Gravel Transport and Morphological Response on a Supply-Limited Beach, Point White, Bainbridge Island, Washington

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Abstract. Direct measurements and observations of coarse sediment (gravel) transport, beach morphological change, scour and accretion patterns, beach sediment characteristics, and forcing mechanisms have been obtained over a number of time intervals from 2000 to present from a mixed sand and gravel (MSG) beach on Bainbridge Island, Puget Sound, Washington. The beach is backed by bulkheads and seawall structures along the full length of the study site (approximately 1 kilometer) and has been exposed to wind waves, vessel-generated waves from both passenger-only fast ferries (POFF) and conventional vessels, and tidal currents. Studies that have included integrated process modeling and direct measurements of gravel transport have been undertaken to quantify the relative role of the different forcing mechanisms and determine the corresponding time scales of sediment transport, morphological response, and scour. This paper provides a synthesis of observations of gravel transport over 14 months and beach morphological response over 8 years on Point White, Bainbridge Island in Rich Passage. The observations indicate distinct differences in transport regime and morphological response between storm and non-storm conditions and between POFF and non-POFF vessel operations. The long-term observations of beach morphology change, transport patterns, and sediment size and volume variations that include a downdrift fining and thinning, are consistent with the observation that the MSG beach at Point White is supply limited and undergoing long-term passive erosion most likely as a result of construction of bulkheads along the length of the study area and severe erosional episodes during previous POFF operations and storms.

Introduction

Accurate predictions of sediment transport and beach response are essential for making well-informed decisions regarding the design, permitting, and placement of both engineered structures and beach nourishment projects in the coastal environment. Improper design of structures may lead to long term erosion of the adjacent or down-drift beaches and subsequent impacts to sensitive beach habitat.

Understanding the seasonal and longer-term dynamics of mixed sand and gravel (MSG) beaches is limited, compared to that for sandy beaches, by the lack of long term data on beach response and forcing mechanisms, and the limited predictive capability of numerical models. In particular, there is a lack of information documenting the impacts (long term and short term) of seawalls and bulkheads on MSG beaches.

The operation of ferries in the fetch restricted coastal system of Rich Passage in Puget Sound, Washington, USA, has provided the unique opportunity to study the dynamics of a MSG beach with bulkhead structures that is exposed to a wide range of wakes, wind waves, and tidal currents. In one sense, the site specific nature of the study described here is somewhat unique owing to the influence of the fast-ferry wakes and the relatively low exposure to wind waves in Rich Passage itself. However, most beaches in Puget Sound are influenced to an extent by a combination of shipwakes, wind waves, and tidal currents, and most beaches exhibit mixed sediments with a morphology broadly similar to that in the Rich Passage area, bulkheads and structures are widespread, and the exposure typically varies widely from place to place. The study results may, therefore, provide a preliminary basis for characterization of mixed beach behavior in Puget Sound. The extension of this work through a system of integrated numerical models (for example, Osborne and MacDonald, 2007) will further extend the applicability of results. During previous passenger-only fast-ferry (POFF) operations from 1999 to 2002, the upper foreshore of beaches in Rich Passage were eroded and the slopes were reduced. It is hypothesized that the longer period POFF wakes caused the flattening and erosion of the upper foreshore, whereas wakes from car ferries have resulted in beach steepening and accretion of the foreshore. The presence of bulkheads or seawalls also is hypothesized to have had a long-term (decadal) impact on sediment supply and thereby contributed to passive erosion in the study area (Osborne and others, 2007).

