c) Rosario Strait at 14 Aug 2011 1800 UTC (Approximate PSDDA site boundary denoted by dashed line)

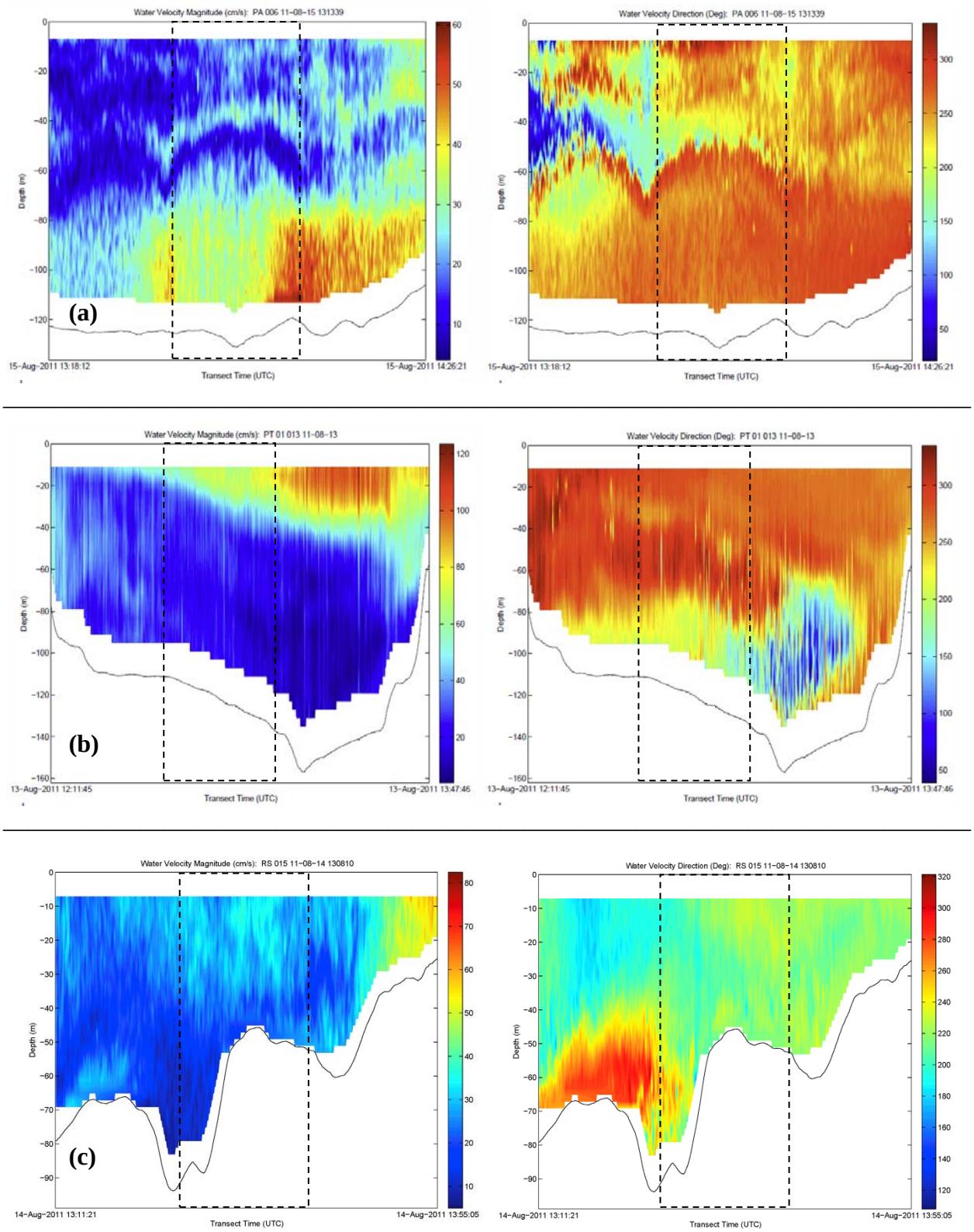

Figure 14. Slack tide velocity and direction at disposal site (a) Port Angeles at 15 Aug 2011 1400 UTC (b) Port Townsend at 13 Aug 2011 1300 UTC (c) Rosario Strait at 14 Aug 2011 1300 UTC (Approximate PSDDA site boundary denoted by dashed line)

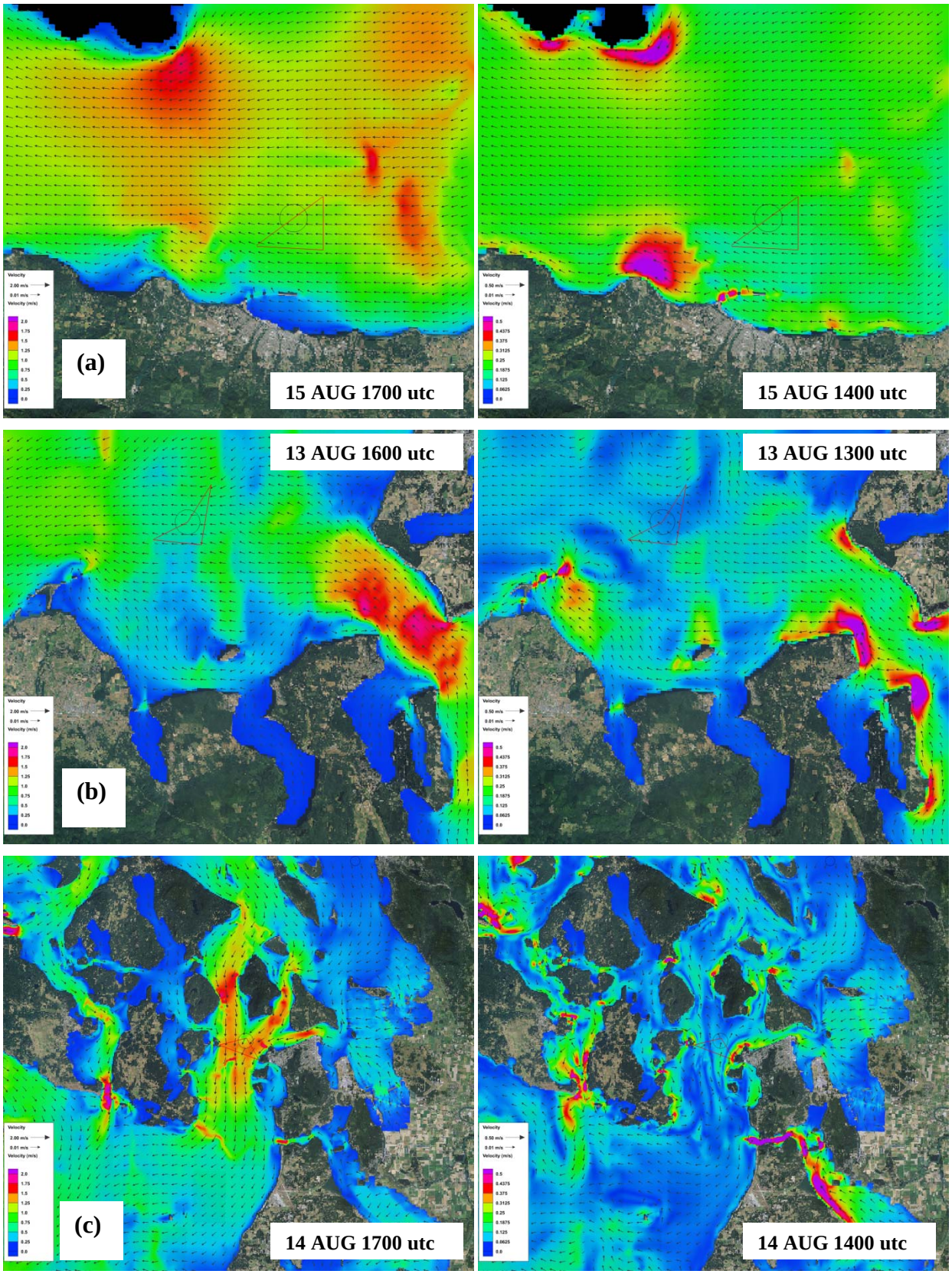

Figure 15. Modeled ebb (left) and slack (right) velocities (a) Port Angeles (b) Port Townsend (c) Rosario Strait

