

POTENTIAL IMPACTS OF TIMBER HARVESTING, CLIMATE, AND
CONSERVATION ON SEDIMENT ACCUMULATION
AND DISPERSAL IN THE SOUTH SLOUGH
NATIONAL ESTUARINE RESERVE,
OREGON

by

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A THESIS

Presented to the Department of Geological Sciences
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Science

September 2015

THESIS APPROVAL PAGE

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Title: Potential Impacts of Timber Harvesting, Climate, and Conservation on Sediment Accumulation and Dispersal in the South Slough National Estuarine Reserve, Oregon

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Degree awarded September 2015

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THESIS ABSTRACT

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Geological Sciences

September 2015

Title: Potential Impacts of Timber Harvesting, Climate, and Conservation on Sediment Accumulation and Dispersal in the South Slough National Estuarine Reserve, Oregon

Accurate sediment flux histories are critical data for deciphering the relative importance of climate and land use factors such as logging and road construction on sediment production and deposition. We use ^{210}Pb activities derived from sediment cores taken on the tidal flats of the South Slough of the Coos Bay estuary to establish temporal variations in sediment accumulation rates. We determined that average deposition varied between 0.4 and 0.81 cm/yr based on two ~80 cm sediment cores. Sedimentation accumulation rates approached 2.1 cm/yr during the 1960s when a rainfall event of extreme intensity coincided with vigorous timber activity. Following this peak, a >40% reduction in peak lumber harvests in the latter part of the 20th century was accompanied by a decrease in sedimentation rates. Mean monthly rainfall during the same time period remained seasonably constant, indicating that land use is likely the key factor governing variations in sediment accumulation.

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ACKNOWLEDGMENTS

I am thankful and appreciative of the years of guidance provided me by Joshua Roering and the excellent laboratory group that he assembled. Special thanks to Corina Cerovski-Darriau and Brian Penserini for their consulting support on technical aspects of this project, as well as to Jim Palandri for keeping the gamma counter running. I am grateful to David Sutherland and Daniel Gavin for serving on my thesis committee, securing the Oregon Sea Grant that has funded this study and my degree, and organizing the field campaign that provided the necessary data for this manuscript. Lastly, thank you to Timothy Chen and Evan Baker, my housemates while pursuing my Masters, for their defense of the ancients: patience, encouragement, and community.

Dedicated to Cecelia, who reminds me that courage is a virtue.

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CHAPTER I

INTRODUCTION

Sediment accumulation rates in estuaries are directly related to upstream processes such as increased rainfall, accelerated erosion, and changes in catchment morphology (Sadler, 1981). Though the precise distributions and geometries of sediment accumulation in estuarine systems with both marine, tidal and fluvial influences are often difficult to ascertain, fluctuations in sediment accumulation rate can be linked to natural and anthropogenic perturbations (Gomez, Carter, & Trustrum, 2007; Pasternack, Brush, & Hilgartner, 2001). The relationship between accumulation rate and these upstream effects varies from site to site, primarily due to sediment dispersal, excessive deep mixing and lag times in sediment delivery to the basin (Lebeuf & Nunes, 2005). Sediment dispersal by tides, currents and proximity of fluvial mouths into the estuary can confound attempts to quantify upstream effects. Excessive deep mixing by organisms has been shown to greatly skew traditional dating techniques, further obscuring the connection (Benninger, Aller, Cochran, & Turekian, 1979). Although these areas of uncertainty exist, it is still possible to detect a robust connection between catchment changes and sediment accumulation if both are properly spatially and temporally constrained.

Previous studies have determined that forest removal can dramatically increase sediment transport from hillsides, especially when combined with road construction (Luce & Black, 1999). Intense precipitation — such as centennial frequency events — have also been shown to deliver high amounts of sediment into fluvial systems in the form of debris flows and landslides (Robison et al., 1999). These climatic and land use catalysts for sediment accumulation can be seen both in coastal systems such as estuaries

as well as in the near shelf environment (Van Eaton et al., 2010; Robert A Wheatcroft, Goñi, Richardson, & Borgeld, 2013). Sediment accumulation rates also tend to decrease with increasing water depth and distance from fluvial inputs (Smith & Walton, 1980). Although many studies have documented sediment perturbations due to logging, intense and/or protracted storms, or dam construction, few have successfully documented whether these perturbations can be reversed by conservation efforts over decadal timescales. By establishing accurate sediment chronologies in areas where we have extensive historic data of both heavy logging and conservation, we can attempt to discern how sediment accumulation responds to these factors.

The Coos Bay Watershed (Fig. 1) is home to the South Slough National Estuarine Research Reserve, the first such ecosystem protected under the Coastal Management Act of 1972. Understanding the ecological and geological processes at work in the estuary is a key aspect of the mission of the reserve. The South Slough is perfectly suited to the goals of this study for several reasons. First, there is an historic record, including aerial photography and USGS hydrological gaging, for the area, allowing for accurate temporal and spatial correlation. Second, Coos County, location of the estuary and the Sough Slough, saw dramatic land use changes and extensive logging in the middle part of the 20th century and at no time prior. This stands in stark contrast to other coastal systems in North America, where logging has been ongoing for hundreds of years, and allows for an accurate assessment of the effect of initial deforestation on sediment budgets. Finally, the radioisotope that we use to construct sediment chronologies, ²¹⁰Pb, possesses a half life of 22.3 years, allowing it to record sediment accumulation rates in the estuary for ~100yrs or ~4 half lives (Nittrouer, Sternberg, Carpenter, & Bennett, 1979).

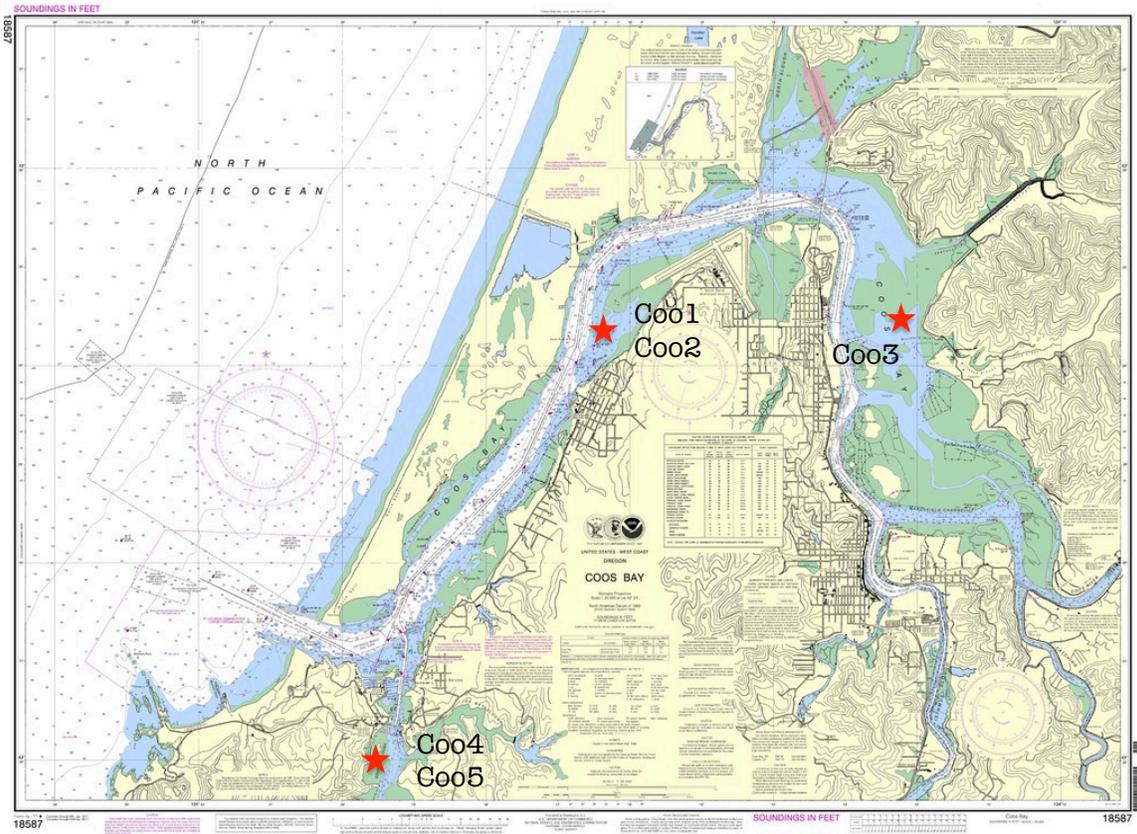


Figure 1: Bathymetric and topographic map of the Coos Bay estuary marked with core collection locations. Cores 1 and 2 correspond to main channel deposition, Core 3 was collected on an active oyster farming bed and therefore discarded, and Cores 4 and 5 were collected from a tidal flat in the South Slough. Core 1, proximal to a dredging channel, was found to possess anomalously high ^{210}Pb levels with little evidence for normal decay and could therefore not be used.

