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Characterization of Coarse Sediment Transport On a Mixed Sand and Gravel Beach: Cherry Point Aquatic Reserve, Blaine, Washington

BY

Meghan E. Weaver

Accepted in Partial Completion of the Requirements for the Degree Master of Science

Kathleen L. Kitto, Dean of the Graduate School

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MASTER’S THESIS

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Meghan E. Weaver
April 10, 2013
Characterization of Coarse Sediment Transport 
On a Mixed Sand and Gravel Beach: 
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A Thesis 
Presented to 
The Faculty of 

Western Washington University

In Partial Fulfillment 
Of the Requirements for the Degree 

Master of Science

By 
Meghan E. Weaver 

April 2013
ABSTRACT

This study examines coarse-sediment transport behavior on a mixed sand and gravel (MSG) beach at Cherry Point Aquatic Reserve in Blaine, Washington. Radio Frequency Identifier (RFId) Passive Integrated Transponder (PIT) tags were used to trace large pebbles and cobbles (51 - 129 mm in diameter) between mid-January and early-March, 2012. Transport data were combined with wind, current and water level data recorded by nearby weather stations, as well as wave data collected by an offshore pressure sensor, into a comprehensive data set. Tide, wind and wave parameters were then input into XBeach, a relatively new nearshore numerical model [Roelvink et al. 2009], to investigate the critical relationships between oceanic and atmospheric factors and the behavior of coarse sediment at the Reserve. Measured displacement of pebbles and cobbles recorded long-shore transport in both directions, with little cross-shore movement. This bi-directional transport supports observations made by Bauer [1976] and adds a new facet of beach behavior to the currently favored, uni-directional net-drift cell model [Schwartz et al. 1991, Johannessen & Chase 2006]. During moderate energy wave activity, the duration of elevated wind speeds above 4 m/s controls the extent of tracer displacement. During high energy winter storms, fetch distance and significant wave height control displacement. Another important discovery is the immobility of the lower beach compared to the middle and upper beach. Computer modeling of wave forcing, roller energy and bed shear stress identifies a critical water level needed to bring roller waves close enough to break over the beach profile and affect coarse-sediment transport.
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I would like to first and foremost acknowledge my advisor, Dr. Scott Linneman, for being ever-patient through the 10+ iterations of the scope of this thesis. At every step, his advice has been a dependable mix of supportive, constructive and realistic. Without such sound advice, I may have been forever stuck trying to plan a way to smuggle LiDAR scanning equipment across the US-Canadian border... or trying to configure the best way to reppel down a 50 foot cliff at Point Roberts...or figuring out how to construct a LiDAR cart with balloon wheels that could traverse stairs, rocks, sand and mudflats AND carry a 40 food tripod AND be able to take night-vision pictures. All in all, I think particle tracing was the way to go.

Next, I’d like to recognize Dr. Eric Grossman for being a huge resource to me during this time. Without his knowledge of coastal processes and his grip on new technology, my data would be nothing but points on a beach. For his enthusiasm, I am ever grateful. By extension, I’d like to thank the United States Geologic Survey for lending me the pressure sensor for my research at Cherry Point. Specifically, I want to acknowledge Dr. Ian Miller for laying the groundwork for the many of the methods used in this thesis. His work in the Elwha Delta is inspiring and his willingness to help me with this project has been a blessing.

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Encyclopedia on beach and coastal environments, calling the thesis draft I just left in his mailbox “very impressive.”

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CHAPTER 1: INTRODUCTION

1.1 Objective

Theories about fine-sediment coastal processes, as well as numerical models that address these processes, have recently made significant advances. Coarse-sediment processes, on the other hand, are still not fully understood, especially when it comes to coarse-sediment transport in mixed sand and gravel (MSG) beach systems [Curtiss et al. 2009]. The purpose of this study is to examine the transport behavior of a fraction of the coarse sediment (large pebbles to large cobbles) present on a northwest Washington State MSG beach. The shoreline of the Cherry Point Aquatic Reserve was chosen as the location for the study, since it has both environmental and political significance in the community, and any insight into beach sediment behavior could have a considerable impact on the way the area is protected or developed. Historically, sediment behavior along this shoreline has been defined in two ways. Bauer [1976] observed bi-directional transport of gravel sediment near the study site towards both the northwest and the southeast. In contrast, more recent studies of long-shore drift cells by Schwartz et al. [1991] and Johannessen & Chase [2006] suggest sediment is mainly moving to the southeast. This thesis employed particle tracers, identified by Radio Frequency Identifier (RFId) Passive Integrated Transponder (PIT) tags, to measure large pebble and cobble transport on the Cherry Point beach between mid-January and early-March, 2012. Transport data is combined with wind, current and water level data collected by nearby National Oceanic and Atmospheric Administration (NOAA) stations, as well as wave data collected by an offshore pressure sensor, into a comprehensive data set that records coarse sediment response to winter weather conditions. Tide, wind and wave parameters were then input to XBeach, a relatively new nearshore numerical model [Roelvink et al. 2009], to investigate the critical relationships between oceanic and atmospheric factors and the behavior of coarse sediment within the beaches of the Cherry Point Aquatic Reserve.

1.2 Regional Setting

The Cherry Point Aquatic Reserve is located along the Salish Sea coastline 40 km north of Bellingham, Washington. The Salish Sea, officially named in 2009, is defined as the saltwater body...
extending from the mouth of the Strait of Juan de Fuca eastward and northward to include Puget Sound and Georgia Strait, with their associated bays, coves, and inlets (Figure 1) [USGS 2013].

The Cherry Point Aquatic Reserve makes up approximately 7.9 mi (12.7 km) of the Salish Sea coastline in northwest Washington (Figure 2). The Aquatic Reserve is located on the southeast coastline of the Georgia Strait, a 240km long seaway that separates mainland British Columbia (B.C.), Canada, from Vancouver Island, B.C.. The United States-Canadian border crosses the southern tip of the Strait. Cherry Point is located on the American side, about 8.5 miles south of the international border, just south of Birch Bay and within the township of Blaine, Washington, USA.

The Aquatic Reserve is bounded to the north by Birch Bay State Park and to the south by the Lummi Indian Nation Reservation. The seaward boundary includes all tidelands within approximately 5,000 ft (1,524 m) of the marine shoreline. All of the aquatic and tidal lands incorporated in the reserve are owned and operated by the Washington Department of Natural Resources (DNR), with the exception of a few stretches of beach that were privately owned or had existing leases in the year 2000, when Cherry Point was officially designated a Reserve. Though ‘reserve’ status was not approved until 2000, the Washington State DNR has been active in monitoring the area ever since the first industrial pier was constructed on state-owned lands in 1954 [EARMP 2010].

Cherry Point’s physical environment makes it both a fragile habitat for a diverse ecosystem and an ideal location for industrial development. Thus, the community encompasses a wide range of often conflicting interests, either falling in favor of environmental protection or industrial and economic development. A series of management plans describing the state of the Reserve and listing the procedures needed to balance these interests were drafted in 2001, 2003, 2007 and 2010 through cooperation of the DNR, local scientists and a number of federal, state, local and tribal authorities [EARMP 2010].

1.3 Ecology of the Aquatic Reserve

The beach is home to some diverse habitats: riparian vegetation, cobble-boulder shoreline, sandy intertidal areas and eelgrass beds (Figure 3). As a result, Cherry Point is well known for a wide variety of flora and fauna. Submerged vegetation composed of eelgrass, kelp and diverse species of algae serve as an important food source, habitat and shelter for many fish and marine birds. Juvenile salmon and herring are common in the nearshore environment. Cherry Point’s nearshore habitat
Figure 1: Map of the Salish Sea. Study site highlighted with yellow star. Modified from Freelan 2009.
Figure 2: Shorelines within the Birch Bay Watershed Management Unit, as defined in SMP 2006.

Figure 3: Ecological boundaries in the Cherry Point Aquatic Reserve. WADNR 2011.
historically spawned over 50% of the Puget Sound’s herring population, but this percentage has rapidly declined since the early 1990’s. Other fish species include forage fish, surf smelt, sand lance, northern anchovy and groundfish. Invertebrates such as snails, mussels, red rock crab, and barnacles inhabit drift vegetation and cobble-boulder beds. In the sandy, eelgrass area, a variety of worms, burrowing anemones, bivalves and clams can be found. Common subtidal invertebrates include seastars, Dungeness and tanner crab, shrimps and sea cucumbers. Cherry Point is also considered an area of significant bird habitat within the northern straits. It is home to over ten threatened or endangered species, such as the marbled murrelet, bald eagle, three species of cormorants, and the peregrine falcon [EARMP 2010].

1.4 Cherry Point’s Development Plan & Industrial Use

Under Whatcom County’s Comprehensive Growth Management Plan [WCCP 2009], Cherry Point is largely zoned as a Major Port/Industrial area and has about 7,000 acres of industrial land. Only a small portion of the shoreline to the north of Point Whitehorn is designated an Urban Growth Area (assigned to accommodate urban sprawl in the next 20 years) (Figure 4). Even though the area is suited to house a growing population, the county’s economy relies heavily on this industrial area. The county has taken action to prevent the remaining industrial land from being used for residential development. Instead, Whatcom County is seeking industrial expansion [WCCP 2009].

Cherry Point is already home to three industrial piers (Figure 5). The southern-most pier was first built in 1954 as the access point for an oil refinery now owned by ConocoPhillips. In 1966, Intalco Aluminum (now Alcoa Intalco Works) built an aluminum smelter with adjacent pier just north of ConocoPhillips. The third and northernmost pier was built in 1971 to serve another oil refinery, now owned and operated by British Petroleum (BP) [EARMP 2010].

In 1997, Whatcom County ‘conditionally approved’ the proposal of Pacific International Terminals (subsidiary of SSA Marine, a cargo terminal operation company) to construct a Gateway Pacific bulk transshipment facility at Cherry Point between the Alcoa Intalco Works and BP piers. The shipping terminal was designed to include a 1,300 ft long pier ending in a 2,600 ft long wharf [WCPDS 1997]. A decade later, the plans have now evolved into a $665 million dollar cargo terminal. The revised Gateway Pacific Cargo Terminal would serve as the largest loading port on the US west coast for grain, coal, and other exports. Proposed coastline construction has expanded to include a 3,000 ft
Figure 4: Land adjacent to Cherry Point is largely zoned for industrial use. EARMP 2010.
Figure 5: Industrial piers within the Cherry Point Aquatic Reserve. Note the available space in the Reserve zoned for a future industrial pier between BP and Alcoa Intalco (proposed structures shown in Figure 6). EARMP 2010.
wharf connected to shore by a 1,250 ft trestle (Figure 6). The terminal now promises to create over 1,000 jobs during the construction process, with 430 full-time, high paying permanent jobs once completed [PIT 2011].

![Figure 6: Proposed structures for the Gateway Pacific Terminal. PIT 2011.](image)

Because the scale of this project has grown, the state has required a new set of permits for the project. These permit applications were submitted to Whatcom County on June 10, 2011 [WCPDS 2011]. Whatcom County Planning & Development, the State Department of Ecology and the U.S. Army Corps of Engineers are currently in the process of conducting a coordinated environmental review of the project [WADOE 2013]. A four-month scoping period took place between September, 2012, and late January, 2013, during which time these agencies were open to suggestions regarding potential environmental factors (e.g., air or water pollution, noise pollution, train traffic concerns) involved in the terminal project. A private consulting firm is now sifting through over 124,000 comments submitted by the public [WCPDS 2013]. Once these are organized, an Environmental Impact Statement (EIS) will be drafted. This preliminary draft is not expected to be made public until 2014 or later. Until these environmental factors can be fully addressed, the leasing of aquatic lands to SSA Marine and construction of the terminal have been put on hold [WADOE 2013].
1.5 Recreational Use

The Cherry Point Aquatic Reserve can be accessed by boat, on the beach from the northwest or southeast boundaries, or through the Point Whitehorn Marine Park. The Marine Park, part of Whatcom County Parks & Recreation, is located about a mile north of the BP Cherry Point Pier and was acquired by the Whatcom Land Trust in 2007 [Point Whitehorn Marine Park]. The park consists of one main 0.75 mile long trail that winds its way through forest and wetlands to the edge of the bluffs along the Strait of Georgia. The trail path then steeply descends by a wooden staircase to the tidelands of the Aquatic Reserve. The park is open year-round, from dawn to dusk, and allows public access for shellfishing.
CHAPTER 2: THE PHYSICAL ENVIRONMENT

Sediment transport is directly affected by several environmental factors that span multiple disciplines. Therefore, an introduction to the local physical environment (Geography, Climate, Oceanography, Geology and Geomorphology) of Cherry Point is described in the following section. Basic theory behind waves and their relationship to tides, winds and sediment transport is also described so that all relationships are made clear prior to the results and discussion sections.

2.1 Geography

The shape and depth of the Georgia Strait and surrounding waterways can be attributed to the region’s rich tectonic and glacial history. Between the late Cretaceous and the Eocene, in the Cascadia convergent margin, the Farallon plate began subducting underneath North America. This subduction spurred the creation of the Coast Range volcanic arc, which caused crustal folding, creating the high-relief terrain of the Coast Mountains and a forearc basin known as the Georgia Basin [England & Bustin 1998]. More recently, during the Pleistocene era, a series of glacial periods caused major ice sheets to advance and retreat over the landscape of North America. The most recent period, called the Fraser Glaciation, funneled great lobes of ice from the Cordilleran Ice Sheet through the Georgia Basin and into the Puget Lowland before becoming so thick as to overtop Vancouver Island and flow west towards the Pacific Ocean [Clague & James 2002]. The force of the glacier’s movement against the rocky basin floor, as well as high pressures exerted by sub-glacial water flow, eroded out a series of deep, north to south oriented and flat-floored basins. These restricted marine basins are now known as the Georgia Strait and the Puget Sound [Hill et al. 2008].

Glacial action carved a steep slope in the Georgia Basin adjacent to present day Cherry Point, which is now reflected in the steep bathymetric gradient observed directly offshore (Figure 7). This is one of the major draws for industrial piers, as large cargo vessels can get close to shore without the owners of the pier having to artificially dredge out a deepwater access point. It is likely that the steep slope from offshore to the nearshore has an effect on wave energy behavior, but this relationship has yet to be defined.
Figure 7: Cherry Point bathymetric map. Study site highlighted in red. Courtesy of Bert Rubash.
The shape of the beach profile at Cherry Point varies laterally, but Figure 8 shows a typical profile of the study area (vertically exaggerated 5 times) illustrated with basic coastal terminology. The shore is the portion of the beach between low tide water level and the upper extent of wave action. This extent of wave action is normally above still-water high tide levels, all the way to the base of the bluff or cliff. The shore is split into two sections, the backshore (above high tide) and the foreshore (also known as the intertidal zone, between high and low tide). Shorelines constantly change with the rise and fall of the tides. The nearshore represents the area between the shoreline and the breaker line, where waves from offshore have steepened and collapsed (section 2.3(b)). This region also changes with the rise and fall of water levels and is usually widest at low tide and thinnest at high tide. Offshore constitutes everything seaward of the breaker line [Bird 2000].

**Figure 8:** Cherry Point beach profile with coastal zone terminology. Beach sediment vertically exaggerated by 5, shore platform and bluff not drawn to scale. Modified from Bird 2000.
2.2 Climate

2.2(a) Local Meteorological Climate

Cherry Point can be classified as having a cross between a Temperate Oceanic and Mediterranean climate. Like other west coast regions, there is a relatively narrow annual temperature range; however, there is also a marked drop in rainfall during summer months, especially in August. Generally, precipitation averages between 115 and 127 cm per year and is mostly attributed to wet winter storms between October and January [SMP 2006].

The National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC)’s Station CHYW1 records temperature, atmospheric pressure, wind direction, and sustained wind and gust speed. It is positioned at the BP Cherry Point pier, and its data, recorded every 6 minutes, are publicly available. Although Washington climate can be categorized into winter, spring, summer and fall seasons, the local wind patterns have a distinct bi-modal seasonality (Figure 9a-b). Winds during the months of April to September are predominantly low energy, with speeds < 6 m/s making up 75-95% of all records. April is the only month that frequently has high energy (>9 m/s) wind. Winds during the second half of the year, from October to March, are significantly more active. Though low energy winds still account for over half of Cherry Point’s records for these months, there is a more even distribution in velocity range, with high energy winds representing over 20% of records for both March and December [NOAA-NDBC 2013].

In general, the prevailing wind direction at Cherry Point is from the south/southeast to the north/northeast (Figure 10a-b). This prevailing wind is most notably seen during the calmer, dryer summer months of June to August when winds are almost exclusively from the south/southeast. However, wind patterns change seasonally. September and October experience a bit more variety in wind directions from the northwest and the northeast. From November to March, during the storm season, a bi-directional pattern emerges. Winds sourced from the east/northeast just slightly edge out south/southeast winds as the most common prevailing wind direction. April and May, like September and October, transition back to prevailing south/southeast winds and show a similar northwestern signature. On average, winds from the northwest and west/northwest account for less
Figure 9(a): Histogram of wind speeds at Cherry Point from 2008-2012; low energy months. Pie charts illustrate the frequency of wind recorded in each velocity range.
Figure 9(a): Histogram of wind speeds at Cherry Point from 2008-2012; high energy months. Pie charts illustrate the frequency of wind recorded in each velocity range.
Figure 10(a): Monthly wind directional patterns at Cherry Point from 2008-2012; low energy months. Pie charts illustrate the frequency of wind recorded from each direction. The most common wind directions are highlighted: Yellow: 5-10%, Light Orange: 10-15%, Dark Orange: 15-20%, Dark Red: 20-30%, Bright Red: >30%
Figure 10(b): Monthly wind directional patterns at Cherry Point from 2008-2012; high energy months. Pie charts illustrate the frequency of wind recorded from each direction. The most common wind directions are highlighted: Yellow: 5-10%, Light Orange: 10-15%, Dark Orange: 15-20%, Dark Red: 20-30%, Bright Red:>30%
than 10% of wind patterns for the stormy season of late fall, winter, and early spring [NOAA-NDBC 2013].

In the highest register of wind speeds, winds sourced from the south/southeast have a much stronger presence, often exceeding the speed of those prevailing winds from the east/northeast (Figure 11). The fastest and therefore predominant winds are sourced from the south/southeast direction. Storms during the month of November tend to produce the strongest winds on record. On November 19, 2009, a particularly strong wind storm from the south/southeast topped out at nearly 52mph sustained speed with gusts up to 64mph. Thus, since data collection began in 2008, winds from the south/southeast have been both the prevailing and predominant winds at Cherry Point.

2.2(b) The Effects of Global Climate Change

The last 20 years rank among the warmest in global sea surface temperatures and near-surface air temperatures over land since 1850 [Trenberth et al. 2007]. Warming has particularly affected the northern hemisphere, as temperatures have increased at rates of up to 0.344 ± 0.096 degrees per decade between 1979 and 2005 [Smith & Reynolds 2005]. There are two major threats for coastal erosion as a result of global warming. The first is sea level rise (SLR). The second, and perhaps more significant, is the expected regional increase in precipitation and storm strength [Allan & Komar 2006].

Sea Level Rise

Mean sea level (MSL) dictates much of the relationship between beach sediment and sea water. When sediment is in contact with water, it is exposed to physical and chemical processes that may induce erosion. Sediment above MSL is generally drier and more protected from erosion. As sea levels rise, more beach area is exposed to wave energy, and more sediment is susceptible to erosion [Bryant 1985]. However, mean sea level rise should be considered from the perspective of both the land and the sea. The measure of relative sea level (RSL) is a combination of steric changes (seawater temperature increase), glacio-eustatic movements (water volume change due to melting land ice), epeirogenic movements (tectonic-driven land uplift), and isostatic movements (land uplift or depression due to glacial or sea water unloading and loading) [Bindoff et al. 2007].
Figure 11: High wind speed & direction at Cherry Point from 2008-2012.
The ocean has been absorbing more than 80% of heat added to the climate system [Bindoff et al. 2007]. This warming causes seawater to expand and is thought to account for over half of sea level rise since 1993 [IPCC 2007]. The melting of ice sheets in the Arctic and in the northern latitudes is introducing more water into the ocean basins and contributing to sea level rise [Bindoff et al. 2007]. However, relative sea level rise is affected by the rise or fall of land due to tectonic and isostatic movements. Glacial melting since the last ice age has allowed for continental crust that was once depressed underneath the weight of massive ice to ‘rebound,’ or rise. In northwest Washington, rebounding from the last glacial ice age (17,000 years ago) only lasted for 3,000 to 7,000 years, and today any uplift due to isostatic rebound is negligible. Hydro-isostatic loading, or the depression of crust due to the weight of added sea water, has too become negligible as most major glacial melting ceased 11,000 years ago [Dethier et al. 1995]. Instead, the region is dominantly uplifted due to its location on a continental-oceanic plate margin. As the Juan de Fuca plate subducts underneath the North American plate, the land is slightly rising [Mote et al. 2008]. Verdonck [2006] estimated that northwest Washington and British Columbia are being uplifted at a rate of 1-4 mm/year. The calculated relative sea level rise combines water volume changes and land movements. At Cherry Point (study site), the average rate of sea level rise from 1979 to 2001 was estimated to be 1.39±0.94 mm/yr [Zervas 2001].

Precipitation & Storm Strength

Average atmospheric water vapor content increases with global temperature because warm air can hold more water vapor in the atmosphere than cold air [Trenberth & Shea 2005]. In the mid-high latitude ranges, annual precipitation has increased by over 5% in the last century [Trenberth et al. 2007]. In the Pacific Northwest, most beach and bluff erosion occurs during winter months as a result of wet, high-energy winter storms [Johannessen & MacLennan 2007]. Landslides and mass wasting of bluff material are often related to the onset of heavy precipitation events [Tubbs 1974, Thorsen 1987].

Storms in the northern Pacific have increased in intensity since 1948 [Graham & Diaz 2001] and are expected to get stronger as climate continues to warm [Allan & Komar 2006]. Bluff erosion has been directly linked to open-water wind strength by way of wave energy, wave height, and wave run-up [Wilcock et al. 1998, Benumof et al. 2000, Ruggiero et al. 2001]. An increase in wind strength during severe storms would have drastic implications for bluff stability and morphology.
2.3 Oceanography

2.3(a) Water Levels

Wind-derived water waves are considered ‘short’ waves; astronomical tides are examples of ‘long’ waves, and are evidenced by the sinusoidal rise and fall of surface water level in response to gravitational pull of earth towards the moon and sun. Tidal cycles controlled by the moon (lunar cycles, like those seen in the Atlantic) tend to produce semidiurnal tides, two high tides and two low tides about every 25 hours. Tidal cycles controlled by the sun (solar cycles, like that in the Arctic) produce diurnal tides, or one high and one low tide every 24 hours. In the Pacific, tides are a mix of both lunar and solar tides, creating unequal highs and lows [Scheffner 2002].

The geometric relationship between the sun, the earth and the moon will affect tidal cycles. Following each new or full moon, when the sun, earth and moon are in alignment, the gravitational effects will be combined, creating a very high or very low tide. These extreme tides are called spring tides. Alternatively, when the sun and moon are at right angles in relation to the earth (a half moon in the lunar cycle), the gravitational effects are not combined and the tidal range is dampened. These moderate tides are called neap tides. The entire lunar cycle, and therefore tidal cycle of spring to neap and back to spring, occurs over a period of about 29 days [Scheffner 2002].

Currents can be generated by tidal change with the introduction of pressure gradients. For example, as water levels rise from low water to high water, water will travel from high pressure (offshore) to lower pressure (onshore). This is called a flood current and is associated with a rising tide or flood tide. Falling tides, or ebb tides, are typically accompanied by ebb currents where water travels from onshore to offshore. Typically, tidal currents get stronger when more water is moved (i.e. during spring tides) [Bird 2000].

Local Tide Climate

In the Puget Sound and surrounding straits, the lunar and solar cycle often combine to produce a mixed set of non-symmetrical tides, high-high tides, low-low tides, low-high tides and high-low tides. Tidal curves are not symmetrical. In this mixed environment, the “tidal range” is defined as the difference between the mean higher high tide and the mean lower low tide. The mean water level
rises with the tide twice daily, generally above 2 meters, making Cherry Point a meso- to macro-tidal environment (Figure 12) [Finlayson 2006]. A buoy positioned on the BP Cherry Point Pier has been recording water level since 1996 [NOAA-TCT 2013]

A surface-float experiment was conducted in 1977 to identify the ebb and flow of tidal currents in and out of Birch Bay (Figure 13) [Schwartz et al. 1972]. During rising tide (flood tide), tidal currents flowed from south-southeast, to north-northwest, along the shoreline of the Aquatic Reserve and into Birch Bay. During ebb tides, tidal currents moved back out of the bay and back to the south-southeast, creating an eddy to the west of Point Whitehorn. In November 2009, a sensor was installed at the BP Cherry Point Pier (South Dolphin North Pier, ID#CP0101) to collect current data [NOAA-TCC 2013]. These data support the findings of Schwartz et al [1972]. A good example of the baseline current behavior at Cherry Point is illustrated by current vectors collected on February 9th and February 10th of 2012 (Figure 14). Flood tides are associated with currents moving in the north, northwest and west direction. Ebb tides are associated with currents moving toward the south, southeast and east direction. During transitional periods at high tide and low tide, currents are sometimes recorded as moving towards and away from the beach (northeast or southwest). Most often, though, currents are recorded in a longshore direction. The baseline current speed ranges between 0 and 30 cm/s. It is weakest when the current is changing direction and strongest in the middle of rising or falling tides. Changes in the duration and strength of currents are attributed to the variation in tidal curves. Though it was not discussed in the 1972 study and no further research has been done on offshore sediment transport in the reserve, Johannessen & Chase [2006] believe these currents have enough power to carry fine sediment in the longshore direction.

2.3(b) Wave Mechanics

While this thesis does not delve deeply into wave theory, a basic familiarity with wave processes and wave parameters is vital in understanding the relationship between water and sediment in the beach environment (Figure 15). The highest point of a wave is called the crest, while the lowest is the trough. These highs and lows oscillate about the still-water level (SWL) by a vertical offset equal to the wave amplitude (a). The total distance between the crest and the trough is the wave height (H). In linear waves, where there is equal wave amplitude between the trough and crest, a = H/2.
Figure 12: Varieties in tidal behavior at Cherry Point for three different weeks.
Figure 13: Flood and ebb tide current directions at Cherry Point. Star marks study site. *Modified from Schwartz et al. 1972.*
Figure 14: Baseline current behavior during the rise and fall of tides over a period of low wind and low wave energy.
Figure 15: Wave parameters in a linear, sinusoidal wave. Modified from Demirbilek & Vincent 2002 et al. 2002.
However, in true sea surface wind waves, amplitudes may vary significantly. Wave length \((L)\) and wave period \((T)\) quantify the distance and time, respectively, between two successive wave crests. The celerity \((c)\) represents wave phase velocity, where \(c = L/T\), and gives a direction to wave propagation [Demirbilek & Vincent 2002].

While linear wave theory helps to understand basic water wave mechanics, outside of a laboratory these monochromatic waves are not a reality. In an ocean setting, waves are irregular, varying in height, period and direction. Where linear waves are singular and uniform in wave height, true water waves tend to move in groups of increasing and decreasing wave heights (Figure 16). Because of this irregularity, wave parameters are measured statistically, with variations on wave height \((H)\) and period \((T)\). It is within these wave groups that wave energy propagation is observed [Demirbilek & Vincent 2002].

Surface wave energy in the Georgia Strait is typically wind derived. Wind energy, which is created by changes in atmospheric pressure, is transferred from winds to open water at the air-sea interface. The amount of energy carried in the surface wave is a product of wind velocity and the duration of the wind force and fetch distance, the amount of open water in which wind can act on wave energy. This energy force on the surface causes a circular orbit in water particles below (Figure 17), resulting in the sinusoidal shape of water waves. Water particles are moved in the direction of wave propagation, creating a mass transport of fluids (and energy) towards the shoreline [Demirbilek & Vincent 2002].

