Golder Associates Inc.

18300 NE Union Hill Road, Suite 200
Redmond, Washington 98052
Telephone: (425) 883 0777
Fax: (425) 882 5498

REPORT ON

CLAM HABITAT IMPACT MODELING AND ANALYSIS

Submitted to:

Pacific International Engineering

for

KITSAP TRANSIT

RICH PASSAGE PASSENGER ONLY FAST FERRY STUDY

Submitted by:

Golder Associates Inc.
18300 NE Union Hill Road, Suite 200
Redmond, Washington 98052

Distribution:

1 Copy - Pacific International Engineering
1 Copy - Golder Associates Inc.

April 23, 2009 | 083-93642.300

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

In order to assess the potential impact of passenger-only fast ferries (POFF) on clam habitat in the Rich Passage – Sinclair Inlet area, a series of computer model-based analyses were conducted in 2008 and 2009. This work makes use of and extends similar modeling work conducted for the Rich Passage Passenger-Only Fast Ferry Study (Osborne and MacDonald, 2007).

This memorandum begins with a description of the clams in the area and identifies aspects of their habitat that could be adversely impacted by POFF operation. This is followed by a description of the design, application and findings of a modeling study of potential impacts.

2.0 BACKGROUND

2.1 Hardshell Clams

The two most common species of hardshell clams found on beaches in the Rich Passage area are the non-native Manila clam (*Ruditapes philippinarum*) and the native little neck clam (*Protothaca staminea*) (Figure 1). These species are similar in size and shape, and in habitat requirements. They occupy similar substrates at the middle to lower intertidal elevations, with the native littleneck tending to be at lower elevations than the Manila clam..

Figure 1: Hardshell calms found in the Rich Passage area. Left: little neck clam (*Protothaca staminea*); Right: Manila clam (*Ruditapes philippinarum*)

2.2 Factors Affecting Clam Populations

Many factors can impact clam populations within Puget Sound. These include loss and alteration of habitat, change in sediment type, pollution, and plankton type and abundance. Development and shore armoring affect clam beds during construction by disturbing the beaches and can continue affecting the system after construction by reducing the supply and quality of sediment. High energy wakes created by previous POFF operations removed fine sediment required for clams, and shore protection has reduced the sediment supply in many areas, limiting the ability for recovery. Pollution in Rich Passage, as well as many other areas of Puget Sound is an issue; all beaches within the study area are closed to shellfish harvest due to pollution.

Clam survival is influenced directly by the physical characteristics of the intertidal substrate. Hardshell clams commonly live at middle to lower intertidal elevations in moderately sloping beaches with a gravel, sand, silt, and shell substrate. Because beaches are dynamic entities, the composition of the substrate is determined by the supply of soil materials together with the wave energy that transports the materials to and from the beach. The wave climate that moves new materials to the beach will also remove materials from the beach if the source of supply is removed or interrupted, resulting in a change in the substrate characteristics toward larger or harder material resistant to the wave energy. The sediment supply and transport conditions determine the physical characteristics of the substrate and its suitability for hardshell clam survival and growth.

Young clams are not likely to survive on beaches with an interrupted sediment supply and/or naturally exposed to high levels of wave energy. High wave energy removes the fine sediment (sand-silt) that is present within the gravel of beaches that support clams. Without a continuous supply of these materials the transport away from the beach will exceed transport to the beach, producing a larger or harder substrate composition unsuitable for hardshell clams. With high energy conditions the young clams tend to be removed with the fine sediment, or crushed by the moving larger material (gravel-cobbles).

Relatively low energy beaches with low levels of wave action retain sand and silt producing a relatively compact gravel, sand, mud and shell substrate that supports clam survival and growth. The gravel/sand/shell substrate provides relatively compact substrate conditions unfavorable for clam predators (crabs and diving ducks). Very low wave energy conditions that are present in accretion areas result in high levels of silt and clay-sized substrate material. Substantial amounts of these fine particle sizes also produce conditions that are not favorable to survival of hardshell clams

2.3 Study Areas

Surveys of the Rich Passage area by the project team led to the identification of two areas clam populations: Point White and Point Glover (Figure 2). The beaches in these areas contain a percentage of shell hash derived from local clam populations. The assessment described in the present memorandum will focus solely on these two areas.

Figure 2: Rich Passage, showing evidence of clam presence (solid white polygons).

3.0 MODEL ASSESSMENT

The preceding section highlighted the sensitivity of the two species of clams to two phenomena that can be directly linked to vessel operation: wave action and sediment disturbance. This section will describe a modeling program that uses these two phenomena as measures to assess the impact of POFF operation.

Wave action on the Rich Passage beaches can result from both wind waves and wakes. Although the headland at Point White is more exposed to wind waves than the beaches along Point Glover, neither has a sufficiently intense wind wave climate to ignore vessel wakes. Since wind waves are independent of vessel wakes, they will not be investigated in this memorandum. Wakes are produced by all vessels that transit the area but, since we are only interested in larger wakes that can mobilize sediment, only those that result from WSF ferry operations or POFF operations are of interest.

Sediment disturbance can be caused by tidal and wave action. The dominant process depends on the location of the point of interest. The relative influence of tidal and wave action on the disturbance of fine sediments varies across a beach profile; waves tend to dominate on the upper beach, whereas tidal currents dominate the areas below low water. From a plan perspective, areas exposed to longer fetches or closer to the ferry sailing route tend to be more disturbed.

3.1 Metric Selection

Care must be taken in selecting a metric by which to assess an impact indicator. In the case of wave action, an overly calm climate may be as valueless as an overly intense climate, since this may lead to a surplus of fines (silts and clays). This should not be the case in Rich Passage with its strong tidal currents and wind waves. Therefore, we will focus this part of our analysis on increases in wave action that would tend to move the gravel-cobble bed or remove the fine sands and silts necessary for clam survival.

It is also important to provide a spatial balance to the assessment; this will be done in two ways. First, the relatively extensive and variable Point Glover shore (see Figure 2) will be divided into four separate study polygons, whereas the Point White shore is small enough to be included in a single polygon (Figure 3). Second, the metrics used will all take into account the area over which the impact occurs so that any localized "spike" in the solution does not dominate other, more representative results. Wakes are transient events; therefore, the impact assessment must also include the duration of any activity. This will allow the impact of wake events of different lengths to be compared

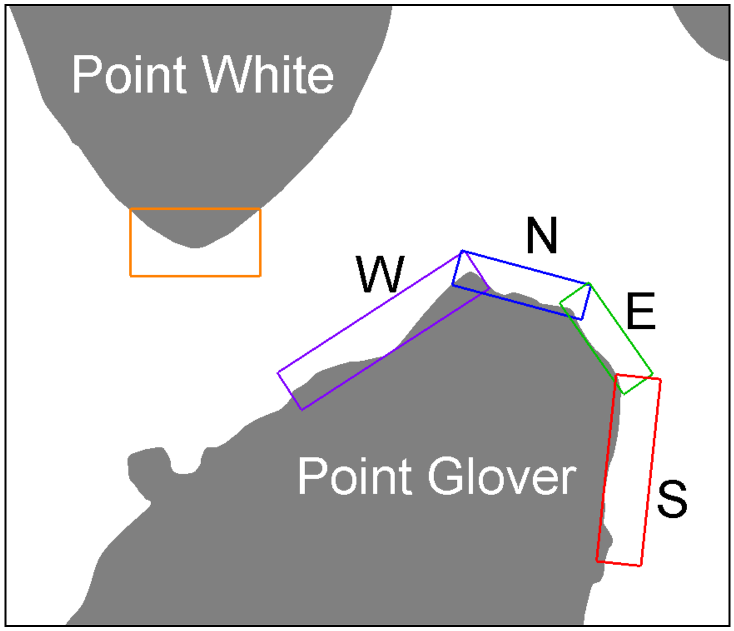

Figure 3: Assessment polygons: Point White (orange); Point Glover West (purple); Point Glover North (blue); Point Glover East (green); Point Glover South (red).

The metrics selected for use in this study are given in Table 1. They are described in detail in the following sections.

