RATES OF BEACH MORPHOLOGY CHANGE AND COARSE SEDIMENT TRANSPORT ON A FETCH RESTRICTED COAST EXPOSED TO VESSEL-GENERATED WAVES

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Abstract

The shorelines along Rich Passage, Puget Sound, WA, USA are characterized by seasonal and annual transport patterns where wind waves force alongshore transport in the winter months and vessel wakes and tidal currents dominate transport during calmer intervals. Measurements of wake properties, wind speed and direction, and water levels, direct measurements of gravel transport, three-dimensional laser scans of beach morphology, and cross-shore beach profiles were collected over an 8 year interval and analyzed to characterize beach response to hydrodynamics. Additional measurements were collected and analyzed to compare beach morphology change and gravel transport under waves generated by a new low wake high speed vessel as compared to hydrodynamic forcing mechanisms during the baseline interval. The effects of limited sediment supply and

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1. Introduction

The Puget Sound region depends on efficient ferry transportation for economic stability, but wake wash from high speed ferries can have an adverse effect on the shorelines and structures bounding these waterways (Osborne et al., 2009a). The operation of ferries in the low energy, fetch restricted coastal system of Rich Passage, in Puget Sound, WA, USA has provided the opportunity to study the dynamics of mixed sand and gravel (MSG) beaches exposed to vessel generated waves, tidal currents and wind waves. Previous studies have shown seasonal transport patterns where wind waves force alongshore transport in the winter months and vessel wakes and tidal currents dominate transport during calmer intervals characteristic of summer months (Curtiss et al. 2009; Osborne et al. 2011). Measurements of beach morphology over an 8 year interval (2004 to 2012) have also shown seasonal fluctuations between non-storm and storm intervals as a change in slope of the upper beach from steep to flat and grain size distribution from coarse to fine. The relatively short period monochromatic wakes produced by car ferries, slow moving displacement vessels, provide a mechanism for post-storm recovery by steepening the beach slopes along this coast. When high speed passenger only fast ferries (POFF) were operated in Rich Passage from 1999 to 2002 erosion of the upper foreshore and reduced slopes of the beaches were observed. A new high speed POFF optimized for low wake performance was operated through Rich Passage over a trial period from June to October 2012 to investigate the beach response to the wake generated by this POFF (*Rich Passage 1*, hereafter referred to as RP1). Field measurements collected during the 4 months of RP1 test operations were analyzed to compare the hydrodynamic forcing and beach response to RP1 to seasonal and inter-annual response over the 8 year baseline interval.

Shoreline change is a function of local topography and bathymetry, exposure of the site to vessel sailing line, size, speed, and operating frequency of vessels, speed and direction of tidal currents, exposure to wind-waves, sediment characteristics, sediment supply and beach slope. The beaches within Rich Passage change significantly each season and each year depending on regional variations in climate as well as the

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variations in the local site-specific factors. This paper focuses on an analysis of beach morphodynamic response in one section of shoreline within Rich Passage where extensive measurements have been conducted to examine the relationships between the relative strength of site specific hydrodynamic forcing mechanisms and beach morphology change. In particular, the measurements allow a direct comparison between a baseline interval and an interval of RP1 operations.

2. Study Area

The study site (Figure 1) is an approximately 750 meters (m) length of MSG beach in Puget Sound on the east shore of Point White, at the southern end of Bainbridge Island, Washington, USA and has previously been described in Curtiss et al., 2009, Osborne et al., 2006, 2009b, 2011. Point White lies at the western end of Rich Passage, a narrow channel that provides the most direct vessel route between downtown Seattle and the city of Bremerton, WA. The beaches are backed by seawalls and revetments of varying type and condition along the length of the study area.

The beach foreshore along Point White is generally steep (1:5 to 1:7), with a 20 to 30 m wide strip of beach gravel (pebble and cobble) overlying mixed sand and gravel or consolidated till. The beach unconsolidated layer varies in thickness from a few centimeters (cm) up to 2 m on the upper foreshore and at the toe of shoreline structures. The unconsolidated layer is generally thicker at the northeast end of the study area (Site 5) than the southwest end (Site 3); the beach to the south of site 3 is a single grain thickness of gravel over till.

The gravel layer varies in the cross-shore from 0.5m to as thin as a single grain thickness of gravel armor on the lower foreshore. The sediments were characterized by pebble counts of the surface layer and sieving samples from the upper 30 cm in 2006 and pebble counts again in 2012. The median grain size for the entire sediment mixture based on sieving in 2006 was 16.0mm at Site 3 and 11.0 mm at Site 4. The median grain size of the surface layer at Site 3 was 22.5 mm in 2006 and 27 mm in 2012. At Site 4 the median grain size of the surface layer was 17 mm in 2006 and 10 mm in 2012. Site 5 was not sampled in 2006, but the surface layer had a median grain size of 17mm in 2012. A unique feature of the beach is the median size of the gravel, which increases with decreasing elevation on the beach.

The fetch distances in the study area are relatively short; therefore wind-wave conditions are fairly mild in the study area as compared to regions of central Puget Sound where the fetches are much longer. Tides are mixed semi-diurnal with a range of approximately 4 meters. The lowest low tides generally occur during the day in the summer and at night in the winter and the beach response to vessel wake wash reflects this seasonal change in water level elevation.

3. Methods

Field measurements collected and analyzed for this study include time series of wakes, wind speed and direction, water levels, gravel transport rates and directions by Radio Frequency Identification (RFID) Passive Integrated Transponder (PIT) technology, laser scans of three-dimensional beach morphology, and two-dimensional cross-shore beach profiles surveyed by Global Position System (GPS). Wake time series were analyzed to compute wake wave characteristics such as wave height and period using zero-crossing analysis as well as spectral analysis methods. The RFID gravel transport measurement techniques developed and used at two sites along a 500 meter length of coast during a previous study (Curtiss et al. 2009) were repeated and expanded to three sites covering 750 meters of coast during 4 months of POFF test operations.