Wave height \((H)\) is directly proportional to wind velocity and fetch, thus stronger winds traveling over a long distance for an extended period of time will create higher waves and carry more energy towards shore. Longer fetch allows for longer wave periods. Waves with similar height will have more energy with longer wave periods and less energy with shorter wave periods. There is a logarithmic relationship between fetch, wind speeds, and significant wave height \((H_{\text{mo}})\), a statistical variation on \((H)\) that represents the mean of the upper 1/3 of wave heights (Figure 18). Wind speed and fetch can also limit one another, especially if fetch is restricted by directional variance (sustained wind does not exceed 15 degrees from the mean direction), and wind speed is restricted by velocity variation (does not exceed 2.5m/s from the mean velocity) as well as the duration of the sustained velocity [Demirbilek & Vincent 2002].
Figure 16: Wave groups. Modified from Demirbilek & Vincent 2002 et al. 2002.

Figure 17: Orbital motion in waves. Modified from Demirbilek & Vincent 2002 et al. 2002.
Figure 18: Fetch-limited wave heights. *Demirbilek & Vincent* 2002.
As waves propagate from deep water into the shallow nearshore environment, the orbital behavior of water particles begins to change. The vertical distance between the waves and the sea floor is decreasing, thus, the negative frictional drag force acting on the wave by the sea floor is increasing. This stretches the orbital motion of water particles into an ellipse shape (Figure 19) [Demirbilek & Vincent 2002]. The change in orbital shape affects the surface shape of the wave, shortening the wave length \( L \) and increasing the wave height \( H \) [Smith 2002]. Depending on the shape and slope of the sea floor, variations in bathymetry will alter speed, direction and amplitude of the waves [Vincent et al. 2002]. When the waves get shallow enough, so that wave height \( H \) is approximately equal to water depth \( d \), the waves collapse and energy dissipates. This critical moment, called incipient wave breaking, marks the transition from the breaker zone to the surf zone [Smith 2002].

2.3(c) Surf Zone Processes

Within the surf zone these waves will continue to decrease amplitude and dissipate energy until they reach the shoreline, or, in the case of bathymetric irregularity, begin to form and break again. The behavior of waves through this zone affects a series of other hydrodynamic processes, including wave set up, runup and nearshore currents [Smith 2002].

Radiation stress, or the excess flow of momentum due to the presence of waves, is a horizontal forcing exerted on the surface flow of seawater. As wave energy enters shallow water, the radiation pressures decrease in response to diminishing wave energy. The pressure change introduces a cross-shore momentum gradient, causing mean surface level increases towards the shoreline (Figure 20). This phenomenon is called wave set up, and is independent of water level rise due to tides or wind. The amount of set up has important implications for sediment transport, especially during stormy periods of high wind and waves [Longuet-Higgins & Stewart 1964].

Once wind waves finally arrive onshore at elevated mean levels due to wave set up, there is a swash effect about the beach slope, namely an uprush of water in the direction of wave energy and a backwash parallel to the slope gradient. Second to the breaker zone, the swash zone has the highest energy dynamics within the nearshore and is responsible for fluid-driven beach sediment transport. By monitoring the maximum elevation of uprush, known as wave runup, the active portion of a beach may be defined over time. Though runup is primarily influenced by wave set up and wind
Figure 19: Shallow vs. deep-water wave orbital motion. Modified from Demirbilek & Vincent 2002

Figure 20: Wave setup. Beach sediment vertically exaggerated by 5, shore platform and bluff not drawn to scale. Modified from Demirbilek & Vincent 2002.
energy, physical characteristics of the beach such as slope, wave reflectivity, porosity, roughness, permeability and groundwater elevation will also affect swash dynamics [Smith 2002].

Nearshore currents within the surf zone are driven by a series of forces. Radiation stress from breaking waves, pressure gradients from changing tides, wind forcing, resistive forces from bottom friction, and lateral mixing all contribute to the total current observed both in the cross-shore and long-shore directions. In the long-shore direction, primary forcing comes from radiation stress created by the energy decay of oblique incident waves (especially in regions with steep wave height) and the long-shore component of wind. These long-shore currents tend to be homogenous with depth. The cross-shore current, however, differs above and below the wave trough. Above the trough there is a mass transport of water particles carried toward the shore. Once these particles reach the swash zone, there is no net mass flux through the beach (groundwater mixing aside). Thus, an undertow reverses the max flux by transporting particles seaward below the trough, balancing transport in the cross-shore direction. Sediment transportation by nearshore currents occurs in both the long-shore and cross-shore [Smith 2002].

Local Wave Climate

The wave energy climate of Cherry Point is considered relatively high due to a steep nearshore gradient into deep water, considerable wave exposure and a large fetch. As shown in Figure 7, Cherry Point has an unusually steep bathymetric gradient (4.7-6.5%). Thus, along with the wave mechanics described above, wave heights are expected to be steeper, exert stronger radiation stress and therefore generate stronger nearshore wave-induced currents than those approaching a shallow (2-3%) nearshore slope.

The Cherry Point Marine Reserve has a large amount of fetch reaching both to the southwest and the northwest (Figure 21). An analysis of fetch for the entire length of the reserve was measured by Johannessen & Chase [2003]. To the southwest, 37 km of open water lie between Point Whitehorn and Stuart Island in the San Juan Islands. To the northwest, 77 km of fetch through the Strait of Georgia lie between the southern portion of the reserve and Gabriola Island in the northern Gulf Islands, B.C. Locally, however, the distance between the study site and Gabriola Island is 72 km to the west/northwest. Directly west across the Strait, 40 km separate Cherry Point from Galiano Island. Up to 39 km was measured between the study site and Stuart Island to the southwest. To the
south/southeast, where winds are prevailing most of the year, the maximum fetch distance is only 29 km to Sinclair Island, with most south/southeast diminished, sometimes as low as 9 km, by Lummi Peninsula. As the Cherry Point coastline trends northwest to southeast, fetch to the east, northeast, and north is negligible.

**Figure 21:** Cherry Point fetch distance. Open water paths to the northwest and southwest from the study site in the Cherry Point Aquatic Reserve. *Basemap courtesy of Google Maps.*

In this region, though waves are directly influenced by winds, they are perhaps more influenced by fetch. For example, taking two different winds of similar 15 m/s velocity and of the same duration and variance, waves from the northwest with a fetch of 77 km can have significantly more energy than waves from the south-southeast (the local prevailing wind direction for most months) of only 10 km fetch. Referring back to Figure 18, the significant mean wave height generated by the second wind will be over twice the size of that created over a shorter fetch distance. Wind speed for the first wind would have to double before matching the wave height of the second, long-fetch wind [Demirbilek & Vincent 2002]. Thus, the predominant (fastest) wind, sourced from the southeast, does not necessarily produce the strongest wave energy at Cherry Point. So, while prevailing winds do produce the most common waves from the south/southeast to the north/northwest, they are fetch-limited, and I hypothesize that these waves are generally lower in energy than those sourced from infrequent but severe windstorms coming from the west/northwest. This hypothesis is supported by the data collected during the course of this thesis, and is addressed later in section 5.1(b).
2.4 Geology

2.4(a) Stratigraphy

The earliest geologic mapping of the Cherry Point area was done by Easterbrook [1963], in which he describes three formations in the area. The oldest formation, dubbed the Cherry Point Formation, consists of blue to brown-gray, well-stratified clay and silt interbedded with fine sand and pebbly clay lenses (Figure 22). The thickness is not defined, as the base of the silt is not exposed anywhere along the coast. The type locality is located south of the industrial piers where the silt reaches a maximum thickness of 43 m. To the south and north, the silt drops below sea level, but it appears in places between the BP pier and Point Whitehorn [Easterbrook 1963, Easterbrook 1976]. Marine fossils at several localities near the type section (Figure 23) indicate this silt was deposited in a predominantly marine environment, with possible coarse material dropped from floating ice bergs [Easterbrook 1963]. The fossils were radiocarbon dated by the U.S. Geological Survey at older than 38,000 years, suggesting that this silt unit predates the last major glacial event by at least 12,000 years [Easterbrook 1963].

Figure 22: Cherry Point silt. Photo taken approximately 1.2 km south of Pt. Whitehorn. Notebook, shown for scale for scale, is 12 cm x 19 cm.
Figure 23: Geologic Map of the Northern Puget Lowland, Washington. Cherry Point Silt type locality is marked by the date "> 38,000." Easterbrook 1963
The silt is unconformably overlain by Vashon Till and a glaciomarine drift (not formally named) [Easterbrook 1963]. The till was probably deposited during the Fraser Glaciation as the Cordilleran ice sheet was advancing into the Puget Lowland (between 25,000 and 15,000 years ago) [Booth et al. 2003]. It is largely made up of clay, silt and sand with intermixed unsorted, unstratified granules, pebbles, cobbles and boulders. Coarse sediment consists of quartzite, chert, diorite, schists, basalt and sandstone (Figure 24). The glaciomarine drift directly overlying the till correlates to the Kulshan drift that crops out along Bellingham Bay, but has yet to be officially named as part of the same unit. The glaciomarine drift has a similar texture to the till, but the in situ presence of barnacles, worm tubes and unbroken bivalve shells suggest marine deposition in continuous close proximity to an ice shelf or ice bergs [Easterbrook 1983]. The glaciomarine drift also likely represents the beginning of interglacial conditions in the area [Armstrong et al. 1965]. The stratigraphy mapped by Easterbrook [1963] was confirmed by Johannessen & Chase [2003] during an investigation into coastal processes taking place between Birch Bay State Park and Point Whitehorn (north of the study area), although the authors refer to the glaciomarine drift as ‘Bellingham’ drift instead of ‘Kulshan’.

2.4(b) Beach Sediment Composition

As previously eroded sediment at the base of the bluffs is pulled out by wave action into the beach system, or as sediment is transported in the longshore direction, coarse particles are dropped out of the transport zone and fines are carried away. The result is a mixed sand and gravel beach, where the majority of particles are coarse sand, granules, pebbles and cobbles with a smattering of large erratic boulders ranging up to 3 m tall (Figure 25).

Sediment characteristics vary along the beach profile (Figure 26). Generally, there is fine to coarse gradient from bluff to offshore that can be described in five segments. However, large erratics are seen in any part of the beach profile. Note that beach conditions at Cherry Point are dynamic and the position/boundaries of the following segments can change almost daily during winter months.

**Upper Backshore:** The base of the bluff is a mix of recently fallen sediments (mostly silt, sand and pebbles with a few cobbles) and woody debris. If large pieces of driftwood or logs are present, these can act as a protective barrier, allowing finer sediment to remain for extended periods at the base of the bluff. Depending on the area, this protected segment can range from 1 to 10 feet.
**Figure 24:** Vashon Till. Photo taken approximately 1.2 km south of Pt. Whitehorn. Notebook, shown for scale, is 12 cm x 19 cm.

**Figure 25:** Mixed sand & gravel beach. Photo taken approximately 1.6 km south of Pt. Whitehorn. Notebook, shown for scale for scale, is 12 cm x 19 cm.
Figure 26: Cherry Point profile & cross shore sediment characteristics.
**Lower Backshore:** Here, there is a high percentage of fine sediment, but large cobbles are rarer than in the upper beach. Instead, disk-shaped pebbles dominate the coarser sediment fraction. The lower portion of the backshore often contains woody debris and lightweight broken shells, marking the extent of high tide. During stormy wave conditions (mostly during winter months), wave action can build gravel berms at high tide levels. Depending on the storm intensity and the pre-storm beach sediment fractions, these berms can be well sorted or poorly sorted. Well sorted berm composition has been observed to range from almost entirely small rounded pebbles, to a mix of coarse disk-shaped pebbles and rounded cobbles. The natural lifespan of a berm, its size, lateral extension, and its position on the beach profile varies widely.

**Upper Foreshore:** This is the most dynamic portion of the beach, and sediment size changes regularly. The surface gravel is mostly made up of cobbles and large pebbles positioned on top of sand and small pebbles. Larger cobbles are more prevalent than in the backshore, and nearly all sediment clasts are rounded to sub angular. Generally, the whole of the upper foreshore is a mix of clast sizes. However, periodically, partial sorting can take place, where piled cobbles may sit directly next to a swath of silt, sand and pebbles. These ‘loosely sorted’ gravel sections can take on a northwest-southeast trending linear pattern alternating fine/coarse/fine along the beach gradient, or they can be random and pattern-less.

**Mid Foreshore:** The sediment here shows a similar clast size variation to the upper foreshore but a marked abundance of coarse cobbles and small boulders, especially at the seaward boundary. Algae, barnacles and sea anemones are sparse but common in the upper portions of the mid foreshore and become prolific lower in the beach profile. The upper limit of this type of sea life falls between Mean Low Water (MLW) and Mean Lower-Low Water (MLLW), where inundation is guaranteed over a series of tidal cycles. The sediments here are much less dynamic than those in the upper foreshore, sometimes not moving during strong storm activity.

**Lower Foreshore:** There is a clear transition between the mid foreshore and the lower foreshore. The lower foreshore is composed of well sorted, fine, sandy mud with little to no coarse clasts, aside from a number of erratic boulders. Ripples and organic (mostly fine, woody) placers are exposed at low tide, along with eel grass and the occasional intact shell.
2.5 Geomorphology

2.5(a) Bluff & Cliff Erosion

Material from bluffs and cliffs serves as the sediment source for beach systems, and transport behavior influences habitat for many marine species. There are numerous ‘bluff side’ and ‘wave side’ factors influencing bluff and cliff erosion. Bluff side elements affecting erosion of the bluff consist of geological, geometrical, biological, and hydrological properties. Wave side controls include wind energy, wave processes and high water levels that control the long-term retreat of the bluff. [Shipman 2004]

Bluff Side Elements

The material that makes up the bluff or cliff-face can dictate the potential for weathering and erosion. A hard-rock formation (like granite) will be more resistant to wave energy, while a soft formation (limestone or glacial till) is more inclined to break down. If multiple formations make up the bluff, the orientation and stratigraphic relationship between these rock units will influence erosional behavior and bluff morphology [Shipman 2004]. The sorting, size, shape and orientation of sediment particles control the porosity and permeability of the bluff material, which governs how wave energy is dispersed once waves hit the bluff surface. If the formation has a high porosity and permeability, energy is diffused as seawater is channeled through many pore spaces [Komar & Allan 2010]. An impermeable rock cannot diffuse wave energy and will bear the brunt force of the wave. However, a rock that can hold water is more susceptible to weathering processes such as thermal expansion and contraction, frost wedging, and salt crystal growth, as well as the chemical weathering processes hydrolysis and dissolution [Trenhaile 2002].

The geometry of a bluff describes its height, shape, and angle in relation to the beach. A high cliff may be dependent on the stability of its base, which is most susceptible to erosion by wave energy [Emery & Kuhn 1982]. Shape is also of concern as a flat surface may erode differently than a rough, uneven surface. When bluffs are composed of loose, unconsolidated sediment, the most important geometrical aspect is their angle of repose. The angle of repose is the maximum angle above
horizontal that sediment can sustain before it fails. So, an over-steepened bluff is more prone to landslides than a gently sloping bluff [Shipman 2010].

Biological activity can prevent or encourage erosion. Birds, insects and marine crustaceans can burrow into the bluff surface, removing sediment, while root penetration in vegetated areas provides structure and stability for soil and sediment. The degree of biological activity varies with climate, habitat and season [EARMP 2010]. The hydrology describes the behavior of water both on the surface and within bluff sediment. Surface runoff facilitates channel incision and sediment abrasion. Glacial till with many jointed fractures experiences accelerated erosion, as fractures serve as conduits for groundwater movement [Highman & Shakoor 1998]. Ground water flow paths are thought to cause instability in the substrate as fluids liquefy sand and soil and undercut younger strata. Undercutting often leads to failure [Shipman 2004].

*Wave Side Elements*

Wave attack is a physical process that acts on rock and sediment as waves repeatedly pummel the bluff. This force releases a series of pressure shock waves that carry energy through the subsurface. As seawater is forced into the rock by wave energy, the air inhabiting the pore spaces is compressed and put under pressure. If the air pressure becomes too great, the rock can fracture and holes will propagate [Trenhaile 2002]. The magnitude and frequency of waves crashing into the toe of the beach bluff directly influences the rate at which sediment is undercut from the slope [Wilcock et al. 1998].

Tide levels are generally more important for beach processes rather than for bluff erosion. However, seawater at high tide must repeatedly reach the base of beach bluffs in order for them to form. Thus, repetitive low-energy waves can cause sediment abrasion and draw loose material away from the bluff base and out into the beach system [Wilcock et al. 1998]. Wind can also act as a mechanism to carry sediment like silt and fine sand away from the bluff surface.

*Local Erosion Statistics*

The glacial ‘feeder’ bluffs in the study area, after long-term exposure to waves, are relatively steep and average about 20m high (*Figure 27*). The profile is a reflection of cohesive glacial sediment and the cyclic process of toe erosion [Shipman 2004]. Wave action works on the base of the bluff to
remove fallen sediment, which destabilizes the bluff and can lead to failure. In a shoreline inventory done for Whatcom County in 2006 on the entire Cherry Point Reach (Point Whitehorn to Sandy Point), toe erosion was observed along 38% of the bluffs, resulting in nearly 50 recent landslides covering 18% of the Cherry Point coastline [SMP 2006]. The feeder bluffs providing the highest quantity of sediment are located in the northern portion of the reach, near the headland [SMP 2006]. Locally, Johannessen & Chase [2003] studied aerial photographs of Point Whitehorn and estimated the headland bluffs have historically averaged an erosion rate of 5.3 m³/m/yr. No volume estimates have been made for the rest of the Aquatic Reserve.

Figure 27: Cherry Point bluffs. Photo taken approximately 1.2 km south of Pt. Whitehorn.
2.5(b) Beach Morphology & Sediment Transport

**Beach Sediment Provenance and Budget**

The provenance of beach sediments dictates the volume of sediment added to the beach, the rate at which beaches are nourished, the behavior of sediments as they enter the beach system, and the initial size and shape of sediment particles. A deposit created by erosion of a bluff composed of glacial material accumulates a wide range of sediment shapes and sizes at a rate dependent on wind and wave energy and the resistance of strata. The size of sediment plays an important role in the profile of the beach. Fine, sandy beaches have a gradual profile, whereas coarser beaches composed of pebbles and cobbles tend to have steeper faces because they are more permeable and able to better diffuse wave energy [Johannessen & MacLennan 2007].

A ‘sediment budget’ quantifies the volume of sediment supplied versus the volume of sediment removed from the beach. A beach is accreting sediment when there is a net gain of sediment, often a result of increased bluff erosion or fluvial sediment input. When a beach is losing more sediment than it is gaining, then the beach is considered to be eroding. Thus, a great reduction in sediment supply from river or bluff often results in an eroding system. Beach erosion and sediment transport in the Pacific Northwest are controlled by high wave energy and high-angle oblique incidence of waves [Shipman 2004]. An increase in the frequency and severity of storms can result in transport of large amounts of sediment and drastically alter beaches in a very short time, especially in a quick succession of high intensity storms [Schwartz et al. 1985, Wallace 1988].

**Constructive and Destructive forces in the Nearshore**

Section 2.3(b) explained that wave propagation towards the shoreline represents a shoreward flux of momentum [Longuet-Higgins & Stewart 1964]. This momentum is transferred from the waves to the water column via radiation stress. The linear momentum profile in the nearshore is greatest at the surface and dissipates with depth, but still manifests itself as bed shear stress acting on bottom sediments (Figure 28) [Dean et al. 2002]. Because this force is pushing sediments towards the shore, it is considered constructive. Wind direction also affects bed shear stress. The surface stress from wind will cause a surface fluid to flow in the wind direction, generating a larger orbital pattern and producing a bed shear stress in the opposite of wind direction (Figure 29) [Dean et al. 2002]. Thus, seaward-directed winds will increase bed shear stress in the shoreward direction (constructive), and
Figure 28: Nearshore vertical distribution of the onshore flux component of momentum. Dean et al. 2002

Figure 29: Bottom stress caused by surface winds. Dean et al. 2002
landward-directed winds will increase bed shear stress velocities in the seaward direction (destructive) [Dean et al. 2002].

Opposing forces happen on the smaller scale as well. The oscillatory nature of waves means flow is not constant, but rather cycles through periods of acceleration and deceleration. Velocities are strong in the direction of wave propagation for a short time as the bed is passed by the wave crest. Then, for a longer period of time, velocity is weakened as the trough passes over the bed [Soulsby & Damgaard 2005]. At a given velocity, accelerating flow will produce more shear stress than constant flow, and decelerating flow will produce less [Komar & Miller 1977]. Orbital motion allows for sediment movement back and forth, but no net transport without a super-imposed longshore current. Sediment transport is therefore proportional to the longshore component of wave energy and any longshore current generated by tides [Komar & Inman 1970].

*Sediment Transport on Mixed Sand & Gravel Beaches*

Regional transport can typically be described by coastal drift cells. A drift cell consists of three phases of sediment activity along a shoreline [Johannessen & Chase 2006]. The first phase represents the input, where a large sediment source is eroding and introducing loose sediment into the beach system. The second phase is transportation, where wave energy moves sediment (drift). When waves arrive at an angle to the shore, they create oblique swash (waves running up the shore) and perpendicular backwash (waves washing back to sea), which promote sediment movement in the longshore direction [Ingle 1966]. This is called longshore drift, and is most rapid when incidence angle is close to 45° from shore. Longshore drift, however, is only well understood on sandy beaches.

Sediment transport on sandy beaches has been well documented, but mixed sand and gravel beaches differ in that beach hydrodynamic response is entirely dependent on swash energy [Kirk, 1975, 1980; Ivamy & Kench 2006; Buscombe and Masselink, 2006]. Only during periods of moderate and high wave energy do pebbles and cobbles have the potential to move, and even then not as far as fine sediment [Masselink et al. 2010]. Factors such as hydraulic conductivity, infiltration and ground water, wave reflection and motion threshold have been identified as controls on coarse sediment transport [Mason & Coates 2001]. Little modeling has been done on transport behavior of mixed sand and gravel beaches, though they serve as an important natural habitat for many coastal
species. Furthermore, modeling of coarse sediment behavior is becoming increasingly important from an engineering standpoint, as coarse sediment, like the natural gravel and cobble berms, is increasingly being used for beach armoring in restoration settings [e.g, Komar & Allan 2010].

Sandy beaches have a much lower hydraulic conductivity than their gravel counterparts, as the sand controls the beach permeability [Quick & Dyksterhuis 1994]. Coarse beaches provide a natural buffer for wave attack, as potential energy carried by breaking waves percolates into the beach, decreasing during backwash flow. During periods with low energy waves, fines (silt, sand and small pebbles) are removed from between coarser clasts, with only minor abrasion and rounding of the larger clasts. The recurrence of low energy fining acts to maintain a more porous armored beach. Cobble and boulder movement only occurs during storm-wave breaking, at which point some or all boulders may shift, roll, or are pushed up-slope [Lorang 2000]. Thus, longshore drift may be occurring in two tiers, based on sediment size.

Following major storms, there is a period of ‘shape-related hydraulic selection’ during which clasts with low sphericity naturally drop out on shore. As the breaker line retreats and wave energy is dissipating, the backshore is built up. Clasts ranging in sphericity are pushed up with the up-rush, but as the backwash rolls clasts back, compact, spherical clasts will fall down slope and less spherical, or platy discs will drop out and remain higher on the beach [Bartholomae et al. 1998]. Through this act of sorting (selection, rejection and acceptance), gravel foreshores become more organized over time, creating distinct ‘mosaics’ of sediment. The grain size and shape distribution patterns then have some control over the flux of energy within the beach sediments and may allow for preferential sorting within the already sorted material [Buscome & Masselink 2006].

The shape of gravel has been found to change over the course of longshore transport. Bartholomae et al. [1998] found gravel to increase in roundness, but maintain the same sphericity. The only significant processes shaping beach sediments occur during high energy storm events, with attrition being the most important modifying factor [Bartholomae et al. 1998]. Over time, attrition during transport will break down softer rocks, leaving an increasing percentage of harder lithologies on the beach. The cross-beach profile, in contrast, shows no change in roundness but rather an increase in sphericity in the offshore direction.
Berms are naturally created when moderate to high energy swash builds up sediment at high tide level, resulting in a laterally extensive, raised pile of coarse sand, pebbles and cobbles. These berms can serve as protective structures between energy of breaking waves and beach bluff. Thus, the height, shape and migration of beach berms may influence sediment erosion at the toe of the bluff. A berm is controlled by sediment type and availability, tidal range, wave exposure [Shipman 2004], as well as its relationship to the beach ‘step’ (the gravel beach analogue to a sandy beach’s nearshore bar) [Buscome & Masselink 2006].

Local Transport Environment

There are two fine-sediment drift cells operating in the Cherry Point Aquatic Reserve [Schwartz et al. 1991, Johannessen & Chase 2006] (Figure 30). Point Whitehorn bears the brunt of most wave and wind energy and serves both as a major sediment source for the drift cells and as a divergence zone for sediment transport. Some sediment is pushed by wave energy to the north, along the southern shores of Birch Bay (one drift cell) and out of the Marine Reserve. Other sediment is pushed to the south, along the industrial piers (another drift cell). The final phase of a drift cell is the depositional phase, when the wave energy is no longer high enough to sustain sediment movement. For the second drift cell, this occurs at the artificial marina entrance channel at Sandy Point [SMP 2006]. While these drift cells define the movement of fine sediment (silt, sand, small pebble) transport in the nearshore, they do not necessarily describe the behavior of coarser sediment (large pebbles and cobbles) in the upper, intertidal region at Cherry Point.

In the early 1970’s Bauer [1976] completed an initial drift characterization of all county shorelines for the Whatcom County Planning Commission. The study was described by Bauer as only a preliminary effort that lacked long-shore drift monitoring, wave-action observations or data collection over a long enough period of time to model long-term baseline movement. Additionally, the methods used by Bauer [1976] are not described, and the only information Bauer presents is qualitative conclusions on the behavior of sediment at various drift locations. The study was also completed when Arco owned the northern industrial pier, prior to the construction of the current BP pier configuration. Some of the drift descriptions, therefore, are no longer accurate. The Bauer [1976] study, then, is considered unsatisfactory to most modern scientists working with Cherry Point; and recent literature about the Cherry Point area favors
Figure 30: Local fine-sediment drift cells at Cherry Point, as observed by Schwartz et al. 1991 and Johannessen & Chase 2006. Star marks study site. Basemap modified from Schwartz et al. 1972
later work by Schwartz et al. [1991] as the primary interpretation of sediment drift. However, Bauer [1976]'s mapping was based on upper foreshore observations, making his study the only previous work done on gravel-sized transport at Cherry Point. He observed two-way drift rates south of Point Whitehorn for most of the reserve shoreline, with only shorelines in the lower 75% of the Cherry Point Aquatic Reserve experiencing a slow net effect in the southeastern direction (Figure 31). This differs from the recent studies that lump all sediment transport south of Point Whitehorn into a single drift cell moving to the southeast [Johannessen & Chase 2006].

Figure 31: Local gravel transport direction at Cherry Point, as observed by Bauer 1976. Star marks study site. Modified from Bauer 1976 and Schwartz et al. 1972
CHAPTER 3: METHODS

3.1 Site Selection

Although the beaches of the Cherry Point Aquatic Reserve are mostly open to the public, only a few public access points are available. The Point Whitehorn Marine Park’s trail was chosen as the best access point for both logistical and experimental reasons. The Marine Park provides a parking lot relatively close to the beach, so equipment could be easily transported to and from the beach. The trail also accesses a portion of the beach that is ideal for sediment transport studies. It is positioned on a relatively straight shoreline, far enough (2.6 km) north from the BP pier to avoid any effects on waves by hard structures and far enough south (1.8 km) of Point Whitehorn to avoid increased waves created by converging bathymetry near the headland.

Tagged particle tracers were deployed near the base of the wooden staircase where Point Whitehorn Marine Park’s trail accesses the beach of the Cherry Point Aquatic Reserve. Because most fieldwork was done after dark, it was necessary to keep tracers close to the access point, both for safety reasons and also to save time on transporting equipment. Although positioning the particle tracer site near the beach access point increased the risk of human interference with the study, there were few days when day-time tides were low enough to expose the tagged pebbles and cobbles (Figure 32).