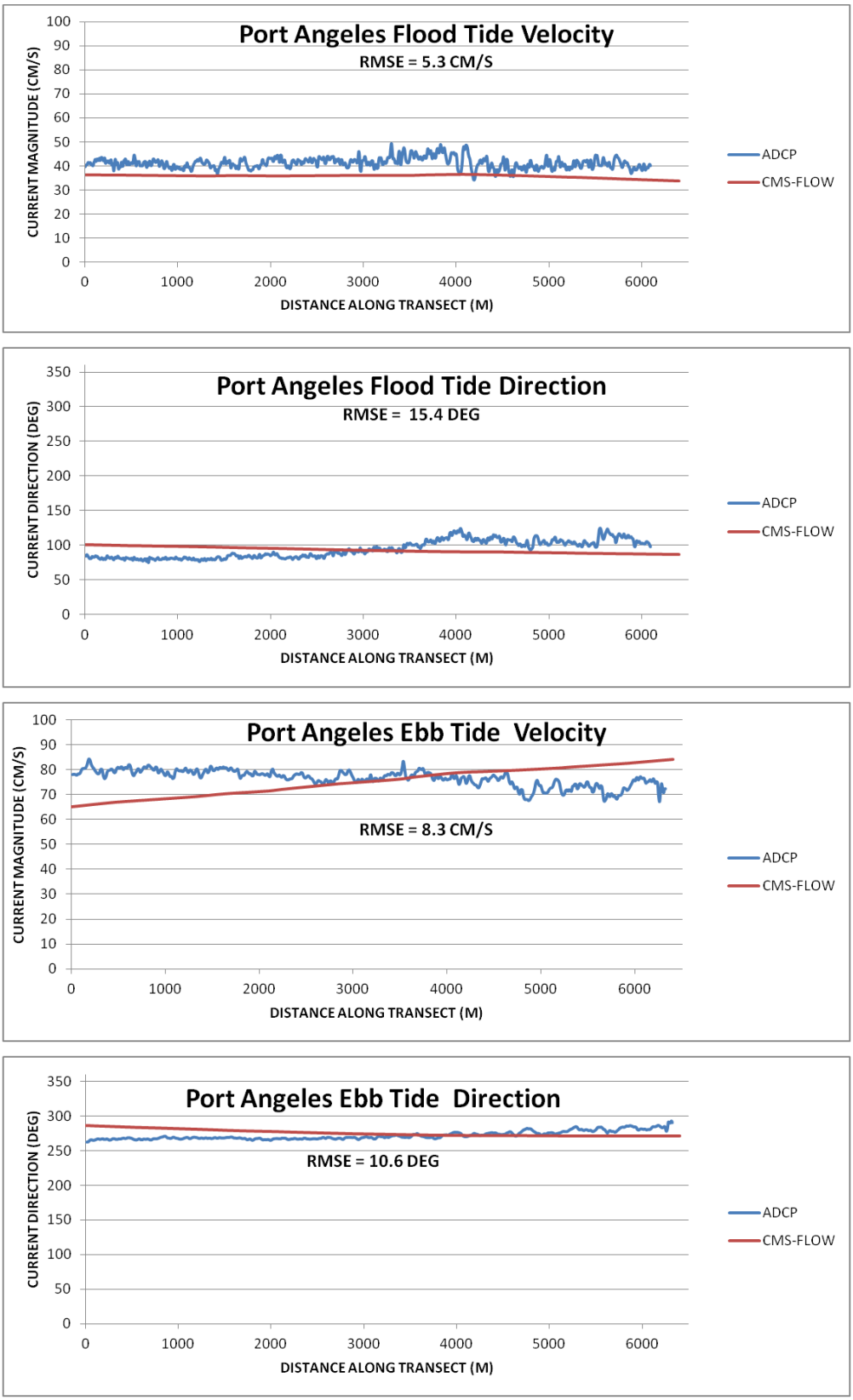

Figure 16: Port Angeles Site measured (blue) vs. modeled (red) velocity and direction. ADCP Transects PA_003 (Flood) and PA_009 (Ebb).

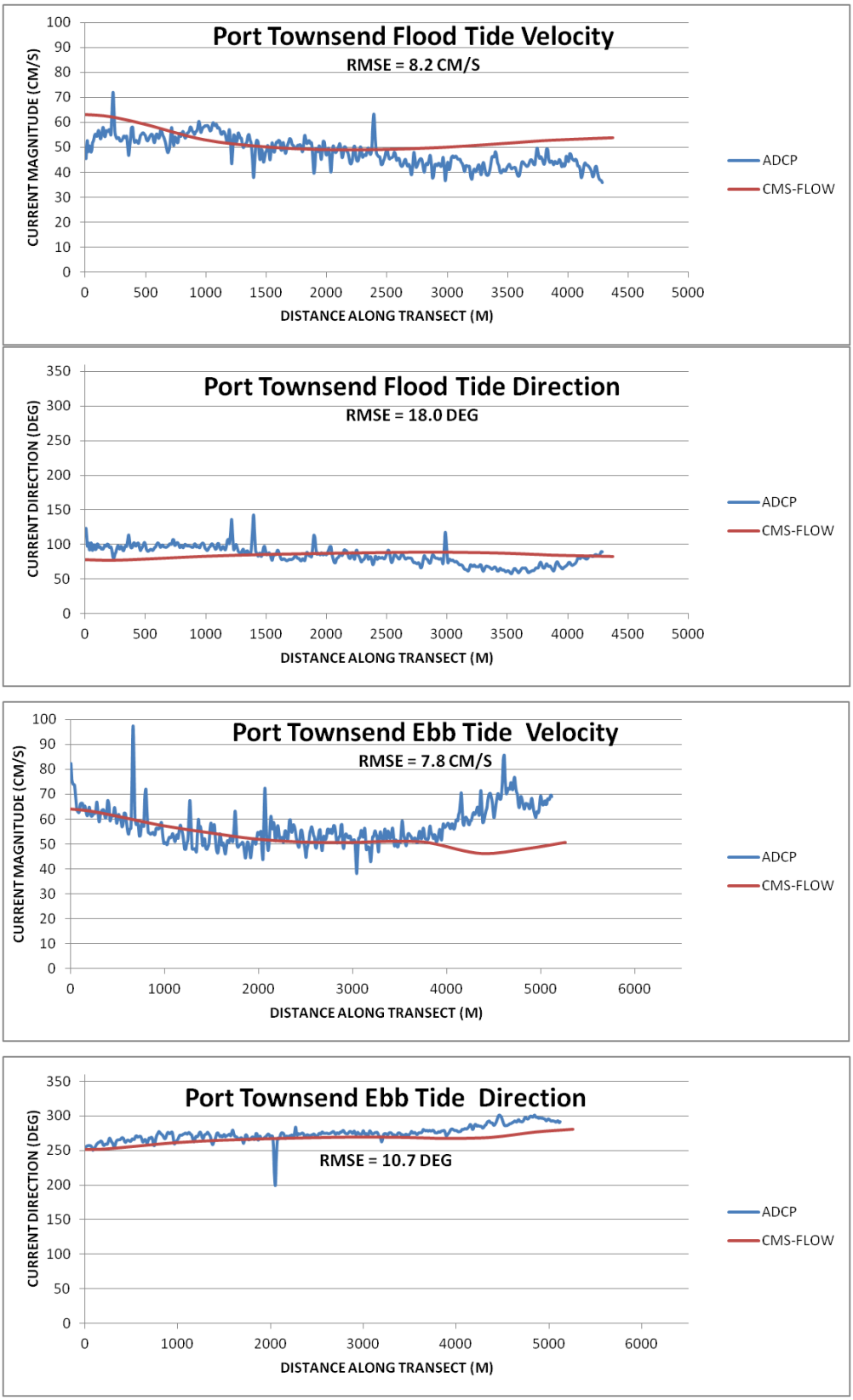

Figure 17: Port Townsend Site measured (blue) vs. modeled (red) velocity and direction. ADCP Transects PT_01_ 021 (Flood) and PT_01_014 (Ebb).