Owing to this multi-decadal timescale, it is unusual to find a site like the South Slough which has a 20th century record containing both intensive land use followed by catchment-wide conservation. The diverse history, relatively small spatial scale, and complete records of the South Slough watershed make it the ideal location for observing the connection between sediment accumulation rates, climate, and land use.

Sediment accumulation rates have been observed in fluvial and estuarine systems before (Brush, 1984; Colman et al., 2002; Van Eaton et al., 2010; Wei et al., 2007), ranging from low accumulation, sediment-starved, passive margins to swift, mountainous

stream systems. Low accumulation levels lie between 0.1 and 0.4 cm/yr and mostly occur in deep water far from fluvial inputs. Sediment accumulation rates can be much higher, ranging as high as 6-7 cm/yr when large sediment sources are present (Wei et al., 2007). Many of these high rates, however, were found on passive margins and in locations where human activities have been altering the landscape for centuries. There does not appear to be a significant difference between passive and active margin rates; the individual coastal system and not the overall tectonics appear to set the range of sediment accumulation rates (Van Eaton et al., 2010; Wei et al., 2007; Robert A Wheatcroft et al., 2013). To establish a cause-and-effect relationship between upstream perturbations and sediment deposition, an accurate sediment chronology, detailed logging records, complete aerial photography coverage and stream gage records are prerequisite. Having all of these data in the South Slough, we aim to provide a rigorous connection between how climate and land use change can affect estuarine systems proximal to mountain ranges.

Part of the difficulty in constraining sediment accumulation rates in coastal systems are the numerous dispersal processes that can obscure sediment production processes. Distinctions have been made between marine-dominated dispersal systems and fluvial-dominated dispersal systems (Robert A Wheatcroft et al., 2013). River sediment load, tidal range, mean wave height and proximity to freshwater inputs are all used to classify what type of dispersal might be in effect. The South Slough lies at the perfect intersection of these two regimes and might provide some evidence as to which process is more influential in estuarine systems.

In this paper, we aim to a) quantify the sediment accumulation rates over the past 100 years in the South Slough of the Coos Bay estuary, b) correlate variations in sediment accumulation with upstream natural and anthropogenic causes, especially with regards to the effects of conservation efforts and the cessation of logging in the watershed, and c) compare our results to other emergent terrain estuaries such as the Columbia River and Umpqua rivers to better quantify modern estuarine sedimentation rates in the Pacific Northwest.

CHAPTER II

METHODS

2.1. Study Area

The South Slough Watershed spans 78.3 km² in a narrow, mountainous catchment bounding the marshes and channels that constitute the slough (Fig. 2). The watershed bedrock is formed by the Coaledo Formation, an Eocene-aged sequence of sandstones, siltstones and shales deposited in deep marine seas and shallow coastal waters during periods of sea level transgression and regression (Madin, I.P., G.W. McInelly, 1995). Miocene and Pliocene deposits and Quaternary marine-cut terraces overlie this bedrock. The South Slough rests atop an asymmetrical, gently dipping syncline with the west side comprised of steeply dipping Miocene and Pliocene sandstones while the east side is comprised of gently sloping marine terraces (Madin, I.P., G.W. McInelly, 1995). This geomorphic difference is actually of critical importance when it comes to sediment delivery and land use throughout the 20th century. The eastern marine terraces were logged far more extensively than the western slopes, where logging occurred proximal to the ridgeline. The key coring locations in this study — Cores 4 and 5 — lie on tidal flats on the western margin of the estuary.

Sea level rise during the Holocene has greatly influenced the development of the South Slough. Sea level has been rising at a rate of 1.4 mm/1000 years for the past 4000 years, creating accommodation space for sediment infilling in the slough (Nelson, Ota, Umitsu, Kashima, & Matsushima, 1998). Although regional uplift — typically between 2.1 – 2.3 mm/yr — has been shown to out pace sea level rise in many parts of the Cascadia Subduction Zone (Burgette, Weldon, & Schmidt, 2009), the synclinal structure

of the South Slough may be responsible for a lack of uplift in the South Slough, allowing for the deposition of the tidal flats (Rumrill, 2007). The tidal flats from which cores 4 and 5 were taken are between 1000 and 2000 years old, according to radiocarbon analysis (Peterson, 1994).

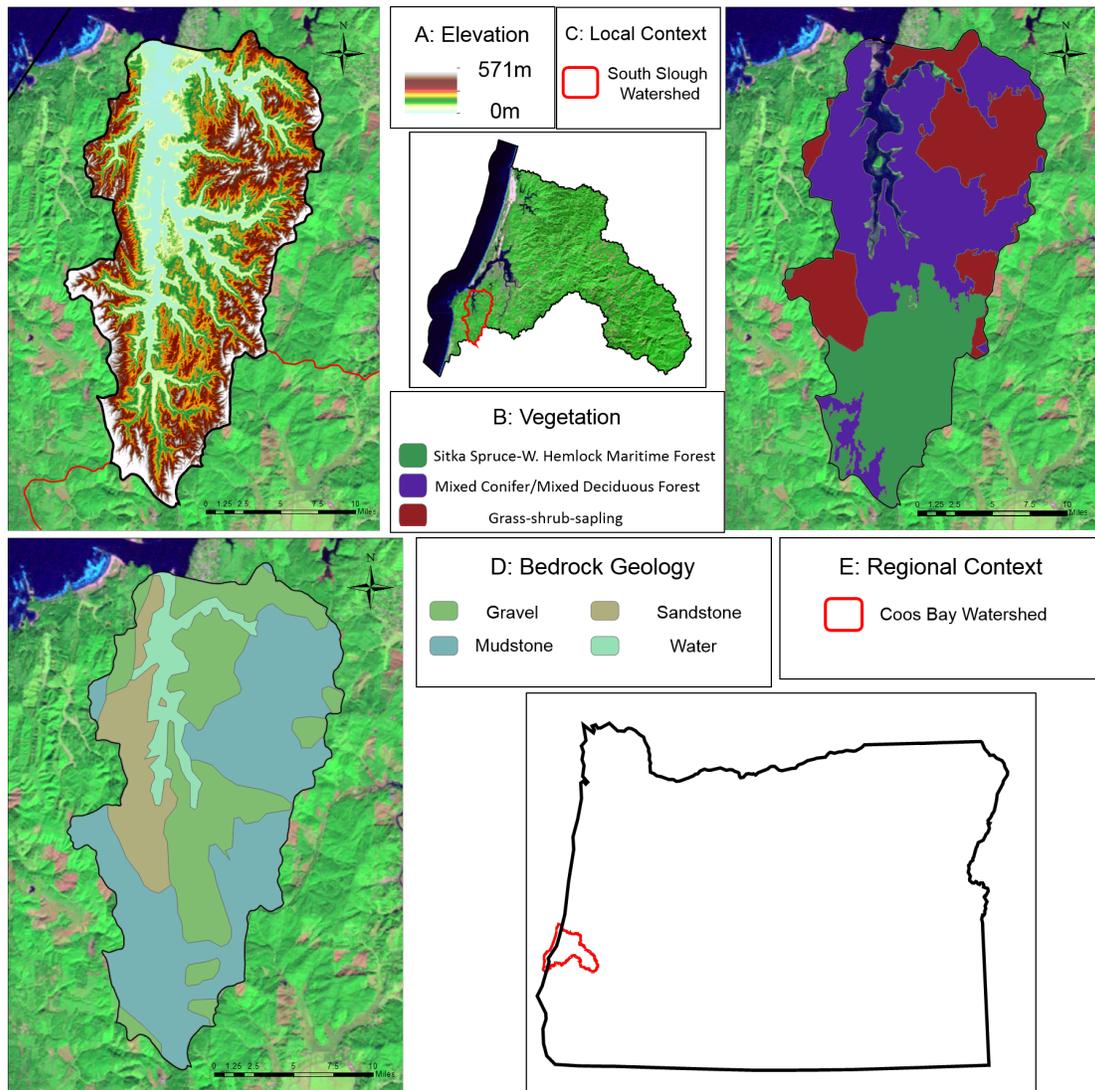


Figure 2: Maps of the South Slough watershed showing a) elevation, which is highly variable throughout the narrow watershed, being more steep in the western flank and gently sloping in the eastern flank, b) major vegetative cover at present day from the OregonGAP Analysis Program, c) local context within the greater Coos Bay estuary and watershed, d) the bedrock geology from the U.S. Geological Survey and e) the regional context of the Coos Bay watershed within the state of Oregon.

