

AN ABSTRACT OF THE THESIS OF

Michael N. Styllas for the degree of Master of Science in Oceanography presented on October 29, 2001. Title: Sediment Accumulation and Human Impacts in Tillamook Bay, Oregon.

Abstract approved: \_\_\_\_\_

Paul D. Komar

Tillamook Bay is the second largest estuary on the Oregon coast, and concerns have been raised whether human induced impacts have been responsible for the perceived increase in sedimentation rates during the past century. Major land-use practices within the five watersheds of the Bay include logging, forest fires, the construction of forest roads, the placement of dikes along the channels of the main rivers and in the estuary, the removal of riparian vegetation, and the construction of jetties at the tidal inlet. Each of these practices has led to impacts on the entire ecosystem of the watersheds and the Bay, but this study focuses on the effects of human disturbances on the Bay's sediment accumulation. This study examines in detail the land-use practices that have occurred in the watersheds, on the beaches, and in the estuary, focusing on those that have had a direct impact on the sedimentation regime of the Bay. One goal of the study is to assess the relative roles of natural processes versus human impacts on the sedimentation.

A general description of the physical characteristics of Tillamook Bay and its surroundings is included, and a brief discussion is provided about the tectonic setting of the Northwest Coast, including its history of subduction earthquakes and the associated sea-level changes. Also provided is a summary of the existing information concerning the arrival of Indians and their environmental impacts, followed by a more detailed account of the major impacts that have resulted from the settlement of the Euro-Americans in the Tillamook area, in the 1850's.

The study then focuses on the description of the watersheds from a geomorphologic point of view, and the important land-use practices that may have affected sediment yields during the past century. Analyses of the hydrology of the Tillamook Bay watersheds are included, and the relations between annual water yields and total precipitation are examined in distinct time intervals, each corresponding to a different period with different amounts of land uses. The results of these hydrology analyses suggest that the Tillamook watershed gradually recovered from a period of major disturbances (from 1933 to 1955) to more normal conditions (from 1977 to 1998). In addition, this part of the study attempts to quantify the sediment transport regime of the rivers draining the watershed by using a hydraulic model that is based on the principle of stream power, and on considerations of availability of transported material. Application of this model during the 1933-1955 period for the major rivers suggests an average sediment yield on the order of 410,540 tons/year, but most important are the relative changes of the delivered sediment through time. The results of the model suggest a 1.6-factor decrease of the

amount of river sediments from the Heavily Impacted Period (1933-1955) of major disturbances to the Normal Period (1977- 1998).

The spatial variations of beach and river derived sediments throughout the Bay are determined from textural and mineralogical analyses of surface sediment samples, with the beach sands dominating the area close to the inlet and the river derived sands being mainly deposited at the southeast and northeast parts of the Bay. The relative contributions of these two major sources of sediment were found to be 60% for the marine beach and 40% for the river sands. Further attempt is made to distinguish between the sand transported into the Bay from the individual rivers, and to determine the main processes that are responsible for the dispersion of sediments within the Bay. The attempts to distinguish sands contributed by the individual rivers involved modal analyses of the frequency curves of the surface sediment samples, and the results mainly suggest a grain-size increase away from the mouth of the rivers as a result of sediment reworking by estuarine processes following its initial deposition during episodic river flooding. The main processes that control the dispersion of sediments and their deposition within the Bay were identified by using factor analysis, the results of which suggest that various estuarine processes are responsible for the observed dispersal patterns.

A brief review is provided of the study undertaken by Dr. James McManus for the collection and analyses of core samples from Tillamook Bay. Down-core geochemical analyses of major and minor elements indicate that there have been times of episodic input of marine sediment in the central and western portions of the Bay, which is a result of either periodic breaching or washover of Bayocean Spit, so

that the beach sand source was more important in the past. This episodic input of marine sand as inferred from the down-core geochemical variations was related to the most recent subduction earthquake, which occurred on January 26<sup>th</sup>, 1700.

Finally, a summary of the results and conclusions of different aspects of this study is presented, so that sedimentation in Tillamook Bay can be viewed as an integrated process involving the watersheds, the estuary, and the ocean beaches.

Sediment Accumulation and Human Impacts  
in Tillamook Bay, Oregon

by  
Michael N. Styllas

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Michael N. Styllas, Author

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# **SEDIMENT ACCUMULATION AND HUMAN IMPACTS IN TILLAMOOK BAY, OREGON**

## **1. GENERAL INTRODUCTION**

The formation of estuaries results from the interaction of numerous geophysical processes, and their classification is associated with the most dominant of those processes. One of the most widespread type of estuaries worldwide is the drowned-river estuary, formed during the past 10,000 years when the sea-level rose by about 100m, after having been lowered during the Ice Age. The mouths of the coastal rivers followed the trend of the shoreline migration, and river valleys that had eroded during the lowered sea-level were flooded by the sea level rise. Studies of relict sediments on continental shelves demonstrate that drowned-river estuaries formed following the retreat of ice caps during older ice ages as well.

Early humans were attracted by the wealth of natural resources in estuaries, and settled in their shores, establishing the first coastal communities. Later humans took advantage of the fact that estuaries are separated from the ocean by a narrow tidal inlet, and used them as natural harbors. With the settlement of humans on the coast, the first impacts appeared in the estuarine environments, resulting from their activities.

As the industrial era began, humans were able to interfere to a greater degree with the estuarine environment, shaping the natural landscape for their own benefit. One of the early problems that humans had to deal with was to maintain the tidal

inlets deep enough for navigation. Removal of deposited sediments by dredging, construction of jetties along the banks of inlets, and placement of dikes near the rivers' mouth were among the first significant environmental impacts. Extensive areas of marshes and wetlands were sacrificed to the altar of agriculture and urbanization. As the Earth's population grew, along with the needs and expectations for higher standards of living, humans turned to take advantage of the river floodplains and their upper watersheds. Logging, road construction, and consequently the use of heavy machinery in upland areas, are just a few of the major land-use practices that have affected estuaries around the world for the past hundred years or longer. The fact that the impacts of these disturbances did not appear immediately, combined with the lack of knowledge about how estuarine systems function, resulted in uncontrolled use of the estuarine resources. Today, our knowledge about estuaries allows us to better understand their nature, but the adverse human impacts have continued and remain of major importance to many coastal communities.

Sediment accumulation is one of these impacts, but unfortunately not the only one. Contamination of estuarine waters, habitat degradation for many organisms, increased water temperatures within coastal streams, complete the circle of so-called "human impacts". Sedimentation in estuaries is important from many different aspects. Sediments block navigation channels, making it difficult for commercial fishery boats to enter the harbors. Increased concentrations of suspended sediment have direct impact on both planktonic and benthic communities, since the sediments intercept the penetration of sunlight through the water column. In addition, increased

suspended sediment can carry more organic matter, the degradation of which reduces the available dissolved oxygen for the biota inhabiting estuarine waters.

Sedimentation is a natural process, but human impacts, especially within the watersheds, can result in an acceleration of sedimentation rates. A good way, if not the only, to define the extent that humans have impacted the natural sedimentation regime is to understand the short and long term cycles of the natural processes responsible for sedimentation in estuaries. The interaction of river discharge with tidal currents and wind induced wave action are the main processes that control the amount and distribution of sediments. Each of these processes has been studied separately, but their interaction is difficult to describe in detail. Superimposed on these natural processes are the human disturbances, which add one more variable to the already complex problem of sediment accumulation in estuaries. The natural complexity of the estuarine systems makes this task more difficult, and even though estuaries have been studied extensively for the past 50 years, quantitative estimates of human versus natural contributions to sedimentation still remain uncertain.

This is the case for Tillamook Bay, Oregon, where concerns have been raised whether human induced impacts are responsible for the perceived increase in sedimentation rates during the past hundred years. Major land use practices within the Tillamook Bay area include logging of the watersheds, major forest fires, generation of landslides, construction of dikes along the main rivers channels, the removal of riparian vegetation, and the construction of jetties at the tidal inlet. Each of these practices has led to impacts on the entire ecosystem, but this study focuses on the effects of human disturbances on the Bay's sediment accumulation.

The overall objective of this study is to examine in detail the dispersion of marine and fluvial sediments within Tillamook Bay, to describe the land use practices that have taken place in the watersheds and have had a direct impact on the sedimentation regime, and finally to assess the relative roles of natural processes versus human impacts affecting the sedimentation in the estuary.

Chapter 2 provides a general description of the physical characteristics of Tillamook Bay and its surroundings. There follows a brief discussion about the tectonic setting of the Northwest Coast, including its history of subduction earthquakes and the associated land-level changes. The second part of Chapter 2 summarizes the existing information concerning the arrival of Indians and their environmental impacts, and then describes in more detail the major impacts that have occurred since the arrival of Euro-Americans in the Tillamook area in the 1850's.

Chapter 3 describes the watersheds from a geomorphologic point of view, and the important land use practices that may have affected sediment yields during the past century. A summary of the main geological formations and sediments found within the watersheds is also provided. In addition, this chapter attempts to quantify the sediment transport regime of each river by using a hydraulic model based on the principle of stream power, and on considerations of availability of transported material. Analyses of the hydrology of the Tillamook Bay watersheds are also included, and empirical relationships between precipitation and river discharge are established.

Chapter 4 provides a review of the previous studies concerning sediment accumulation in Oregon and Washington estuaries. The past studies that have

focused on the Tillamook Bay sediments are presented, and their results and conclusions are discussed in more detail.

Chapter 5 establishes the spatial variations of beach and river components throughout the Bay, as determined in this study from textural and mineralogical analyses of surface sediment samples. Further attempt is made to distinguish the sand transported into the Bay from the five major rivers, and to establish the main processes that are responsible for the dispersion of riverine sediments within the Bay. The attempt to distinguish sands contributed by the individual rivers included modal analysis of the frequency curves of surface sediment samples, while determination of the depositional environments and processes from the sediment samples grain-size distributions was accomplished by using factor analysis.

Chapter 6 reviews the study undertaken by Dr. James McManus involving the collection and analyses of core samples from Tillamook Bay, and his conclusions concerning the recent history of sedimentation within the Bay. Of special interest are the major events important to sedimentation of the Bay, specifically the last subduction earthquake and the associate tsunami, which occurred three hundred years ago.

Finally, Chapter 7 summarizes the results and conclusions of the different aspects of this study, so that sedimentation in Tillamook Bay is viewed as an integrated process involving the watersheds, the estuary and the ocean beaches. Following the summary of the conclusions, suggestions are made for areas of future research needed to delineate the Bay's sediment patterns in greater detail and attempt to relate them to results obtained from research involving other disciplines such as

biology, fisheries and geochemistry. The last part of this chapter presents the general management implications of the results in terms of planning and actions that should be taken to reduce the present problems associated with excess sedimentation in Tillamook Bay.

## **2. TILLAMOOK BAY - SETTING AND HISTORY**

### **2.1 Description of the Study Area**

Tillamook Bay, Figure 2-1, located 80 km south of the Columbia River, is the second largest of the eighteen estuaries along the Oregon coast. It is a drowned-river estuary, as are the other Oregon estuaries, and covers an area of approximately 34 km<sup>2</sup> (10 km long on its N-S axis and 3-4 km wide), of which 50-60% is exposed during low tide (Percy *et al.* 1974). Tillamook Bay formed at the confluence of five coastal rivers, the Miami, Kilchis, Wilson, Trask, and Tillamook Rivers, approximately 9,000 years ago when the rising sea level inundated their valleys. It is

separated from the ocean by Bayocean Spit, a narrow sand spit about 5 km in length that extends north from Cape Meares. The Coast Range surrounds the Bay, rising more than 1,600 meters in elevation. Following its initial formation, Tillamook Bay evolved and changed shape until an equilibrium was reached between fluvial and marine processes. This dynamic equilibrium has been changing over time and depends on the rate of the sea-level rise relative to the tectonic uplift of the Northwest Coast.

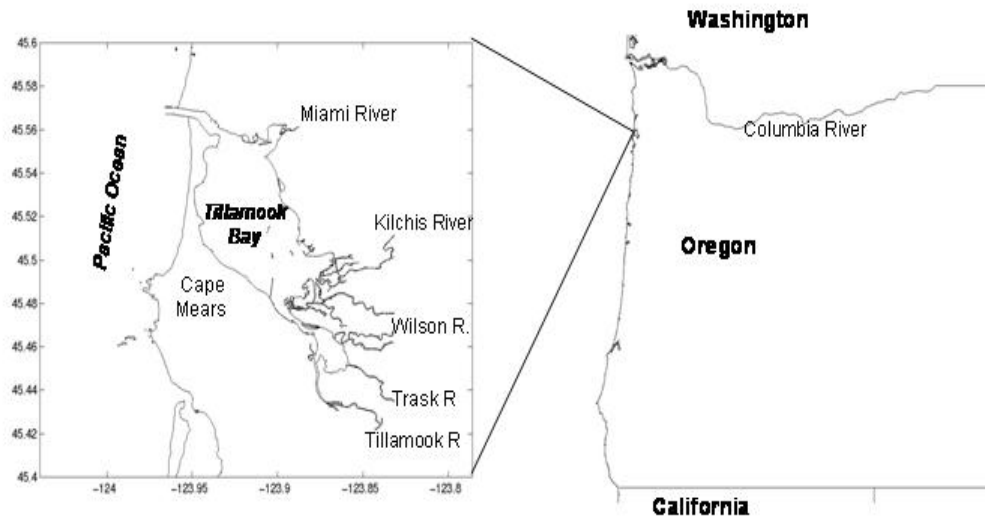


Figure 2-1. Regional setting of Tillamook Bay on the Oregon Coast.

## 2.2 The Northwest Coast

The Northwest Coast is a tectonically active area, being part of the broader Pacific margin where the oceanic lithosphere of the Juan de Fuca plate is being subducted beneath the continental crust of the North American plate (Figure 2-2). The process of subduction is accompanied by the episodic generation of major

earthquakes. As can be seen from Figure 2-2, the coastline of the Northwest lies almost parallel to the trend of the subduction zone. The continuous motion of the Juan de Fuca plate underneath the North American continent is accompanied by strain accumulation. Even though the upper crust is brittle, a certain amount of strain can be supported leading to plastic deformation of the crust and consequently to uplift or submergence of various areas in relation to the mean sea-level rise. On the far north coast of Oregon and along the south coast close to the California the tectonic uplift exceeds the sea-level rise, while along the north and central portion of the coast, including the Tillamook Bay estuary, sea-level rise exceeds land-level elevation. Moreover, when accumulated strain exceeds a threshold value, which depends on mechanical properties of the adjacent rock formations, a subduction earthquake occurs. The history of subduction earthquakes in the Northwest, as recorded in coastal sediments and fault scarps, suggests a re-occurrence period that ranges from 300 to 1000 years, with the last subduction earthquake having occurred 300 years ago. Studies that have examined the thickness of beach sands carried inland and deposited on top of marshes suggest that the last subduction earthquake generated a tsunami large enough to transport sand significant distances from the shore (Komar, 1997). These sand layers suggest that the main mechanism responsible for these deposits during subduction earthquakes is an abrupt subsidence of the coast, which is then overwashed by the generated tsunami that sweeps over the area and deposits the sand. Such layers are found in Willapa and Netarts Bay, and carbon-14 dating suggests that major subduction earthquakes have occurred along the Northwest Coast at least six times during the past 7,000 years. Studies such as Darienzo and Peterson

(1995) concluded that some of these earthquakes had magnitudes on the order of 8, possibly 9, as inferred from observations of simultaneous marsh subsidence and the thickness of tsunami sands within several estuaries of the Northwest Coast.

A more recent study (Satake *et al.*, 1996) provides evidence about the time and magnitude of the last subduction earthquake on the Northwest Coast. Based on damage reports from various sites along the Pacific Coast of Japan, the authors concluded that the height of the generated tsunami when it reached that coast was on the order of 2-3m. The authors examined historical data and applied a finite-difference model for tsunami propagation to real bathymetric data for the North Pacific Ocean. Their results suggest that the occurrence time of the earthquake was around 21:00 on 26 January 1700 and that the reported damages on the Japan Coast were caused by a tsunami generated from an earthquake with magnitude 9, which extended along the entire Cascadia zone.

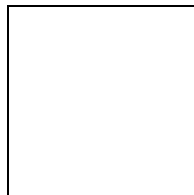


Figure 2-2. Tectonic setting of the Pacific Northwest Coast (from Komar, 1997).