TABLE 1

Impact indicators and metrics

Indicator	Metric
Wake intensity	seabed stress beyond that sufficient to mobilize gravel
Sediment disturbance	potential quantity of fine sand transport

3.1.1 Wake Intensity Indicator

The wake intensity indicator is designed to assess disturbance of coarse bed material (i.e. rocking and rolling of gravel and cobble sized material that can damage young clams). This disturbance can be determined by quantifying the amount of movement of the coarser fraction of the bed material (i.e. D_{50} > 3 mm). The amount of movement will be proportional to the excess shear stress, M, i.e. the shear above that required to initiate movement:

$$M = \tau - \tau_{cr} \qquad (1)$$

where τ is the shear stress applied to the bed and τ_{cr} is the critical shear stress for the sediment grain. The critical shear stress for a sand grain is usually computed from the experimentally-derived Shields' curve, which here will be approximated using the formulation of Soulsby and Whitehouse (1997):

$$\tau_{cr} = \rho g D\left(\frac{\rho_s}{\rho} - 1\right)\left\{\frac{0.30}{1+1.2D_*} + 0.55\left[1 - \exp\left(-0.02D_*\right)\right]\right\} \quad (2)$$

where D is the sediment grain size, ρ is the density of the fluid and ρ_s is the density of the grain and g is gravitational acceleration. D_* is the dimensionless grain size:

$$D_* = D\left[\frac{g}{\upsilon^2}\left(\frac{\rho_s}{\rho} - 1\right)\right]^{1/3} \quad (3)$$

Here υ is the kinematic viscosity of the fluid. For the present work, the bed material will be taken as fine gravel. Assuming standard values for the physical parameters, Equation (2) yields a critical shear of 2.1 Pa for a grain size of 3 mm. It is an implicit assumption of the present work that this grain size is representative of the surface bed material.

As indicated previously, temporal and spatial information will be included in this measure to ensure that the duration and extent of the action is represented. Therefore, the wake intensity indicator W will be presented as:

$$W = \iiint M \, dxdydt \quad (4)$$

Where x and y are the horizontal coordinate directions and t is time. In other words, W is a spatial and temporal integration (area × time) of the excess shear stress for gravel.

3.1.2 Sediment Transport Indicator

The sediment transport indicator will provide a measure of the potential to remove the fine material that is necessary for clam survival. This potential can be determined by quantifying the amount of transport of the finer fraction of the bed material, taken as D_{50} = 0.2 mm. The potential sediment transport, q, will be computed using the Lund formulation (Camenen and Larson, 2007), which is a total load (i.e. bed load and suspended load) potential transport formula.

As with the wake intensity indicator, temporal and spatial information will be included in this measure to ensure that the duration and extent of the action is represented. Therefore, the sediment transport indicator Q will be presented as:

$$Q = \iiint q \, dxdydt \quad (5)$$

In other words, Q is a spatial and temporal integration (area × time) of the potential sediment transport for fine sand.

3.2 Modeling Approach

Since wakes impacting on the shore are influenced by tidal currents through which they must propagate and the tidal elevation at which they arrive at the shore, it is necessary to model tides as well as wakes. The computer models used for the study are *ADCIRC*, *LSV* and *PTM*. Full descriptions of the first two models, which describe the tide and wakes, can be found in the Phase 2 Report 2, *Integrated Modeling of Wake Impacts* (Osborne and MacDonald, 2007). The *PTM* model will be used to assess the impact of the hydrodynamics on the bed and is described in MacDonald et al. (2006). The models will be run and their solutions assessed by a quantification of a metric that can be used as an indicator of the degree to which an impact is likely.

3.2.1 Tidal Current Modeling

The ADCIRC tidal model (Luettich et al., 1992) was selected for use in the Rich Passage study because of its accuracy and ability to model large areas efficiently. The ADCIRC model solves for the time dependent, free-surface elevation and depth-averaged flow velocities using a finite element formulation. The model is one of the most numerically-advanced and highly-validated tidal models available. Because of problems associated with finite element solution of the classical momentum and continuity equations in their primitive form, the ADCIRC model has been formulated to solve the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) form. This approach produces a smooth and stable, yet highly accurate solution. The velocity field is obtained from the solution of the depth-averaged momentum equations. All non-linear terms have been retained in both of these equations.

The ADCIRC model was applied using Cartesian coordinates, because of the small area of the domain. A time step of 1 sec, which is quite short for tidal modeling, was required, because of the fineness of the mesh in the nearshore areas of Rich Passage. The wetting and drying option in the model was turned on. The model was calibrated using field data collect by the projects team and was found to provide accurate predictions (within 10%) of the current speed and directions at each point. The model's set up, application and calibration procedure is described in Osborne and MacDonald (2007). The present assessment uses the simulations described in that report.

3.2.2 Vessel Wake Modeling

Far-field wake modeling was performed using the Lagrangian Super-critical Vessel (*LSV*) model (MacDonald, 2005). This model was specifically developed to model the transformation of wakes generated by high-speed vessels over large distances. The *LSV* model was developed to predict both the generation and the transformation of wakes from high speed vessels, such as POFFs. *LSV* is based on the conservation of wave energy and the kinematic conservation principle for small amplitude waves. The theory has been extended to include interaction with depth-averaged currents. The *LSV* model provides a realistic and accurate estimation of the wake train duration and amplitude distribution in space and time and considers geometric features that may cause amplification or reduction of the wake as it travels away from the vessel.

Although new simulations were performed for the present study, the general calibration with measured data and model application discussed in Osborne and MacDonald (2007) is still applicable to the present application.

3.2.3 <u>Sediment Transport Modeling</u>

PTM is a coupled Lagrangian-Eulerian sediment transport model that has been developed with the support of the US Army Corps of Engineers. As described in MacDonald et al. (2006), the *PTM* model works on a finite element spatial grid of seabed geometry and flow conditions. The model then computes sediment transport conditions across the grid and uses a Lagrangian (particle-based) scheme to compute the pathways and fate of sediments. These calculations are under-pinned by extensive Eulerian (mesh-based) calculations of bed conditions (e.g. shears, sediment transport, bedform growth, morphology etc.). Initially designed for the analysis of coastal inlets and dredging operations, the Eulerian components of the *PTM* model can also be used for the evaluation of the response the seabed to sediment transport processes. Several different potential sediment transport schemes are available in *PTM*, but the Lund formulation (Camenen and Larson, 2007) will be used in the present work as it provides the fullest solution for combined wave-current flows, especially under breaking wave conditions. Use of *PTM* in combination with flows and vessel wakes is described in Osborne et al. (2006).

The *PTM* simulations use the *ADCIRC* and *LSV* model output as input. The *LSV* model is Lagrangian in structure and represents the wake as individual parcels of wave energy that propagate and transform under the influence of the currents and bathymetry. This output must be converted to an Eulerian structure for it to be used as input to *PTM*. This conversion is a key feature of the work and is described in the following section.

3.3 Model Input

Each simulation executed was comprised of a tidal level, vessel type, vessel route and location. The input and example output are described in the following sections.

3.3.1 <u>Tidal Model Simulations</u>

Five *ADCIRC* simulations were used to represent the tidal climate in Rich Passage. These were chosen by an examination of a long tidal record to be representative of average conditions for that state. The states are shown in Table 2.

<u>TABLE 2</u>

Average Test Water Surface Elevation

Tidal State	**Average Water Surface Elevation (m, MSL)**
High Water	1.5
Peak Ebb	-0.2
Mid Tide	-0.1
Peak Flood	-0.9
Low Water	-2.8

Tidal flow patterns for these levels are shown in Figure 4 through Figure 8.