Changes in beach morphology were monitored at quarterly intervals during the baseline interval from 2004 to 2012 with cross-shore beach profile surveys. Time series of sediment volume changes above and below mean tide level were calculated from quarterly beach profile surveys. In addition, geo-referenced photographs of the beach at the interface with structures have been recorded quarterly to monitor the beach elevation relative to the toe of shoreline structures. In 2011, laser scanning surveys were implemented to provide high resolution three dimensional maps of beach morphology at two of the three gravel transport sites. The laser scanning maps recorded at regular intervals were differenced to produce spatial maps of beach morphology change. In addition, a systematic analysis of beach volume change was conducted to analyze cross-shore and alongshore exchanges of beach volume within each of the survey boundaries for comparison with gravel transport results and hydrodynamic forcing.

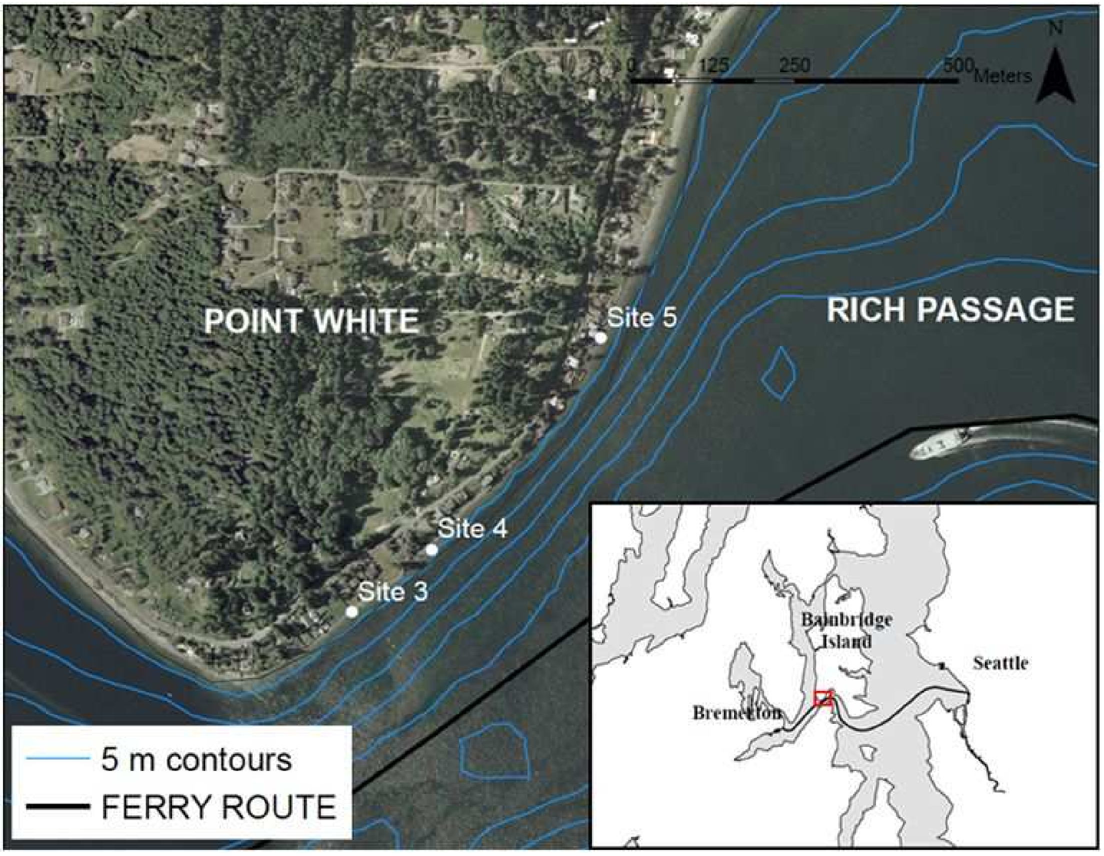

Figure 1. Study Area on Point White, Bainbridge Island in Puget Sound, WA, USA.

4. Baseline Conditions

During previous studies, existing vessel wake wash, wind-wave energy, and tidal currents were established as the baseline hydrodynamic forcing mechanisms to be used for comparison with future POFF operations in Rich Passage (Osborne et al, 2007). Although fetch distances are relatively short, numerical modeling of wind-waves has shown that the largest breaking wave heights with the potential to drive sediment transport in the study area occur along the western side of Point White (closest to Site 3). A 1-in-64-year storm event occurred in December 2006, and generated significant wave energy which caused a surge in alongshore transport at Site 3 on Point White (Curtiss et al, 2009). In general, winters with a larger number of storms correlate with larger changes in beach volume through both cross-shore and alongshore transport. Storms are not as common in summer months. During non-storm intervals, the wave climate is dominated by vessel-generated wake wash primarily resulting from large displacement vessels operated by Washington State Ferry (WSF) service sailing through Rich Passage.

Beaches at the study site have exhibited a long term decline in beach volume both above and below mean tide level at Site 3 (Figure 2), and a reshaping of the beach profile at Site 4 (Figure 3 and 4). Decline in beach volumes have also been observed at Site 5 (Figure 5) both above and below MTL, but to a lesser degree than at Site 3. The limitation in sediment supply is attributed to the presence of structures which result in long term passive erosion. The difference in response between sites 3, 4, and 5 is attributed to variability in the exposure of the site to wake wash, wind-waves, and tidal currents as well as the constraints imposed by sediment supply.