### **2.3 Arrival of Indians and their Environmental Impacts**

The condition of Tillamook Bay and its surroundings prior to 1800 is not well documented because exploration of the area by Euro-Americans was sporadic, and also because it was difficult for their ships to approach the coast. The Tillamook Indians inhabited the Bay area, living in ten villages along the shoreline of the Bay and in the river delta area (Coulton *et al.* (1996)). According to carbon-14 dating, the earliest documented Native American village adjacent to Tillamook Bay is approximately 1,000 years old. Because of the abundant resources of fish, crab, oysters, berries and other plants and roots, the Tillamook Indians had no need for agriculture. When fishing was limited, hunting was undertaken in the interior of the floodplains, which were covered by trees and dense vegetation. The hunters' trails followed the river courses, which later became the trails used by the Euro-American settlers and eventually some of these trails led to the present day roads. It is believed that the Tillamook Indians limited their exploration near the tidewater portions of the Bay, without visiting the upper parts of the watersheds which were steep and heavily forested.

One environmental impact that can be attributed to the Tillamooks is the extensive burning of the areas surrounding the floodplains. Oregon pioneer Jesse

Applegate observed that the Tillamooks, along with other Native American tribes, would "burn off the whole country" late in autumn every year (Winters 1941). This resulted in the existence of prairies in both the floodplains and at higher elevations in the Tillamook watersheds, where significant areas of old growth spruce and Douglas fir were also burned. The first land use impacts in the Tillamook Bay watersheds can therefore be attributed to the Native Americans, but the extent to which these practices took place in the watersheds is not known with certainty.

#### **2.4 Arrival of Euro-Americans and their Impacts**

The first Euro-American settlers began arriving in Tillamook Bay in the middle of the nineteenth century. Until the turn of the twentieth century, the tidelands around Tillamook Bay were forested with large amounts of Sitka spruce and Western hemlock, but during World War I the increased demand for spruce resulted in extensive harvesting of the tideland forests. Increase in tree harvesting can also be attributed to the higher demand for local building needs, as the population surrounding Tillamook Bay had increased.

In summer of 1933 the Tillamook Watershed experienced one of the nation's largest fires in modern times. The Tillamook Fire burned significant acreage of Douglas fir, and was the most destructive of a sequence of fires (Table 2-1) that took place during an 18-year period, which can be considered as the most significant disturbance on the watersheds for the last hundred years.

The total burned area from the fires has been estimated to be 708 km<sup>2</sup> (Table 2-1), more than half of the total watershed area. The watersheds affected most by the multiple fires are the Kilchis, Wilson and Trask, while the Miami watershed was affected only by the 1933 and 1945 fires and the Tillamook River watershed was unaffected.

After World War II, the use of diesel powered tractors and logging machinery made even more remote upper watershed areas accessible. The construction of logging roads in the upper watersheds was initiated in the 1930's after the first Tillamook Burn, and increased significantly during World War II. As more forest roads were opened, trucks began to move thousands of board meters of timber daily during periods of peak timber harvesting. The use of mechanical bulldozers in later years allowed road building to occur on ridges having slopes up to 20 percent.

The timber harvest peak for Tillamook County coincided with the first reforestation efforts that followed the 20th century disastrous Tillamook Burns. The Tillamook Burns were the main reason for reforestation, but extensive clear cutting in the watersheds was also significant.

Table 2-1. Summary of Tillamook Burns (Tillamook Bay Task Force, 1978).

<b>FIRE NAME</b>	<b>YEAR</b>	<b>AREA BURNED (acres)</b>
Tillamook Fire	1933	239,695
Saddle Mountain Fire	1939	50,091

Wilson River & Salmonberry Fires	1945	65,150
North Fork & Elkhorn Fires (1951)	1951	32,700
Total Area burned	1933-1951	387,636

The most common logging practice in the Tillamook Bay watersheds after the 1960's has been clearcutting in patches of 40 acres. According to a comparison of MSS (Landsat Multispectral Scanner) satellite images, approximately 77.4% of the Tillamook watershed remained unchanged between 1974 and 1986, 17% experienced regrowth, and around 5.4% was clearcut (Strittholt and Frost, 1995). During this 11-year period the Tillamook watershed experienced by far the most clearcutting (22.8% of its total area). The time interval between 1986 and 1992 shows a similar pattern (Figure 2-3). The Tillamook watershed remained the main clearcutting area, with an additional 11.4% of its total area impacted. During this 6-year period, a doubling in the cutting rate occurred in the Miami and Trask watersheds (Figure 2-3).

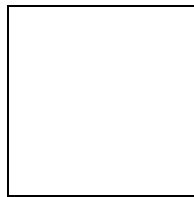


Figure 2-3. Relative areas (% of total) of clearcut for the Tillamook Bay watersheds (Strittholt and Frost, 1995).

Forest fires, clearcutting and the construction of forest roads resulted in higher surface erosion rates. Exposed soils were subjected to intense precipitation, creating landslides and resulting in changes the hydrologic response to surface runoff. Areas

that have been subjected to repetitive burnings show a degraded ability to store moisture in surface soils because of the reduction of void spaces. This results in very slow infiltration rates, and thus increased surface runoff, which enhances soil erosion and sedimentation to the rivers, especially in the upper watersheds due to their steeper slopes, thinner layers of soil, and greater amounts of precipitation.

Another important land-use practice that began in the early 1900's was the drainage and diking of the lower parts of the watersheds for flood control and the creation of farm land. A reduction of flooding meant more pastureland and thus more productive dairies. According to the USDA (1952), from 1910 to 1919 an estimated 3,423 acres of valley lands had been drained, 1,671 followed between 1920-29, and 549 acres between 1940-49 for a total of 5,643 acres (2.28 km<sup>2</sup>) between 1910 and 1949. During 1948 the Corps of Engineers began repairing the existing dikes and levees in the lowland areas of all major rivers as a flood control measure. The dikes along the Wilson and Trask Rivers were constructed from sediments that had been dredged from the river mouths. Dikes in the lower portions of the Tillamook, Trask and Wilson Rivers were primarily built to prevent pasture flooding from tidal overflow. But this was not successful during the 1964, 1972, 1996 and 2000 major floods when high waters flanked the dikes further upstream and produced widespread flooding behind diked areas, resulting in extensive damage to farms, dairy pastures and homes.

In addition to the dredging of the river sediments for dike construction, significant amounts of gravel have been removed from the reaches of the rivers for use as aggregate. From a hydraulic standpoint, both of these practices resulted in

increased streambank erosion, since the water level drops with an increase in the cross sectional area, and portions of the streambank that were previously below the water surface are now above it, losing their moisture content so that when they are subjected to higher flow velocities they are more susceptible to erosion. Gravel removal can also result in erosion of the finer sediments from the bottom of the channel, which are either deposited in the channel further downstream or in the Bay, depending on the flow characteristics.

In conclusion, human impacts in the Tillamook watershed have altered natural weathering, erosion and sediment transport processes, both in the elevated areas and in the lowlands, and have changed the spatial and temporal patterns of sediment delivery to the estuary.

## **2.6 Harbor and Jetty Construction**

Since the time of Euro-American settlement around Tillamook Bay, modifications of the natural environment were not limited to the watersheds but also included the Bay itself. Navigation to the harbors in the Bay was the main reason for human disturbances in the estuary. Soon after settlement three harbors had been developed: Garibaldi in the northeast corner of the estuary, Bay City on the eastern central shore, and Tillamook City further to the south.

Improvements for navigation eventually led to the construction of the north jetty on the entrance of Tillamook Bay, which begun in 1914 and was completed in 1917. Soon after the construction of the north jetty the first impacts on the longshore

sediment transport became apparent. The jetty blocked the longshore transport from the north, so that smaller amounts of beach sediments could reach the shore of Bayocean Spit (Komar and Terich, 1976). The northward littoral drift, which occurs during the winter months, resulted in erosion of material from the beach of Bayocean Spit, and transported it to the Bay's entrance and finally into the Bay itself. Soon after the construction of the north jetty in 1917 the navigation channel between the harbors of Tillamook City and Bay City was abandoned because it was difficult to maintain water depths sufficient for ocean boats (Tillamook Bay Environmental Characterization, 1998). The progressive erosion of Bayocean Spit led to its breaching in 1952. The gap was 1,200 m wide (1,600 m wide during high tides), and ocean swells passed into the Bay, transporting considerable quantities of beach sediments. The breach was closed in 1956 by the construction of a dike, and a second jetty was constructed on the south side of the inlet in 1974, resulting in a more stable situation for the longshore sediment transport regime in the area of Bayocean Spit (Komar and Terich, 1976).

### **3. THE WATERSHEDS – THE EFFECTS OF HUMAN IMPACTS ON RIVER HYDRAULICS AND SEDIMENT YIELDS**

#### **3.1 Introduction**

This chapter focuses on the amount of sediment derived from the Tillamook Bay watersheds, and how it may have been affected by the human impacts discussed in Chapter 2. The chapter begins with a summary of the watersheds' topographic and hydrographic characteristics. It then turns to analyses of both spatial and temporal

variability of precipitation. The relationships between precipitation and river discharge are investigated in annual time scales, and the results of those analyses are interpreted in terms of environmental impacts. The last section of this chapter focuses on the geology of the watersheds, the river sediments, and reviews the results and methods of previous sedimentation studies undertaken by other researchers. Finally, assessments of the Tillamook Bay watershed sediment yields are provided based on a different approach from the previous studies.

### **3.2 Watershed Sizes and Topographies**

The Tillamook watershed consists of five main subwatersheds that are drained by the Miami, Kilchis, Wilson, Trask and Tillamook Rivers (Figure 3-1 and Table 3-1). The Tillamook River originates on the east side of Cape Lookout and follows a north course to the Bay, while the other four rivers originate on the west slope of the Coast Range. The entire Tillamook watershed has an area of 1397 km<sup>2</sup>, of which 511 km<sup>2</sup> comprise the Wilson watershed and 460 km<sup>2</sup> the Trask watershed.

Table 3-1. General characteristics of the five watersheds.

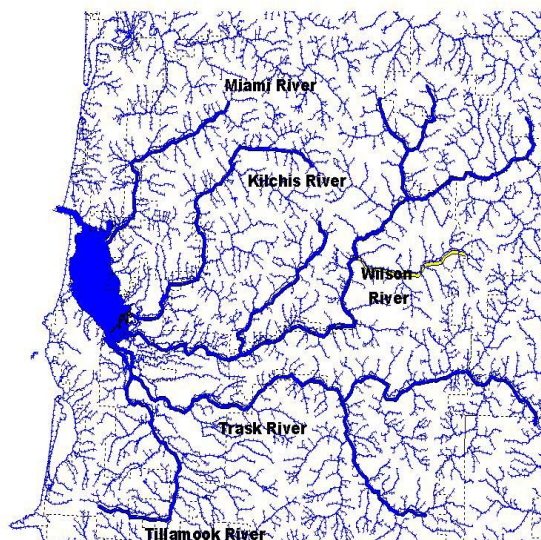
<b>River</b>	<b>Drainage<sup>a</sup> (km<sup>2</sup>) (% of total)</b>	<b>River Length<sup>b</sup> (km)</b>	<b>Annual Water Yield (x 10<sup>9</sup> m<sup>3</sup>) (% of total)</b>
<b>Miami</b>	108.8 (7.7%)	93	0.1272 (7.17%)
<b>Kilchis</b>	166.7 (11.9%)	174	0.4501 (14.87%)
<b>Wilson</b>	511.2 (36.6%)	500	1.1337 (37.46%)

<b>Trask</b>	460.8 (33.0%)	456	0.9225 (30.48%)
<b>Tillamook</b>	149.4 (10.7%)	158	0.3027 (10.00%)

<sup>a</sup> USGS, 1998

<sup>b</sup> Percy *et al.*, 1974

The five subwatersheds comprising the Tillamook Bay watershed differ in areas, slopes and hydrographic networks. These geomorphic characteristics are particularly important when evaluated in relation to certain land use practices. For example, the extensive forest fires during the 1930's and 1940's resulted in large areas of exposed soils. . Within those areas the generation of landslides is more likely to have occurred where the slopes are steeper. In general, the lower parts of the watersheds are underlain primarily by sedimentary rocks of marine origin, and the topography can be characterized as gently sloping with floodplains and rolling hills. The upper parts of the Tillamook watershed contain old volcanic rocks, and are characterized by steep slopes and v-shaped canyons.



he five main

### **3.3 Precipitation Records and Patterns**

The direct measurements of precipitation for the Tillamook watershed come mainly from a single gage (Tillamook 1W), which has operated since 1889 and is located in Tillamook City. Average monthly precipitation data for the Tillamook 1W station extend from 1889 to present, while daily records are available since 1961. Other rain gages that were established during the past are no longer in operation (Tillamook 12ESE from 01/50 to 12/51, Tillamook 13 ENE from 01/70 to 12/78). For the purpose of our study we use the available data from the Tillamook 1W station, to detect how changes in precipitation affected the discharge of the major rivers.

The amount of precipitation influences the river runoff, the number of landslides, surface erosion and thus sediment yields from the watersheds. In order to detect the extent of human impacts on the watersheds and on sedimentation, each of these processes has to be considered individually, but this would be extremely complex.

Our main interest in the climate controls on precipitation comes from the fact that in order to distinguish the effects of the land use practices over natural processes, one has to consider the long term climate trends as well. As previously discussed, during the period from 1933 to 1955 the Tillamook watershed experienced the greatest amount of human impacts (the Tillamook Burns, river channel modifications,

and peak period of logging). For this reason here, we divide the precipitation records into three periods:

1933 – 1955 Heavily Impacted Period (HIP)

1956 – 1976 Recovery Period (RP)

1977 – 1998 Normal Period (NP)

In doing this we are assuming that after a 21-year recovery period the Tillamook watershed had returned to “normal” conditions by 1977 (this is somewhat subjective since land use practices are still taking place but to a lesser extent). In this way we will be able to compare the “normal” with the “heavily impacted” periods in order to obtain a perspective about the extent of the human impacts on the watersheds. The annual averages of the precipitation for each of these periods is graphed in Figure 3-2. The patterns of the three periods are only slightly different, as summarized in Table 3-2. The means are nearly identical for the three periods as it also comes from the application of Analysis of Variance (ANOVA) for the three different periods. The HIP and NP appear to be more variable (high standard deviations), while precipitation during the RP appears to be more uniformly distributed over the length of the record.

Table 3-2. Comparison of the basic statistics of annual precipitation for the three selected periods of the precipitation record.

<b>Period</b>	<b>Mean (mm)</b>	<b>Standard Deviation (mm)</b>	<b>Number of Years Exceeding the Mean of the Record (2,263mm)</b>
<b>Heavily</b>	2,225	420.5	9

<b>Impacted</b>			
<b>Recovery</b>	2,334	310.8	14
<b>Normal</b>	2,227	403.2	9

These conclusions will be useful later in this chapter when compared with the annual watershed runoff and sediment yield values for the same time periods.

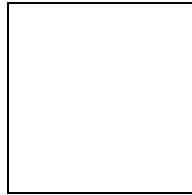


Figure 3-2. Temporal distributions of average annual rainfall for a calendar year, for the three selected periods.

### **3.4 River Discharges**

River discharge is one of the most significant hydrologic parameters since all of the sediment produced in the upper watersheds, either by natural processes or by human induced factors, is transported to the Bay by the flows of the five rivers. Wilson and Trask Rivers flow data are collected by the USGS. Wilson River flow data extend from 1931 to the present, while the Trask River data are available from 1961 to 1971 and from 1996 to the present. River discharge data for the Miami, Kilchis and Tillamook Rivers are collected by the Oregon Water Resources Department (OWRD). The OWRD gages have been operating only since 1995, so the length of available discharge data is relatively short. All of the discharge gages are located in the lower reaches of the rivers, with the Wilson River gage located 20.2

km from the Bay while the Trask River gage is located 19 km from the Bay. The USGS discharge gages collect measurements at 30-minute intervals and measurements are averaged to daily values, while the ODWR gages take measurements at 15-minute intervals.

The data sets provided by the ODWR for the Tillamook, Kilchis and Miami Rivers contain a number of small gaps. Those gaps were filled by Sullivan *et al.* (1998) by using a series of simple linear regressions, each corresponding to a period of missing data. All of the regressions were based on the Wilson River data, which is the most complete data set having no gaps. We received the complete data sets for the Miami, Kilchis and Tillamook Rivers, from 1995 to 1998, and all of the processing that follows is based on these complete data sets provided to us by Sullivan *et al.* (1998). We reduced the hourly data to daily totals for the rivers, and then ran regression analyses for each season (fall, winter, spring, summer) for the data between the Wilson (dependent variable) and the Trask, Kilchis, Miami, and Tillamook Rivers (independent variables). In this way we were able to expand the flow data for all rivers back to 1933, when the HIP and the precipitation records began. The parameters of the regression coefficients are listed in Table 3-3.