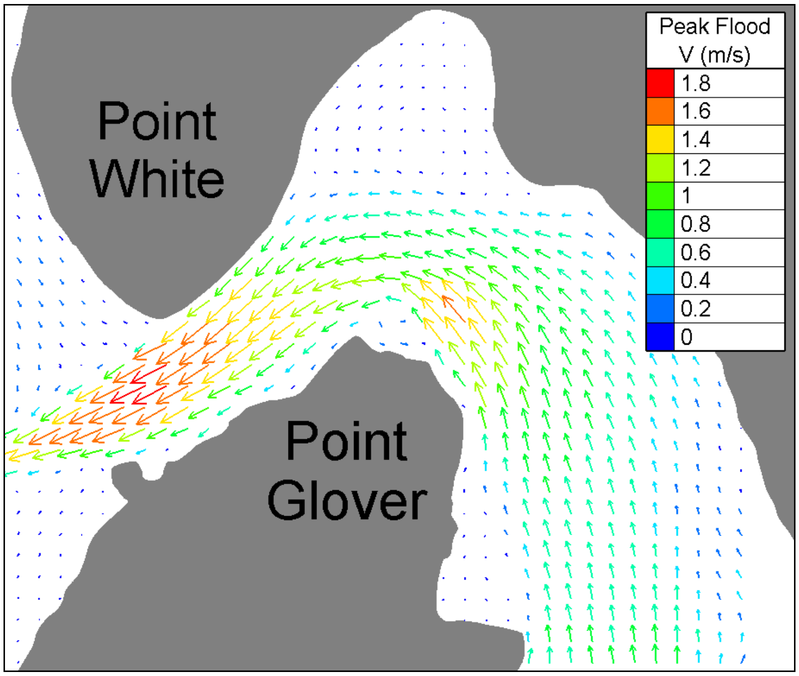

Figure 4: Tidal current pattern for Peak Flood case

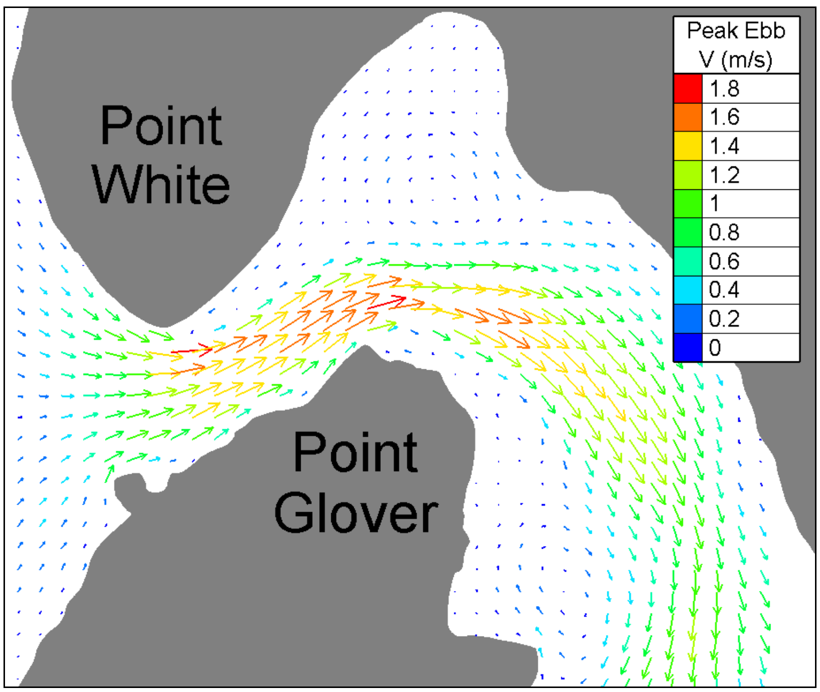

Figure 5: Tidal current pattern for Peak Ebb case

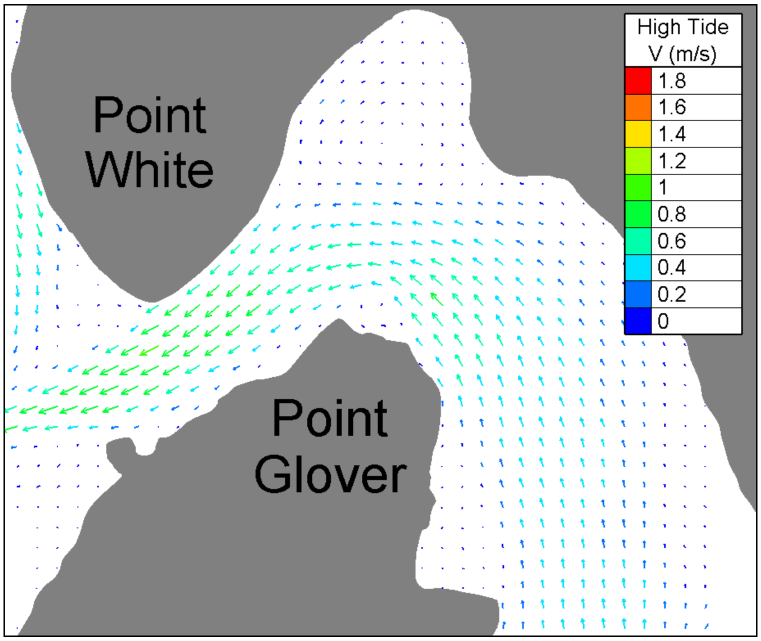

Figure 6: Tidal current pattern for High Tide case

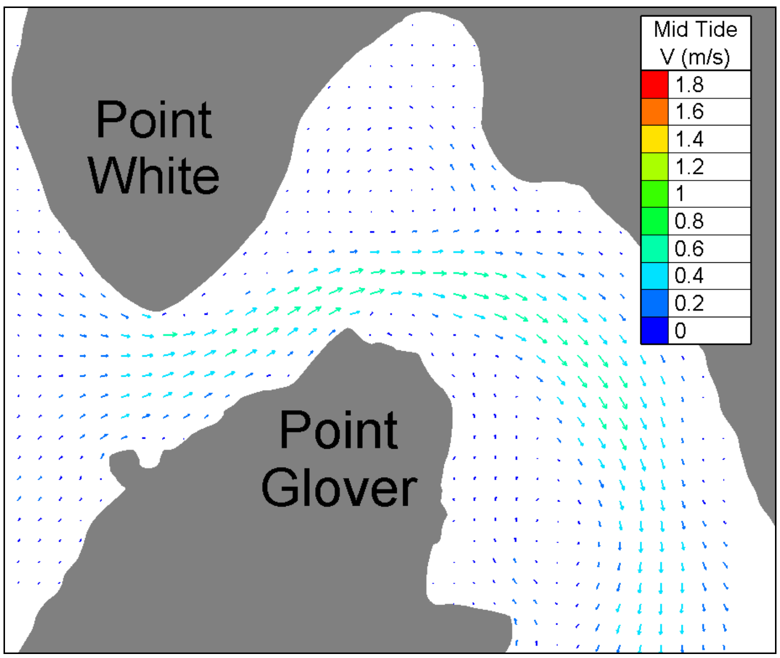

Figure 7: Tidal current pattern for Mid Tide case

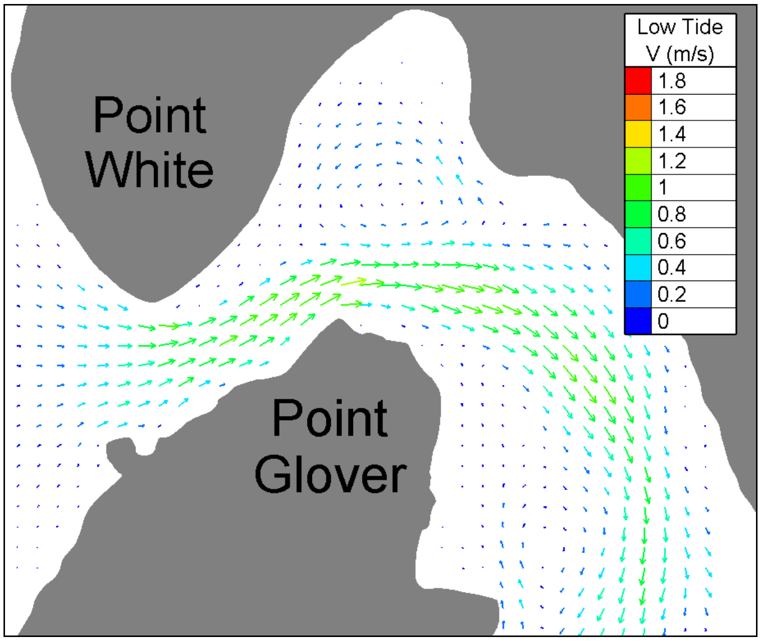

Figure 8: Tidal current pattern for Low Tide case

3.3.2 Vessel Model Simulations

Two vessel routes were used for the *LSV* model simulations, Bremerton to Seattle and Seattle to Bremerton. The routes are based on the long-term average routes as determined by vessel position measurements (Osborne and MacDonald, 2005). The routes are shown in Figure 9.