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The goals of the present study were to resolve seasonal patterns of sediment transport and morphology change on a MSG beach that is backed by bulkheads, quantify the relative role of the different forcing mechanisms (wakes, waves, and tidal currents), and apply the measurements to validation of a system of integrated numerical models that can be used for wake impact assessment in the study area. In this paper, we provide an overview of the results of direct measurements and observations of coarse sediment (gravel) transport and beach morphological change obtained over a number of time intervals from 2000 to present from a MSG beach on Bainbridge Island, Puget Sound, Washington. From these data, we comment on the relationships between sediments and supply, morphology, processes, and forcing on a typical Puget Sound beach that has been armored by bulkheads and subject to variable wake and wave climate for several decades. The study is part of a large multi-disciplinary study investigating the feasibility of re-introducing POFF operations to the Seattle-Bremerton ferry route, which includes extensive physical and biological data collection, integrated impact assessment modeling, and vessel design, optimization, and in-situ testing. The interested reader is referred to papers by Curtiss and others (2009), Osborne and others (2007), and Osborne and MacDonald (2007) for more detailed discussion of the measurements and modeling. Additional technical information on the study may be found on the project web site (Pacific International Engineering, 2009) at www.pugetsoundfastferry.com.

Study Area and Sediment Characterization

The study site (fig. 1) is an approximately 500-m length of MSG beach in Puget Sound on the east shore of Point White, at the southern end of Bainbridge Island. 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, Washington. The beaches are backed by bulkheads and revetments of varying type and condition along the length of the study area. Data including wind, wave, current measurements, sediment samples, and gravel tracer measurements were collected at two separate sites which are denoted here as PWA and PWB (see Curtiss and others, 2009, for details).

The sites were selected for study because of their location in proximity to the vessel sailing line on the Seattle-Bremerton ferry route, and because they both occur in relatively close proximity to one another within the same drift cell but exhibit notable differences in sediment properties and response. Beach and inter-tidal deposits at Point White are a thin layer of unconsolidated sediment eroded into a beach platform composed of consolidated Holocene age Vashon till (Haugerud, 2005). The mobile sediment layer is the result of reworking of coastal exposures of till, outwash sediments, and glaciomarine and glaciolacustrine deposits (Finlayson, 2006). The beach foreshore along Point White generally is steep (slopes from 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 up to 2 m in places on the upper foreshore and at the toe of bulkheads. The unconsolidated layer generally is thicker at PWB than at PWA; the beach to the south of PWA is a single grain thickness of gravel over till. The gravel layer varies from 0.5 m to as thin as a single grain thickness of armor on the lower foreshore. The cross-shore sorting is related to the relationship between swash energy, tide, and gravity/slope effects (for example, Osborne and Simpson, 2005). The sediments were characterized by pebble counts of the surface layer and sieving samples from the upper 30 cm. The median grain size based on the pebble count is 22.5 mm at PWA and 17.0 mm at PWB. The median grain size for the entire sediment mixture based on the results of sieving is 16.0 mm at PWA and 11.0 mm at PWB. A unique feature of the beach is the median size of the gravel, which increases with decreasing elevation on the beach, which was also observed by Nordstrom and Jackson (1993) on a low energy estuarine beach.

Gravel Tracer Measurements

Direct measurements of pebble and cobble (gravel) transport were obtained at Point White using Radio Frequency Identification (RFID) Passive Integrated Transponder (PIT) particle tracking methods (Allan and others, 2006). Tracer particles were made from samples of beach surface sediment chosen to match the size and shape of the native distributions as closely as possible but constrained by the minimum size of the PIT tags (12 mm). Sets of 48 tracers were deployed in random grids with 30-m spacing about the mean tide level at PWA and PWB from 1 August 2006 through 5 October 2007. A tracer survey consisted of finding the tracers with the RF control module and recording their positions with the RTK-GPS, leaving the tracers undisturbed. The RFID tracking methodology provided high recovery rates of the tracers. In general, the recovery was greater than 80 percent (minimum of 73 percent) throughout the study. Lowest recovery occurred during winter months, when storms resulted in higher burial rates, offshore transport, and higher tidal elevations during surveys which generally coincided with daylight hours. Tracers surveys were conducted approximately twice per month during the deployment interval (Curtiss and others, 2009).