Table 3-3. Parameters (intercept, slope) and correlation coefficients for the regressions used to estimate the daily discharges ( $m^3/sec$ ) between the Miami, Kilchis, Trask, and Tillamook Rivers.

<b>River</b>	<b>Fall</b>	<b>Winter</b>	<b>Spring</b>	<b>Summer</b>
<b>Trask</b>	0.4606	5.1268	2.8140	1.2353

	0.6952 (R <sup>2</sup> =0.98)	0.7246 (R <sup>2</sup> =0.99)	0.7435 (R <sup>2</sup> =0.98)	0.7012 (R <sup>2</sup> =0.9)
<b>Kilchis</b>	1.8420 0.4637 (R <sup>2</sup> =0.96)	9.6251 0.4056 (R <sup>2</sup> =0.81)	-0.1335 0.5349 (R <sup>2</sup> =0.90)	0.0352 0.5935 (R <sup>2</sup> =0.5)
<b>Tillamook</b>	0.6573 0.1535 (R <sup>2</sup> =0.85)	2.0254 0.1339 (R <sup>2</sup> =0.93)	0.5885 0.1836 (R <sup>2</sup> =0.92)	0.0183 0.2356 (R <sup>2</sup> =0.73)
<b>Miami</b>	0.43217 0.1907 (R <sup>2</sup> =0.81)	-0.2679 0.1853 (R <sup>2</sup> =0.83)	0.3681 0.2119 (R <sup>2</sup> =0.94)	0.9401 0.2123 (R <sup>2</sup> =0.61)

The statistics of the regressions are significant for all seasons. The fact that we are able to reconstruct the daily river flows back to 1933 allows us to calculate both the monthly and annual water yields, and to use these discharge values as input into a hydraulic model that provides estimates of sediment yields.

Having extended the daily discharge values for the five rivers that drain the Tillamook watershed, we average the daily values to yield monthly values, and the monthly to annual values so we can obtain the average annual water yield for the five rivers flowing into Tillamook Bay. Even though there is a loss of information in averaging, this is the most accurate way to obtain estimates for the monthly and annual variations of the rivers. Another way to accomplish this was to regress the river flows with the daily precipitation values, but this was avoided for two reasons:

daily precipitation data contain a large number of missing values, and daily precipitation data began only in 1961, so we could not obtain any discharge estimates for the HIP.

In order to evaluate the effects of human impacts on the rivers hydraulics we derived the ratio of precipitation times the watershed area to runoff, also defined as effective precipitation. In Figure 3-3 the average annual discharge is compared with the corresponding annual precipitation for the HIP, RP, and NP, in a graph of their ratios and by regressions for the three periods. The mean value of the precipitation to runoff ratio is greater for the HIP than for the NP. Also, there is much more scatter in the data for the HIP, and as we move toward the NP the scatter progressively decreases, which can be also inferred from the  $R^2$  values of the regressions (Figure 3-3). The slopes of the regression lines for the three periods increase from the HIP towards the NP.

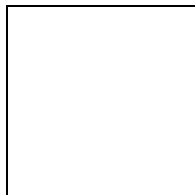


Figure 3-3. (Top) Normalized ratio between annual water yields and annual precipitation for the total length of the record. Dotted lines represent the mean of the ratio for the HIP and NP. (Bottom) Relationships between annual water yields and annual precipitation values for the three selected periods.

Thus, we can conclude that during the HIP less precipitation was required to generate a certain runoff value when compared with the other periods, leading to the conclusion that the human impacts described above had an effect on the discharge regime of the rivers entering Tillamook Bay.

There is a trend in runoff to precipitation ratio as can be observed from the means of the ratio, with the mean of the HIP being highest, and decreasing towards the NP. From the graph of Figure 3-3 it is apparent that during the HIP the annual runoff to precipitation ration displays remarkable variability, which gradually decreases towards the NP. This can be explained by the fact that the Tillamook watershed, after a period of major disturbance, returned gradually to normal conditions as reestablishment of vegetation took place simultaneously with a decrease in the amount of adverse land use impacts, resulting in more balanced runoff to precipitation ratios.

In order to be more quantitative in the comparisons, we have derived the regression equations between the annual water yields and annual precipitation values for the three different periods. For example, if we take the average mean precipitation ( $X_{1,2,3} = 2.27\text{m}$ ) of the total record and enter it in the regression equations that appear in Figure 3-3, it would yield  $Y_1 = 29.94 \times 10^9 \text{m}^3$  for the HIP,  $Y_2 = 29.15 \times 10^9 \text{m}^3$  for the RP and  $Y_3 = 27.25 \times 10^9 \text{m}^3$  for the NP, suggesting a 9.84% increase in annual water yields between NP and HIP.

### **3.5 Watershed Geology and River Sediments**

The geologic rock formations found within the Tillamook Bay watersheds vary in ages, textures and mineralogies. Their erosion releases sediments ranging in grain sizes from cobbles to sand, and fine grained silts and clays. Processes such as gully erosion, debris avalanches and landslides, forced by stream runoff and overland

flow, move these sediments through small streams into the five main rivers, and eventually into the Bay.

Important are the distributions of rock formations found in each of the five watersheds, with the steeper parts of the upper watersheds producing more sediment than the Quaternary and Tertiary deposits which are susceptible to erosion caused either by overbank flow or river channel migration. The geologic map prepared by Walker and MacLeod (1991) provides descriptions of the rock formations, but it is beyond the scope of this thesis to discuss them in detail. A detailed description of the geologic formations found within each of the five watersheds is provided by Bostrom and Komar (1997). The major rivers originate in both marine sedimentary formations and volcanic formations, but the majority of the river sediments delivered to the Bay is composed of rock fragments which are released from volcanic formations. Of interest here are the sediments found in the rivers which accordingly reflect the mineralogies of the rock formations in their watersheds. Studies that involved analyses of the non-opaque heavy minerals of the sand fractions within Tillamook Bay (Kulm *et al.*, 1968, Glenn, 1978) suggest that the derived non-opaque heavy minerals are limited almost exclusively to augite and diopside. These two minerals account for 92% and 98% of the non-opaque heavy minerals, with titanite making up most of the balance at 0 to 6%, with the Trask River containing the most (6%) according to Kulm *et al.* On the other hand, Glenn found the highest titanite concentrations in the Wilson River (17%), but included “rock fragments” in the counts. While both studies showed general agreement between rock type and river sediment mineralogies, there has not been sufficient study to establish the existence

of significant differences between the five major rivers, which could permit the tracing of sediments contributed by each river.

As part of the present study sediment samples were collected from the five rivers and were analyzed for their compositions and grain-size distributions. The samples consist almost entirely of rock fragments and small amounts of heavy minerals. Some minor amounts of quartz and feldspar were detected in the sample collected from the Miami River, and probably represent eroded material from the Quaternary deposits. The grain-size distributions of all river samples are in the sand range and are strongly polymodal (i.e. consist of a number of sediment subpopulations with different grain-sizes), reflecting the various flow and sediment transport regimes (Figure 3-4). The gravel component is significant in the river channels as can be inferred from Figure 3-4, but not in the Bay. The methods incorporated for determining the frequency curves of the surface sediment samples collected from the rivers and the Bay are discussed in Chapter 5.

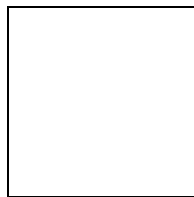


Figure 3-4. Frequency grain-size distributions of the surface sediment samples obtained from the channels of the Miami and Wilson Rivers. Both samples

are polymodal, with the Miami River sample containing a significant gravel component.

### **3.6 Previous Studies of River Sediment Yields**

There have been three previous studies that attempted to estimate the quantities of transported sediment into the Bay from the watersheds. The first attempt was made by the Tillamook Bay Task Force (USDA, 1978), and the subsequent attempts are the study by E&S Environmental Chemistry (Sullivan *et al.*, 1998) and the master thesis by Melancon (1999). In addition, there have been related studies such as that of Mills (1997), who provided estimates of the amount of eroded sediment for the Kilchis watershed resulting from erosion of forest roads and landslides.

The Tillamook Bay Task Force study (1978) provides estimates for the sediment yields of 11 different sub-basins within the Tillamook watershed. Table VII-20 in their report provides values for gross erosion, sediment yields, numbers of landslides, and road and stream miles for each sub-basin. They concluded that the East Fork Trask, the Main Trask and the upper Wilson sub-basins produce most of the sediment.

The importance of landslides on the Tillamook watershed is indicated by the study of Mills (1997), who concluded that most of the landslide generated sediment between 1995-96 was related to forest roads, and the study of Swanson *et al.* (1977) who concluded that landslides near forest roads produce almost 30 times more sediment than landslides generated within clearcuts. Even though exposed soils

during the HIP definitely resulted in higher sediment yields, we can conclude that for the NP the major human impact on the Tillamook watershed is the existence of old forest roads and the construction of a few new roads. Mills (1997) also concluded that most of the road landslides were caused by failure of the road material, and were observed on steep slopes (70-80%) near stream crossings. The road delivery of sediments to the streams was found to be 25-40% of the total produced material.

The results of the E&S Environmental Chemistry study (Sullivan *et al.*, 1998) are based on a one-year storm sampling project where the total suspended solids (TSS) were measured at two different sites for each river; the primary sites were located close to the Bay, and the secondary sites were located at the forest/agriculture interface. The total suspended sediment (mg/lit) was estimated by multiplying the measured concentrations by the discharge values. Comparisons of the derived values between two sampling sites revealed that the primary sites had consistently higher suspended load concentrations for all rivers, suggesting that the areas below the forest agriculture interface do contribute sediment to the Bay. This can be attributed to greater availability of sediment in the lower reaches of the rivers, greater bank erosion due to removal of riparian vegetation, channel erosion, and/or greater sheet erosion caused by overbank flow. This particular study did not include any grain-size analyses, and this is a limiting factor for the applicability of the results since suspended sediment is primarily composed of fine particles (silts and clays), which in the case of Tillamook Bay are efficiently flushed out through the estuary.

The results of the Melancon (1999) study are based on a GIS model that initially provides estimates of the surface runoff for each of the watersheds. The

spatial distribution of the surface runoff in the watersheds was estimated from empirical equations between annual values of precipitation and river discharge. Annual discharge values were derived by summing the daily discharge data of the Wilson and Trask Rivers as measured by the USGS gages. Annual precipitation values were extrapolated from the PRISM project at the Trask and Wilson gage locations and were regressed with the annual discharge values at the same locations. By applying the two regression equations between discharge and precipitation, together with equations that estimate the surface runoff and baseflow from the modeled discharge to the entire basin, the GIS model provides assessments of surface runoff for the entire watershed. In addition, sediment concentration profiles were calculated along the river channels from the upper watersheds to the Bay by using an Arc View extension tool. Modeled concentrations were low if only surface runoff concentrations were considered, compared with measured concentrations by Sullivan *et al.* (1998). For this reason additional sediment loads were calculated by using the average sediment concentration in runoff from dairy lands, which is 200 mg/lit (Moore, 1999), and the flow-weighted average concentration at the forest/agriculture interface, 20 mg/lit, as determined by Sullivan *et al.* (1998). This model rather oversimplifies the sediment yields from the Tillamook watershed since sediment load estimates are based on average annual discharges, which for the Miami, Kilchis and Tillamook watersheds are extrapolated from the PRISM project precipitation data which have a medium spatial resolution with each cell covering an area of 21.5 km<sup>2</sup>. The results of this study refer to the wash load, a major part of which is flushed through the Bay. Also, it is questionable if the precipitation-discharge relationships

established for the Wilson and Trask Rivers can be applied to the three other watersheds. Finally, the data provided by the PRISM project cover the time period from 1961 to 1990, excluding the HIP which is of greatest interest.

A summary of the results from the three studies is given in Table 3-4, which shows that there is an order of magnitude difference between the results of the Tillamook Bay Task Force study and the two most recent studies. This can be attributed to different methods used by the studies. In addition, the Tillamook Bay Task Force study determined the amount of sediment derived from the agricultural lands, which is equal to 9,010 tons. Even if this amount is added to the total amount of sediment derived from the upper watersheds, the sediment yields are still an order of magnitude less than the other studies. Noteworthy are the relative percentages of sediment derived from the largest subwatersheds, the Wilson and Trask. While the Tillamook Bay Task Force concludes that the Trask watershed contributes 48%, and the Wilson watershed 25% of the total derived sediment, the study by Sullivan *et al.* (1998) estimates that the Wilson watershed contributes 54.8% and the Trask watershed 32.3%, and the study by Melancon (1999) suggests 48.4% and 36.4% of the total derived sediment is contributed by the Wilson and Trask watersheds. The sediment yields estimated by these studies are average annual values, and no previous study has attempted to estimate sediment yields for different years, which is the goal of this study.

Table 3-4. Comparison of annual sediment loads (tons/year) from various studies.

<b>Watershed</b>	<b>Tillamook Bay Task Force (1978)</b>	<b>E&amp;S Environmental Chemistry</b>	<b>Texas A&amp;M (Melancon, 1999)</b>
<b>Miami</b>	2,038	16,500	14,075
<b>Kilchis</b>	4,381	53,900	44,178
<b>Wilson</b>	13,069	345,400	280,724
<b>Trask</b>	24,741	203,500	211,114
<b>Tillamook</b>	7,096	11,000	30,083
<b>Total sediment</b>	51,352	630,300	580,174

### **3.7 Assessments of Sediment Yields**

The amount of sediment transported by a river is a function of the flow velocity  $V$  and the slope of the channel  $S$ , the product of which ( $VS$ ) is defined as the stream power (Yang, 1972). There are many hydraulic models that have been used successfully to provide estimates of the amount of transported sediment through a known river cross section. Since we are interested in the amount of sand that enters the Bay from each watershed, a sediment transport model has been used that is based on the principle of stream power as defined by Yang (1972). This model that works well for grain-sizes in the sand range has been chosen because our analyses of surface sediment samples collected from the Bay suggest that most of the material transported from the rivers to the Bay is sand. Small amounts of gravel are observed near the mouths of the rivers, while the finer particles (silts and clays) are flushed out of the Bay.

Such a model is provided by Yang (1972, 1996), and is based on the fact that the quantity of transported sediment is directly related to the stream power. Applications of Yang's model in natural rivers with bed material in the sand range show very good agreement with observed values both for flows with relatively low sediment concentrations and for rivers that drain areas with high erosion rates (e.g. the Yellow River in China). The particular model takes into account incipient grain motion criteria for various flow regimes and Reynolds numbers so that the critical velocities required to entrain certain grain-sizes deposited within the channels are a function of the mean critical velocity. The use of this model for the Tillamook Bay rivers provides daily, monthly and annual sediment discharge values for time periods equal to the length of the river flow data. The main assumption in applying this model is that there is sufficient material to be transported by the river flow. This may not be true all the time for the rivers draining into Tillamook Bay, since the amount of material transported from a river during a particular storm may result in limited material available for transport during the next period of high discharge.

For the case of the Tillamook watershed, during the HIP there would have been a greater availability of material as a consequence of the high surface erosion rates, while for the RP and NP this is questionable. Even if this is true, the model can be used to obtain estimates for potential sediment yields from the five rivers during each year, contrasting the three periods.