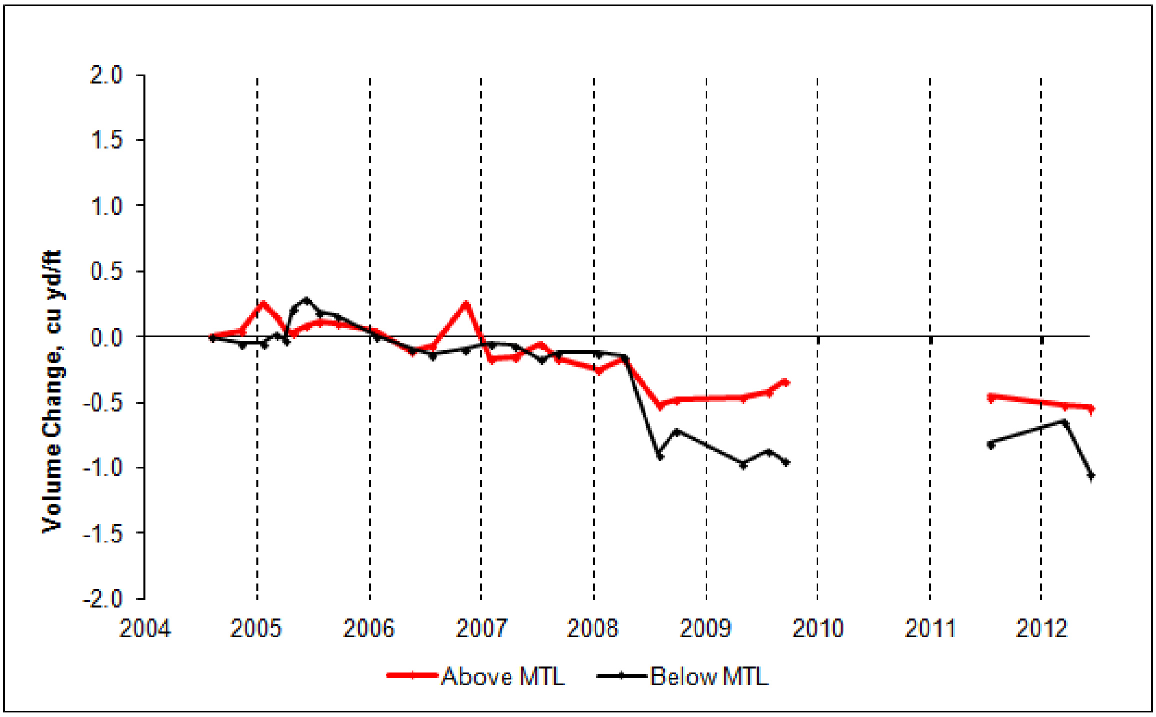

Figure 2. Beach volume change at Site 3 on Point White relative to August 2004.

The beach morphology change at Site 3 is very similar in the areas above and below MTL. This can be an indication that sediment transport patterns are dominated by alongshore movement driven by seasonal shifts in the relative dominance of WSF car ferry wake wash and wind-waves. Cross-shore sediment transport is interpreted as the predominant mode of beach volume change when the changes above MTL are a mirror image of the changes below MTL, such that material is being eroded from the upper beach and being deposited on the lower beach. Cross-shore transport is observed at Site 4 in 2006 (Figure 4) when there were no significant storm events for over 9 months (February through October) and vessel wake wash was the primary hydrodynamic force.

The increase in beach volume below MTL at Site 4 is related to local changes in the curvature of the shoreline and adjacent properties and structures inhibiting the alongshore transport of material. Seasonal variability is characterized by beach volumes reaching an annual peak in the summer and gradually declining throughout the winter. At Site 4, large inter-annual variations are evident during the baseline period indicated by the divergence of beach volume changes above and below MTL on approximately a 4-year cycle. The volume below MTL begins increasing in 2004 thru 2008, decreases significantly from early 2008 to early 2009 and then increases again through 2012 (Figure 4). There was a significant storm event in June 2008 (a seasonal anomaly), which slowed the recovery of the beaches that year compared to typical seasonal recoveries observed in other summer months. The data suggests that a new 4-year cycle is starting with a decline in beach volumes at the end of 2012. Beach volume change analysis at Site 5 suggests a similar 4-year cycle but with beach volumes changes of a smaller magnitude (Figure 5).
Gravel transport studies were conducted at sites 3 and 4 in 2006 to 2007 to determine the magnitude of alongshore and cross-shore transport between survey periods as well as any dominant patterns based on particle size or location on the beach. These studies showed the alongshore movement of gravel during storm events was similar at sites 3 and 4, but was significantly higher at site 3 as compared to site 4 during non-storm intervals since Site 3 is more exposed to tidal currents and wake wash.

It has been observed that gravel is transported from northwest to southeast along Point White in wave like patterns and the rate of transport is correlated with the magnitude, direction, and frequency of wind events (Curtiss et al, 2009 and Osborne et al, 2011). High resolution laser scanning surveys were used to calculate volume change within a bounded area at Sites 3 and 4 to determine the volume gains or losses and potential sediment pathways. The most significant volume change at Site 3 was a loss of 59 cubic yards (CY) during storm dominated months (September 2011 to June 2012). Site 4 experienced a net gain of 10 CY during the same interval supported the theory of northeasterly alongshore transport. The difference map created from laser scanning surveys at Site 4 (Figure 6) clearly depicts erosion (cool colors) of the beach to the southwest end of the survey area and accretion (warm colors) of material on the northeast end (Figure 4) over a 1-year interval. The continual decline of beach volumes along Point White is evidenced by beach volume loss of 24 CY or 22% of the gross transport within the boundary cell at Site 3 over a 1-year interval.

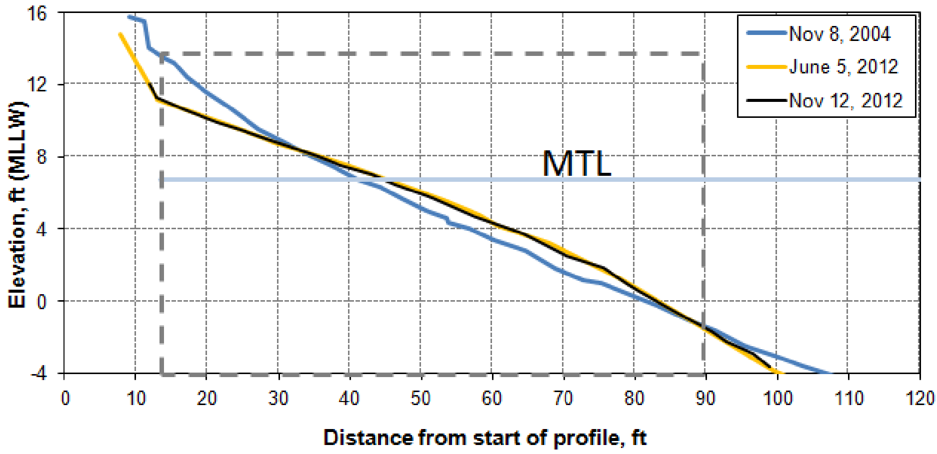

Figure 3. Beach profile at transect 4 on Point White.