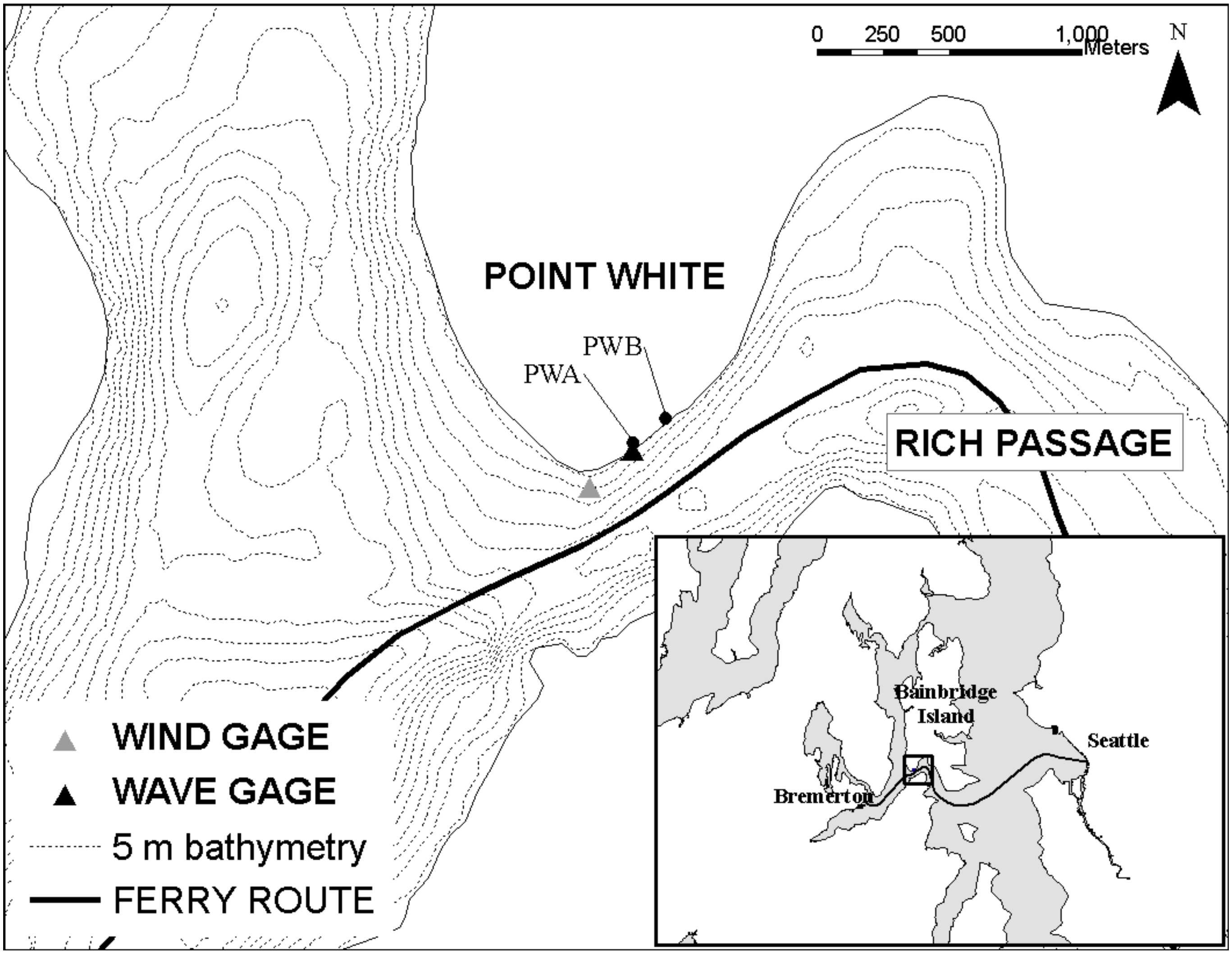

Figure 1. Study area and the location of tracer deployments, and wind and wave measurements.

