Regional Sediment Budget of the Columbia River Littoral Cell, USA

Analysis of Bathymetric- and Topographic-Volume Change

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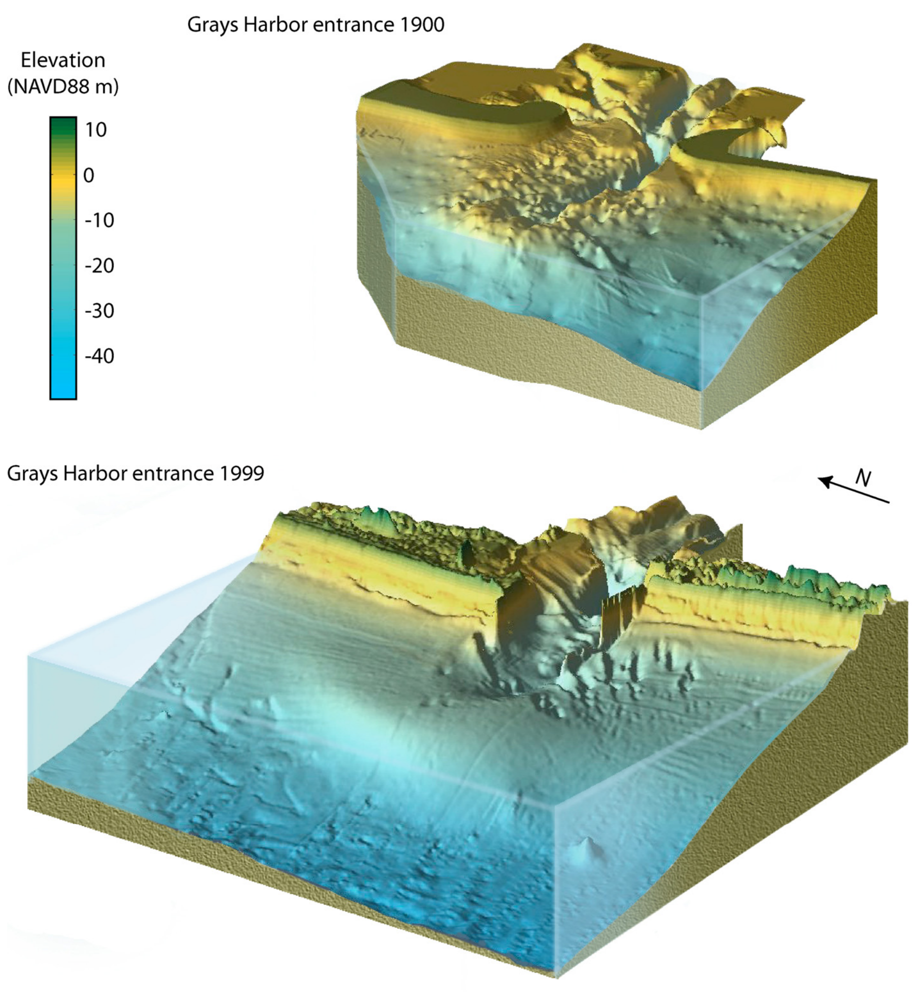

Open-File Report 02-281

Prepared in cooperation with Washington State Department of Ecology

March 2003
U.S. Department of Interior
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Cover Graphs

Top: Three-dimensional representation with perspective of the Grays Harbor entrance, circa 1900. Graph shows the morphology of the Grays Harbor entrance at the start of jetty construction. Due to the lack of data, no topographic surface is calculated above the horizontal plane outlined by the shoreline.

Bottom: Three-dimensional representation with perspective of the Grays Harbor entrance, circa 1999. Graph shows the altered morphology of the Grays Harbor entrance due to jetty construction.

The datasets and the methodologies used to calculate these bathymetric and topographic surfaces are presented in Section 2.

SUMMARY

In this Open-File Report we present calculations of changes in bathymetric and topographic volumes for the Grays Harbor, Willapa Bay, and Columbia River entrances and the adjacent coasts of North Beach, Grayland Plains, Long Beach, and Clatsop Plains for four intervals: pre-jetty - 1920s (Interval 1), 1920s - 1950s (Interval 2), 1950s - 1990s (Interval 3), and 1920s - 1990s (Interval 4). This analysis is part of the Southwest Washington Coastal Erosion Study (SWCES), the goals of which are to understand and predict the morphologic behaviour of the Columbia River littoral cell on a management scale of tens of kilometers and decades. We obtain topographic Light Detection and Ranging (LIDAR) data from a joint project by the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), National Aeronautic and Space Administration (NASA), and the Washington State Department of Ecology (DOE) and bathymetric data from the U.S. Coast and Geodetic Survey (USC&GS), U.S. Army Corps of Engineers (USACE), USGS, and the DOE. Shoreline data are digitized from T-Sheets and aerial photographs from the USC&GS and National Ocean Service (NOS). Instead of uncritically adjusting each survey to NAVD88, a common vertical land-based datum, we adjust some surveys to produce optimal results according to the following criteria. First, we minimize offsets in overlapping surveys within the same era, and second, we minimize bathymetric changes (relative to the 1990s) in deep water, where we assume minimal change has taken place. We grid bathymetric and topographic datasets using kriging and triangulation algorithms, calculate bathymetric-change surfaces for each interval, and calculate volume changes within polygons that are overlaid on the bathymetric-change surfaces.

