TECHNICAL MEMORANDUM

Oakland Bay Geomorphic Assessment
Mason County

Prepared for

Washington Department of Ecology
Toxics Cleanup Program
Southwest Regional Office

March 2009

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Southwest Regional Office
300 Desmond Drive SE
Lacey, Washington 98503

Prepared by

Herrera Environmental Consultants, Inc.
2200 Sixth Avenue, Suite 1100
Seattle, Washington 98121
Telephone: 206/441-9080

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Glossary

Anastomosing. The characteristic of a stream with many branches that intermingle.

(Marine) bedforms. Sediment shapes on the sea bed produced by tides and currents that may take the form of ripples, dunes, and anti-dunes.

Bedload. Sediment load transported near the bed; generally only sediment coarser than sand (i.e., gravel and cobble) can be transported as bedload.

Delta. An area defined by the accumulation of sediment at the mouth of a stream or river.

Drogue. An instrument designed to float along a given density interface in order to measure currents at mid-depths in the ocean.

Fetch. The distance over the water that the wind blows to create waves.

Glaciomarine drift. Generally fine-grained material, occasionally with outsized sediment, deposited in seawater near the edge of a glacier.

Hydrograph. Referring to the physical processes responsible for transport of water and solids in a marine setting.

Lapse rate. The rate of decrease of temperature with elevation above sea level.

Outwash. Sediment discharged in front of a glacier, typically composed of clean gravels and sand released from erosion underneath the glacier.

Picocuries/gram. A common unit of measurement of the activity of different radioisotopes present in a given sediment sample.

Suspended load. The load of sediment transported in the water column. Generally only silt and clay are transported, although sand can be suspended in nearshore areas or other areas where flow is concentrated (e.g., streams).

Swell. Waves originating from the open ocean, swell has a much longer period than locally generated wind waves.

Till. Poorly sorted (wide range of grain sizes) sediment, generally highly compacted by overlying glacial pressure.

T-sheet. A series topographic maps produced by US Coast Survey in the late eighteenth century illustrating the coast of the US. T-sheets are often used to determine historical shoreline changes.

Wave period. The average time between wave crests.

Executive Summary

Oakland Bay is a shallow embayment located in south Puget Sound, with the town of Shelton and its industrial waterfront and harbor located at the southwest corner. It is connected to Puget Sound by Hammersley Inlet, an approximately 8-mile-long tidal channel. This study addresses the pathways of sediment input (broadly defined as any negatively buoyant solid material, including wood waste), transport, and deposition that occur in Oakland Bay and the western half of Hammersley Inlet.

Modern sediment input to Oakland Bay is limited to several creeks, the most notable of which is Goldsborough Creek, which discharges to Shelton Harbor. All of the creeks have extensive deltas at their mouths. The Goldsborough Creek delta is exceptionally large and coarse grained, most likely a result of extensive channelization and fill of formerly intertidal marshes.

Geophysical and bathymetric surveys conducted across the study area identified a distinct layer of recent sedimentation ranging from 1 to 8 feet in depth across all of Oakland Bay. While there are a few areas with large woody debris present, most of this layer is featureless. Hammersley Inlet does not possess an extensive surficial layer of sediment, but rather has a predominantly hard-bottom, with a few localized bedforms where sediment has accumulated. This limited surface sediment moves into Oakland Bay from Hammersley Inlet, as interpreted from bedform orientations. Freshwater exits primarily near the bay surface, causing most of the (denser) sediment originating in Oakland Bay to remain there.

A sediment budget was developed by estimating accumulation rates determined from sediment core dating and a common sediment production model. The budget confirms that nearly all sediment deposited within the study area stays within the confines of greater Oakland Bay (including Shelton Harbor and Chapman Cove). While there is some transport of fine-grained sediment (silt and clay) from Shelton Harbor to central Oakland Bay, most sediment discharged to the bay remains close to where it first enters marine waters.

1.0 Introduction

Oakland Bay is a shallow embayment located in south Puget Sound, with the town of Shelton and its industrial waterfront and harbor located at the southwest corner (Figure 1). Oakland Bay is defined by all marine waters north and west of Eagle Point and Munson Point, including Chapman Cove and Shelton Harbor. The Washington State Department of Ecology (Ecology) is directing sediment investigations and a sediment transport study of Oakland Bay and its surroundings, focusing on the marine environment associated with terrestrial and aquatic sediment sources. The study area boundaries follow the upper creek basin boundaries that contribute to Oakland Bay and the western half of Hammersley Inlet (Figure 2).

Oakland Bay, like most marine basins, is filling with sediment (broadly defined as any solid material denser than water, including woody debris) from sources on land. Sediment transport is a complicated physical process that cannot be easily measured directly, so several different techniques and analyses are used to build a coherent, qualitative picture of transport and fate mechanisms. Understanding of each analysis and the assumptions made is essential to develop a complete picture of sediment transport across the bay.

The purpose of this assessment is to describe the existing geomorphic conditions of the shoreline and marine waters of the study area, perform a geophysical survey and interpret the results from it, and perform a simple sediment budget of the study area based upon estimated sediment inputs and sediment accumulation rates found using radioisotopic measurements and other sedimentological characteristics. This report describes the geomorphic ramifications of the human activities cataloged in the *Summary of Existing Information and Identification of Data Gaps Technical Memorandum* (Herrera 2008).

The assessment uses a process-based approach to describe sediment transport, with three primary physical processes responsible for sediment transport (treated in order from source to sink):

- Sediment input from creeks
- Geomorphic transport environments
- Sediment accumulation by deposition.

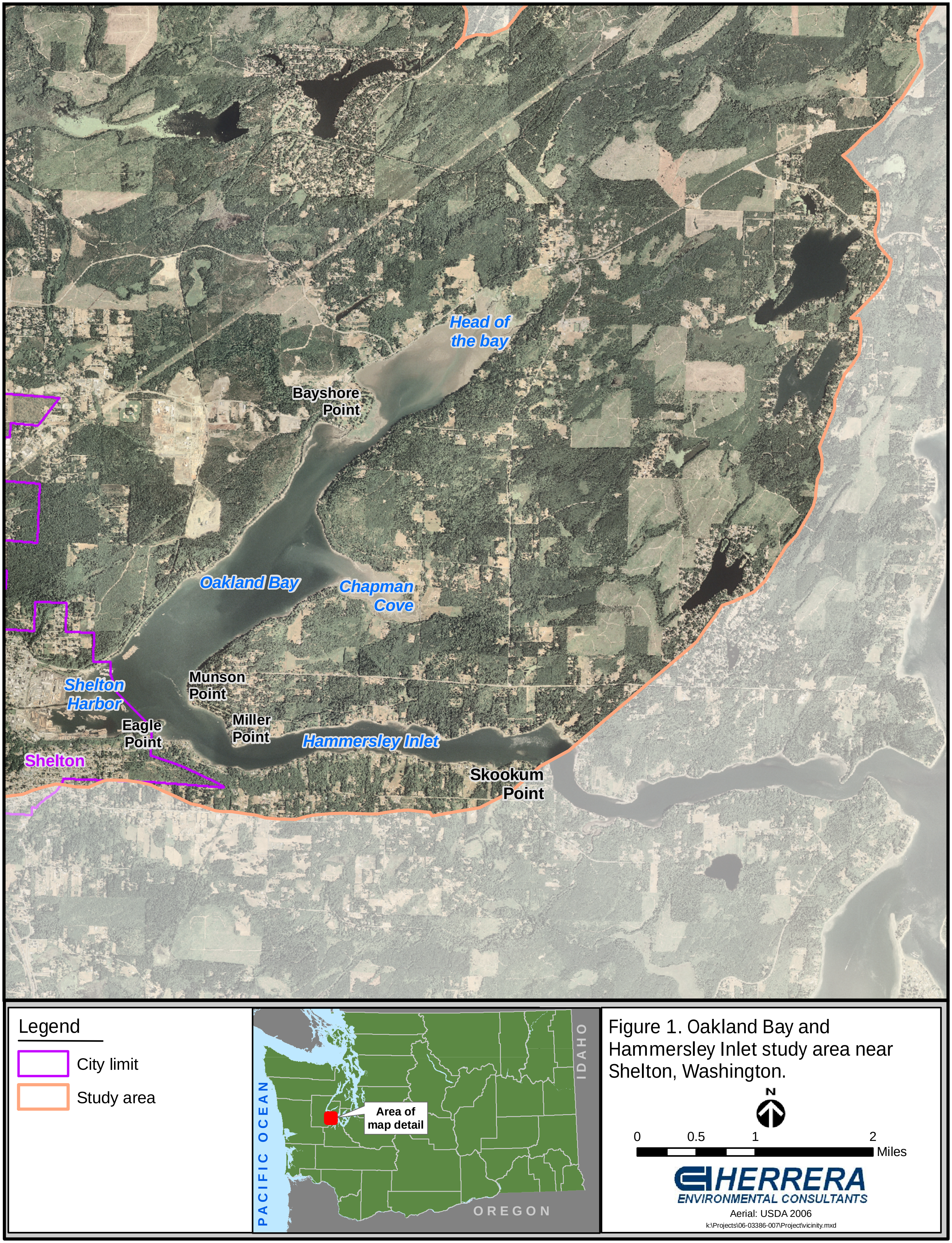


Figure 1. Oakland Bay and Hammersley Inlet study area near Shelton, Washington.

2.0 Methodology

In order to understand the fate and transport of sediment in the study area, it is necessary to quantify sediment inputs, describe the pathways by which sediment is transported, and measure the sediment accumulation rate. Each of these analyses is described in that order.

2.1 Sediment Input

Total sediment input to Oakland Bay was estimated using a method that calculates general sediment input from unmonitored basins (Syvitski et al. 2005), hereafter referred to as the Syvitski model. The Syvitski model has been shown to be appropriate for temperate basins in the northern hemisphere, such as the Oakland Bay basin. The model is purely empirical and therefore does preserve unit dimensions. The governing equation of the model is the following:

$$Q_s = 6.15 \times 10^{-5} A^{0.55} R^{1.12} e^{0.07T} \quad (1)$$

Where: Q_s is the long-term average sediment input (kilograms per second)

A is the basin area (square kilometers)

R is the maximum relief in the basin (meters)

e is the base of the natural logarithm, approximately equal to 2.718

T is the *calculated* average annual temperature throughout each subbasin (degrees Celsius).

The average annual temperature T is frequently not known for sediment contributing subbasins, and therefore must be estimated from an elevation based equation:

$$T = T_0 - LH \quad (2)$$

Where: L is the lapse rate of the atmosphere (i.e., the decrease in temperature with elevation above sea level [calculated to be 7.22°C/km for Oakland Bay])

T_0 is the measured average annual temperature, for the purposes of this analysis, the average annual temperature at a NOAA's Cooperative Observer Program (COOP) weather station in Shelton, Washington (station 457584) was used as the average annual temperature, which is 10.7°C (WRCC 2008).