Climate in the Oregon Coast Range is highly seasonal with wet and stormy winters giving way to dry summers. January is typically the wettest month with 40 cm of rainfall while less than 10 cm is typical of the summer months. Sediment delivery is thought to be tightly coupled with precipitation in the Coast Range and particularly with heavy storm events (Beschta, 1978; Kulm & Byrne, 1966). Three gaging stations, the Coquile River (43°09'28.59"N, 124°10'54.46"W), Tenmile Creek (43°34'35"N, 124°11'30"W), and the west fork of the Millicoma (43°28'35"N, 124°03'20") give relatively continuous flow data for the region from 1954 through the present, capturing all major storm and drought events during that time period. There are currently 5 active gaging stations operating within the South Slough itself, but these only have complete data since 2011, with one going as far back as 1983.

There are more than 255 km of streams moving freshwater into the South Slough from the east, west, and south (Stone, 1987). These inputs are highly seasonal, with six perennial streams and over 30 intermittent creeks. Like in most of the Oregon Coast Range, the streams of the South Slough experience their greatest discharges in the winter months. The Hayward Creek drainage is the most proximal to the core samples collected in this study, although it is one of the smallest streams in the watershed, providing 0 to 0.6 m³/s depending on the time of year (Harris, D.W., W.G. McDougal, W.A. Patton, 1979). The South Slough experiences significantly less tidal flushing than does the main channel of the Coos Bay estuary but is still flushed completely every 3 days (C. Wilson, 2003). This leads to an estuary that is well mixed vertically, allowing for relatively constant vertical salinity (O'Neill, 2014).

The upland forests of the South Slough watershed are relatively characteristic of a temperate coastal rainforest. Western hemlock and Sitka spruce as well as Douglas fir dominate the watershed, the exact geospatial distributions of which can be seen in Figure 2. Timber harvesting of these populations began in the 1850's but did not become intensive until after World War II. Many of the clear-cut sites in the South Slough watershed were replanted in the late 1950's with Douglas fir. Understory vegetation composed of ferns and shrubs grow in the deep moist soils that lie underneath the trees, leaving little bare ground (Rumrill, 2007).

Road development in the uplands of the South Slough watershed was prevalent during periods of significant logging, but few of these roads were permanent black-top and most have since been abandoned. As of the writing of this paper, most of the South Slough watershed is dominated by 30 to 80 year-old conifer forests, as logging has been curtailed due to the area's protected status (Rumrill, 2007).

2.2. Sample Collection and Analysis

We collected four sediment cores in March 2014, varying from 64 to 84 cm in length. These cores were collected on a cruise by the R/V *Pugettia* along the margins of the main channel of the estuary and in the tidal flats of the South Slough. We employed Push cores constructed from acrylic tubes with expandable plugs were used, with samples being taken in 1-2.5 m water depth. Once collected the cores were stored vertically to avoid mixing and transported to the University of Oregon. We carried out a CT scan on two of these cores at the Oregon State Animal Hospital to assess their cohesion and the severity of mixing that they exhibited (Fig. 3). Three cores, Cores 1, 4, and 5, were extruded in 1cm increments, air-dried, ground by mortar and pestle to a fine-grain, and

placed in separate, pre-weighed screw top storage containers. Wet and dry masses of each 1cm horizon were taken. Between 25 and 70g of sediment were counted for 24 – 48 hours on a CANBERRA low energy germanium detector, and the 46.5 and 661.6 keV photopeaks were used to quantify ^{210}Pb and ^{137}Cs activities, respectively (Robert A Wheatcroft et al., 2013).

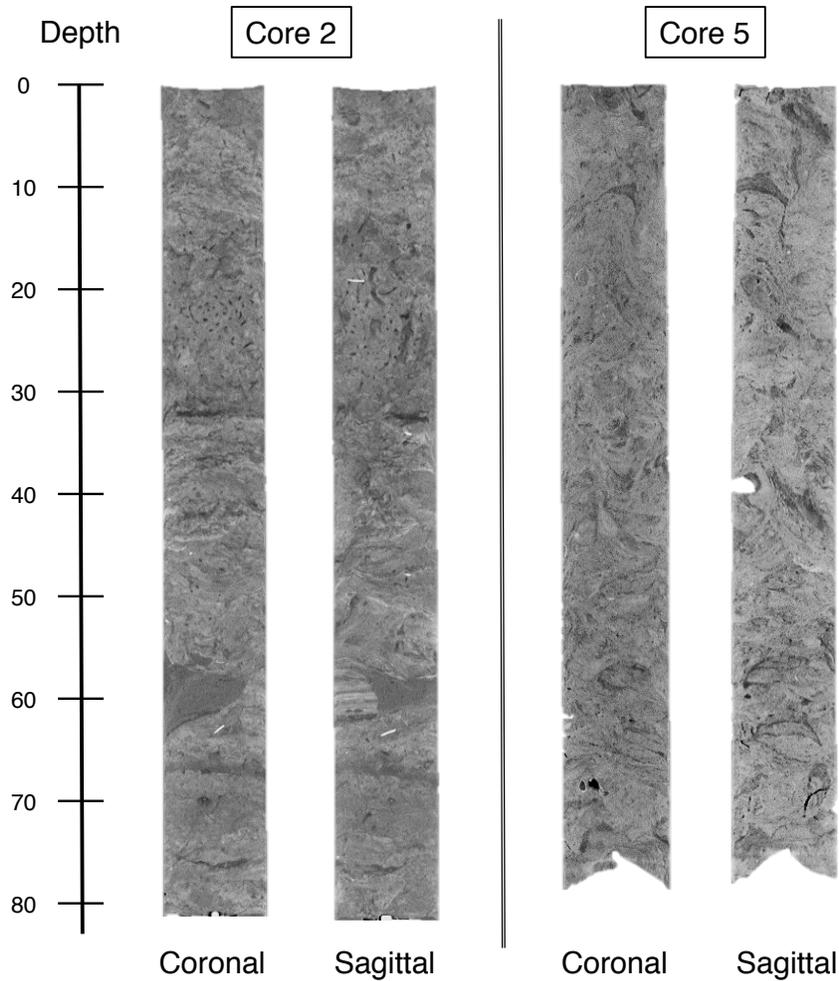


Figure 3: CT-Scans of Cores 2 and 5 taken at the Veterinary Hospital at Oregon State University. Both cores appear to be extensively mixed, with Core 2 exhibiting evidence of non-biotic disturbance in its lower section.

By measuring the abundance of the atmospheric radionuclide ^{210}Pb in several core samples collected from the Coos Bay estuary and the South Slough, we can provide reliable geochronological information for estuarine sedimentary deposition occurring

over the past ~100 years. Most ^{210}Pb is delivered to estuarine systems through a combination of atmospheric deposition, oceanic input, and catchment runoff (P G Appleby & Oldfield, 1978). ^{210}Pb rapidly absorbs onto sediment particles, accumulating on estuary bottoms. By distinguishing the “excess”, or “unsupported” activities of ^{210}Pb ($^{210}\text{Pb}_{\text{xs}}$) from the background, or “supported” activities, it becomes possible to achieve time-dependent sedimentation rates. Considering ^{210}Pb soil accumulation varies with the rate of deposition, it can be used to elucidate anthropogenic and climatic changes to sediment supply for a closed system (P.G. Appleby, 2008).

Here, we use a constant rate of supply (C.R.S.) model for $^{210}\text{Pb}_{\text{xs}}$ generation. In contrast to the constant initial concentration (C.I.C.), which assumes that sediments possess a constant $^{210}\text{Pb}_{\text{xs}}$ level, the C.R.S. model assumes that $^{210}\text{Pb}_{\text{xs}}$ varies with the amount of sediment supplied to a system. Because sedimentary systems often experience varying levels of sediment input, the C.R.S. is more reliable for most coastal systems (P.G. Appleby, 2008).

One of the most common complications with gamma-ray detection is self-absorption that occurs during the counting process. Gamma rays generated in the upper part of a sample must pass through the body of the sample before hitting the detector crystal, during which time they can be reabsorbed and therefore not counted. To mitigate this error, we applied a point source correction by running a uranium standard resting on top of a large sample size of core samples with varying masses. By regressing the gamma ray counts across a range of masses, we were able to determine the influence of mass on self-absorption and therefore correct the $^{210}\text{Pb}_{\text{xs}}$ activities accordingly for each sample.