We find similar morphologic changes near the entrances to Grays Harbor and the Columbia River following jetty construction between 1898 and 1916 at the Grays Harbor entrance and between 1885 and 1913 at the Columbia River entrance. The inlets and inner deltas eroded and the outer deltas moved offshore and accreted. The adjacent coasts experienced accretion over alongshore distances of tens of kilometers. North of the Grays Harbor entrance along North Beach and north of the Columbia River entrance along Long Beach the shoreface and the beach-dune complex mainly prograded, whereas south of the Grays Harbor entrance along Grayland Plains and south of the Columbia River entrance along Clatsop Plains the beach-dune complex above -10 m NAVD88 prograded and the shoreface between approximately -30 m and -10 m NAVD88 eroded. In the decades following jetty construction, the rates of erosion and accretion at the entrances decreased and the centers of deposition along the adjacent coasts moved away from the entrances. The rates of change have decreased, suggesting the systems are approaching dynamic equilibrium. Exceptions to this behaviour are the accretion of the beach-dune complex of Long Beach, the erosion of Cape Shoalwater, and the northward migration of the Willapa Bay

ebb-tidal delta during all intervals. The net shoreline advance of Long Beach increases from 0.28 m/yr in pre-jetty conditions to 3.78 m/yr during Interval 4. The erosion of Cape Shoalwater and the northward migration of the Willapa Bay ebb-tidal delta are related to the northern migration of the Willapa Bay North Channel.

Volume changes at the Grays Harbor, Willapa Bay, and Columbia River entrances and the Columbia River estuary are balanced against losses and gains due to littoral transport and sand supply from the Columbia River. Based on these sediment balances, we infer the following pathways: sand that eroded from the inlets and inner deltas at the Grays Harbor and Columbia River entrances moved offshore and northward to accrete the outer deltas and the beaches to the north; sand from the south flank of the Grays Harbor delta and shelf along Grayland Plains moved onshore to accrete the beach dune complex of Grayland Plains and moved northward to maintain accretion of the outer delta and the beach-dune complex of North Beach; sand that eroded from the south flank of the Columbia River delta and shelf along Clatsop Plains contributed to the accretion of the beach-dune complex of Clatsop Plains and the Columbia River outer delta. The net volume change for Interval 1 and 3 at the Grays Harbor entrance and for Interval 1 at the Columbia River entrance is erosion, whereas the net change for the other intervals is accretion. For the entire CRLC, there is a net loss of 185 Mm^3 for Interval 1, a net gain of 357 Mm^3 for Interval 2, and a net gain of 187 Mm^3 for Interval 3. These imbalances can be the result of incomplete bathymetric coverage of the bays and shoreface, uncertainties in the adjustments of vertical tidal datums, inconsistencies in the bathymetric data, and uncertainties in the sediment supply of the Columbia River.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Southwest Washington Coastal Erosion Study

This analysis is part of the Southwest Washington Coastal Erosion Study (SWCES). The SWCES is a Federal - State - Local cooperative research project initiated to examine the coastal evolution, processes, geology, and hazards of the Columbia River littoral cell (CRLC). The study is cosponsored by the U.S. Geological Survey (USGS) Coastal & Marine Geology Program and the Washington Department of Ecology (DOE) - Coastal Monitoring & Analysis Program. The study area extends approximately 165 km along the United States Pacific Northwest coast between Tillamook Head, Oregon and Point Grenville, Washington (Figure 1-1). The project involves fundamental and applied studies aimed at developing a regional-scale understanding of coastal processes and shoreline change over a variety of time scales. Research efforts are directed towards developing an understanding of the littoral-cell morphology and dynamics to facilitate land-use planning and resource-management decisions into the future.

1.2 Regional Sediment Budget of the Columbia River Littoral Cell

Following jetty construction at the Grays Harbor and Columbia River entrances in the CRLC (Figure 1-1) in the late 1800s and early 1900s the morphology of the entrances and adjacent coasts changed significantly. The Grays Harbor and Columbia River ebb-tidal deltas migrated offshore, the inlets and inner deltas eroded, and the adjacent coasts of North Beach, Grayland Plains, Long Beach, and Clatsop Plains accreted. These changes affected coastal areas over tens of kilometers and several decades. In this study, we use a sand budget to assess and evaluate these widespread and complex changes.