H is the average basin elevation (kilometers).

Geographic information system (GIS) spatial analyst tools were used to delineate subbasins that drain to the study area from a U.S. Geological Survey 10-meter digital elevation model for the water resource inventory area watersheds draining to the study area (Figure 2). Subbasins within the study area were delineated by hand from digital elevation models. The size of the drainage basins and their maximum elevations were used in the Syvitski model calculations.

Areas immediately adjacent to Oakland Bay not identified as part of a subbasin may be sources of sediment in the bay (especially bare, unstable slopes). These potential sediment inputs have not been calculated and are assumed to be negligible in comparison to the total estimates of sediment yield to Oakland Bay. Support for this assumption comes from the disconnection of many bluff areas from the shoreline due to development, which is detailed in the following section.

2.2 Geomorphic Environments

The delineation of geomorphic environments, distinct areas where sediment transport processes are similar, arose from a variety of existing resources describing the topography and geology of the study area. The Shelton geologic map was used to identify bedrock areas and the extents of different substrate types (Schasse et al. 2003). Historical maps and aerial photographs enabled the delineation of fringing beaches and tidal flats (NOAA 1878, DNR 1942). GIS slope and shoreline data (Ecology 1978-1980) of Oakland Bay defined areas of extensive shoreline development. These data were manually digitized into GIS shape files.

Shoreline development and evolution was investigated by using several different historical resources. A topographic sheet representing conditions in 1878 (NOAA 1878; provided in Appendix A), oblique aerial photographs taken by the U.S. Coastal Survey (Ecology 1977, 1992, 2001, and 2006; provided in Appendix B), and historical aerial orthophotographs of Oakland Bay (DNR 1942, 1957, 1965, 1980, and 2003; provided in Appendix C) were used to delineate creek deltas and describe shoreline development and historical changes to subbasin creek estuaries.

A geophysical survey conducted by Global Geophysics mapped the bathymetric and subbottom features of Oakland Bay south of Bayshore Point and the western portion of Hammersley Inlet. The geophysical survey was conducted between June 25 and 27, 2008. Bathymetric data were collected with a Reson precision echosounder using a 300-kilohertz (kHz) transducer. Point data acquired from the bathymetric survey were interpolated to create polygons indicating areas of similar depth within a 5 foot lateral range. Analyzing the bathymetric survey data in GIS, a continuous line of spatially low polygons was delineated as a subglacial channel.

Global Geophysics also collected subsurface (acoustic) reflection data using an EdgeTech Chirp system. A high-frequency (4- to 24-kHz) signal was discharged three times per second and the resulting subsurface reflection data recorded. Subsurface data were viewed and analyzed using EdgeTech software (Discover SB 3200-XS). While in the field, a Herrera geomorphologist noted bedform features southeast of Shelton Harbor on a real-time digital display aboard the data collection vessel. Locations of the bedform features were mapped in GIS and the direction of travel noted. In reviewing the subsurface data, screenshots were taken of the EdgeTech digital display record and bedform geometry was noted. Side-scan sonar data were also collected with a Lowrance Sonar/M1 Side Scan Sonar device (300 kHz), providing a digital image of the sea bottom. Electrical resistivity was also collected, but it was found that it was strongly biased by

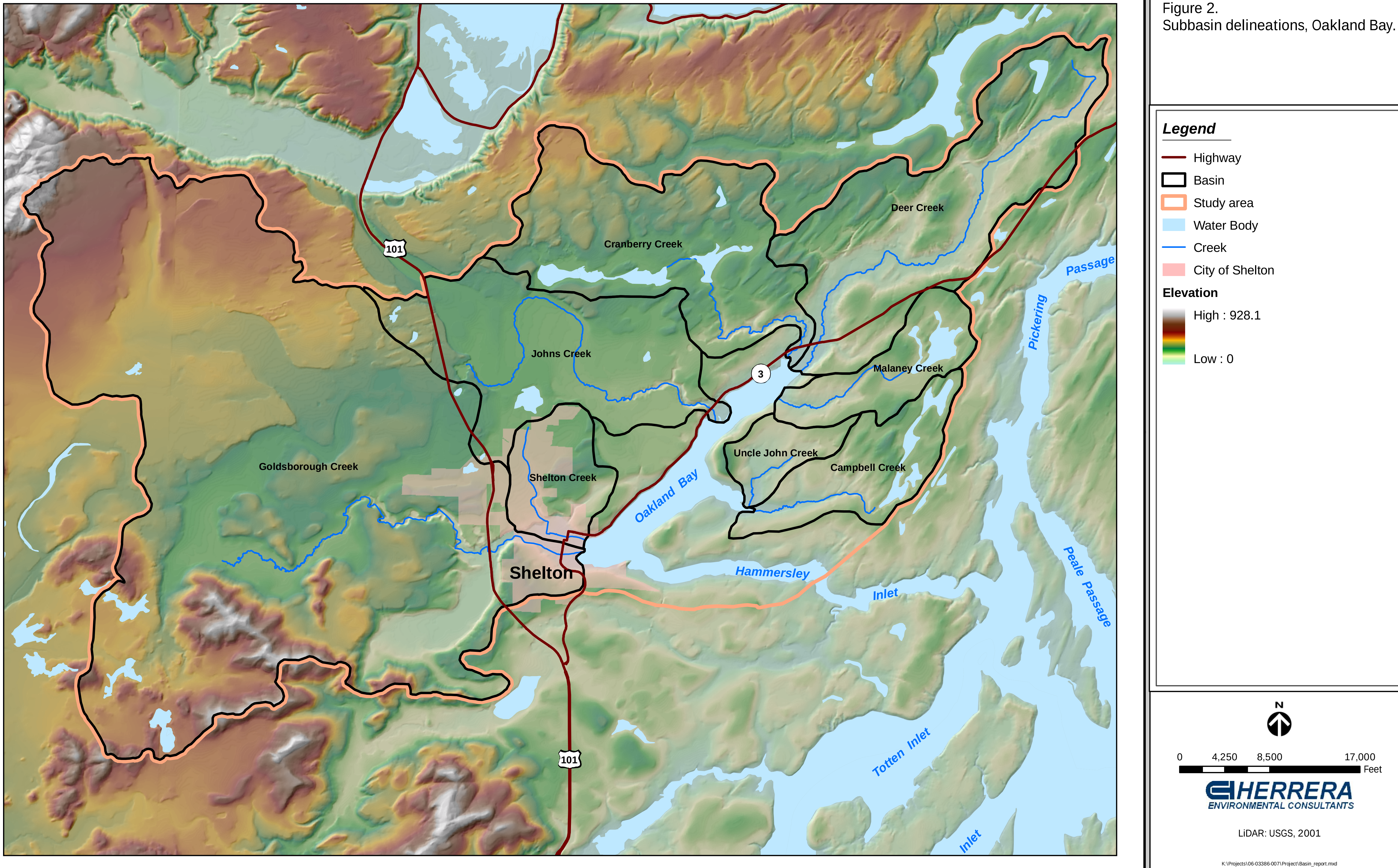


Figure 2.
Subbasin delineations, Oakland Bay.

bed surface abnormalities and not useful for description of geomorphic features or the presence of wood waste.

2.3 Sediment Accumulation

Three sediment cores from Oakland Bay and Shelton Harbor (SH-17, OB-15, and OB-16) were sampled for the presence and concentration of the isotopes cesium-137 (^{137}Cs) and lead-210 (^{210}Pb). Core locations (shown in Figure 5) were specifically selected to avoid areas of known disturbance identified by local shellfish growers. Radioisotopic analysis was performed on sediment samples collected every 10 centimeters (approximately 4 inches) apart. The samples included 2 centimeters (cm) of core, with mean depth of the sample reported as the depth in this analysis. ^{210}Pb and ^{137}Cs analyses are complementary, and when taken together, can provide an estimate of the sediment accumulation rate at a particular location.

^{210}Pb is a radioactive form of lead, having an atomic weight of 210. It is one of the last elements created by the radioactive decay of the isotope uranium-238 (^{238}U). ^{210}Pb forms naturally in sediments and rocks that contain ^{238}U, as well as in the atmosphere, a by-product of radon gas. Within 10 days of its creation from radon, ^{210}Pb falls out of the atmosphere. It accumulates on the surface of the earth where it is stored in soils, lake and ocean sediments, and glacial ice. The ^{210}Pb eventually decays into a non-radioactive form of lead. ^{210}Pb has a half-life of 22.3 years, which means that after 22.3 years, only half of the original amount is undecayed. If the sediment layers are undisturbed, then as the sediment ages it slowly loses its radioactivity. We can determine how old a sediment layer is by how much ^{210}Pb it contains. It takes about 7 half-lives, or 150 years, for the ^{210}Pb in a sample to reach near-zero radioactivity. In addition, net accumulation rates can be determined from age and depth of ^{210}Pb samples.

^{137}Cs, with a half-life of 30.3 years, is a radioactive form of cesium and a thermonuclear byproduct. Its presence is directly related to the atmospheric testing of nuclear devices during the latter half of the 1950s and early 1960s. Because it was not present in the atmosphere or on the Earth's surface prior to 1945 (63 years since the cores were taken), it is an independent check on the results of ^{210}Pb analysis. ^{137}Cs analytical results are evaluated for presence-absence, so the test is performed following analysis of ^{210}Pb results for portions of the core estimated to be 50 to 60 years old.

In order to determine the amount of sediment that leaves the study area, accumulation rates were compared to sediment input estimated using the Syvitski model. To properly compare accumulation rates of fine (suspended) sediment with estimates of total sediment loading, an assumption must be made about the relative volume of bedload (deposited on the delta) to suspended load (transported farther into the bay). The Syvitski model assumes that 15 percent of the total volume of sediment in transport is bedload (i.e., sediment load transported near the bed), which was applied to each of the Oakland Bay creek basins.

3.0 Study Area Background

Oakland Bay is located at the southwest end of the Puget Lowland, which occupies a basin bounded on the west by the Olympic Mountains and on the east by the Cascade Mountains. Oakland Bay, which includes Shelton Harbor and Chapman Cove, covers 1,856 acres, with 8 creeks flowing to it, and a contributing area equal to roughly 83,000 acres, including numerous small unnamed coastal drainages. Land use in the basin has historically been dominated by commercial logging and lumber production, which began in the 1850s. The Johns Creek basin, and the Shelton waterfront and harbor, have been historically and are currently used by a number of timber and wood product manufacturing industries, including saw mills and plywood manufacturing, pulp and paper production, and insulation board and fiber board manufacturing. The waters of Oakland Bay also became a center for economic production, as by 1902, hundreds of acres were under oyster and shellfish cultivation. Today, there are 21 shellfish growers in Oakland Bay, in addition to the Squaxin Island Tribe, as well as some recreational shellfish harvesting on public and private beaches.