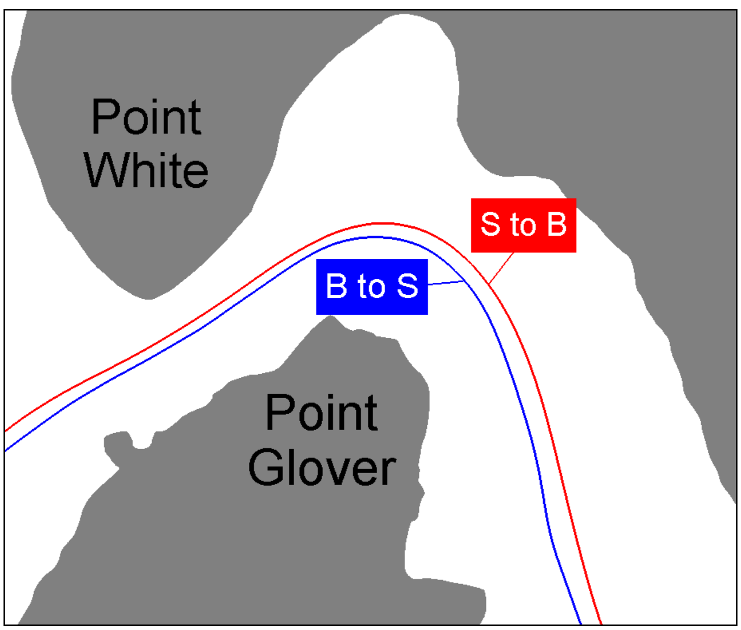

Figure 9: Vessel routes: Bremerton to Seattle (blue); Seattle to Bremerton (red).

Three vessel types were studied: two POFF vessels (350-passenger *M/V Snohomish* and the 149-passenger *M/V Spirit*) and a Washington State Ferries (WSF) car ferry. *LSV* model simulations of the vessels were calibrated during Phase 2 of the Rich Passage Study (Osborne and MacDonald, 2007).

An example *LSV* model output is shown in Figure 10. This figure shows the instantaneous wake height pattern on the Point Glover shore from a Seattle-bound *M/V Spirit* at 37 knots. Note how the wake height decays away from the vessel but increases near the shore due to shoaling.

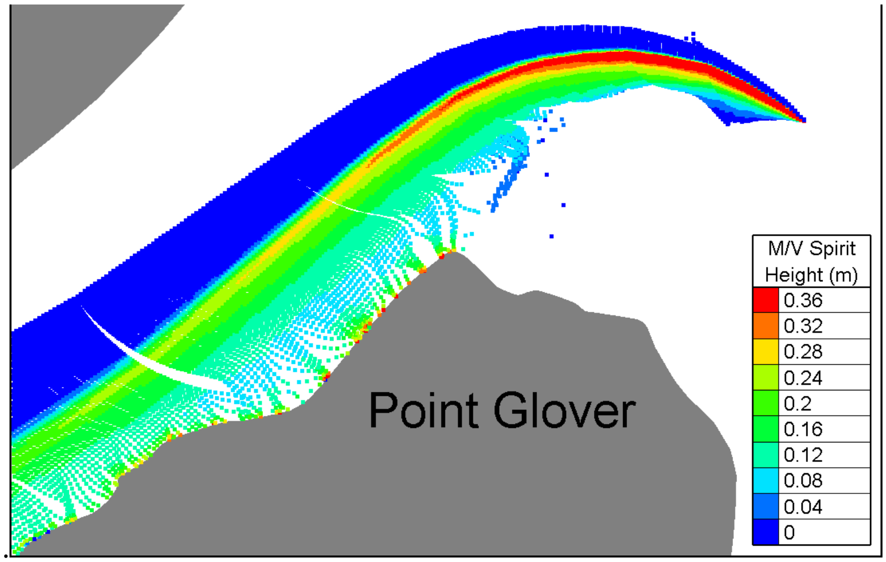

Figure 10: Example LSV solution for instantaneous wake height on the Point Glover shore from a Seattle-bound M/V Spirit at 37 knots. (Note: only starboard wake shown)

3.3.3 Lagrangian to Eulerian Conversion

As was discussed above, the *LSV* model produces individual wake energy packets that propagate from the vessel to the shore. A process involving two post-processing programs is required to convert this spatially- and temporally-varying output data to a time series format that can then be used as input to the erosion model.

The *CMS-Wave* model (Mase et al., 2005) is supported by *PTM* and, as it is a wind wave model, its structure supports that same data as *LSV* (e.g., height, period, direction, breaking energy dissipation). Therefore, *LSV* output is converted into this format. The first step in the process is to divide the area of interest into a number of small areas. Four polygons were defined (Figure 3): Point White, Point Glover West, Point Glover North, Point Glover East and Point Glover South. A *CMS-Wave* grid with a uniform 15 m cell size was then generated for each polygon.

Wake packets propagating in these polygons are recorded by the *LSV* model and written to a file. Each wake event is recorded with its time, position, wake height, wake period, and energy dissipation. This last quantity is solely due to wake breaking, and so will be zero outside the surf zone. The wake event data in the large *LSV* output file is processed using two programs. The program *ReadEulerianOutput* is used to separate the spatially-random events in the *LSV* output file into an individual file for grid cell of the *CMS-Wave* model grids. The program *AverageEulerianOutput* is then used to convert the temporally-random events in the individual cell files into continuous time series of wake height and period using a moving-average technique. The resulting output for each polygon are time series files of wake height, period, direction and energy dissipation for a single wake train in *CMS-Wave* output file format.

An example of this process is shown in Figure 11, which shows both the original Lagrangian LSV model output (individual parcels) and the converted Eulerian output (solid contours within the Point Glover North polygon) for a single time step.

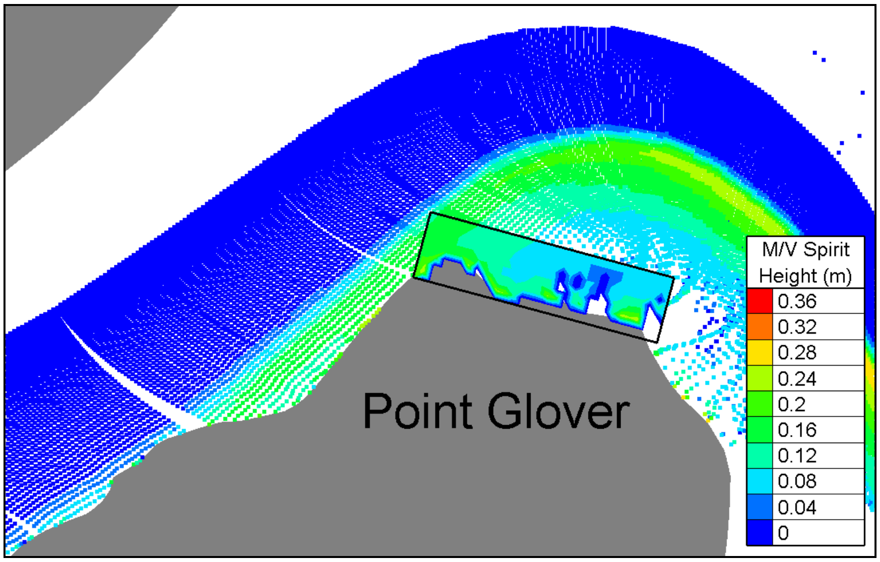

Figure 11: Instantaneous wake height pattern on the Point Glover shore from a Seattle-bound *M/V Spirit* at 37 knots (*see text for description*)

3.4 Model Simulations

The *PTM* model was applied to each of the 150 test cases (5 areas × 5 tidal levels × 3 vessels × 2 routes). This section will present examples of the model's output and an integration of all the results for the indicator analysis. Each *PTM* simulation provides a time series output. The duration of each run was taken as the length of the wake event in question, so each simulation represents a single boat passage.

3.4.1 Wake Intensity Results

Since each *PTM* simulation provides a time series output, there are several ways in which the data can be analyzed. Figure 12 through Figure 14 show the maximum excess shear stress on the bed, M, from simulations for a WSF car ferry, *M/V Spirit* and *M/V Snohomish*, respectively. It is clear from these plots that the only areas in which gravel is put in motion from wake activity is directly on the shore, most likely from breaking of the waves in the wake train. Note that the activity of the *M/V Snohomish* is more intense than the other, in some cases shears in excess of 50 times that required for gravel movement is predicted. In the case of the WSF car ferry, shears at breaking generally do exceed 5 times critical.