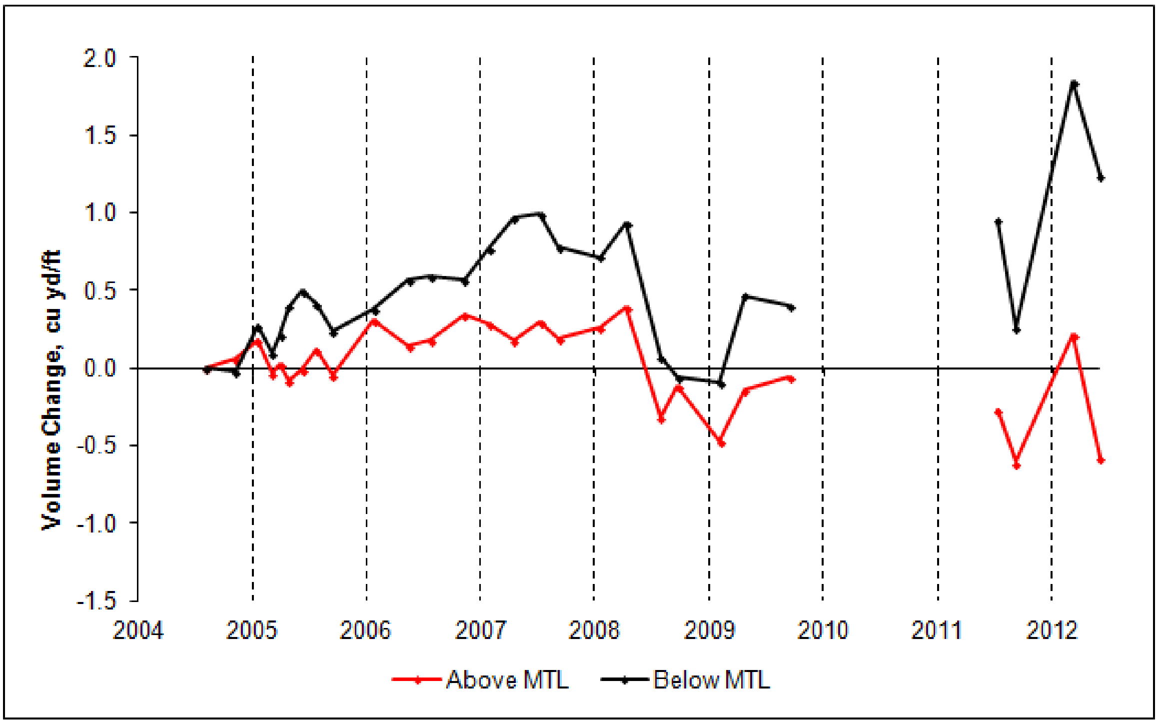

Figure 4. Beach volume change at transect 4 on Point White relative to August 2004.