3.1 Geology

Oakland Bay topography and geology is primarily influenced by glacial advance and retreat. The exception to this is in the heavily developed areas west of Shelton Harbor, where nonglacial deposits, including fill, have been placed by man. This area has been filled by clay, silt, sand, gravel, organic matter, riprap, and debris to elevate the land surface and reshape the surface morphology.

Throughout the last million years, the Puget Lowland was inundated by a continental ice sheet, which laid down a predictable sequence of glacial sedimentary deposits. As many as six distinct glacial advances filled the lowland with sediment to an elevation of more than 400 feet above present sea level (Booth 1994). Sediments of the last advance, the Vashon Stade, remain the dominant material exposed in the study area and are discussed in depth below. Some pre-Vashon glacial deposits (from earlier glacial occupations) also have been mapped in the area (Schasse et al. 2003). These deposits have been cemented and are well compacted. They are found on steep slopes between the till and recessional deposits, particularly north and south of fill material in Shelton Harbor and along the eastern slopes of Oakland Bay. Typically, the unconsolidated deposits are underlain by volcanic basalt bedrock in this area.

The Vashon Stade, and the sediment laid down during that time, began with an ice dam forming in Admiralty Inlet from the Cordilleran Ice Sheet advancing southward from the Fraser River valley in Canada approximately 20,000 years ago. The dam cut southern Puget Sound off from marine influence and caused the accumulation of silt and clay, sometimes called the Lawton Clay. These materials are relatively impermeable. Exposure is relatively limited in the study area, the materials likely underlie many of the more recent sediments.

As the glacier advanced toward the study area, it delivered outwash sand and gravel to areas in front of it. The advance outwash is commonly exposed where topography is steep and the overlying till has been removed by erosion. It is found along the northwest shoreline of the bay, on the shoreline and slopes north of Chapman Cove, and near Eagle and Miller Points. Advance outwash may contain prolific water-bearing zones.

Glacial till, consisting of a highly compacted mixture of clay, silt, sand, and gravel deposited directly by glacial ice, was the last type of material laid down in front of the advancing glacier. Even though ice remained over the study area for only a few hundred years, till is widespread. It flanks Shelton Harbor to the north and south and also is found in the upland areas above the steep slopes of the eastern shoreline. Typically, glacial till has a low infiltration rate and does not yield much water due to its compact nature and clay and silt content.

The study area has an extensive record of sedimentation from times following the Vashon glacier collapse, approximately 17,000 years ago (i.e., recessional deposits). Vashon recessional outwash and pre-glacial stratified sand and gravel, with variable amounts of silt, were deposited as the glacial ice was receding. These deposits occur west of Shelton Harbor and continue toward the northwest; they also occur about 2 miles northeast of Shelton on the western shoreline continuing to the north end of the bay. Clay-rich lake deposits from the receding Vashon Stade of glaciation occur in Chapman Cove.

As a result of the unloading of glacial ice, south Puget Sound experienced drastic sea level fluctuations from 17,000 years ago until approximately 6,000 years ago. Relative sea levels during this time were much lower in the south Puget Sound than the current elevation. Streams draining upland areas sharply eroded their valleys in an effort to reach the sea. This gave rise to postglacial alluvial deposits of silt, sand, gravel, and peat in deltas where creeks flow into the Oakland Bay system. Major alluvial deposits are found in two areas within Oakland Bay: a large prominent deposit that extends along the west shoreline at the outlet of Johns Creek (Bayshore Point) and deposits at the head of the bay. Sea level rise associated with deglaciation drowned these carved river valleys, forming narrow inlets and embayments (Shipman 2008). Oakland Bay and Hammersley Inlet is one such drowned river valley that likely occupied a former subglacial channel.

By approximately 6,000 years ago, most of the sea level rise to current levels had already occurred, although slow sea level rise persists today at approximately 0.06 inches per year. As sea level rose to its present level, bluffs along the modern-day shoreline of the harbor began eroding and left the landscape in the conditions found at the time of European settlement, as reflected in the topographic sheet (T-sheet) of the area (NOAA 1878).

3.2 Hydrology (Surface Water, Stormwater Runoff, and Wetlands)

The study area is located within WRIA 14, often called the Kennedy-Goldsborough watershed. The Kennedy subbasin drains the Black Hills to the south of Oakland Bay and lies outside of the assessment extents of this report. The Goldsborough subbasin consists of the southeast one-third of Mason County and a small northwest portion of Thurston County. The Goldsborough subbasin includes all of Oakland Bay and Hammersley Inlet, including Shelton Harbor, Chapman Cove and numerous small, unnamed coastal drainages.

The study area features an extensive network of low-elevation streams that issue from springs, wetlands, small lakes, and surface water drainages. Principal streams that discharge into Oakland Bay include Goldsborough, Shelton, Johns, Cranberry, Deer, Malaney, Uncle John, and Campbell creeks (Figure 2). Despite its abundance of creeks, WRIA 14 has no major rivers.

Because of its low elevation, the study area includes no high-elevation ice packs or snow fields to sustain streamflows; streams within this watershed depend upon direct precipitation and groundwater inflow to maintain flow levels. Streamflow volumes reflect seasonal variations in precipitation. Direct precipitation either becomes runoff that flows overland into streams and other water bodies or percolates into the ground to recharge the groundwater aquifer system, which supports baseflow to streams depending upon availability.

Peak runoff in these streams occurs during the winter and early spring months during high precipitation. As precipitation subsides in late spring and early summer, streamflow decreases such that by August, the streams have reached their lowest levels. Streamflow then increases as precipitation increases in the fall.

Surface water within the study area is used for a variety of purposes. Shelton Springs, the headwaters of Shelton Creek, is the source of the municipal water supply for Shelton. Much of the creek is conveyed in concrete conduits beneath the city. Goldsborough Creek is used by Simpson Timber Company for industrial water supply.

3.3 Wind and Waves

As southern Puget Sound is isolated from the Pacific Ocean by the Olympic peninsula, waves in Puget Sound are generated locally by wind blowing over the basins, rather than by swell from the eastern Pacific. The consequences of this are that (1) the waves are fetch-limited and low energy compared to incident waves on the Pacific coast, and (2) the wave climate is tightly coupled to local wind patterns (Finlayson 2006). Predominant winds in Puget Sound are from the south or southwest during the winter and from the north or northwest during the summer (Overland and Walter 1983).

3.4 Hydrography

Modern-day Oakland Bay functions like an estuary. In estuarine environments with limited fetch length and low-energy wave climates like that of Oakland Bay, tides and freshwater input from uplands are the dominant drivers for fluid motion and sediment transport. The observed tidal range in Oakland Bay and Hammersley Inlet is one of the greatest in the Puget Sound, at 4.5 meters (14.8 feet) (Finlayson 2006). Estuarine circulation of fresh water from the creeks and seawater from the sound ensures that denser seawater flows into the bay along the bottom of the water column, possibly capable of transporting sediment; fresh water flows out of the bay on the surface, not capable of transporting sediment because flow is concentrated at the water surface (Fischer et al. 1979).

Oakland Bay is a high-refluxing and low-flushing estuary (Albertson 2004). This means that a significant amount of fluid is exchanged between Oakland Bay and greater Puget Sound over the tidal cycle, but the water in the bay has a long residence time. This is because most of the exchange occurs in the dense (saltier) bottom layer. Estimates of residence time in the bay vary from 2 to 5 days, based on evaluating tide gauges, conducting tidal simulations with the Hammersley Oakland Bay Oceanographic (HOBO) model, and observing movement across portions of the system (Albertson 2004). This study evaluated only fate and transport of suspended aqueous material and not sediment transport. Sediments are negatively buoyant and less mobile than suspended aqueous material, and they will not remain suspended in the water column for a long period. In such a naturally low-flushing environment, sediment is likely to remain undisturbed from the location in which it settled. Observations made herein were needed to fully understand the hydrodynamics of the seabed and sediment transport in the bay.

4.0 Results

Results of the geomorphic assessment are arranged in order from source to sink; final sediment budget calculations are provided in the Sediment Accumulation section.

4.1 Sediment Input

Sediment input to the study area comes from four primary sources: the head of the bay (including Cranberry, Deer, and Malaney Creeks), Chapman Cove (including Uncle John and Campbell Creeks), Shelton Harbor (including Goldsborough and Shelton Creeks) and Johns Creek. Creek basin characteristics are summarized in Table 1.

Within the head of the bay, the upper Cranberry Creek drainage area extends northwest toward Annas Bay and the Skokomish River basin, the Deer Creek and Malaney Creek basins drain the lowland areas northeast of Oakland Bay. Johns Creek drains land northwest of the central portion of Oakland Bay. The small basins of Uncle John Creek and Campbell Creek drain land northeast of Chapman Cove. The largest drainage basin is that of Goldsborough Creek, which drains areas directly west in the foothills of the Olympic Mountains. The Shelton Creek drainage basin is one of the smallest in the watershed, with a drainage area directly west of Oakland Bay.

Table 1. Characteristics of creek basins in Oakland Bay.

Creek	Maximum Elevation in Watershed (feet)	Size of Drainage Basin (acres)
Johns Creek	420	7,833
Malaney Creek	266	2,459
Shelton Creek	295	2,269
Goldsborough Creek	1,375	38,621
Campbell Creek	295	3,097
Cranberry Creek	502	8,235
Deer Creek	390	9,291
Uncle John Creek	279	1,214

Using the basin areas found in Table 1, sediment input was estimated using the Syvitski model for each Oakland Bay creek (Table 2). Goldsborough Creek drains the largest area by an order of magnitude and has a maximum elevation more than twice that of the other Oakland Bay subbasins, resulting in the largest estimated sediment contribution to Oakland Bay (67 percent). The estimated total sediment input to Oakland Bay is 9,622 tons/km^2/year.

Table 2. Volumetric estimates of sediment input to Oakland Bay from contributing creeks.