3.2 Sediment Transport

3.2(a) Previous Methods

Sediment transport studies cover a wide range of technology and methods. Though remote sensing equipment and gauging stations have their merits, ‘particle tracking’ or ‘sediment tracing,’ offers a way for scientists to examine the transport pathways of a wide variety of sediment sizes in numerous environments. A particle tracking study begins with the marking or tagging of natural or artificial sediment, plants the identifiable ‘tracers’ into an transport setting and uses their displacement to gain insight into the natural sediment transport environment [Black et al. 2007].
**Figure 32:** Northwest and southeast extent of cobble transport study.
Attempts at sediment tracking have been explored since the early 1900’s [Richardson 1902]. Since then, methodologies have evolved to include deploying broken bricks [e.g. Kidson & Carr 1961], pulverized coal [e.g. Shinohara et al. 1958], magnetic concrete [e.g. Pantin 1961], sediment dyed or painted non-fluorescent colors [e.g. King 1951], painted shingles [e.g. Dobbs 1958], radioactively tagged sediment [e.g. Inose & Shiraishi 1956], sediment dyed or painted fluorescent colors [e.g. Yasso 1965, Ingle 1966], fluorescent glass beads [e.g. Ventura et al. 2001], and sediment tagged with rare-earth elements [e.g. Zhang et al. 2001].

More recently, radio-activated tagging devices have been used to track coarse sediment transport in mixed sediment systems with relative success [e.g. Lamarre et al. 2005; Allan et al., 2006; Dickson et al. a. 2011]. These tags, called Radio Frequency Identification (RFID) Passive Integrated Transponders (PIT) tags (Figure 33), have long been used in fish and wildlife research, but in the last decade have been applied to coarse-particle transport. The tags do not need a battery since their power comes from an electromagnetic pulse emitted from a reader. The PIT tag responds to the pulse by emitting a unique frequency number that is picked up by an antenna. The unique frequency identifies the tag. This particle-tracing method is preferred, because there is no chemical introduced to the beach system, there is no worry of paint labels or numbers fading or being abraded, and PIT tags can be tracked even when buried. Locally, in the state of Washington, RFID PIT tags have been proven useful in monitoring the mixed beaches of Grays Harbor [Osborne 2005], Bainbridge Island [Curtiss et al. 2009] and, more recently, the Elwha River delta [Miller et al. 2011].

3.2(b) Gravel Collection & Tag Insertion

Nearly 100 spherical pebbles and cobbles were chosen from the beach of the Cherry Point Aquatic Reserve to be used as carriers for tracking tags. Lithologies selected were limited to granite, diorite, quartzite and sandstone as these are weathered to equant or sub-equant shape with size ranging from 3cm to 13cm in diameter. The equant or sub-equant shape was preferred as these tracers were expected to travel more easily along the beach than disk- or blade-shaped clasts. Tagging...
equipment was purchased from Biomark Inc., a company specializing in electronic tagging of wildlife. Therefore, Full Duplex (FDX), 134.2 kHz, 23mm RFID PIT tags were used for this study. FDX tags, as opposed to HDX tags, constantly emit a signal back towards the reader (when the reader is turned on), as opposed to only signaling half of the time. These tags are Biomark’s largest-sized and highest frequency tags and were chosen to maximize tag range, since range of reception increases with size and frequency.

The tagging procedure is similar to that used by Miller et al. [2011]. Small holes, greater than 23 mm deep and about 0.5 mm in diameter, were drilled into each rock using a roto-hammer drill. When possible, holes were preferentially drilled into the short axis of the rock in order to maximize radio frequency strength, as signal strength is greatest at the polar ends of the tags. The holes were then plugged using fast-setting construction-grade epoxy. This process ensured the PIT tag would not escape the rock or be damaged as the tracer is jostled around during high energy storms.

A set of 60 tracer particles were chosen to be deployed on the beach. After being tagged; dimensions, mass, volume, and density were measured. Tracers ranged in size from 3.9 cm on the shortest axis of the smallest pebble (177 g) to 12.9 cm on the longest axis of the largest cobble (1,262 g). Tracer size was limited on the low end by the length of the tag, as well as the inherent strength of the rock. Small clasts of more brittle rock like quartzite tended to crack when drilled, as opposed to granite or diorite. Using a permanent marker, each particle tracer was labeled with the last 3 numbers/letters of the PIT tag’s unique 12 character ID. For example, if a tag read 3D6.000B567E10, it would be labeled and recorded as tracer E10. An inventory of all gravel particle tracers and their measurements is listed in Appendix 1. Each tracer was also photographed and the photograph was archived. Figure 34 shows a small sample of tracers. A comprehensive image catalogue of all tracers can be found in the DVD data depository.
Figure 34: Sample of particle tracers, labeled by tag ID number. Penny for scale.
3.2(c) GPS Configuration

A benchmark was created by pounding a 1.5m long piece of rebar into the beach near an easily identified boulder approximately 20 m southeast of the wooden staircase. The length of the rebar ensured that the benchmark would be anchored below the sediment transport zone and thus would not move throughout the study. Global Positioning coordinates were collected over a period of two hours using the Trimble Zephyr. These GPS data were then corrected for atmospheric error using the National Geodetic Survey’s (NGS) Online Positioning User Service (OPUS). During tracer deployment and recovery, a Trimble R6 was used as a base, centered over the benchmark, and a Trimble GeoXH was used as the rover (Figure 35).

Figure 35: Base and rover GPS setup. The Trimble R6 is positioned on the tripod, centered over the benchmark (flagged with orange tape). The handheld device, shown in the image insert, is collecting data while balanced on a tagged cobble (also flagged with orange tape).
3.2(d) Particle Tracer Deployment

Tracers were deployed to the south of the benchmark in various formations along a line parallel to the beach gradient. The location of this line was chosen based on easy access to the park staircase. Deployment transects typically contained twenty to thirty particle tracers and extended from the base of the bluffs to the shoreward boundary of the mudflats. The number of tracers used in each deployment was limited by the availability of only one reader and antenna (and therefore the amount of time it took one person to locate all tracers), the time needed for a second person to record positions for each tag, and the length of time available between high tides.

Deployment #1, January 12th: 28 TRACERS DEPLOYED (Figure 36)
Tagged pebbles and cobbles spanned from the bluff to the edge of the mudflats. The lower twelve tracers were evenly spaced 1.5 m apart, while the upper sixteen tracers were more densely spaced at 0.75 m in anticipation of greater sediment movement on the upper beach (transport zone) and thus a greater risk of lost tags.

Deployment #2, January 31st: 30 TRACERS DEPLOYED (Figure 37)
This deployment combined a series of eleven tracers left in situ from the last deployment with a new line of nineteen tracers spanning from the upper beach to the start of the barnacles. In the line of tracers, fourteen of the tags were concentrated at 0.75 m apart within the transport zone. The lower four tracers were widely spaced at 1.3 m apart, and a single tracer was positioned 1.3 m up-beach of the concentrated set.

Deployment #3, February 14th: 34 TRACERS DEPLOYED (Figure 38)
Packaged sets, or small groups of particle tracers deployed directly adjacent to one another, were placed in the upper beach. The sets contained two to four tracers of various sizes. Packages of two or three tracers contained clasts with a similar diameter, usually small or extra small (Figure 39). Packages with four tracers contained different sized clasts in the following pattern: in the downslope direction, one small or extra-small clast, one medium or large clast, one extra-large clast, and one small or extra-small clast (Figure 40). This strategy aimed to collect data regarding the preferential movement of different clast sizes under (at least initially) the same wave forces. Seven packaged sets were placed 0.75 m apart in the upper beach. Set one (up slope limit) through seven (down slope limit) consisted of the following number of tracers, respectively: two tags, four tags,
Figure 36: First Deployment - January 12, 2012
Figure 37: Second Deployment - January 31, 2012. Cobbles that are known to be located in the lower beach but were not logged due to tide or time constraints are shown in grey.
Figure 38: Third Deployment – February 14, 2012
Figure 39: Packaged set with two tracers.

Figure 40: Packaged set with four tracers.
three tags, four tags, two tags, and four tags. In addition, eleven tracers (four in the lower beach, two in the middle beach and five in the upper beach) from the past deployments were left in situ and not moved.

Deployment #4, February 16th: 39 TRACERS DEPLOYED (Figure 41)
This deployment combined the packaging technique of the third deployment with the cross shore coverage of the first and second deployments. The same seven packages were deployed in the upper beach, equally spaced at 0.75 m apart. Below the packages, seven tracers covered the middle beach, equally spaced at 0.60 m apart. Below these, three larger tracers were spaced at 1.5 m down slope. Only the lower six of the eleven tracers previously left in situ were kept in place for this deployment. Of these six, the lowest four positions were unable to be logged because these tracers were under water. They were, however, present on the beach during this time, so they are considered part of this deployment.

Deployment #5, February 21st: 39 TRACERS DEPLOYED (Figure 42)
The final cross shore line of deployed particle tracers was identical to the fourth deployment. Again, the lowest four tracers were not logged due to high water levels.

3.2(e) Particle Tracer Recovery

Tracers were left on the beach for a period of 24 to 72 hours before recovery. Tags were scanned manually after transport using the Biomark FS2001F-ISO reader and racquet antenna (Figure 43) Coordinates were measured with the Trimble GeoXH centered over the pebble or cobble at surface level. Often, the tracer would be buried or partially buried during transport. Since the Biomark antenna has a theoretical range of 17-22", any buried tracers were dug out (if possible) in order to accurately record their positions. Sometimes tracers were not able to be uncovered and were recorded as best estimates based on sensitivity of the reader. This best-estimate method was often used during heavy rain when the water table on the beach was raised to just a few centimeters below surface level, flooding any attempts at digging.

Once found, GPS positions were measured using a three-step process. First, the GeoXH was carefully placed at beach level with the handheld antenna centered over the tagged pebble or cobble, facing
Figure 41: Fourth Deployment – February 16, 2012. Cobbles that are known to be located in the lower beach but were not logged due to tide or time constraints are shown in grey.
Figure 42: Fifth Deployment – February 21, 2012. Cobbley that are known to be located in the lower beach but were not logged due to tide or time constraints are shown in grey.
seaward. Once stable, it was left there for 30-60 seconds, depending on cloud coverage and weather conditions. This wait allows the device to collect more satellite data even before it begins to record the tracer’s actual position. Next, a way point, or a point location record, was created under the tracer’s ID, and the device began to log position points. Twenty points provided the best post-processed accuracy. After 20 points were recorded, the GeoXH was left still to again collect satellite data for 30-60 seconds.

3.2(f) Post Processing

GPS data recorded by the GeoXH was post-processed in Trimble GPS Pathfinder software. For each point, the software does a pre- and post- calibration of the satellite coverage recorded before and after a way point was taken. Thus, letting the handheld remain stationary before and after logging positions helped to decrease the GPS error. Atmospheric error was calculated by comparing positions recorded from the R6 base station to the true location of the benchmark, as configured by OPUS. This atmospheric correction was then applied to the data points collected by the GeoXH, significantly reducing the standard deviation.

The vertical and horizontal precision for each gravel tracer position, when logged correctly, can be as low as ±0.01 m. This precision is more frequently seen in the horizontal direction (73% of data) as opposed to the vertical direction (44%). Precisions of ±0.05 m or less are equally common (78%). Nearly all measurements (96% horizontal, 95% vertical) are within range of ±0.1 m. Increased error/decreased precision can be attributed to the recording of too many or not enough points
during logging, the jostling of the GeoXH before, during, or after logging, or logging through windy conditions, when the R6 may have been slightly swaying back and forth.

After post-processing, tracer positions for each field day were exported both as ESRI shapefiles and ACII files. The tracer positions were then mapped using ArcMap 10, along with other important recorded beach features such as boulders, debris piles, bluff boundaries, the boundary of barnacled rocks, and the shoreward extent of mudflats.

3.3 Wind & Wave Data Collection

3.3(a) Offshore Pressure Sensor

In conjunction with pebble and cobble tracking, a Seabird SEAGUAGE Wave and Tide Recorder, the SBE26plus (Figure 44), was loaned to Western Washington University by the United States Geological Survey (USGS) to monitor wave flux within the swash zone of the Cherry Point Aquatic Reserve. The SBE26plus uses a precision chronometer and a Quartz crystal pressure sensor to collect high resolution wave and tide data. It was programmed for deployment using SEASOFT for Waves software, a product made specifically for SBE sensors. Tides were measured for a total of 60 seconds every 20 minutes. On every third tide sample (once an hour), a wave burst lasting 4096 seconds, at 0.25 Hz was recorded.

The pressure sensor was anchored securely in a small metal crab pot that was weighted with concrete and repurposed steel. Two anchors were attached to the pot, as well as a rope tied to a labeled research buoy and a mid-level float (Figure 45). The sensor was deployed on February 3rd, 2012, in a sandy bed surrounded by large boulders covered with microalgae, far from any eel grass. The pot was situated approximately 170 m offshore, and 3.4 m below mean sea level (Figure 46). Though all tagged pebbles and cobbles were pulled from the beach on March 5th, the SBE26plus remained in the water collecting wave data until mid-day on April 22nd.

Wave and tide data were post-processed using SEASOFT for Waves. The wave frequency for wave data during post-processing was restricted to between 0.5 and 0.022 Hz, values that reflect the instruments’ ability to accurately record short wave frequencies at depths between 1 and 5 m.
Figure 44: SBE26plus, with dimensions. Image & diagram courtesy of Sea-Bird Electronics, Inc.

Figure 45: SBE26plus crab pot configuration with concrete and steel weights and marked buoy.
Figure 46: Pressure sensor offshore location (schematic).
3.3(b) Weather Stations

Data Buoy Station CHYW1 positioned next to the BP Cherry Point pier provides archived wind (direction, speed and gust), atmospheric pressure and water level data at an interval of 6 minutes. The buoy began collecting temperature data in 2005 but did not begin collecting wind information until September of 2008. A separate station, South Dolphin North Pier, ID#CP0101, has been collecting current data since November of 2009. Minimum fetch distance was measured from every degree angle in respect to the SBE26+ using Google Earth. The values are considered minimums because they reflect the distance between the sensor and any dry land, including small islands and marshy coastline.

3.4 Coastal Numerical Modeling

3.4(a) Background

While particle-tracing studies quantify transport rates and behavioral patterns of beach sediment, computer modeling can address the processes that drive sediment transport in order to better understand how and why sediments respond to natural forces in a dynamic beach environment. Though the prediction of beach evolution is often the goal of modeling, analytical transport models simplify the equations needed to predict beach evolution and are often restricted to uncomplicated offshore boundary conditions [Rosati et al. 2002]. Mathematical modeling (aka numerical modeling), in contrast, can handle difficult boundary conditions (i.e. hard offshore structures, irregular and complex bathymetry) by allowing for time series input parameters, complex wave transformations and morphologic changes in the shoreline. For the purpose of this review, only numerical models will be discussed.

Numerical models for beach sediment transport are the geomorphic extension of water wave models. Basic wave numerical models, like that of NMLONG (Numerical Model of the LONGshore current) [Larson & Kraus 1991], assume uniform waves and uniform bathymetry in order to calculate wave transformation and longshore current through the surf zone. More advanced numerical models use hydrodynamic equations developed by Joseph Valentin Boussinesq [Smith 2002].
Examples of time-domain Boussinesq models include the use of surface rollers to represent water and sediment mixing induced by breaking waves and energy dissipation [Schäffer et al. 1993], generation of low-frequency waves in the surf zone to measure repetitive wave forcing and shear waves [Madsen et al. 1997] and reproduction of irregular wave transformation [Kobayashi & Wurjanto 1992]. Currently, a number of software packages are available that simulate fluid hydrodynamics. Some of the most popular include FLOW3D, FLUENT, CGWAVE, SWAN, DELFT3D, WAM and BOUSS-2D.

Sediment transport models combine the hydrodynamic equations used to model wave processes with those used to describe bulk transport. An ideal model would address coastal sediment evolution in three dimensions over time. Unfortunately, three-dimensional models [e.g. Perlin & Dean 1983] are complex and require significant computer computational time [Smith 2002]. More common models assume that the beach and nearshore profile is static, and apply all numerical equations to a single contour line. These are referred to as ‘one-line’ models. Many of these models have been developed and tested for finer, sandy nearshore transport [e.g. Komar 1973, Dean & Yoo 1992, Hanson 1987]. Numerical models used to compute gravel-beach dynamics have been less successful. BREAKWAT [Van der Meer 1988], a parametric numerical model, simulates cross-shore beach transport vs. wave energy but does not allow for a permeability parameter, and thus it is limited in modeling run-up, overwash and breaching. The current version of SHINGLE [Powell 1990], another parametric numerical model, includes a permeability parameter but still under-predicts wave run-up and inundation. The two models currently available that combine all ideal parameters (wave and current, cross-shore and longshore momentum, roller equations, permeable layer models, etc.) are Xbeach (eXtreme Beach behavior model) [Roelvink et al. 2009] and CSHORE (Cross SHORE numerical model) [Kobayashi 2010]. Xbeach was chosen for this study over CSHORE for two reasons. One, though it is still a very young model, it is slightly older than CSHORE and therefore more developed as a software. Xbeach is a free, open-source model with a small, but active on-line community. The opportunity to interact with XBeach programmers increases over-all transparency of the model’s architecture, as well as the ability to get help when needed.
3.4(b) Xbeach

Xbeach is a robust, process-based, two dimensional horizontal (2DH) model of the nearshore and beach, designed to solve coupled cross-shore and long-shore hydro- and morphodynamic equations on the time-scale of wave groups [Roelvink et al. 2009]. The model contains algorithms used to address short wave envelope propagations and dissipation, non-stationary shallow water equations, sediment transport and bed update. Xbeach is advanced in that it allows different wave groups to travel in different directions [Williams & Ruiz de Alegria-Arzaburu 2011]. Originally developed to predict impacts on barrier islands by hurricanes, the processes modeled in this model are categorized by four different ‘impact regimes’ associated with hurricane impacts, as described by Sallenger [2000]: 1) swash regime, 2) collision regime, 3) overwash regime and 4) inundation regime. The following section describes the processes considered when Xbeach was developed. For a more detailed look at the algorithms used in the model, see Roelvink et al. [2010].

1) SWASH REGIME

*Short Wave (Wind & Swell) Transformation* – A wave-energy balance-equation [e.g. Holthuijsen et al. 1989] was derived from the time-varying wave-action balance [Phillips 1977] combined with the dissipation of breaking waves in wave groups [Roelvink 1993].

*Roller Energy (Wave Breaking)* – A roller model is used to apply momentum stored in surface roller waves, causing a shoreward wave-forcing [Nairn et al. 1990].

*Longshore & Cross-shore Currents* – Wave-group forcing drives both longshore and cross-shore currents. The interaction between waves and currents at the wave boundary layer results in bed shear stress [Soulsby et al. 1993], which is well predicted using a constant drag coefficient [Ruessink et al. 2001].

*Suspended and Bedload Sediment Transport* – Short-wave and long-wave orbital motion, currents, and breaker-induced turbulence all contribute to sediment transport. The Van Rijn formula [Van Rijn 2007] is a simple way to resolve wave groups in the surf zone [Soulsby 1997]. This method addresses sediment concentrations, solves the 2DH advection diffusion equation [e.g. Galapatti 1983], and produces total transport vectors that can be used to adjust bed levels during the modeled period.
2) COLLISION REGIME

*Dune Erosion (Avalanching)* – Continual undercutting of dunes or bluffs during wave-beach interaction leads to episodic slumps, where dry sediment is transported seaward to the wet swash zone by way of backwash motion and undertow [Stelling & Duinmeijer 2003]. This formula is also relevant to the overwash regime, in the form of drying/flooding and bed elevation changes.

*Return Flow* - The Generalized Lagrangian Mean (GLM) approach [e.g. Walstra et al. 2000] uses the flow velocities gleaned from wave group mass flux to contribute to depth-averaged undertow, providing information about return flow’s effect on bed shear stresses and sediment transport.

3) OVERWASH REGIME

*Landward Sediment Transport* – Wave-flow interactions, specifically low-frequency motion on the time scale of wave groups, are described by non-linear shallow-water equations (NSWE) that take into account long waves [Reniers et al 2004].

4) INUNDATION REGIME

*Breach Evolution* – Though specifically designed for barrier island models, bank-erosion mechanisms and a combination of shallow-water equations and suspended-transport models allow for modeling of channel-flow processes in the wake of avalanche-triggered erosion [Visser 1998].

*Groundwater Model*– Darcy’s Law is applied to include infiltration and exfiltration [Van Thiel de Vries 2009].

Xbeach was initially designed to model sand sized sediment. Recent developments have allowed for the addition of multiple sediment sizes, but accurate modeling of coarse sediment transport is still in development phase. This project attempts to evaluate the use of XBeach for modeling transport on a mixed-sediment beach by comparing simulations of physical forces affecting sediment transport (wave forcing, wave set up, radiation stress, and bed shear stress) driven by measured wind, wave
and tide data to measured cobble transport. By identifying pattern changes within these forces, relationships are defined between sediment transport and oceanic and atmospheric conditions.

3.4(c) Software Installations

There are four different versions of XBeach. Each version produces data in a different format. The basic version of Xbeach outputs to a MatLab file format and is only run through a toolbox within the MatLab interface. Another Xbeach version will export netCDF (Network Common Data Form) compatible files, a format that allows for sharing of scientific data across a number of softwares. A third option exports to MPI (Message Passing Interface) format, allowing for a different type of program interface, like MPICH2, to run Xbeach on multiple computers. A fourth option will produce both MPI and netCDF files.

The netCDF version of Xbeach was compiled to a computer equipped with an additional 3 TB hard drive, an Intel (R) Core(TM)2 Quad central processing unit set to run at 2.66GHz, 8.00 GB of installed memory and a dual boot startup to run both Windows 7 and the Fedora Red Hat Linux operating systems. Xbeach was outfitted with the ‘skillbed’ option to allow for constant updates from the Xbeach developers, ensuring the most up-to-date version was being used whenever a model was run. By running Xbeach in Linux with a netCDF format, no MatLab interface was needed, and models could be executed in a terminal window. Resulting files were opened and interpreted using NCView, a user friendly visual browser of netCDF data.

3.4(d) Grid Design

The first step in modeling was to establish an elevation grid of the seafloor, beach and bluffs. The grid used for this study was created by Bert Rubash, a local modeler who is also on a committee for the Cherry Point Aquatic Reserve. Two National Oceanic and Atmospheric Administration (NOAA) bathymetric surveys (H12368 & H12322) from 2011 were merged with a USGS regional Puget Sound aerial Light Detection and Range (LiDAR) survey from 2006 (Figure 47).
Figure 47: Grid surveys. Three surveys were used to piece together the Cherry Point grid.
Both NOAA surveys were registered vertically to mean lower low water (MLLW), which at Cherry Point is 1.61 m below mean sea level (MSL) (Appendix 2). The LiDAR survey was registered to vertical datum NAVD88, a datum that applies a mean sea level value not representative of local tides. To prevent an unnatural vertical shift in the nearshore, the LiDAR survey was adjusted to MLLW. The adjustment process was accomplished in two steps. First, a true sea level was forced onto the LiDAR survey to clean up backscatter caused by infra-red beam reflections off of surface water. This was done by identifying the mean elevation of the sea surface data points (Figure 48). Because NAVD88 is in units of feet, the sea surface was estimated to be at -1.40817 ft (~0.4292 m). Second, using a free software through NOAA called Vdatum to identify the local vertical offset between MLLW and NAVD88, the LiDAR survey was converted from feet to meters and then shifted up +0.2866 m.

Like nearly all nearshore areas in the Puget Sound and Strait of Georgia, a pronounced data gap between offshore bathymetric and onshore LiDAR in the Cherry Point nearshore presented a challenge to modeling. Bathymetric surveys often use a large vessel outfitted with instruments designed for deep water data collection and do not venture into the shallow nearshore. In the case of the NOAA surveys, data were only collected offshore from the study site in waters ~4 m or deeper. The LiDAR survey used for this project was a topographic LiDAR that does not penetrate water, and therefore the LiDAR data was limited to land elevation above the water at the time of the survey flight. Locally this is anything above 0.7158 m (i.e. 0.4292 m sea surface + 0.2866 m datum offset). So, the beach profile was interpolated between -4.0 m and +0.7158 m where data was missing from the merged grid. A slope was mathematically interpolated using nearest neighbor algorithm to fill the missing data gap (Figure 49).

Once complete, the grid was rotated 53 degrees clockwise so that the beach was oriented along the right side of the model grid and the bathymetric gradient was parallel with the x-axis. Then, it was cropped to three different sizes, each roughly centered offshore of the study site (Figure 50). For each model, XBeach applies wave parameters to the left boundary of the grid. The applied wave energy then propagates in the assigned wave direction towards the beach. For the model to be successful, grid dimensions need to balance the need for accurate wave statistic forcing with computational time restraints. Grid A, measuring 1,830 m x 415 m, would have taken multiple days to run a simple 6 hour model. Also, wave statistics collected with the SBE26plus would not
Figure 48: Backscatter graph of LiDAR beam returns. Each red data point represents an elevation signal (y-axis) from beams reflected off the water along a grid length (x-axis). Blue line indicates the mean elevation in NAVD88 datum. *Graph courtesy of Bert Rubash.*

Figure 49: Missing grid data interpolation. Grey, data gap on left is filled with interpolated bathymetry values. *Background image, Bert Rubash.*
Figure 50: Grids of different dimensions tested with XBeach. Grid B produced the best results. Background image, Bert Rubash.
accurately represent waves over 1.5km offshore. Grid C, measuring only 200 m x 552 m was positioned with the left boundary at the pressure sensor, in order to constrain wave forcing and minimize computational time (a simple model may take 8 hours). However, because the wave forcing at the left boundary started at such shallow depths, the algorithms designed for long wave propagation were no longer accurate. Thus, Grid B (674 m x 552 m), extending another 472 m offshore from the pressure sensor, was found to be a workable size (simple model would take 12-18 hours). Grid cell resolution is also a factor. Though enough data was available to create a 0.5 m x 0.5 m grid, computational time using such a high resolution is also considered unreasonable (simple model would need to run multiple days). Because the nearshore grid is interpolated and therefore is essentially a plane with uniform sloping bathymetry (i.e. no abrupt changes in gradient or large offshore boulders), it was decided that decreasing resolution to a 2 m x 2 m grid was the best option for keeping resolution high while also keeping computational time reasonable. Models ran on Grid B with 2 m x 2 m resolution in a reasonable time-frame without computational errors and produced a realistic representation of wave statistics in the nearshore.

3.4(e) Model Input Parameters

There are over 200 optional input parameters for an XBeach model. Most of these are for advanced tools in the program, so they are not applied in this study. Of the variables used, many are just tools used to turn on or off features such as wave-current interactions or to direct XBeach to an associated text file, like that created to input waves or tides. Nearly all parameters are defined in the text file named params.txt that is automatically created when Xbeach is first used. If a parameter is not defined in this text file, it is automatically set to a default value (assigned by Xbeach developers) during model processing. In the following section, only the most important input parameters are described. For a full list of input and output parameters used in each model, see the accompanying DVD data depository.

MODEL SCOPE

The first but most important parameter is \( t_{stop} \), which defines the model duration time (in seconds). This same value is also input for \( rt \), a wave spectrum parameter that defines the wave spectrum duration.
GRID PARAMETERS (Figure 51)

Parameters \( nx \) and \( ny \) describe the number of grid points in the grid on the x and y axis, respectively. This number will change with the size or resolution of the grid used. As mentioned in the previous section, the grid used for this study is 674 m wide by 552 m tall, at a resolution of 2 m x 2 m. Thus, \( nx = 337 \) and \( ny = 256 \). The \( \alpha \) parameter relates the rotated grid with its real world orientation. It is defined as the angle of counter-clockwise rotation from true x direction (real world East to West) to the grid x direction (left to right, offshore to onshore), so that the beach is positioned on the left side boundary of the grid (Figure 51b). For this grid, \( \alpha \) is 53°. Xbeach uses this parameter to reference other real world directional variables, such as wind and wave direction, to the rotated grid. Another important set of directional parameters are \( \theta_{\text{min}} \) and \( \theta_{\text{max}} \). They define the directional wave envelope by setting the upper and lower limit of wave discretization. In the case of this grid, since the beach is fairly straight and the model should allow all possible wave directions, \( \theta_{\text{min}} \) and \( \theta_{\text{max}} \) are 180° and 0° rotations from \( \alpha \) (53° counter-clockwise from true north), i.e. 127° and 307°, respectively (Figure 51c). Since only one grid was used for all the models, all of these values remain the constant with each run.