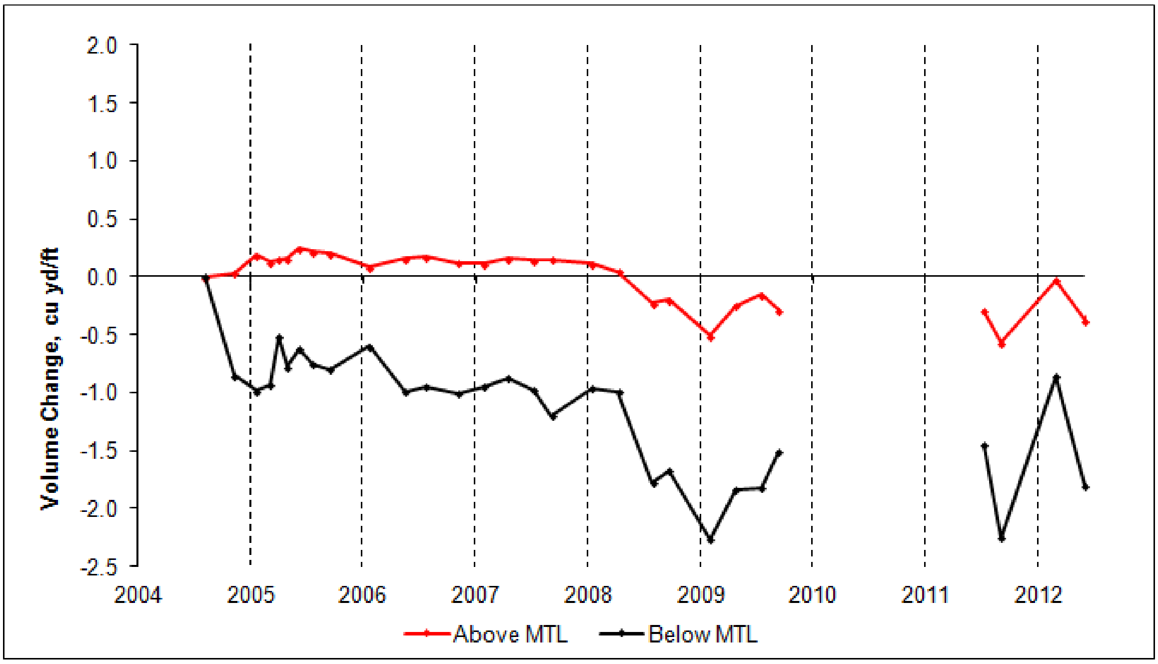

Figure 5. Beach volume change at transect 5 on Point White

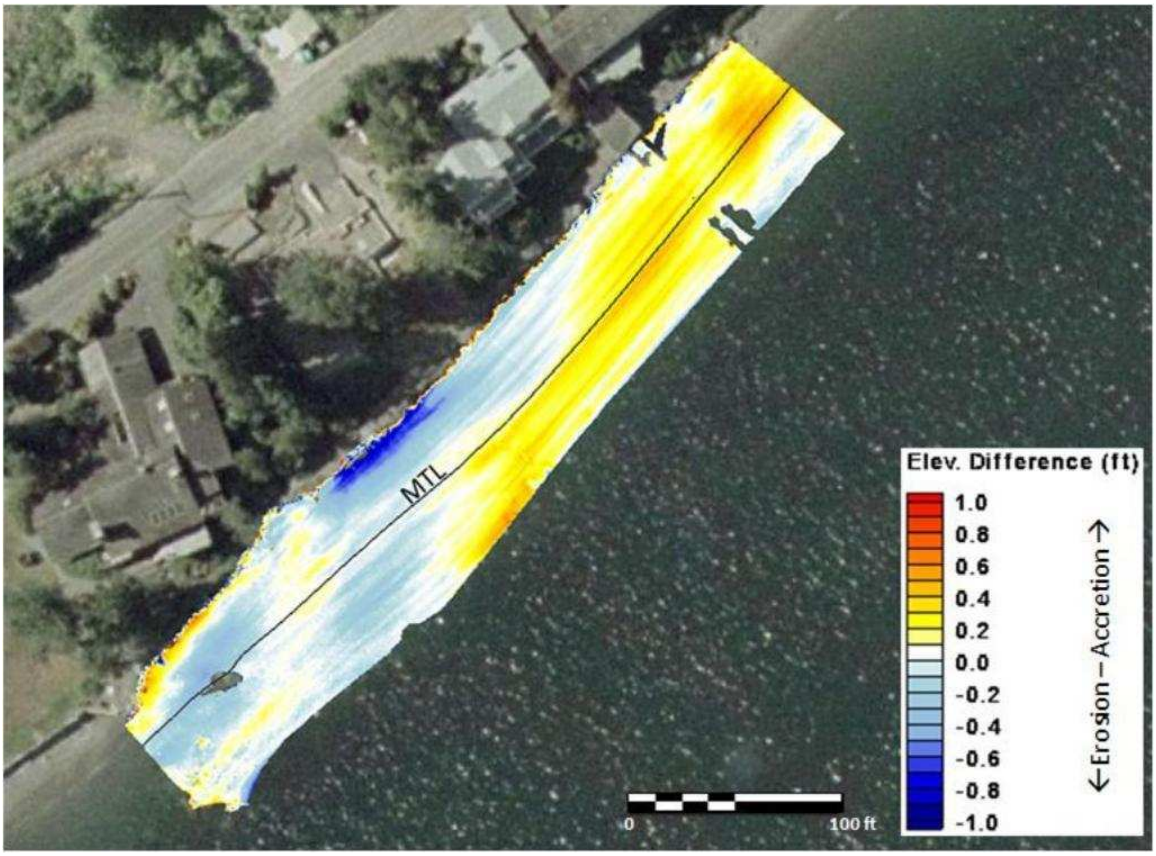

Figure 6. Difference map of laser scanning surveys measured at Site 4 on Point White between 9 September 2011 and 4 June 2012

5. Beach Response to RP1 wake wash

Full scale measurements of the wake wash from RP1 shows a spread in the energy spectrum as a result of the variability in the wave period characteristic of a vessel operating at super-critical speeds. The initial waves in the wakewash have periods of approximately 10 seconds followed by successively shorter period waves. Although wave height from RP1 is similar to wave height from the WSF car ferries, wake wash from POFF vessels can be significantly more energetic because their periods are longer than wakes from slower and smaller vessels. The longer POFF waves result in greater swash and backwash excursion which interact with beaches at mid to low tides. It is also important to note, the wake wash from RP1 contributed additional forcing that was not present during the baseline interval.

The difference plot presented in Figure 7 shows the beach change during the entire RP1 testing interval (June-November 2012) at Site 3 which also corresponds to the summer season. The hot colors (red) near the bulkhead indicate there was net accretion on the upper beach during this interval. The alternating pattern of warm colors (accretion) and cool colors (erosion) indicate sediment moves in waves alongshore, particularly at the interface of the beach and the bulkhead, similar to the patterns observed during the winter 2011-2012, but with more accretion in the summer (RP1 test interval) and more erosion in the winter. Figure 8 shows a one-month difference plot representing the post-RP1 operation period for November to December 2012. The gravel mounds at the bulkhead have moved cross-shore away from the bulkheads but remain in the upper beach. This is a typical winter seasonal shift resulting from the increasing wind-waves and higher tides during the day such that wake wash and wind-waves have a more significant effect on the upper beach.

At Site 4 on Point White, subtle gravel bars form parallel to the shoreline, which indicates cross-shore sorting of gravels in response to wave forcing on the lower beach (Figure 9). During RP1 operations there is a small decrease in beach elevation on the upper beach and accretion of sediment on the lower beach. The area with the most accretion is on the upper beach near the mouth of a creek. The runoff from the creek contributes sediment to the beach at this location, but the curvature of the shoreline can cause sediment moving alongshore to be trapped at the creek mouth. Beach sediments are transported alongshore to the north as well as to the south at Site 4. From November to December, there is erosion of sediment at the mouth of the creek, which is deposited on the lower beach (Figure 10). The gravel bars present on the lower beach in the summer have moved up the beach during this winter interval, essentially reversing the erosion and accretion patterns between the summer and winter season.