By assuming that there was negligible mixing outside of the upper portion of the cores and that $^{210}\text{Pb}_{\text{xs}}$ was added to the system at a constant rate, we are able to estimate the relative age of each soil horizon and thereby calculate sediment accumulation rates given the relationship (P G Appleby & Oldfield, 1978):

$$t = \frac{1}{k} \ln \frac{A_0}{A_x} \quad (1)$$

where t is the age of a layer of depth x , k is the decay constant 0.0311 y^{-1} , A_0 is the total $^{210}\text{Pb}_{\text{xs}}$ activity in the core sample and A_x is the total activity below depth x . The larger the ratio between A_0 and A_x — the deeper the interval — the lower t and the younger the sediment. A least squares fit for the log of the horizon activity A against the depth yields a sediment accumulation rate for that section of the core. Alternatively, the sediment accumulation for a given soil horizon can be measured by the simple relationship:

$$S = \frac{\Delta x}{t} \quad (2)$$

where S is the sediment accumulation rate, Δx is the change in depth and t is years before present. Because we hypothesize that the South Slough experienced different sediment accumulation rates at different periods of its recent history, there should be multiple line fits for a given core. The inflection point between these lines can be used to interpret whether sediment accumulation was accelerating or decelerating, with positive inflections corresponding to increases in sediment delivery and negative inflections corresponding to decreases.

2.3. Photogrammetry

Aerial photo analysis is a key component of understanding the ^{210}Pb chronologies of each core as they provide spatial evidence for land use changes and show the proximity of logging activities to core locations. We scanned and analyzed historical

In addition to textural classification, road densities in the aerial photos were also measured. Each visible road was taken into consideration and then normalized to a km/km^2 based on the extent of the aerial photo mosaic in question.

CHAPTER III

RESULTS

3.1. ^{210}Pb Activities

Due to the length of time required to generate a complete activity profile, of the four complete cores taken only two (Cores 1 and 4) were run for their entire length. The upper 50 cm of Core 5 were also analyzed as a means of corroborating the age estimates from Core 4, as they were taken at the same location. Full $^{210}\text{Pb}_{\text{xs}}$ values from the gamma-ray detector are shown in Figure 5 and described below.

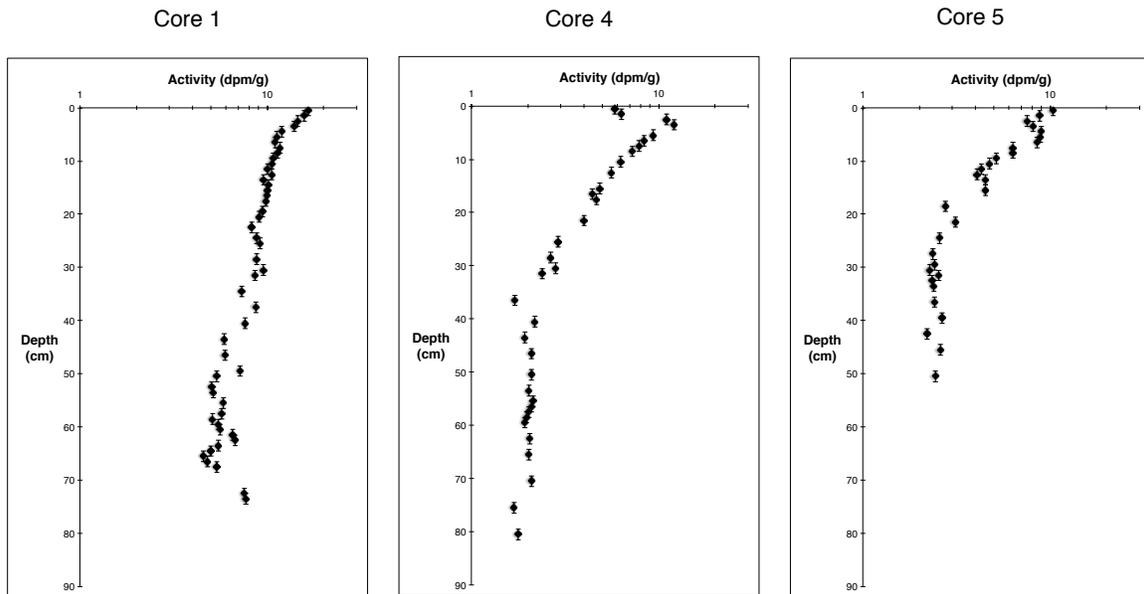


Figure 5: $^{210}\text{Pb}_{\text{xs}}$ activity profiles for Cores 1, 4, and 5. Cores 4 and 5 demonstrate the characteristic logarithmic decay expected and needed by the constant rate of supply (C.R.S.) model. Core 1 consistently exhibited higher activity levels that never approached a background, supported level. The speed of decay and shape of the decay curve are the basis for the C.R.S. model and yield sediment accumulation rates and accumulation inflection points.

Cores 4 and 5 both exhibit logarithmic decay of ^{210}Pb consistent with low-mixing deposition. Their surficial activities, both in excess of 10 dpm/g, decayed to a background level of ~ 2 dpm/g after 35 cm in Core 4 and 25 cm in Core 5. The upper 5 cm of each

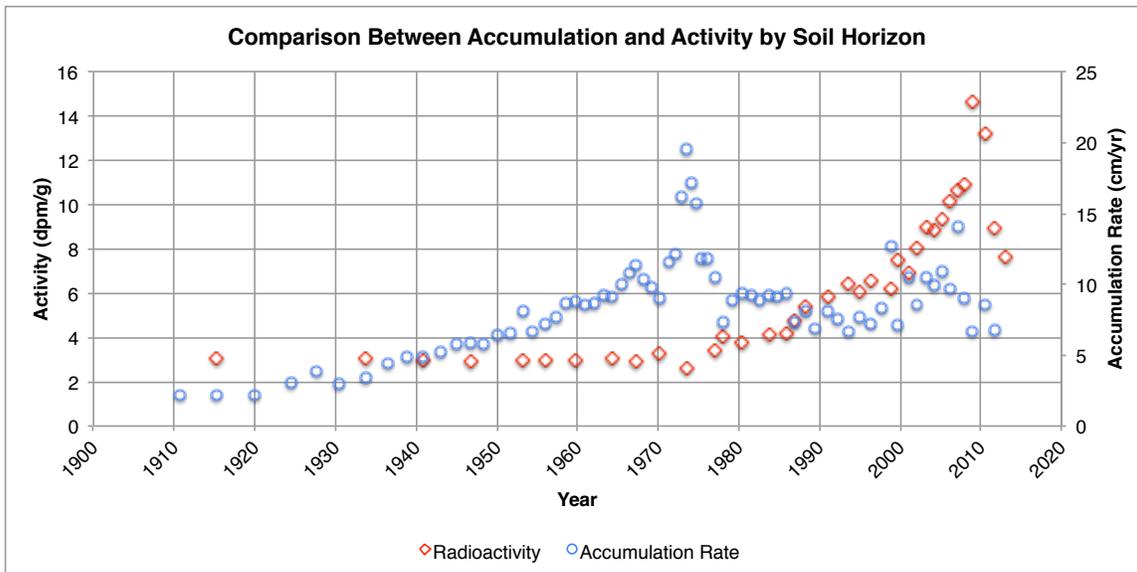


Figure 6: $^{210}\text{Pb}_{\text{xs}}$ activity (red) and sediment accumulation rate (blue) for Core 4, one of the two tidal flat cores. Relative low points in radioactivity correspond to high sediment accumulation rates. The core indicates a period of high sediment accumulation in the early 1970s followed by a relative low period.

sample exhibits heavy mixing, with highly variable activity level. Because of this mixing, it is important only to consider the unmixed layer beneath the upper 5 cm of mixing when calculating age estimates. The C.R.S. model, applied to Cores 4 and 5, indicates average sediment accumulation rates of 0.86 cm/yr and 0.51 cm/yr, respectively. Although these core-averaged sediment accumulation rates can provide a general idea of how quickly sediment accumulates in a basin over time, closer examination of the activity profiles provides information about the variation in sediment accumulation rate throughout the past 100 years.

Core 4 shows moderate mixing in the upper 5 cm, manifesting itself in a relatively low $^{210}\text{Pb}_{\text{xs}}$ activity of 7.63 ± 2.76 dpm/g at the top, increasing to a peak of 14.68 ± 3.83 dpm/g before decaying to a background level of ~ 2.0 dpm/g at a depth of 27 cm (Fig. 6).