BED COMPOSITION PARAMETERS

The two parameters used to describe the beach sediment size are \( D_{50} \) and \( D_{90} \). These represent the sediment group as a whole. \( D_{50} \) marks the median sediment diameter, in which 50% of all sediment within the grid is smaller in diameter than this number. \( D_{90} \) marks the size in which 90% of all sediment diameters are smaller. Because this study is attempting to glean information about coarse beach sediment, specifically those sediments within the size range of the gravel particle tracers, \( D_{50} \) and \( D_{90} \) were calculated based on the gravel tracer populations. \( D_{50} \) was found to be 6.7 cm, or 0.067 m, and \( D_{90} \) was found to be 10.1 cm, or 0.101 m.

Sediment density, or \( \rho_{\text{s}} \), is used to calculate sediment transport within the system. Again, this was calculated based of the population of gravel tracers and set equal to 2696 kg/m³. Porosity (\( \rho_{\text{p}} \)) was defined as 0.45, raised just above the default of 0.4 to reflect the increase in porosity expected for a mixed sand and gravel beach compared to the fine beaches for which XBeach default parameters were originally designed. These bed composition parameters also remained the same throughout all models.
Figure 51: a) grid in its true orientation, shown with origin and real-world cardinal directions; b) counter-clockwise rotation of true cardinal directions to fit grid axis by an angle, \( \alpha \), of 53°; c) wave direction domain as defined by \( \theta_{\text{min}} \) (127°) and \( \theta_{\text{max}} \) (307°); d) rotated grid with dimensions. *Grid image courtesy of Bert Rubash.*
WAVE BOUNDARY CONDITIONS

Wave height and wave period data collected from the pressure sensor could be put into the model by way of the wave boundary condition. With Xbeach, there are a number of options when inputting wave information. The preferred method for many studies, including this one, is to use instat = jons, or instat = jons_table. These two options use the JONSWAP (JOint North Sea WAve Project) spectrum to generate a parametric wave group spectrum that fits the defined significant wave height and wave period parameters. This wave spectrum is forced onto the offshore (x=0) boundary of the previously static system. Wave spectrum energy then propagates towards the shoreline, over time, in the assigned wave direction.

The more basic wave model, instat = jons, assigns a single set of jonswap parameters to the offshore boundary. A separate text file, which is then referenced using parameter bcfile, is created that contains the variables Hm0 (significant wave height), fp (peak wave frequency) and mainang (average wave angle), along with a series of other jonswap coefficients. Because the pressure sensor does not record peak frequency, the significant wave frequency was calculated by taking 1/significant wave period. This basic wave option is best used to run simple models that have little variation in wave energy over time.

A more realistic model of wave energy can be produced by using instat = jons_table. Using the same bcfile referenced text file, a series of wave bins can be assigned to the system. The jonswap input is similar to instat = jons, except that, instead of peak frequency, Tp (peak wave period) is used, and, instead of one single set of parameters, multiple sets are applied to define changes in wave energy over time. Each set, or bin, is given a duration of time (in seconds). Since the pressure sensor recorded data once every hour, a duration of 3600 seconds was assigned to each set of wave parameters. There need to be enough bins to cover or exceed the total model time. For example, if a model lasts 5.5 hours, at least 6 lines of 3600 s duration need to be specified in the text file. While using this advanced option produces more accurate results, computational time is drastically increased. For example, an 11 hour storm would take over 100 hours of computation time). Thus, this option was only used for very small, test models. For the final models runs, basic jonswap parameters were used.
TIDE BOUNDARY CONDITIONS

Change in water levels due to tides can be defined in another text file, referenced through zs0file. This text file contains a tide time series consisting of model time (s) and water level (m). This time series format differs from the bin wave file format by allowing for the definition of water levels at random intervals as opposed to uniform duration intervals. Again, tidal information is needed to reach or exceed the total model time. For spatially larger models, Xbeach has the option to force tidal information from separate tide stations onto all four grid boundaries through the parameter tideloc. Since the grid used for this model is relatively confined with a nearby tide station, tideloc was set to 1, applying wave heights to the offshore (x=0) boundary. Initial water level, zs0, can be assigned on its own or through the separate text file.

WIND PARAMETERS

Though this option is not yet described in the Xbeach manual, recent versions of Xbeach allow for a wind time series to be included in the model, as opposed to a single averaged wind speed (windv) and wind direction (windth). A time series text file similar to that used for tidal boundary conditions can be referenced through windfile. In it, model time (s), wind speed (m/s) and wind direction (true nautical degrees) are defined. Because little information is available on this new wind series option, it is unclear how these wind values are applied to the model, whether they too are forced on the offshore boundary or if changes in wind are applied instantaneously throughout the entire grid. It should also be noted that Xbeach does not have a fetch parameter option, so wind input will likely not be as influential in the model as it is in natural wave settings. For this study, the wind series option was deemed a low priority. Therefore, singular averaged parameters windv and windth were used when modeling all wind conditions.

3.4(f) Model Output Parameters

There are a few output parameters needed by Xbeach to correctly produce spatial model data. First, outputformat indicates what type of Xbeach version is in use. In this case, outputformat = netcdf. Next, the model output is constrained using time parameters. The parameter tstart signifies the start time for the output data. For this study, tstart was always set to 0 seconds. The time interval
output for global values, or \textit{tintg}, defines the time-step in between data points. A low \textit{tintg} interval creates more data points than a high interval, and therefore significantly increases computation time. Through experimentation, a \textit{tintg} of 2 seconds was a suitable compromise between high resolution data results and computation time.

This study only used one type of output, the regular spatial output option \textit{nglobalvar}. This option allows up to 20 output variables to be defined spatially across the entire model domain over time intervals defined by \textit{tintg}. Eighteen variables were output during each model run. Those in bold were of special interest, as they are considered potential proxies for sediment transport.

- \textit{zb} bed level elevation – for this study, the bed level did not change over time, so this variable serves as a proxy for DEM/bathymetry maps and is used for spatial reference.
- \textit{zs} surface elevation – over water, this is surface water elevation, on land, it is land elevation
- \textit{zs0} water elevation due to tide alone, wave set up can be measured when the difference is taken between \textit{zs0} and \textit{zs}
- \textit{u} water velocity in the x-direction, as recorded in the grid cell’s center
- \textit{v} water velocity in the y-direction, as recorded in the grid cell’s center
- \textit{E} wave energy
- \textit{H} wave height
- \textit{Fx} wave forcing in the x-direction (onshore vs. offshore forcing)
- \textit{Fy} wave forcing in the y-direction (lateral forcing)
- \textit{R} total roller energy
- \textit{n} directionally distributed roller energy (distribution in radians)
- \textit{D} total wave dissipation
- \textit{DR} wave dissipation due to rollers only
- \textit{Sxx} radiation stress, or momentum flux in the principal stress direction
- \textit{Syy} radiation stress, or momentum flux in the transverse stress direction
- \textit{Sxy} radiation stress, or flow of x momentum across the y-plane
- \textit{taubx} bed shear stress in the x-direction
- \textit{tauby} bed shear stress in the y-direction
3.4(g) Model Design

Using the results of the gravel transport study and wave data collected from the pressure sensor, two real-life, low wave-energy transport periods were chosen to be modeled, along with one model that used high energy wave parameters over a rapid rising tide. The parameters file and supporting text files can be referenced in Appendix 3. Beach profiles are relatively consistent laterally along the Cherry Point shoreline, so a single profile, y=117, was chosen for analysis as it falls within the central portion of particle tracer study area. For each model, data was extracted along y=117 at a series of ten points along the beach profile (Figure 52).

![Figure 52: Profile of line y = 117 in MLLW Vertical Datum. Yellow dots represent data points extracted for analysis.](image)

The first transport period was divided into a set of two smaller model runs (one ebb tide and one flood tide) covering the evening of February 9th and the morning of February 10th. As mentioned previously in section 2.3(a), wind and wave energy was especially low during this time. Gravel tracers on the beach showed little to no transport. This data set provides an opportunity to look at the baseline forces created by flood and ebb tides and the relationship of these forces to coastal sediment. A tide time series was used for this model, but wave and wind data were input as average values. The ebb tide model took 15.5 computational hours to produce 6.25 hours of real tide time. The flood tide model took a little longer, taking just over 17 hours computational time to produce 6.75 hours of real tide time.
The second transport period represents classic winter storm wave conditions over a 6 hour flood tide. During a storm recorded from the evening of February 17\textsuperscript{th} to the afternoon of February 18\textsuperscript{th}, sustained high-speed (over 5 m/s) winds from the south strengthened wave energy, causing maximum wave heights to reach over 1.7 m. Tracers logged on the evening of the 18\textsuperscript{th} showed significant transport during this time, with many tracers recording over 50 m of displacement. This movement can almost exclusively be attributed to the overnight storm, as the tidal cycle prior to the afternoon of the 17\textsuperscript{th} showed very little wave activity. Thus, this storm is an ideal example to model forces resulting from strong energy winter storms. Unfortunately, a model using all available data supplements to the parameters file (tide time series, wind time series, and wave bin series text files) would take weeks of computational time. So, the model was simplified. Wind and wave data collected during the high energy peak of the storm (five consecutive hours), were averaged. These averages were put into the parameters file along with a tide time series that defined a linear rise in water level from -1.5 m (MSL) to +1.5 (MSL) over six hours. This tide time series does not represent a real observed tide. Real flood tides at Cherry Point are not linear, have a smaller tidal range and usually take about 7 to 8 hours to rise from low tide to high tide. The advantage of this simplified model is that wave processes can be modeled at all water levels and comparisons can be made between the low beach and the high beach without too many changing variables. Another advantage of this simplified model is that instead of needing over 100 hours to run, the model can be run in less than a day.

By running these three models, a series of sensitivity tests are conducted between low-energy flood tides and low-energy ebb tides, low-energy flood tides and high-energy flood tides, and lower-beach vs. upper-beach wave behavior during high-energy flood tides. These sensitivity tests establish relationships between representative wave conditions, wave forcing, and the potential for coarse sediment transport. These relationships are then compared to actual gravel transport behavior observed during the Cherry Point particle transport study.
CHAPTER 4: RESULTS

4.1 Weather Data Collection

Wind, tide and current data collected from the Cherry Point Pier weather stations via NOAA’s website can be found in table form in the DVD data depository included with this report. For each transport period, data are graphically represented and described, along with wave data, in Appendix 4.

4.2 Offshore Pressure Sensor

Post-processed data collected by the pressure sensor is located in table form in the DVD data depository. The DVD files contain sensor depth data and essentially measure water level at the pressure sensor. These data have the potential to provide exact tidal information at the site, as opposed to using tidal data collected from the station at Cherry Point. However, because the exact depth of the pressure sensor in relationship to MSL is not known, the Cherry Point station data is favored in analyses, and pressure sensor water level data are referenced only as a supporting data set.

The DVD files also contain wave statistics generated from raw data collected by the pressure sensor. The sensor uses two analytical methods, time series and auto spectrum, to calculate variables. For each wave burst, the following values are calculated: energy $E$ (both time series and auto spectrum), mean wave height $H_{avg}$, significant wave height $H_{m0}$, i.e. the average height of the highest 1/3 of recorded waves (both time series and auto spectrum), $H_{1/10}$, i.e. the average height of the highest 10% of recorded waves, $H_{1/100}$, i.e. the average height of the highest 1% of recorded waves, maximum wave height $H_{max}$, number of waves per burst, average wave period, significant wave period (both time series and auto spectrum), and variance, i.e how far wave frequencies vary from the mean (both time series and auto spectrum).
4.3 Sediment Transport

The post-processed tracer position data for each field day, along with a companion table of all gravel transport history, including qualitative observations, can be found in the DVD data depository. A transport ‘session’ is defined as starting at the beginning of a deployment field day and ending at the termination of the following retrieval field day. A total of sixteen transport sessions were recorded: Jan. 12th - 15th, Jan. 31st - Feb. 3rd, Feb. 3rd – 6th, 6th – 8th, 8th – 10th, 10th – 12th, 12th – 14th, 14th – 16th, 16th – 18th, 18th – 21st, 21st – 23rd, 23rd – 25th, 25th – 27th, Feb. 27th – Mar. 1st, Mar. 1st -3rd, and 3rd – 5th. A comprehensive review describing gravel transport and oceanic/atmospheric conditions observed during each transport session is located in Appendix 4. Graphs of wind, wave, tide, current data, transported tracer data and transport maps are included for each of the sixteen sessions. Not including tracers lost during the hiatus between January 15th and January 31st, tracer recovery was 88%.

There was a large range in gravel tracer movement observed, both to the northwest and to the southeast. The lowest amount of tracer transport was observed from February 8th to February 10th, when the maximum tracer displacement was 0.42 m (Figure 53). This corresponds to winds out of the northwest and very low wave activity over the course of the transport session (Figure 54). The largest tracer transport recorded was between February 16th and February 18th, following a winter wind storm sourced from the southwest (Figure 55). Significant wave height exceeded 0.8 m and maximum wave height exceeded 1.7 m (Figure 56). As a result, pebbles and cobbles experienced a large transport to the northwest, up to 52.8 m.

A statistical analysis of displacement magnitudes was done for each transport session (Table 1). A set of metrics were developed that quantitatively describe the magnitudinal distribution of displacement: T90, T67 and T50. These values are calculated in the same way as sediment parameters D90 and D50, which were described in section 3.4(e). T90 represents the lower limit of the largest 10% of transport displacement, or rather, 90% of the tracers logged during the period recorded transport less than this value. T67 represents the lower limit of the top 33% of transport, or rather, 67% of the tracers logged during the period recorded transport less than this value. T50 represents the median transport value.
Figure 53: Map of local tracer transport with inset window showing cobble positions with respect to the entire study area.
Figure 54: Stacked graphs represent tidal, current, wave and wind data during the transport session.
Figure 55: Map of local cobble transport with inset window showing cobble positions with respect to the entire study area.
**Figure 56:** Stacked graphs represent tidal, current, wave and wind data during the transport session.
<table>
<thead>
<tr>
<th>SESSION</th>
<th>Maximum Displacement (m)</th>
<th>Minimum Displacement (m)</th>
<th>Average Displacement (m)</th>
<th>T90 (m)</th>
<th>T67 (m)</th>
<th>T50 (m)</th>
<th>Average Upper Beach Displacement (m)</th>
<th>Average Middle Beach Displacement (m)</th>
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<td>01/12 - 01/15</td>
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<td>0.16</td>
<td>4.18</td>
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</tbody>
</table>

Table 1: Statistical analysis of each transport session.
Though the maximum, minimum and average are also calculated, the T90-67-50 series quantifies the behavior of the particle tracer group as a whole, and can therefore provide more information about gravel response to wind-wave energy. A small percentage difference between T90 and T67 suggests a more uniform behavior, like that observed after large displacements on Feb. 16-18th and the 23rd-25th, when nearly all tracers recorded significant movement. A large percentage difference, like from Feb. 10th-12th, 12th-14th, and 25th-27th, signifies a strong segregation of movement somewhere on the beach. Sometimes, segregation is due to a lower than average tidal range (25th-27th). However, normally this segregation is between high transport zones of the middle and upper beach and low transport zones within the lower beach or within the zone of barnacles (10th-12th, 12th-14th). It should be noted that this is not the primary method of classifying tracer group behavior, as transport sessions that only logged tracers in the mid to upper beach (like Feb. 21st-23rd) will naturally have a lower percentage drop between T90 and T67. Similarly, sessions that recorded little to no transport (like Feb. 8th-10th) show a large drop in percentage but not in magnitude.

Using these statistics, transport sessions are divided up into groups of low, medium and high transport, as defined by T90. Each of these groups is addressed in the discussion section, as each illustrates important relationships between tides, currents, winds, waves, and gravel transport.

4.4 Coastal Numerical Modeling

A total of three coastal numerical models (ebb tide – low energy, flood tide – low energy, flood tide - high energy) were run using XBeach. For each of these models, key output variables were extracted for ten points along the beach profile. These model outputs are found in table form in the DVD data depository, and are graphed and briefly described in Appendix 5. For each model, the following ten points are analyzed (Figure 57):

- (270, 117) – dark purple
- (272, 117) – purple
- (274, 117) – dark blue
- (276, 117) – light blue
- (278, 117) – green
- (280, 117) – yellow
- (282, 117) – orange
- (284, 117) – dark orange
- (286, 117) – red
- (288, 117) – pink
For each point, a series of output variables were extracted. Each variable provides information about the wave environment at Cherry Point. The most important data yielded by the models for this study are those variables that influence sediment movement. These are wave forcing, radiation stress and bed shear stress. The relationship between all variables and transport observed in the particle tracking study is examined in the discussion section.

Figure 57: Grid with location of profile along y = 117. Colors at ten points on the profile represent the color scheme used in all graph data.
CHAPTER 5: DISCUSSION

5.1 Particle Tracer Transport

The following sections discuss particle tracer transport behavior in response to wind speed, fetch, waves, tides, and currents. Unless otherwise noted, wave height discussed in this section refers to the significant wave height (Hm0), which measures the average height of the upper 1/3 of recorded wave heights.

5.1(a) Low-magnitude Tracer Transport

Transport sessions are considered low-magnitude when T90 is less than 1m displacement. This occurs in four out of sixteen sessions: February 3rd-6th, 6th-8th, 8th-10th and 14th-16th.

These sessions, listed below in order of T90, are very important because they have recorded a baseline, low energy environment that is periodically interrupted by very quick bursts of energy, often caused by winds. These data allow for a detailed look at transport that can be caused by singular, small wind events, as opposed to transport over multiple days of moderate to high energy winds and waves. Because these data are so important, the behavior of wind and waves for each individual event is described.

February 8th –10th: T90 = 0.017m (Figures A4.9 & A4.10)

This field day showed practically no movement, with the maximum displacement being 0.42m. Winds during this time were out of the northeast. So, even though they are fairly strong (ranging 5 – 11 m/s), the bluff was blocking the wind energy from acting on the surface water. Consequently, there was very little wave energy (waves heights were consistently 0.1 m or less), and with no wave energy there was not enough force acting on the beach to move tracers.

February 14th-16th: T90 = 0.21m (tracers above high tide level not included) (Figures A4.15 & A4.16)

EVENT #1: Winds started low and scattered but, around the intermediate low in the first tidal cycle, winds started to consistently blow from the southeast, increasing in intensity to
over 4 m/s. This increased wave energy. As winds built up speed, wave energy strengthened, both climaxing at the second high tide peak in the cycle, when currents were changing from flood to ebb. There was a change in wind direction coinciding with the low tide between cycles (but not a current direction change), and wave energy dropped.

EVENT #2: Winds out of the northeast did not provide any wave energy during most of the second tidal cycle, until winds again shifted at the second high tide peak of the second cycle. These moderate to high speed (7 m/s) winds from the southeast quickly built up wave energy. It is unclear whether the quick build was due to wind velocity or if it was an effect of wind traveling in the opposite direction from ebb tide currents. Significant wave height diminished over the course of the ebb tide and fell below 0.1 m at low tide. Again, low tide coincided with a change in wind direction, this time from the southeast to the northeast.

SESSION OUTCOME: During this time, tracers traveled generally to the northwest, with movement seen along a wide swath of the profile. This wide swath of moving tracers is consistent with a tidal range of -0.5 m (low movement) to + 0.9 m (most movement).

February 3rd–6th: T90 = 0.45m (Figures A4.5 & A4.6)

EVENT #1: Wind was scattered or from the northeast (low fetch) for much of the first cycle until the second high tide peak, at which point winds from the northwest began to build wave energy, peaking at over 6 m/s and then dropping over the course of the ebb tide. During low tide winds continued to be sourced from the northwest, but they were low in energy (less than 4m/s).

EVENT #2: Winds did not exceed 4 m/s again until the second high tide peak of the second cycle. Winds reached about 6 m/s only briefly before dropping due to winds no longer having a high fetch.

EVENT #3: Wave height rose when winds from the northwest rose above 4 m/s. The speed of winds during this time was very similar to Event #2 observed during Feb 14th to the 16th, when winds were out of the southeast. The difference however, is that wind direction on the 6th was from the northwest, over a higher fetch distance. Based on the relationship between fetch distance and wave height discussed in section 2.3(b), wave energy would be
expected to be higher with the winds from the northwest [Demirbilek & Vincent 2002]. But, that is not what was recorded. Unfortunately, current data is not available over the full range of this event; however the peak wind and peak wave energies occurred during a low-velocity flood tide.

SESSION OUTCOME: Tracers generally traveled to the southeast, but transport was limited to only a thin zone on the profile. This thin zone matches the tidal levels that coincide with significant wave heights of above 0.2 m.

February 6th–8th: \( T90 = 0.58\text{m} \) (Figures A4.7 & A4.8)

EVENT #1: Prior to this event, winds were out of the east (minimum fetch). At the second tidal peak of the first cycle, there was a change in source direction from east to the northwest. Though wind speeds were falling, they were still above 4 m/s and generated wave energy. These winds did not ever reach 6 m/s, and thus significant wave height did not meet or exceed 0.2 m. Wind data was spotty during the ebb tide, so it is unclear what caused the drop in wave height, whether winds weakened first before changing direction. However, wave energy had dropped by the time wind data started collecting a wind direction switched back to the minimal fetch easterly source.

EVENT #2: During the second high tide peak of the second cycle, wind switches from a low fetch source (this time, from the northeast) to a higher fetch southeasterly source. Winds exceed 4 m/s and quickly build wave energy. Winds temporarily reach 6 m/s, but significant wave heights last above 0.2 m/s for much longer, lingering above 0.2 m/s until winds drop below 4 m/s. No current data is available for this event.

SESSION OUTCOME: Significant wave height was high in the last event during water levels of 0.0 to 0.75 m. This combination of high wave energy and tidal range helps to describe the relatively wide zone of small but recordable transport or vertical change seen across the beach profile. Also, though displacement was slightly in the northwest direction, there was a smaller lateral transport component compared to the previous transport sessions. This is likely because Event 1 (winds from the northwest) and Event 2 (winds from the southeast) may have cancelled out much of the lateral displacement in either direction. As a result, most gravel tracer movement can be described as up-beach or down-beach.
These four low-magnitude transport sessions revealed a few key oceanic-atmospheric relationships at Cherry Point.

1. Wind energy sourced by minimal fetch (0-0.5km) did not build wave energy, regardless of wind speed.

2. Winds sourced from fetch distances greater than 0.5 km promoted greater wave energy when wind speeds reached 4 m/s or above.

3. After wind speeds peaked and began to weaken, wave energy remained elevated (Hm0 above 0.2 m) even when wind speeds fell below 4 m/s. When wave energy fell, it was usually associated with a change in wind direction to a low-fetch source.

4. There is an apparent relationship between wind direction, wind speed and tides. In seven out of the eight tidal cycles recorded during these low-transport sets, there is a marked shift in wind direction occurring routinely at the second high tide peak. The change in wind direction, whether sourced from either the southeast or the northwest, is also associated with higher wind speeds, which build wave energy. This wave energy then acts on the beach at peak water levels. Depending on the duration of the winds, a larger or smaller range of falling tide water levels is affected by the heightened wave action. This change in tidal constraint results in a larger or smaller zone of transported tracers, respectively.

5. Because the elevated wave events described above so closely coincide with the behaviors in tides, it is possible that there is some sort of atmospheric-oceanic interaction going on. Or perhaps this could also be linked to tidal currents (data for which is not consistently available for these transport sessions). Without doing a long-term, statistical study of the winds and tides at Cherry Point, it is hard to provide a good explanation for this phenomenon. However, the appearance of these winds affect the results of this study, as they created a regular source of energy capable of moving gravel tracers, even during tidal cycles associated with little to no wave energy.

6. During these short, low-speed wind events, winds from the southeast (fetch generally less than 10 km) occasionally generated higher wave energy than winds from the west/northwest (fetch generally 10 – 50 km). This was likely due to the short duration of
each event. Even though there was a long distance for winds from the west/northwest to act on open water, winds were not coming from this direction long enough to fully develop waves with longer periods than those waves sourced from the southeast.

7. The energy needed to transport gravel tracers during this study was entirely sourced by wind-generated waves. Currents did not have enough energy to move the tracers on the beach during Feb. 8th-10th when there was no elevated wave energy. Transport was only ever notable when significant wave height reached above 0.2 m. Thus, the displacement direction of tracers was controlled only by the direction of the force vectors created by waves acting on the beach (i.e. wave forcing and bed shear stress). The direction of these force vectors was a function of wind direction and offshore bathymetry. Unfortunately, wave angle data was not collected by the pressure sensor, so the exact angle of these forces for each event is unknown.

5.1(b) Moderate-magnitude Tracer Transport

Transport sessions are considered moderate-magnitude when T90 is less than 20 m, but greater than 1m displacement. This occurs in ten out of sixteen sessions: Jan. 12th-15th, Jan. 31st - Feb. 3rd, Feb. 10th-12th, 12th-14th, 18th-21st, 21st-23rd, 25th-27th, Feb. 27th – Mar. 1st, Mar. 1st-3rd and 3rd-5th. Transport sessions with moderate displacement tended to record a combination of events, instead of the small, single events recorded in the low-magnitude transport sessions. Then by extension, tracer displacement is a response to multiple events, and not a single event. Thus, individual sessions and their events will not be described in detail. However, these data do provide information about how pebble and cobbles respond to prolonged wave energy. They also shed light on the relationships between higher wind speeds, fetch distance and wave energy.

1. Winds sourced over long fetch distances did not always build up to high wind speeds. Also, long-fetch winds with speeds below 4 m/s did not build significant wave energy. They did, however, have the ability to sustain energy slightly longer than winds of the same speed sourced from less fetch. This lag-time for elevated wave energy represents the length of time it takes for wave energy to decay after long-fetch wind speeds relax in the Georgia
Strait. A good example of this is recorded on the evening of February 13th (Figures A4.13 & A4.14), when high-fetch winds from the west dropped from 5 m/s to under 2 m/s.

2. Windspeed, fetch distance and significant wave height data collected during this time support the theoretical relationship of these variables discussed in section 2.3(b). For example, in the afternoon and evening of February 21st (Figures A4.19 & A4.20), two peaks in wind speed were recorded. The first peak, lasting about 2 hours, topped out at 9.5 m/s with winds from the south. A second peak occurred 4 hours later when winds changed from the south to a southwestern source. This peak lasted about 1.5 hours, and reached speeds of 11.1 m/s. These peaks, though different in wind speed, correlate with peaks in significant wave height of equal magnitude (0.5 m). If the average wind speed and average fetch distance are plotted onto the logarithmic graph from Figure 18 (section 2.3b) for both peaks, it is expected that each peak will have the same significant wave height (Figure 58). On the chart, this expected value is 0.7 m, which is 0.2 m above the recorded data. This discrepancy may be because the values used for wind speed and fetch are averages. Also, there are about 2.75 km of open water distance between the Cherry Point wind station and the pressure sensor, so winds acting on waves approaching the sensor may be slightly different than those recorded at the BP pier.

3. These moderate transport sessions record several events of elevated wave energy lasting for an entire tidal cycle, or for multiple days. Waves are interacting with the beach over the full tidal range. As a result, most, if not all, zones along the beach profile experience wave energy capable of moving pebble and cobbles. Naturally, these high winds and waves will strengthen and weaken over time and will not have uniform magnitudes for the entire duration of the tidal range. Instead, periodic increases in wind energy create peaks in wave energy.

One of my hypothesis for transport behavior at Cherry Point was that tide levels coinciding with the greatest wave energy would record the largest tracer movement. Because wave energy and tide water levels are not directly related, these zones of high transport created by high wave energy should occur at any position along the beach profile. This position would also change from storm to storm, as peaks in wave energy occur at different tidal
Figure 58: Two different winds create the same significant wave height. Fetch, significant wave height and wind velocity relationships for the first and second wind and wave energy peaks on the evening of February 21, 2012.
levels for different storms. However, the data collected during the Cherry Point study do not support that hypothesis.

For example, the storm on February 22nd (Figures A4.21 & A4.22) had several peaks in wave energy, the largest of which coincided with the highest tide mark. If wave energy magnitude was the only variable influencing gravel movement, then the tracers highest on the beach (but still within the tidal range) would show the most movement. They do not. Instead, tracers in the lower – upper, and upper-middle beach tended to travel farther, with transport decreasing in magnitude both up-slope and down-slope. The elevation of this transport zone fell between 0 and 0.5 m above mean sea level. This area was exposed to surface water action four times during each tidal cycle, more than those above 0.5 m or below 0 m. Therefore, the magnitude of tracer transport over multiple events was more closely linked to the amount of time tracers were exposed to elevated wave heights.