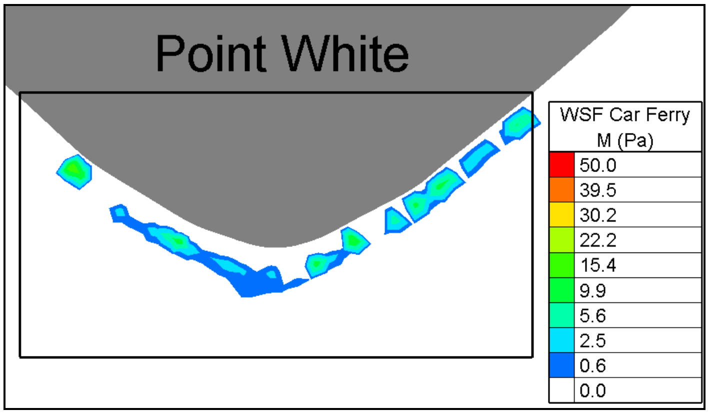

Figure 12: Maximum excess shear stress on the Point White shore from a Seattle-bound WSF car ferry at 17 knots and mid-tide

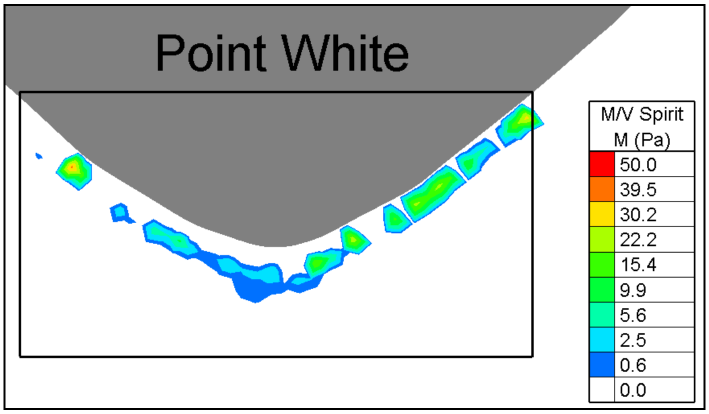

Figure 13: Maximum excess shear stress on the Point White shore from a Seattle-bound *M/V Spirit* at 37 knots and mid-tide

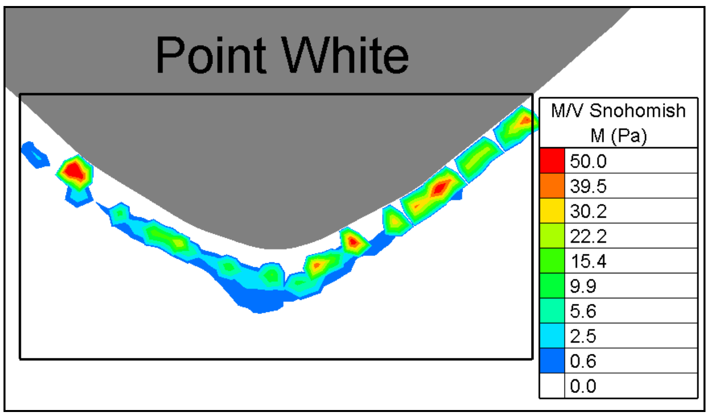

Figure 14: Maximum excess shear stress on the Point White shore from a Seattle-bound *M/V Snohomish* at 37 knots and mid-tide

The preceding results do not take into account the duration of the wake. To include this the simulation results for M are integrated spatially and temporally according to Equation (4) to yield the wake intensity indicator W. Three examples of these are shown in Figure 15 through Figure 17; these show the results for Point White, Point Glover South and Point Glover North, respectively. In each case, the two POFF vessels show higher values of the wake intensity indicator than the WSF car ferry, and *M/V Snohomish* is significantly worse than *M/V Spirit*.

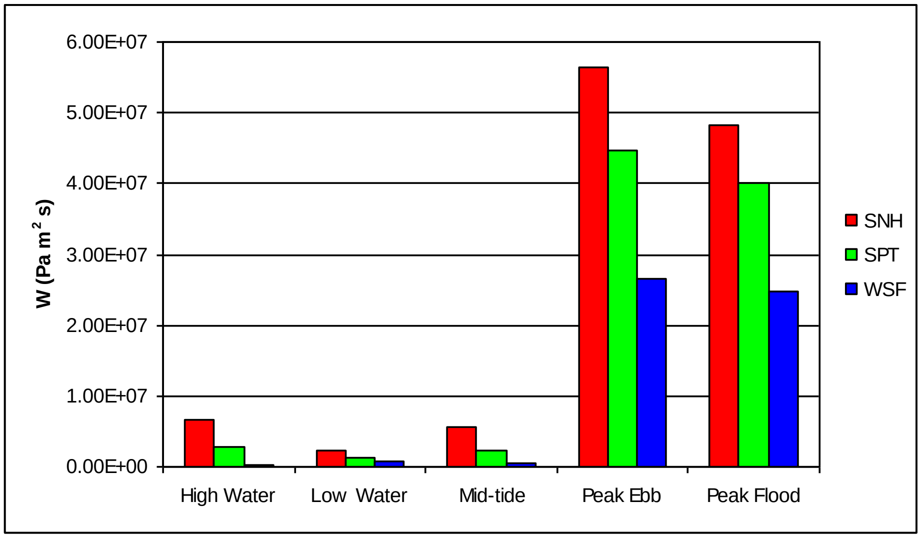

Figure 15: Wake intensity impact factor - Point White - Seattle to Bremerton

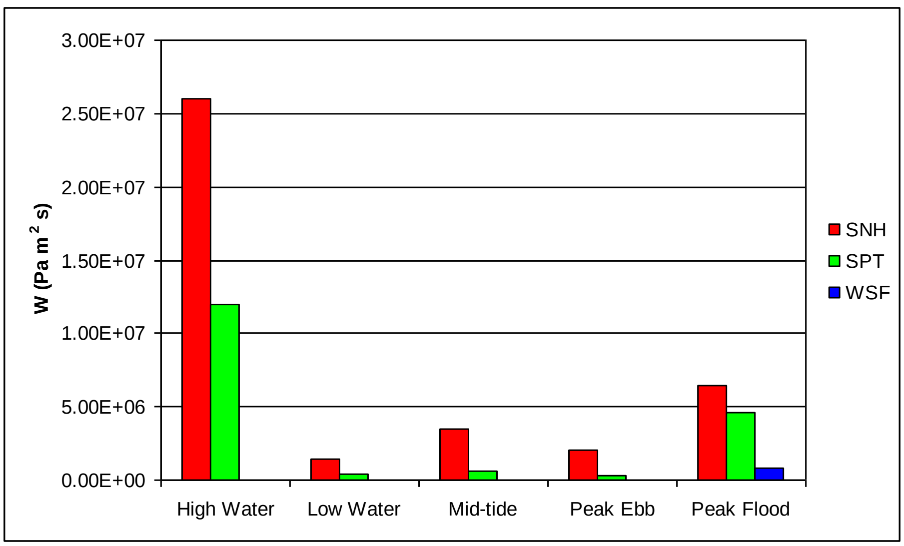

Figure 16: Wake intensity impact factor - Point Glover South – Seattle to Bremerton

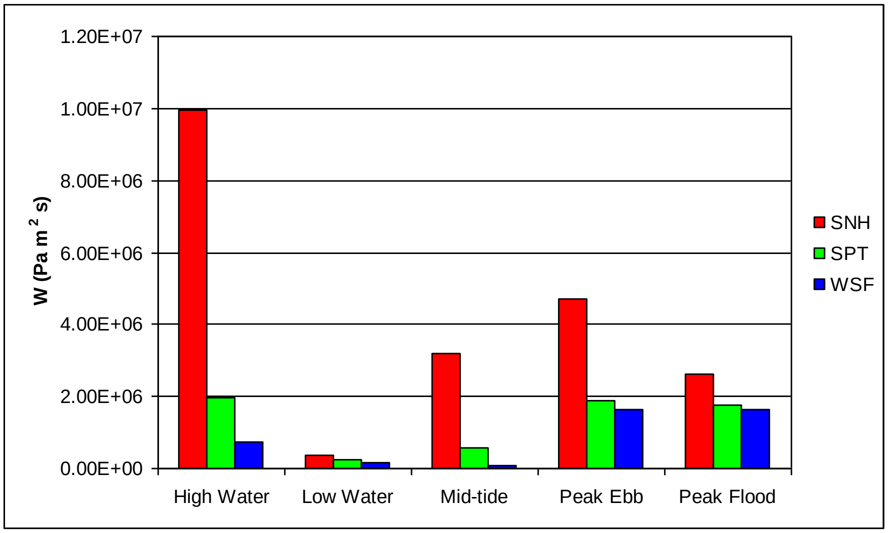

Figure 17: Wake intensity impact factor - Point Glover North – Bremerton to Seattle

The results for all the simulations are presented in Figure 18 and Figure 19. The former figure shows the results for each vessel at each site. The impact is greatest at Point White. Indicators for the two POFF vessels exceed that of the WSF car ferry at each location. Figure 19 shows the same data as, Figure 18, but the values of the two POFF vessels at each site are normalized by the value of the WSF car ferry at that site. Since WSF car ferries are in operation, this format represents the relative increase in activity due to POFF operation. The normalized values for *M/V Snohomish* exceed those of *M/V Spirit* at each site. The normalized values for each vessel averaged over all sites are 317% for *M/V Snohomish* and 161% *M/V Spirit*. The normalized values for each vessel averaged only over the Point Glover sites are 692% for *M/V Snohomish* and 227% *M/V Spirit*.