This interval corresponds to ~30 years of sedimentation, giving an average rate of sedimentation of 0.9 cm/yr over the entire interval.

A series of uncharacteristically low $^{210}\text{Pb}_{\text{xs}}$ activities from 39 – 42 cm creates a window of high sediment accumulation rates (1.21 – 1.96 cm/yr) in the early 1970s. The $^{210}\text{Pb}_{\text{xs}}$ activities then increase slightly before slowing dropping to the background level of 2.0 dpm/g.

Core 5 displays a similar $^{210}\text{Pb}_{\text{xs}}$ profile to its companion Core 4. There is no initial interval of low $^{210}\text{Pb}_{\text{xs}}$ activities; the activity begins at 10.38 ± 3.23 dpm/g and rapidly decreased to <4 dpm/g in the first 20 cm. This interval corresponds to ~55 years of sedimentation, giving an average rate of sedimentation of 0.36 cm/yr, 0.54 cm/yr lower than that of Core 4. The low $^{210}\text{Pb}_{\text{xs}}$ values from 18 – 21 cm create a window of high sediment accumulation rates (0.51 – 0.68 cm/yr) in the late 1960s. Unlike in Core 4, there is a second period of heightened sediment accumulation rates at 27 – 33 cm that corresponds to accumulation rates from 0.79 – 1.04 cm/yr in the mid-1950s. Although this second peak is unaccounted for in Core 4, it is encouraging to have duplicate peaks at nearly the same time period in two adjacent cores.

The discrepancy in the sediment accumulation rates given by Cores 4 and 5 are, in part, a consequence of the difference in the length of their profiles. Because the $^{210}\text{Pb}_{\text{xs}}$ inventory, A_0 , is a sum of the activities for each horizon of the core, longer cores yield slower burials (having greater ratios between A_x and A_0). For this reason, it is advisable to take and analyze cores of similar length.

Core 1, the main channel core, yielded much higher $^{210}\text{Pb}_{\text{xs}}$ than either Core 4 or Core 5 with a surface activity of 16.6 ± 4.1 dpm/g (Fig. 5). This high surficial value

decayed comparatively slower than the tidal flat cores, maintaining $^{210}\text{Pb}_{\text{xs}}$ activities greater than 7.0 dpm/g for the first 40 cm of the core. Though the activity decreases to a low of 5.1 ± 2.2 dpm/g by 52 cm depth, it slowly increases again from 53 – 63 cm. Because the C.R.S. model necessitates that the $^{210}\text{Pb}_{\text{xs}}$ converge on a background, supported level for ^{210}Pb , it is impossible to apply the model to this core. This was likely a consequence of anthropogenic disturbances to the core post-deposition, as the sampling site lies close to a dredged estuary channel.

3.2. Land Use Change

The vast coniferous forests of the Pacific Northwest have, since the late part of the 19th century, been actively logged to provide timber to fuel local and state economies. This intense form of land management has brought with it a host of profound ecological, geochemical, and geomorphological changes throughout the region (C. G. Wilson, Matisoff, & Whiting, 2007). Anthropogenic changes in watershed use were quantified in two main ways; first by historical timber sales in Coos County compiled by Andrews and Kutara (2005) and second by analysis and classification of aerial photos dating back to the 1940s.

The historical timber sales furnish a general trend for logging activity throughout the county but do not provide specific spatial data as to where and exactly when those stands were harvested. They do, however, give a general idea of when logging activity peaked in Coos County and when the most intensive infrastructural development occurred. This data (Fig. 7), used in conjunction with the aerial photos, provides additional geospatial constraints on key anthropogenic processes that occurred in the South Slough like road building and clear-cutting.

The timber sale data are subdivided into public and private sales, which indicate that although timber production peaked between 1950 and 1975 at 7×10^8 board feet, private sales have held consistent at $2 - 4 \times 10^8$ board feet since data first started being recorded for them in 1961.

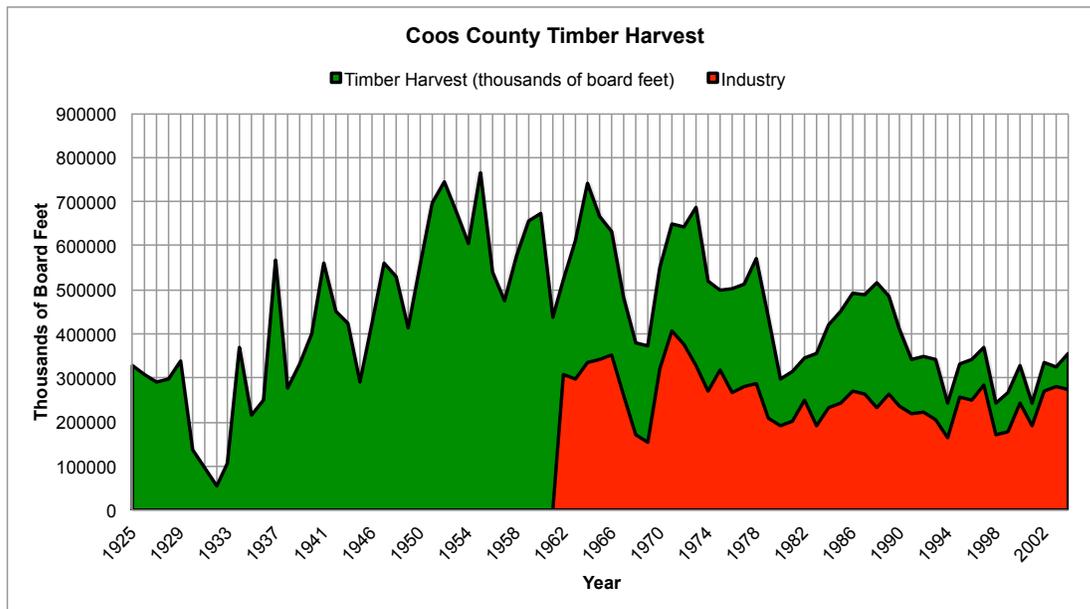


Figure 7: Timber harvest abundances for Coos County, Oregon derived from tax record data. According to these records, timber harvesting peaked between 1952 and 1974 and underwent a sharp then steady decline beginning in 1980. The green slice corresponds to total timber harvest while the red slice corresponds to private timber harvest. Private harvest remained relatively consistent even after the downturn in 1980.

The aerial photogrammetry provides necessary details about land use in the South Slough throughout the 20th century: how far clear-cut and regrowth areas are from coring sites and approximate timeframes under which the South Slough was logged and reforested. The first available images from 1942 show a relatively undeveloped catchment, with more than 68% of the visible catchment exhibiting dense, old forest and only 3.81% showing evidence of logging. Contrast this result with the distribution of

forest stand age in 1969, when 27.3% of the visible catchment has been recently deforested and only 17.9% of the old growth remains (Fig. 8).