The equations comprising the model are given by Yang (1972, 1996), but a discussion here of the input variables is necessary. The main input variables required for the model are:

- River discharge ( $Q$ )
- Cross sectional area ( $A$ ), channel depth ( $D$ ) and width ( $W$ )
- Channel slope ( $S$ )
- Kinematic viscosity ( $\nu$ )
- Sediment grain-size ( $d$ )
- Manning's roughness coefficient ( $n$ )

We were not able to obtain these data for all rivers, so a number of assumptions have been made. For the Wilson and Trask Rivers, cross-sectional area data are measured by the USGS, together with the flow velocity and estimates for the Manning's bottom roughness coefficients. The locations of those surveys are at the sites of the discharge gages. The channel slopes ( $S$ ) of the Wilson and Trask Rivers were calculated by dividing the elevation of the gage above sea-level by the distance of the gage from the Bay (MLLW), which has a zero elevation. Flow depth was calculated from the regression equations between depth and discharge provided by the USGS, so that for every discharge value we had a different value for flow depth. For grain-sizes the mean diameters of the samples that we collected from the channels of the five rivers were used. The discharges for the Trask, Tillamook, Kilchis and Miami Rivers are from the reconstructed time series, which extend from 1933 to 1998. Similar variables ( $n$ ,  $W$ ,  $D$ ) for the Kilchis River are provided by the Kilchis River Watershed Project (TBNEP, 1995-96) during which stream surveys on the tributaries and the main stem took place during the summers of 1995 and 1996. We were unable to obtain the regression between depth and discharge, so we used a constant value for depth ( $D=1.89\text{m}$ ), which is the bankfull depth for the main stem of

the Kilchis River. The cross-section areas for the three rivers are shown in Figure 3-5. These surveys provide all the required data, in contrast with the Miami and Tillamook Rivers for which such data do not exist at the time of this study.

The model was run for daily discharge values and for the hydraulic data discussed above. I then summed the values to obtain the annual sediment yields for each of the rivers, with the results given in Table 3-5 and in Figure 3-6. Again, the sediment evaluated represents the amount of sand that each of those rivers can transport through those cross-sections for the given grain-sizes. Not all of this material immediately reaches the Bay, since part of it can be deposited within the channels further downstream, or in the marshes near the deltas of the rivers as a result of overbank flow.

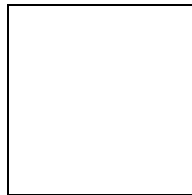


Figure 3-5. Cross-section data and velocity distributions for the three larger rivers, which were used as an input to the sediment transport model. The data for the top graphs were obtained from the USGS (1999), while the data for the Kilchis River from the Kilchis River Watershed Project (TBNEP, 1995-96).

Table 3-5. Annual loads (tons/year) for the major rivers, and the total amount of sediment that is potentially transported to the Bay.

	<b>Total load</b>	<b>Wilson River</b>	<b>Trask River</b>	<b>Kilchis River</b>	<b>Miami River</b>	<b>Tillamook River</b>
<b>Mean value</b>	410,540	285,370	75,896	49,265	?	?
<b>Maximum</b>	882,770	593,280	162,700	126,790	?	?

<b>load</b>						
<b>Minimum load</b>	105,160	70,130	22,209	11,941	?	?

A comparison of the results of our approach with the results of the study by Melancon (1999) given in Table 3-4 suggests a good agreement between the average annual sediment load of the Wilson and Kilchis watersheds, but not for the Trask. The study by Sullivan *et al.* (1998) suggests higher average annual sediment loads for the Wilson, relatively similar for the Kilchis, but much higher for the Trask, when compared with our assessments. The higher average annual load for the Wilson watershed calculated by Sullivan *et al.* (1998) is explained by the fact that their results are based on only storm sampling when sediment concentrations are high, and bias the extrapolated equations towards higher concentrations.

Of special interest are comparisons of the average annual sediment yields of the Tillamook watershed in the three time periods (HIP, RP and NP) to assess the effects of the land use practices. The results of the average annual sediment yields for the HIP is  $102.5 \times 10^5$  tons for the total 22-year period, with a mean value of 445,940 tons/year, for the RP the total is  $92.2 \times 10^5$  tons with a mean value of 439,070 tons/year, while for the NP the total is  $63.8 \times 10^5$  tons, with a mean value of 336,140 tons/year. In conclusion, during the HIP there was 1.6 times more sediment potentially transported to the Bay than during the NP, but this ratio was likely actually be greater because there was sufficiently less sediment available in the Tillamook watershed during the NP as a result of the watershed recovery and the decrease of human impacts. Further insight into the transported river sediment in the

Bay is provided in Chapter 5, where the processes that control the dispersion of fluvial sediments are analyzed, and in Chapter 6 where assessments of the amount of sediment that has been deposited in the Bay, both from the ocean beaches and the rivers, are evaluated in terms of bathymetric changes.

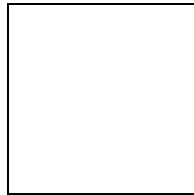


Figure 3-6. Average annual sediment yields for the Tillamook Bay watershed, as derived from the application of a sediment transport model based on the hydraulic properties of the Wilson, Trask and Kilchis Rivers.

#### **4. NORTHWEST COAST ESTUARINE SEDIMENTATION - PREVIOUS RESEARCH**

##### **4.1 Studies of Sediment Accumulation in Northwest Estuaries**

There have been several studies of sediment accumulation in Oregon and Washington estuaries, confirming that different estuaries trap fluvial sands to varying

degrees, depending on their hydraulics and other environmental conditions. This has been established by the studies of Kulm and Byrne (1966, 1967) in Yaquina Bay, by Scheidegger and Phipps (1976) in Grays Harbor, Washington, and by Peterson *et al.* (1982, 1984) in Alsea Bay and other Oregon estuaries.

One of the main goals of the studies was to identify the distance that the marine sedimentary component extends into the estuary from the inlet, or inversely the distance that fluvial sediments are deposited from the river mouths and whether riverine sand is able to pass through the estuary. In each case there a transition zone where the marine and fluvial sediments mix. The dimensions and shape of this transition zone are a function of the estuary's dimensions, river discharge, tidal range and the existence of other sources of sediment such as wind blown sand from the dunes that may cover the spit separating the ocean from the estuary.

In the case of Yaquina Bay, Kulm and Byrne (1966) were able to identify three different mechanisms of deposition. Their results demonstrate that the marine component dominates the area near the tidal inlet and extends approximately 2.5 km into the bay; the fluvial component dominates the upper reaches of the estuary near the mouth of the river. In between there is a broad "mixed" zone with varying proportions of marine and river components. Their conclusions were based on measurements of grain sizes, and in particular on heavy mineral compositions, with differences existing between the heavy minerals of the river and beach sands. Heavy minerals such as staurolite and kyanite derived from the Klamath Mountains, found in the beach but not in the river sands, were used as tracers for marine sand movement into Yaquina Bay. In addition, Kulm and Byrne (1966) used "yellow grains" to trace

the beach sands. Yellow grains are diagnostic of the marine sands, having concentrations of 10% of the light minerals, consisting of weathered feldspar and chert that is covered with iron oxide; the yellow grains are derived from erosion of marine terraces backing the ocean beach.

Peterson *et al.* (1982) found similar patterns of mixing of the beach and river sands in Alsea Bay. He employed factor analysis of the heavy mineral concentrations, together with quantitative measurements of grain rounding. Their results provided a more detailed mapping of the dispersion and transport paths of the sands in Alsea Bay. The variables inserted into their factor analysis were the concentrations of 15 non-opaque heavy minerals as derived from analyses of surface sand samples. Two factors were found to account for 95% of the total sample variance. The loadings of each factor in each sand sample represented the relative contributions of the marine versus the fluvial component. The first factor consisted almost entirely of augite derived from the Alsea River, while the second factor was composed of an array of minerals such as hypersthene, hornblende and garnet, representative of the marine component. In addition, Peterson *et al.* (1982) found distinct differences in the grain roundness of the two components, with the fluvial hornblende and augite grains being angular, while those of marine origin were rounded. The dispersal patterns of sand in Alsea Bay as derived by factor analysis and grain roundness analyses were similar, indicating that both methods can be used in defining transport paths of sediments in estuarine environments. The general patterns that were identified in Alsea Bay are similar to these found by Kulm and Byrne (1966) in Yaquina Bay, with marine sand dominating the area near the ocean

entrance, fluvial sand occurring in the upper estuary, and a broad transition zone of marine-fluviatile mixing. Furthermore, the study in Alsea Bay indicated that the marine sediment enters the bay through the tidal channels, reaching all the way to the central estuary where it is mixed with the fluvial sands, providing an assessment of the tidal current's ability to remobilize sand grains.

Similar studies have been undertaken for other estuaries of the Northwest Coast: Grays Harbor, Washington (Scheidegger and Phipps, 1976), Tillamook Bay, Siletz Bay and the estuaries of the Siluslaw and Salmon Rivers (Peterson *et al.*, 1984). Most of these studies are in agreement with the general concept that estuaries trap both fluvial and marine sands, but it has been difficult to establish the proportion of river sand that is able to pass through the inlet and become a source of beach sand. Heavy minerals derived from coastal rivers are abundant on the adjacent beaches, and may be a result of present-day fluvial transport, but more likely represents deposits that reached the beaches during lower sea level when estuaries did not exist (Clemens and Komar, 1988). Clemens and Komar (1988) analyzed the grain roundness of augite in beach samples near the Nestucca River and found that the more angular grains represent recent sediments derived from the Nestucca River, while the more rounded grains are related to relict sands. Either way, the heavy mineral concentrations found in the beaches may not be representative of the amount of river sand that presently can reach the beaches.

## **4.2 Previous Investigations of Tillamook Bay Sediments**

There have been only two previous studies that examined sediments in Tillamook Bay, the thesis work of Avolio (1973) and the USGS study of Glenn (1978). Neither study attempted to distinguish between human impacts versus natural processes. Here I briefly describe the methods they followed and their results.

Avolio (1973) collected 35 surface sediment samples from the Bay with additional samples from the beaches, the dunes on Bayocean Spit, and from the rivers entering the Bay. Grain-size distributions of the collected samples were determined by dry sieving of the sand sized fraction and pipette analyses for the finer fractions. Depositional environments for the sand, silt and clay fractions were illustrated graphically in a plot based on their percentages. Spatial distributions of these grain size fractions suggest that sand is mainly concentrated in the north portion of the Bay, close to the tidal inlet and in the channels of the main rivers at the south end. These environments experience the highest energy levels due to tidal currents and river flows, so that deposition of silt and clay is not likely. Silty sand was found in the southwestern area of the Bay, the sand representing littoral sediments transported into the Bay during the 1952-56 breaching of Bayocean Spit. At the center of the area occupied by the breach a tongue of even finer material (silty sand) existed, having accumulated in this low-energy area of the Bay since the breach was closed in 1956.

The most important study of sediments concerning the Holocene sedimentary filling of Tillamook Bay is that of Glenn (1978). Based on analyses of surface sediment samples for heavy mineral contents, Glenn was able to distinguish the main

sources of sediments in Tillamook Bay: (1) the five major rivers, (2) marine sediments carried into the Bay through the inlet and during the 1952-56 breaching of the Bayocean Spit, and (3) the small creeks draining into the Bay as well as shoreline erosion. Based on microscopic analyses, Glenn noticed the dominance of pyroxene group minerals and rock fragments in sediments from Tillamook Bay rivers. He reported that the rivers contribute mainly clinopyroxenes (diopside and augite), rock fragments, and minor amounts of orthopyroxenes (mainly hypersthene). The rock fragments are composed by two constituents, usually a feldspar and (or) a pyroxene, and a fine-grained groundmass. In addition, small amounts of amphiboles and olivine were found in the river sediments. Glenn did not find any significant compositional differences between the rivers that enter Tillamook Bay, but he noticed a progressive decrease of pyroxenes and increase of rock fragments from southern to northern rivers. The heavy minerals characteristic of the marine source of sediments are mainly rounded orthopyroxenes, and probably amphiboles. Finally, Glenn observed that in addition to compositional variations between river and marine sands, there are differences in the degree of grain rounding, with marine sands that dominate the western part of the Bay being well rounded to subrounded, while the river sands are angular to subangular.

Glenn (1978) also obtained 17 cores, 15 of which were from within the Bay and two were from the adjacent marsh lands. The cores were examined for stratigraphic variations in mineralogy, texture and color, and also were used to establish sea-level variations from radiocarbon dating of organic material.

The compositional analyses of the core samples revealed the same sources of sediments as analyses of the surface samples. Furthermore, downcore mineralogical variations provide insight into the temporal variations of the relative contributions of the three main sources. Glenn concluded that there was a transgressive-regressive sedimentation pattern in Tillamook Bay; during the regressive phases sedimentation was dominated by river and shoreline erosion deposits, while during transgressive phases marine sediments were deposited above the river sands.

Stratigraphic analyses of the cores provided significant information about the Bay's early evolution and sedimentation. The lower parts of ten cores penetrated all the way to the Oligocene-Miocene basement, which consists of consolidated weathered sandstones and siltstones with rare conglomerate layers. Pleistocene weathered gravels above less weathered gravels, sands and silts were also recovered in these cores. The boundary between Holocene and pre-Holocene deposits was found in 11 of the 17 cores, defined by changes in drilling characteristics and stratigraphy. The thickness of the sediments deposited since the formation of the Bay varies from 1 to more than 32 m, with a progressive increase in sediment thickness from the eastern margin towards the central part of the Bay.

The greatest sediment thickness was found in the deltas of the main rivers and at the western margin.

The sediments of the Holocene fill of the Bay are generally fine grained and consist of 60 % sand and 40 % silt, and follow a general downcore grain size pattern with the middle part appearing well-stratified and coarser, while the top part is sandier and less well-stratified, regardless the core location. Small fragments of

organic matter were also recovered from the cores, mainly from the river deltas, and were consisted of small wood fragments and fibrous to fine woody organic materials. Radiocarbon dates of the organic material are plotted in Figure 4-1, and are based on the analysis of cores derived from the both the Miami River delta, and the deltas of the other major rivers in the south Bay. The data show that sediments comprising the Holocene fill of the Bay have ages younger than  $8,400 \pm 400$  years B.P. Linear extrapolation of the age-depth data for the thickest sediments suggests that the Bay began to fill with sediment between about 8,600 and 9,200 years B.P. From the data shown in Figure 4-1 it can be concluded that there was a period of rapid sediment accumulation after the initial formation of the estuary to about 6,000 years B.P., (averaging approximately 1 cm/year), with sediment composed of well-stratified silts and clays. This period was followed by a subsequent slower rate of sedimentation (approximately 0.2 cm/year), beginning after 6,000 years B.P., with sediments being coarser and less well stratified.

The youngest age of dated material by Glenn (1978) is  $3,300 \pm 200$  years B.P., so that study did not document changes in sedimentation rates that may have occurred in the past 3,000 years, including the past 200 years when sedimentation rates may have been different due to human impacts.

Neither of these previous studies of Tillamook Bay sediments were able to delineate the present dispersal patterns of sediment, or to distinguish the contributions of each the five individual rivers. Moreover, neither study investigated the possible importance of human impacts on sedimentation rates, or the probable importance of subduction earthquakes, which were unknown at the times of these studies.

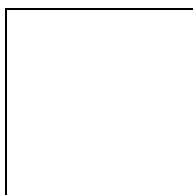


Figure 4-1. Down-core ages of sediments in the South Bay and Miami River delta regions (from Glenn, 1978).

## **5. TILLAMOOK BAY SURFACE SEDIMENTS – COMPOSITIONS, GRAIN SIZES AND DISPERSAL PATTERNS**

This chapter discusses the laboratory methods used to distinguish the main mineralogical components of surface sediments collected in Tillamook Bay, and the analyses used to derive the grain-size distributions for each component. The results indicate that the marine and fluvial sources of sediments make up almost equal contributions to sediments filling the Bay. The spatial distributions of the main mineralogical components were used to establish the general dispersal patterns of sediments in the Bay. Modal analyses of the grain-size distributions of the Bay sediments derived from the major rivers were used to classify the fluvial sands and relate certain grain-sizes to hydraulic conditions occurring within the estuary. A multivariate statistical technique was employed to provide further insight into the processes and depositional environments that control the observed grain-size

distributions of both fluvial and marine components. The results of these analyses demonstrate that sedimentary processes occurring in Tillamook Bay are complex, and the existing data and analyses cannot provide the means to distinguish between the relative contributions made to the Bay's sediments by the individual rivers.

## **5.1 Sample Collection and Analysis Techniques**

### **5.1.1 Introduction**

One hundred and six surface sediment samples were collected within the Bay, from the five rivers, and from the adjacent ocean beaches in order to provide a detailed spatial coverage (Figure 5-1). The sediment samples were returned to Oregon State University for analyses in the Sediments Laboratory of COAS. The sand and gravel fractions, representing more than 95% of the sediment, were isolated by wet sieving (less than the  $4\phi$  sieve fraction) to remove the finer sediments (silt and clay), following standard procedures (Lewis, 1984). The separation at  $4\phi$  yields the coarser fraction – sand and gravel – that is amenable to detailed grain-size analyses by sieving, which is expected to be most informative as to the sources of sediment fill

in Tillamook Bay, with differences existing between the river and marine sources in their respective grain-size distributions and compositions. The separated coarse fractions from all samples were subjected to sieving analyses, first by drying and then by splitting them down to 100-200 grams. Sieving procedures for all samples employed an array of sieves having  $0.25\phi$  intervals from  $-2\phi$  to  $4\phi$ . Such an extensive array of sieves was needed to yield grain-size distributions having the desired high level of detail, making possible the separation of individual grain-size modes, which potentially could reflect different sources and transport paths and estuarine processes.