It should be remembered that the values presented here represent per trip values. Also, the approach assumes that 3 mm gravel is present at the site. If the bed is comprised of exposed bedrock or hard bottom, then these results should not be applied.

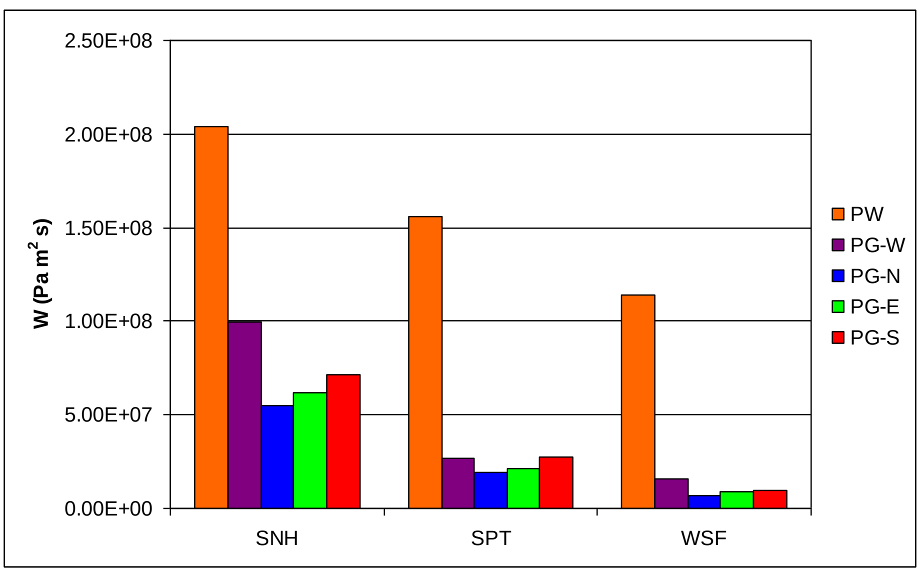

Figure 18:Wake intensity indicator for each vessel by site

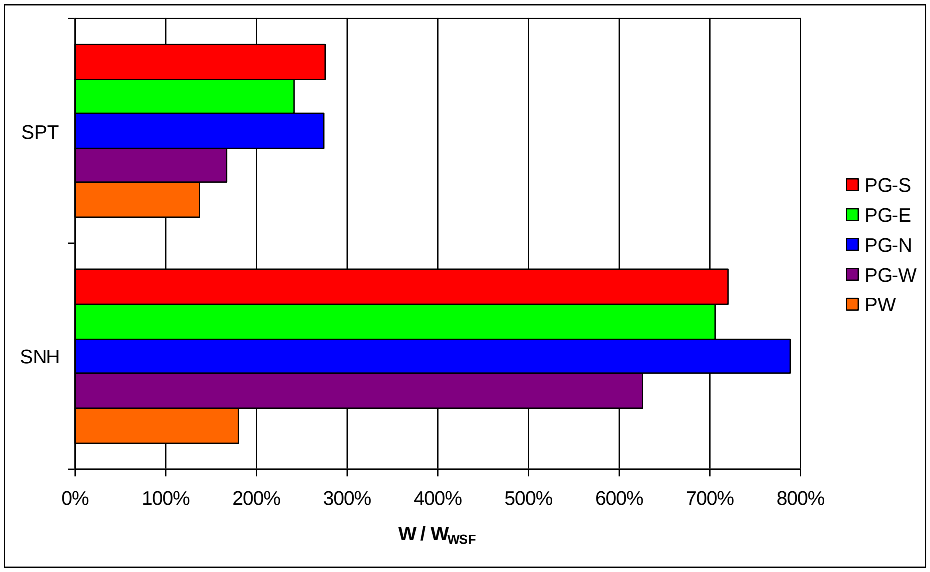

Figure 19: Normalized wake intensity indicator (*see text for description*)

3.4.2 Sediment Transport Results

Maximum potential sediment transport rate, q, at Point Glover West are shown Figure 20 through Figure 22 for the three vessels on a Bremerton-bound route at peak ebb. All three vessels induce sediment transport at the northeastern end of the polygon, but only the two POFF vessels move sediment near the shore. The potential transport is far more vigorous with *M/V Snohomish* than with *M/V Spirit*. Again, this analysis assumes that 0.2 mm sediment occurs at that location.

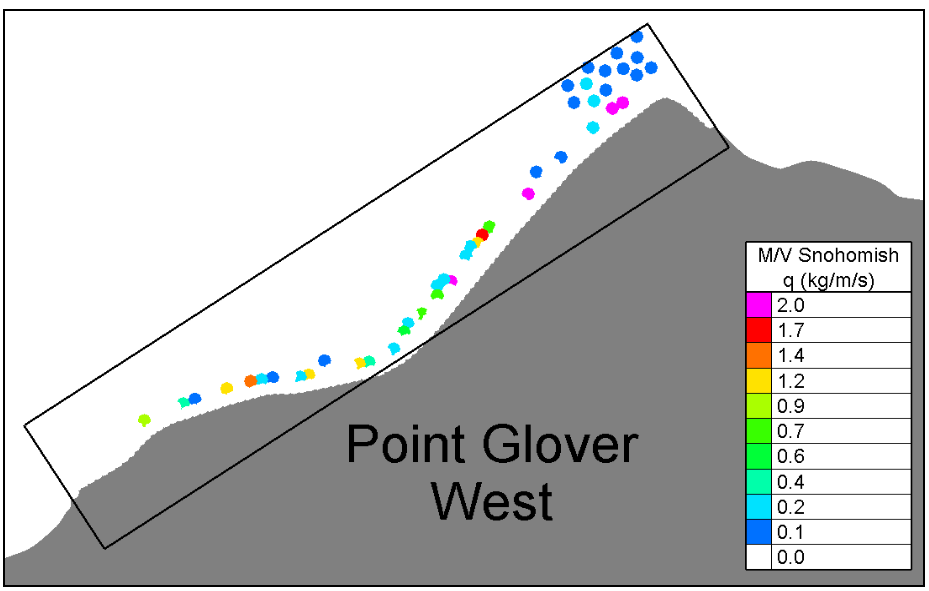

Figure 20: Maximum potential sediment transport rate for *M/V Snohomish* Bremerton-bound at 37 knots and peak ebb at Point Glover West

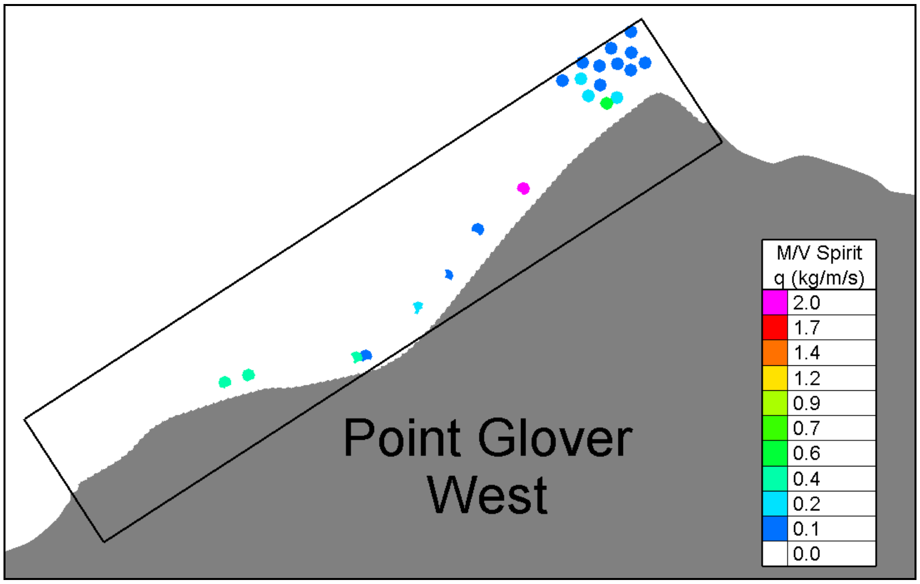

Figure 21: Maximum potential sediment transport rate for *M/V Spirit* Bremerton-bound at 37 knots and peak ebb at Point Glover West