The particle tracking data were analyzed 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. Figure 2 is a map of the tracer distributions on August 1, 2006, and October 5, 2007, and of the centroid of the tracers through time. Tracers moved predominately alongshore to the northeast at both sites, with greater transport magnitude occurring at PWA than at PWB. Following an initial episode of southwesterly alongshore transport at PWB, the tracers moved to the northeast. Figure 3 is a time series of the alongshore transport distance for the tracer centroids at PWA and PWB. The most noticeable feature is the amplified alongshore movement of the tracers to the northeast at both sites between November 2006 and the end of December 2006. Tracers at PWA move alongshore at a rate of approximately 0.065 m/d between April and November, whereas at PWB, the rate of movement alongshore is 0.005 m/d in the same interval. The daily transport rate at PWA increases by a factor of 6 in the period between November and January. At PWB, the alongshore transport rate increases by a factor of 90 during December. The transport during December largely is a result of the 10-year storm that occurred on December 13–14, 2006. The magnitude of alongshore movement in December is similar at both sites. However, the magnitude of alongshore movement during the non-storm intervals is higher at PWA and is possibly explained by site specific differences in exposure to wind waves and vessel wakes. The patterns of dispersal in relation to forcing are discussed in more detail in Curtiss and others (2009).

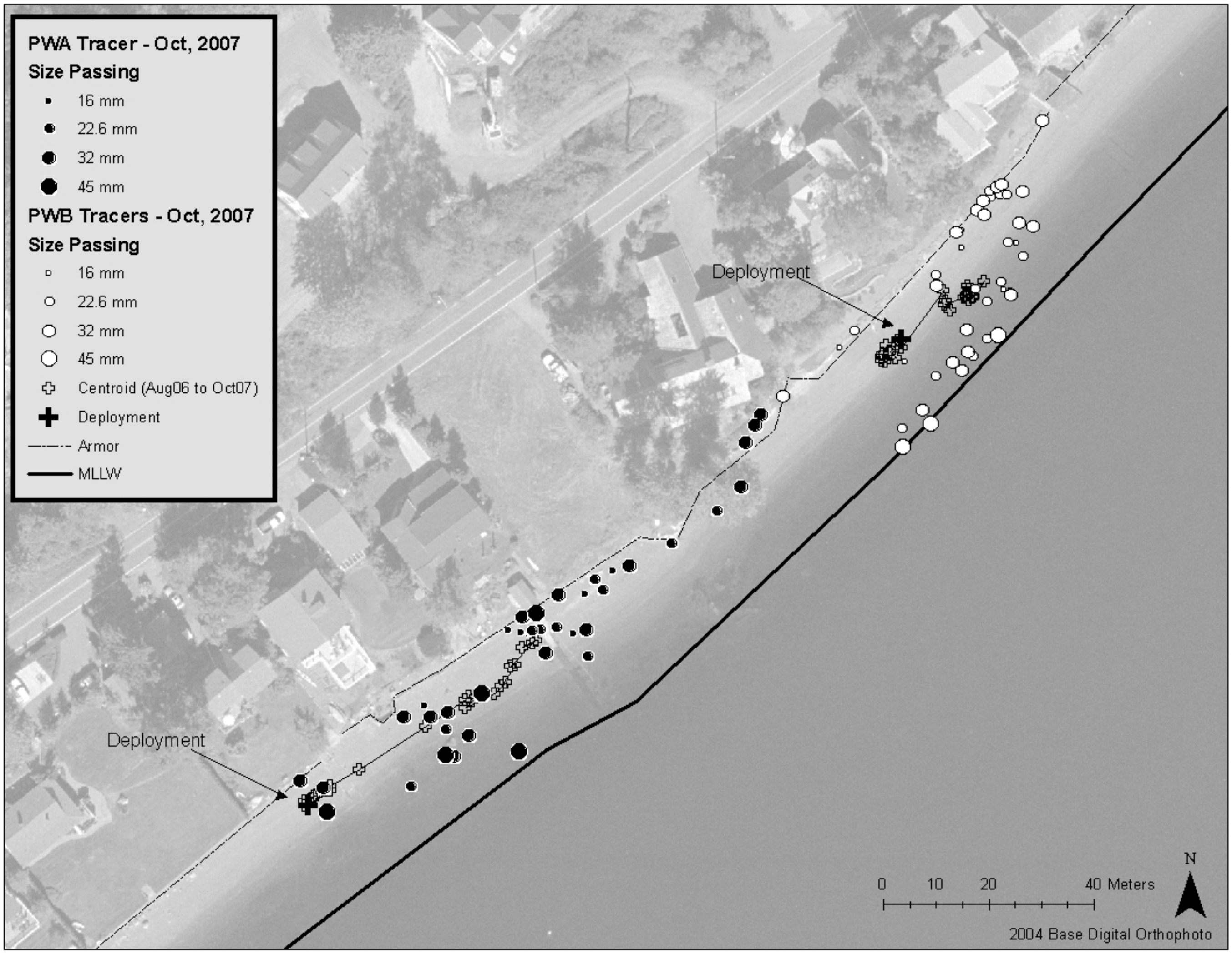

Figure 2. Spatial map of tracer distributions at the final survey in October 2007 and the position of tracer centroids through time between August 2006 and October 2007 at Point White (PWA and PWB are data-collection sites at Point White).

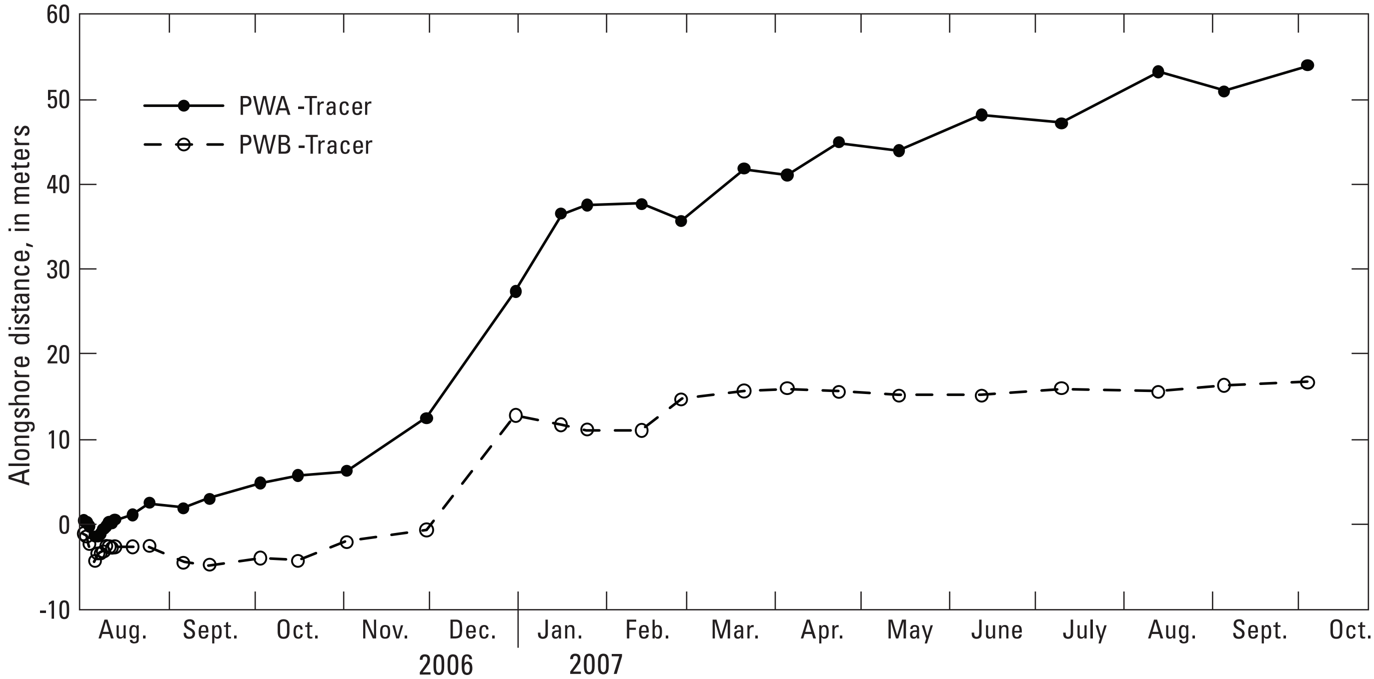

Figure 3. Alongshore transport distances of the tracer centroids between August 2006 and October 2007.