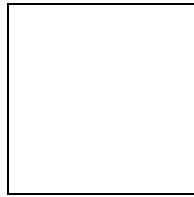


Figure 5-1. Sample locations for the surface sediments collected in Tillamook Bay and from potential sediment sources.

The final procedure in the laboratory analyses of the surface sediment samples involved determinations of the compositions of all sieve fractions for each sample. This was accomplished by inspection of sediment grains under a binocular microscope and classifying 300 individual grains by their compositions (this large number is required to provide meaningful results). Three mineralogical components were distinguished in the compositional counts: rock fragments (RF), quartz and feldspar (Q/F), and heavy minerals (HM); other components such as shell fragments

were minor. Moreover, inspection of the samples collected from the rivers and beaches established that the rock fragments are derived primarily from the rivers, whereas the beach sand consists almost entirely of clean quartz and feldspar grains. The rivers also contribute small amounts of quartz, mainly chert, but most of it is in the very coarse size ranges. Furthermore, the beach sand contributed small amounts of rock fragments to the Bay, mainly during the 1952-56 breaching of Bayocean Spit. Heavy minerals are contributed by both the marine beach and rivers, but form only a small portion of the samples.

### **5.1.2 Sediment Grain-Sizes**

The results of the analyses indicate that most of the sediment accumulating in the Bay is in the sand sizes, with some silt and clay. It appears that the sand and gravel fractions are accumulating in the Bay, while the finer sediment is being efficiently flushed through the inlet to the ocean. Gravel forms a significant portion of only a few samples collected in Tillamook Bay. The samples with the highest proportions of gravel were collected near the mouth of the Miami River and just offshore from the gravel beach that has formed on the landward end of the south jetty, while a smaller gravel component was found in samples collected near the mouths of the other rivers.

Figure 5-2 shows the results for the analysis of the grain-size distributions of the rock fragments and quartz and feldspar in a sample collected near the center of the Bay where both of the major components are found. The relative percentages of the

heavy mineral component are not included, since they represent only a minor portion. The upper graph of Figure 5-2 gives a histogram of the entire grain-size distribution, where the dominant grain-size mode is centered at about  $2.75\phi$  (0.148mm). The middle graphs are the mineral compositions of the sieve fractions, obtained from the individual grain counts under the microscope. Rock fragments represent the coarsest fractions within this particular sample, while quartz and feldspar dominate the medium to fine sand sieve fractions. The lower graphs of Figure 5-2 were derived by multiplying the upper graph by the relative compositions given in the middle graphs, yielding the grain-size distributions for the two mineralogical components. Such analyses were completed for each sample collected in Tillamook Bay. The results of the mineralogical analyses for each sieve fraction result in distinct grain-size distributions of the rock fragments and quartz and feldspar, distributions that are needed in analyses presented later, undertaken in an attempt to further define the sources of the sediments.



Figure 5-2. Compositional grain-size distributions of a surface sample, as derived from analyses under the microscope for each sieve interval.

### **5.1.3 Spatial Variations of the River and Beach Components and Inference of General Transport Paths**

Having determined the relative percentages of the main components for every sieve fraction in a sediment sample, adding these proportions for the entire sequence of sieves yields a determination of the total percentages of quartz and feldspar, rock fragments, and heavy minerals within that sample. The spatial patterns for percentages of quartz and feldspar versus rock fragments for the Bay are given in Figure 5-3. Since these two components dominate the sediment compositions, the patterns are nearly inverse to each other.

The highest percentages of the rock fragments are found close to the river mouths, and more generally in the eastern side of the Bay. The highest concentrations occur along the main eastern channel, which is also the main ebb flow

channel, suggesting that the observed pattern is enhanced by the estuarine circulation with the fresh water of the river discharge dominating the eastern side of the Bay as it flows toward the tidal inlet. In contrast, the quartz and feldspar concentrations are higher along the western half of the Bay, and especially near the area of the inlet, indicating that the main mechanism contributing ocean sand to the Bay are tidal currents transporting the sand from the ocean beach. When flood currents enter the Bay through the inlet, they flow southward along the backside of Bayocean Spit, through a well-defined channel. The 1952-56 breaching of Bayocean Spit also contributed large quantities of beach sand to the southwestern part of the Bay, and together with wind blown material entering the Bay from the dunes on Bayocean Spit represents the other two mechanisms that transport marine sediment into the Bay.

The spatial patterns of percentages of river derived rock fragments (RF) and marine quartz and feldspar (Q/F) sands provide a general view of the sediment movement and mixing, with the sand accumulating in the Bay. These patterns of sediment movement are expected to follow the water flow in the Bay, since tidal currents and river flows are the main processes that control the dispersion of sediments in Tillamook Bay. Figure 5-4 shows the transport paths of sediments as inferred from the relative contributions of rock fragments and quartz and feldspar measured in the surface sediments. These patterns were likely different in the past when the proportions of sediment contributed from two main sources were different, and when the channels may have followed different courses.

The results from the surface sediment analyses can be used to establish a “budget of sediments” for Tillamook Bay. This was accomplished by spatially

integrating the percentages of rock fragments and quartz and feldspar (Figure 5-3) across the Bay. By assuming that the heavy minerals are equally contributed by the two major sources, it is concluded that about 60% of the sand fraction of the sediment fill is derived from the ocean beaches, while the remaining 40% is contributed by the rivers. When the finer sediments (silt and clay), derived mainly from the rivers, are included in the sediment budget, the relative contributions of the two major sources to the surface sediments balances to approximately 50% each. Again, these results are based on analyses of the surface sediments and would have been different in the past, for example following the Tillamook Burns, when the fluvial component may have been more important to the sedimentary filling of the Bay.

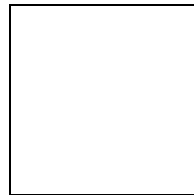
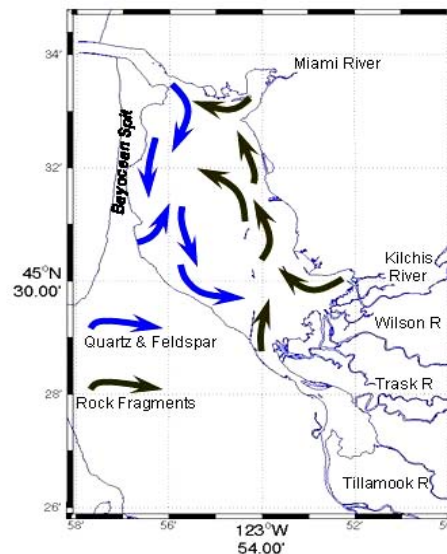


Figure 5-3. Spatial patterns and percent contribution for the marine (quartz and feldspar) versus the fluvial (rock fragments) component.



on the

### 5.2.1 Multimodal Analyses of Sediments

During the long history of studies of sediment grain-size distributions there has been considerable research regarding how grain sizes are related to the mechanisms of sediment transport and deposition. Several authors utilized grain-size modes in studies of sediment mixtures in order to discriminate between the dispersal patterns of the deposited subpopulations (Curry, 1960; Van Andel, 1964,1973; Oser, 1972, Dias and Neal, 1990).

The grain-size distribution of a sediment sample is generally believed to be log-normal (Krumbein and Pettijohn, 1938). If instead of a linear scale we use a logarithmic scale such as the  $\phi$  scale, the distribution is usually normal or Gaussian, and grain-size parameters such as the mean, median, standard deviation and skewness are effective descriptors of the size distribution (Folk and Ward, 1957; Inman, 1952). However in the case of a complex environment such as an estuary, the hydrodynamic conditions result from the combined action of the river flows, waves and tidal currents, so the above mentioned parameters are often ineffective in describing the origin and distribution of the existing sediment populations. In such environments the sediments commonly consist of two or more distinct populations of grain sizes, each described by a different normal distribution. The resulting distribution curve is said to be multimodal (Curry, 1960).

A powerful method for analyzing multimodal grain-size distributions is the decomposition of the frequency curves into their elementary component curves in order to identify the individual characteristics (amplitude, mean and standard

deviations) of the resulting subpopulations. The application of this method is based on the assumption that the multimodal distribution is composed of several overlapping log-normal subpopulations. Several authors have suggested that the derived subpopulations may not overlap, but instead are truncated, and also that the curves are not log-normal. Other studies such as Dias and Neal (1990) have demonstrated that the utilization of grain-size modes (normal distribution peaks) is an effective and simple method in deducing certain aspects of sedimentary processes. In this section we use all the information contained within the multimodal distributions of the rock fragments of the Tillamook Bay surface sediments, and attempt to relate the derived sediment sub-populations to potential river sources and to sedimentary processes within the estuary. Here we view modal analysis of sediments as a means to both “naturally” classify the river-derived sediment deposited in the Bay, and to relate the derived modal classes to specific hydrodynamic conditions, which differ spatially through the.

The grain-size distributions of the rock fragments derived from sieving and mineralogical analyses were processed by using an analytical technique for deriving frequency curves (Burger, 1965), which approximates with spline functions the log-probability plots of the cumulative curves. Once the frequency curve of each individual sample was established, a computer program that fits Gaussian distributions to frequency curves was used to detect the statistically significant grain-size modes with 95% confidence intervals. The number of statistically significant normal distributions fitted to each frequency curve represents the number of grain-

size modes for the sample. The numbers of detected modes found in the samples are given in the histogram of Figure 5-5, showing that most samples contain five modes.

In addition, the percentage of each mode was calculated for every sample. This was accomplished by dividing the area under the polymodal curve into very small increments ( $\Delta\phi = 0.005\phi$ ), and then expressing the area occupied by each sub-population's Gaussian distribution (mode) as a percentage of the total area under the frequency curve. Mathematically this involves integrating the exponential function that describes each normal distribution / mode adding the integral's values for each detected mode, and expressing the area of each mode as a percentage of the total area. For each mode I determined the values for the mean, amplitude, and standard deviation. In order to eliminate spurious modes, a detected mode was eliminated when: 1) its frequency percent was five times smaller than the class interval, following Schlee and Webster (1965), and/or 2) when the mode was defined by only a single point (Curry, 1960).

The detected modes of all samples were grouped into eight classes A through H, based on the peaks of a  $0.25\phi$  class interval histogram (Figure 5-6). The results obtained by the procedures described above indicate the occurrence of eight statistically significant modal classes in the Tillamook Bay sediments. Moreover, the boundaries between the adjacent modal classes were chosen by adding and subtracting the standard deviation of each natural class (Gaussian distribution) from the mean of the same class. Table 5-1 lists the selected boundaries for each modal class, as well as the relative contribution of each class to the total amount of river sediments deposited in Tillamook Bay.

Table 5-1. Grain-size range and overall concentrations of the eight natural classes.

<b>Grain Size</b>	<b>Class A</b>	<b>Class B</b>	<b>Class C</b>	<b>Class D</b>	<b>Class E</b>	<b>Class F</b>	<b>Class G</b>	<b>Class H</b>
$\phi$	-0.91-0.17	0.10 to 0.6	0.58 to 1.11	1.07 to 1.61	1.56 to 2.10	2.07 to 2.64	2.54 to 3.08	3.13 to 3.49
mm	1.87 to 0.9	0.93 to 0.65	0.67 to 0.46	0.47 to 0.32	0.33 to 0.23	0.23 to 0.16	0.17 to 0.11	0.11 to 0.08
(%)	7.83%	16.28%	18.58%	17.7%	13.72%	13.04%	10.49%	2.05%

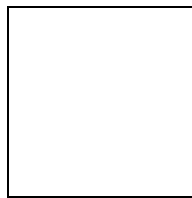


Figure 5-5. Polymodal character (numbers of modes in each sample) of the river sediments (rock fragments frequency distributions) in Tillamook Bay. About 90% of the samples are polymodal and the most common polymodal character is five modes.

The relative contribution is examined together with the spatial distribution of each modal class, in order to determine the origin, dispersion, and hydrodynamic controls on the river sediments deposited in Tillamook Bay, but first the polymodal character of the Bay sediments needs to be examined.

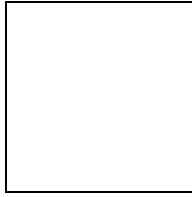


Figure 5-6. (Top) Histogram shows all detected modes grouped in  $0.25\phi$  intervals. (Bottom) Deduced normal distribution curves allow the definition of eight “natural” classes (A through H).

Figure 5-7 summarizes the polymodal character (number of modes per sample) of the surface sediment samples collected in Tillamook Bay, giving a first impression of the complexity of the sedimentary processes occurring in the estuary. Sediments near the inlet and the mouths of the southern rivers appear to be bimodal or trimodal. An increase in the number of modes per sample is observed away from the main sources, along the main channel in the eastern Bay and close to the mouth of the Miami River. Samples with five modes are frequent in those areas. This fact can be related to the higher complexity of sediment dynamics in the middle of the estuary, and probably to slightly higher energy levels due to the superposition of the tidal currents on the river flows.

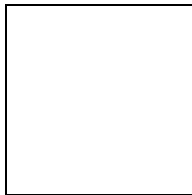


Figure 5-7. Modal composition across the Bay. A general increase in the polymodal character is present from north to south. (Scale refers to the number of modes per sample).

### **5.2.2 Distributions of Modal Classes**

Particles from Class A and B modes (Table 5-1) are in the range of sandy gravel to coarse sand, and are associated with the high-energy environments in the Bay. These environments include the tidal inlet, where the tidal current velocities are the highest, on the order of 1.5 m/sec (USACE, 1974), the area near the Garibaldi boat basin (where the highest concentrations of modal Class A are found, about 35%), and inside the tidal channels in the north part of the Bay. Both modal classes, represent channel environments where erosion, transportation and deposition change rapidly. The origin of modal Class A is related in part to the Miami River, but particles in the range of Class A also occur in the channels of other rivers. The Miami River is the shortest river, has the highest number of landslides (Tillamook Bay Task Force, 1978), and the fastest hydrologic flood response, so a greater amount of coarse sediment can be expected to reach the Bay from the Miami River during flooding. The spatial distribution of modal Class A (Figure 5-8) reflects this condition since the highest concentrations are found near the mouth of Miami River, and also in two patches in a southwestern direction from its delta. The other zone of Class A is observed in the central Bay, but with lower concentrations (10-15%), and

may be related to coarse rock fragments transported into the Bay during the 1952-56 breaching of Bayocean Spit.

In order to be more precise in describing the origin of these modal classes, I also analyzed the modal compositions of the samples collected in the channels of the rivers. The results are shown in Figure 5-10, and discussed later in this chapter, where the percent contribution of each modal class in each river has been calculated using the same method as for the Bay samples. The samples collected from the rivers were also strongly polymodal, possibly reflecting various discharge regimes. Unfortunately this makes it impossible to detect certain modal classes that represent the river sources.

Modal Class B has its highest concentrations along the western side of the Bay, near the north shore of Bayocean Spit (Figure 5-8). The spatial distribution of this class indicates that it is potentially derived from a source that has sufficient power to transport coarse sand for significant distances. This source could be either the Wilson or the Trask River, which have the highest discharges and thus the greatest sediment transport ability. A comparison to the relative contributions of modal Class B by the individual rivers, Figure 5-10, suggests that it occurs in higher concentrations in the Trask River, and its percentage is reduced gradually in the Kilchis, Wilson and Miami Rivers. The zones of Class B in the western part of the Bay near Bayocean Spit, with concentrations of about 50%, may be related to coarse sand swept into the Bay during the Spit breaching.

Class C (0.66 mm) occurs mainly in the northern half of the Bay Figure 5-8, distant from the mouths of the rivers in the southern Bay. Particles of modal Class C

are the most abundant (18.58%) in the Bay according to Table 5-1. The spatial distribution of this class represents sediment that has bypassed the center of the Bay, and has been deposited in a distal position at the northern part of the Bay. This can occur during river flooding when increased flows are able to transport sand in the grain-size range of Class C, all the way to the north part of the Bay. From its area of accumulation in the Bay, sediment of Class C cannot be directly associated with any specific river (Figure 5-8).