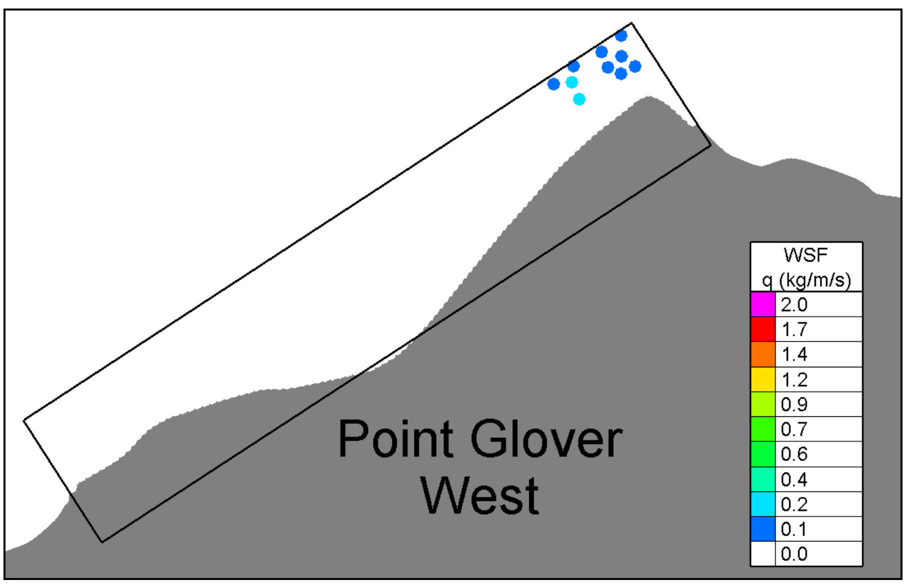

Figure 22: Maximum potential sediment transport rate for a WSF car ferry Bremerton-bound at 17 knots and peak ebb at Point Glover West

Figure 23 and Figure 24 show sediment transport indicator, Q. The indicator takes into account the duration of the wake train. The two examples show the results for Point Glover West and South, respectively. In the first case, there is little transport except at peak ebb. In the second case, the transport occurs predominantly at high water and peak flood. There is little if any transport generated by the WSF car ferry in most cases. The potential transport is from *M/V Snohomish* is greater than that of *M/V Spirit*.

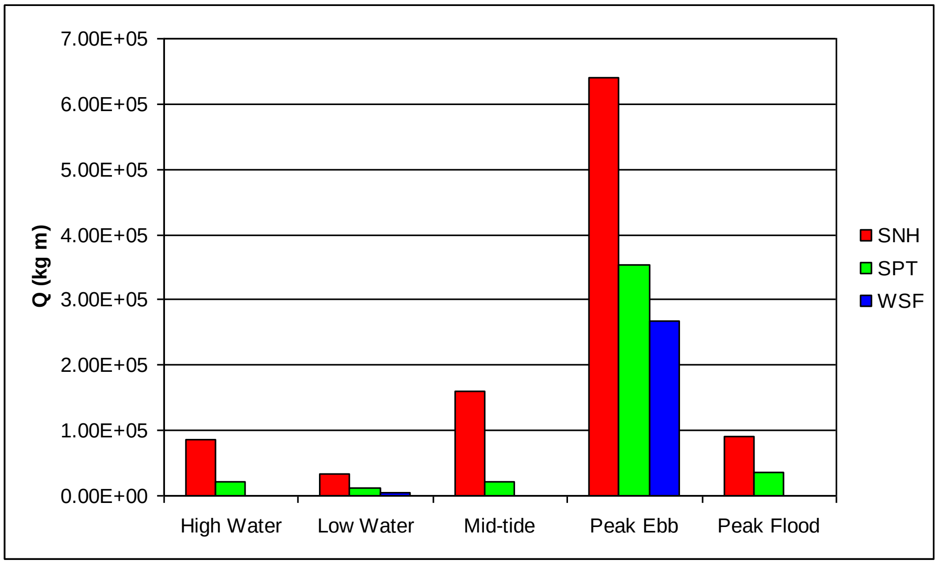

Figure 23: Sediment transport indicator **-** Point Glover West – Seattle to Bremerton

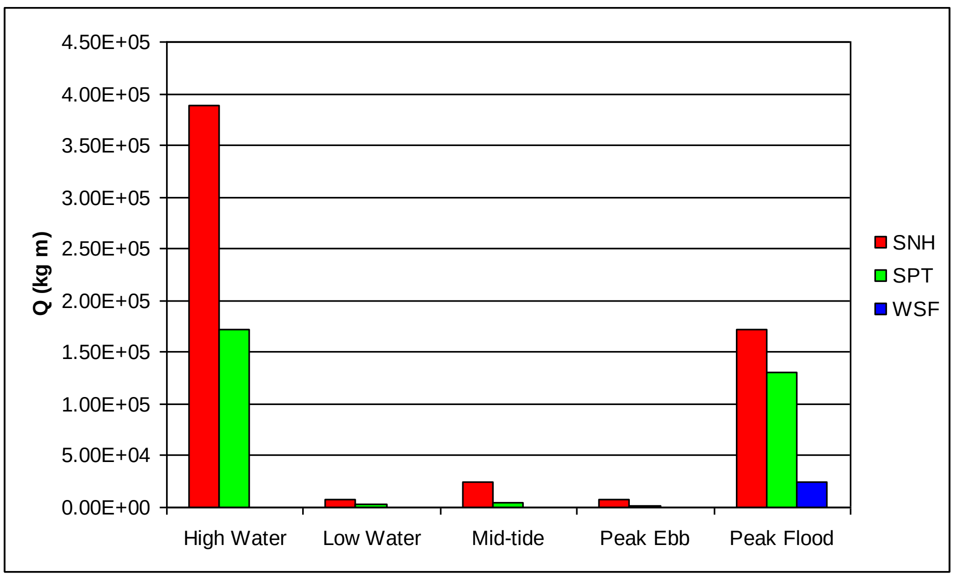

Figure 24: Sediment transport indicator **-** Point Glover South – Seattle to Bremerton

The results for all the simulations are presented in Figure 25 and Figure 26. The former figure shows the results for each vessel at each site. The impact is greatest at Point White, which highlights the intensity of the wake climate there. Indicators for the two POFF vessels exceed that of the WSF car ferry at each location. Figure 26 shows the same data as Figure 25, but the values of the two POFF vessels at each site are normalized by the value of the WSF car ferry at that site. Since WSF car ferries are in operation, this format represents the relative increase in activity due to POFF operation. The normalized values for *M/V Snohomish* exceed those of *M/V Spirit* at each site with Point Glover West being more sensitive. The normalized values for each vessel averaged over all sites are 190% for *M/V Snohomish* and 135% *M/V Spirit*, but these values are strongly affected by the large values at

Point White. The normalized values for each vessel averaged over the Point Glover sites are 360% for *M/V Snohomish* and 167% *M/V Spirit*.