So, by extension, gravel transport is closely linked to the tidal signature at Cherry Point. Pebbles and cobbles will likely move farthest within profile zones most frequently exposed to surface water. This explains why there is a consistent zone of high-transport in the upper part of the middle beach and the lower part of the upper beach (Figure 59).

Figure 59: Lower beach, low transport zone. Red line shows segregation of low cobble transport (lower beach) and normal cobble transport (mid-upper beach) zones.
4. Because tracer movement is primarily controlled by the direction of wave forces, transport over multiple events can be broken down into multiple displacement vectors. The final position of the tracer at the end of the transport session reflects the summation of all of these displacement vectors. If two wind-wave events are sourced from opposing directions, there is a potential for lateral transport in either direction to be cancelled out, or, depending on the position of water level when the winds switched directions, a single transport session can show gravel movement both to the southeast and the northwest, such as observed during the March 3rd-5th session (Figures A4.31 & A4.32).

5. The pattern of transport in the middle and upper beach has already been explained by tides. But one of the most interesting patterns observed in gravel transport behavior was the lack of displacement in the lower portions of the beach profile, such as on Jan. 12-15 (Figures A4.1 & A4.2), Jan. 31- Feb. 3 (Figures A4.3 & A4.4), Feb. 10-12 (Figures A4.11 & A4.12), 12-14 (Figures A4.13 & A4.14), and Mar. 3-5 (Figures A4.31 & A4.32). Even though these zones were not at surface water level as often as the upper beach, they still experienced events of heightened wave energy. For example, in the early morning of Feb. 11th, when tide was at 1.0 m below MSL, significant wave height peaked above 0.4 m. Still, pebbles and cobbles in this zone remained relatively stationary. In addition, four tracers (#’s 984, DF6, E03, DF2) were left in the lower beach and the barnacled area over the entire study duration, from January 12th to March 5th. Despite the frequent exposure to elevated wave heights, and even after three winter storms, these tracers showed little displacement (Figure 60). Insight into this phenomenon is provided by numerical models, thus, this topic is discussed later, in section 5.2.

5.1(c) High-magnitude Tracer Transport

Transport sessions are considered high-magnitude when T90 is greater than 20 m. This level of transport is only recorded in two out of sixteen sessions: Feb. 16th-18th and 25th-27th.

These data sets captured winter storms similar to those experienced at Cherry Point periodically from October to March. Where low-magnitude events provided important information about
Figure 60: Lower four cobbles show minimal displacement over seven weeks of wave energy.
baseline winter transport and possible summer weather transport behavior, high-magnitude events
gave insight to gravel response to high winter wave conditions. These winter wave conditions
generated the highest displacement per event. These winter wave events, in turn, are likely
responsible for the majority of sediment transport on the beach over the course of the year. Thus,
the two transport sessions described below are perhaps the most important data collected during
this study. The first transport session is considered a ‘simple’ high-magnitude transport session
because it only recorded a single, well constrained storm. The second transport session, considered
a ‘complex’ high-magnitude transport session, recorded two storms that occurred back to back.
Each session is described here in detail, by storm.

February 16th - 18th: T90 = 42.9 m (SIMPLE SESSION) (Figures A4.17 & A4.18)

Wave energy leading up to and after the storm was minimal, as winds were out of the
northeast and east. Wind direction throughout the storm also remained relatively constant.
Thus, all gravel tracer transport was be attributed to this single storm, coming from a single
direction. In this case, winds were sourced from the southeast and south throughout the
storm. Though the fetch in these directions was moderate (1-25 km), winds remained well
above 4 m/s for over 24 hrs with top winds recorded at just over 10 m/s. Wave energy was
able to build continuously over this time, and significant wave heights peaked at over 0.8 m.
The duration of the storm allowed for all portions of the profile to be affected by the high
wave energy. Therefore, notable transport to the northwest was observed in nearly all
tracers. Tracers positioned above + 0.5 m were exposed to the most energy for the longest
amount of time. Thus, as expected, pebbles and cobbles on the upper beach experienced
the most movement (displacement averaged 28.3 m).

Tracer transport during this time is also a good illustration of the seemingly random paths
pebbles and cobbles can travel when exposed to wave energy. For deployment, packaged
sets were strategically placed with the intent to compare the transport behavior of
immediately adjacent tracers, as well as gravel tracers of the same sizes at different
elevations in the profile. After the storm, the paths of tracers within each set were mapped
and labeled by size (Figure 61a-e).
Figure 61(a): Transport observed after the February 18th storm, by packaged sets and beach zone. Sets #1 & #2.
Figure 61(b): Transport observed after the February 18th storm, by packaged sets and beach zone. Sets #3 & #4.
Figure 61(c): Transport observed after the February 18th storm, by packaged sets and beach zone. Sets #5 & #6.
Figure 61(d): Transport observed after the February 18th storm, by packaged sets and beach zone. Sets #7 & the upper-mid beach.
Figure 61(e): Transport observed after the February 18th storm, by packaged sets and beach zone. Mid beach and lower-mid beach.
All pebbles and cobbles traveled in the same lateral direction (to the northwest), but varied in their up-slope or down-slope transport components. Most of the upper and middle beach tracers showed a distinct down-slope movement whereas those in the lower and lower-mid beach showed an up-slope movement. Within the upper and middle beach, there was a clear bi-modal directionality to transport. Half of the tracers traveled far laterally up the beach (40-50 m), with little to no down-slope movement. The other half traveled a shorter distance (about 25 m) to the northwest and downslope.

Two tracer clasts of the same size, positioned immediately next to one another, often experienced very different transport paths (such as the two small clasts in Set #5). Alternatively, two clasts of different sizes sometimes traveled together over time, such as the cluster of two extra small/one small clasts in Set #3. There were multiple instances of larger clasts in the set traveling farther than their smaller counterparts (Sets 1, 3, 4 and 6).

February 23\textsuperscript{rd}-25\textsuperscript{th}: T90 = 36.3 m (COMPLEX SESSION) (Figures A4.23 & A4.24)

This transport session was a combination of two storms. Thus, tracer displacement was a combination of both the first storm (winds from the southeast) and the second storm (winds from the west/southwest).

STORM #1: This storm was very similar in wind direction, wave energy and storm duration to the one previously described. It began just after midnight on the 24\textsuperscript{th} and ended around 04:00 the morning of the 25\textsuperscript{th}. Winds were consistently from the south and southeast, with wind speeds reaching over 14 m/s. These winds were actually much stronger than those of the previous storm, but they were a bit scattered and ranged from 8 to 13 m/s in a short period of time. Wave energy followed an average wind speed (about 8 – 9 m/s), and was similar to that in the February 18\textsuperscript{th} storm (maximum Hm0 about 0.8m). Also like the last storm, the duration allowed for wave energy to act on gravel tracers during nearly the full tidal range. I hypothesize that tracers would likely have moved to the northwest at nearly the same displacement magnitudes as the February 18\textsuperscript{th} storm.

STORM #2: There was a shift in winds during the flood tide on the morning of the 25\textsuperscript{th}, from a south source to a southwestern (10-25 km fetch) and western (50+ km fetch) source. The winds with a large fetch had very high energy, matching the 14 m/s speed of the previous
storm. Wave heights were quickly built to the largest recorded significant wave heights during the transport study, $H_{m0} = 0.96$ m. The high speeds did not last long, however, and gradually dropped over the ebb tide. Wave energy was still elevated during the field session at low tide. The final locations of the tracers logged on the 25th recorded significant southeastern movement over the two days.

The high-magnitude transport sessions provide the following conclusions:

**1.** There was a loose inverse relationship between cobble size and the upper and lower extents of tracer movement. The largest distance traveled was by a small pebble, and the shortest distance traveled was by an extra-large cobble. However, beyond this upper and lower limit, there was no clear relationship between beach position, tracer particle size and transport path.

**2.** There was no relationship found between movement and clast shape. This lack of relationship may be attributed to the dynamic and variable nature of wave force vectors acting on a beach. Sediment separated by only a few centimeters will still experience different force vectors from waves and shear stress. Those vectors may promote transport in slightly different directions, at which point new force vectors are introduced and may push or pull sediment farther apart. The culmination of this process results in tracer particles of similar shape and similar origin taking completely different transport paths. These random transport paths make it especially difficult to predict the transport path of pebbles and cobbles, even with the use of very fine scale (0.5 m resolution) computer modeling.

**3.** For the complex transport session, I hypothesized that the first storm could have moved tracers a great distance to the north (potentially moving upper beach tracers between 40 and 50 m). If this assumption is correct, then the second storm must have moved tracers a tremendous distance in the opposite direction in order to overcome the first transport, and move them a net distance of up to 46 m southeast of their original starting position. Unfortunately, this hypothesis cannot be tested, since no other severe winter storm from the west was recorded during the gravel transport study. If found true, however, the
potential for single storm movements of nearly 100 m in a single storm has important implications for the overall sediment budget of Cherry Point.

5.2 Coastal Numerical Modeling

The results from the three models described in section 3.4(g) (low wave height ebb tide, low wave height flood tide, and high wave height flood tide) are compared below. Figures referenced in this section can be found in Appendix 5. References to grid coordinates reflect points on the beach profile as illustrated in both Figure 57 and Figure A5.1. Data points on each graph represent two second averages based on the 2 second time-step interval defined in the model output parameters.

5.2(a) Low Wave Height Ebb Tide vs. Low Wave Height Flood Tide

These low wave height ebb tide and flood tide models are representative of the wave environment during falling water levels and rising water levels. The results from these models reflect zero wind speed or direction and a uniform wave field (e.g. no fluctuations in wave energy). They are also not biased in wave direction, as the main wave angle input into each model was perpendicular to the beach (217 degrees). Thus, they are a representative baseline for the relationships between non-storm waves and water levels at the Cherry Point shoreline based on real wave and tide data. These data illustrate that, while ebb and flood tides with the same wave heights may record similar tidal ranges, the energy, force and stress experienced along the profile are not uniform during a tidal cycle.

Comparing ebb tides and flood tides with similar significant wave heights, there is a stark difference in magnitude of wave energy, wave forcing, radiation stress, and bed shear stress. Under weak wave conditions, wave energy and wave forcing (in both x and y directions) are over two times higher during flood tide as compared to ebb tide (Figures A5.5 & A5.6). Radiation stress in the principle and transverse direction are nearly three times larger during flood tide than ebb tide and off-diagonal radiation stress is about four times larger (Figures A5.7, A5.8 & A5.9). Disregarding positive/negative direction, bed shear stress in the x-direction and average bed shear stress in the y-direction are both
three times larger during flood tide (Figures A5.10 & A5.11). Maximum stress in the y-direction is approximately the same for both ebb and flood tides.

Wave Forcing (Figures A5.5 & A5.6)

The largest magnitudes of the x (Figure A5.5) and y (Figure A5.6) components of wave forcing are consistently in the positive direction (x: onshore, y: northwest) for both ebb and flood tides. This consistent onshore and northwesterly long-shore forcing suggests that when waves reach the shore at a right angle, the natural forcing will be to the north at and around water level. Below surface water level, the forcing will be to the south. The difference between forcing at water level and forcing below water level creates a natural balance to the cross-shore and lateral forcing of waves. If waves were approaching the shoreline at a non-90 degree angle, there would be a larger long-shore force component, potentially creating wave-generated currents.

In the low-energy flood tide, onshore wave force curves sharply increase when waves are even with the point elevation (Figure 62). This increase corresponds to the forward motion of water particles in wave orbit. Once tides rise past the point, the curve decreases to the negative direction, signaling that the point is now on the backside, or negative side of wave orbit. Eventually, water level is high enough, and the wave base is far enough from the point, that wave force is reduced to around zero.

The heightened energy, force and stress acting on pebbles and cobbles during flood tides suggest that coarse-sediment is more likely to move during a flood tide as opposed to an ebb tide. However, the ability of pebbles and cobbles to move still relies on the presence of elevated wave heights, which, as discussed in the previous section, is reliant on winds of a minimum speed and fetch.

Radiation Stress (Figures A5.7, A5.8 & A5.9)

There is also a significant difference in the behavior of the off-diagonal component of radiation stress (Sxy)(Figure A5.9). During flood tide, radiation stress is positive, which indicates that the flow of momentum is moving towards the shore. Radiation stress is strongest in the lower beach (points 270-276) when the depth of the water is less on the barnacled platform. Because the cross-shore force of radiation stress reaches its maximum at the lowest vertical point of a wave [Wlodzimierz 2008], perhaps the close proximity between the platform and the wave base at low wave height creates a larger momentum in the positive, onshore direction.
Figure 62: Evolution of wave force in the x direction - Low-energy flood tide over model times T1, T2, and T3.
Ebb and flood tides vary in both the x (Figure A5.10) and y (Figure A5.11) component of bed shear stress (Figure 63). During ebb tides, bed shear stress is very low and in the negative (offshore) direction for the middle and upper beach slope, but shear stress shows a strong increase, again in the offshore direction, in the lower portion of the low beach/barnacle area. Also, the long-shore component of shear stress is consistently negative across the entire profile, suggesting bed shear stress is mostly in the south direction (or, in terms of component, Grid South and offshore). The exception to this directional behavior is at point 274, at the junction between the lower beach platform and the steeper beach slope, where there is a relatively large increase in shear stress laterally to the southeast (or Grid South), and a decrease in cross-shore magnitude, but this time to the north. This reverse in bed shear stress to the east may have to do with the change in slope at this location, where there may be a small degree of wave reflection during low-water levels, which shows up on this graph because shear stress is already so low due to the low-energy nature of outgoing tides. The flood tide, on the other hand, is largest in the onshore direction when first reaching the barnacle platform. A degree of lateral shear stress spreading occurs between points 270-276. Points 270 and 272 both show preference to the southeast and both points 274 and 276 show preference towards the northwest. Flood tides also oscillate between negative and positive lateral stress in the upper beach.

5.2(b) Low Wave-Height Flood Tide vs. High Wave-Height Flood Tide

Naturally, when comparing a flood tide with a low significant wave height to a flood tide with a very high significant wave height, there will be a drastic difference in the energy acting on the beach. Therefore, the magnitude of energy, wave force, radiation stress and bed shear stress should increase drastically between a flood tide that shows no tracer movement and a tide reflecting storm-waves that moved tracers over 50 m. The magnitude increase is expected to change depending on the difference in wave heights between the two models and the model can help inform if this difference is linear or non-linear.

The high wave height model did impose a wave direction of 207 degrees, or 10 degrees south of the x-axis. The use of this forced wave direction was meant to model a flood tide with a more realistic
Figure 63: Low wave-height flood and ebb tide, bed shear stress components. Vectors not to scale.
force direction, as wind is from the south and flood currents are pushing water towards the northwest. This change also inherently increased the positive long-shore components of each data set, when compared to the low wave-height flood tide.

So, it is more useful to look at the behavior of data curves over time, as opposed to the differences in magnitude, when comparing the low energy and high energy flood tides.

*Wave Forcing* (Figures A5.5, A5.6, A5.16 & A5.17)

When compared to the low wave-height flood tide discussed in section 5.2(a), the high energy flood tide is found to have a series of projected differences in wave forcing. First, there is a more gradual climb in wave force following initial contact with water. This gradual response of wave force to wave energy makes sense as waves run up the beach when breaking onto shore, interacting with elevations above still-water level. Thus, points will show wave forcing for a period prior to when true water level reaches the point. Wave run up is minimal for low-energy, low-height waves. Second, wave forces in both the lateral and cross-shore directions remain low while water level rises over the lower and lower-middle beach. It is not until water level reaches the upper-middle beach (point 282) that wave force increases in the low-beach/barnacles, oscillating in all directions.

Finally, the duration of elevated wave forcing at each point above the low-beach lasts longer for the high-energy flood tide than the low-energy flood tide. As previously illustrated in Figure 62, in the low-energy flood tide model, at each point, wave force curves sharply increase when water level reaches the elevation of that point. Once tides rise past the point, the curve decreases to the negative direction. Eventually, water level is high enough, and the wave base is far enough from the point, that wave force is reduced to around zero. In the high energy flood tide with high wave heights, the base of the wave orbit is deeper. This explains why wave force remains high for a longer period of time, and also why there is not a consistent negative wave force once water level surpasses each point.

*Radiation Stress* (Figures A5.7, A5.8, A5.9, A5.18 & A5.19)

Recall that low-energy flood tide pattern of relatively high radiation stress diminishes to low stress in both the principle and transverse components with rising tide. The high-energy flood tide shows the opposite. Radiation stresses start low and then build to high-magnitudes. Fluctuations between
high and low values continue for the rest of the model, and never fully weaken. This pattern can also be attributed to early stress exposure from run up waves, as well as a vertical change in wave height/orbit.

The off-diagonal component also behaves differently. Where the flood tide shows a large, onshore momentum flow in the low-beach before weakening over time, high energy wave-induced momentum flow is more uniform along the entire beach profile. This behavior difference is likely again due to the change in wave height, which raises the wave base to a greater distance above the barnacle platform.

*Bed Shear Stress* (Figures A5.10, A5.11, A5.19 & A5.20)

The shear stress patterns in both x and y components for both models are very similar; however, the bed shear stress values in the high-wave flood tide are obviously much higher in magnitude than the low-wave flood tide and the maximum shear stress at each point is more uniform across the profile (Figure 64). The initial high peak in the low-beach is no longer the maximum recorded shear stress, either onshore/offshore or laterally. Instead, under high waves, shear stress maximums are recorded in the middle and upper beach. Another difference is that the range of negative values for the x component for the low energy model is more limited than that of the high energy model. In fact, the higher energy model’s maximum offshore shear stress is higher than its onshore shear stress, suggesting an increase in seaward movement of sediment. This offshore bed shear stress is not, however, reflected in the particle tracing study results, as there is no observed pattern of gravel moving in the offshore direction. Thus, it is possible that the bed shear stress values, especially the cross-shore components of bed shear stress, are not large enough to cause coarse sediment movement at Cherry Point.

5.2(c) *Lower Beach vs. Middle & Upper Beach (High Wave Height Flood Tide Model)*

One of the most curious observations that came out of the 2012 gravel transport sessions was the segregation in tracer transport behavior between the low beach and the middle and upper beach. Tracers in the low beach, especially on the platform, rarely experienced transport, even during the largest recorded storms. This correlates to the dense presence of barnacles living in the middle-
Figure 64: Low wave-height and high wave-height flood tides, bed shear stress components. Vectors not to scale.
The high energy flood tide models output not just wave energy, wave forcing, bed shear stress and radiation stress, but also roller energy and dissipation. Many of these data show a distinction between the lower beach and the upper beach, specifically, between points 270-276 and 278-288.

**Wave Energy and Dissipation (both regular and roller waves)** (Figures A5.14 & A5.15)

The overall energy observed during the high-wave flood tide actually shows little distinction between patterns of the lower, middle and upper beaches. The dissipation of this energy, however, does illustrate a difference. There is seemingly juxtaposition of a single dissipation pattern on two different scales. In the lower beach, dissipation slowly rises at point 270 and then falls to about zero. The maximum dissipation reached is 51 W/m². Interestingly, the scale of this dissipation pattern decreases at point 272 (max 35 W/m²), then even lower to point 274 (max 21 W/m²), but increases back up to point 276 (max 26 W/m²). The jump from point 276 to 278 marks the transition into the upper dissipation range for the beach slope. This second, upper tier of dissipation magnitude ranges from 103 W/m² (at point 278) to 205 W/m², but keeps the same behavioral pattern (slow rise and gradual fall).

This pattern is observed in both the roller energy data set and roller dissipation. This pattern signifies that there is indeed something going on in the lower beach that is affecting physical wave processes. The presence of overall energy, but not roller energy in the lower beach, suggests that waves are not breaking near the lower beach points. Instead, waves are breaking farther offshore, and the energy observed at the lower beach points is essentially the post-break, already dissipated waves. This off-shore wave break also explains why dissipation is so low in this area. As water level increases, waves are able to break closer to shore. Thus, a higher energy due to rollers and more dissipation is recorded at points along the beach slope.

**Bed Shear Stress & Wave Forcing** (Figures A5.16, A5.17, A5.19 & A5.20)

Each bed shear stress curve in the lateral direction shows a similar peak to that observed in the low energy flood tide, but differs in the form of consistent negative, moderate-magnitudes recorded in the low-beach following the initial peak. Magnitudes begin to fall as tides rise, markedly by point 280, and oscillate about zero by the time water level reaches point 282. This timing aligns with the wave force pattern observed in both the x and y component, when wave force remains moderate in
the low beach before changing to a sporadic high/low pattern. In turn, these patterns suggest a close link between wave force, bed shear stress, and water level elevation within the profile. The fact that the change occurs around point 280 signifies that this may be the ‘critical water level’ needed to bring the breaking line of waves close enough to break over the beach profile. This elevation equates to about +1.2 m above MLLW, or -0.41 m (MSL).

This proposed critical water level correlates to the transitional zone between the upper-lower beach and lower-middle beach, as described previously in this study. It also correlates to the upper limit of the low-transport zone observed repeatedly in the transport sessions. I interpret that pebbles and cobbles below this critical water level (especially those on the lower platform) have insufficient exposure to larger wave forces associated with breaking waves on the beach slope and therefore do not experience a combination of lateral or cross-shore wave force, roller energy, and bed shear stress needed to move pebbles and cobbles 5.1 cm diameter or larger. They will, however, receive enough force to experience vertical mixing, as is recorded in seven transport sessions (Jan 12th – 15th, Jan. 31st – Feb. 3rd, Feb. 3rd – 6th, 6th – 8th, 10th – 12th, 18th – 21st and Mar. 1st – 3rd). Though bed shear stress observed in the lower beach is higher during high energy waves than low energy waves, the difference in magnitude is nowhere near as great as that seen in other variables (Figures A5.10, A5.11, A5.19 & A5.20). Since it seems that a relatively high bed shear stress is recorded in the low beach for both low energy wave environments and large storms, it is likely that vertical mixing of otherwise immobile pebbles and cobbles is directly associated with bed shear stress.

5.3 Local Implications

5.3(a) Sediment Drift Direction along the Cherry Point Aquatic Reserve

Prior to this study, there were two different descriptions of sediment drift south of Point Whitehorn. Bauer [1976] made qualitative observations of gravel moving both to the northwest and the southeast. However, his study included no quantitative data to support his claim. Therefore, the theory of bi-directional transport has been dismissed in the wake of more recent studies that measure fine-sediment transport behavior. Now, the more favored theory is that Point Whitehorn marks the divergence of two net-shore drift cells [SMP 2006]. The southern drift cell indicates that
all sediment south of Point Whitehorn mainly travels alongshore to the southeast [Schwartz et al. 1991, Johannessen & Chase 2006].

By nature, a net-shore drift cell encompasses three parts: sediment input, sediment transport and sediment deposition. In the case of the Aquatic Reserve, sediment input is mostly from feeder bluffs. This sediment is pulled out from the base of the bluff into the beach and nearshore waters. While some fine sediment stays on the beach (mixed sand and gravel), most fines are pulled into the nearshore environment. Coarse sediment, like the large pebbles and cobbles used for this study, remain on the beach. Thus, there are two tiers of transport within the drift cells. There is long-shore drift, which characterizes the direction of fine sediment in the nearshore, and there is beach drift, which characterizes the behavior of both fine and coarse sediment on the beach. The issue with the current net-shore drift cell characterization is that coarse sediment beach drift and fine-sediment long-shore drift are lumped together, when in fact, they may have very different behaviors.

While fine sediment has been proven to travel south [Schwartz et al. 1991, Johannessen & Chase 2006], quantifiable data from this study supports bi-directional transport of coarse sediment in the middle and upper beach, as originally observed by Bauer [1976]. This bi-directionality is not a product of drift cell divergence at a headland, but rather a consequence of wind patterns in the Georgia Strait that produce waves sufficient to drive cobble transport. Winds from the southeast, which create waves forcing sediment to the northwest, are predominant (fastest) during all months of the year months and are prevailing during most months. However, during this study, winds from the northwest capable of moving large pebbles and cobbles were observed both in small scale single events and extremely large displacement events (up to 100 m) when sourced from a large fetch distance (50+ km). Thus, coarse sediment shifts continuously back and forth laterally along the middle and upper beach. Because the Aquatic Reserve shoreline is fairly uniform in orientation and slope, this bi-directional transport probably occurs in the middle and upper beach along all northwest/southeast trending shoreline, and possibly along the north/south trending beach near the Alcoa and Conoco Phillips piers. Though Bauer [1976] showed bi-directional transport only occurring just south of Point Whitehorn, current beach access near the industrial piers is restricted, so gravel transport in those areas can only be guessed.

Coarse sediment in the lower beach remains relatively stationary over time. This section of the beach should not be referred to as a lag deposit because sediments are still active and experience
vertical mixing and very slight lateral movement. It is unclear how coarse sediments in the lower beach made it to their current position, as few tracers were observed moving down-slope at a large enough scale to reach this non-active zone. I hypothesize that these pebbles and cobbles were once part of the middle and upper beach when the bluffs of Cherry Point were about 20 m seaward of their current location. As water levels rose and undercut the bluffs, the middle and upper beaches migrated with the retreating bluff line, leaving those offshore coarse sediments stranded on a low-energy platform.

Calculating a sediment budget for beach-drift contribution to net-drift over time would be very complex (see section 5.4); thus the overall direction of coarse sediment transport remains uncertain. However, considering there is no large, local deposition features of coarse-sediment (or at least, no coarse-sediment equivalent to Sandy Point, the sandy spit depositional feature), it is possible that coarse sediments on the beach are moving continuously back and forth along the beach, and long-term net-beach drift is very low or non-existent. At the very least, while coarse sediments are actively moving with day-to-day average wind energy, beach-drift is significantly less than long-shore drift. This information is valuable for those wishing to study beach habitat or coarse-sediment beach armoring at the Cherry Point Aquatic Reserve.

5.3(b) Previous Interpretations of Washington's MSG Beaches

Three previous studies looked at the travel behavior of gravel-sized sediment in the Washington State/Puget Sound area. Each study took place in a different mixed sediment beach environment, and each study focused on separate aspects of the gravel transport. A brief overview of each is discussed here, followed by a discussion of how well the results of the present study at Cherry Point varies.

Osborne [2005] used magnetic tracers to study gravel transport along the inner bank of a tidal inlet in Half Moon Bay, Grays Harbor, Washington. Daily transport was monitored over a three day period in December 2003 and a five day period in February 2004. The inlet was separated from Pacific winter wave conditions averaging around 3.4 m Hm0 by a jetty that reduced Hm0 to a maximum of 1.3 m Hm0 just inside the bay. The tracer particles ranged from 2.6 cm to 13.8 cm and traveled at a maximum velocity of about 10 m/day (in December) and only averaged 5 m/day in February.
The Grays Harbor study found that the beach of the tidal inlet is predominantly modified by longshore transport. This was also the case at Cherry Point for south/southeast winds and waves, since nearly all tracer transport was recorded to the northwest or northeast, with minor cross-shore components. The Grays Harbor study also found that smaller particles showed more movement in the cross-shore direction than larger particles. This is generally not observed within the Cherry Point transport sessions, as all pebbles and cobbles have been recorded moving with strong components in the up-slope, down-slope or entirely lateral directions. Osborne [2005] also observed a preferential displacement of particles within the 5.4 cm and 7.0 cm diameter range. Smaller and larger particles show a decreased affinity for transport. This result is hypothetically linked to selective entrainment or overpassing of larger particles. Unfortunately, particle tracers under 5.4 cm were not used in this Cherry Point study. Therefore, this preference cannot be confirmed or disputed with the data collected. However, there seems to be only a loose relationship between gravel transport and clast size at Cherry Point.

Curtiss et al. [2009] used three different types of PIT tags over a period of two years, measuring tracer transport along the southwest coast of Bainbridge Island at two different deployment sites every two to four weeks. The particle tracers used in this study, ranging from 1.6 cm to 4.5 cm diameter, are smaller than those used at Cherry Point. Perhaps this environment is most similar to the shorelines of Cherry Point, as the beach is located along a lengthy stretch of open water (9 km maximum fetch), though the fetch is not nearly as long as at Cherry Point. The area can record some very high winds, however, as the highest winds recorded during the study reached 18.8 m/s. Despite the high winds, tracers traveled much shorter distances compared to those at Cherry Point. Following a year of transport, tracers had moved a net distance of 50 m at one site and only 20 m at the other.