Creek	Total Average Annual Sediment Input (tons/year)	Total Average Annual Bedload Sediment Input (tons/year)	Total Average Annual Suspended Sediment Input (tons/year)	Sediment Input to Oakland Bay (tons/km²/year) [b]	Average Potential Accumulation Rate [a] (cm/year)
Goldsborough Creek	56,633	8,495	48,138	6,406	0.377
Cranberry Creek	7,832	1,175	6,657	886	0.052
Deer Creek	6,316	947	5,369	713	0.042
Johns Creek	6,240	936	5,304	706	0.042
Campbell Creek	2,525	379	2,146	286	0.017
Shelton Creek	2,128	319	1,809	241	0.014
Malaney Creek	1,976	296	1,680	224	0.013
Uncle John Creek	1,415	212	1,203	160	0.009
Total	85,065	12,759	72,306	9,622	0.566

Note: Assumes sediment density of 1.7 tons/m^{3}and a uniform deposition throughout Oakland Bay.
[a] The average potential accumulation rate assumes that all sediment discharged by the creeks is retained in the bay.
[b] Assumes suspended sediment is the sole source of sediment inputs in Oakland Bay.

In order to verify modeled sediment input results for Oakland Bay, a comparison to observations made at nearby creeks and rivers is necessary. Based on the Skokomish, Hamma Hamma, Duckabush, Dosewalips, and Quilcene Rivers on Hood Canal, the Goldsborough Creek basin falls in the midrange of estimated average sediment yield (Downing 1983; Wise et al. 2007), despite its being somewhat smaller and lower in peak elevation (Table 3). Sediment flux results for Goldsborough Creek appear to be within an acceptable range of values for local rivers, but likely represent an upper limit of the sediment contributed to the bay.

Table 3. Comparison of calculated sediment yield from Goldsborough Creek basin and other Hood Canal river basins.

Creek/River Basin	Average Sediment Production in River Basins (tons/km²/year)
Goldsborough Creek	431
Hood Canal rivers [a]	193
Hood Canal rivers [b]	610

[a] Source: Downing (1983).
[b] Source: Wise et al. (2007).

Sediment input provided in Table 2 compares the sediment input across the bay area (km^2) and potential accumulation rate contributions by creek, whereas Table 3 compares the average sediment yield across basin areas (km^2) resulting from erosional processes among basins in southern Puget Sound. Sediment input is notoriously difficult to characterize, but the Syvitski model is bounded by two independent observations of sediment production in similar areas.

4.2 Geomorphic Environments

Oakland Bay is a shallow embayment approximately 4 miles long and 3/4 of a mile wide, with water depths generally ranging to 35 feet below mean lower low water (depths described hereafter are all with respect to mean lower low water). Areas up to 85 feet deep stretch from the southwest shore of Hammersley Inlet into Oakland Bay and along the western shoreline north of Shelton Harbor, as far as the midway point between Shelton Harbor and Johns Creek (Figure 3). A deep water area covering 1,000 feet by 500 feet varies in depth from 45 to 80 feet at the juncture of Oakland Bay and Hammersley Inlet. Shallow tidal flats up to 10 feet deep dominate most of central Oakland Bay, Chapman Cove, and the head of the bay. Much of Shelton Harbor is dominated by shallow areas ranging up to 15 feet deep.

Localized geomorphic features help to describe the sedimentology of Oakland Bay (Figure 4). Between 1977 and 2006, a range of tides is visible in the oblique aerial photographs available from the Coastal Atlas (Ecology 1977, 1992, 2001, 2006). These photographs help to delineate tidal areas (subject to wetting and drying associated with tides) and foreshore areas (influenced by waves). The descriptions rely heavily on the Coastal Atlas oblique aerial photographs (Appendix B) and the aerial orthophotographs (Appendix C).

Broadly speaking, marine portions of the study area can be divided into two broad categories: creek deltas and their associated embayments and deeper portions of Oakland Bay and Hammersley Inlet. Creek deltas are shallow areas influenced by small local waves and drainage from creeks. Deep water portions of Oakland Bay and Hammersley Inlet are dominated by tidal exchange and only influenced by waves on their periphery. The following subsections summarize shoreline modifications and their impacts on sediment supply and storage based on the available data. For shoreline features, typology and terminology proposed by Terich (1987) is used.

4.2.1 Creek Deltas and Associated Embayments

There are four regions within the study area where sediment accretion (accumulation) is rapid and water depths are shallow. Because these regions have the same physical processes acting on them, they are addressed collectively below.

4.2.1.1 Shelton Harbor

Shelton Harbor is an area of extensive development associated with the town of Shelton. The erosion of large areas of unstable bluffs surrounding Shelton Harbor might have once been an important sediment source in Shelton Harbor; however, extensive armoring of the shoreline and development between the bluffs and the shoreline have completely cut off the bluffs as a source of sediment.

The 1878 T-sheets (topographic maps) indicate that the harbor shoreline had been hardened, but Goldsborough Creek and Shelton Creek had not yet been channelized (Appendix A). By 1942, Goldsborough Creek and Shelton Creek had been channelized through Shelton and into the harbor. Shelton was well developed and a large portion of the Shelton Creek basin consisted of impervious surface (i.e., constructed surfaces that water is unable to penetrate). Intensive logging also was occurring along Goldsborough and Shelton Creeks (intensive logging is visible on the northwest shore and inland of Oakland Bay). Extensive log rafts are visible in photographs from all the years (Appendix C). Goldsborough Creek was dammed in 1885, but the dam was small and the reservoir filled quickly. The dam was removed in 2001 and likely has produced more sediment in recent years than in years previous; however, this increase in sediment transport has been negligible compared to the background sediment transport rate in the creek (US Army Corps of Engineers 1999).

By 1957, new vegetation and development in the hills surrounding Goldsborough Creek and Shelton Creek is visible and U.S. Route 101 (US 101) is visible west of the harbor. Aerial photographs from 1965 show an active quarry on Goldsborough Creek west of US 101 (west of the extents in the aerial photograph shown in Figure C-3, Appendix C), which appears to have operated through 2006. Goldsborough Creek is heavily channelized in all of the Coastal Atlas aerial photographs for the years 1977 through 2006 (Figures B-7 through B-10, Appendix B). Shelton Creek is piped or channeled through the city, with the lower portion open to the surface.

Both Goldsborough Creek and Shelton Creek discharge to the north side of Shelton Harbor, with Goldsborough Creek directed northward by a constructed berm on the south bank. The resulting delta extends primarily north from the creek mouth, with a portion wrapping around the berm to the south and west. The 1965 aerial photographs show a small delta from Goldsborough and Shelton creeks during high tide. Both of the 1980 and the 1992 aerial photographs were taken during low tide and expansion of the Shelton Harbor delta system is clearly visible between those years.

Goldsborough Creek represents two-thirds of the total sediment input to Oakland Bay. Even though the Goldsborough Creek delta expansion is visible throughout the photographic record, accumulated sediment volumes cannot be estimated reliably because of the possibility of significant human alterations of these expanded areas.

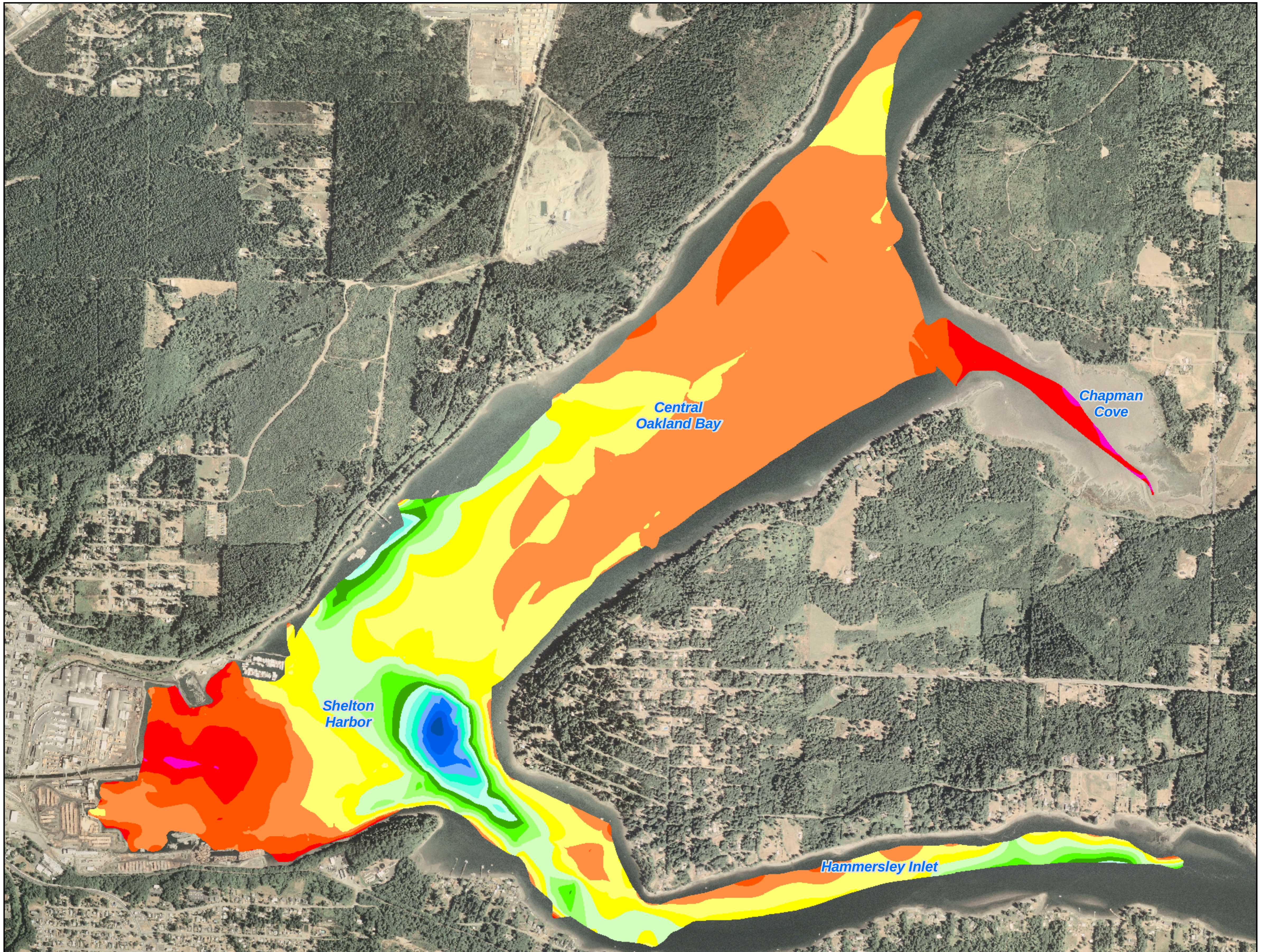
4.2.1.2 Chapman Cove

Chapman Cove is similar to Shelton Harbor, but much less developed. Historical oblique aerial photographs of Chapman Cove from 1977, 1992, 2001, and 2006 show a large horizontal and vertical area under the influence of tides. Between 1977 and 2006, Uncle John Creek and Campbell Creek changed very little. The lower reaches of the creeks wind through narrow riparian (vegetated) corridors flanked by residential property and cleared land.