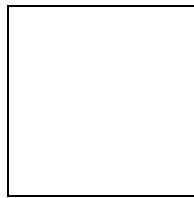


Figure 5-8. The distribution and concentration of classes of modes A,B,C, and D, together with their mean grain sizes.

A closer look at Figure 5-10 shows that Class C is found within the channels of the Kilchis, Wilson and Miami Rivers, and therefore cannot be attributed to any specific river. This modal class has a transitional character since it appears to have been remobilized from its initial area of deposition within the Bay. This becomes obvious by observing the spatial distribution of this class (Figure 5-8), where it's concentration near the tidal inlet of the Bay decreases rather abruptly. This suggests that grains of this class are removed after their initial deposition, and are transported

near the entrance of the inlet by the combined action of tidal currents and superimposed wind induced waves, which are moving from a northwest to a southeast direction during the summer months, following the predominant wind patterns. The absence of this class in the main channels of the estuary is an indication that the bottom shear stresses are greater near the inlet entrance, rather than further south within the Bay

The distribution pattern of Class D (Figure 5-8) is totally different from that of Class C. Sediment in Class D is restricted to the shallow intertidal areas in the center of the Bay, while two patches of lower concentrations (30-40%) occur in the intertidal zones along the north side of Bayocean Spit and close to the mouth of the Miami River (Figure 5-8). This suggests that grains of Class D are removed by estuarine processes from their initial areas of deposition, and come to rest with the highest concentrations at sites where the bathymetry and estuarine hydraulics restrict shear stresses to levels that are sufficiently low to deposit these grain sizes (0.47mm). Class D can be traced back to the Tillamook and Trask Rivers (they enter the Bay from the same channel), while minor contributions are derived from the Kilchis and Miami Rivers. Class D is absent in the channel deposits of the Wilson River (Figure 5-10).

Modes of Class E (0.33 mm) occur mainly in patches at the northeastern and southern parts of the Bay (Figure 5-9). The highest concentrations are found near the mouth of the Miami River and in scattered zones further to the south. Modal analyses of the samples collected from the channels of the rivers (Figure 5-10) suggest that this class is found in all rivers, so it can be considered as a common grain-size class. The

fact that this class does not exist near the tidal inlet is also explained by the fact that it is easily transported by the waves and the estuarine circulation, and therefore is restricted to low energy intertidal zones.

The distribution of Class F (0.23 mm) differs from than of Class E (Figure 5-9), but also appears to be deposited away from the mouths of the rivers, bypassing the deltas of the rivers, and being deposited in the areas of the prodelta slopes where the depth is slightly greater. The patch on the eastern side of the central Bay could be related to the Kilchis River, but Figure 5-10 indicates that this modal class is present in all river channels, except the Kilchis. A reasonable explanation for the distribution of Class F would be to consider that this class is remobilized by the tidal currents soon after its initial deposition, coming to rest in low-energy environments.

Class G also represents the deposition of progressively finer material away from the river sources. This class exists entirely in the south part of the Bay (Figure 5-9), and is related to deposits from the four southern rivers. If we accept that the estuarine circulation is more intense in the northern part of the Bay near the tidal inlet, then we can conclude that grains of Class G are flushed out from the northern part of the estuary, accumulating only in the low energy south end.

The distribution of Class H (Figure 5-9) even more closer represents the silt fraction. Its distribution bears no relation to the channels of the estuary, and is strictly concentrated on the tidal flats on the southern edge of the Bay. Deposition of this class is connected with environments that have low shear stress levels, away from tidal channels. It can be directly related to the Wilson and Trask-Tillamook Rivers, since it is found only in their channels (Figure 5-10).

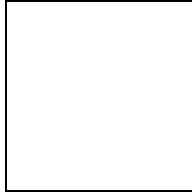


Figure 5-9. Spatial distribution of the finer modal classes E,F,G and H, with their mean grain-sizes.

### **5.2.3 Significance of the Observed Modal Classes**

The main goal of the modal analysis was to trace the observed modes within the Bay back to their potential river sources. Folk (1966) suggested that a specific source may supply particles having a distinct size mode; finding that size mode in the sediment mixture therefore identifies its source. However, this is not the case for the samples collected from the channels of the main rivers entering Tillamook Bay, since they show a higher polymodal character (Figure 5-10) than do the Bay's samples. This can be attributed to fact that the rivers drain watersheds that do not have a unique modal composition, and a range of discharges in the river may give rise to additional modes. This results from the issue of availability of sand material in the channels of the rivers, which has been discussed in detail in Chapter 3. It also has to be mentioned that there is no lack of sediment modes in the Bay that corresponds to

the sources, that is, all the modes found in the channels of the rivers are present in the Bay, but in different proportions as inferred from Table 5-2. The different proportions of the modes between the Bay and river samples suggest that grain-size modes in Tillamook Bay are the result of depositional and sorting processes that have affected the sediments once they reached the Bay. Furthermore, there might be another source that has contributed rock fragments to the Bay, probably associated with eroded material from Cape Mears that has made its way into the Bay along with quartz and feldspar sand, either during the breaching of Bayocean Spit or by northward longshore transport and passage through the inlet. If this is the case, a marine source of rock fragments probably occurred until 1977, when the construction of the south jetty reduced beach sand movement into the Bay.

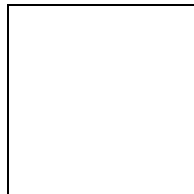


Figure 5-10. The relative contributions of each detected modal class to the samples collected from the channels of the main rivers. All of the river samples are polymodal.

Further insight into the dispersion of river sediments in the Bay can be obtained by comparing the different amounts of the observed modal classes between the sources and the sites of deposition. Modal Classes B, C, D and E, which cover the size range of medium sand, appear to be more abundant in the Bay, while the

coarsest Class A, and the finer Classes F, G and H are present in higher concentrations in the river channels. In order to obtain a broader view concerning the processes that contribute and disperse the fluvial sediments in Tillamook Bay, I grouped the modal classes into three general categories following the terminology of Lewis (1984). These three categories are:

Coarse sand, from -1 to 1 $\phi$ , or from 2 to 0.5mm (Classes A and B),

Medium Sand, from 1 to 2 $\phi$ , or from 0.5 to 0.125mm (Classes C, D and E),

Fine sand, from 2 to 4 $\phi$ , or from 0.125 to 0.0625mm (Classes G and H).

Table 5-2. Relative proportions of the observed modal classes in the rivers and the estuary.

<b>MODAL CLASS</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>	<b>G</b>	<b>H</b>
<b>Estuary (%)</b>	7.83	16.28	18.58	17.70	13.72	13.04	10.49	2.05
<b>Wilson R.</b>	0	9.65	12.66	0	15.58	12.55	22.42	27.11
<b>Trask-Tillamook R.</b>	8.27	19.59	0	9.50	8.89	20.02	33.71	0
<b>Kilchis R.</b>	20.60	13.51	23.24	18.74	9.24	0	14.65	0
<b>Miami R.</b>	18.50	1.68	14.70	9.34	11.38	27.96	0	16.40
<b>Rivers average (%)</b>	11.84	11.10	12.65	9.39	11.27	15.13	17.69	10.87

The spatial distributions of these broad categories are shown in Figure 5-11, and suggest an inverse relationship between grain-size and distance from the main sources, if we accept that the main sources of rock fragments are only the five rivers,

excluding the possibility of a significant rock fragment marine source. The patterns illustrated in Figure 5-11 suggest that the coarse sand modes are deposited in the northwest part of the Bay, close to the inlet, while deposition of progressively finer modes occurs closer to the mouths of the rivers. These patterns are best explained by accepting that almost all the river sand is transported to the Bay by episodic flood events, and then is sorted by the estuarine circulation and tidal currents. During floods the sediment transport ability of a river increases, but the timings of the peak flows are different from river to river because of their different drainage areas, with the smaller watersheds (i.e. Miami, Tillamook) reaching peak flows much faster than larger watersheds for a given rainfall intensity and duration. Despite the timing, during such peak flows the rivers transport their sediment load into the Bay, depositing it at significant distances from their mouths. After the sediment has settled, tidal currents begin to sort it. The area near the entrance of the Bay where the tidal current velocities are in the order of 2 m/sec (USACE, 1974) is dominated by the coarser modal classes, while medium and fine sand are removed from this high energy environment (Figure 5-11). Medium sand is mainly deposited in the subtidal areas at the north and central portions of the Bay, while lower concentrations occur in the main channels. The finer modal classes remain only in the southern part of the Bay where the tidal current velocities are substantially lower, demonstrating the importance of the estuarine processes on the sorting of the river sediments.

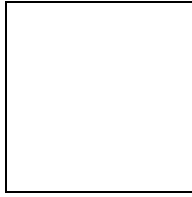


Figure 5-11. Grouping of the eight modal classes in terms of coarse, medium and fine sand. (Scale is in percent of total concentration).

### **5.3 Factor Analysis of River and Marine Sediments Deposited within Tillamook Bay**

#### **5.3.1 Introduction**

During the past thirty years the use of multivariate statistics in sedimentology has made significant advances. Factor analyses of grain-size distribution data in particular has been found to be useful in determining depositional environments (Klovan, 1966). In the case of Tillamook Bay our problem is to distinguish the relative contributions made by each of the individual rivers, especially during floods

when most of the sediment is transported to the estuary. As previously shown, modal analysis of the rock fragment populations in the Bay sediments was effective in classifying the fluvial sands, explaining their dispersal patterns, but could not provide insight concerning the contributions made by the different rivers, since most of the modal classes are contributed to the Bay by more than one river. In addition, modal analysis introduced the possibility of there being another rock fragment source, associated with material derived from the erosion and breaching of Bayocean Spit.

This section presents the individual steps and the results of the application of factor analysis to the compositional sediment data obtained from Tillamook Bay, with the ultimate objective being to develop a model that postulates a sedimentary filling Bay having a number of different sources, each characterized by different grain-size distributions.

### **5.3.2 Analytical Technique**

In grain-size analyses a sieve fraction is a discrete portion of a continuous range of grain-sizes. The amount of sediment in each fraction is a unique attribute of the particular sample. In a previous section of this chapter I discussed the procedures followed in sieving the surface sediment samples at  $0.25\phi$  intervals, so that each sample can be considered as consisting of 25 components (sieve fractions from  $-2$  to  $4\phi$ ). If we view the data set in such a way that each sieve fraction represents a different variable, the use of multivariate statistics is possible. Since we are mainly interested in distinguishing between the five main rivers, initially we take into

account only the rock fragments population, which as previously shown represents the river component of sediments, with probably a minor spit component. Then, the same methods are applied to the quartz and feldspar grain-size distributions in order to identify the depositional patterns of the beach sands in the Bay as well.

Factor analysis provides a still more objective approach for examining variations in a series of grain-size distributions. By treating the various class intervals as different variables, Q-mode factor analysis determines whether the samples can be treated as mixtures of end-members, and if this is true we are able to express each sample as a proportion of those end-members. The original data matrix is different from the one used in the modal analysis, and consists of the percent weights of rock fragments or quartz and feldspar in each sieve fraction ranging from  $-2$  to  $4\phi$ . The weight percentages in each sample sum to a constant 100%. The sieve intervals are the columns and sample weight percentages the rows of the original data matrix. The matter of constant row sums has been the subject of extensive discussions in the mathematical geology literature, but it has been shown that this method can be applied to data matrices without having constant row sums (i.e. not closed systems) as well (Full, Ehrlich and Klovan, 1981).

The original data matrix for the Tillamook Bay sediments was transformed to maximum percent where each sample was expressed as a proportion of the maximum value and all minimum values were set to zero. The purpose of this scaling is to give each compositional variable an approximately equal weight in the factor analysis. Without scaling variables having large variances, such as the coarse sand ( $-2$  to  $0.5\phi$ ), may completely dominate the outcome, while variables having small variances (fine

sand-silt) may exert little or no influence. In effect, the use of scaling emphasizes the fact that minor compositional components can be as diagnostic as major components in sedimentary models. In addition, the transformed data matrix was row-normalized, that is, each row of the matrix is adjusted so that the sum of squares of the values within it is unity. This adjustment is done automatically by computing the cosine- $\theta$  matrix (coefficient of proportional similarity), which is computed as the major product of the row-normalized data matrix and its transpose. The use of the cosine- $\theta$  matrix allows treatment of each row of the data matrix as a vector of unit length, permitting subsequent computations and interpretations. For example, if two vector samples are collinear in the multivariate space, then the angle between them is zero and the cosine of that angle is 1, indicating perfect similarity. On the other hand, if the angle between these two sample vectors is  $90^\circ$ , the cosine of this angle is zero, indicating total dissimilarity.

Furthermore, the cosine- $\theta$  matrix of the sample vectors in the multivariate space contains all the information on the relationships of the vector samples but not in an easily interpreted form. However, the objective is to simplify the data set and find a solution that explains some major part of the compositional variability. The eigenvalues of the cosine- $\theta$  matrix indicate that most of the sample vectors for the Tillamook Bay river samples occur in five dimensions (five principal components or factor axes), and account for 91.49% of the total variability. The part of the variability unexplained can be attributed to sampling errors or to sedimentary processes that have only minor effects on the variation of the rock fragment grain-size compositions. The principal component axes are positioned in the vector system so

that the projections of the sample vectors on the first of the axes is as high as possible. The second principal axis is positioned orthogonally to the first but is oriented so that the sample vectors have as large projection on it as possible, considering the orthogonality constraint. Subsequent axes are positioned in the 5-dimensional space, but are orthogonal to preceding axes.

As the factor axes located by this method are not in the most meaningful positions, they are rotated to positions that make interpretation easier. The mathematical technique for rotating the principal component axes is known as varimax rotation. In our case a computer program is used that performs varimax rotation based on the approaches developed by Miesch (1976a).

The variances explained by the five factors retained for our model, following varimax rotation, are 40.62%, 23.68%, 22.00%, 9.23% and 4.20%. Using the varimax factor loadings, we are searching in the rotated factor space (varimax space) for samples having extreme compositions, also termed end-members. The solution to this problem is known as oblique rotation of the reference axes. The computed set of composition scores for the varimax axes contains a few negative values. This is undesirable for the purpose of this study, and applying the oblique solution we move the reference axes, one at a time, from the varimax positions, by small increments towards the sample vectors. In the search for end-member samples, we are searching for the samples in the varimax space on which all the initial loadings of the other samples are less than one, following the procedure developed by Imbrie and Van Andel (1963). The coordinates (loadings) of these samples in the oblique space are related to points in varimax space by dividing the squared varimax factor loadings by

the communalities as derived following varimax rotation (Miesch, 1976b). The procedure leads to a model that approximates the conventional varimax solution, but the axes are oblique. The advantage of the oblique model is that end-members are more likely to be real samples.

According to the method of deriving the oblique factor model, the five end-members samples were chosen as those having the largest projections (loadings) on the varimax reference axes. Having defined the end-members and their compositions, we look next to the partitioning problem of the data set. Based on the assumption that the proportions of a sample are linearly related to the end-members, we attempt to solve the partitioning problem using least squares criteria for minimizing the residuals in the model. In order to succeed in this, a set of equations is set for each sample with five variables (as many as the end-member samples), and we solve for the coefficients of those variables, which are the relative contributions of each end-member to the samples in our data set. These equations have the form of a regression equation, and a constrained least squares approach is selected to solve the partitioning problem. The matrix of coefficients as derived from the constrained least squares solution indicates that each of the selected end-members is not related to the total number of samples. One could argue about how accurate this matrix of contributions might be, and up to what extent the constrained least squares solution is related to the factor analysis solution. In order to check this, we calculate from the Q-mode factor solution an estimate of the values of the original data set, that is, we try to reconstruct the initial data set. A coefficient of determination is then calculated for each variable, and where the correspondence is close (high values of the coefficient of

determination), it can be said that the variable is a major contributor to the solution. The goodness of fit statistics for the constrained least squares solution (Figure 5-12) indicate that our proposed sedimentary model provides a good description for most of the variables within the data set, except those that represent the coarsest fractions ( $-2$  to  $0.6\phi$ ).

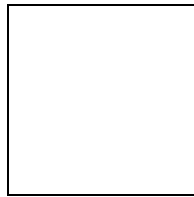


Figure 5-12. Goodness-of-fit statistics for the end-members of the factor model of the rock fragments grain-size distributions in Tillamook Bay.