Sediment budgets employ mass conservation and can be valuable tools for assessing change in coastal environments (BOWEN and INMAN, 1966; KOMAR, 1996). There have been several attempts to evaluate sediment budgets at the Grays Harbor and Columbia River entrances and the adjacent coasts of North Beach, Grayland Plains, Long Beach, and Clatsop Plains. In USACE (1967) and USACE (1997) the historical bathymetric-volume change at the Grays Harbor entrance in relation to jetty construction/rehabilitation is discussed. BURCH and SHERWOOD (1992) continued the bathymetric volume-change analysis at the Grays Harbor entrance started in USACE (1967). In addition, they analyzed the historical shoreline change along Half Moon Bay and along northern Grayland Plains. SHERWOOD et al. (1990) calculated bathymetric-volume change for the period between 1868 and 1958 at the Columbia River estuary and entrance and estimated the supply of Columbia River sediment to the estuary. BYRNES and LI (1999) performed a bathymetric-change analysis at the Columbia River entrance for the period between 1868 and

1994 and a shoreline-change analysis for Long Beach and Clatsop Plains for the period between 1868 and 1957. PHIPPS and SMITH (1978) evaluated historical shoreline change along North Beach, Grayland Plains, and Long Beach and did an approximate sand budget study for the entire CRLC. However, these studies only consider relatively short time periods, cover a limited area (e.g. smaller than the CRLC), and do not combine the bathymetric and topographic changes.

This report and the studies by GELFENBAUM et al. (1999), GELFENBAUM et al. (2001), KAMINSKY et al. (1999a), and KAMINSKY et al. (2000), as part of the SWCES, are among the first studies to integrate historical bathymetric- and topographic-volume change at the Grays Harbor, Willapa Bay, and Columbia River entrances and adjacent coasts of North Beach, Grayland Plains, Long Beach, and Clatsop Plains. The bathymetric- and topographic-change volumes presented in the latter four studies are either preliminary or incomplete. In this report, we provide updated and more complete bathymetric- and topographic-change volumes. The objectives of this study are as follows:

1. Calculate historical bathymetric- and topographic-change volumes and rates at the Grays Harbor, Willapa Bay and Columbia River entrances and adjacent coasts of North Beach, Grayland Plains, Long Beach, and Clatsop Plains for four time intervals: pre-jetty - 1920s (Interval 1), 1920s - 1950s (Interval 2), 1950s - 1990s (Interval 3), and 1920s - 1990s (Interval 4).

2. Establish sediment balances at the Grays Harbor and Columbia River entrances for these four intervals.

3. Describe and interpret the morphologic changes that occurred in the CRLC during these four intervals.

4. Infer sediment-transport pathways from patterns of erosion and accretion.

5. Provide historical information about dredging and disposal of sediments at the Grays Harbor and Columbia River entrances.

6. Provide a foundation for further research, e.g., numerical shoreline and morphodynamic modeling, for the preparation of scientific papers on sediment budgets in the CRLC, etc.