The authors found that tracer particles became well sorted by size within the first two weeks of deployment. This finding led to a warning for future studies that short term sediment monitoring may not fully represent long term transport. However, there was no sorting observed at Cherry Point. And while no single deployment remained un-touched for a full two weeks, tracer particles at Cherry Point were observed long enough to discount any shape or size relationship to transport. Tracers positioned highest on the beach by Curtis et al. [2009] were found to move the farthest. Again, this is not the case at Cherry Point, for two reasons. First, tidal levels at the latter do not
always reach all portions of the upper beach. Thus, gravel at the base of the bluffs may remain dry for days at a time. Second, at Cherry Point, transport magnitudes are highest in the upper portions of the middle beach and lower portions of the upper beach, where pebbles and cobbles are exposed to wave energy the most often. Vertical mixing was found during the Bainbridge Island study to increase during high energy storms. The Cherry Point data agree, although minor mixing does occur during low energy periods as well.

Finally, Curtiss et al. [2009] found that winter wave conditions dominated transport. During low energy periods, currents did not have the strength to move sediment, but a combination of tidal currents and vessel wakes could lead to measurable transport. Cherry Point currents were also found to be too weak to move larger gravel tracers. The fact that sediment as small as 1.6 cm in diameter is not moved by currents (even high speed currents, reaching over 1 m/s) at Bainbridge Island supports this interpretation. There are no notable ferry vessel wakes at Cherry Point, so all elevated wave energy is generated by winds. Thus, gravel transport during non-winter conditions will likely still be controlled by the presence of wind speeds over 4 m/s from directional sources with greater than 0.5 km fetch distance.

Miller et al. [2011], a study of the Elwha River Delta, is the most recent mixed sand and gravel beach study in Washington. Particles ranging from 3.2 cm to 25.6 cm were tagged using PIT tags. Transport was observed at three different sites around the delta, over eight one-day periods and one two-day deployment. Five deployments took place in August (three in 2008, two in 2009), three in February (2009) and one in April (2009). The largest recorded Hm0 at the delta was 2.0 m during a winter storm in April. Particle tracers at this study showed major movement, with all tracers mobile under most wave conditions, and reached velocities of up to 100 m/day during winter wave conditions.

Miller et al. [2011] paid special attention to the width and depth of the active beach layer. They found that an increase in the angle of incidence increased transport velocity, but decreased the depth and width of the mobile layer. Unfortunately, incident wave angle was not collected at Cherry Point. Thus, it cannot be linked to vertical mixing or to transport velocity. The only information available for the Cherry Point study is wind direction. Though not a direct substitute for wave angle, wind data supports the finding that gravel movement is largest in the direction of the long-shore component of wave energy.
Miller et al. [2011] also classify the relationships between particle size in both ‘winter’ and ‘summer’ conditions. Winter conditions showed that the alongshore tracer velocity was not related to tracer size. The authors hypothesize that the whole of the mixed sediment unit is moving as an active layer, and all grain sizes are moving in the long-shore direction at equal speeds. Cherry Point transport sessions support the lack of relationship between velocity and particle size, as well as the presence of an active transport layer. However, because the design of particle tracer deployments at Cherry Point was in a cross-shore line, this study found that the local active layer was compartmentalized with elevation and sections of the profile were moving faster than others (i.e. in the upper-middle and lower-upper beach zones) (Figure 65). Because consistent vertical mixing in these zones is lacking at Cherry Point, it is not likely that there is an active layer on the beach during all transport sessions. Summer conditions at the Elwha Delta favor sediment movement that is inversely related to clast size. Because gravel transport at Cherry Point was only monitored during winter months, it is not possible to compare their findings to summer conditions on the beaches of the Cherry Point Aquatic Reserve.

Figure 65: An example of compartmentalized tracer transport in the middle and upper beach. Bell curve transport ‘envelope’ shown in green, critical water level shown in red.
5.3(c) Beach Protection & the Potential Effects of Sea Level Rise

None of these other studies observe the severe segregation of gravel transport zones in the lower and upper beach. The relationship between wave energy and elevation in the low beach at Cherry Point may be unique, but the presence of this coarse, un-moving sediment plays an important role in shoreline processes at the Aquatic Reserve. As previously discussed, within the lower beach shallow water over the platform acts as a buffer between wave forcing and beach sediment. As a result, pebbles and cobbles in the lower beach are not relocated, and remain relatively stationary even during high energy winter storms. Barnacles and other sea life start to grow on this relatively inactive portion of the beach. Because these coarse sediment clasts do not move over time, this lower section of beach gives a degree of protection to the upper beach and bluff.

With the potential onset of climate change and sea level rise, the balance between water levels and this portion of the beach may shift. As sea level rises over time, the ‘critical water level’ will be reached more frequently. The middle and upper beach will be exposed to more energy from roller waves and a higher degree of wave forcing. This wave-beach interaction will also last longer, supporting increased coarse-sediment transport in the upper profile of the beach. Until a net-beach drift sediment budget is calculated, it is not clear what effect this increased transport would have on the beach. If there is overall long-term net movement of coarse-sediment to the southeast, then there will likely be a net loss of upper beach pebbles and cobbles in the northwest. Since coarse sediments in the upper beach serve as a buffer, and dissipate wave energy as it crashes onto shore, removing these sediments would compromise natural protection currently in place for the bluffs. Feeder bluffs to the northwest of the study site near Point Whitehorn already contribute the most sediment in the Cherry Point reach [SMP2006]. This new exposure, combined with the onset of heightened winter storms and increasing water levels, would likely lead to massive undercutting and subsequent failure of these feeder bluffs. Not only would this rapidly compromise the natural life-span of the headland, but it would also introduce an enormous flux of fine sediment into the beach and nearshore at rapid rates. This additional sediment could potentially lead to a change in transport regime along the entire beach profile and would greatly impact the balance of the ecosystem at the Cherry Point Aquatic Reserve. Plants, bird, fish or invertebrate species that rely on the balance of coarse and fine sediment in the Reserve habitat would be affected.
5.4 Future Work

This study collected a small portion of potential data on the coarse-sediment transport regime at Cherry Point. Data presented here can be improved upon by using particle tracers to observe either single, day to day events, or long-term sediment transport over multiple seasons (particularly summer conditions). Monitoring beach profile evolution (particularly berm development), tracking the depth and width of the active beach layer (i.e. vertical mixing), or incorporating finer sediment particle tracking would also provide more information on the Cherry Point beach system.

Early versions of this thesis included the use of Light Detection and Range scanning to monitor bluff erosion over the winter months. The logistics of getting the scanner out far enough from the beach and onto the mudflats during daylight low tides proved difficult, so it was dropped from the scope of this project. However, collecting information about bluff erosion would provide details about beach sediment input for both short term timescales (bluff response to wind and wave energy), and long term timescales (summer vs. winter sediment input). Additionally, a combination of LiDAR and particle tracing could provide data on the amount of time sediment stays at the base of the bluff in post-failure debris piles.

Because historic wind, wave, tide and fetch information is publicly available, an estimate of long-term sediment transport behavior could be statistically modeled using these variables. Now that the limiting factors for wind speed, significant wave height, water levels and fetch distance have been identified for the movement of coarse sediment, historical data can be filtered to isolate the times in which gravel movement was occurring. Based on this data, a scalar would have to be applied for each storm event based on wind/wave energy and duration, fetch distance and water level in order to properly estimate sediment transport in the northwest of southeast direction. Then, when all transport over a season or a year is combined, a loose sediment budget can be estimated, and the long-term drift direction of coarse sediment may be established.

Finally, there are many ways to improve upon the modeling done in this thesis. First, XBeach is currently equipped to model wave, wind and tides in changing intervals. With the data collected during this study and an increase in computer power, models could be generated that allow for wind directional changes as often as 6 minutes or significant wave height changes every hour. Using these detailed time-step intervals does increase computational time, but in evaluating short events or
with an increase in computer memory or processing speed, this type of modeling is possible. Also, because groundwater modeling and the use of multiple sediment fractions are still in early development stages, they were not used for this study. Both would improve the quality and accuracy of our understanding of coarse sediment behavior at Cherry Point in response to oceanic and atmospheric forces. With the addition of these parameters, it may be possible to start predicting sediment transport as opposed to modeling only for the purpose of understanding physical processes affecting the beach.
CHAPTER 6: CONCLUSIONS

A particle tracing study was completed using RFID PIT tags secured in large pebbles and cobbles on the mixed sand and gravel beach of the Cherry Point Aquatic Reserve in Blaine, Washington, from mid-January to early-March 2012. These data were combined with validated wind, tide and current data from two nearby NOAA stations, as well as wave data collected from an offshore pressure sensor. These data highlight the relationships between wind speed, wind fetch distance, wave energy and tides, as well as their effect on coarse sediment transport.

Large pebble and cobble displacement requires a significant wave height of over 0.2 m. This elevated wave energy is generated by winds sourced from a fetch distance greater than 0.5 km. Winds must also meet or exceed velocities of 4 m/s. It appears that large pebble and cobble transport is almost entirely sourced by wind-generated waves. Local currents were not found to influence coarse sediment. Because of this, coarse-sediment exhibits bi-directional transport, based solely on the direction of wind-created waves. Wind-waves sourced from the southeast, south and south-southwest will push gravel laterally to the northwest. Wind-waves sourced from the north, northwest, west and west-southwest will push gravel laterally to the southeast. This transport behavior supports Bauer’s [1976] observations of bi-directional gravel sediment transport near Cherry Point, a theory that has long been overlooked in the wake of more modern studies that describe fine-sediment dominated net-shore drift [Schwartz et al. 1991, Johannessen & Chase 2006].

The extent of coarse-sediment transport is primarily controlled by the duration of elevated wave heights, which is directly linked to both storm duration and the behavior of tides. Only during high-magnitude wave-height winter storm events does increased wave energy and fetch distance show more influence on the extent of large pebble and cobble transport compared to the duration of wave energy. The largest recorded transport (52.84 m in the upper beach) was observed after a storm on February 18\textsuperscript{th}, 2012. The storm lasted 24 hours, reaching wind speeds out of the southeast (moderate fetch of 10-25 km) at 11.6 m/s and significant wave heights of 0.84 m. Two more winter storms were recorded from February 24\textsuperscript{th} – 25\textsuperscript{th}, 2012, but they occurred back to back in between field days. Therefore, the resulting cobble transport is a combination of a similar storm from the southeast (24 hours, moderate fetch of 10-25 km, peak wind speed of 15.2 but only maximum
significant wave height of 0.79 m) and a shorter (6 hour), large-fetch (50+ km), large energy (wind speeds reached 13.8 and a significant wave height of 0.96 m) storm from the west/southwest. Though cobble transport recorded during this period is less than that recorded during the February 18th storm, the assumption that cobbles should have moved to the northwest by a magnitude similar to that recorded on the 18th before being pushed back to the southeast, suggests that the highest recorded tracer movement of 46.2 m may actually represent a southeastern movement of up to 100 m during the second, high fetch storm.

During large transport events, the smallest pebble tracer moved the farthest and the largest cobble tracer moved the least. Beyond this basic relationship there was a wide range of movement for all tracer sizes. Therefore, there was not a strong correlation between coarse-sediment size and displacement magnitude. There was no relationship found between sediment shape and transport behavior.

Pebbles and cobbles in the lower beach were continuously shown to be transport-limited, regardless of wave conditions. Through modeling of a high wave-height flood tide in XBeach, a coastal numerical modeling software, a distinct difference in roller wave energy and wave forcing was found between the low beach and the middle and high beaches. Roller waves are not present in the low beach when water is rising over the lower portion of the beach profile. Instead, roller waves are breaking farther offshore and the energy observed at the lower beach is essentially the post-break, already dissipated waves. Wave forcing in both the cross-shore and lateral direction is minimal during this time as well. When water levels reach + 1.2 m above MLLW, or -0.41 m (MSL), wave forcing finally starts to increase and affect sediment at surface water level. This tide elevation may be the ‘critical water level’ needed to bring the breaking line of waves close enough to break over the beach profile. This proposed critical water level correlates to the transitional zone between the upper-lower beach and lower-middle beach. This critical level also correlates to the upper limit of the low-transport zone observed repeatedly in the transport sessions. Thus, sediments below this critical water level (especially those on the lower platform) are not exposed to the wave forces associated with breaking waves on the beach slope, and therefore do not experience the combination of lateral or cross-shore wave force, roller energy, and bed shear stress needed to move coarse-sediment. These findings could play an important role when preparing for the potential onset of sea level rise in the Georgia Strait.
This thesis provides a solid platform for more work to be done at the Cherry Point Aquatic Reserve. Specifically, tracking coarse sediment transport over summer months, measuring bluff erosion, monitoring changes in beach profile, using historic oceanic and atmospheric data to develop a long-term beach-drift sediment budget, and inclusion of a fine-sediment transport study are all potential next steps in defining total sediment transport behavior in the Aquatic Reserve.
LITERATURE CITED

LITERATURE CITED:


APPENDIX 1: PARTICLE TRACER INVENTORY
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57F
58A
58C
5A3
5B4
5BA
5C9
5CC
5D6
95C
95D
95E
95F
96D
97A

FIRST
DEPLOYED
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LAST
DENSITY LENGTH LENGTH LENGTH RELATIVE SEDIMENT
ACTIVE MASS (g) VOL (mL) (g/mL) A (cm) B (cm)
C (cm)
SIZE
CLASS
3/5/2012
162
70
2.31
5.7
4.1
4.0
XSMALL V. C. Pebble
3/5/2012
349
130
2.68
6.6
6.4
4.8
SMALL
XS Cobble
3/5/2012
1004
380
2.64
10.1
7.4
7.0
X‐LARGE
S Cobble
3/5/2012
334
120
2.78
6.7
6.1
4.7
SMALL
XS Cobble
2/14/2012
557
200
2.79
8.6
6.4
5.4
LARGE
S Cobble
3/5/2012
779
280
2.78
9.0
8.3
5.7
LARGE
S Cobble
3/5/2012
159
70
2.27
5.3
4.1
3.8
XSMALL V. C. Pebble
3/5/2012
159
70
2.27
5.5
4.9
3.5
XSMALL V. C. Pebble
3/5/2012
159
50
3.18
6.0
4.4
4.0
SMALL V. C. Pebble
3/5/2012
612
230
2.66
7.8
6.5
6.2
MEDIUM
S Cobble
3/5/2012
429
150
2.86
6.7
5.6
5.5
SMALL
XS Cobble
1/15/2012
317
110
2.88
7.6
7.0
5.4
MEDIUM XS Cobble
1/15/2012
334
180
1.86
7.5
7.4
5.0
MEDIUM XS Cobble
3/5/2012
1262
455
2.77
12.9
10.1
7.3
X‐LARGE
M Cobble
11/22/2011
528
190
2.78
8.3
8.1
6.2
LARGE
S Cobble
2/3/2012
605
220
2.75
9.4
7.8
7.5
LARGE
S Cobble
3/5/2012
572
200
2.86
7.6
7.7
5.0
MEDIUM XS Cobble
1/15/2012
201
80
2.51
6.5
6.0
3.9
SMALL
XS Cobble
3/5/2012
197
80
2.46
5.6
5.2
3.7
XSMALL V. C. Pebble
3/5/2012
1100
400
2.75
12.5
9.5
7.7
X‐LARGE
M Cobble
2/14/2012
627
240
2.61
11.0
8.4
6.2
X‐LARGE
M Cobble
11/22/2011
607
220
2.76
8.5
8.3
7.2
LARGE
S Cobble
2/14/2012
594
225
2.64
9.8
8.2
5.6
LARGE
S Cobble
2/21/2012
346
130
2.66
7.4
7.4
5.5
MEDIUM XS Cobble
3/5/2012
845
320
2.64
10.6
8.9
6.7
X‐LARGE
S Cobble
3/5/2012
223
80
2.79
6.5
4.9
3.9
SMALL
XS Cobble
2/14/2012
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7.2
6.4
LARGE
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1/16/2012
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75
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4.5
SMALL
XS Cobble
3/5/2012
1189
440
2.70
10.1
8.7
6.7
X‐LARGE
S Cobble
11/22/2011
154
45
3.42
5.6
5.0
4.2
XSMALL V. C. Pebble
3/5/2012
268
100
2.68
7.0
4.3
4.3
MEDIUM XS Cobble
3/5/2012
469
170
2.76
7.2
6.1
5.3
MEDIUM XS Cobble
3/5/2012
297
110
2.70
6.7
6.7
4.0
SMALL
XS Cobble
3/5/2012
161
60
2.68
5.9
5.0
3.9
XSMALL V. C. Pebble
2/14/2012
403
150
2.69
7.4
6.0
4.8
MEDIUM XS Cobble
3/5/2012
1114
400
2.79
10.1
7.8
6.5
X‐LARGE
S Cobble
3/5/2012
321
130
2.47
7.4
5.2
4.7
MEDIUM XS Cobble
3/5/2012
418
150
2.79
6.9
5.7
5.5
SMALL
XS Cobble
3/5/2012
380
140
2.71
6.4
6.1
5.7
SMALL
XS Cobble
3/5/2012
171
60
2.85
5.7
4.7
4.1
XSMALL V. C. Pebble
3/5/2012
528
190
2.78
8.3
8.1
6.2
LARGE
S Cobble
3/5/2012
1079
400
2.70
9.9
8.4
6.6
LARGE
S Cobble
2/18/2012
153
60
2.55
5.1
4.5
4.0
XSMALL V. C. Pebble
3/5/2012
265
100
2.65
6.3
5.2
4.4
SMALL V. C. Pebble
3/5/2012
453
160
2.83
8.0
7.4
5.9
LARGE
S Cobble
11/22/2011
224
79
2.84
6.7
6.0
3.9
SMALL
XS Cobble
2/21/2012
228
79
2.89
6.5
6.1
4.4
SMALL
XS Cobble
3/5/2012
573
210
2.73
8.6
8.5
8.3
LARGE
S Cobble
2/21/2012
284
100
2.84
6.7
6.0
5.3
SMALL
XS Cobble
1/15/2012
653
235
2.78
9.0
7.7
7.2
LARGE
S Cobble

142


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<th>FIRST DEPLOYED</th>
<th>FINAL STATUS</th>
<th>LAST ACTIVE</th>
<th>MASS (g)</th>
<th>VOL (mL)</th>
<th>DENSITY (g/mL)</th>
<th>LENGTH A (cm)</th>
<th>LENGTH B (cm)</th>
<th>LENGTH C (cm)</th>
<th>RELATIVE SIZE</th>
<th>SEDIMENT CLASS</th>
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<td>S Cobble</td>
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<td>1/15/2012</td>
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<td>S Cobble</td>
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<td>5.5</td>
<td>MEDIUM</td>
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<td>E19</td>
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<td>3/5/2012</td>
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<td>100</td>
<td>2.75</td>
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<td>6.1</td>
<td>4.2</td>
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</tr>
<tr>
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<td>3/5/2012</td>
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<td>80</td>
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<td>4.0</td>
<td>SMALL</td>
<td>XS Cobble</td>
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APPENDIX 2: CHERRY POINT VERTICAL DATUMS

*From [NOAA-TCT] 2013.*

<table>
<thead>
<tr>
<th>Datum</th>
<th>Value</th>
<th>Description</th>
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</thead>
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<td>4.721</td>
<td>Mean Higher-High Water</td>
</tr>
<tr>
<td>MHW</td>
<td>4.468</td>
<td>Mean High Water</td>
</tr>
<tr>
<td>MTL</td>
<td>3.599</td>
<td>Mean Tide Level</td>
</tr>
<tr>
<td>MSL</td>
<td>3.543</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>DTL</td>
<td>3.327</td>
<td>Mean Diurnal Tide Level</td>
</tr>
<tr>
<td>MLW</td>
<td>2.729</td>
<td>Mean Low Water</td>
</tr>
<tr>
<td>MLLW</td>
<td>1.933</td>
<td>Mean Lower-Low Water</td>
</tr>
<tr>
<td>STND</td>
<td>0.000</td>
<td>Station Datum</td>
</tr>
<tr>
<td>GT</td>
<td>2.788</td>
<td>Great Diurnal Range</td>
</tr>
<tr>
<td>MN</td>
<td>1.739</td>
<td>Mean Range of Tide</td>
</tr>
<tr>
<td>DHQ</td>
<td>0.253</td>
<td>Mean Diurnal High Water Inequality</td>
</tr>
<tr>
<td>DLQ</td>
<td>0.796</td>
<td>Mean Diurnal Low Water Inequality</td>
</tr>
<tr>
<td>HWI</td>
<td>0.79</td>
<td>Greenwich High Water Interval (in Hours)</td>
</tr>
<tr>
<td>LWI</td>
<td>7.08</td>
<td>Greenwich Low Water Interval (in Hours)</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.846</td>
<td>Highest Observed Water Level</td>
</tr>
<tr>
<td>Max Date</td>
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<td>Highest Observed Water Level Date</td>
</tr>
<tr>
<td>Max Time</td>
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</tr>
<tr>
<td>Minimum</td>
<td>0.634</td>
<td>Lowest Observed Water Level</td>
</tr>
<tr>
<td>Min Date</td>
<td>19851213</td>
<td>Lowest Observed Water Level Date</td>
</tr>
<tr>
<td>Min Time</td>
<td>07:18</td>
<td>Lowest Observed Water Level Time</td>
</tr>
<tr>
<td>HAT</td>
<td>5.282</td>
<td>Highest Astronomical Tide</td>
</tr>
<tr>
<td>HAT Date</td>
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<td>Highest Astronomical Tide Date</td>
</tr>
<tr>
<td>HAT Time</td>
<td>15:30</td>
<td>Highest Astronomical Tide Time</td>
</tr>
<tr>
<td>LAT</td>
<td>0.756</td>
<td>Lowest Astronomical Tide</td>
</tr>
<tr>
<td>LAT Date</td>
<td>19860622</td>
<td>Lowest Astronomical Tide Date</td>
</tr>
<tr>
<td>LAT Time</td>
<td>19:00</td>
<td>Lowest Astronomical Tide Time</td>
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</table>

Tidal Datum Analysis Period: 01/01/1983 - 12/31/2001
APPENDIX 3: MODEL INPUT PARAMETERS

This Appendix lists the values used in each input file associated with each of the three models. For the original files with parameters in their original format, see the DVD data depository.

**MODEL 1: LOW WAVE HEIGHT EBB TIDE**

**INPUT PARAMETERS FILE (params.txt)**

<table>
<thead>
<tr>
<th>%%% Bed composition parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 = 0.067</td>
<td></td>
</tr>
<tr>
<td>D90 = 0.101</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%%% Flow boundary condition parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>front = abs_2d</td>
</tr>
<tr>
<td>back = abs_2d</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%%% Flow parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C = 55</td>
<td></td>
</tr>
<tr>
<td>lat = 48.88</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%%% Grid parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>depfile = bed.dep</td>
<td></td>
</tr>
<tr>
<td>posdwn = 0</td>
<td></td>
</tr>
<tr>
<td>nx = 336</td>
<td></td>
</tr>
<tr>
<td>ny = 276</td>
<td></td>
</tr>
<tr>
<td>alfa = 53</td>
<td></td>
</tr>
<tr>
<td>vardx = 1</td>
<td></td>
</tr>
<tr>
<td>thetamin = 127</td>
<td></td>
</tr>
<tr>
<td>thetamax = 307</td>
<td></td>
</tr>
<tr>
<td>dtheta = 20</td>
<td></td>
</tr>
<tr>
<td>thanaut = 1</td>
<td></td>
</tr>
<tr>
<td>gridform = delft3d</td>
<td></td>
</tr>
<tr>
<td>xyfile = xy.grd</td>
<td></td>
</tr>
</tbody>
</table>

| %%% Model time       |          |
| tstop = 25920        |          |

<table>
<thead>
<tr>
<th>%%% Morphology parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>morfac = 10</td>
</tr>
<tr>
<td>wetslp = 0.1</td>
</tr>
<tr>
<td>dryslp = 1</td>
</tr>
</tbody>
</table>
%%% Tide boundary conditions
zs0 = 2.378
zs0file = tide.txt
tideloc = 1

%%% Wave boundary condition parameters
instat = jons

%%% Wave-spectrum boundary condition parameters
bcfile = jonswap
random = 1
rt = 25920
dtbc = 1

%%% Wave dissipation
break = 1
gamma = 0.55
n = 10
gammax = 2

%%% Wave roller model
roller = 1

%%% Wind parameters

%%% Sediment Transport
rhos = 2696
por = 0.45

%%% Output variables
outputformat = netcdf
tintm = 25920
tintg = 2
tstart = 0
nglobalvar = 18
zb
zs
zs0
u
v
E
n
R
D
DR
H
Fx
Fy
taubx
tauby
Sxy
Syy
Sxx

**INPUT TIDE FILE (tide.txt)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Tide</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>2.378</td>
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<tr>
<td>3600</td>
<td>2.443</td>
</tr>
<tr>
<td>7200</td>
<td>2.265</td>
</tr>
<tr>
<td>10800</td>
<td>1.864</td>
</tr>
<tr>
<td>14400</td>
<td>1.338</td>
</tr>
<tr>
<td>18000</td>
<td>0.802</td>
</tr>
<tr>
<td>21600</td>
<td>0.346</td>
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<tr>
<td>25200</td>
<td>0.156</td>
</tr>
<tr>
<td>25920</td>
<td>0.153</td>
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</tbody>
</table>

**INPUT WAVE FILE (jonswap)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<td>0.3309</td>
</tr>
<tr>
<td>mainang</td>
<td>227</td>
</tr>
<tr>
<td>gammajsp</td>
<td>3.3000</td>
</tr>
<tr>
<td>s</td>
<td>20.0000</td>
</tr>
<tr>
<td>fnyq</td>
<td>.75</td>
</tr>
</tbody>
</table>
MODEL 2: LOW WAVE HEIGHT FLOOD TIDE

INPUT PARAMETERS FILE (params.txt)

%%% Bed composition parameters
D50 = 0.067
D90 = 0.101

%%% Flow boundary condition parameters
front = abs_2d
back = abs_2d

%%% Flow parameters
C = 55
lat = 48.88

%%% Grid parameters
depfile = bed.dep
posdwn = 0
nx = 336
ny = 276
alfa = 53
vardx = 1
thetamin = .127
thetamax = 307
dtheta = 20
thetanaut = 1
gridform = delft3d
xyfile = xy.grd

%%% Model time
tstop = 27360

%%% Morphology parameters
morfac = 10
wetslp = 0.1
dryslp = 1

%%% Tide boundary conditions
zs0 = 0.281
zs0file = tide.txt
tideloc = 1

%%% Wave boundary condition parameters
instat = jons
%% Wave-spectrum boundary condition parameters
bcfile = jonswap
random = 1
rt = 27360
dtbc = 1

%% Wave dissipation
break = 1
gamma = 0.55
n = 10
gammax = 2

%% Wave roller model
roller = 1

%% Wind parameters

%% Sediment Transport
rhos = 2696
por = 0.45

%% Output variables
outputformat = netcdf
tintm = 27360
tintg = 2
tstart = 0
nglobalvar = 18
zb
zs
zs0
u
v
E
n
R
D
DR
H
Fx
Fy
taubx
tauby
Sxy
Syy
Sxx

INPUT TIDE FILE (tide.txt)

1  0.281
3600  0.153
7200  0.323
10800  0.731
14400  1.313
18000  1.939
21600  2.519
25200  2.903
27360  3.001

INPUT WAVE FILE (jonswap)

Hm0    =  0.0577
fp     =  0.3061
mainang =  207
gammajsp  =  3.3000
s      =  20.0000
fnyq   =  .75
MODEL 3: HIGH WAVE HEIGHT FLOOD TIDE

%%%% Bed composition parameters
D50    = 0.067
D90    = 0.101

%%%% Flow boundary condition parameters
front  = abs_2d
back   = abs_2d

%%%% Flow parameters
C      = 55
lat    = 48.88

%%%% Grid parameters
depfile = bed.dep
posdwn = 0
nx     = 336
ny     = 276
alfa   = 53
vardx  = 1
thetamin = 127
thetamax = 307
dtheta  = 20
thetanaut = 1
gridform = delft3d
xyfile  = xy.grd

%%%% Model time
tstop  = 21600

%%%% Morphology parameters
morfac = 10
wetslp = 0.1
dryslp = 1

%%%% Tide boundary conditions
zs0    = 0.11
zs0file = tide.txt
tideloc = 1

%%%% Wave boundary condition parameters
instat = jons

%%%% Wave-spectrum boundary condition parameters
bcfile = jonswap
random = 1
rt = 21600
dtbc = 1

%%% Wave
break = 1
gamma = 0.55
n = 10
gammax = 2

%%% Wave roller model
roller = 1

%%% Wind parameters

%%% Sediment Transport
rhos = 2696
por = 0.45

%%% Output variables
outputformat = netcdf
tintm = 21600
tintg = 2
tstart = 0

nglobalvar = 18
zb
zs
zs0
u
v
E
n
R
D
DR
H
Fx
Fy
taubx
tauby
Sxy
Syy
Sxx
INPUT TIDE FILE (tide.txt)

1  0.11
21600 3.11

INPUT WAVE FILE (jonswap)

Hm0 = 0.8075
fp = 0.3155
mainang = 217
gammajsp = 3.3000
s = 20.0000
fnyq = .75
APPENDIX 4: PARTICLE TRACER TRANSPORT SESSION RESULTS

A transport ‘session’ is defined as starting at the beginning of a deployment field day and ending at the termination of the following retrieval field day. A total of sixteen transport sessions were recorded: Jan. 12th - 15th, Jan. 31st - Feb. 3rd, Feb. 3rd - 6th, 6th - 8th, 8th - 10th, 10th - 12th, 12th - 14th, 14th - 16th, 16th - 18th, 18th - 21st, 21st - 23rd, 23rd - 25th, 25th - 27th, Feb. 27th - Mar. 1st, Mar. 1st - 3rd, and 3rd - 5th. The figures and tables in this appendix offer a comprehensive review describing gravel transport and oceanic/atmospheric conditions observed during each transport session. The data sets used for all tables, graphs and maps can be found in the DVD data depository.
TRACER TRANSPORT SESSION: January 12, 2012 to January 15, 2012

DEPLOYMENT: FIELD DATE 01/12/2012 RETRIEVAL: FIELD DATE 01/15/2012
START TIME 23:02:05 START TIME 14:43:50
END TIME 23:49:50 END TIME 16:32:25

TRACER INVENTORY:

On January 12th, a line of twenty-eight tracers (described in Figure 36) was deployed from the bluff (bluff base elevation is about 1.2 m above mean sea level) to the shoreward edge of the mudflats (mudflats start at about 1.2 m below mean sea level). On the 15th, twenty-four tracers were logged, including one tracer (#957) found from an earlier beta test deployment. This tracer was removed from the beach at the end of the field day. Four tracers were permanently lost, all from the upper beach and adjacent to or just down-beach from the base station. One tracer, #977, was not logged due to tidal constraints.