4.2.1.3 Johns Creek Delta

Historically, the Johns Creek delta was a large estuarine marsh before it was filled and drained in order to accommodate the golf course at the Bayshore Golf Club (see Appendix A). The 1977 aerial photographs show an active quarry southwest of the Johns Creek outfall (Figure B-1, Appendix B). The 1977 aerial photographs also show a more forested and less residential basin than visible in 1992. An anastomosing (branching) channel through the lower reaches of Johns

Figure 3.
Bathymetric data from geophysical survey in Oakland Bay and Hammersley Inlet.



Legend

Bathymetry

(feet below mean low water)

- -20 - -15
- -15 - -10
- -10 - -5
- -5 -0
- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 40
- 40 - 45
- 45 - 50
- 50 - 55
- 55 - 60
- 60 - 65
- 65 - 70
- 70 - 75
- 75 - 80
- 80 - 85

N

0 750 1,500 3,000
Feet

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Aerial: USDA 2006

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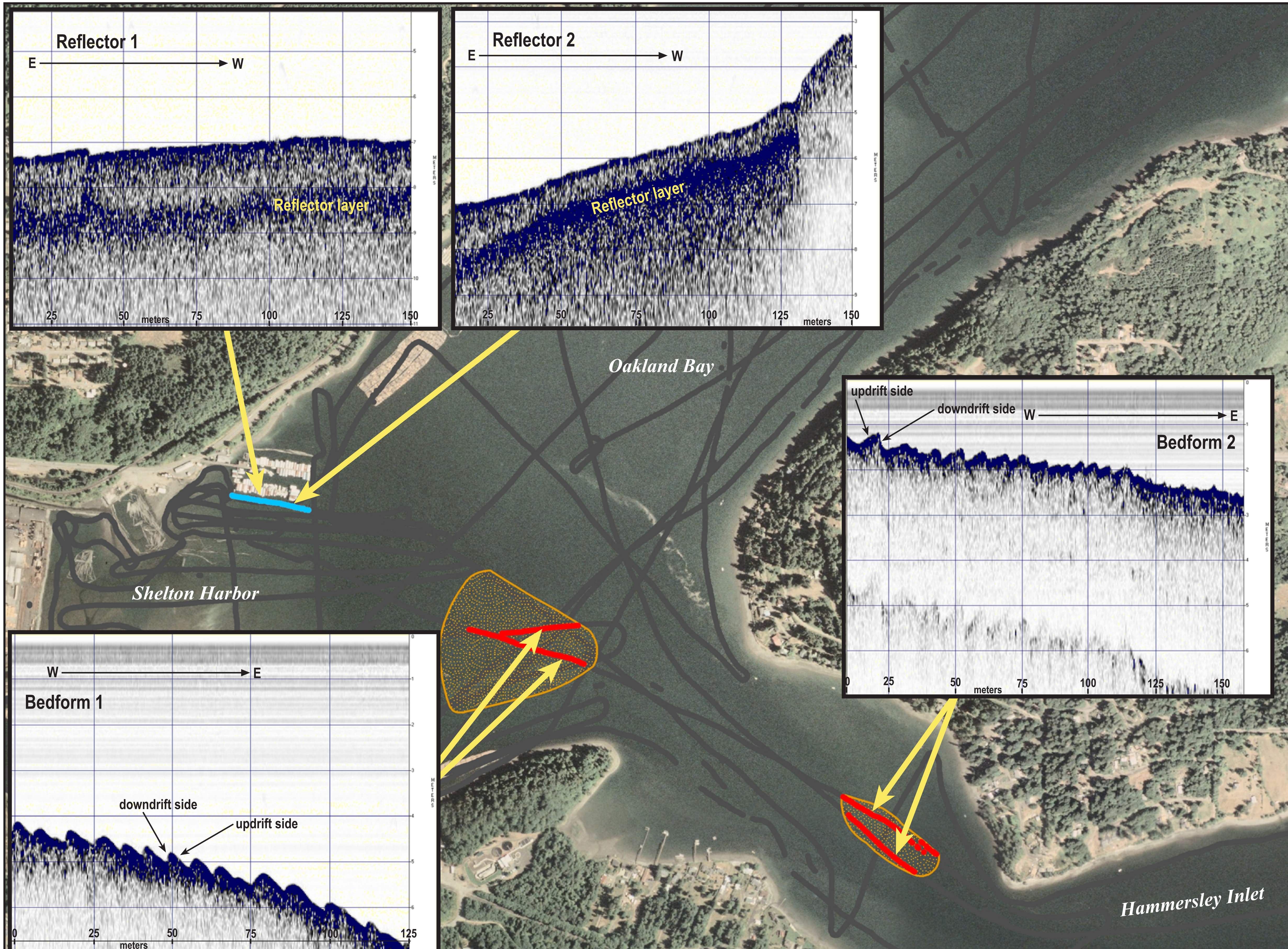
Figure 4.
Subbottom geophysical data from Oakland Bay and Hammersley Inlet.



Legend

- Geophysical Survey Transect
- Bedform Location
- Reflector Location
- Marine bedform

N

0 400 800 1600
Approximate scale in feet

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graphics/02-13-09/rtb/HEC-R/06-03386-007/Geomorphic Rpt

Creek is visible in the 1977 aerial photographs. By 1992, Johns Creek appears to have a natural or constructed levy extending into Oakland Bay (Figure B-2, Appendix B). The photographs indicate few or no changes to the channel between 1992 and 2006 (Figures B-2 through B-4, Appendix B); only the areas near the golf course have experienced an increase in residential construction.

4.2.1.4 Head of the Bay

The head of the bay is characterized by a tidal flat exposed during low tides. This intertidal zone consists predominantly of mud flats with narrow deep channels associated with Deer, Cranberry and Malaney Creeks.

Deer Creek has a stable, single threaded channel that has maintained its sinuous form and vegetated coverage during the photographic record, from 1977 to 2006. Cranberry Creek appears well vegetated inland of the creek mouth. The 1977 oblique aerial photograph shows a mildly anastomosing lower Cranberry Creek (Figure B-15, Appendix B), which has become more channelized by 2006 (Figure B-19, Appendix B). The smooth, low-sloping topography between Cranberry and Deer creeks is a relic of the Vashon glacial advance. Fluted landscape features associated with glacial scour are most pronounced along the upper basins of Cranberry and Deer creeks. All the photographs of Malaney Creek show a braided creek mouth with limited lateral migration over time. The only lateral migration is evident between the 1977 and 1992 aerial photographs (Figures B-5 and B-6, Appendix B), when the channel had migrated into the right bank just before it met the bay. Adjacent to the creek is an area of land that was once cleared, but all of the recent aerial photographs show dense trees surrounding the creek channel, most likely supporting a stable channel alignment.

4.2.2 Central Oakland Bay and Hammersley Inlet

Central Oakland Bay and the western half of Hammersley Inlet include a relatively deep basin beneath the influence of wave action, bounded by steep shorelines. The erosion of unstable slopes along the adjacent shorelines was likely an important source of sediment to the area before European settlement. More recently, shoreline armoring and the construction of roadways between the bluffs and shoreline have limited the contribution of sediment from overland flow and landsliding; however, one identified unstable slope has experienced a recent slide on the southwest shoreline of Oakland Bay (Figure 5). The shoreline near the slide has had minimal modifications. It is possible that the slide is a small, but ongoing, source of sediment to Oakland Bay.

Hardpoint bedrock outcroppings are common in the area, typified by Vashon advance outwash found at the interface between Hammersley Inlet and Oakland Bay. This is evident from the subbottom profiles identified during the geophysical survey. The hardpoints at the interface of Oakland Bay and Hammersley Inlet effectively constrict tidal flow through a narrow and deep subglacial channel.

Central Oakland Bay and Hammersley Inlet are most probably the remnants of a subglacial channel formed during glacial retreat. That channel extends from Hammersley Inlet across Oakland Bay in front of Shelton Harbor, and then along the western shore north of the harbor to

Bayshore Point. The deep-water area in Oakland Bay, just to the west of Hammersley Inlet, is likely a result of energetic tidal exchange around Munson and Miller Points. Bedforms located to the east and west of the deep water area demonstrate that tidal flow preferentially transports sediment into the bay at depth (Figure 5). The return flow at the water surface does not export sediment out of the bay because of the deep (erosional) hole at the junction of Oakland Bay and Hammersley Inlet.

The bathymetric survey indicates a smooth surfaced, undulating seabed through most of the bay, broken in places by the presence of marine bedforms. Seismic reflection data indicate two distinct bedform fields (a group of similarly oriented marine bedforms): Bedform 1 is located at the southwest side of the entrance to Oakland Bay from Hammersley Inlet and Bedform 2 is located in the center of the lower (eastern) portion of Hammersley Inlet, just before it transitions into Oakland Bay (Figure 5). The marine bedforms are steeper on the west and have shallower slopes on the east. Bedform 1 is located in the deep-water region of the bay (13 to 40 feet) and bedform 2 is located in shallow-water (3 to 7 feet). Both display east-west orientations, but with opposing steepened sides, indicating net eastward transport out of Oakland Bay.