7. Provide information that can be used to guide decision making within the CRLC.

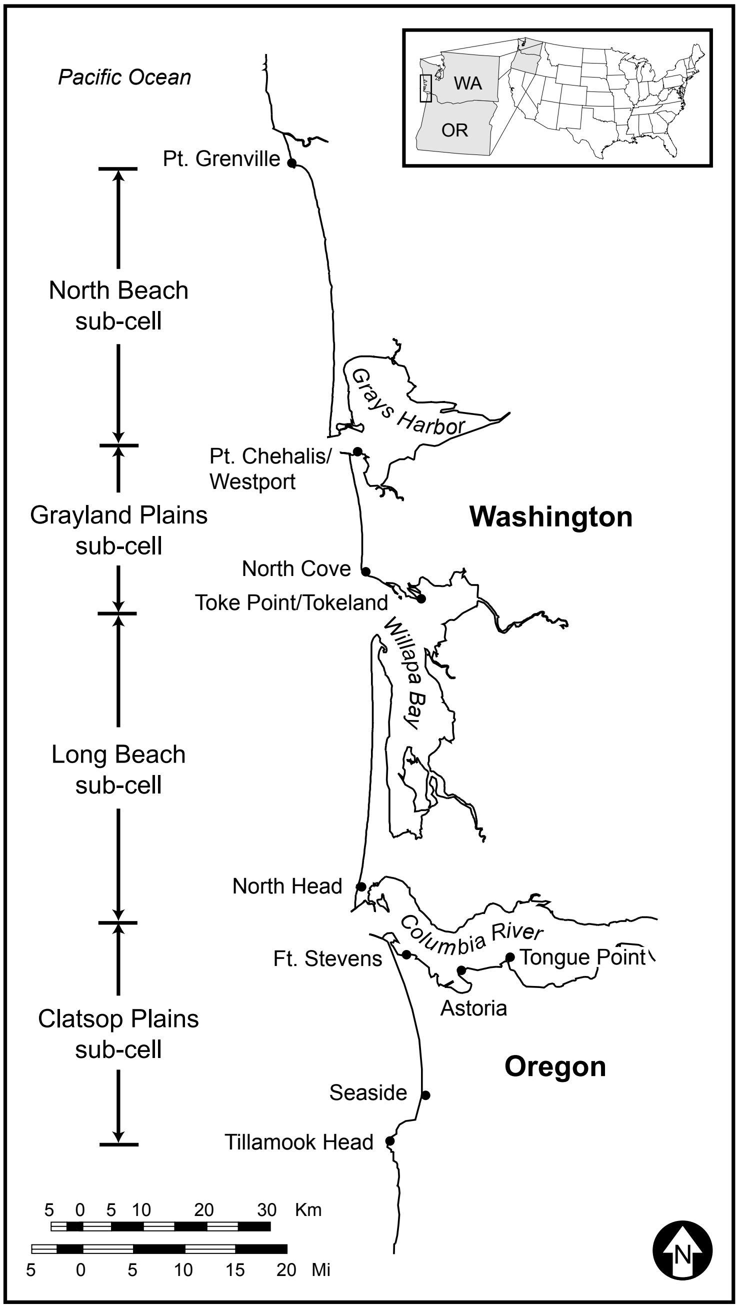


Figure 1-1. The Columbia River littoral cell.

1.3 Outline

Section 2 describes the datasets used for the bathymetric- and topographic-volume calculations, the horizontal and vertical control of the bathymetric datasets, the adjustments of the vertical datums, the methodology of the volume calculations, and estimates of uncertainty. In Section 3 we present bathymetric- and topographic-change calculations for the Grays Harbor and Columbia River entrances and adjacent coasts by means of figures and tables. The results of the calculations are discussed in Section 4. We present conclusions in Section 5. In Appendices A, B, C, D, E we describe the Columbia River estuary compartments, the Columbia River sediment supply, dredging and disposal at the Grays Harbor entrance, dredging and disposal at the Columbia River entrance, and calculation of the Interval 2 and Interval 3 volume change of the beach-dune complex of southern Clatsop Plains, respectively.

1.4 Abbreviations

CR	Columbia River
CRLC	Columbia River littoral cell
CP	Clatsop Plains
dn	delta north
DEM	Digital Elevation Model
DOE	Department of Ecology
ds	delta south
GH	Grays Harbor
GL	Grayland Plains
GPS	Global Positioning System
LB	Long Beach
LIDAR	Light Detection and Ranging
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
NASA	National Aeronautic and Space Administration
NAD	North American Datum
NAVD88	North American Vertical Datum of 1988
NB	North Beach
NGS	National Geodetic Survey
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
RMS	Root Mean Square
RTK	Real-Time Kinematic
SWCES	Southwest Washington Coastal Erosion Study
USACE	U.S. Army Corps of Engineers
USC&GS	U.S. Coast and Geodetic Survey
USGS	U.S. Geological Survey
UTM	Universal Transverse Macerator
WB	Willapa Bay

1.5 Disclaimer

The data and conclusions provided in this Open-File Report are preliminary and may contain errors that remain undetected. Therefore, this information is provided to and accepted by the user with any accompanying errors. Any person or entity that relies upon information generated by or obtained herein does so at his or her own risk.

2 METHODOLOGY OF VOLUME CALCULATIONS

2.1 Data

This analysis of bathymetric and topographic change covers the Columbia River littoral cell (CRLC) including the inlets of Grays Harbor, Willapa Bay, and Columbia River, the littoral sub-cells of North Beach, Grayland Plains, Long Beach, and Clatsop Plains, and associated nearshore areas (Figure 1-1). The 165-km long CRLC mainly contains Columbia River sediments and is confined between the rocky headlands of Point Grenville to the north and Tillamook Head to the south (PETERSON et al., 1991).

Available bathymetric and topographic data are assigned to four eras (periods of nearly contemporary surveys). They are Era I (1860s - 1900s), Era II (1920s - 1930s), Era III (1940s - 1950s), and Era IV (1990s - 2000s). Analyses of bathymetric and topographic change in the CRLC are performed for four intervals:

- Interval 1: Era I - Era II (1860s - 1900 to 1920s - 1930s)
- Interval 2: Era II - Era III (1920s - 1930s to 1940s - 1950s)
- Interval 3: Era III - Era IV (1940s - 1950s to 1990s - 2000)
- Interval 4: Era II - Era IV (1920s to 1990s)

Bathymetric and topographic change analyses are performed at both the Columbia River and the Grays Harbor entrances for Intervals 1, 2, and 3. Bathymetric data are not available for the Columbia River estuary for Era IV, and therefore, volume change inside the estuary is not calculated for Interval 3. Bathymetric changes in the Columbia River estuary are taken from SHERWOOD et al. (1990). There is inadequate bathymetric coverage in the Grays Harbor and Willapa Bay tidal basins for volume-change analysis. Sufficient bathymetric coverage is only available at the Willapa Bay entrance for Era II and Era IV, allowing for bathymetric- and topographic-change calculations for Interval 4.