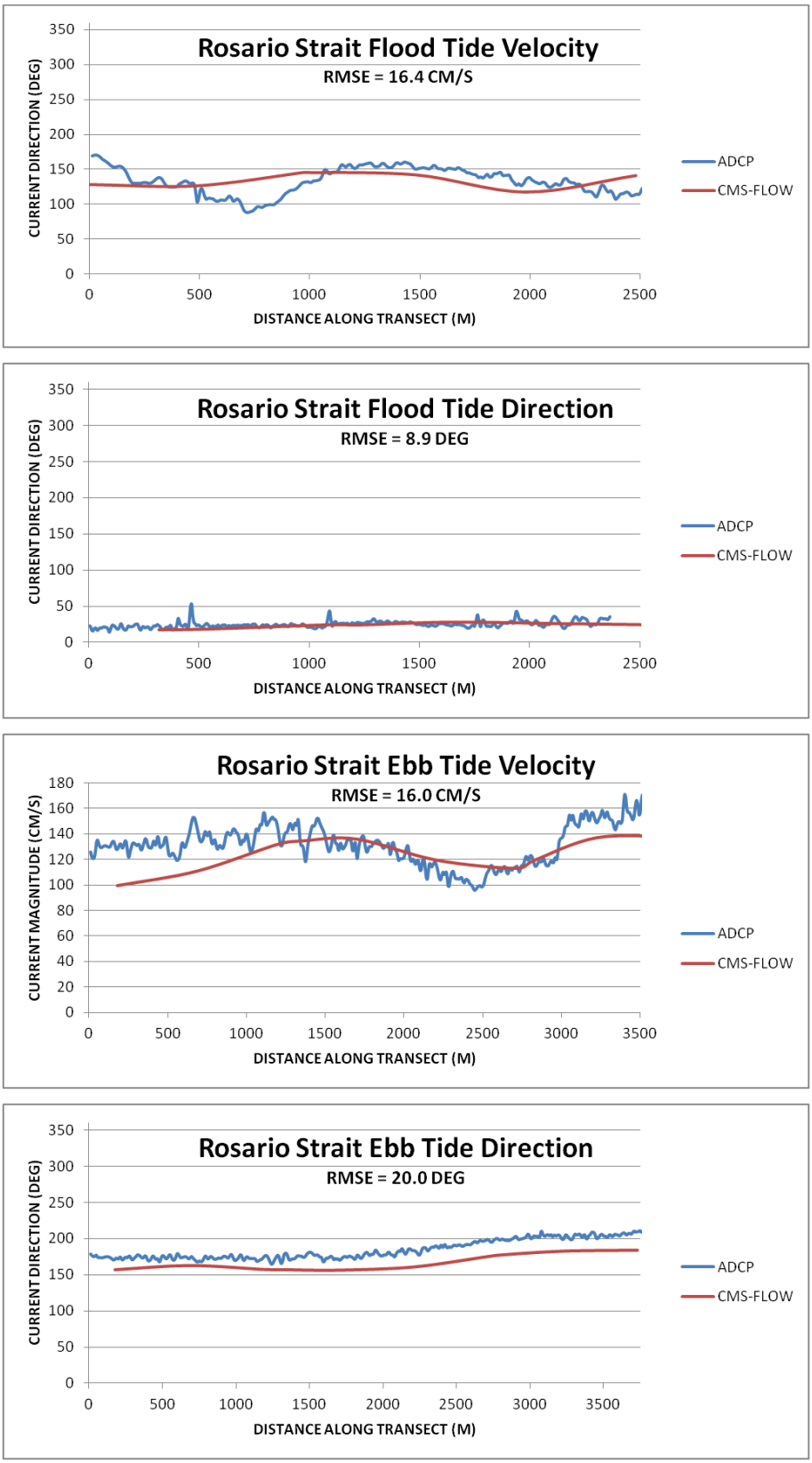

Figure 18: Rosario Strait Site measured (blue) vs. modeled (red) velocity and direction. ADCP Transects RS_034 (Flood) and RS_021 (Ebb).

2.4 Particle Tracking Model

2.4.1 Physical disposal process

Dredged material placed at the dispersive sites is typically dredged by mechanical clamshell bucket. Dredged material is then loaded into a barge and transported via tug to the PSDDA site. Dredged material is typically loaded into bottom dump scows which release the sediments into the water column a few feet below the water surface. On smaller dredging projects consisting of only a few disposals, flat deck barges have been used in the past. During these disposals dredged materials are mechanically transferred off the deck directly into the water column at the surface. Dump logs obtained from DNR were used to specify model parameters such as source rates (mass per unit time), vessel characteristics, and vessel position at the beginning and end of a dump.

2.4.2 Model setup

In order to simulate the disposal of dredged material the disposal sites were specified in the PTM as point mass rate source inputs. The amount of sediment dumped by one barge was specified using DNR dump logs. 700 cubic yards (cy) per disposal was specified at Port Townsend and Port Angeles and 1000 cy per disposal was specified at Rosario Strait. The release of sediment parcels was specified to occur over a 15-minute duration within a 165 foot (50 meter) radius of the disposal site centers.

Table 3 lists six scenarios simulated in the PTM which include both fine and coarse grained sediments. Historic dumps at the Port Townsend and Rosario Strait sites have included silts and clays (grain size d<0.075 mm) and sands (grain size d > 0.075 mm) at the dispersive sites over the 21 years the sites have been utilized. The Port Angeles site has only been utilized one time and this disposal event consisted of a majority of fines (53.3%). A hypothetical scenario simulating sands placed at the Port Angeles site is also included for comparison. Here, the same sediment characteristics for the Port Townsend scenario are assumed. The sand scenarios specify median grain size of d_{50} = 0.1 mm for Port Angeles and Port Townsend sites and 0.2 mm for the Rosario Strait site. Each assumes a standard deviation of 0.8φ[3] about the median grain size to represent a typical sediment distribution. In the fines scenarios, the median grain size is specified as d_{50} = 0.03 mm for the Port Townsend and Port Angeles disposal events. The Rosario Strait site received very fine grained material from the Squalicum Waterway in DY92; for this scenario a d_{50} = 0.002 mm is specified. Values for fall velocity and critical shear stress were left as the default values in the model. Specific gravity of all sediments is assumed as 2.65. The simulation run time is specified to 72 hours to compute short term fate only.

2.4.3 Model results

Figures 19-24 display the results from the PTM at 15 minutes, 6 hours, 12 hours, 24 hours, 48 hours, and 72 hours after a dump for each sediment type. In order to assess the relative influence of dredged material fate on shellfish harvesting areas near each site, the locations of designated Washington Department of Fish and Wildlife (WDFW) Wild Stock Commercial

[3] Phi scale is represented as $\varphi = -\log_2 d$, where d is the grain size diameter

Geoduck Clam Fishery units are overlaid onto the model results. The yellow polygons, provided by WDFW, represent the known geoduck resources co-managed by the Tribes and State.

Table 3. Representative disposal scenarios for modeling.

Scenario	Project	DMMU	DMMU Volume (CY)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	d_{50} (mm)
Port Angeles (*sand*)[1]	USACE Port Townsend O&M (DY09)	C2	500	0.6	5	94.9	0.3	0.1
Port Angeles (fines)	Holnam Inc. / Ideal Cement (DY96)	C1	18,200	5.5	47.8	46.7	0.3	0.03
Port Townsend (sand)	USACE Port Townsend O&M (DY09)	C2	500	0.6	5	94.9	0.3	0.1
Port Townsend (fines)	Point Hudson Marina (DY06)	C1	10,300	13.8	45.7	40.4	0	0.03
Rosario Strait (sand)	USACE Swinomish (DY95)	C2	48,000	0	0	92	8	0.2
Rosario Strait (fines)	USACE Bellingham O&M / Squalicum Waterway (DY92)	C8	4,073	10.3	90.1	2.4	0	0.002

[1]hypothetical scenario; did not actually occur

2.4.3.1 Port Angeles

Figures 19 and 20 display sediment parcel location over time for the sand and fines disposal scenarios at the Port Angeles site respectively. The Port Angeles site is the most dispersive of all sites with nearly all of the material moving in an east-west trajectory concurrent with the ebb and flood tides. This pattern continues through several tide cycles resulting in wide dispersal of sediments. Fine grained sediment parcels remained active up to 19 km west of the disposal site after 72 hours of simulation. However, no sediment parcels are computed to enter WDFW shellfish areas after 72 hours for either sand or fines dumped at the site as shown in Appendix B, Figure B1.