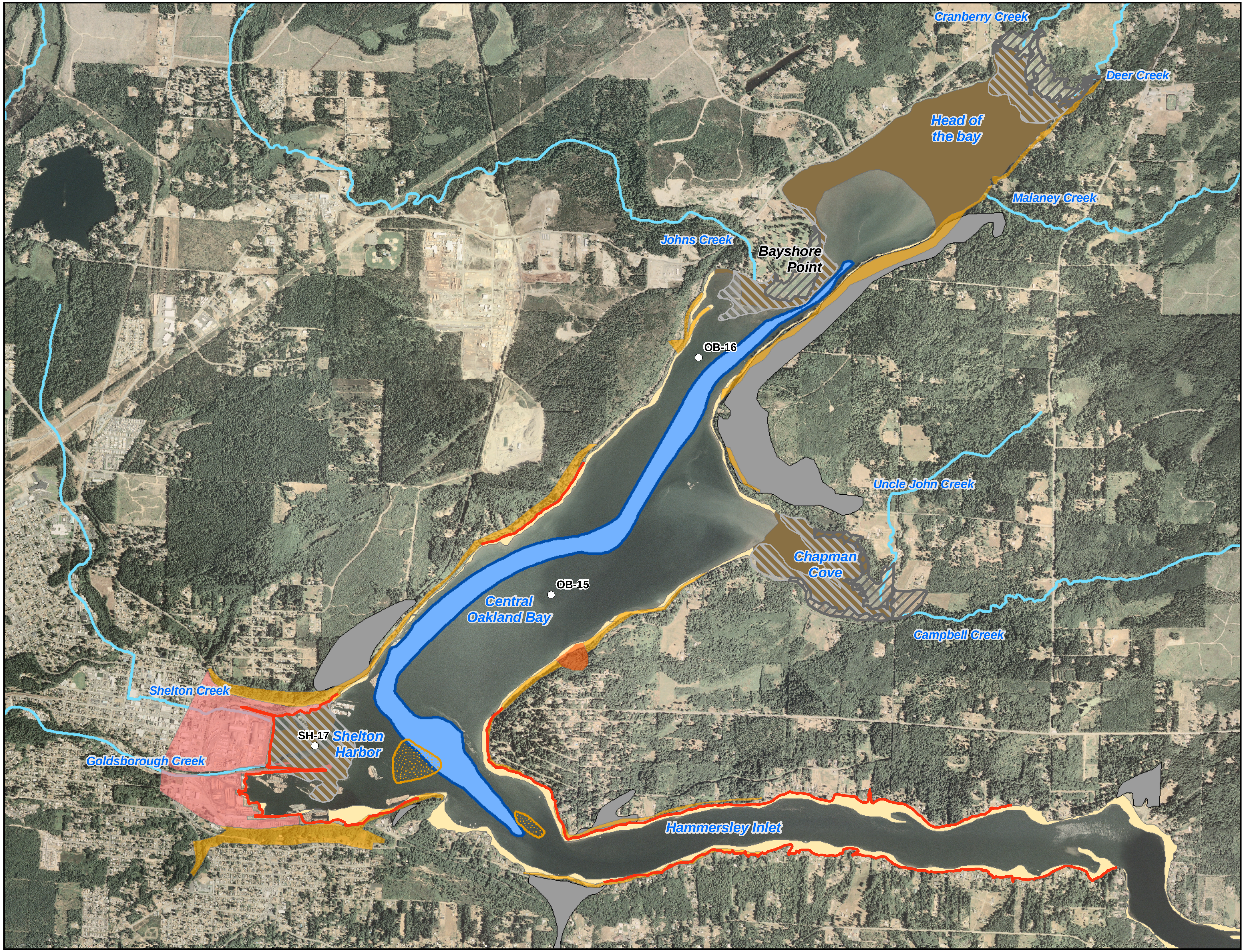
In addition to surficial marine bedforms, a strong reflector (a line of high reflectivity, dark in color, and with sharp edges) appeared between 1 and 8 feet beneath the surface throughout Oakland Bay (Figure 4). This reflector was continuous for much of the central portion of the bay and near all of the creek deltas. It typically indicates a hard surface. For most of the bay and Shelton Harbor, the reflector was 2 to 3 feet beneath the bed surface**.** The reflector is not to be confused with a multiple; a line parallel to the seabed surface that occurs approximately twice the depth from water surface to seabed. An example of a multiple is illustrated in the image of Bedform 2 (Figure 4).

Side-scan data indicated submerged logs immediately north of the Shelton Marina on the western shore of Oakland Bay and at a few random locations throughout Shelton Harbor; otherwise the seabed was mostly featureless. Raw data collected during the geophysical survey can be found in Global Geophysics (2008).

4.3 Sediment Accumulation

Sediment accumulation rates were estimated using radioisotopic analysis of cored sediment. One core was collected from the center of Oakland Bay (OB-15), one was collected from the edge of Shelton Harbor (SH-17), and one was collected from south of Bayshore Point (OB-16). Table 4 summarizes ^{210}Pb measurements conducted on the three sediment cores, while Table 5 summarizes the results of the ^{137}Cs measurements. The ^{210}Pb results provide limits on sediment accumulation rates across the bay, as they show the expected drop in activity (measured in picocuries/gram) with depth below the bed surface and increasing sediment age. The ^{137}Cs results benchmark initial radioisotope deposition associated with the nuclear age. Each core location is discussed separately below, followed by a summary of the results with respect to the overall sediment budget estimate.

Figure 5.
Geomorphic features of Oakland Bay and Hammersley Inlet.



Legend

- Radio-isotopic location
- Modified Shoreline - 70 - 100 % modified
- Upland_Delta
- Intertidal_deltas

Slope

- Modified
- Unstable
- Unstable Recent Slide
- Hardpoint Bedrock Outcrop
- Creek
- Marine bedform
- Subglacial Channel
- Beach
- Tidal Flat

N

0 1,000 2,000 4,000 Feet

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Soil: USFS 1999
Aerial: USDA 2006

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Table 4. ^{210}Pb measurement results, Oakland Bay.

Core Location [a]	Depth Below Surface Interval (cm)	^{210}Pb activity (picocuries/gram)	Grain Size
OB-15	0-3	1.57	silty clay
	10-12	1.03	silty clay
	19-21	1.22	silty clay
	28-30	0.81	silty clay
	37-39	1.13	silty clay
	46-48	n/d	silty clay
	55-57	0.65	silty clay
	64-66	0.45	silty clay
	73-75	0.62	silty clay
	82-84	n/d	silty clay
	91-93	0.64	silty clay
	100-102	0.32	silty clay
	109-111	0.65	silty clay
	118-120	0.37	silty clay
OB-16	0-3	2.09	silty clay
	10-12	1.26	silty clay
	19-21	1.22	silty clay
	28-30	1.30	silty clay
	37-39	0.49	silty clay
	46-48	0.77	silty clay
	55-57	0.71	silty clay
	64-66	0.83	silty clay
	73-75	0.61	silty clay
	82-84	0.41	silty clay
	91-93	0.61	silty clay
	100-102	0.93	silty clay
	109-111	0.43	silty clay
	118-120	n/d	silty clay
SH-17	0-3	0.88	clayey silt
	10-12	0.52	clayey silt
	19-21	0.48	clayey silt
	28-30	0.38	clayey silt
	37-39	0.25	clayey silt
	46-48	0.24	sand
	55-57	n/d	sand
	64-66	n/d	gravel
	73-75	n/d	gravel
	82-84	0.30	sandy silt
	91-93	n/d	sandy silt
	100-102	n/d	sandy silt
	109-111	0.40	sandy silt
	118-120	n/d	sandy silt

[a] Core locations on Figure 5
n/d – Not detected,.

Table 5. ^{137}Cs measurement results, Oakland Bay.

Core Location	Depth Below Surface Interval (cm)	Cs-137 present? Presence of ^{137}Cs
OB-15	7-9	present
	16-18	present
	31-33	not present
OB-16	0-3	present
	16-18	present
	25-27	present

^{210}Pb data analysis first requires establishing a "supported" level of ^{210}Pb activity (Appleby 2008). This is the radioactivity level associated with no remaining atmospherically produced ^{210}Pb, which is dependent on factors such as sediment accumulation rate, grain-size distribution, and other sediment mineralogical characteristics. In the OB-15 core, the radioactivity seen in the samples deeper than 47 cm exhibit no trend with depth and average 0.53 picocuries/gram (in samples where ^{210}Pb was detected). Therefore, approximately 0.5 picocuries/gram constitute the "supported" level of ^{210}Pb activity. The presence of unsupported ^{210}Pb in the 38 cm sample and the lack of unsupported ^{210}Pb at greater depths suggest an accumulation rate of approximately 0.31 cm/year, assuming that the first undetected ^{210}Pb at 47 cm represents material that was deposited 150 years ago.

^{137}Cs samples were selected to bracket the depth expected of ^{137}Cs appearance (i.e., 63 years of sediment accumulation) based on the estimated accumulation rate (Table 5). The presence of ^{137}Cs at 17 cm deep and its absence at 32 cm implies that the accumulation rate occurs between 0.27 and 0.51 cm/year. The ^{137}Cs results provide an independent check on the accumulation rate estimated from ^{210}Pb activity. Because of the imprecise nature of dating sediment, the range of sediment accumulation rates provided by the ^{137}Cs results are the best estimate of sedimentation in central Oakland Bay.

The SH-17 core exhibited large quantities of sand and gravel associated with creek discharges, resulting in a less straightforward interpretation of lead data. ^{210}Lead only adsorbs to fine-grained sediment (predominantly clay); therefore, the total amount of ^{210}Pb per sample volume was greatly reduced (Table 4). All of the core sample activities, except for the surface, were close to or less than the laboratory detection limits of the laboratory analysis. Coarser grained materials are likely associated with rapid mass movements from stream basins to the sea. As such, they do not pick up nearly as much ^{210}Pb as clayey sediments that are transported slowly through the drainage basin. Without a clear supported level of ^{210}Pb, there is no way to make a quantitative estimate of the accumulation rate at the SH-17 core location. For these same reasons, an analysis of ^{137}Cs was not performed on this core.

The grain-size data does provide qualitative information with respect to the sedimentary environment at SH-17. The presence of sand and gravel is inconsistent with the sedimentary environment indicated prior to development because the creek mouths were far away and sediment supply was mediated by a large marsh complex (NOAA 1878). Sediment deposited prior to European settlement at SH-17 would have been restricted to silt- or clay-sized material. Therefore, the presence of sand and gravel implies that the sediment has been delivered to the SH-17 core location since upland development began, resulting in channelization of the creeks. It can therefore be assumed that nearly all of this sediment was laid down since the marshes were filled and channelized prior to 1942, implying an accumulation rate greater than 1 cm/year.

Radioisotope data results for OB-16 are unclear. Similar to OB-15, ^{210}Pb activity seen in the OB-16 core lacks an apparent trend for depths greater 38 cm; however, the apparent supported radioactivity level in OB-16 (0.64 picocuries/gram) is greater than the supported level in OB-15 (0.52 picocuries/gram). There is also more scatter in the apparent supported activities in the OB-16 core. If 0.63 picocuries/gram is the supported level of activity of ^{210}Pb, the accumulation rate at the core site would be approximately 0.25 cm/year, consistent with the OB-15 rate of 0.31 cm/year. However, the presence of ^{137}Cs at 26 cm is entirely inconsistent, suggesting an accumulation rate in excess of 0.6 cm/year. Either the site has been disturbed (if the site was dredged, old sediment with low ^{210}Pb activity would have been mixed with recent deposits containing ^{137}Cs present) or the actual supported level of ^{210}Pb is less than 0.64 picocurries/gram. In this case, the ^{210}Pb results would imply a sediment accumulation rate of 0.79 cm/year or greater. Additional ^{137}Cs testing at OB-16 is required to distinguish between the possibilities.