Beach Morphology Change

A number of different POFF vessels have been operated periodically through Rich Passage from the late 1980s until October 2002. All operations thus far have met with opposition from waterfront property owners because of reported damages to property and erosion of beaches (see Osborne and MacDonald, 2005, for a review). Figure 4 shows the most recent intervals since 1998 of passenger fast ferry operations in Rich Passage and the volumetric change to the upper and lower profile (above and below mean tide level) from the last 8 years at both PWA and PWB relative to May 2000, when a beach profile monitoring program was initiated. The resumption of high-speed ferry operations in 2000 initially resulted in erosion from the upper foreshore and accretion on the lower foreshore. The lower foreshore eventually eroded as well at both sites. The profile at PWA indicates a gradual erosion trend since 2004; erosion during the winter of 2008 was particularly severe. Between 2004 and the time of the gravel tracer study, the entire beach at PWB was slowly accreting sediment such that the beach recovered to the volumes present in May 2000. Erosion of the entire profile occurred during the winter of 2008 (fig. 4). It is evident that this winter erosion, which is caused by wind waves, is equivalent in magnitude to the erosion caused by the fast ferries. The winter storm erosion appears to remove sediment from both the upper and lower profile (profile retreat) rather than to re-distribute the sediment across shore (profile flattening or steepening).

Discussion

The gravel tracer measurement from the MSG beach on Point White indicate the system is dominated by alongshore sediment transport from southwest to northeast under existing conditions. The transport largely is driven by wind waves during winter storms. Storms also enhance offshore transport of gravel and cobble and result in flattening of the beach profile and exposure of sand. The combination of car ferry wakes and tidal currents contribute to a weak net alongshore transport to the southwest during non-storm conditions at PWB but not at PWA, where the net tidal flux is weaker. Car ferry wakes also contribute to net shoreward transport during non-storm conditions (Curtiss and others, 2009). In contrast, passenger-only fast-ferry operations may result in a significant cross-shore shift of sediment volume and flattening of the beach profile, which can dominate storm-induced and seasonal variations depending on site-specific conditions (Osborne and others, 2007).