2.4.3.2 Port Townsend

Figures 21 and 22 display sediment parcel location over time for the sand and fines disposal scenarios at the Port Townsend site respectively. At the Port Townsend site the bathymetric features (e.g. banks) limited the dispersion of material to the south and southeast resulting in a significant reduction in active sediment mobility after the first 24 hours. High current velocities result in a larger dispersal of material and transport of sediment parcels to the west up to 48 hours after disposal. Fine grained sediment parcels remained active up to 8 km west of the disposal site after 72 hours of simulation. However, no sediment parcels are

computed to enter WDFW shellfish areas after 72 hours for either sand or fines dumped at the site as shown in Appendix B, Figure B2.

2.4.3.3 Rosario Strait

Figures 23 and 24 display sediment parcel location over time for the sand and fines disposal scenarios respectively at the Rosario Strait site. The Rosario Strait site has the highest current velocities of the three sites. In the sand dump scenario, sand transported to the north can be temporarily deposited on the south side of Cypress Island on a slack tide, but is resuspended by subsequent tidal currents. Some of this northward-bound sand is eventually deposited on the north side of the island. A majority of the sand traveling southward from the disposal area is captured by Lawson Reef, the large underwater ridge shown in the figures. . In the fine grained disposal scenario, sediment parcels remained active up to 21.5 km south of the disposal site after 72 hours of simulation. Some sediment parcels were also found to enter the Whidbey subbasin through Deception Pass and into Bellingham Bay through Bellingham Channel and Guemes Channel. However, no sediment parcels are computed to enter WDFW shellfish areas after 72 hours for either sand or fines dumped at the site. While Figure 24 shows fine-grained sediment parcels being transported in the direction of the Point Partridge shellfish tract on the Northwest coast of Whidbey Island, these parcels are confined to deeper water as shown in Appendix B, Figure B-3 and have little chance of impacting this tract.

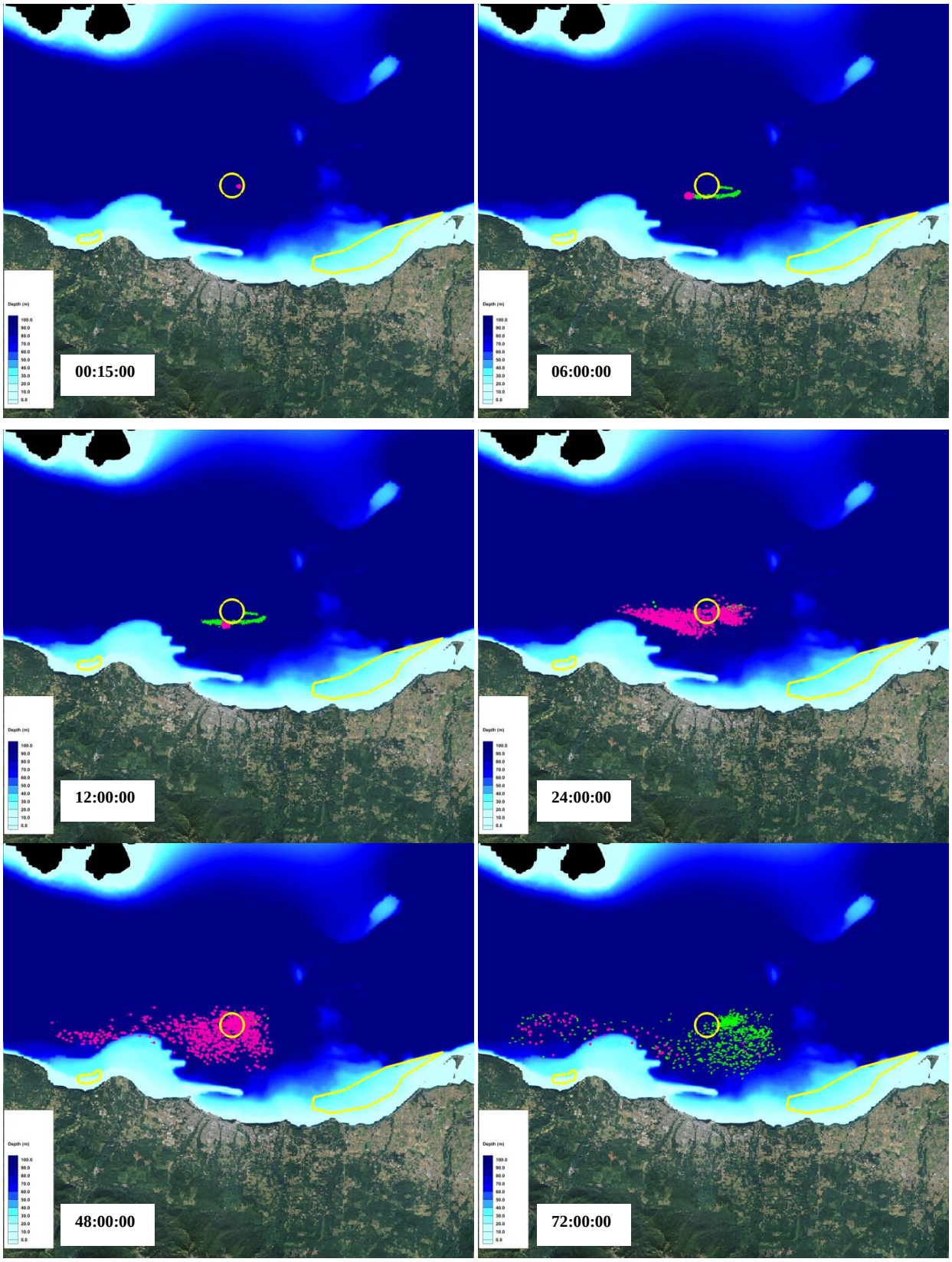

Figure 19: Port Angeles Site <u>Sands</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active parcels; Green = Dead parcels