Typically, the bathymetric and shoreline surveys of the same era were performed during different years. The majority of the volume calculations are not corrected for these time discrepancies because the annual morphologic change was small compared to interval-scale change. Exceptions are the volume calculations involving the Era II surveys of the Columbia River estuary. The Era II bathymetric surveys of the Columbia River estuary used for volume calculations by SHERWOOD et al. (1990) were performed in 1935, 1936, and 1937, whereas the surveys of the entrance and ocean seafloor were performed in 1926 and 1927. We adjust the volume changes of the estuary compartments for intervals 1868 - 1930s and 1930s - 1958 to match the volume changes of the seafloor compartments for intervals 1868 - 1920s and 1920s - 1958, assuming that the rate of change in the estuary was constant during these intervals. We reduce the volume changes in the estuary of Interval 1 by 13% ((67 years - 58 years) / 67 years x 100%) and add the remainder to the volume changes of Interval 2 (Table 3-4 and Table 3-10).

The bathymetric data used in this report are obtained from various sources. The U.S. Coast and Geodetic Survey (USC&GS) surveys, except the H8421 survey, are obtained from the National Ocean Service (NOS) (NOAA - NGDC, 1998). The U.S. Army Corps of Engineers (USACE) surveys at the Grays Harbor and Willapa Bay entrance are obtained from the USACE Seattle District (ERIC NELSON, personal communication, 1999). The USACE surveys at the Columbia River entrance, except the USACE 1935 survey, are obtained from the USACE Portland District (HANS R. MORITZ, personal communication, 1999). The USC&GS H8421 and USACE 1935 surveys are obtained from Applied Coastal Research and Engineering, Inc. (MARK R. BYRNES, personal communication, 1999; BYRNES and LI, 1999). Nearshore surveys obtained with the Coastal Profiling System (CPS; RUGGIERO et al., 1999; RUGGIERO AND VOIGT, 2000) and Multibeam surveys were performed as part of the SWCES by the U.S. Geological Survey (USGS) in cooperation with the Washington State Department of Ecology (DOE). The USACE Annual Surveys of the Grays Harbor Entrance of 1900, 1927, and 1954 are digitized from Annual Survey sheets. Additional data for the spits and shoals present at the mouth of the Columbia River in 1868 are digitized from an 1870 chart of the U.S Coast Survey of the mouth of the Columbia River reprinted by THE OREGON HISTORICAL SOCIETY COLLECTIONS (1980). The digital elevation model (DEM) used in the topographic-volume calculations is extracted from Light Detection and Ranging (LIDAR) data collected by a joint USGS/NOAA/NASA project in April 1998 (SALLENGER et al., 1999). All surveys of the Grays Harbor and Willapa Bay entrances are presented in Table 2-1 and the surveys at the Columbia River entrance are presented in Table 2-2. The boundaries of bathymetric surveys for Era I, Era II, Era III, and Era IV are plotted in Figure 2-1, Figure 2-2, Figure 2-3, and Figure 2-4, respectively. Only specific parts of the USACE 1927 and USACE 1999 surveys are used to complement the Era II USC&GS and Era IV CPS and Multibeam surveys, respectively. Figure 2-5 shows close-ups of these surveys. If necessary, original horizontal and vertical datums are converted to Washington State Plane South and to NAVD88 as discussed in Section 2.2 and 2.4, respectively. In these sections we further discuss Table 2-1 and Table 2-2.

Shorelines from Era I, Era II, and Era III are digitized from USC&GS topographic sheets (T-sheets) (KAMINSKY et al., 1999b). A portion of the 1957 shoreline at Long Beach and the Era IV shorelines are digitized from aerial photographs obtained from the National Ocean Service (NOS). The shoreline data are presented in Table 2-3 and Table 2-4.

Table 2-1. Bathymetric data collected at the Grays Harbor (GH) and Willapa Bay (WB) entrances and along North Beach and Grayland Plains.

Era	Survey	Date	Location	Original Vertical Datum	Vertical Datum Relative to NAVD88 (m)	Correction to Charted Depths (m)
Era I	USC&GS H1800	1887	Offshore Grayland Plains	MLLW near North Cove	-0.24	-0.24
	USACE	1900	GH delta and entrance	MLLW Pt. Chehalis, Westport[1)]	-0.46	-0.46
Era II	USC&GS H4621	1926	Nearshore Grayland Plains	MLLW Ft. Stevens	-0.16	-0.16
	USC&GS H4620	1926	WB delta, Grayland Plains, and Long Beach	MLLW Ft. Stevens	-0.16	-0.16
	USACE	1927	GH delta	MLLW Pt. Chehalis, Westport [1)]	-0.46[2)]	-1.11[2)]
	USC&GS H4710	1927	Nearshore North Beach	MLLW Pt. Grenville	-0.36	-0.36
	USC&GS H4728	1927	Offshore Grayland Plains and North Beach	MLLW Pt. Grenville	-0.36	-0.36
	USC&GS H4658	1928	WB delta	MLLW Pt. Grenville	-0.36[2)]	-0.16[2)]
Era III	USACE	1954	GH delta and entrance	MLLW Pt. Chehalis, Westport[1)]	-0.46[2)]	+5%[2)]
	USC&GS H8252	1955	Offshore GH entrance	MLLW Pt. Chehalis, Westport	-0.46[2)]	0[2)]
Era IV	USACE	1998	WB delta, entrance and bay	MLLW Toke Point	-0.24	-0.24
	USGS/ DOE CPS	1999	North Beach and Grayland Plains	NAVD88	0	0
	USGS/ DOE Multibeam	1999	GH delta and offshore Grayland Plains	NAVD88	0	0
	USACE	1999	GH delta and entrance	MLLW Westport[3)]	-0.46	-0.46