In order to define the relationship between the matrix of contributions of the end-members and the output of the factor analysis (varimax loadings), we tested each varimax factor with the corresponding end-member contributions through a cross-correlation function, to obtain a matrix of cross-correlation coefficients. The cross-correlation coefficient between the first varimax factor and the first end-member is 0.88, between the second varimax factor and the second end-member is 0.80, for the third it is 0.834, for the fourth varimax factor and the fourth end-member is 0.3 and for the last one it is 0.31. This indicates that the first three end-members are highly correlated with the corresponding varimax factors from which they were actually derived, but this is not true for the last two end-members. This can be attributed in part to the oblique rotation of the varimax reference axes (since the axes are moving

there should be some loss of information), and in part to the assumption of linear relationships between end-members and samples. This further suggests that the last two end-members are mixtures of samples that represent more complicated processes and/or depositional environments. Thus, we can conclude that the matrix of proportions of the samples to each end-member contains almost all of the information derived from the factor analysis, and can be used to model the different sources and the distribution of the deposited rock fragments population in the Bay.

### **5.3.3 Interpretation of Results**

Five end-members have been mathematically derived from the varimax reference loadings, and the next step is to determine whether they have any physical significance. The frequency histograms (Figure 5-13) of the end-member samples may provide a first indication about the sources or processes that they describe. End-members 1, 2, 3 and 5 have polymodal distributions that are similar to sand samples collected in the Bay. In contrast, end-member 4, also polymodal, is different in that it corresponds more to the coarser modes, which appear to be well sorted and represent the coarse sand and fine gravel fractions. Fine sand occurs mainly in end-member 3, showing minor contributions to the other end-members.

A question that arises when trying to interpret the results is whether the end-members represent potential sediment sources, specifically different rivers, or estuarine sedimentary processes. This can be examined by comparing the end-members with the frequency curves of the potential sources of rock fragments, the five rivers and a

possible contribution from the spit breaching. Figure 5-14 shows the frequency curves of the samples obtained in the channels of the rivers. The frequency curves of the river samples are also polymodal and do not appear to be correlated with any of the end-member samples, except perhaps the sample collected from the Miami River channel which shows a similarity with end-member 4, but with additional finer modes. End-member 1 has a typical “medium sand” bimodal distribution and relatively small standard deviations for both modes. It seems to be related to an environment that has sufficient energy to remobilize such grain-sizes and where there also is winnowing of the finer modes. Such an environment could be a surf zone where reworking of the finer sediments by wave action results in well-sorted sands with small standard deviations.

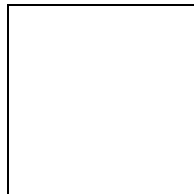


Figure 5-13. Frequency histograms of the end-member samples.

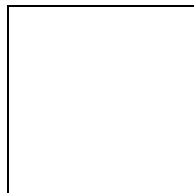


Figure 5-14. Frequency histograms of the samples obtained from the potential sources of rock fragments in Tillamook Bay.

Furthermore, by comparing the frequency distribution of the sample collected from the beach near Cape Mears with end-member 1, it is found that the two frequency curves are reasonably similar, with the frequency curve of end-member 1 being better sorted and slightly shifted towards finer grain-sizes. This can be interpreted as a result of sorting during longshore transport and tidal currents which carry the sand through the inlet into the Bay. The geographic distribution of end-member 1 is shown in Figure 5-15, demonstrating that it is found mainly in the northwestern Bay near the inlet, indicating a possible marine source for these rock fragments.

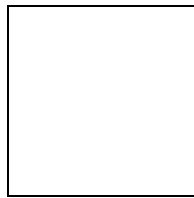


Figure 5-15. Spatial distribution of end-member 1 in Tillamook Bay. The units in the colorbar are the percent contributions of the particular end-member in the samples collected from the Bay.

The observed pattern of end-member 1 can be explained as follows. Cape Mears is composed of basalt, so the sediments found in the beach adjacent to Cape Mears consist of both quartz and feldspar sand and eroded material from the Cape, that is basalt rock fragments, as verified from field observations. The grain-size distribution of the rock fragments at this site is predominantly in the gravel fraction, but there is a significant component of sand as well. The mineralogical analyses of

the samples collected from the ocean beaches reveal that the average proportions of quartz and feldspar are about 82%, the rock fragments are 3%, and the heavy minerals are 15. These results are based on only three sediment samples, and the proportions of the mineralogical components might have been much different in the past, especially at the time of spit breaching when the wave action would have been stronger resulting in transport of significant quantities of rock fragment sand in Tillamook Bay.

In conclusion, the patterns illustrated in Figure 5-16, combined with the estuary's circulation patterns (Figure 5-4), provide reliable evidence that end-member 1 is related to eroded rock fragments from Cape Mears, which entered the Bay through the inlet and at the time of Spit breaching.

End-member 2 also has a polymodal character (Figure 5-13), with minor contributions by the coarser modal Classes A and B, while the most dominant modal size (Class E) of this end-member is in the range of medium sand. The areal distribution of end-member 2 (Figure 5-17) is concentrated in three main patches in the north and central Bay, away from the river mouths. Recalling the patterns of the modal classes as they appear in Figures 5-8 and 5-9, the patch of end-member 2 located near the tidal inlet appears to represent the coarser modes present in its frequency distribution (Figure 5-13), since modal classes A and B are restricted in the northern part of the Bay. Consequently, the patches located in the central Bay are mixtures of modal classes D and E.

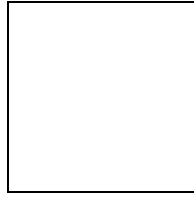


Figure 5-16. The areas of erosion and sediment deposition following construction of the north jetty at Tillamook Bay in 1917 (Komar and Terich, 1976).

This pattern indicates that end-member 2 is related to a process that is able to transport a small amount of coarse sediment near the inlet, but is also able to transport medium sand to concentrated areas in the middle Bay. A potential agent that comes to mind is transport under wind-induced waves, which are generated within the Bay. Near the inlet there is coarser material available (Figure 5-9), so that waves are able to transport the existing material further south during the summer months when the predominant wind directions are from northwest to southeast. Further south in the Bay, waves transport the already deposited sediment (modal Classes D and E) up to a point where the Bay's bathymetry allows this to happen. When these wind waves break deposition occurs. In a previous section it was mentioned that there are two well-marked channels hugging the eastern and western sides of the Bay. The main patches of end-member 2 are located where these two channels become shallow, not allowing further transport because of wave breaking.

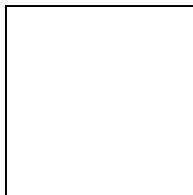


Figure 5-17. Areal distribution of end-member 2 and its associates samples. End-member 2 represents the transport of rock fragments under waves that are generated in the Bay.

The high concentrations of end-member 2 observed at these sites are a result of continuous enrichment of sediment due to waves generated within the Bay. Thus, we can conclude that end-member 2 represents an internal estuarine process associated with sediment transport and deposition under wind induced waves.

End-member 3 has a bimodality that is a mixture of medium and fine sand populations. The areal distribution of end-member 3 is shown in Figure 5-18, suggesting that it is associated with a process mainly restricted to the southern Bay. In addition, end-member 3 cannot be directly related to any specific source since it appears in low concentrations near the mouths of all rivers. Two areas of high concentration exist on the shoals between the main channels in the south central Bay, but not within the main circulation channels. If we also consider the frequency distribution of end-member 3, which is composed of medium and very fine sand, we can support that it is related to a mixing process. A mixing agent that comes to mind is current activity. Sediment derived from the rivers is initially deposited throughout the Bay, and is progressively removed from the main channels by tidal currents. In the northern Bay where tidal current velocities are higher, the material of end-

member 3 is almost entirely removed, except for small patches between the main circulation channels and from the sheltered area within Miami Cove. In the southern Bay tidal currents slow down and sediment transport through the main channels is mainly driven by the river flows.

The frequency curve of end-member 3 (Figure 5-13) is composed of a minor amount of modal Class C, while the most dominant grain sizes are in the range of Class D and H. Since, both modal classes can be removed from the northern Bay, but not from the southern Bay, end-member 3 can be related to deposition in sheltered environments by tidal current activity.

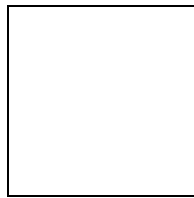


Figure 5-18. Spatial distribution of end-member 3. Notable is its absence of from the circulation channels of the Bay.

So far, we have examined the physical significance of the first three end members that show the greatest similarity with the results of the factor analysis as inferred from the cross-correlation coefficients. These end-members revealed the existence of another rock fragments source, associated with the erosion of Cape Mears and present in the beach sand, but also emphasized the significance of the wind-generated waves and tidal currents in the dispersion of the river sediments after

it has entered Tillamook Bay. Our initial hope when employing this method was to be able to identify the contributions of the individual rivers, but the approach has not been successful in accomplishing this.

End-member 4 is probably related to various sources as it has a number of modes that range widely in grain-sizes. In contrast to end-member 3, end-member 4 is present within the main circulation channels in the southern Bay, but the highest concentrations occur in the channel of the Miami River and more general throughout the area of Miami Cove (Figure 5-19). In addition, the frequency curve of end-member 4 and its associated samples is dominated by gravel (Figure 5-13), and to a certain degree it appears to be similar to that of the sample obtained from the channel of the Miami River (Figure 5-14), especially for the coarser fractions. On the other hand, the areal distribution of end-member 4 reveals a more complex pattern in that significant concentrations are also present in the gravel beach next to the south jetty, close to the shore of Boulder Point in the southwestern Bay, and within the entire eastern channel. Thus end-member 4 represents multiple sources of rock fragments that are in the range of coarse sand to gravel, found in Tillamook Bay.

In section 5.3.2 the varimax loadings of each factor were compared with the corresponding end-member contributions through a cross-correlation function, with the first three end-members being highly correlated with the corresponding varimax factors, while cross-correlation coefficients for the fourth and fifth end-members were low. This was attributed in part to the oblique rotation, and in part to potential nonlinearities of the estuarine processes that the particular end-members might represent,

since for our sedimentary model we assumed linear relationships between end-members and samples.

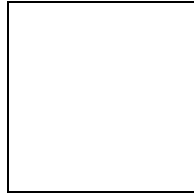


Figure 5-19. Spatial distribution of end-member 4, with the highest concentrations in the channel of Miami River and close to Boulder Point at the southwestern Bay. Also, significant concentrations are observed at the inlet and within the eastern channel.

Looking back at the distribution of end-member 4, I mentioned that it represents the coarse sand / gravel component deposited in Tillamook Bay, but part of this end-member is related to sediment derived from the Miami River, another part is related to material transported from the rocky beach next to the inlet, part to material transported within the eastern channel, and finally part of it is related to coarse sand / fine gravel brought into the Bay from Boulder Point. Near Boulder Point there is no significant creek or slough, and the potential mechanisms that might transport gravel into the Bay are landslides or overland flow. The conclusion is that end-member 4 represents a number of different sources and processes, which cannot be linearly related to all samples. Therefore it is better to conclude that end-member 4 represents the coarse sand / fine gravel components in Tillamook Bay, and any attempts to

further model the various processes contributing the particular grain-sizes to the Bay are unnecessary.

Finally, the grain-size distribution of end-member 5 is typical sand and consists almost entirely of sediment in the range of modal Class D (Figure 5-13). The spatial distribution of end-member 5 (Figure 5-20), suggests that it bears no relation to any of the five rivers, and similar to end-member 4 is related instead to a number of different sources. Figure 5-20 shows three distinct areas of high concentrations that are located along the eastern shore of Bayocean Spit, on the shoals south of the tidal inlet, and very close to the southeastern shore of the Bay, at the site named Dick Point. It appears that end-member 5 has no relation to the main circulation channels of the estuary, so we can conclude that it likely represents material preferentially deposited on the tidal flats.

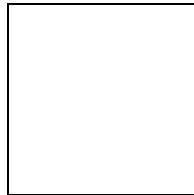


Figure 5-20. Spatial distribution of end-member 5.

#### **5.4 Depositional Environments and Dispersal Patterns of Marine Sediments**

I also used Q-mode factor analysis to examine the grain-size variability of the marine sediments deposited in Tillamook Bay, but not to the extent undertaken for the river sediments. I used the same raw data structure for the quartz and feldspar

populations, consisting of the percent weights of each sieve fraction from  $-2$  to  $4\phi$ , and followed the same procedures described in section 5.3.2 up to varimax rotation of the principal component axes. There was no particular need to further model the variability of the quartz and feldspar grain-size distributions in terms of linear equations between factors and samples (in the case of rock fragments, I had hoped that the resulting end-members would reflect the contributions of five-rivers, and application of a linear solution to the end-members' partitioning problem was expected to model their dispersal patterns, which unfortunately was not the case). Furthermore, the outcome of the analysis of the quartz and feldspar following varimax rotation provides a clear picture about the processes and depositional environments represented by the retained factors.

Three factors were found to account for 88.82% of the compositional variability of the initial data set, while the amount of unexplained variability can be attributed to sampling errors and minor depositional processes. We are interested in the processes that control the variability of the marine sediments, and whether the effects of various human impacts, such as the construction of the jetties and the breaching of Bayocean Spit, have affected this variability.

Figure 5-21 shows frequency histograms for the three selected factors and their factor scores, which are a measure of the response of the selected factor to each variable (sieve fraction). Factor 1, which accounts for most of the observed variability, is a single well-sorted mode with a median grain-size centered at  $2.5\phi$  (0.185 mm), which is the typical mean grain-size of the marine sand found in Tillamook Bay (section 5.2). The spatial distribution of factor 1 (Figure 5-22) shows

that it dominates the area near the tidal inlet and along the length of the eastern side of Bayocean Spit, but is also present in significant concentrations along the eastern channel as a result of transport by the tidal and estuarine circulation. It is obvious that factor 1 represents the beach sand that enters the Bay through the tidal inlet, driven by the tidal currents, and its dispersal patterns follow the general circulation as shown in Figure 5-4.

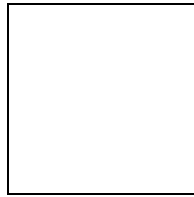


Figure 5-21. Varimax factor scores of the factor analysis for the quartz and feldspar grain-size distributions. Also shown the amount of the total variability explained by each factor.

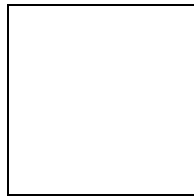


Figure 5-22. Spatial distribution of varimax loadings for factor 1, which represents the marine sand that enters the Bay from the tidal inlet.

Factor 2 shows a different grain-size distribution and represents the finer fractions of the marine sediment deposited in Tillamook Bay (Figure 5-21). Such fine material was transported into the Bay during the 1952-56 breaching of Bayocean Spit,

while today another source of this fine sand may be wind blown material from the dunes of Bayocean Spit. Factor 2 exists almost entirely in the southeast part of the Bay where the lowest energy levels occur, supporting the conclusion that fine sand can be permanently deposited only in low energy environments within the Bay (Figure 5-23).

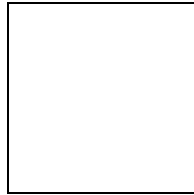


Figure 5-23. Spatial distribution of factor 2. This factor is associated with fine material which tends to be deposited in the same areas as the fined-grained rock fragments.

Finally, factor 3 represents a wide range of grain sizes including the coarser fractions of quartz and feldspar that exist in the Bay (Figure 5-21). The spatial distribution of this factor reveals a selective deposition throughout the Bay, with the higher concentrations found along the eastern channel and in two patches in the southwestern Bay (Figure 5-24). The high concentrations of this factor probably represent coarse material that had been transported into the Bay during the breaching of the Bayocean Spit, which is now trapped at these specific locations.

The dispersal patterns of the quartz and feldspar are similar to those of the rock fragments and confirm that deposition in Tillamook Bay today is controlled by

estuarine processes, determined by the energy levels of the tides, circulation and wind-generated waves.

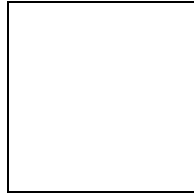


Figure 5-25. Spatial distribution of the varimax loading of factor 3.

## **6. TEMPORAL SEDIMENTATION VARIATIONS**

### **6.1 Introduction**

Having defined the sediment sources and the processes responsible for the transport and dispersion of the marine and fluvial sediments at the present time as recorded in the Bay's surface sediments, we now need to examine how these sources and depositional patterns have changed through the past hundred to thousand years. In order to do this I will review the results of studies that involved the analysis of sediment cores, so we can better understand how the human impacts might have altered the sedimentation regime in Tillamook Bay.