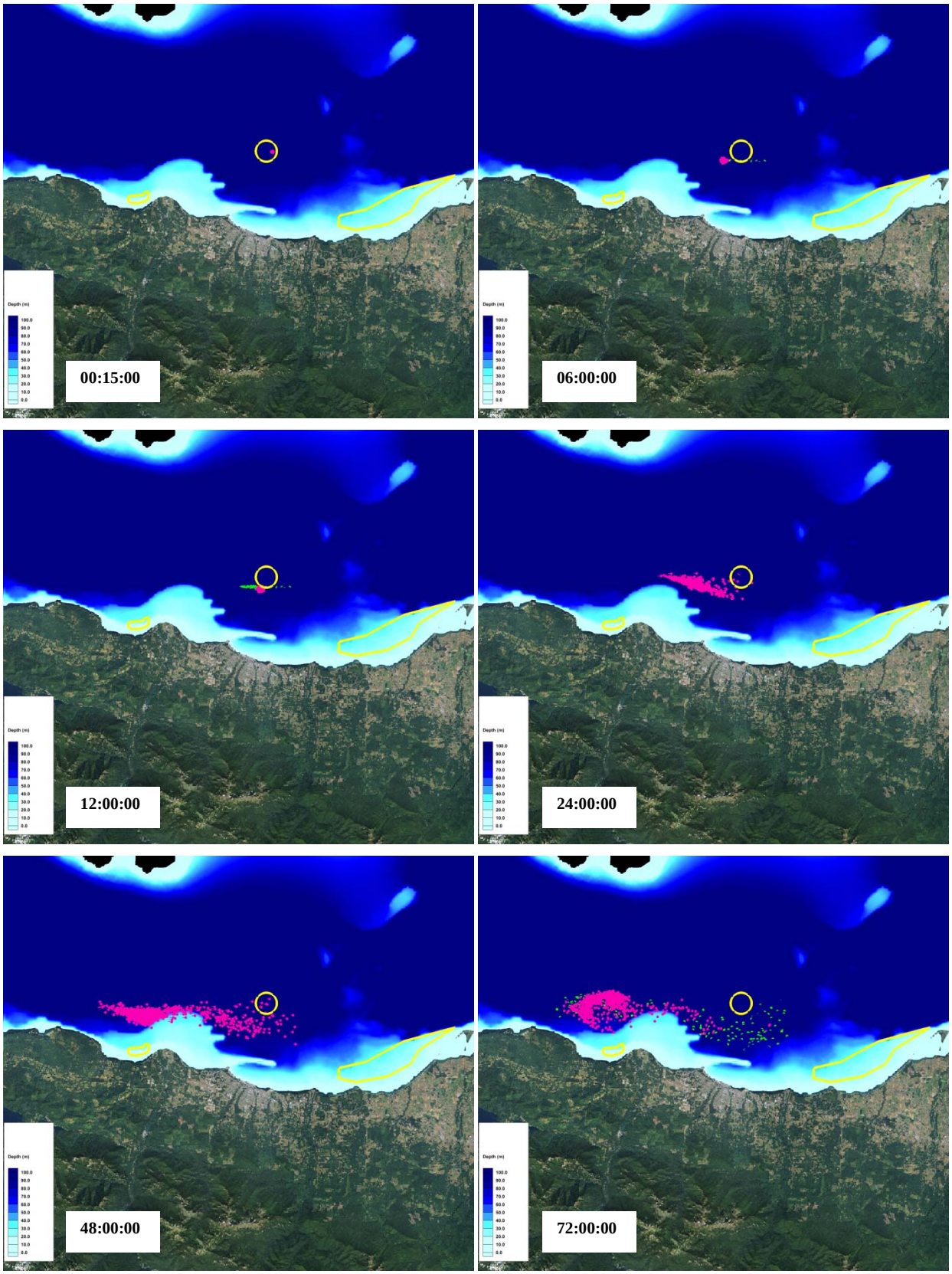

Figure 20: Port Angeles Site <u>Fines</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active parcels; Green = Dead parcels

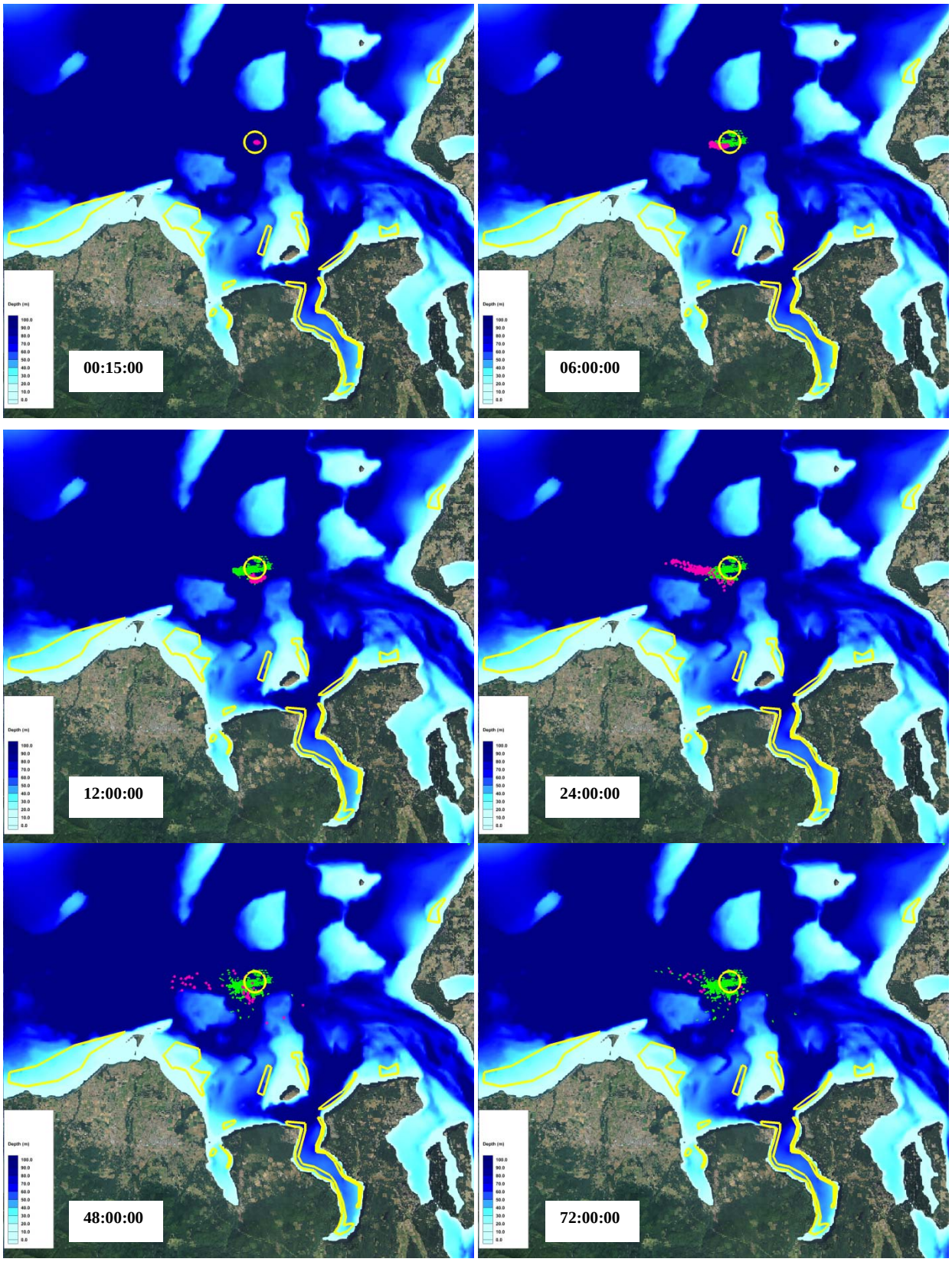

Figure 21: Port Townsend Site <u>Sands</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active parcels; Green = Dead parcels

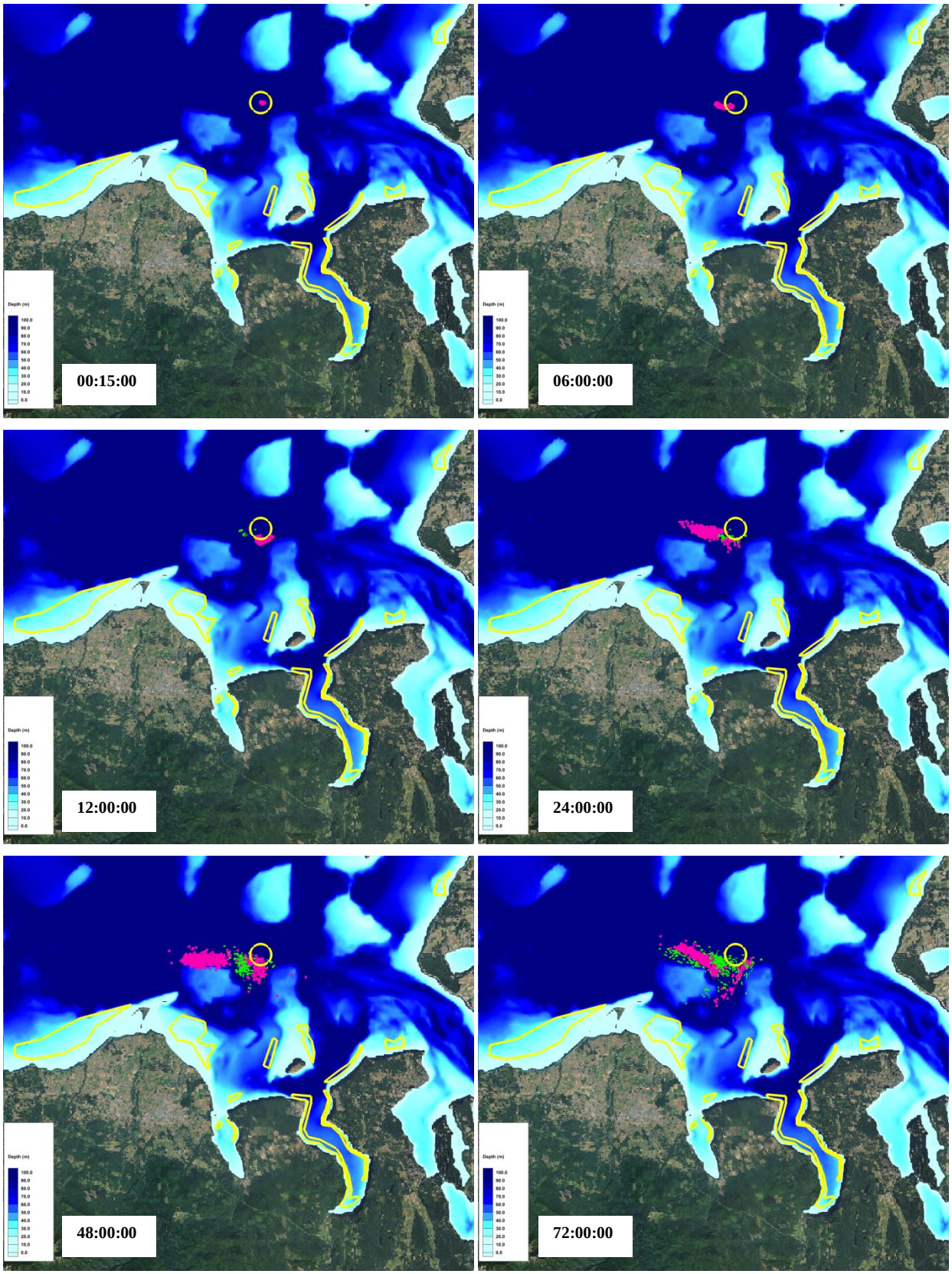

Figure 22: Port Townsend Site <u>Fines</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active; Green = Dead