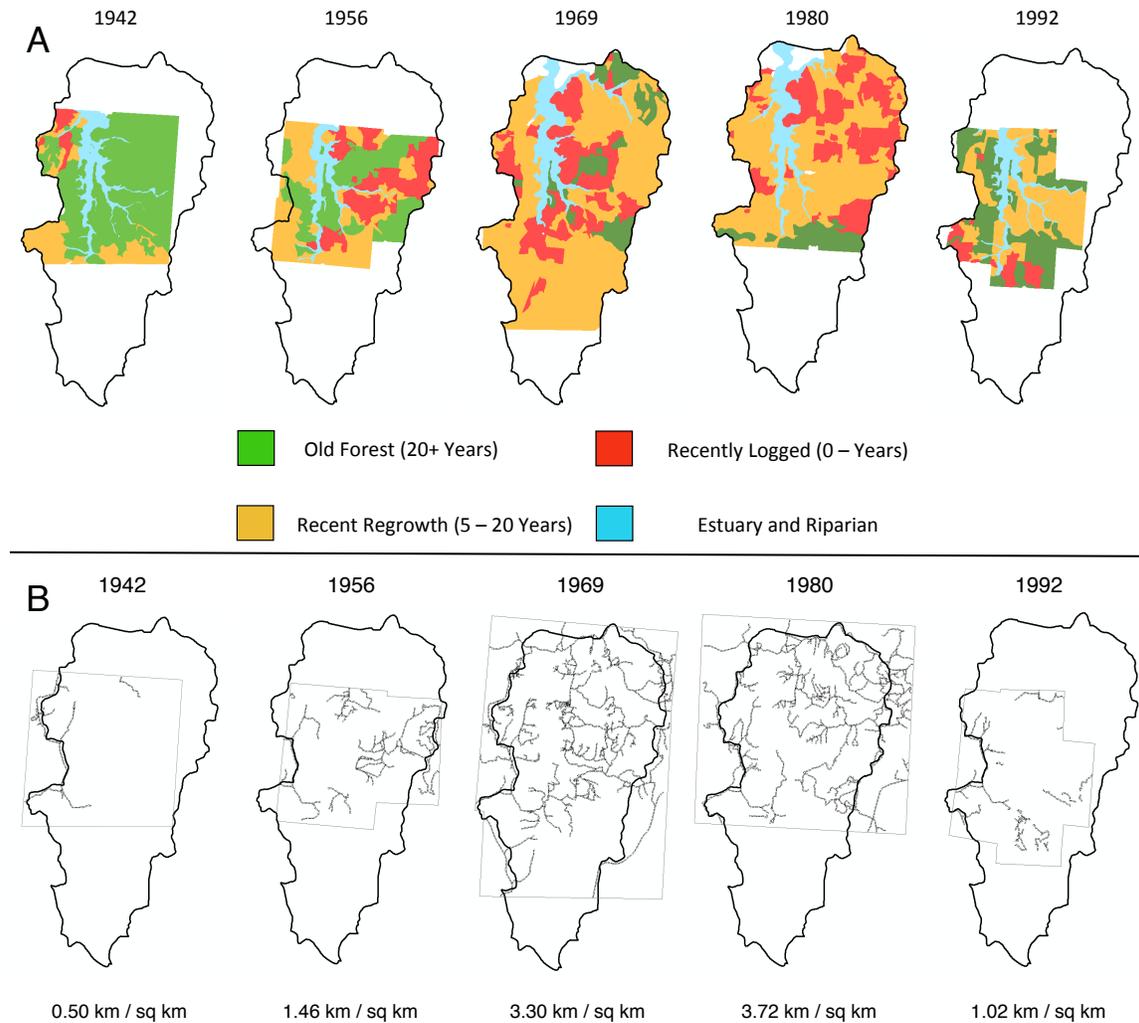


Figure 8: Results of the photogrammetry section of the study. The evolution of a) logging and b) road development in the South Slough from analysis of historic aerial photos. Logging peaked in the South Slough in the late 1960s, and began to slowly decrease in the early 1980s, ultimately resulting in the moderate regrowth we see in 1992. Most clear-cutting occurred on the gently-sloping western flank of the watershed. Intensive logging was mostly conducted on the more gently sloping eastern side of the slough. Grey boxes in b) indicate the extents of the aerial photos for those years.

This suggests that logging in the South Slough watershed differed from logging in Coos County in general in that logging intensity dropped dramatically by the late 1970s, about a decade prior to when Coos County experienced its greatest decline. The 40-year interval between the cessation of logging in the South Slough watershed and the present allows for regrowth to have occurred in the catchment, providing an opportunity for us to resolve the effects of regrowth on sedimentation rate.

The most intensive logging activity, according to this analysis, occurred between the mid 1960s and late 1970s. Road density analysis also corroborates this time interval (Fig. 8), increasing to a peak in the 1970s and then being abandoned in the last 15 years of the 20th century. 1969 and 1980 possess by far the highest road density, each with over 3 km/km² for the aerial photos. The next closest year is 1956 at 1.46 km/km². The fact that many of the roads seen in the 1980 aerial mosaic had become so overgrown and indistinct by 1992 suggests that these roads were not actively used after 1980, further affirming the decline of logging in the watershed.

3.3. Climate Data

Hydrological data from four gaging stations in or near Coos County were used in this study. In addition to the three stations mentioned in the Methods section — the Coquille, Tenmile, and Millicoma stations — the North Umpqua river station was also used, as it provides data back to 1906. Discharges in these representative rivers fluctuate from nearly 0 cubic feet per second in the summer months to between 700 and 1300 cubic feet per second in the winter months (Fig. 9).

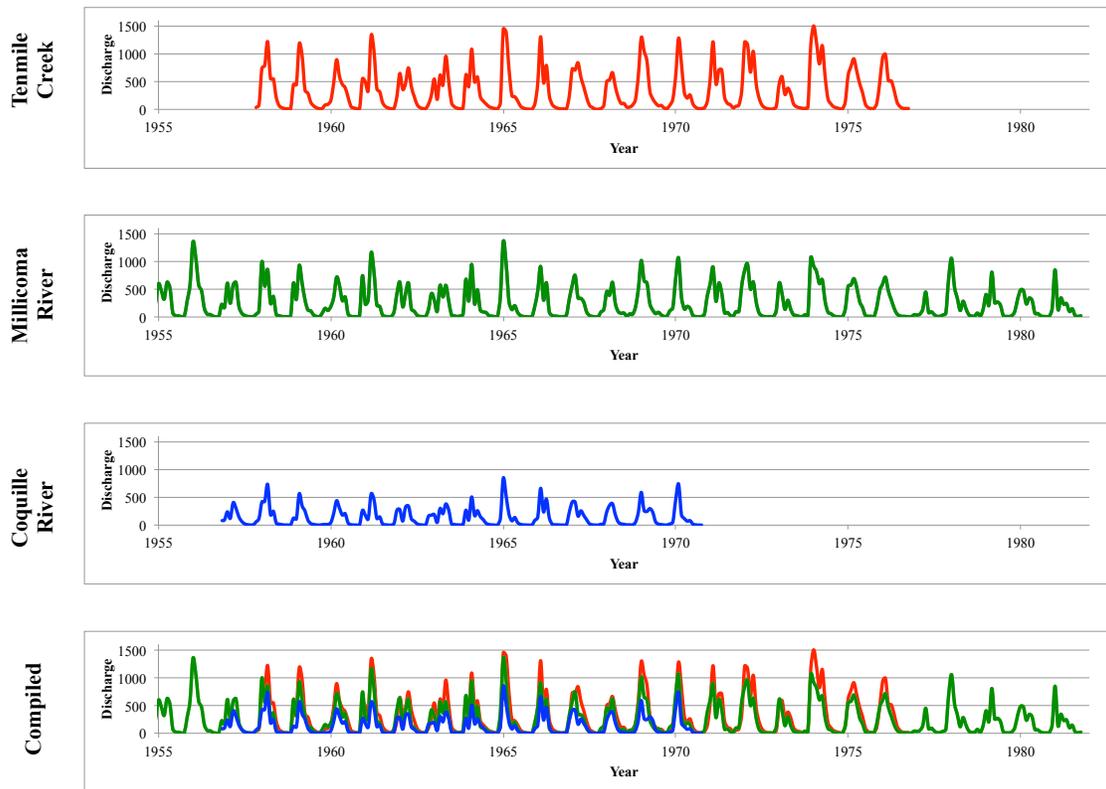


Figure 9: Monthly average discharges (in cubic feet per second) for Tenmile Creek and the Millicoma and Coquille Rivers, the three closest long-term USGS gages to the South Slough watershed. Discharge in the Oregon Coastal Range is highly seasonal, dropping by an order of magnitude in the summer months while rising during the winter. January is the wettest month of the year, averaging over 40 cm of precipitation.

When it comes to understanding the sediment accumulation history of the estuary, peak stream flow tends to be a useful metric, as large storm events are usually those most responsive for large depositional events in this region (Baker, 1978; Robison et al., 1999). For this reason, when correlating sediment accumulation rates from the tidal flat cores, we compare against peak flows: they are those most likely to disperse sediment in an estuary or shelf (R A Wheatcroft, Sommerfield, Drake, Borgeld, & Nittrouer, 1997).

CHAPTER IV

DISCUSSION

4.1. Decadal Sedimentation Trends

The activity profiles generated by this study show both local spikes and dips in sediment accumulation rate as well as longer term, decadal trends in deposition. The most striking sudden change in sediment delivery manifested in the cores is a major spike in sediment delivery in the 1970s. Sediment accumulation jumps to over 2.0 cm/yr, the highest value indicated by any of the core profiles and significantly higher than the 0.86 cm/yr average value over the past 100 years. This spike in sediment accumulation rate is key to understanding the overall dynamics of the South Slough and what catchment changes are most important in affecting sediment delivery.