1) Location of the tide gauge assumed.
2) See discussion in Section 2.4 about the adjustments of the vertical datums.
3) USACE performed survey using RTK-GPS. This survey is referenced to MLLW at Westport.

Table 2-2. Bathymetric data collected at the Columbia River (CR) entrance and along Long Beach and Clatsop Plains.

Era	Survey	Date	Location	Original Vertical Datum	Vertical Datum Relative to NAVD88 (m)	Correction to Charted Depths (m)
Era I	USC&GS H1018	1868	CR estuary	MLLW Astoria[1)]	-0.02	-0.02
	USC&GS H1019	1868	CR delta	MLLW Astoria[1)]	-0.02	-0.02
	USC&GS H1378	1877	Offshore Clatsop Plains	MLLW Astoria	-0.02	-0.02
	USC&GS H1379	1877	Offshore Long Beach	MLLW Astoria	-0.02	-0.02
Era II	USC&GS H4611	1926	Nearshore Clatsop Plains	MLLW Ft. Stevens[1)]	-0.16	-0.16
	USC&GS H4618	1926	CR delta	MLLW Ft. Stevens	-0.16	-0.16
	USC&GS H4619	1926	Nearshore Long Beach	MLLW Ft. Stevens	-0.16	-0.16
	USC&GS H4634	1926	Offshore Long Beach	MLLW Ft. Stevens	-0.16	-0.16
	USC&GS H4635	1926	Offshore Clatsop Plains	MLLW Ft. Stevens	-0.16[3)]	-1.84[3)]
	USACE	1935	CR entrance	MLLW Ft. Stevens[2)]	-0.16	-0.16
Era III	USC&GS H8416	1958	Offshore Long Beach	MLLW Ft. Stevens	-0.16[3)]	-0.45[3)]
	USC&GS H8417	1958	Offshore Clatsop Plains	MLLW Ft. Stevens	-0.16[3)]	-0.45[3)]
	USC&GS H8421	1958	Lower CR estuary	MLLW Ft. Stevens	-0.16[3)]	-0.45[3)]
	USC&GS H8423	1958	CR delta	MLLW Ft. Stevens	-0.16[3)]	-0.45[3)]
Era IV	USACE	1998	Offshore Long Beach	MLLW Ft. Stevens	-0.16	-0.16
	USGS/ DOE CPS	1999	Long Beach and Clatsop Plains	NAVD88	0	0
	USACE	1999	Offshore northern Long Beach	MLLW Ft. Stevens	-0.16	-0.16
	USACE	2000	CR approaches and disposal sites	MLLW Ft. Stevens	-0.16[3)]	+0.19[3)]
	USACE	2000	CR delta, offshore Clatsop Plains	MLLW Ft. Stevens	-0.16	-0.16

[1)] Location of the tide gauge assumed.
[2)] Original survey is referenced to Mean Low Water (MLW) at Ft. Stevens; we obtained survey referenced to NGVD'29 from Mark R. Byrnes (Applied Coastal Research and Engineering, Inc., personal communication, 1999), and we adjusted it by +1.1 m to MLLW to allow for better comparison with USC&GS surveys.
[3)] See discussion in Section 2.4 about the adjustments of the vertical datums.

Table 2-3. Shoreline data collected at the Grays Harbor and Willapa Bay entrances and along North Beach and Grayland Plains.

Era	Data Source	Date	Location
Era I	T-1783	1887	North Beach
	T-1782	1887	North Beach
	T-1781	1887	North Beach
	T-1701	1886	North Beach
	USACE Annual Survey	1900	North Beach
	T-1701	1886	Grayland Plains
	T-1262	1871	Grayland Plains
Era II	T-4306	1927	North Beach
	T-4305	1927	North Beach
	T-4254	1926	Grayland Plains
	T-4253	1926	Grayland Plains
Era III	T-9514	1950	North Beach
	T-9515	1950	North Beach
	T-9517n	1951	North Beach
	T-9517s	1951	North Beach
	T-9518s	1951	Grayland Plains
	T-9517s	1951	Grayland Plains
	T-9521	1951	Grayland Plains
	T-9634n	1950	Grayland Plains, Cape Shoalwater
Era IV	NOS Aerial photographs	1995	North Beach
	NOS Aerial photographs	1995	Grayland Plains

Table 2-4. Shoreline data collected at the Columbia River entrance and along Long Beach and Clatsop Plains.