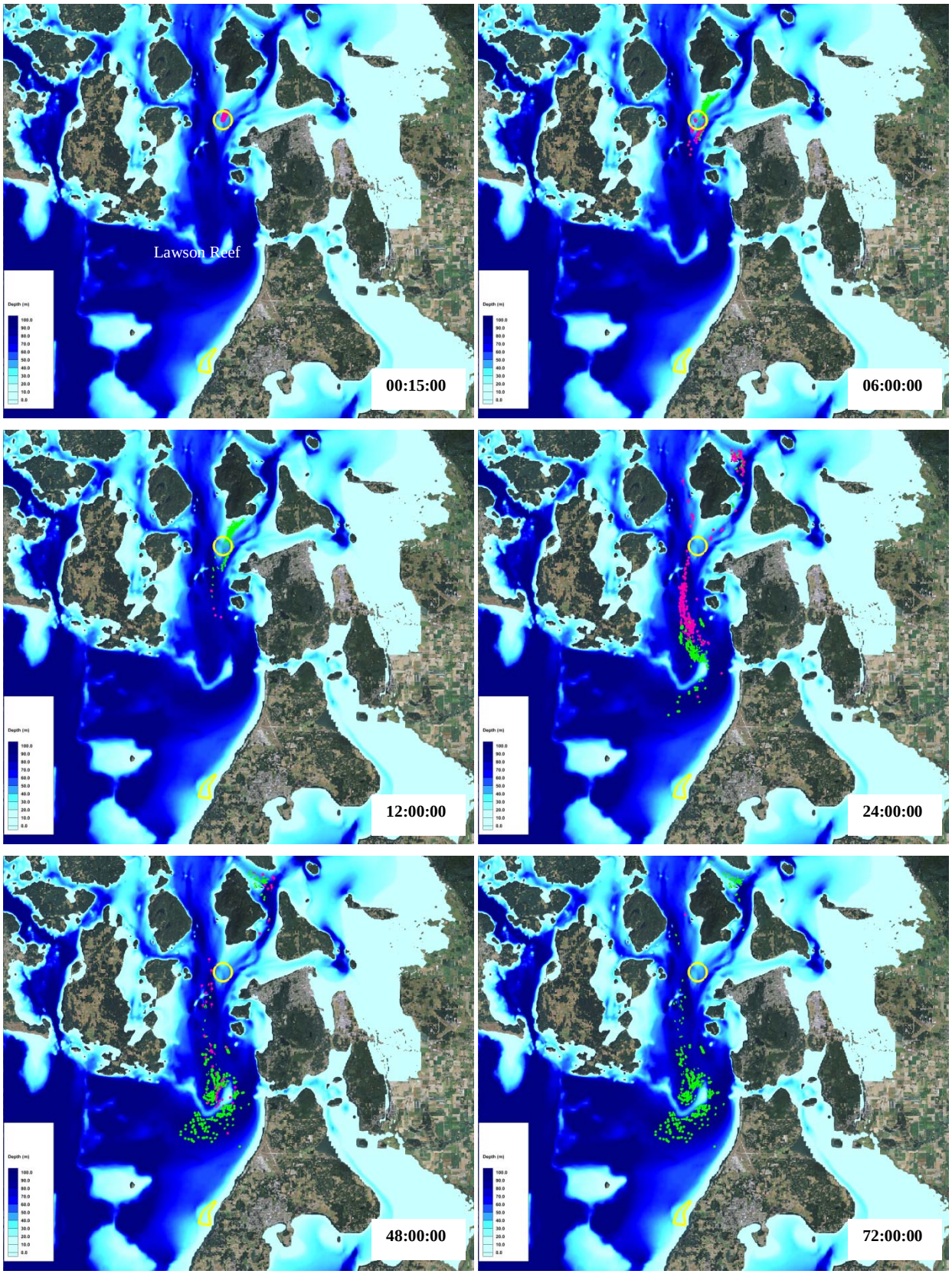

Figure 23: Rosario Strait Site <u>Sands</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active parcels; Green = Dead parcels

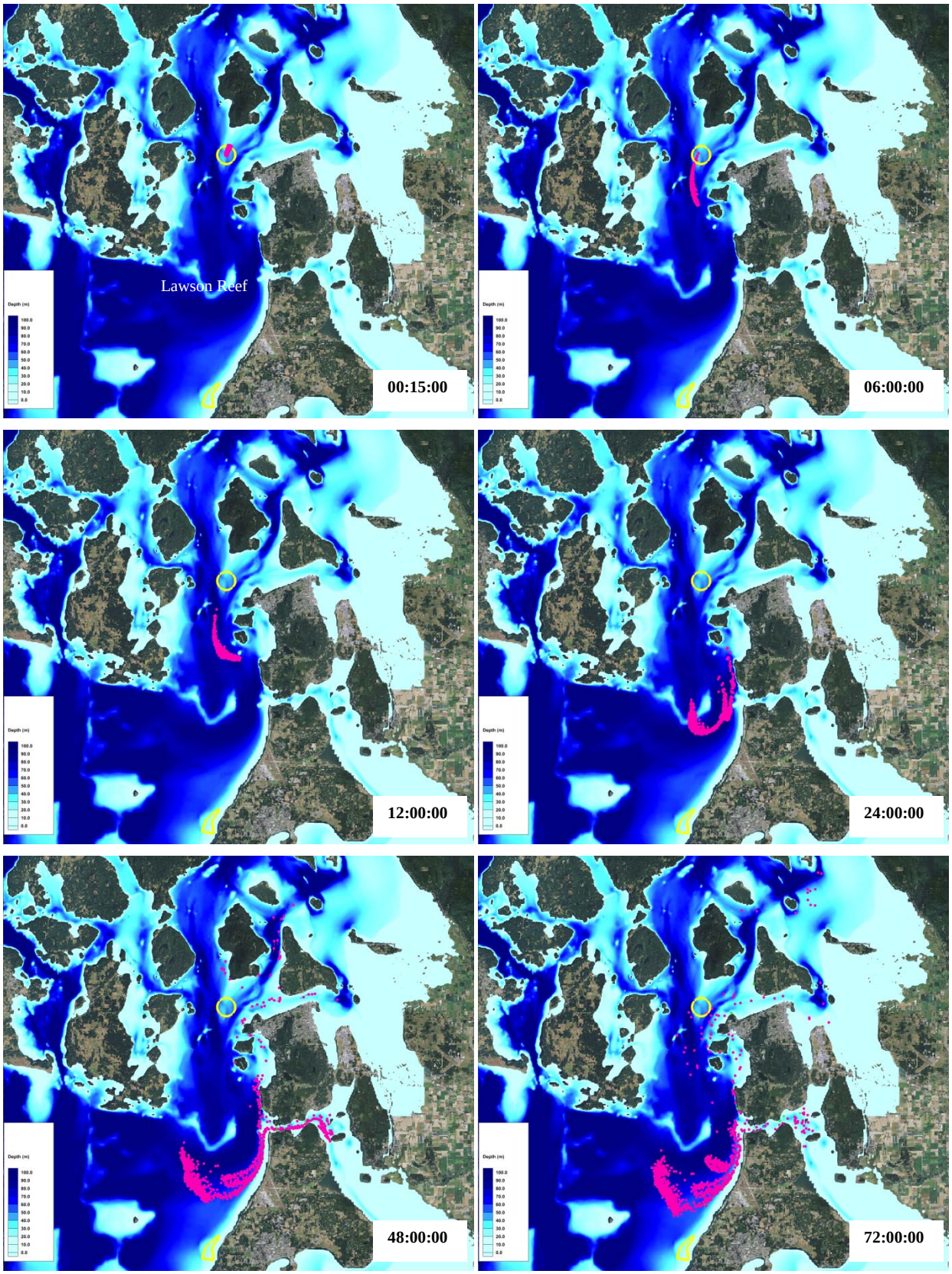

Figure 24: Rosario Strait Site <u>Fines</u> results starting 12-Aug 2011 (Yellow circle is disposal site boundary; Yellow polygons designate WDFW Shellfish Areas). Magenta = Active parcels; Green = Dead parcels