As with the baseline study, alongshore movement of monitored gravel particles towards the northeast is the most noticeable feature at the three sites (Figure 11 and 12). However movement is greater at Site 4 than Site 3 and substantially greater at Site 3 and Site 4 than Site 5. Several short-term reversals in alongshore transport occurred at all three sites in July and August and another reversal was observed at Site 4 that lasted from September to November, spanning several survey periods. Tracer movement at Site 3 and Site 5 averaged 0.07 and 0.03 m/day, respectively during the entire survey period while tracer movement at Site 4 averaged 0.15 m/day in June and July and decreased to an average of 0.05 m/day for the remainder of the survey. Average tracer movement at Site 3 in 2006 was approximately equal to average tracer movement in 2012 (Figure 11). However, average tracer movement at Site 4 was significantly higher in 2012 as compared to 2006; transport of 0.005 m/day in 2006 as compared to 0.05 m/day in 2012. Gravel tracer studies were not conducted at Site 5 in 2006.

The same set of gravel tracers, and therefore grain size distribution of tracers, was used in 2006 as in 2012, which was developed based on the resident grain size distribution at Sites 3 and 4 in 2006. The grain size distribution of the tracer particles is approximately equivalent to the beach surface samples at Site 3 in 2012. The tracer distribution is significantly coarser than the resident grain size distribution of the beach measured at Site 4 in 2012. At Site 3, the rapid transport rates in June and July (0.15 m/day) are explained by the incompatibility in grain size distribution between the gravel tracers and the beach sediments at this site. In general, the median grain size of the beach gravel increases with decreasing elevation on the beaches along Point White and most of Puget Sound (Finlayson 2006). This pattern is more pronounced at Site 4 due to the weak hydrodynamic forcing combined with gravitational affects as compared to Site 3, which is more exposed to wind-waves and wake wash. As a result, the larger size tracer particles were transported to lower elevations to match the distribution of the resident beach sediment. The sorting of beach sediments by grain size was also observed in 2006, but occurred in the first one to two weeks of deployment as compared to two months in 2012. This transport pattern is also reflected in the long term beach profile measurements at Site 4 showing an overall beach flattening.

In the baseline study, transport increased by at least a factor of 6 during the storm interval from November 2006 to January 2007. The last gravel tracer monitoring prior to publishing this paper was conducted on 9 December 2012, which was prior to any significant storm events that might have shown significant increase in transport rates. However, several short-term reversals in alongshore transport occurred at all three sites in July and August and another reversal was observed at Site 4 that lasted from September to November, spanning several survey periods. These intervals were characterized by reversals in wind direction. Gravel tracers will be monitored again in May 2013.

6. Conclusions

Previous observations have indicated that both cross-shore and alongshore transport contribute to the morphologic response along the beaches of Rich Passage, particularly during non-storm intervals. During previous intervals of no POFF operations (2007), rates of cross-shore gravel transport were less than during the interval of POFF test operations in 2012. Furthermore, observations of gravel tracers at measurement sites 3 and 4 during non-storm intervals in 2006 showed predominantly onshore transport, while cross-shore transport patterns at the same sites in 2012 are predominantly offshore directed. Maps of morphologic change from consecutive laser scanning surveys show a predominance of alongshore sediment transport that occurs in wavelike patterns at site 3. In comparison transport patterns at site 4 are dominated by cross-shore movement of gravel bars. New observations of gravel transport at site 5, located north of sites 3 and 4, showed cross-shore transport similar to Site 4 and cross-shore sorting resulting in a reverse-graded pattern characteristic of a lower energy regime.

The intensive beach observations during the RP1 testing program that employ laser scanning and gravel tracer methods reveal a complex temporal and spatial variability of the beach response that was not previously revealed during the less intensive baseline monitoring. At some sites within the study area, beach slope was slightly reduced and sediments were redistributed during the RP1 testing interval. The pattern is characteristic of the response anticipated for a POFF operation based on historical observations. However, there are also significant temporal variations in beach response during the testing interval that can only be attributed to natural forces (e.g., wind-waves and tidal current).

Over longer time scale gravel is transported from northwest to southeast along Point White in wave like patterns. The lack of sediment supply to shorelines at Site 3 has created a long term deficit in sediment budget. Although, Sites 4 and 5 also show a long term decline in sediment volumes, particularly about MTL, the volume of the beach below MTL fluctuates from no net loss to net gain on approximately a 4-year cycle. The only sediment supply to sites 4 and 5 is from beaches to the southwest (Site 3) and small creeks.