Table A4.1: TRACER TRANSPORT DATA; JANUARY 12-15, 2012

<table>
<thead>
<tr>
<th>TAG ID</th>
<th>SIZE CLASS</th>
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<th>PRECISION (±m)</th>
<th>DISP. LESS THAN PRECISION?</th>
<th>CARDINAL DIRECTION</th>
<th>DIRECTION (deg)</th>
<th>POSITION CHANGE</th>
<th>BEACH ZONE</th>
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<td>7.24</td>
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</tbody>
</table>

Note: table only shows data for tracers logged on both field days.
Figure A4.1 (following page): Physical Environment January 12-15, 2012

Stacked graphs represent tidal, current and wind data during the transport session.

Tracers were left on the beach for two and a half tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.48 m above mean sea level, and likely reached the base of the bluff. This is the highest tide observed throughout the entire the duration of the gravel transport study. Due to the nature of the tides during this session, the presence of a second, lower high tide correlated with a longer ebb tide. Thus, tidal currents were moving water to the south, east and southeast for most of the day. Current speeds fluctuated between 10 and 30 cm/s to the southeast and increased speed only slightly during periods of moderate to high winds. During the first tidal cycle, winds were low to moderate (Hm0 = 0 – 4 m) and out of the northeast (<0.05 km fetch). Winds gradually increased during the second ebb tide of the first cycle before shifting from a northeasterly source to a southeast/southerly source (10-25 km fetch) during the first flood tide of the second cycle. Winds peaked at over 12 m/s out of the southwest and west (10-50 km fetch) during the first ebb tide of the second cycle.
Figure A4.1: PHYSICAL ENVIRONMENT January 12-15, 2012
Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

There is a clear distinction in transport behavior during this session between the lower beach and the middle to upper beach. Little to no tracer movement was recorded within the barnacled area (i.e. the middle-foreshore) and only slight movement (less than 1m) was recorded in the lower beach. Tracers in the middle and upper beach moved in random directions up beach, down beach and laterally. Most of the tracers in the middle beach were lost, but those recovered showed an increase in lateral displacement to the northwest, compared to the lower beach. Three of the four middle beach tracers also exhibited downslope movement. This bimodal transport (northwest, laterally and northwest, downslope) was also observed in the upper beach, but with greater displacements than the middle beach. Maximum transport reached over 13 m to the northwest, with tracer particles of all size classifications experiencing movement. Two tracers in the upper beach moved northwest and up-slope, while one anomalous tracer showed no lateral transport component, only moving downslope into the lower beach. Seven of the tracers were found buried or partially buried beneath beach sediment.
TRACER TRANSPORT SESSION: January 31, 2012 to February 3, 2012

DEPLOYMENT: FIELD DATE 01/31/2012 RETRIEVAL: FIELD DATE 02/03/2012
START TIME 18:48:00 START TIME 18:24:20
END TIME 21:03:35 END TIME 19:57:40

TRACER INVENTORY:

Tracers logged on January 15th were left out on the beach for two weeks during a hiatus in tracer logging. By January 31st, only twelve of these tracers were recovered. Three tracers were lost permanently, and nine tracers went missing but were later found during the study. Of the twelve recovered on the 31st, five do not have recorded locations. Three positions (#57A, 976, 981) were lost due to a logging malfunction, and two (#977, 5BA) tracers were under water and unreachable. Only #57A was pulled from the beach at the end of the field day due to a loose PIT tag. All other tracers were logged and left in place. Added to the eleven tracers left on the beach was a new line (Figure 37) consisting of 19 tracers. This brought the total number of tracers used for January 31st deployment to thirty.

Between January 31st and February 3rd, only two tracers were (temporarily) lost. Thirty tracers were logged on the 3rd, including one tracer (#DFB) found from an earlier beta test deployment and one tracer (#984) found from the January 12th deployment. Both of these tracers were left in place. There were no tidal restrictions on tracer logging, so all known tracer positions were recorded. Tracer #967 was pulled for a loose PIT tag at the end of the field day, leaving twenty-nine active tracers on the beach after the February 3rd field day.
Table A4.2: TRACER TRANSPORT DATA; JANUARY 31 – FEBRUARY 3, 2012

<table>
<thead>
<tr>
<th>TAG ID</th>
<th>SIZE CLASS</th>
<th>MAX DIAMETER (cm)</th>
<th>LATERAL DISPLACEMENT (m)</th>
<th>PRECISION (±m)</th>
<th>DISP. LESS THAN PRECISION?</th>
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<th>DIRECTION (deg)</th>
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Note: table only shows data for tracers logged on both field days.
Figure A4.3 (following page): Physical Environment January 31 – February 3, 2012

Stacked graphs represent tidal, current and wind data during the transport session.

Tracers were left on the beach for three tidal cycles. Within each cycle, two nearly-equivalent high tides and one low tide was recorded. The highest recorded tide was only 0.87 m above mean sea level. Thus, water levels did not reach portions of the upper beach. The ebb and flood currents are almost balanced, but flood tides slightly prevail over ebb tides. Average speeds are lower, oscillating between 0 and 20 cm/s. Winds were strongest during the second peak of the first tidal cycle, with recorded maximum speeds of about 9 m/s from the west (50 + km fetch). During the second tidal cycle, winds died off to under 3 m/s from the southeast (0.5 – 10 km fetch) during flood tide, and raised slightly to under 6 m/s from the northwest (minimal fetch) during the second high tide peak. The third tidal cycle had even weaker winds from the north (again, minimal fetch) during the first flood tide and increased to multi-directional, 7 m/s winds during the second high tide peak.
Figure A4.3: PHYSICAL ENVIRONMENT January 31 – February 3, 2012
Figure A4.4 (following page): Tracer Transport January 31 – February 3, 2012

Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

There is a clear distinction in transport behavior between upper and lower portions of the beach. Little to no movement was recorded within the middle-foreshore area, lower beach and lower portions of the middle beach. This limited movement was again in random directions up beach, down beach and laterally. Transport of pebbles and cobbles in the upper beach, however, was to the southeast with only minor movement in the downslope direction. Displacement was not large, but still notable at 7 m. All class sizes experienced transport and seven of the tracers were found buried or partially buried. The upper three tracers showed no notable movement as they were situated above high tide.
Figure A4.4  TRACER TRANSPORT: JANUARY 31 - FEBRUARY 3, 2012

TRANSPORT BEHAVIOR
- STAYED ON TOP
- BURIED

GRAVEL TRACERS
- DEPLOYED
  - X-LARGE (100-130 mm)
  - LARGE (80-99 mm)
  - MEDIUM (70-79 mm)
  - SMALL (60-69 mm)
  - XSMALL (50-59 mm)
TRACER TRANSPORT SESSION: February 3, 2012 to February 6, 2012

DEPLOYMENT: FIELD DATE 02/03/2012 RETRIEVAL: FIELD DATE 02/06/2012
START TIME 18:24:20 START TIME 19:06:30
END TIME 19:57:40 END TIME 21:18:45

TRACER INVENTORY:

Between February 3rd and February 6th, no tracers were lost. Thirty one tracers were logged on the 6th, including two tracers (#535, DFD) found from the January 31st deployment. Both of these tracers were left in place. There were no tidal restrictions on tracer logging, so all known particle positions were recorded. No tracers were pulled, leaving 31 active tracers on the beach after the February 6th field day.

Table A4.3: TRACER TRANSPORT DATA; FEBRUARY 3 - 6, 2012

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Note: table only shows data for tracers logged on both field days.
Tracers were left on the beach for three tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.13 m above mean sea level, again, not quite reaching the entire upper beach. The presence of a second, lower high tide extends the flood current duration instead of the ebb current. Thus, tidal currents were moving water to the north, west and northwest for most of the day. Average current speeds oscillated between 5 and 25 cm/s from the southeast during flood tides and increased to between 20 and 40 cm/s during ebb tides. Winds during the first cycle stayed under 3 m/s from the northeast (minimal fetch) during tidal lows and increased to about 6 m/s during tidal highs. The first peak coincides with more winds from the northeast, but the second peak records winds coming from the northwest (10 – 50+ km fetch). Winds weaken and lose any distinct directionality during the first half of both the second and third tidal cycles, but again strengthen with the onset of northwesterly winds during the second peak. Winds generally stayed under 3 m/s and were predominantly sourced from the northwest and occasionally sourced from the northeast (minimal fetch). The collection of wave data shows that despite the northwesterly, high-fetch winds, significant wave heights were small and tended to peak at only Hm0 = 0.25 m.
Figure A4.5: PHYSICAL ENVIRONMENT February 3 - 6, 2012
Very little movement is observed during this transport session. Only one tracer (#593) in the upper beach shows notable movement, with all other tracers moving less than 0.5 m. There were, however, various vertical position changes in the lower, middle and upper beach, as five tracers were unearthed and one tracer was buried. Tracer #5B4 was found within the mudflats, having previously been located in the middle beach. Given that no other tracer experienced such a large displacement, and movement of this nature (from the beach downslope and out onto the sandy mudflats) had not been observed at any point during this study, this tracer is considered artificially displaced by a non-natural force such as a park visitor or one of Cherry Point’s many sea-birds.
Figure A4.6

TRACER TRANSPORT: FEBRUARY 3 - FEBRUARY 6, 2012

TRANSPORT BEHAVIOR
- STAYED ON TOP
- BURIED
- STAYED BURIED
- UNEARTHED

GRAVEL TRACERS
- DEPLOYED
- X-LARGE (100-130 mm)
- LARGE (80-99 mm)
- MEDIUM (70-79 mm)
- SMALL (60-69 mm)
- XSMALL (50-59 mm)

LANDMARKS
- BASE STATION
- VEGETATED BLUFF
- PARK STAIRS
- BOULDERS

UPPER BEACH & BLUFF
- VEGETATED BLUFF
- BASAL DEBRIS - LOWER LIMIT
- TREE LIMBS

LOWER BEACH
- BARNACLES - UPPER LIMIT
- MUDFLATS - UPPER LIMIT
TRACER TRANSPORT SESSION: February 6, 2012 to February 8, 2012

DEPLOYMENT: FIELD DATE 02/06/2012 RETRIEVAL: FIELD DATE 02/08/2012
START TIME 19:06:30 START TIME 20:41:00
END TIME 21:18:45 END TIME 22:31:35

TRACER INVENTORY:

Between February 6th and February 8th, no tracers were lost. Thirty two tracers were logged on the 8th, including one tracer (#95C) found from the January 12th deployment. This tracer was left in place. There were no tidal restrictions on tracer logging, so all known tracer positions were recorded. No tracers were pulled, leaving thirty-two active tracers on the beach at the end of the February 8th field day.

Table A4.4: TRACER TRANSPORT DATA; FEBRUARY 6 - 8, 2012

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Note: table only shows data for tracers logged on both field days.
Figure A4.7 (following page): Physical Environment February 6 - 8, 2012

Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.25 m above mean sea level, and likely would have reached most, if not all of the upper beach and into the base of the bluff. The presence of a second, lower high tide extends the flood current duration during this transport session. Current data during this session is very spotty, but what little is recorded seems to suggest fairly balanced ebb and flood tides, oscillating between 0 and 30 m/s. The first tidal cycle coincided with winds ranging from 8 to 12 m/s from the east (minimal fetch). Winds dropped to below 6 m/s, first out of the northwest during the second peak, and then again out of the east/northeast during the first portion of the second tidal cycle. The second peak of the second cycle shows a change in wind direction to a southeasterly source with a higher fetch distance (1 -25 km), but speeds remain below 6 m/s. Wave height is minimal during the windy periods (Hm0 < 0.3 m) but showed spikes during the second peak of the both the first and second tidal cycles, where Hm0 reaches 0.19 m and 0.25 m, respectively.
Figure A4.7: PHYSICAL ENVIRONMENT February 6 - 8, 2012
Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

Very little movement is observed during this transport session. Only two tracers showed notable movement; in the upper beach, tracer (#593) traveled to the southeast and up-slope, and #5B4 in the mudflats traveled laterally to the southeast. All other tracers moved less than 0.5 m. There were various vertical position changes in the lower, middle and upper beach, as five tracers were unearthed and two tracers were buried.
TRACER TRANSPORT SESSION: February 8, 2012 to February 10, 2012

DEPLOYMENT: FIELD DATE 02/08/2012  RETRIEVAL: FIELD DATE 02/10/2012
START TIME  20:41:00     START TIME  14:04:50

TRACER INVENTORY:

Between February 8th and February 10th, no tracers were lost. Only twenty-five tracers were logged on the 10th, as the field day took place when water levels were around mean sea level. The seven tracers positioned below mean sea level (those within the middle-foreshore and mudflats) were not logged. No tracers were pulled, keeping thirty-two tracers active on the beach at the end of the February 10th field day.

Table A4.5: TRACER TRANSPORT DATA; FEBRUARY 8 - 10, 2012

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<th>PRECISION (±m)</th>
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Note: table only shows data for tracers logged on both field days.
Figure A4.9 (following page): Physical Environment February 8 - 10, 2012

*Stacked graphs represent tidal, current, wave and wind data during the transport session.*

Tracers were left on the beach for one and a half tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.39 m above mean sea level, reaching the base of the bluff. Current data during the first flood tide is missing, but the data collected for the rest of the transport session shows well balanced ebb and flood tides, oscillating between 0 and 30 m/s. Combined with little to no wave activity, and winds out of the northeast, this is considered a good representation of naturally occurring long-wave current behavior that is not influenced by winds or waves. The first tidal cycle coincides with winds ranging from 4 to 10 m/s from the northeast (minimal fetch). Then, during the first flood tide of the second cycle, winds dropped to below 4 m/s, sourced from varying directions. Winds briefly strengthened with the first flood tide of the second cycle, and were sourced from the east (again, minimal fetch). Wave height is very low throughout the transport session, even during the windy periods (Hm0 < 0.2 m).
Figure A4.9: PHYSICAL ENVIRONMENT February 8 - 10, 2012
Figure A4.10 (following page): Tracer Transport February 8 - 10, 2012

Map of local tracer transport with inset window showing tracer positions with respect to the entire study area.

There was very little movement recorded during this session. All tracers moved less than 0.5 m, with only four tracers in the middle and upper beach moving more than 10 cm. No tracers were buried and only three were unearthed in the middle and upper zones.
TRACER TRANSPORT SESSION: February 10, 2012 to February 12, 2012

DEPLOYMENT: FIELD DATE 02/10/2012 RETRIEVAL: FIELD DATE 02/12/2012
START TIME 14:04:50 START TIME 14:20:30
END TIME 15:22:45 END TIME 16:29:00

TRACER INVENTORY:

Between February 10th and February 12th, no tracers were lost. Thirty tracers were logged on the 12th, with two tracers in the lower beach (#977, 5B4) not logged due to tidal constraints. No tracers were pulled, keeping thirty-two tracers active on the beach at the end of the February 12th field day.

Table A4.6: TRACER TRANSPORT DATA; FEBRUARY 10 - 12, 2012

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<th>SIZE CLASS</th>
<th>MAX DIAMETER (cm)</th>
<th>LATERAL DISPLACEMENT (m)</th>
<th>PRECISION (±m)</th>
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<th>CARDINAL DIRECTION (deg)</th>
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Note: table only shows data for tracers logged on both field days.
Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for two total tidal cycles, starting with the second peak of one cycle and ending on the first peak of a third. Within each cycle, uniform double peaks consisting of two high tides and two nearly equivalent low tides were recorded. The highest recorded tide was 1.45 m above mean sea level, reaching the base of the bluffs. Due to the exaggerated double peak nature of the tides during this session, flood and ebb tides were well balanced and oscillated between 0 and 30 cm/s. Winds started out of the east and northeast (minimal fetch) between 6 and 9 m/s. From the final ebb tide of the first cycle to the first ebb tide of the second cycle, winds were out of the southeast (1-10 km fetch) and varied in velocity between 2 and 7 m/s. The intermediate tidal low in the second tide marked the change of wind direction from a southwesterly to a southerly source (10-25 km fetch), and a greater range of between 1 to 9 m/s. There was a temporary switch again to a southeastern source during the second ebb tide of the second cycle, and then a final change back again to winds from the south. These winds kept a consistent wind speed of about 7 m/s until the first ebb tide of the third cycle, when winds weakened to < 1.0 m/s. Wave heights correlated well with the presence of winds from the southwest and south, but peaked early (Hm0 = 0.44 m) between the first and second tidal cycle when winds were sourced from the southeast.
Figure A4.11: PHYSICAL ENVIRONMENT February 10 - 12, 2012
**Figure A4.12 (following page): Tracer Transport February 10 - 12, 2012**

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Little to no movement was recorded within the middle-foreshore, lower beach and lower portions of the middle beach. Any limited movement was in seemingly random directions up beach, down beach and laterally. Transport in the upper beach reached 5 m to the west (moved lateral and downslope) and was limited to only a thin section of the beach profile, as the two tracers on the highest portion of the upper beach showed little displacement. Vertical position changes were observed in the lower, middle and upper beach, as three tracers were found unearthed and two tracers were buried.
TRACER TRANSPORT SESSION: February 12, 2012 to February 14, 2012

DEPLOYMENT: FIELD DATE 02/12/2012 RETRIEVAL: FIELD DATE 02/14/2012
START TIME 14:20:30 START TIME 15:33:45
END TIME 16:29:00 END TIME 18:17:20

TRACER INVENTORY:

Between February 12th and February 14th, no tracers were lost. All thirty-two active tracers were logged on the 14th, as there were no limitations due to high water levels. To prepare for a new line deployment, eleven tracers were left in place, twelve tracers were pulled off the beach, and nine tracers were relocated and paired with new tracers to produce a deployment line of packaged ‘sets’ (Figure 38). Between the eleven tracers left in situ and the twenty-three tracers in the new line, thirty-four active tracers remained on the beach at the end of the February 14th field day.

Table A4.7: TRACER TRANSPORT DATA; FEBRUARY 12 - 14, 2012

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Note: table only shows data for tracers logged on both field days.
Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.35 m above mean sea level, again, reaching the base of the bluffs. Flood and ebb tides were equally represented. The first cycle showed slow current speed at less than 15 cm/s but spiked during its second ebb tide at almost 40 cm/s. The second cycle current speed was similar to past transport sessions, oscillating between 0 and 30 cm/s. Winds from the north and northeast (minimal fetch) started out very weak during the first peak of the first cycle, before switching to a stronger, northwesterly source (.5 – 50 km fetch), ranging from 6 to 8 m/s during the intermediate low tide. The second peak coincided with a shift back to a northern source and a subsequent drop in wind strength, before picking up again with a western and northwestern source (10-50+ km fetch) during the first cycle’s second ebb tide. The second tidal cycle is mostly characterized by winds from the southeast (1-10 km fetch), ranging from 2 to 7 m/s. Wave heights were at a maximum (Hm0 = 0.43 m) during the second flood tide of the first cycle, coinciding the stronger northwesterly source. Wave energy gradually decreased before strengthening slightly when winds from the southeast showed an increased southern component (10-25 km fetch).
Figure A4.13: PHYSICAL ENVIRONMENT February 12 - 14, 2012

[Graph showing data related to physical environment with various parameters such as sea level, wind speed, current speed, wave height, and fetch distance over a period from February 12 to 14, 2012.]
Little to no movement was recorded within the middle-foreshore, lower beach and lower portions of the middle beach. Any limited movement was in random directions up beach, down beach and laterally. In the upper-middle and upper beach, tracers were displaced to the south/southeast, both laterally and downslope. Transport in the upper beach reached 19.4 m laterally to the southeast. Vertical position changes were observed in the lower, middle and upper beach, as three tracers were unearthed and five tracers were buried.
TRACER TRANSPORT SESSION: February 14, 2012 to February 16, 2012

DEPLOYMENT: FIELD DATE 02/14/2012 RETRIEVAL: FIELD DATE 02/16/2012
START TIME 15:33:45 START TIME 17:35:25
END TIME 18:17:20 END TIME 19:10:40

TRACER INVENTORY:

Between February 14th and February 16th, no tracers were lost. Due to an inadequately charged battery, the lower four tracers were skipped, and only the middle and upper beach tracers logged. Of these, only the middle beach tracers and the lowest two packaged sets showed movement. Five of the seven middle beach tracers left in situ from the 14th were re-positioned into a new deployment line (Figure 41), and tracers displaced from the two lowest packaged sets were repackaged and put back in to their previous locations. Between the six tracers left in place (lowest four not logged) and the thirty-three tracers in the new deployment line, thirty-nine active tracers remained on the beach at the end of the February 16th field day.
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**Note:** table only shows data for tracers logged on both field days.

**RED BOX INDICATES PACKAGED SET**
Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 0.99 m above mean sea level, falling short of much of the upper beach. The presence of a second, lower high tide extended the flood current duration during this transport session. Thus, tidal currents were moving water to the north, west and northwest for most of the day. During the flood tide of the first cycle, currents were moving the quickly, between 20 and 50 cm/s, before falling to less than 20 cm/s for the remainder of the cycle. The second tidal cycle showed a more typical baseline velocity signature, oscillating between 0 and 30 cm/s. Winds in the first tidal cycle were typically out of the southeast and south (1-25 km fetch), and ranged from 2 to 6 m/s, with maximum speed coinciding with the second tidal peak. The second tidal cycle was split. First, winds built up strength from the east/northeast (minimal fetch) up to 7 m/s before the second high tide peak. After the peak, winds weakened from the southeast (1-10 km fetch) to about 2 m/s. Wave energy peaked during the second high tide of each tidal cycle, with the first cycle weaker (Hm0 = 0.24 m) than the second (Hm0 = 0.37 m).
Figure A4.15: PHYSICAL ENVIRONMENT February 14 - 16, 2012

- **Sea Level (m)**
- **Wave Height (m)**
- **Wind Speed (m/s)**
- **Near Surface Current Speed (cm/s)**
- **WSFO (m/s)**
- **Fetch Distance:**
  - 0-0.5km: 0.5 km
  - 0.5-1.0km: 1.0 km
  - 1.0-2.0km: 2.0 km
  - 2.0-5.0km: 5.0 km

Legend:
- N-NW-W
- S-SW-E
- NE-SW

TRACER EXPOSURE
Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

Slight (< 1 m) movement laterally and to the northwest was recorded in the middle beach tracers. The lowest packaged set showed smaller diameter particle tracers moving farther than the larger particle tracers. The second lowest packaged set was only somewhat displaced, and the rest of the deployed sets showed no movement. Nearly all tracers maintained their vertical position. Only tracer #976 in the middle beach was unearthed.
Figure A4.16  TRACER TRANSPORT: FEBRUARY 14 - FEBRUARY 16, 2012

TRANSPORT BEHAVIOR
- STAYED ON TOP
- STAYED BURIED
- UNEARTHED

GRAVEL TRACERS
- DEPLOYED
  - X-LARGE (100-130 mm)
  - LARGE (80-99 mm)
  - MEDIUM (70-79 mm)
  - SMALL (60-69 mm)
  - XSMALL (50-59 mm)
- PACKAGED SET

LANDMARKS
- BASE STATION
- PARK STAIRS
- BOULDERS

UPPER BEACH & BLUFF
- VEGETATED BLUFF
- BASAL DEBRIS - LOWER LIMIT
- TREE LIMBS

LOWER BEACH
- BARNACLES - UPPER LIMIT
- MUDDYFLATS - UPPER LIMIT

Scale: 12.5, 25, 50 Meters
TRACER TRANSPORT SESSION: February 16, 2012 to February 18, 2012

DEPLOYMENT: FIELD DATE 02/16/2012 RETRIEVAL: FIELD DATE 02/18/2012
START TIME 17:35:25 START TIME 19:00:20
END TIME 19:10:40 END TIME 22:33:30

TRACER INVENTORY:
Between February 16th and February 18th, one tracer (#5CC) was permanently lost. The remaining active thirty-eight tracers were logged, plus an additional seven tracers were found from past deployments (#E0A, 96D, 983, 97C, E15, E1A, 95E). There were no tidal restrictions on tracer logging, so all known tracer positions were recorded. Four of the seven found tracers (#97C, E15, E1A, 95E) were pulled from the beach at the end of the day, leaving forty-one active tracers left on the beach for the next transport session.

Table A4.9: TRACER TRANSPORT DATA; FEBRUARY 16 - 18, 2012

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Note: table only shows data for tracers logged on both field days.
Figure A4.17 (following page): Physical Environment February 16-18, 2012

Stacked graphs represent tidal, current and wind data during the transport session.

Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two nearly equivalent low tides were recorded. The highest recorded tide was 1.24 m above mean sea level, and likely reached most of the upper beach. The presence of a second, lower high tide extended the flood current duration during this transport session. Thus, tidal currents were moving water to the north, west and northwest for most of the day. During the flood tide of the first cycle, current speed was between 10 and 35 cm/s. Currents weakened during the first ebb tide to less than 10 cm/s, before strengthening during the second half of the second ebb tide. The second tidal cycle had stronger currents, reaching 40 cm/s during the first flood tide and 30 cm/s during the second flood tide before weakening to between 0 and 10 cm/s at the end of the second ebb tide. Winds started out around 2 m/s from the east/northeast (minimal fetch) and strengthened to 8 m/s during the first ebb tide of the first tidal cycle. During the second ebb tide, wind direction and speed varied widely, transitioning from easterly to southerly winds (10-25 km fetch). During the first ebb tide of the second tidal cycle, winds switched to a southwesterly source (1-10 km fetch) and increased speeds to between 6 and 8 m/s. Winds remained out of the southwest for most of the second cycle, until the final ebb tide when winds speed sharply dropped and wind changed to a northeastern (minimal fetch) source. Wave energy started out minimal (Hm0 < 0.2 m) during the first tidal cycle, but started to build by the second ebb tide. The second tidal cycle coincided with the largest wave energy yet recorded, maxing out after the first ebb tide, when Hm0 = 0.82 m, and Hmax = 1.75 m. Wave energy abruptly weakened back to Hm0 < 0.2 m during the second ebb tide of the second tidal cycle.
Figure A4.17: PHYSICAL ENVIRONMENT February 16 - 18, 2012
Figure A4.18 (following page): Tracer Transport February 16-18, 2012

Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

Nearly all tracers showed significant displacement to the northwest. The upper beach saw the most movement, with over half of the tracers exceeding 20 m. The largest displacement was 52.8 m to the northwest and downslope. Only one tracer (#E12) in the upper beach showed minimal movement of less than 2 m. In the middle beach, tracers saw slightly less movement than the upper beach, maxing out at 24.1 m. Tracers on the lower beach from the new deployment showed moderate movement (< 5 m), but the two tracers previously left in situ (#568, 976) showed the least amount of movement (< 1 m). Fourteen middle and upper beach tracers were buried during transport.
TRACER TRANSPORT SESSION: February 18, 2012 to February 21, 2012

DEPLOYMENT: FIELD DATE 02/18/2012 RETRIEVAL: FIELD DATE 02/21/2012
START TIME 19:00:20 START TIME 20:53:15
END TIME 22:33:30 END TIME 00:19:00

TRACER INVENTORY:

Between February 18th and February 21st, two tracers (#EOA, 96D) were permanently lost. Because tracers were spread out over 50+ m of beach, the lower four tracers were skipped in the interest of time. The other thirty five active tracers were logged. All tracers from the February 16th deployment line were then collected and repositioned in the same line order as the 16th deployment (Figure 42). The six tracers left in situ on the 16th (the four lowest and # 976, 568) were again left in place and not repositioned. No tracers were pulled, leaving thirty-nine active tracers on the beach at the end of the February 21st field day.
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Note: table only shows data for tracers logged on both field days.
Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for three tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.27 m above mean sea level, reaching much of the upper beach. Flood and Ebb currents were equally represented during these tidal cycles and follow the typical range in speed from 0 to 30 cm/s, except during the first flood tides of the first and third tidal cycle. During these stronger flood currents, maximum speeds ranged between 45 and 55 cm/s. Winds started out generally sourced from the southeast (1-10 km fetch) at a moderate-low speed of less than 4 m/s. A change in wind direction out of the north (minimal fetch) did not change wind speed. Strong winds from the southwest (25-50 km fetch) coincide with the first tidal cycle’s intermediate low tide, and decreased gradually over the second tide peak before switching back to a moderate-low energy wind (4 m/s) out of the southeast (1-10 km fetch). The second tidal cycle is characterized by moderate energy winds (4-7 m/s) from the northeast during the first peak, and less energetic, less directionally consistent winds (0-4 m/s) during the second peak. Energy picked up again during the third cycle with stronger winds from the south (10-50 km fetch) ranging from 4 to 11 m/s. Waves were strongest during the transition between the first ebb tide and second flood tide for both the first and third tidal cycle (Hm0 = 0.40 and 0.51 m, respectively). The second tidal cycle had very low wave activity (Hm0 < 0.1 m).
Figure A4.19: PHYSICAL ENVIRONMENT February 18 - 21, 2012
Figure A4.20 (following page): Tracer Transport February 18-21, 2012

Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.

Tracers in the mid and upper beach showed a range of movement to the northwest, both up and down slope. Tracer #E12, which had minimal displacement in the last transport session, traveled the farthest at 6.6 m laterally. Tracers on the lower beach near the base station showed minimal movement. Ten tracers were unearthed and six were buried, signifying extensive vertical position changes within all beach zones.
Figure A4.20  TRACER TRANSPORT: FEBRUARY 18 - FEBRUARY 21, 2012

TRANSPORT BEHAVIOR
- STAYED ON TOP
- BURIED
- STAYED BURIED
- UNEARTHED

GRAVEL TRACERS
- DEPLOYED
  - X-LARGE (100-130 mm)
  - LARGE (80-99 mm)
  - MEDIUM (70-79 mm)
  - SMALL (60-69 mm)
  - XSMALL (50-59 mm)

LANDMARKS
- BASE STATION
- PARK STAIRS
- BOULDERS

UPPER BEACH & BLUFF
- VEGETATED BLUFF
- BASAL DEBRIS - LOWER LIMIT
- TREE LIMBS

LOWER BEACH
- BARNACLES - UPPER LIMIT
- MUDFLATS - UPPER LIMIT

Scale: 0 25 50 Meters
TRACER TRANSPORT SESSION: February 21, 2012 to February 23, 2012

DEPLOYMENT: FIELD DATE(S) 02/21-22/2012 RETRIEVAL: FIELD DATE(S) 02/23/2012
END TIME 00:19:00 END TIME 00:24:20

TRACER INVENTORY:

Between February 21st and February 23rd, one tracer (#5B4) was temporarily lost. The six tracers in the lower beach were skipped in the interest of time. The other thirty-two active tracers were logged and left in place. No tracers were pulled from the beach and therefore thirty-eight active tracers remained on the beach at the end of the February 23rd field day.

Table A4.11: TRACER TRANSPORT DATA; FEBRUARY 21 - 23, 2012

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Note: table only shows data for tracers logged on both field days.
Figure A4.21 (following page): Physical Environment February 21-23, 2012

Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 1.20 m above mean sea level, reaching much of the upper beach. Flood and Ebb currents are equally represented during these tidal cycles and follow the baseline range in speed from 0 to 30 cm/s, except for a few stronger flood measurements reaching over 40 cm/s during the first flood tides of both tidal cycles. Winds during this transport session were almost exclusively out of the west and southwest (10-50 km fetch), and only varied in energy over time. The first tidal cycle winds ranged between 6 and 10 m/s, with only a brief drop in energy during the first flood tide. Winds began to weaken during the first peak of the second tidal cycle and reached as low as 0 m/s before recovering to 6 m/s during the second peak. Wave strength remained elevated (Hm0 ranging from 0.3 to 0.5 m) throughout most of the transport session, except for during the first cycle’s first flood tide and the second cycles second flood tide, when Hm0 dropped to 0.13 m and 0.05 m, respectively.
Figure A4.21: PHYSICAL ENVIRONMENT February 21 - 23, 2012
Figure A4.22 (following page): Tracer Transport February 21-23, 2012

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Transport was observed in nearly all tracers to the southeast laterally, up or down slope. The most amount of movement was observed in the lower- upper and upper- middle beach, with the longest displacement being 8.9 m. Transport distance decreased down beach and up beach from this heavy transport zone. Two tracer sets showed little to no movement, and remained packaged in the same order. All tracer sizes experienced transport and eight of the tracers were found buried, or partially buried beneath beach sediment.
Figure A4.22  TRACER TRANSPORT: FEBRUARY 21 - FEBRUARY 23, 2012

TRANSPORT BEHAVIOR
- STAYED ON TOP
- BURIED

GRAVEL TRACERS
- DEPLOYED
- X-LARGE (100-130 mm)
- LARGE (80-99 mm)
- MEDIUM (70-79 mm)
- SMALL (60-69 mm)
- XSMAALL (50-59 mm)
- PACKAGED SET

LANDMARKS  UPPER BEACH & BLUFF  LOWER BEACH
- BASE STATION  - VEGETATED BLUFF  - BARNACLES - UPPER LIMIT
- PARK STAIRS  - BASAL DEBRIS - LOWER LIMIT  - MUDFLATS - UPPER LIMIT
- BOULDERS  - TREE LIMBS
TRACER TRANSPORT SESSION: February 23, 2012 to February 25, 2012

DEPLOYMENT: FIELD DATE(S) 02/23-24/2012 RETRIEVAL: FIELD DATE 02/25/2012
START TIME 22:38:20 START TIME 11:46:30
END TIME 00:24:20 END TIME 15:13:25

TRACER INVENTORY:

Between February 23rd and February 25th, two tracers (#535, E19) were temporarily lost and one previously lost tracer (#584) was found. The four lowest tracers that had been left in place on the 23rd were again skipped in the interest of time. The remaining thirty-two active tracers were logged and again left in place. No tracers were pulled; therefore thirty-seven active tracers remained on the beach at the end of the February 25th field day.

Table A4.12: TRACER TRANSPORT DATA; FEBRUARY 23 - 25, 2012

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Note: table only shows data for tracers logged on both field days.
Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for one and a half tidal cycles. Within each cycle, two near-equivalent high tides and two near-equivalent low tides were recorded. The highest recorded tide was 1.19 m above mean sea level, reaching much of the upper beach. Despite the similarity of the three high tide peaks, flood and ebb currents are not equally represented, and the flood current is dominant. Current speeds oscillate from 0 to 20 cm/s during ebb tides and between 5 and 35 cm/s during flood tides. The transport session started out on a falling tide with moderate to low energy winds (< 6 m/s) from the southwest (10-50 km fetch). Wind direction switched to a southwesterly source (1-25 km fetch) during the first cycle’s first flood tide and wind speed strengthened. While wind velocities varied widely during the rest of the cycle (from about 5 m/s to 15 m/s), energy remained elevated and direction remained consistent. During the second ebb tide of the first cycle, wind direction changed to a southerly (10-50 km fetch) source. This slightly slowed wind speed, but velocities above 5 m/s were still maintained. During the first peak of the second cycle, winds switched to out of the west (25-50+ km fetch), increasing wind speed once again to between 10 and 15 m/s. Winds decreased by the end of the second cycle’s first ebb tide into a multi-directional highly varying wind pattern. Wave height remained high for nearly all of this transport session, with maximum Hm0 (0.79 m for the first tidal cycle, and 0.96 m for the second tidal cycle) correlating to peaks in wave velocity for both cycles.
Figure A4.23: PHYSICAL ENVIRONMENT February 23 - 25, 2012
Figure A4.24 (following page): Tracer Transport February 23-25, 2012

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Transport was observed in nearly all tracers to the southeast laterally, up or down slope. The most amount of movement was observed in the lower-upper and upper-middle beach, with the longest displacement being 46.2 m. Displacement decreased down beach (#57F showed the least amount of movement, at 1.45 m), and large displacement occurred in all tracers in the upper beach. All tracer sizes experienced transport. A significant portion of the tracers experienced vertical position change, with seventeen of the tracers buried and three tracers unearthed.
TRACER TRANSPORT SESSION: February 25, 2012 to February 27, 2012

DEPLOYMENT: FIELD DATE 02/25/2012 RETRIEVAL: FIELD DATE 02/27/2012
START TIME 11:46:30 START TIME 14:33:30
END TIME 15:13:25 END TIME 16:57:15

TRACER INVENTORY:

Between February 25th and February 27th, no tracers were lost and one previously lost tracer (#E19) was found. Positions were taken for the four lowest tracers that had not been logged since February 18th. All tracers were left in place and no tracers were pulled from the beach, leaving thirty-eight active tracers on the beach at the end of the February 27th field day.

Table A4.13: TRACER TRANSPORT DATA; FEBRUARY 25 - 27, 2012

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Note: table only shows data for tracers logged on both field days.
**Figure A4.25 (following page): Physical Environment February 25-27, 2012**

*Stacked graphs represent tidal, current, wave and wind data during the transport session.*

Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 0.83 m above mean sea level, likely missing portions of the upper beach. Reliable current data is only available for the first half of the first tidal cycle, so a balanced, low speed (0 to 20 cm/s) flood and ebb tide can only be guessed. Wind records for the first flood tide of the first cycle show scattered winds with variable speeds. From the first tidal peak until the end of the cycle, winds from the northwest/west (10-50+ km fetch) weakened from 13 m/s to 3 m/s. The second tidal cycle is characterized by winds from the northeast/east (minimal fetch) ranging between 4 m/s and 12 m/s, with the maximum velocity recorded during the first ebb tide. Wave heights were moderate-high (Hm0 reaches 0.67 m) within the first tidal cycle, but were very low (Hm0 < 0.1 m) for the second cycle.
Figure A4.25: PHYSICAL ENVIRONMENT February 25 - 27, 2012
Figure A4.26 (following page): Tracer Transport February 25-27, 2012

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Tracers in the mid and upper beach showed a range of movement to the southeast, both up and down slope. The tracer that traveled the farthest, #5A3 at 16.3 m, was the southernmost tracer on the beach before transport. In addition to tracers that did undergo transport, there were a number of tracers in the lower and middle beach and, most notably, the upper beach that showed minimal movement. Only four of the twenty-two previously buried tracers were unearthed, and an additional 3 were buried.
TRACER TRANSPORT SESSION: February 27, 2012 to March 1, 2012

DEPLOYMENT: FIELD DATE 02/27/2012 RETRIEVAL: FIELD DATE 03/01/2012
START TIME 14:33:30 START TIME 17:55:40
END TIME 16:57:15 END TIME 20:12:55

TRACER INVENTORY:

Between February 27th and March 1st, six tracers (#DF6, 57F, E1A, 974, 959, 597) were temporarily lost and one tracer (#535) was found. Tidal constraints prohibited the logging of the lowest tracer, #DF2. The remaining thirty-one logged tracers were left in place and no tracers were pulled from the beach, leaving thirty-three active tracers on the beach at the end of the March 1st field day.

Table A4.14: TRACER TRANSPORT DATA; FEBRUARY 27 – MARCH 1, 2012

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Note: table only shows data for tracers logged on both field days.
Tracer were left on the beach for three tidal cycles. Within each cycle, two high tides and two low tides were recorded. The highest recorded tide was 0.95 m above mean sea level, likely missing the highest portions of the upper beach. Current data is missing for much of the first tidal cycle, but is available for the second and third cycles. The second cycle is dominated by the flood tide (ranging 0 to 30 cm/s), whereas the third cycle is dominated by the ebb tide (0 to 50 m/s). While the two cycles appear to balance one another out, on the scale of the entire transport session, the ebb tide is more dominant. Winds during the first cycle were generally from the east (minimal fetch) and had a moderate speed (4 – 7 m/s). Briefly, during the second ebb tide of the first cycle, an influx of high energy (7-10 m/s) winds from the southeast (0.5 – 10 km fetch) punctuated the steady easterly winds. Another period of even higher wind speeds (7-14 m/s) from the south/southeast (10-25 km fetch) occurred during the intermediate low of the second cycle. The end of the second cycle coincided with a fall in wind speed and a change in source from the southeast to the northeast (minimal fetch). The remainder of the third cycle records scattered, multi-directional winds with velocities below 6 m/s. The only notable wave activity occurred at the end of the first tidal cycle and throughout the second tidal cycle when Hm0 reached up to 0.77m, corresponding to stronger wind speeds from the southeast.
Figure A4.27: PHYSICAL ENVIRONMENT February 27 – March 1, 2012
**Figure A4.28 (following page): Tracer Transport February 27 – March 1, 2012**

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Tracers in the mid and upper beach showed a range of movement to the northwest, both up and down slope. The tracer that traveled the farthest was #E19 at 16.7 m. Tracers in the high upper beach and lower beach showed minimal movement. Five tracers were unearthed, and two more tracers were buried.
TRACER TRANSPORT SESSION: March 1, 2012 to March 3, 2012

DEPLOYMENT: FIELD DATE 03/01/2012 RETRIEVAL: FIELD DATE 03/03/2012
START TIME 17:55:40 START TIME 19:42:40
END TIME 20:12:55 END TIME 22:06:25

TRACER INVENTORY:

Between March 1st and March 3rd, no tracers were lost, and the six tracers (#DF6, 57F, E1A, 974, 959, 597) lost during the previous transport session were recovered. No tidal constraints prohibited the logging of tracers, so all thirty-nine active tracers were logged and left in place at the end of the March 3rd field day.

Table A4.15: TRACER TRANSPORT DATA; MARCH 1 - 3, 2012

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Note: table only shows data for tracers logged on both field days.
Figure A4.29 (following page): Physical Environment March 1-3, 2012

Stacked graphs represent tidal, current, wave and wind data during the transport session.

Tracers were left on the beach for two tidal cycles. Within each cycle, two near-equivalent high tides and two low tides were recorded. The highest recorded tide was 0.75 m above mean sea level, leaving much of the upper beach untouched. Ebb and flood currents had equal representation in the first cycle, averaging between 0 and 20 cm/s. The second tidal cycle had a stronger flood current, reaching up to 35 cm/s during the first flood tide before dropping back down to the baseline 0-20 cm/s range. Winds during this transport session were almost exclusively out of the south/southeast (1-50 km fetch), building from 4 m/s during the first flood tide of the first cycle to just under 12 m/s during the first ebb tide of the second cycle and then quickly weakened again to 4 m/s over the final ebb tide of the second tidal cycle. Wave activity was elevated \((Hm0 > 0.2 \text{ m})\) during this session, and peaked at \(Hm0 = 0.67 \text{ m}\) in conjunction with maximum wind speed.
Figure A4.29: PHYSICAL ENVIRONMENT March 1 - 3, 2012
Figure A4.30 (following page): Tracer Transport March 1-3, 2012

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Tracers in the high-middle, upper beach and lower beach showed minimal movement. Only seven tracers traveled more than 1 m, with the maximum displacement (#5BA) recorded at 2.36 m. Those that did move traveled to the northwest, both up and down slope. Four tracers were unearthed, and four tracers were buried.
TRACER TRANSPORT SESSION: March 3, 2012 to March 5, 2012

DEPLOYMENT: FIELD DATE 03/03/2012
START TIME 19:42:40
END TIME 22:06:25

RETRIEVAL: FIELD DATE 03/03/2012
START TIME 17:17:30
END TIME 20:58:05

TRACER INVENTORY:

Between March 3rd and March 5th, one tracer was permanently lost (#974). No tidal constraints interfered with tracer logging. Of the remaining thirty-eight active tracers, all were logged and then pulled from the beach, concluding the particle tracing study.

Table A4.16: TRACER TRANSPORT DATA; MARCH 3 - 5, 2012

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Note: table only shows data for tracers logged on both field days.
Tracers were left on the beach for two tidal cycles. Within each cycle, two high tides and two near-equivalent low tides were recorded. The highest recorded tide was 1.05 m above mean sea level, leaving some of the highest portions of the upper beach untouched. Though the current data are bit spotty, flood currents were more dominant during both tidal cycles. Current speed was at a baseline range of 0-20 cm/s, with peaks in flood current velocity between 30 and 45 cm/s during the first flood tide of each cycle, and the peak in ebb current velocity reaching about 35 cm/s during the second ebb tide of the second cycle. Winds out of the south and southeast (10-50 km fetch) continued to dominate during the entire first tidal cycle and the first half of the second cycle. The associated velocities with this wind ranged from 5 to 11 m/s, with a brief drop to as low as 0 m/s during the low tide in between cycles. During the second flood tide of the second cycle, winds shifted to being sourced from the west (50+ km fetch) and then the northwest (10-50 km fetch) for the rest of the tidal cycle. During this time, wind strength decreased rapidly to 2 m/s by the end of the final ebb tide. Wave activity was elevated (Hm0 > 0.2 m) for the first tidal cycle, but was stronger during the second tidal cycle, with three peaks above Hm0=0.4 m that coincided with heightened wind velocities.
Figure A4.31: PHYSICAL ENVIRONMENT March 3 - 5, 2012
Figure A4.32 (following page): Tracer Transport March 3-5, 2012

*Detailed local tracer transport and inset window show tracer positions with respect to the entire study area.*

Nine tracers traveled more than 1 m, with the maximum displacement (#5A3) recorded at 5.05 m. Many tracers in the lower, middle and upper beach showed minimal movement. Those that did move traveled to the southeast, both up and down slope. Two tracers were unearthed and two tracers were buried.
APPENDIX 5: COASTAL NUMERICAL MODEL RESULTS

This Appendix contains figures of graphs of data produced by each of the three numerical models. The first section is comprised of data from the low wave height ebb tide and the low wave height flood tide models. Figures for water level, energy, wave height, wave forcing, radiation stress and bed shear stress are shown, often including both ebb tide and flood tide data results in the same figure. The second section contains figures for water level, wave height, energy, dissipation, roller wave energy, roller dissipation, wave forcing, radiation stress and bed shear stress for the high wave height flood tide model.

Note: For more information on the parameters of each run, see Appendix 3.

For each model, the following grid (x,y) points were analyzed:

(270, 117) – dark purple  (280, 117) – yellow
(272, 117) – purple      (282, 117) – orange
(274, 117) – dark blue   (284, 117) – dark orange
(276, 117) – light blue  (286, 117) – red
(278, 117) – green       (288, 117) – pink

Figure A5.1: Position of the ten (x,y) points along profile y =117, with associated color scheme.
LOW ENERGY MODELS: February 9, 2012 to February 10, 2012

**MODEL #1:**  EBB TIDE  02/09-10/2012  **MODEL #2:**  FLOOD TIDE  02/10/2012
**DURATION**  7 HR 12 MIN  **DURATION**  7 HR 36MIN

**Figure A5.2:** Ebb & Flood Model water levels. X-cells 270 to 288 measure total water level. Line zs0 shows water level due to tides alone.

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NOTES: While both tides show similar patterns, the flood tide shows much higher energy. Also, maximum energy occurs at different places: 284 for ebb tide and 286 for flood tide.

**Figure A5.3**: Ebb & Flood Model wave energy
NOTES: The average for these waves are based on the assigned significant wave height, however there are differences in the location, magnitude and timing of the maximum wave height.
Figure A5.5: Ebb & Flood Model wave forcing in the x-direction. Positive: onshore, Negative: offshore

NOTES: The onshore/offshore component of wave forcing during flood tide is larger than during ebb tide. There is significantly less wave force magnitude at points 270, 272 and 274 (within the barnacles) compared with the rest of the beach.

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NOTES: The wave forcing in the along shore component is very similar in pattern to forcing onshore/offshore, except the along shore shows an increase in magnitude, both in the positive and negative directions.

Figure A5.6: Ebb & Flood Model wave forcing in the $y$-direction. Positive: Grid North, Negative: Grid South.
NOTES: The radiation stress observed during flood tide is much higher in magnitude than ebb tide. Generally, there is a similar pattern observed with each point, although within the barnacles (270-274) magnitude is slightly less than the rest of the beach.

Figure A5.7: Ebb & Flood Model radiation stress, principle shear stress component
NOTES: The patterns for the transverse shear stress are similar to the principle shear stress, but lower in magnitude.

**Figure A5.8:** Ebb & Flood Model radiation stress, transverse shear stress component
Ebb tide shows an offshore flow of momentum for most of the ebb tide, except in the lower beach (270-276). Flood tide shows the largest magnitude in shoreward flow of momentum.

**Figure A5.9**: Ebb & Flood Model radiation stress, ‘off-diagonal’ radiation stress component (flow of x momentum across the y-plane). Positive: onshore, Negative: offshore
Figure A5.10: Ebb & Flood Model bed shear stress. Positive: onshore, Negative: offshore

NOTES: Ebb tide shows mostly offshore, low magnitude bed shear stress. Early spikes at point 282 can be attributed to the model getting warmed up. In the lower beach, 274 (but not 270 or 272) reverses stress direction towards onshore. Flood tide shear stress is strongly onshore, until the upper beach where it shows stress magnitudes both in the onshore and offshore directions.
NOTES: Bed shear stress in the y-direction shows a similar pattern to the x-direction. Again, early spikes at point 286 can be attributed to the model getting warmed up. There is a large negative magnitude recorded during ebb tide at 274. During flood tide there is a large negative magnitude recorded at 272. Neither of these is present in the x-direction.

Figure A5.11: Ebb & Flood Model bed shear stress. Positive: Grid North, Negative: Grid South
STORM WAVE CONDITIONS MODEL: Based on recorded waves from February 18, 2012.

MODEL #3: FLOOD TIDE 02/12/2012
DURATION 7 HR

Figure A5.12: Storm Wave Condition water levels. X-cells 270 to 288 measure total water level. Line zs0 shows water level due to tides alone.

NOTES: Water rises from -1.5 m to +1.5m MLLW. Modeled waves closely follow this linear trend.

Figure A5.13: Storm Wave Conditions, wave height

NOTES: Wave pattern is consistent throughout the rise in tides. The significant wave height onshore is significantly less than what is forced at the offshore boundary.
Figure A5.14: Storm Wave Conditions, wave energy and wave dissipation

NOTES: For wave energy, all curves are a similar pattern and magnitude. The lower beach locations show slightly more energy than the upper beach. For dissipation, there is a clear difference between the lower and upper beach. The lower beach is very low in dissipation (minimum at 274 and 276). The middle beach shows the highest dissipation (at 282).
NOTES: Curves for both roller energy and roller dissipation are similar to overall wave dissipation. Roller energy is highest in the upper beach and low to moderate in the lower and middle beach, with the lowest energy occurring at points 274 and 276. Roller dissipation shows a similar pattern to roller energy.
NOTES: There is a significant difference in onshore/offshore wave forcing between the lower beach/mudflats and the beach slope. The lower beach experiences low magnitude positive forces when waves are first approaching the beach. The beach slope, beginning at point 278, experiences much stronger positive forces. Each point in the upper beach shows strong onshore wave forces as soon as water level reaches the point's elevation. The force remains strong for a period before dwindling, and alternating between positive (onshore) and negative (offshore) forces. The magnitude of the point's initial positive wave force increases with elevation.

Figure A5.16: Storm Wave Conditions, wave forcing in the x-direction. Positive: onshore, Negative: offshore
NOTES: The curve signature for lateral wave forcing is very similar to onshore/offshore wave forcing, however lateral forcing is larger both in the positive and negative direction.

Figure A5.17: Storm Wave Conditions, wave forcing in the y-direction. Positive: Grid North, Negative: Grid South
Figure A5.18: Storm Wave Conditions, principle and transverse components of radiation stress

NOTES: The curves for principle and transverse radiation stress are very similar, but principle stress is nearly four times as large as the transverse component.
NOTES: The primary direction of the off-diagonal radiation stress is onshore for each point immediately after exposed to water. This increases in magnitude for a period before diminishing and oscillating back and forth between onshore and offshore momentum flow. The lower beach (270-276) experiences off-diagonal stress in a similar pattern, at about the same time. The beach slope (278-280) follows the same pattern, but there is a time delay in between each point (the time it takes water to rise and reach the elevation of each point).

**Figure A5.19:** Storm Wave Conditions, ‘off-diagonal’ radiation stress component (flow of x momentum across the y-plane). Positive: onshore, Negative: offshore
Figure A5.20: Storm Wave Conditions, bed shear stress in the x direction. Positive: onshore, Negative: offshore

NOTES: For most points, the highest onshore bed shear stress is experienced immediately following the first exposure to waves. The highest positive bed shear stress is observed in the lowest elevations on the beach (at 270-274). In this area, shear stress is high and in the onshore direction but brief, and falls quickly to low shear stress magnitudes in the offshore direction. On the beach slope, the majority of bed shear stress is in the offshore direction, with peaks of high magnitude onshore shear stress.
NOTES: Bed shear stress in the lateral direction has a different pattern than in the onshore direction. The distribution between positive and negative shear stress is more balanced, overall. In the lower beach, there is a spike in negative stress followed by a spike in positive stress. This diminishes again before building up a period of consistent, negative shear stress. Eventually, by the time water level reaches point 280, the lower beach is reduced to low magnitude stress oscillating between positive and negative. On the lower portions of the beach slope, (278-282), magnitudes are higher both in the positive direction for a period and are reduced, but never to the negative direction. The upper portions of the beach slope (284-288) show oscillations in strong magnitudes in both the positive and negative direction.
APPENDIX 6: DVD DATA DEPOSITORY FILE CATALOGUE

Particle Tracer Image Catalogue – folder with .jpeg files
XBeach Parameters List of Definitions – Delft 3D pdf
XBeach Manual - Delft 3D pdf
Quality Controlled Wind data – Microsoft Excel spreadsheet
Quality Controlled Tide data – Microsoft Excel spreadsheet
Quality Controlled Current data – Microsoft Excel spreadsheet
Quality Controlled Wave data – Microsoft Excel spreadsheet
Cobble Transport History Table – Microsoft Excel spreadsheet (Organized by Tag ID#)
Cobble Transport History Table – Microsoft Excel spreadsheet (Organized by Logging Date)
Numerical Model Outputs – folder with associated .data files