Although there is a distinct spike in sediment accumulation in the early 1970s, the period following this spike yielded some of the lowest sedimentation rates in the entire core. The data from Cores 4 and 5, those taken on the tidal flats of the South Slough, indicate an apparent decrease in recent sediment accumulation rates. The main evidence for this change comes from the inflection points found at the 13 cm horizon in Core 4 and the 14 cm horizon in Core 5 (Fig. 10). At each of these points the line of linear regression through the semi-log scatter plot inflects, becoming shallower. A shallowing trend in semi-log space corresponds to an increase in sediment accumulation since activity falls off slower with depth. This implies that sediment accumulation rates were higher in the middle sections (~13 – 30cm) of the core than in their upper parts. Although such inflections could be the consequence of bioturbation mixing that confounds the activity profiles, numerous studies have indicated that this type of deep biodiffusive mixing does

not occur in shallow shelf and estuarine environments in this region (Nittrouer, DeMaster, McKee, Cutshall, & Larsen, 1984; Robert A Wheatcroft et al., 2013). Because bioturbation mixing is mostly limited to the upper 5 cm of these tidal flat deposits, we can therefore conclude that any systematic variation in the activity profile is the consequence of changes in sediment accumulation rate and therefore a change in catchment characteristics.

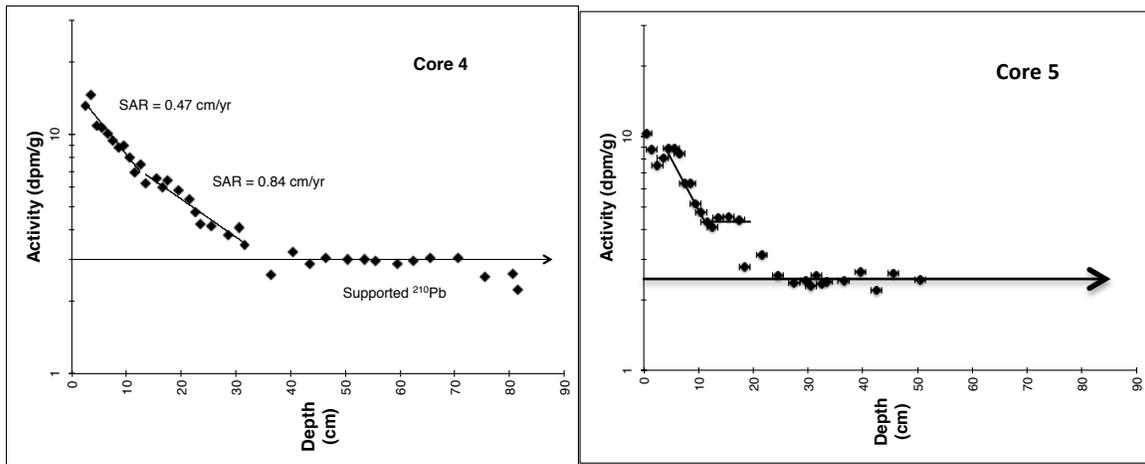


Figure 10: ²¹⁰Pb_{xs} activity curve for Cores 4 and 5 plotting the inflection point between recent low sediment accumulation rates (0.47 cm/yr) and previous higher sediment accumulation rates (0.84 cm/yr). This point occurs in 1988 ± 7 years and may signal the transition into South Slough conservation and increased tree cover in the watershed. Irregular decay in Core 5 prevented statistically significant regression for the inflection point.

The greater the initial level of unsupported ²¹⁰Pb in a given core, the more accurate the C.R.S. method is at resolving fluctuations in sediment accumulation. Most studies using ²¹⁰Pb_{xs} use cores whose surface activities are at or above 10 dpm/g for the first 10 cm, owing to slower rates of accumulation. When there is surficial mixing combined with rapid sediment accumulation, the C.R.S. model fails to properly resolve years and rates. Cores 4 and 5 ²¹⁰Pb_{xs} levels fell close to background levels by 20 cm depth, a more rapid rate of loss than is typical for this method.

Nevertheless, the systematic variation in ^{210}Pb activity shown in both cores raises three key questions: (1) what period of time is represented by these inflection points, (2) how much did sediment accumulation change between the two regimes, (3) what are the possible causes for this change?

To answer the first question we must return to the C.R.S. model and the basic radioisotope decay assumptions. Because we assume that the ratio between the total core activity and the activity below a chosen horizon corresponds to the age of that horizon we can calculate the age of the inflection point t_{ip} :

$$t_{ip} = \frac{I A_0}{k A_{ip}} \quad (3)$$

When considering the linear regression of the semi-log plot of Core 4, it appears that the sediment accumulation rate decreased by half between the middle part of the 20th century and the latter part, with an inflection point occurring in 1998 ± 7 years according to Core 4 and 1982 ± 16 years according to Core 5. These inflection ages place the start of the reduction in sediment accumulation rate in the latter part of the 20th century, a decade after heavy conservation efforts had begun and the South Slough watershed had begun regrowth. Here we actually resolve a reduction in sediment accumulation rates following conservation, an occurrence that is much less documented in the literature than sediment accumulation rate increases. This likely occurs because a) degraded or altered estuaries tend to be more studied than recovering or pristine ones and b) surficial mixing in cores often obfuscates the most recent years captured by a ^{210}Pb chronology, years where conservation is more likely to have occurred.

Regardless, both demonstrate a positive inflection in the latter part of the 20th century, signaling a slow-down in sediment accumulation. Because this is the only clear

inflection point observed in either core, either there was no period of higher sediment accumulation rate in the South Slough tidal flats due to intense logging in the mid-century or the sedimentation rates and dynamics are such that ^{210}Pb has too short a half-life to resolve the increase. Because identifying inflection points requires large soil intervals both prior to and after the inflection, it is possible that high logging-related sediment accumulation rates were simply too old to generate enough data points before $^{210}\text{Pb}_{\text{xs}}$ approached background.

4.2. Causes for Sedimentation Variation

What could be responsible for this decrease in sediment accumulation rate? To answer this question, we consider both land use and climate. First we consider climate. Rainfall in the Pacific Northwest fluctuates extensively throughout the 20th century, with the largest, 100-year flood even occurring in the form of the Christmas Storm of 1964 (Fig. 11). This single event produced discharge levels up to 48,900 cubic feet per second, on the Umpqua River, a river that lies nearby to the south, and is considered the largest discharge event seen in the Oregon Coastal Range since the rain-on-snow event of 1861 (Wallick et al., 2011).

Because of the literature-verified causal relationship between intense rainfall and high sediment transportation, the early 1970s increase in sediment accumulation seen in Core 4 and the late 1960s increase seen in Core 5 can be possibly explained by the 191% increase over the normal monthly discharge of 1750 cubic feet per second in discharge that occurred in neighborhood rivers during the 1964 Flood. In addition to the 1964 Flood, rainfall was anomalously high during the middle part of the 20th century (Fig. 11b). The Pacific Decadal Oscillation, a climatic anomaly proven to influence rainfall in

the Oregon Coast Range (McKenzie, Gedalof, Peterson, & Mote, 2004; Robert A Wheatcroft et al., 2013). These large flood events often do not manifest themselves in a single flood deposit but disperse most of the sediment they move across a large basin or shelf. All of this rainfall may have acted as a primer, causing weathering in the catchment and preparing the landscape for the big event that would transport the bulk of the sediment to the estuarine basin.