The three sediment cores collected for radioisotope analyses represent relatively undisturbed central Oakland Bay, the fringe of substantial creek sediment input to Shelton Harbor, and an area of transition between disturbed and undisturbed portions of Oakland Bay near Bayshore Point. Analytical results of each core reflect physical sedimentation processes associated with historical use of both the shoreline and bay for both commercial and industrial purposes. It appears that sediment accumulation rates vary across the Oakland Bay system, between 0.27 and 0.51 cm/year in central Oakland Bay and possibly exceeding 1 cm/year in areas of preferential sediment accumulation (i.e., near deltas). Average accumulation rates predicted from the sediment input analysis suggest that if 0.566 cm/year were found, it would imply that nearly all of the sediment discharged to the bay stays in the bay. The high rates of accumulation within central Oakland Bay imply that some sediment does migrate from Shelton Harbor. In sum, since many areas seem to exceed the average accumulation rate estimated from the sediment input analysis and areas far from sediment sources achieve somewhere between 50 and 90 percent of the anticipated accumulation rate, it appears that sediment does not leave Oakland Bay. It is important to note that these conclusions are consistent with other qualitative evidence of near-bed flow and associated sediment transport (e.g., bedforms oriented into the bay, hydrographic modeling, etc.).

5.0 Summary and Conclusions

Based on modeled sediment inputs and physiographic features, it appears that most Oakland Bay creeks have small sediment contributions to the bay, with the exception of Goldsborough Creek. Historical sources of sediment from the adjacent shore bluffs have been greatly reduced by shoreline development. Near Goldsborough Creek, a large sand and gravel delta has formed in recent times. Accumulation rates of sand and gravel on the delta in Shelton Harbor likely exceed 1 cm/year. Most suspended material delivered via the creeks is transported into the main body of Oakland Bay. This includes material from Goldsborough Creek, Shelton Creek and other points in Shelton Harbor.

Past work describing geologic and hydrographic conditions in Oakland Bay indicates a low-energy, tidally influenced estuary that occupies a drowned drainage network. The extreme tide range in Oakland Bay ensures strong near-bed flood currents, little ebb tide flushing (mostly through surface waters), and a high retention rate of local sediment inputs (Albertson 2004). This means that although there are local high velocity tidal currents at the junction between Oakland Bay and Hammersley Inlet, most sediment that originates in Oakland Bay remains there. Evidence from marine bedforms found at the entrance to the bay confirms this hypothesis of density stratified tidal flow. The dense seawater delivered to the bay may be flowing along the drowned channel bottom (Figure 3), as evidenced by marine bedforms at its south end (Figure 4). Shallow-water marine bedforms oriented toward the rest of Puget Sound in Hammersley Inlet also confirm that less dense, less saline flow is occurring out of Oakland Bay in shallower depths (Albertson 2004).

Subbottom profiling of the sea bed in the harbor identified a strong acoustic reflector that varied between 1 and 8 feet beneath the sediment surface. Observed accumulation rates (between 0.27 and 0.51 cm/year, or 2 to 3 feet in the 100 years since development) suggest that this reflector is likely an indication of the onset of deforestation. The onset of deforestation associated with European settlement has been shown to create significant sediment composition transitions in similar environments (Gomez et al. 2007). In Oakland Bay, the presence of wood waste may enhance the geophysical expression of this transition.

A sediment budget comparing the estimated sediment inputs with sedimentological characteristics and radioisotopic measurements suggests that very little if any sediment that originates Oakland Bay basin is transported into Hammersley Inlet and beyond.

6.0 References

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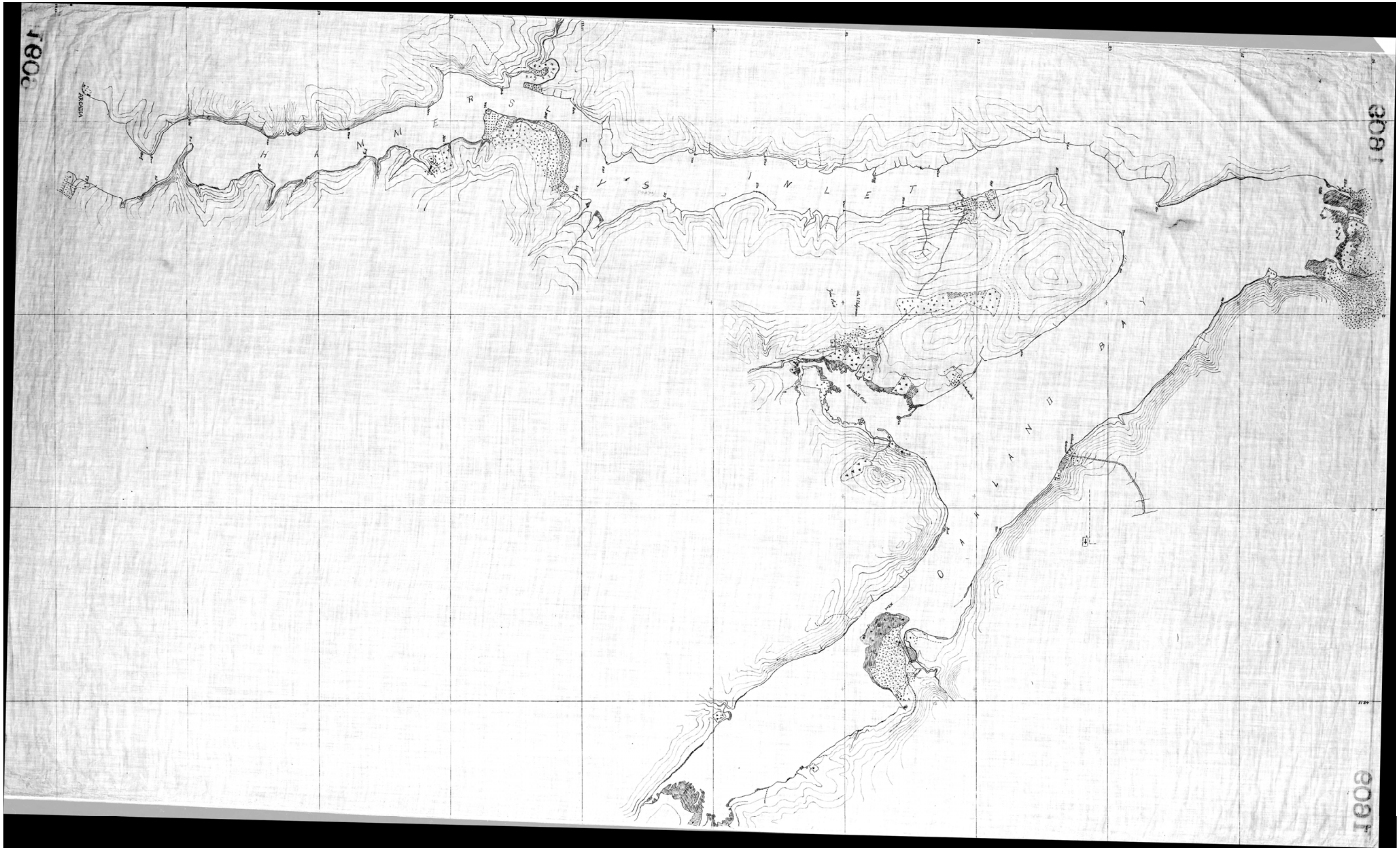
APPENDIX A

Topographic Survey of Oakland Bay in 1878



Oakland Bay 1878 Topographic Survey

APPENDIX B

Historical Photographs of Creek Deltas in Oakland Bay

B-1. Johns Creek, 1977 Coastal Atlas oblique aerial photograph.

B-2. Johns Creek, 1992 Coastal Atlas oblique aerial photograph.

B-3. Johns Creek, 2001 Coastal Atlas oblique aerial photograph.

B-4. Johns Creek, 2006 Coastal Atlas oblique aerial photograph.

B-5. Malaney Creek, 1977 Coastal Atlas oblique aerial photograph.

graphics/01-15-09/rtb/HEC-R/06-03386-007

B-6. Malaney Creek, 1992 Coastal Atlas oblique aerial photograph.

B-7. Goldsborough and Shelton Creeks, 1977 Coastal Atlas oblique aerial photograph.

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B-8. Goldsborough and Shelton Creeks, 1992 Coastal Atlas oblique aerial photograph.

graphics/01-15-09/rtb/HEC-R/06-03386-007

B-9. Goldsborough and Shelton Creeks, 2001 Coastal Atlas oblique aerial photograph.

B-10. Goldsborough and Shelton Creeks, 2006 Coastal Atlas oblique aerial photograph.

B-11. **Uncle John and Campbell Creeks, 1977 Coastal Atlas oblique aerial photograph.,**

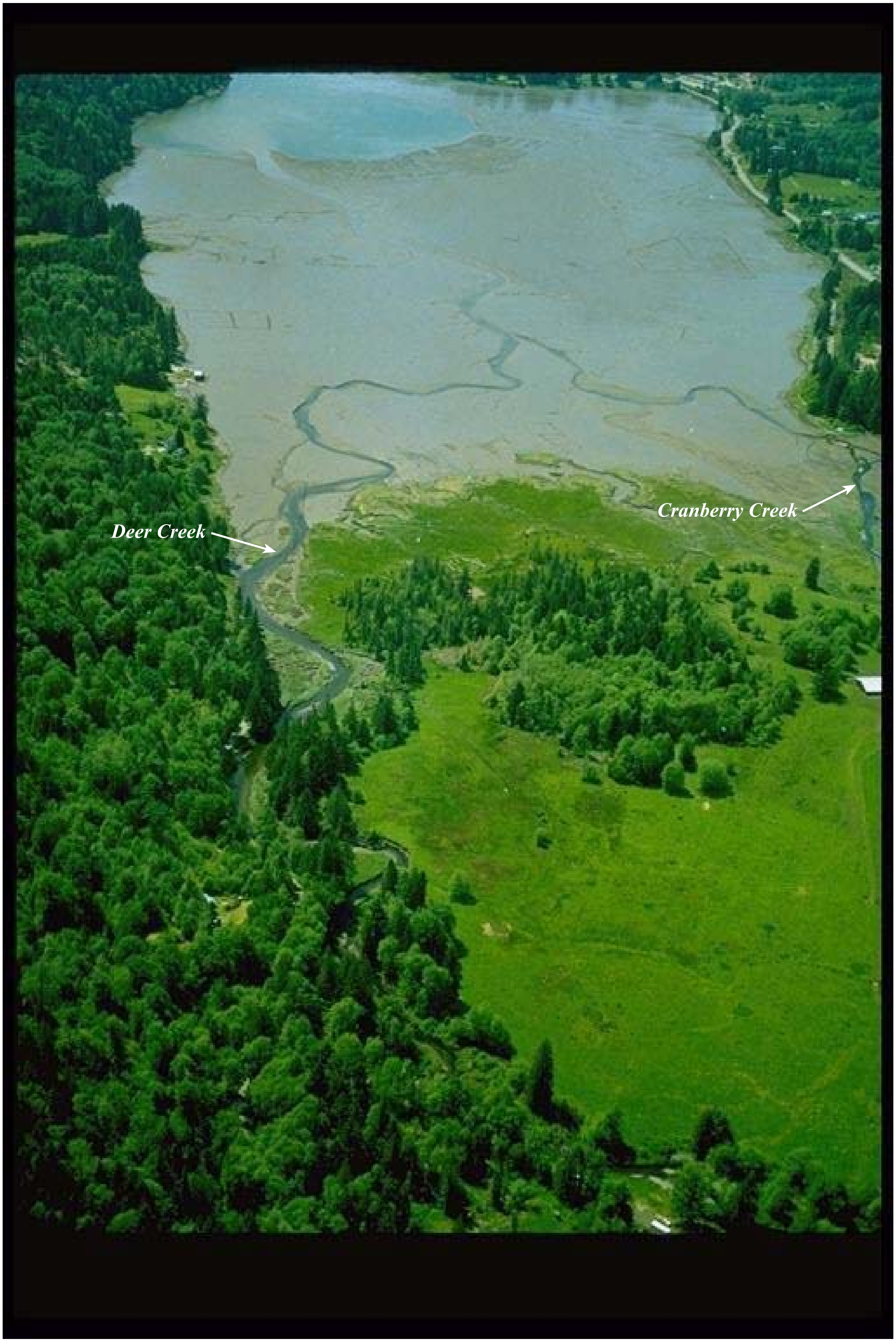
B-12. Uncle John and Campbell Creeks, 1992 Coastal Atlas oblique aerial photograph.