2.5 Sediment Mobility

Sediment mobility refers to conditions where sediment parcels are actively being transported by the tidal currents. A simulation period of 72 hours represents a maximum duration at which the fate and transport predictions of actively mobile sediments are believed to be dominated by tidal circulation processes and reasonably accurate. Model uncertainties increase with time and fate and transport will become increasingly dependent on meteorological processes, therefore predictions after this time were not analyzed in the modeling analysis. Figure 25 shows the percent of sand sediment parcels (e.g. sand scenario) which are actively mobile at each disposal site up to 72 hours following a dump event. The following observations were made from the sand scenario model results:

- *Port Townsend:* Model results indicate more than 80% of the sediment parcels deposited on the seabed ("dead") within the first 12 hours after disposal and 90% of the sediment parcels are inactive after 36 hours.
- *Rosario Strait*: Approximately 20% of the sediment parcels deposited in the first 12 hours after disposal. The remaining 80% of sediment parcels remained active up to 36 hours following disposal. However after 60 hours more than 90% of the sediment parcels were predicted to be deposited on the seabed.
- *Port Angeles:* Close to 100% of the sediment parcels remained active after 72 hours indicating that this site is the most dispersive of the three disposal areas. During each peak ebb and flood, sediment parcels would be resuspended and dispersed.

In the fines disposal scenarios, shown in Figure 26, a portion of sediments placed at all three sites maintained mobility in the water column following the 72-hour simulation period. However, model simulations indicate that 99% of sediment parcels were located below the 1-meter surface layer after 18 hours. Table 4 shows the percentage of sediment parcels located in the top 20 meters of the water column at the same time intervals displayed in Figure 24. The following observations were made from the fines scenario model results:

- *Port Townsend and Port Angeles:* After 24 hours less than 10% of sediment parcels placed at the site are within the top 20 meters of the water column and after 72 hours less than 3% remain there.
- *Rosario Strait:* Due to the amount of clay and silt in dredged material from the Squalicum Waterway, approximately 41% of the sediment parcels remained in the top 20 meters after 24 hours in the simulations. These fines were predicted to remain suspended in the top 20 meters layer even after 72 hours.

The results suggest that fine-grained sediments remain in the water column and are highly dispersive for an extended period of time following disposal. However, very little of the suspended sediment remains in the top meter of water. Wind-generated currents that are capable of transporting suspended materials shoreward are primarily contained within the top 1-meter surface layer. Therefore, there exists a relatively low potential for onshore transport of dredged material placed at any of the three disposal sites. In some instances vertical mixing caused by

density gradients may contribute to resuspending a fraction of sediments into the upper 20 meters of the water column. These effects may be more pronounced in the Strait of Juan de Fuca during periods of ocean upwelling on the Pacific Ocean and near freshwater river plumes (e.g. near the Elwha and Dungeness River deltas).

Table 4: Percent of Initially Released Material Residing in Top 20 Meters of Water Column (Fines Scenario).

Percent of Initially Released Fines Residing in the Top 20 Meters of the Water Column						
Time Since Disposal (Hours)	**0.25**	**6**	**12**	**24**	**48**	**72**
Port Angeles	100%	49%	25%	7%	9%	3%
Port Townsend	100%	72%	37%	10%	8%	1%
Rosario Strait	100%	55%	57%	41%	42%	39%

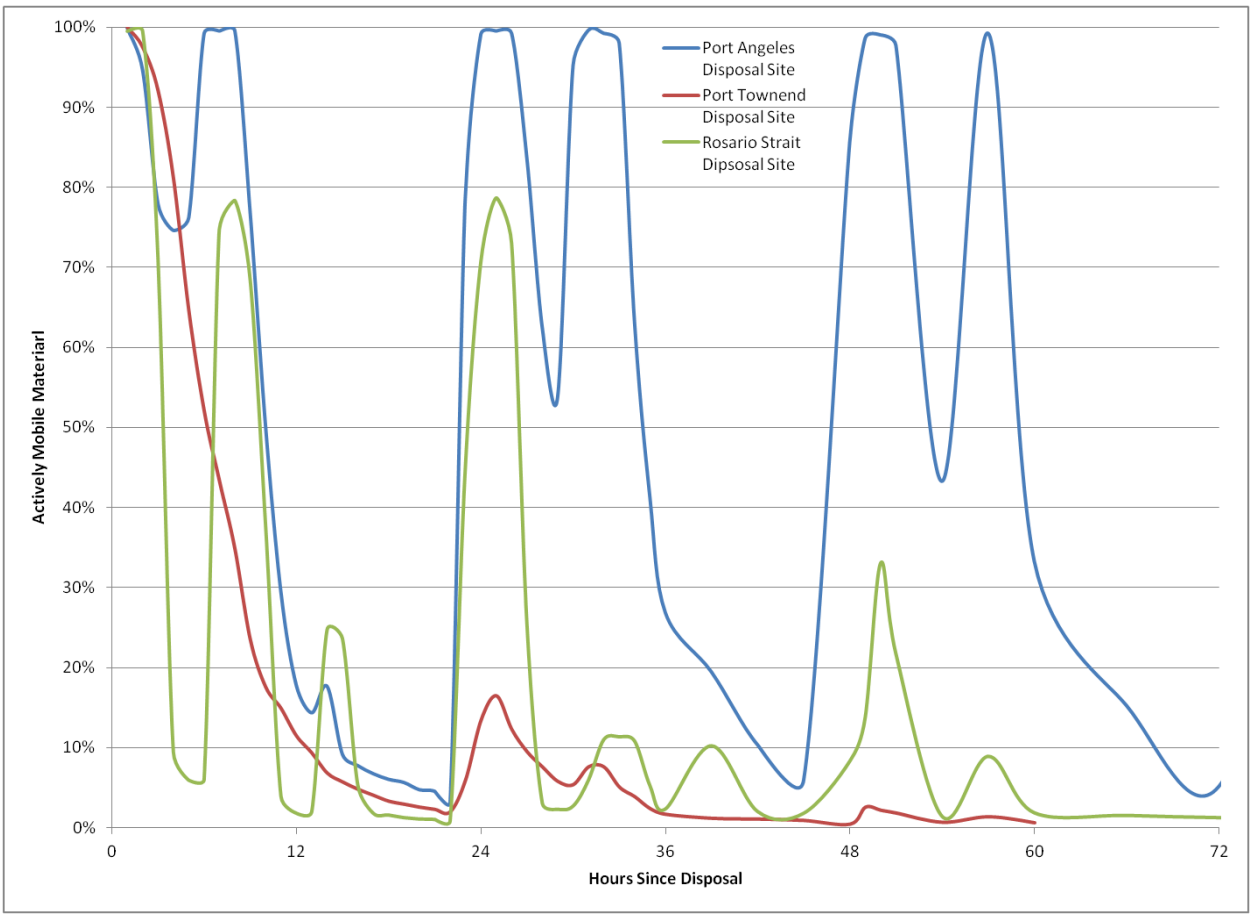

Figure 25: Dredged material particle mobility as a function of time (sand scenarios)