Such studies of cores in Tillamook Bay include that by Glenn (1978) and by McManus *et al.* (1998). The study by Bernert and Sullivan (1998) involved analyses and comparisons between a series of bathymetric surveys spanning more than a century. As reviewed in Chapter 4, Glenn (1978) obtained long cores (~30m) and undertook analyses of down-core mineralogical compositions and carbon-14 dating of organic debris. In contrast, McManus *et al.* (1998) obtained short cores ( $1.5 \pm 0.25$ m), and examined the down-core geochemical variations that are related to sediment sources, and based sedimentation rate values on carbon-14 dating of the shells and lead-210 profiles of the sediments. Glenn's methods and results have already been discussed, so here I mainly focus on the recent studies by McManus *et al.* (1998) and Bernert and Sullivan (1998).

## **6.2 Core Collection, Analysis and Interpretation by McManus *et al.* (1998)**

McManus *et al.* (1998) collected sediment cores from nine different sites throughout Tillamook Bay (Figure 6-1). They also collected a number of surface sediment samples for geochemical investigations, with the hope that different river sources would be reflected by distinct geochemical compositions. This was true for the beach and river sediment sources, but no distinction could be made between the individual rivers. Attempts to determine the relative contributions of the marine versus riverine sources through time were based on down-core differences of major and minor element concentrations. Sediment accumulation rates were based on carbon-14 dating of shells found in the cores, and measurements of lead-210 profiles down-core. In addition, the cores were processed for color reflectance with the ultimate goal of distinguishing dark carbon-rich layers that could reflect material from the Tillamook Burns. A more detailed description about the core collection and processing methods is provided in the report by McManus *et al.* (1998).

Their geochemical investigations of the surface sediments successfully distinguished between the two major sources of sediment in Tillamook Bay, the river and beach sand sources. Major elements involved in the geochemical analyses include titanium ( $\text{TiO}_2$ ), which is a major element in the volcanic rocks of the watersheds, and therefore in Tillamook Bay occurs in high concentrations in the fluvial sands, whereas there are low concentrations in the marine sands. Aluminum has a fairly constant concentration in crustal rock (~8%), so that Al:Ti ratios provide an effective means to distinguish between the relative contributions made by the two major sources, with higher Al:Ti ratios corresponding to an increase in the marine source relative to the rivers.

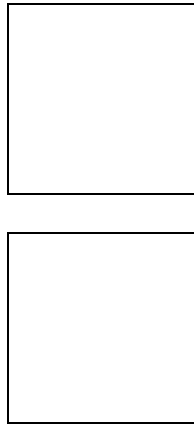


Figure 6-1. Locations and down-core variations of the Al/Ti ratios from the sediment cores collected from Tillamook Bay [data by McManus *et al.*(1998)].

The lower graph of Figure 6-1 plots the down-core variations of the Al:Ti ratios, for several cores. It can be seen that cores SAC-005 and SAC-006, which are from the south Bay, have low Al:Ti ratios throughout their lengths, demonstrating that in the past this area had been dominated by river sediments, just as it is today. In contrast, core SAC-007 from the eastern Bay near the main ebb channel shows an increase in Al:Ti ratio with depth, suggesting a progressive down-core shift in the sedimentation regime with progressively increasing quantities of marine sand in the past. Core SAC-010 is located west of core SAC-006, closer to Bayocean Spit, and shows greater variability in the Al:Ti ratios, with major peaks at core depths of 42 and 82 cm, which were interpreted by McManus *et al.* (1998) as reflecting past episodes of breaching or overwash of Bayocean Spit, and most likely resulted from the most recent subduction earthquake and tsunami in the year 1700. The tsunami washed

over much of the spit, and transported large quantities of beach and dune sand into the Bay.

As reviewed in Chapter 4, the results from Glenn (1978) suggest that sedimentation rates between about 7,000 and 8,000 years B.P., soon after the formation of the Bay by the sea-level rise, were on the order of the 200 cm/century, but after 7,000 years B.P. they dropped to about 20-30 cm/century, which are viewed as the “natural” sedimentation rates. Glenn’s results are based on dating organic carbon, but the youngest age of dated material is  $3,300 \pm 200$  years B.P., so his study did not document changes in sedimentation rates that may have been affected by Euro-American impacts.

McManus *et al.* (1998) estimated sedimentation rates in the Bay during the past few hundred years based on carbon-14 dating of two shells that were found within the cores and from measured lead-210 profiles in five cores. Their carbon-14 results were corrected for the age of the north Pacific water, yielding average sedimentation rates on the order of 20 cm/century for core SAC-006 and 43cm/century for core SAC-013. The lead-210 profiles were measured for five of the collected cores but were affected by burrowing of ghost shrimp, particularly in the upper 50cm, and provided different results for different depth intervals. As a result, neither the sediment accumulation rates nor the mixing rates could be uniquely determined. For this reason, McManus *et al.* (1998) created a sediment accumulation model, based on the “best fit” between the theoretical mathematical relationships that describe the sediment accumulation and mixing for the lead-210 profiles, and the actual measurements for different depth intervals. Depending on the choice of the depth

interval and whether mixing was included, their model yielded different values of sedimentation rates. The results were more consistent with other studies when generated by application of the model below a depth of 75cm, beyond which burrowing of the ghost shrimp was less. In conclusion, the lead-210 profiles suggest that sedimentation in Tillamook Bay exhibits a rather complex pattern where a continuous and non-mixed accumulation of sediments occurs at a relatively fast rate, followed by periods of slower accumulation rates, characterized by more mixing.

### **6.3 Bathymetric Surveys**

There have been three bathymetric surveys for Tillamook Bay (1867, 1956 and 1995). Based on these surveys, Bernert and Sullivan (1998) reconstructed bathymetric maps for Tillamook Bay by using statistical methods, which demonstrated the existence of large amounts of variance between different surveys. In addition, they noticed several sources of errors associated with water depth measurements and inadequate documentation of benchmarks so that bathymetric changes during the times between surveys could not be quantified. However, they managed to extrapolate changes in the volume of the Bay during the intervening periods. Their results suggest that the Bay's volume has decreased by 7,587,107 m<sup>3</sup> between 1867 and 1956, followed by an increase by 1,363,947 m<sup>3</sup> between 1956 and 1995. The most remarkable changes in bathymetry occurred between 1867 and 1956, with the Bay's morphology changing from a complex network of channels and

intertidal areas to a simpler bathymetry consisting mainly of two channels on each side of the Bay. In addition to the changes in the estuary's volume between 1867 and 1956, of greater notice are the patterns of these changes summarized in Table 6-1 as surface areas between different depth intervals for the three bathymetric surveys. The fact that between 1867 and 1995 the intertidal (+1 to +2m) areas almost disappeared and the subtidal (0 to -2m) areas increased by approximately 11% can be explained by the increased amounts of sediments deposited in the Bay during the HIP and the subsequent changes in the estuary's hydraulics.

Table 6-1. Percentage of the Bay's bottom within different depth intervals in relation to MLLW [after Bernert and Sullivan, (1998)].

<b>Interval (m)</b>	<b>1867</b>	<b>1956</b>	<b>1995</b>
<b>+2 to +1</b>	1.1	0.09	16.06
<b>0 to -2</b>	80.45	91.15	70.7
<b>-3 to -5</b>	16.08	7.10	10.08
<b>-6 to -8</b>	1.69	1.20	1.69
<b>-9 to -11</b>	0.55	0.33	0.96
<b>-12 to -14</b>	0.13	0.11	0.38
<b>-15 to -18</b>	0.01	0.03	0.13

#### **6.4 Sediment Budget**

Estuarine sediment budgets involve considerations of the rate of sand volume changes in an estuary in relation to processes that have resulted in gains or losses of sand through time. Processes that contribute sediment to Tillamook Bay include the five rivers, wind blown material from the dunes of Bayocean Spit, the transport of sediments into the Bay through the inlet due to waves and flood tidal currents, while

processes that result in losses of sediments from the Bay include flushing of sediments by the ebb currents and river flows, and human activities such as dredging and jetty construction. The application of a sediment budget to Tillamook Bay is an effective approach for evaluating the relative significance of sediment sources, which have been contributing to the shoaling of the estuary through time, and the effects of human impacts on the natural sedimentation regimes.

In Chapter 3 the sediment yields from the watersheds were assessed for three different time intervals. During the HIP (from 1933 to 1955) I estimated that the deposited sediment in the Bay was on the order of  $102.5 \times 10^5$  tons. Glenn (1978) reports that the rock fragments density is  $2.95 \text{ g/cm}^3$  ( $2950 \text{ kg/m}^3$ ), so the watershed sediment yield becomes  $4.51 \times 10^6 \text{ m}^3$  if it is assumed that 30% of this volume is void space. Komar and Terich (1976) focused on the changes of sand transport due to the construction of the north jetty and the 1952-56 breaching of Bayocean Spit. They established a budget of beach sediments and found that the amount of sand deposited in the Bay near the breaching area was  $1.5 \times 10^6 \text{ m}^3$ , and near the inlet of the Bay was approximately  $3.3 \times 10^6 \text{ m}^3$ . The total deposited beach and river sediment is therefore on the order of  $9.3 \times 10^6 \text{ m}^3$  during the 22-year HIP. This is more than the  $7.58 \times 10^6 \text{ m}^3$  that were calculated between the 1867 and 1956 bathymetric surveys. This difference can be explained by the fact that the average sedimentation rates between the different bathymetric surveys were calculated below the MLLW, and do not include the intertidal areas of the Bay where Bernert and Sullivan (1998) found the greatest amount of sediment accumulation. Also, not all of the material transported by the rivers was deposited in the Bay since some portion was deposited either within

the river channels or in the deltas, resulting in the observed delta propagation between 1867 and 1977 which is in the order of  $1.19 \text{ km}^2$  (Levesque, 1980). Finally, the Army Corps of Engineers records suggest that the total amount of dredged material between 1929 and 1979 is in the order of  $1.24 \times 10^6 \text{ m}^3$ , but we cannot include this value in our sediment budget since there is no reference concerning the amount of material dredged between 1933 and 1955.

Our assessment is for the 22-year period 1933-1955, yielding a sedimentation rate equal to  $1.22 \text{ cm/year}$  as opposed to  $0.68 \text{ cm/year}$  found by Bernert and Sullivan (1998). This suggests that almost all of the dramatic changes in the bathymetry of Tillamook Bay occurred during the HIP. Of course we cannot be absolutely certain about these estimates, but our results demonstrate that the dramatic changes in sedimentation in Tillamook Bay were likely due to human impacts mainly on the beaches, since most of the sand deposited in the Bay during the HIP came from the ocean beaches. This further suggests that a significant portion of the river sediments produced in the watersheds during the HIP is most likely still trapped within the channels of the main rivers.

## 7. SUMMARY OF CONCLUSIONS

Tillamook Bay was formed by the flooding of five coastal rivers, the Miami, Kilchis, Wilson, Trask and Tillamook Rivers, approximately 9,000 years ago when the rising sea-level inundated their valleys. The rapid sea-level rise that followed the last Ice Age marked the beginning of the Holocene sedimentation of Tillamook Bay, which began  $8,400 \pm 400$  years B.P. The thickness of the sediments deposited since the formation of the Bay has not been uniform, with sediment thickness increasing from the eastern margin towards the central and western parts of the Bay. The greatest sediment thickness is found in the deltas of the main rivers in the southeastern corner of the Bay.

Tsunamis generated by subduction earthquakes have occasionally contributed large amounts of sand in Tillamook Bay. The history of subduction earthquakes in the Northwest, as recorded in coastal sediments and fault scarps, suggests a re-occurrence period which ranges from 300 to 1000 years, with the last subduction

earthquake having occurred 300 ago, which generated a tsunami that was large enough to transport sand for significant distances into the Bay. An important mechanism for transport and deposition of marine sediments during and following a subduction earthquake is an abrupt subsidence of the coast, after which Bayocean Spit could be more easily overwashed or breached by major storms, so the addition of beach sand to the Bay after the earthquake in 1700 may have continued for a long time.

The first humans that settled into the Tillamook area about a thousand years ago were the Tillamook Indians, who lived in ten villages along the shoreline and in the river delta area. The primary environmental impact in the watersheds and floodplains that can be attributed to the Indians is the extensive burning of the areas surrounding the floodplains, but the extent to which this took place it is not known with certainty. The first Euro-American settlers began arriving in Tillamook Bay in the middle of the nineteenth century. By the turn of the twentieth century increased tree harvesting began to take place, together with the drainage of the floodplains, the construction of dikes along the channels of the rivers and in the Bay, and the construction of the north jetty at the entrance of the Bay for navigational purposes. The results of these practices soon became apparent, and generally included changes of the tidal circulation with extensive shoals forming near the entrance, concentrated river and sediment flows into the southeast Bay, and prevention of overbank sediment deposition in the floodplains. The rapid filling of the estuary at its southeast corner resulted in abandoning the navigational channels to Tillamook City and to Bay City in 1925.

The summer of 1933 marks the beginning of the Heavily Impacted Period (HIP) from 1933 to 1955, for the Tillamook watershed, which experienced one of the nation's largest fires in modern times. The series of fires burned almost half of the total watershed area (708 km<sup>2</sup>) during an 18-year period, and together with the construction of logging roads and salvage logging, the impacts resulted in high surface erosion rates in the watersheds. Comparisons of the annual water and sediment yields between the HIP and Normal Periods (NP from 1977 to 1998), indicate that the average annual water yields were enhanced by 9.84% by the human impacts, while between the same periods 1.6 times more sediment was produced from the watersheds. In addition to the major disturbances in the watersheds, the breaching of Bayocean Spit in 1952 contributed beach sands to Tillamook Bay. The north jetty constructed in 1917 was the cause of the erosion of Bayocean Spit, leading to its breaching (Komar and Terich, 1976). The gap was 1,200 m wide (1,600 m wide during high tides), and ocean swells passed into the Bay, transporting considerable quantities of beach sands. The breach was closed in 1956 by the construction of a dike, corresponding to the end of the HIP. The large amounts of sediment that had been deposited in the Bay during this period altered the tidal regime, so that up to the present the deposition of beach sediments in the Bay has been controlled by the flood currents, resulting in an increase in the intertidal areas, while ebb currents caused scouring of the deeper channels.

Following HIP the watersheds began to recover as reforestation efforts took place. The most common logging practice in the Tillamook Bay watersheds after the 1960's has been clearcutting in patches of 40 acres. The construction of a second

jetty on the south side of the inlet took place in 1974, and resulted in a more stable situation for the longshore sediment transport regime along Bayocean Spit, and a reduction of beach-sand input into the Bay.

After 1976 Tillamook Bay entered what I defined as the Normal Period (NP), since the watersheds had largely recovered and not many major disturbances have taken place. Even though surface sediment erosion during the NP has decreased, the most important source of sediments in the upper watersheds remains the generation of landslides along old and new forest roads, especially near stream crossings. Sediments from the watersheds are now mainly controlled by episodic flooding of the rivers which initially deposit their load throughout the Bay, with the estuary's tidal circulation then sorting the sediments with the coarser material remaining near the inlet and progressively finer material dominating the low-energy south part of the Bay.

River sediments consist mainly of rock fragments which are deposited in the eastern part of the Bay and comprise nearly 40% of the Bay's sediments, while beach sediments consisting mainly of quartz and feldspar dominate the western part of the Bay, and account for 60% of the total sediments. The depositional environments of the rivers and beach sediments in the Bay are mainly controlled by internal estuarine processes – tides, the estuarine circulation and wind-generated waves.

In conclusion, the intense human activities in the watersheds, in the estuary, and along the beaches of the large Tillamook Bay ecosystem resulted in significant changes in the sediment sources, the quantities derived from these sources, and the deposition patterns of sediments in the Bay. The results of this study emphasized and

attempted to quantify the practices that have been important to sedimentation in the Bay, and suggest that there was a “pulse” of increased sedimentation from 1933 to 1955 during the Heavily Impacted Period. Similar periods of increased sedimentation likely occurred in the past due to tsunamis and other natural processes, but following those events the estuary would eventually have achieved a natural equilibrium, returning gradually to its normal conditions.

The human impacts though have proved to be irreversible, and it has become apparent that it will take the Bay a very long time, if ever, to recover to its natural state, demonstrating the importance of these human activities over long-term scales. The entire Tillamook Bay ecosystem is still functioning under various land use practices, and has reached a new sedimentation regime compared with earlier this century. The main question that arises is *How will Tillamook Bay look in a hundred years from now assuming that the present sedimentation regime remains the same?*

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