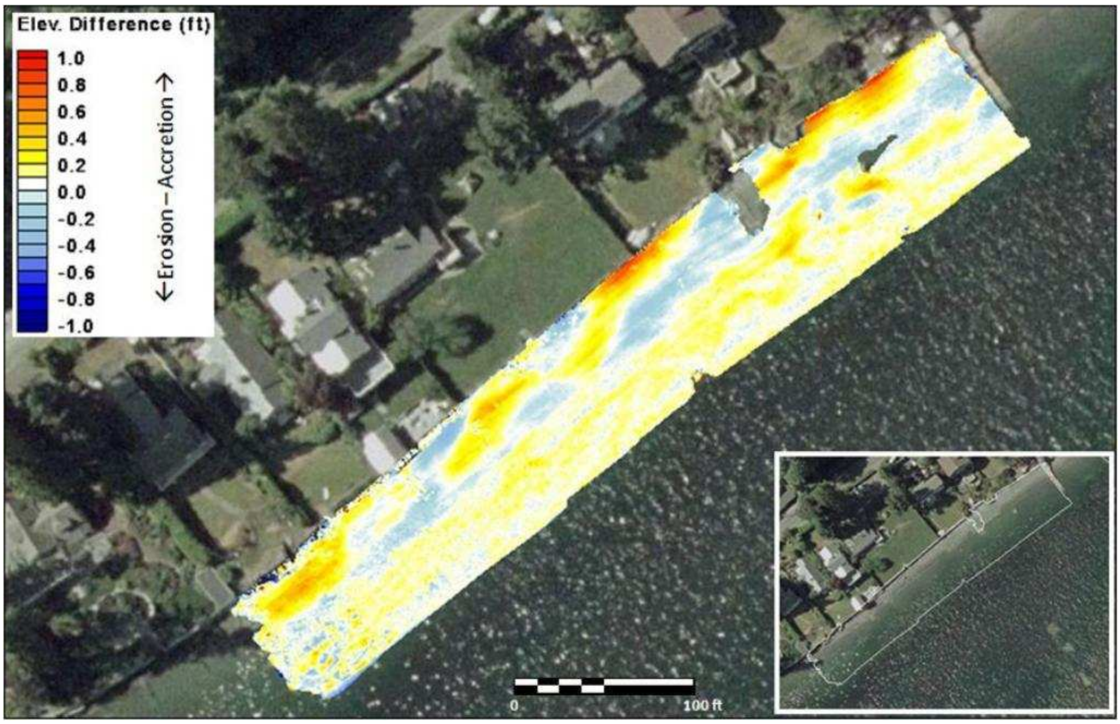

Figure 7. Elevation difference at Point White – Site 3 between 04 June 2012 and 12 November 2012.

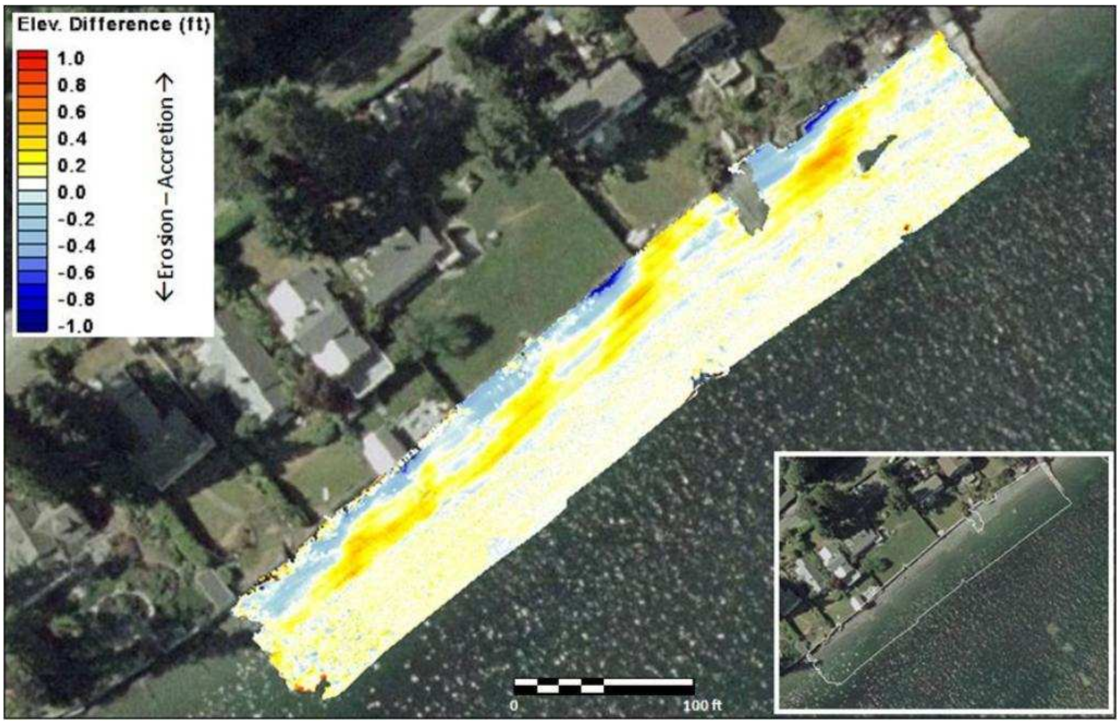

Figure 8. Elevation difference at Point White – Site 3 between 12 November 2012 and 11 December 2012

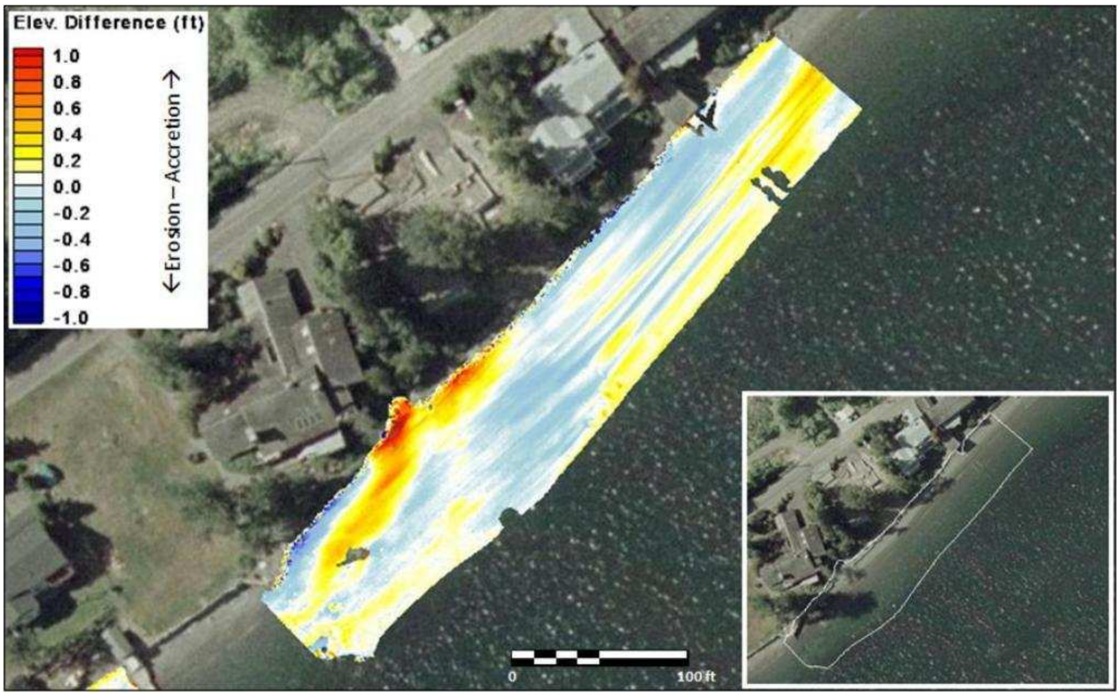

Figure 9: Elevation difference at Point White – Site 4 between 04 June and 12 November 2012.