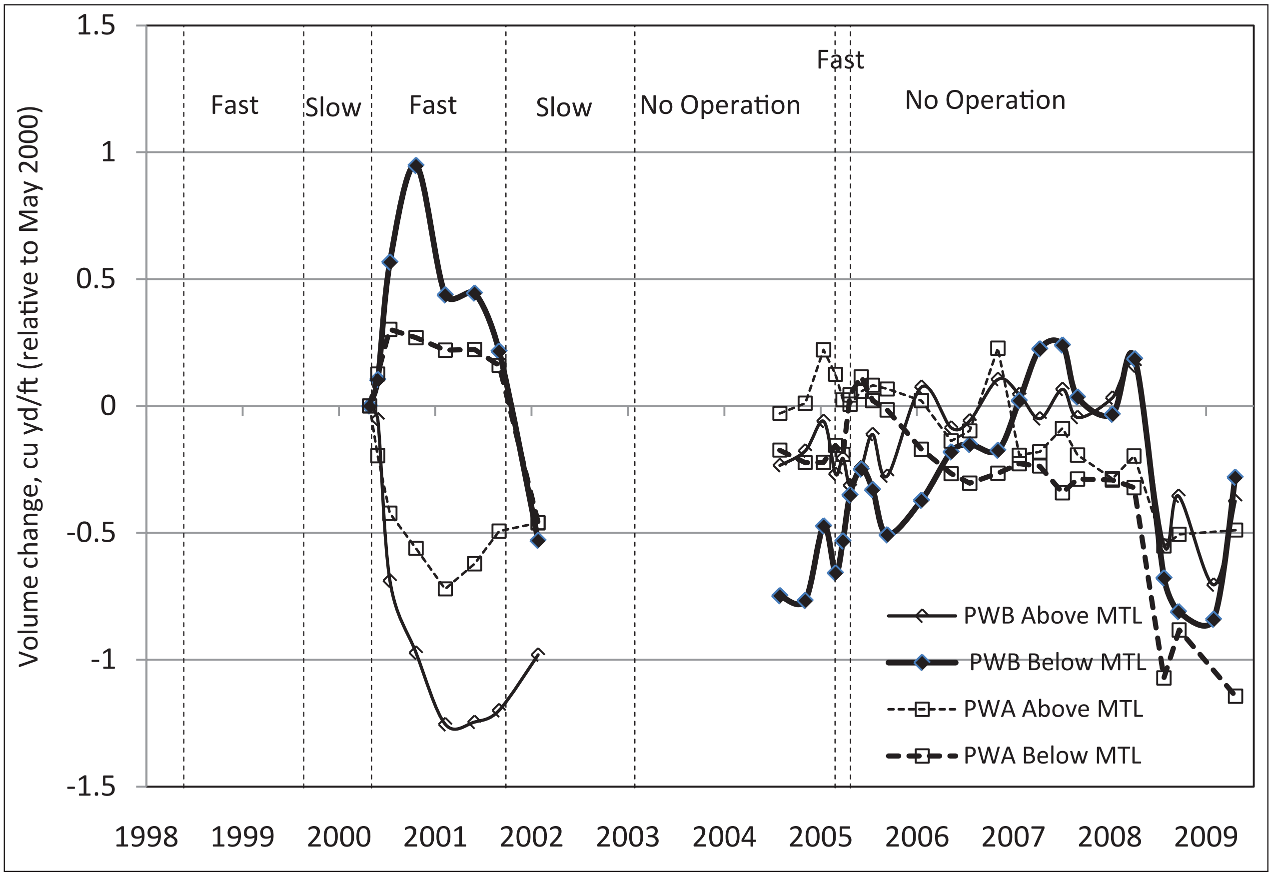

Figure 4. Volume change at PWA and PWB over an 8-year period relative to May 2000 above and below mean tide level. The intervals of fast, slow, and no operation of passenger-only fast ferries are shown with vertical dashed lines. The long-term data indicate the beach is gradually losing sediment at PWA but not at PWB.

The following observations indicate that the beach is supply limited and undergoing long-term, passive erosion, most likely as a result of construction of bulkheads along the length of the study area:

- The layer of unconsolidated sediment overlying consolidated Vashon till increases in thickness from no more than a single grain of cobble just south of PWA to more than 1 m of MSG at PWB. The median grain size also decreases in the downdrift direction between PWA and PWB consistent with a reduction in supply of finer sediments to the beach and the development of a gravel/cobble lag at the proximal end of the drift cell.

- The differences in the trends in volume change at the two sites are consistent with the above interpretation and may be attributed to their respective location in the alongshore drift cell on Point White and the relative sediment supply. PWA is near the proximal end of the drift cell where sediment supply is limited, whereas PWB is more distal and the sediment supply to the latter is being maintained thus far by erosion of the updrift beach.

Conclusions

The observations indicate differences in the sediment transport regime and morphology response between storm and non-storm conditions and between POFF and non-POFF vessel operations.

Storm intervals (typically from November through April) are characterized by an alongshore sediment transport rate of 6 to 90 times the rate during non-storm intervals as a result of offshore transport of coarse sediment (removal of surface armor) and the exposure of sand on a flat upper beach slope induced by wind waves.

Non-storm intervals (typically from May through October) are characterized by minimal alongshore transport (resulting from contributions by vessel wakes and tidal currents), and weak onshore transport, which leads to gravel berm formation on the upper beach and steepening.

Despite small differences in wave height, POFF wakes 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 often interact with structures. Beach profile response to

POFF operation is rapid, occurring over an interval of several weeks. Large POFF wakes mobilize and remove sand and coarse-grained sediments from the upper foreshore and deposit it on the middle and lower foreshore and shallow sub-tidal areas. Smaller and shorter period wakes from smaller and slower vessels (such as car ferries) result in net accretion of sand and gravel on the upper beach over periods of months to years.

Downdrift portions of the beach have recovered from previous POFF operations nearly a decade ago as a result of continued longshore sediment transport and dominating onshore transport under the prevailing wake regime. However, bulkhead construction along the length of the study area has reduced sediment supply to the beach and the long term morphological observations over the past 8 years indicate a passive erosion trend beginning near the proximal end of the drift cell on Point White.

Acknowledgments

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