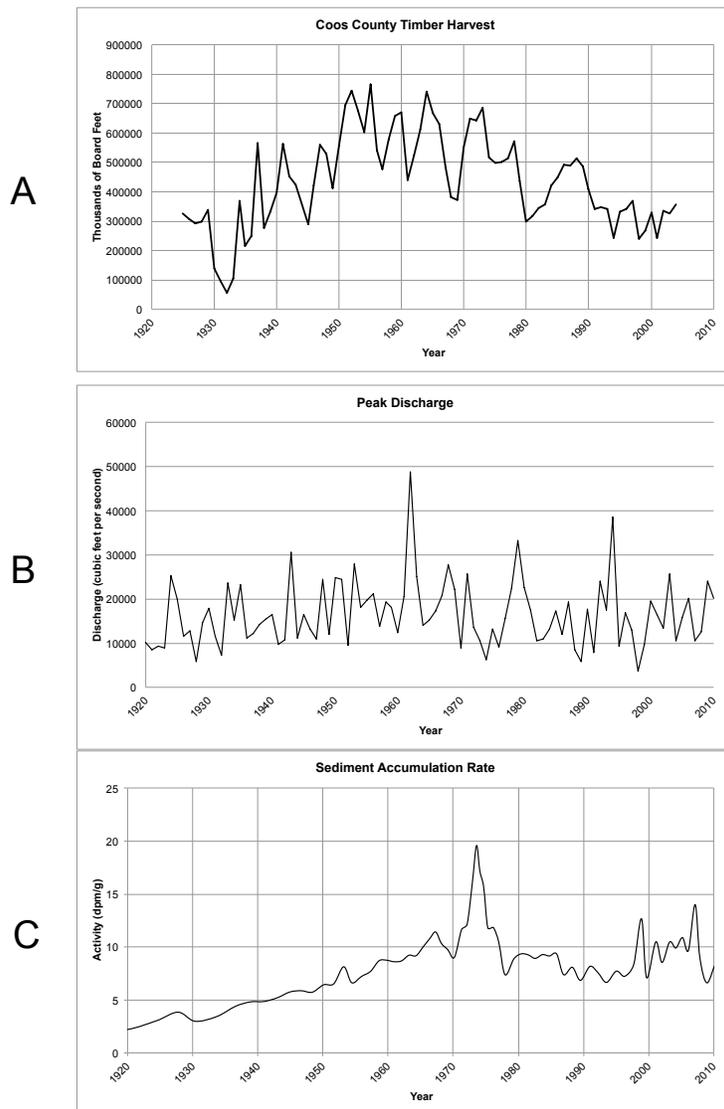


Figure 11: Key hydroclimatic and land use data for the Coos Bay Estuary and South Slough during the 20th century. Panel A is a record of board feet of timber harvested in Coos County, Oregon based on tax records. Panel B is the peak annual discharge for the Coquille River, the largest river gaged near the South Slough National Estuarine Reserve with the longest running stream gage. Panel C is the sediment accumulation rate calculated from the ^{210}Pb activity profile of Core 4, the most complete core in the South Slough. Harvest data from Andrews and Kutara (2005) and hydrological data from the U.S. Geological Survey.

Interestingly enough, this 30-yr period of anomalous rainfall aligns with an equally unusual time for land use in Coos County. Analyzing the tax records compiled by Andrews and Kutara (Andrews, Kutara, 2005) it is apparent that the logging history of Coos County can be broken down into four distinct periods: (1) a pre-1940s period of limited timber production disturbed by a drop-off during the Great Depression, (2) a 15-year period of steady increase ending in a peak harvest year in 1955, (3) a 25-year period of fluctuating but elevated harvest, and finally (4) a steady decline throughout the 1980s reducing to about one third of the peak harvest. The 25-year period of elevated harvests occurred at the same time as the anomalously wet climate.

The photogrammetry conducted in this study does not indicate that peak harvesting occurred exactly at the times indicated by the tax records in the South Slough, but may have actually been slightly delayed (Fig. 12). Stands 20 years or older, classified by their texture, constitute 62% of the 1954 images, with 1969 corresponding with the peak of recent logging in the Slough, meaning that peak logging likely occurred in the mid-1960s. This places peak logging in the South Slough concurrent with the Christmas Flood of 1964, a coincidence that may have contributed to high sediment production along coastal watersheds.

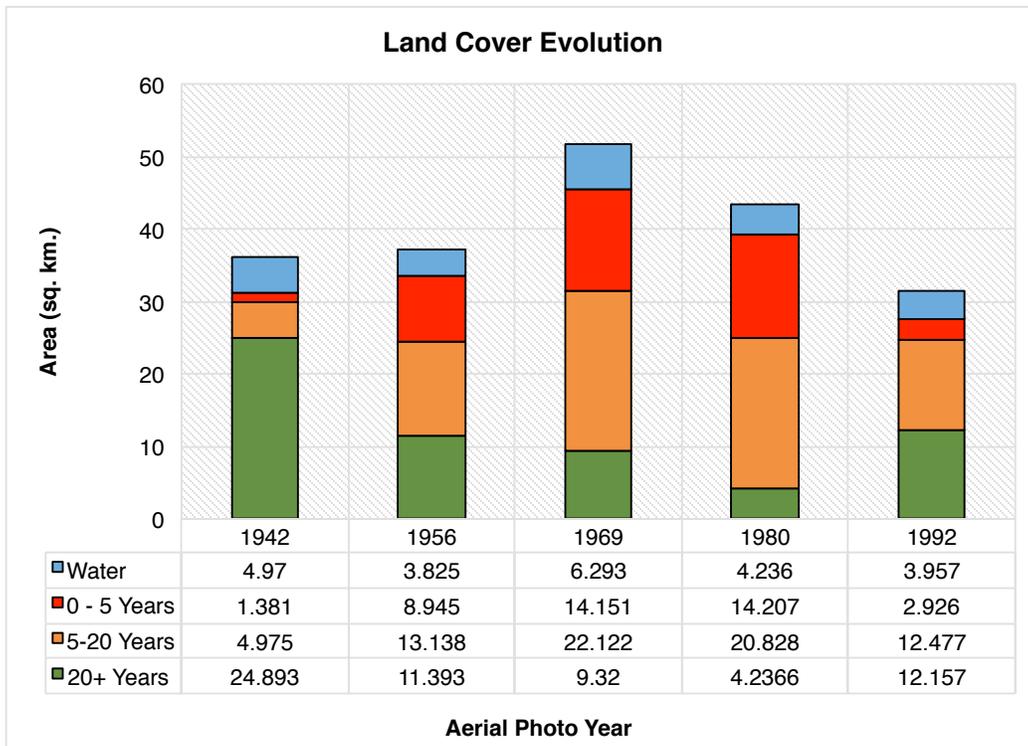


Figure 12: Change in land cover in the South Slough watershed from 1942 to 1992 based on photogrammetry with acreages. 20+ year-old forests dominated in 1942, while heavy logging in the 1960s lead to a peak of non-forested land in 1969. Lack of dense tree coverage continued in the watershed until the early 1990s.

CHAPTER V

CONCLUSION

The synthesis of land use change, sediment chronology and climate data in this study yields three key conclusions.

First, sediment accumulation rates of 0.46 – 0.81 cm/yr in the South Slough of the Coos Bay estuary are slightly above average for estuaries, although rates can be much higher (Table 1). This is likely a consequence of the high sediment supply characteristic of mountainous catchments and the high average annual precipitation. It is interesting to contrast these rates with those found in Pacific Northwest continental shelves, where they are almost an order of magnitude lower. The proximity to the relatively small basin of the tidal flats concentrate sediment from the catchments that may otherwise be distributed across a wider shelf.

Table 1: Table summarizing the range of sediment accumulation rates found using ^{210}Pb activities in estuarine and marine shelf systems. The average rates from the South Slough, displayed in yellow, are intermediate to high for estuarine systems.

Reference	Location	Sediment Accumulation Rate (cm/yr)
Benninger (1979)	Long Island Sound, NY	0.11
Ravichandran (1995)	Sabine-Neches Estuary, TX	0.04 - 0.05
Mathabane (2015)	South Slough, OR	0.46 - 0.81
Mudie (1980)	Central-Southern California Estuaries	0.1 - 0.5
Nittreour (1978)	Washington Continental Shelf	0.374
Peterson (1984)	Ales Bay, OR	0.21
Smith (1980)	Saguenay Fjord, Quebec (Near River Mouth)	7.0
Smith (1980)	Saguenay Fjord, Quebec (Deep Basin)	0.1
Van Eaton (2010)	Naples Bay, FL	0.2 - 0.3
Wei (2007)	Yangtze Estuary, China	2.0 - 6.3
Zwolsman (1993)	Scheldt Estuary, Netherlands	0.84 – 1.7

Second, the combination of intense logging and road building in the 1960s and the century-scale flood in 1964 created a pulse of high sediment accumulation in the South Slough, peaking at 2.1 cm/yr in the early 1970s. This pulse was followed by a period of decreasing sediment accumulation rate that continued into the end of the century. This decrease occurred about 15 years following inception of the South Slough National Estuarine Research Reserve, indicating that regrowth could slow sediment supply into an estuary. These two examples of a sediment accumulation pulse and decrease indicate a close source-to-sink relationship in the South Slough.

Finally, the window over which ^{210}Pb is able to resolve a change in sediment accumulation rate is narrow and requires relatively high $^{210}\text{Pb}_{\text{xs}}$ levels. The tidal flat cores analyzed in this study possessed the characteristic logarithmic decay required by the C.R.S. method, but their relatively low overall activity levels and rapid fall-off may have inflated the importance of minor kinks in the profile. Judicious care must be taken when selecting cores to which to apply the $^{210}\text{Pb}_{\text{xs}}$ method, as relatively common externalities like mixing and rapid burial can introduce significant error. A greater sample size of cores across more diverse regions of the estuary would allow for a greater likelihood of a core for which the C.R.S. method is well suited.

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