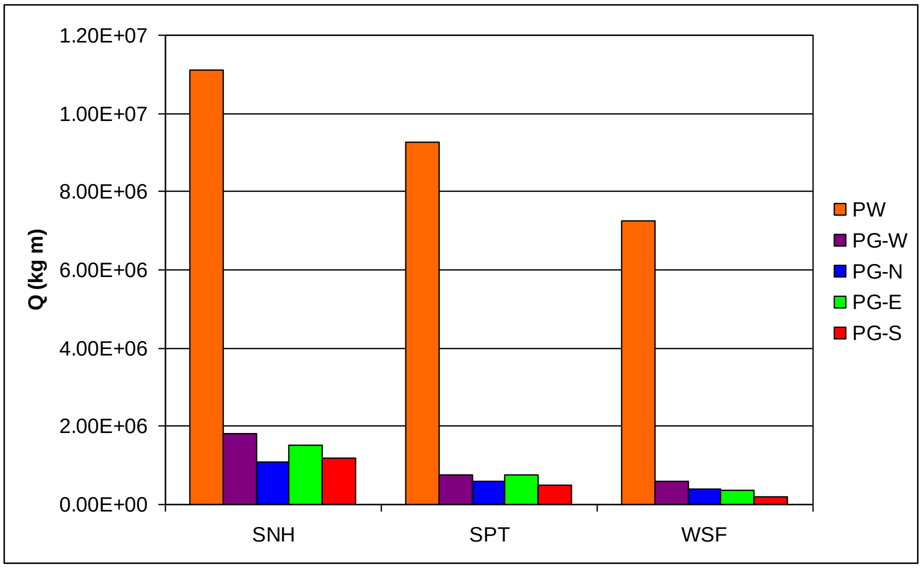

Figure 25: Sediment transport indicator for each vessel by site

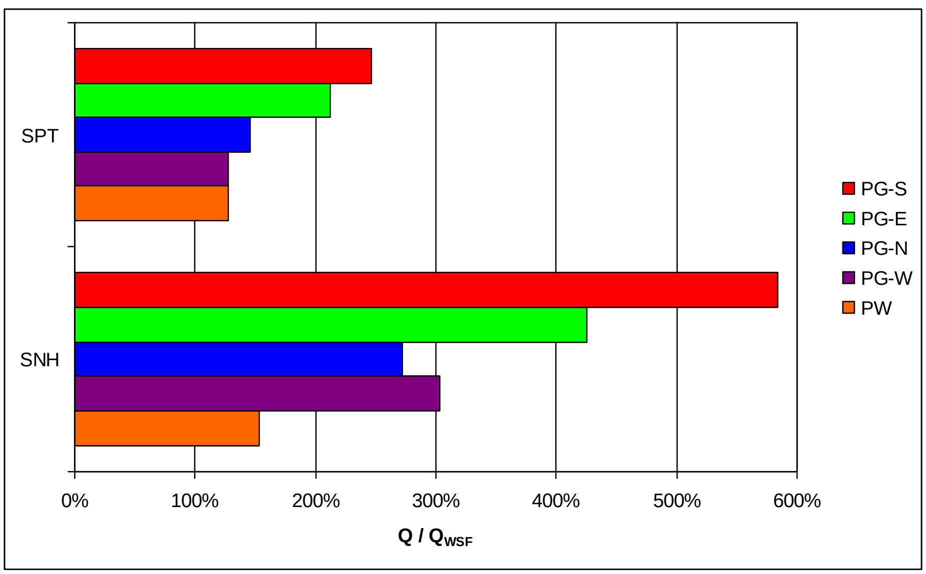

Figure 26: Normalized sediment transport indicator (*see text for description*)

It should be remembered that the values presented here represent per trip values. Also, the approach assumes that 0.2 mm sand is representative of fine material available at the site.

4.0 SUMMARY AND CONCLUSIONS

This memorandum describes an effort to quantify the impact of POFF operations on clam habitat in the Rich Passage area. The effort was based upon a numerical modeling program that included *ADCIRC* tidal modeling, *LSV* wake modeling and *PTM* sediment transport modeling. A set of 150 wake train simulations were investigated, which represented 5 areas (Point White, Point Glover West, Point Glover East, Point Glover North, Point Glover South) × 5 tidal levels (peak ebb, peak flood, mid-tide, high water, low water) × 3 vessels (350-passenger *M/V Snohomish*, 149-passenger *M/V Spirit*, WSF car ferry) × 2 routes (Bremerton-bound, Seattle-bound). The model simulation results were analyzed by examining two indicators of adverse impact to the habitat: the wake intensity indicator was chosen to assess the disturbance of bed material, such as the rocking and rolling of gravel and cobble sized material that can damage young clams, and the sediment transport indicator was chosen to provide a measure of the potential to remove the fine sediment that is necessary for clam survival. It should be noted that the wake intensity indicator technique assumes that 3 mm gravel is present at the site and the sediment transport indicator technique assumes that 0.2 mm sand is representative of the fine material present at the sites. Also, the values presented here represent per trip values, and should be adjusted if the sailing frequencies are not equal.

The results showed that a wake train from a 350-passenger POFF similar to *M/V Snohomish* was over three times as damaging as a WSF car ferry in terms of wake intensity (3.17 or 317%) and 90% more damaging in terms of sediment disturbance (1.90 or 190%). The results for the 149-passenger POFF *M/V Spirit* was approximately one and one-half times as damaging a WSF car ferry in terms of wake intensity (1.61 of 161%) and approximately 35% more damaging in terms of sediment disturbance (1.35 or 135%). The relative impacts were found to be larger on the Point Glover sites. These numbers would be in addition to the existing WSF impact. In the case of the large 350-passenger POFF, these impacts are fairly large. They are smaller for the 149-passenger vessel. Based on the two measures investigated, it can be concluded that the low intensity POFF operations with a small vessel would not present a severe danger to the two areas of clam habitat examined, unless sailing frequencies were increased significantly beyond that of the existing WSF car ferry schedule.

One condition that was not studied in the present work but could likely impact clam habitat, especially in the case of larger POFF vessel, is the complete removal of granular material from the beach face and large-scale beach profile reshaping. This was observed during previous POFF operations; the beach on the west side of Point White experienced significant erosion between the spring of 2000 and the late fall of 2001. Although this would not be expected to occur in the five areas examined in this work, changes of this magnitude would have a significantly adverse effect on clam habitat in any area in which it occurred. The principle aim of the present Rich Passage Passenger-only Fast Ferry Study is to ensure that any future POFF system would not induce beach changes of a magnitude remotely similar to that previously experienced.

5.0 REFERENCES

Camenen, B. and Larson, M. (2007): *A Unified Sediment Transport Model for Inlet Application.* Technical Report ERDC/CHL CR-07. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Luettich, R. A., Jr., Westerink, J. J. and Scheffner, N. W. (1992): *ADCIRC: An advanced three-dimensional circulation model for shelves, coasts, and estuaries*, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Technical Report DRP-92-6.

MacDonald, N.J. (2005): Super-critical Vessel Modeling. In: *Proceedings of the Canadian Coastal Conference*, Halifax, NS, Canada.

MacDonald, N. J., Davies M. H., Zundel A. K., Howlett J. D., Lackey, T. C., Demirbilek, Z. and Gailani J. Z. (2006): *PTM: Particle Tracking Model, Report 1: Model theory, implementation, and example applications.* Technical Report ERDC/CHL TR-06-20, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

MacDonald, N.J. (2005). Super-critical Vessel Modeling. In: *Proceedings of the Canadian Coastal Conference*, Halifax, NS, Canada.

Mase, H., Oki, K., Hedges, T., and Li, H. J. (2005): Extended energy-balance-equation wave model for multi-directional random wave transformation. *Ocean Engineering*, **32**, pp. 961-985.

Osborne, P.D. and MacDonald, N.J. (2005): *Wave Energy Evaluation of Passenger Only Ferries in Rich Passage*. Pacific International Engineering PLLC, Edmonds, WA, USA. [Available from National Technical Information Service, orders@ntis.fedworld.gov]

Osborne, P.D., MacDonald, N.J. and Davies, M.H. (2006): *Detailed Assessment of the Potential for Boat Wake Erosion of Sand Bars in Hells Canyon, Snake River: Phase 3: Sediment Transport Modeling*. Pacific International Engineering PLLC, Edmonds, WA, USA.

Osborne, P.D. and MacDonald, N.J. (2007): *Rich Passage Passenger Only Fast Ferry Study – Phase 2. Report 2: Integrated Modeling of Wake Impacts*, Pacific International Engineering PLLC, Edmonds, WA, USA. [Available from National Technical Information Service, orders@ntis.fedworld.gov]

Soulsby, R. L. and R. J. S. W. Whitehouse (1997): Threshold of sediment motion in coastal environments. In: *Proceedings Pacific Coasts and Ports '97*, University of Canterbury, Christchurch, NZ. pp. 149-154.