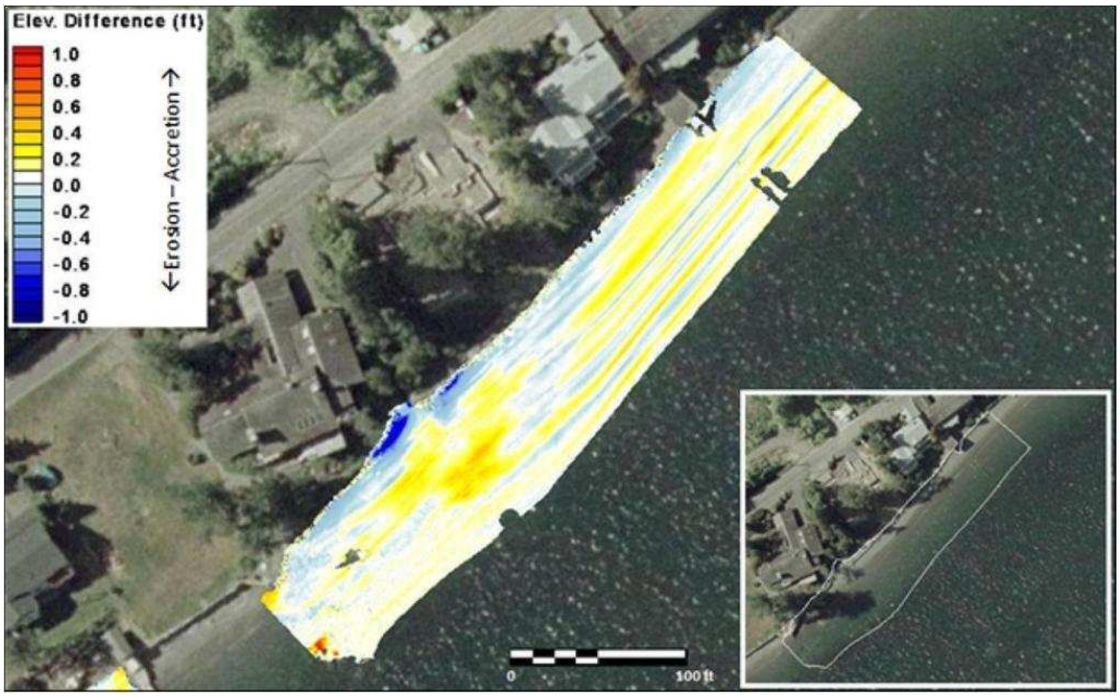

Figure 10. Elevation difference at Point White – Site 4 between 12 November and 11 December 2012.

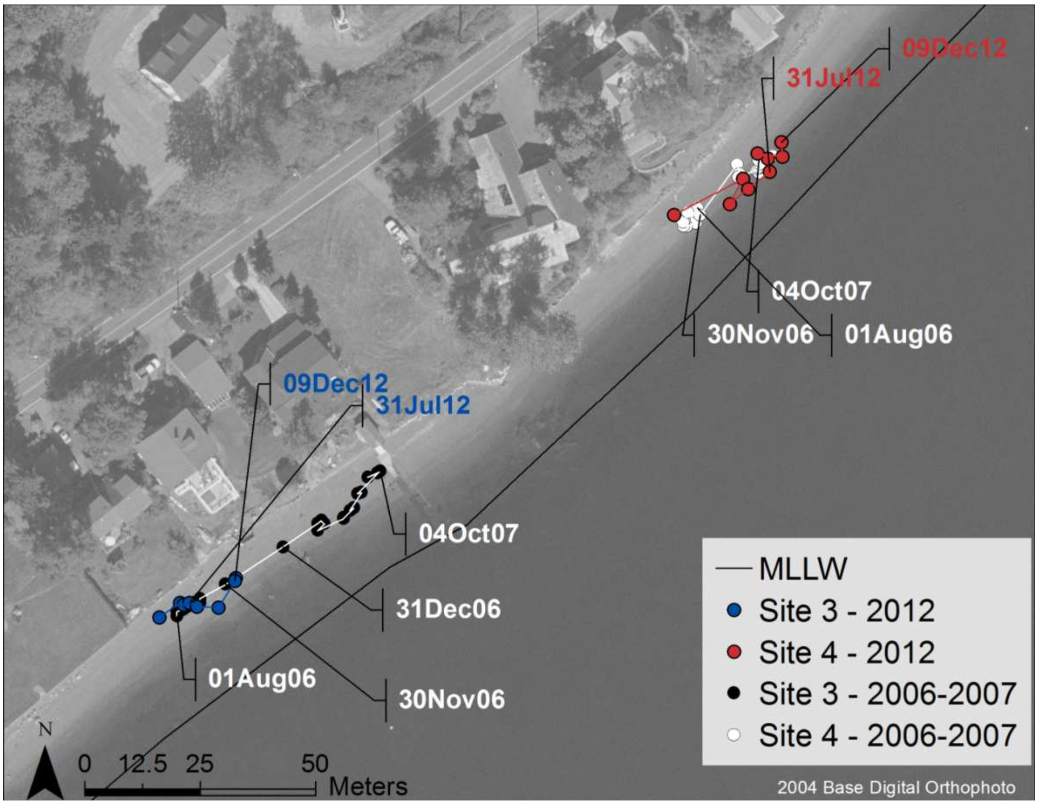

Figure 7. Location of tracer centroids for the 2006-2007 and 2012 survey at Sites 3 and 4

Figure 8: Location of tracer centroids for the 2012 survey at Site 5

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