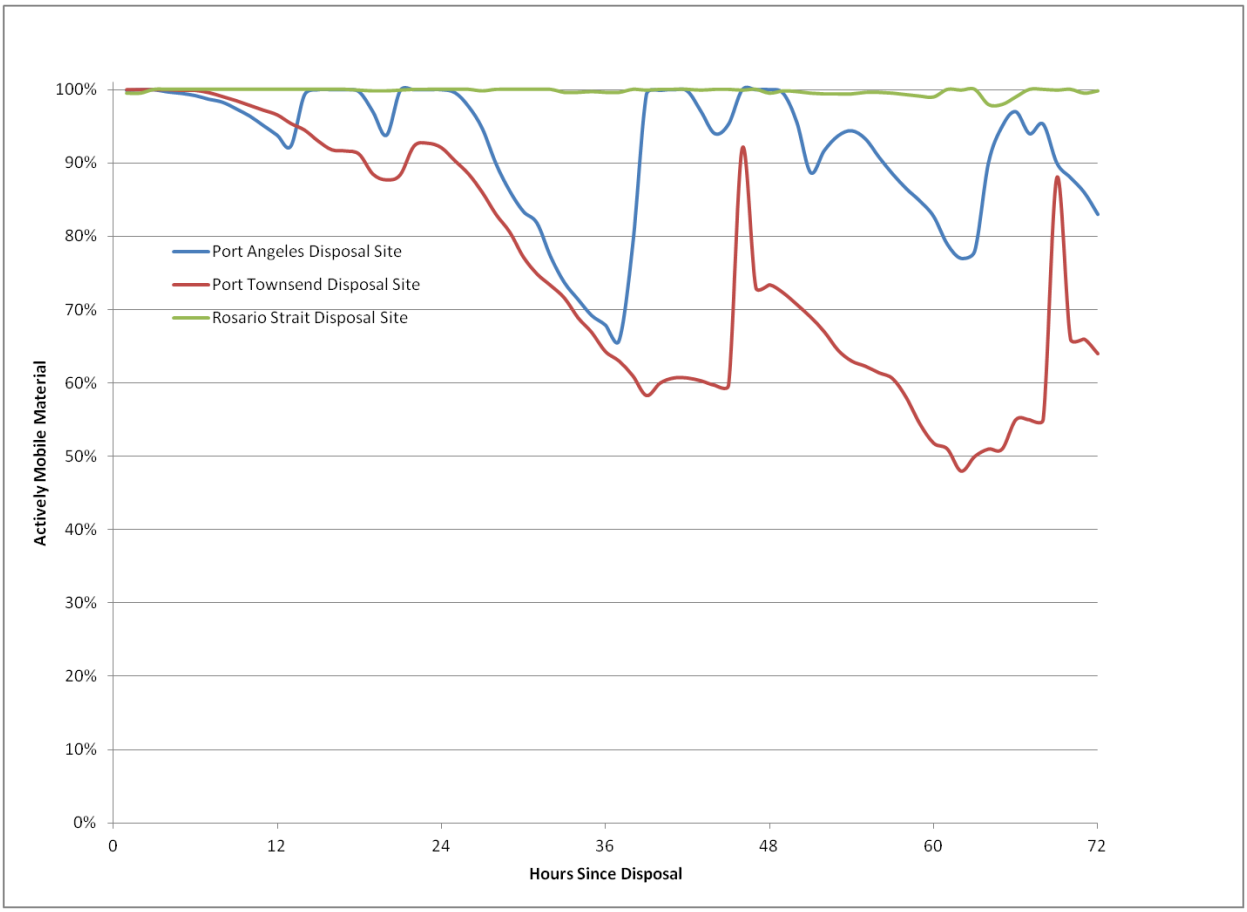

Figure 26: Dredged material particle mobility as a function of time (fines scenarios)

3 Conclusions

The CMS-FLOW tidal circulation model was coupled with a Lagrangian particle tracking model to predict the fate of dredged material placed at three dispersive dredged material sites located in Puget Sound and Strait of Juan de Fuca waters. CMS-FLOW water levels and tidal currents were validated with measured water level and ADCP velocity survey data. The measured data indicate vertical stratification in velocity and direction exists in the water column, primarily at the Port Angeles and Port Townsend sites during slack water conditions. Model results accurately predicted the vertically uniform currents observed near Rosario Strait. RMSE of the depth-averaged velocities across each ADCP transect varied from 5 to 16 cm/s between the observed and modeled currents.

The PTM results suggest dredged material placed at each site generally has transport pathways following the net current direction at the site. It was determined the most significant parameter affecting dredged material fate was sediment grain size. This was determined through modeling six different scenarios representing placement of both fine-grained (clays and silts) and coarse-grained (sand) sediment at each of the three PSDDA dispersive sites.

In general, coarser-grained sand sediments followed the principal current directions. These were east-west at the Port Angeles and Port Townsend sites and southwest-northeast for the Rosario Strait site. At the Port Townsend site the bathymetric features (e.g. banks) limited the dispersion of material, resulting in a significant reduction in active sediment mobility after the first 24 hours. Similar bathymetric features (e.g. Lawson Reef) exist south of the Rosario Strait site, restricting sediment transport southward of this feature. Still, high current velocities in Rosario Strait result in a larger dispersal of material and mobility of sediment parcels up to 48 hours after disposal. The Port Angeles site was found to be the most dispersive site with sediment remaining active after 72 hours. It was found that nearly 100% of sand remobilized after reaching the seabed during the next ebb and flood tide cycle.

Finer-grained material remained in the water column longer due to longer fall times. As a result, these sediments were found to travel farther than coarser-grained sediments. This was particularly the case at the Rosario Strait site where some sediment parcels were found to enter the Whidbey subbasin through Deception Pass. Other sediment parcels reached Bellingham Bay through Bellingham Channel and Guemes Channel and remained mobile following the 72-hour simulation time.

Using available information on shellfish areas from WDFW, the effect of sediments placed at the dispersive sites was investigated. The simulations show the vast majority of sediment parcels staying in deep water, away from the shoreline where shellfish beds are located. In none of the six scenarios did any of the disposed dredged material enter the shellfish areas during the 72-hour simulation period. This suggests that tidal circulation plays a prominent role in dispersing sediment but does not actively transport sediment in significant quantity toward critical shellfish habitat.

Wind-generated currents that might transport sediment parcels toward shore are generally restricted to the top meter of the water column. The modeling results show that 99% of the fine-grained particles have settled to depths greater than 1 meter after 18 hours, where wind-generated currents would have little effect.

At the Port Townsend and Port Angeles sites, at least 90% of the fine-grained particles have descended to depths greater than 20 meters after 72 hours. Commercial geoduck tracts only extend to depths of 70 feet (21 meters), so are largely out of the depth range of fine-grained material after that time. Since the modeling showed that none of the material had entered any of the shellfish beds within the first 72 hours, and because most of the disposed material had descended to depths deeper than the shellfish beds after that time, it is improbable that dispersive disposal would result in significant impacts to the commercial shellfish beds co-managed by the Tribes and State.

The Rosario Strait and Port Angeles sites are highly dispersive. Accumulation of fines at any one place is miniscule. Therefore, even in the event that some fine-grained particles reach the shellfish beds, the contribution to local concentrations of chemicals-of-concern, such as dioxin, would be negligible. The Port Townsend site, while still dispersive, is much less so than the other two sites. But here the majority of the disposed material stays far off shore, away from shellfish beds. It should be noted that, while less dispersive than the other two sites, the disposal of dredged material at the Port Townsend site does not result in mounding on the seafloor, due to the size of the area over which the material is dispersed.

These interpretations come with the caveat that the CMS-FLOW tidal circulation model is limited to depth-averaged currents and is not capable of representing the effects of vertical mixing associated with freshwater river input and the associated changes in currents and density through the water column. Measured data indicate that depth-averaged currents (or uniform flow) is a valid assumption for predicting fate and transport at the Rosario Strait PSDDA site. The Rosario Strait site has received the largest amount of dredged material of any of the dispersive sites and confidence in model results is greatest there. However, at the Port Townsend and Port Angeles sites vertical stratification of currents was observed, indicating more complex circulation. Additionally, high river discharges such as the Elwha River plume (Warrick et al. 2011) influence circulation and may also influence fate and transport of sediments placed at the Port Angeles site. Representing these processes would require a three-dimensional circulation model. However, due to the limited historical usage of the Port Angeles site, a complex and computationally intensive modeling effort does not seem to be justified at this time.

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