B-13. **Uncle John and Campbell Creeks, 2001 Coastal Atlas oblique aerial photograph.**

B-14. Uncle John and Campbell Creeks, 2006 Coastal Atlas oblique aerial photograph.

B-15. Deer and Cranberry Creeks, 1977 Coastal Atlas oblique aerial photograph.

graphics/01-15-09/rtb/HEC-R/06-03386-007



B-16. Deer and Cranberry Creeks, 1992 Coastal Atlas oblique aerial photograph.

B-17. Deer and Cranberry Creeks, 2001 Coastal Atlas oblique aerial photograph.

B-18. Deer Creek, 2006 Coastal Atlas oblique aerial photograph.

B-19. Cranberry Creek, 2006 Coastal Atlas oblique aerial photograph.

APPENDIX C

Historical Aerial Photographs of Oakland Bay

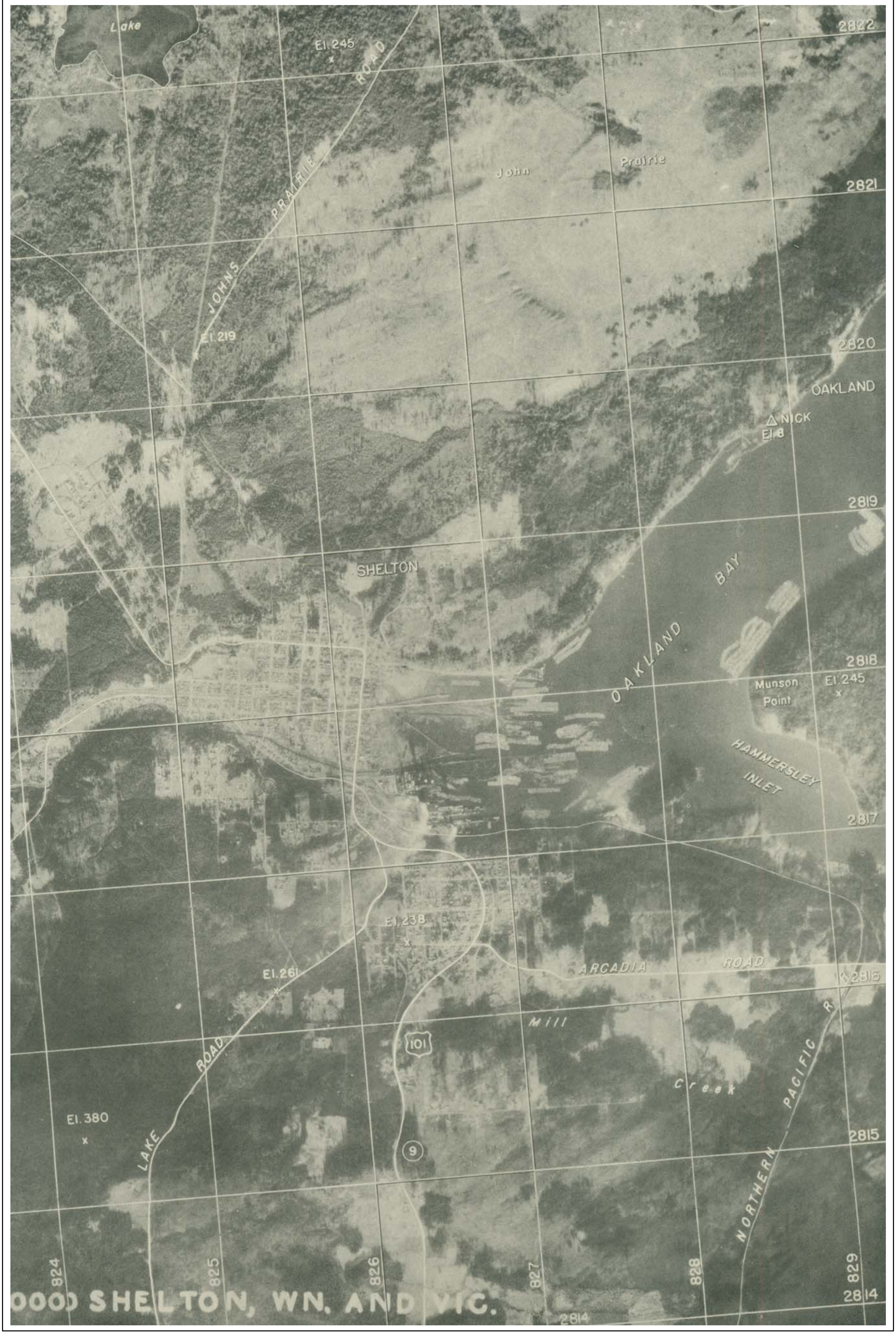


Figure C-1. 1942 University of Washington historical aerial photograph.

Figure C-2. 1957 University of Washington historical aerial photograph.

Figure C-3. 1965 University of Washington historical aerial photograph.

Figure C-4. 1980 University of Washington historical aerial photograph.

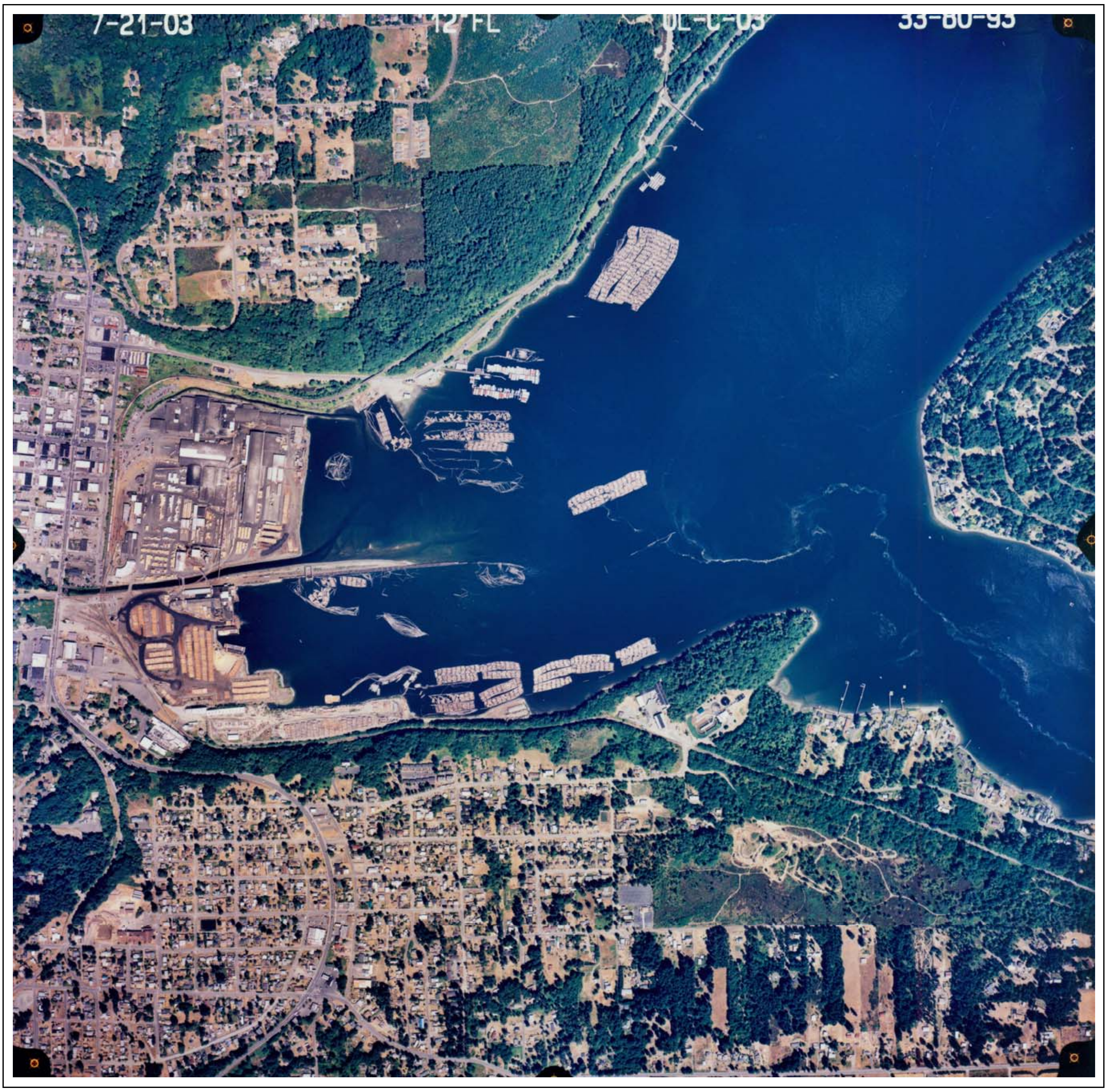


Figure C-5. 2003 University of Washington historical aerial photograph.