Era	Data Source	Date	Location
Era I	T-1261	1871	Long Beach
	T-1293	1872	Long Beach
	T-1341a&b	1873	Long Beach
	T-1138	1869	Long Beach
	T-1112	1868	Clatsop Plains
	T-1381a&b	1874	Clatsop Plains
Era II	T-4252	1926	Long Beach
	T-4251	1926	Long Beach
	T-4250	1926	Clatsop Plains
	T-4226	1926	Clatsop Plains
	T-4227	1926	Clatsop Plains
Era III	T-9634s	1950	Long Beach
	T-9637n&s	1950	Long Beach
	NOS Aerial photographs	1957	Long Beach
	T-10649	1957	Long Beach
	T-10340	1957	Long Beach
	T-10344	1951	Long Beach
	T-10345	1957	CR entrance, Sand Island
	T-10346	1955	Clatsop Plains
	T-10352	1955	Clatsop Plains
	T-10353	1957	Clatsop Plains
	T-10359	1957	Clatsop Plains
	T-10650	1948	Clatsop Plains
Era IV	NOS Aerial photographs	1995	Long Beach
	NOS Aerial photographs	1995	Clatsop Plains

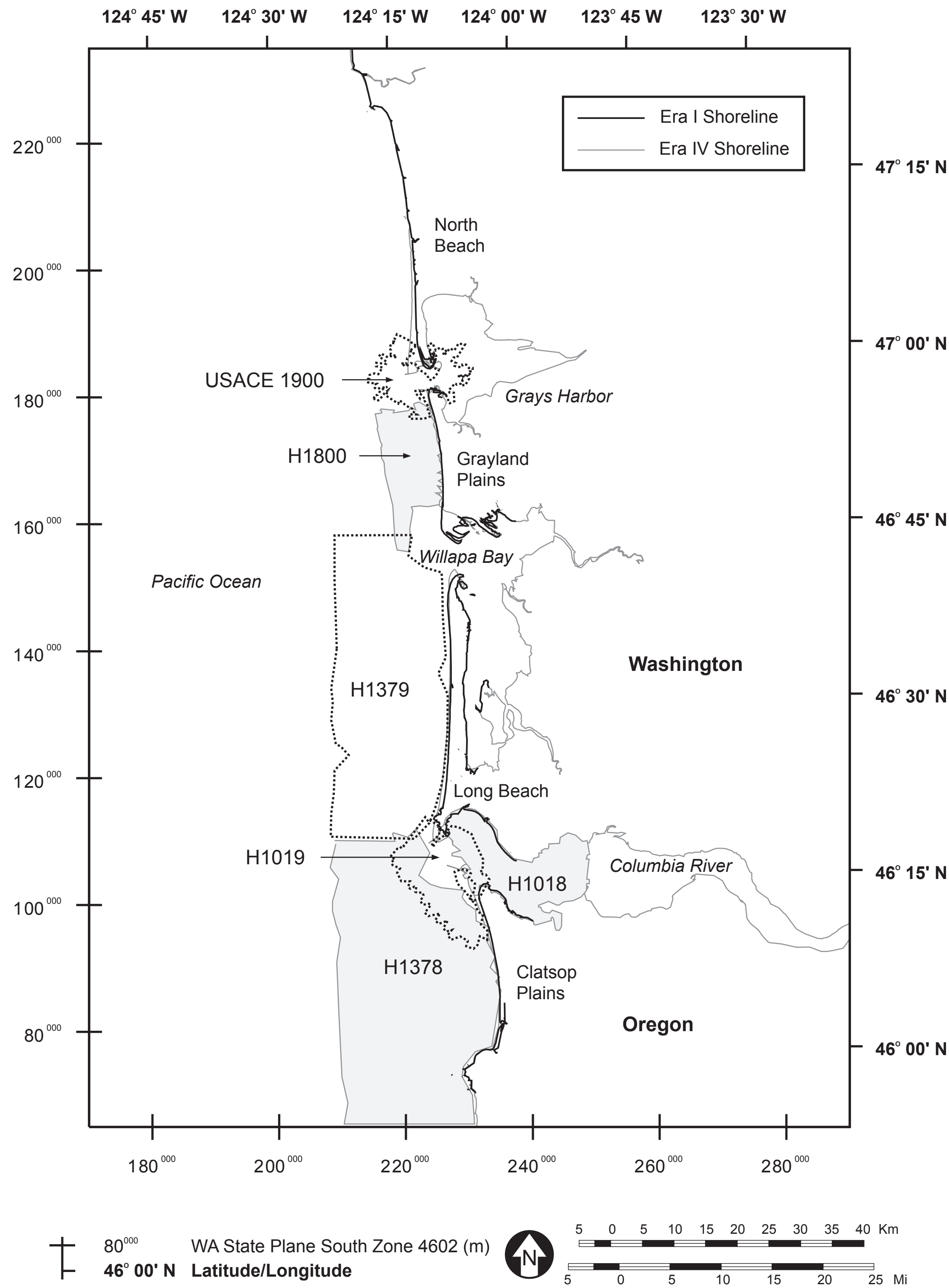


Figure 2-1. Location of the Era I bathymetric surveys and shoreline within the CRLC. The numbers refer to the surveys presented in Table 2-1 and Table 2-2. Various line styles and shading have been used to differentiate surveys.

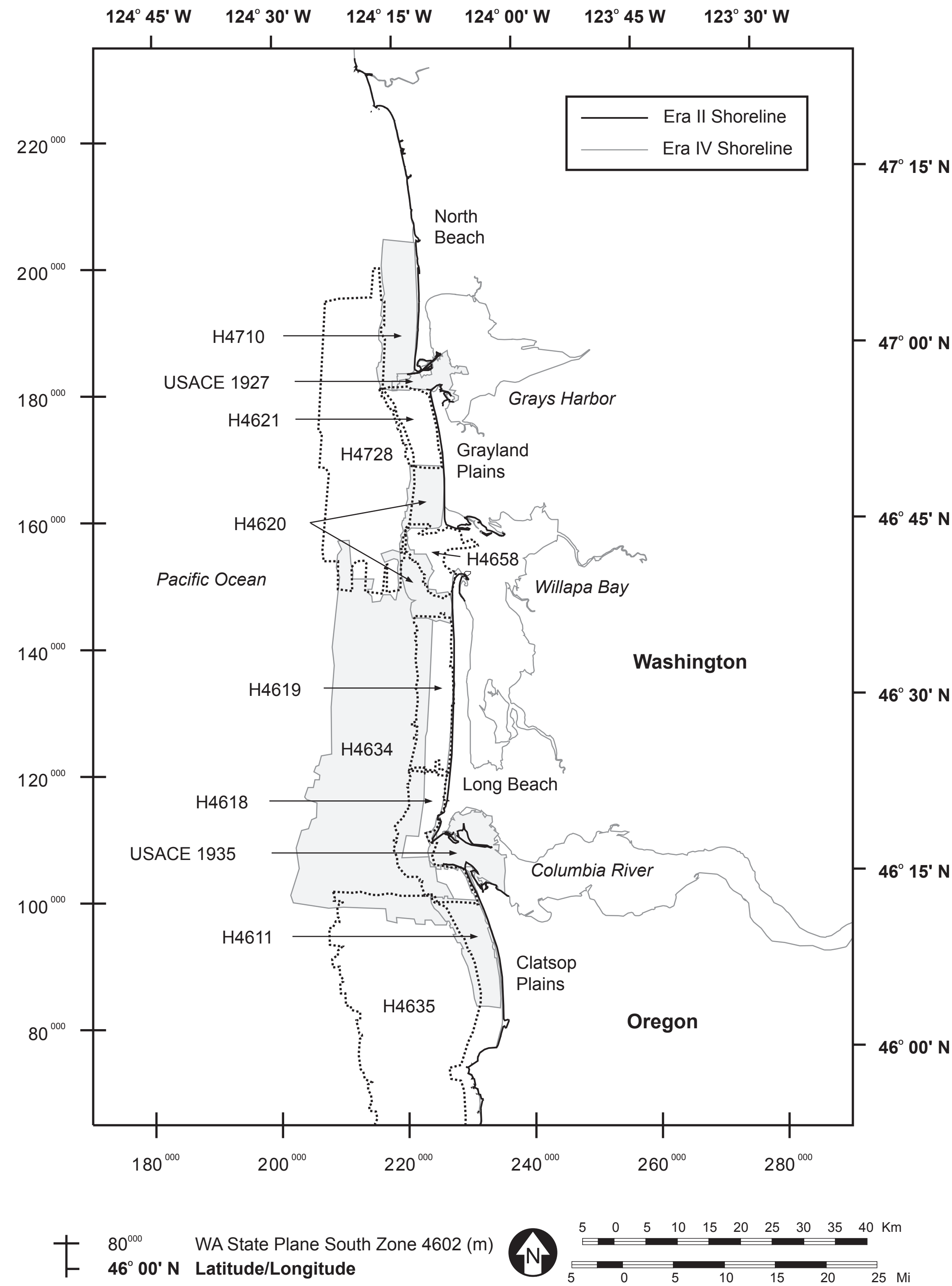


Figure 2-2. Location of the Era II bathymetric surveys and shoreline within the CRLC. The numbers refer to the surveys presented in Table 2-1 and Table 2-2. Various line styles and shading have been used to differentiate surveys.

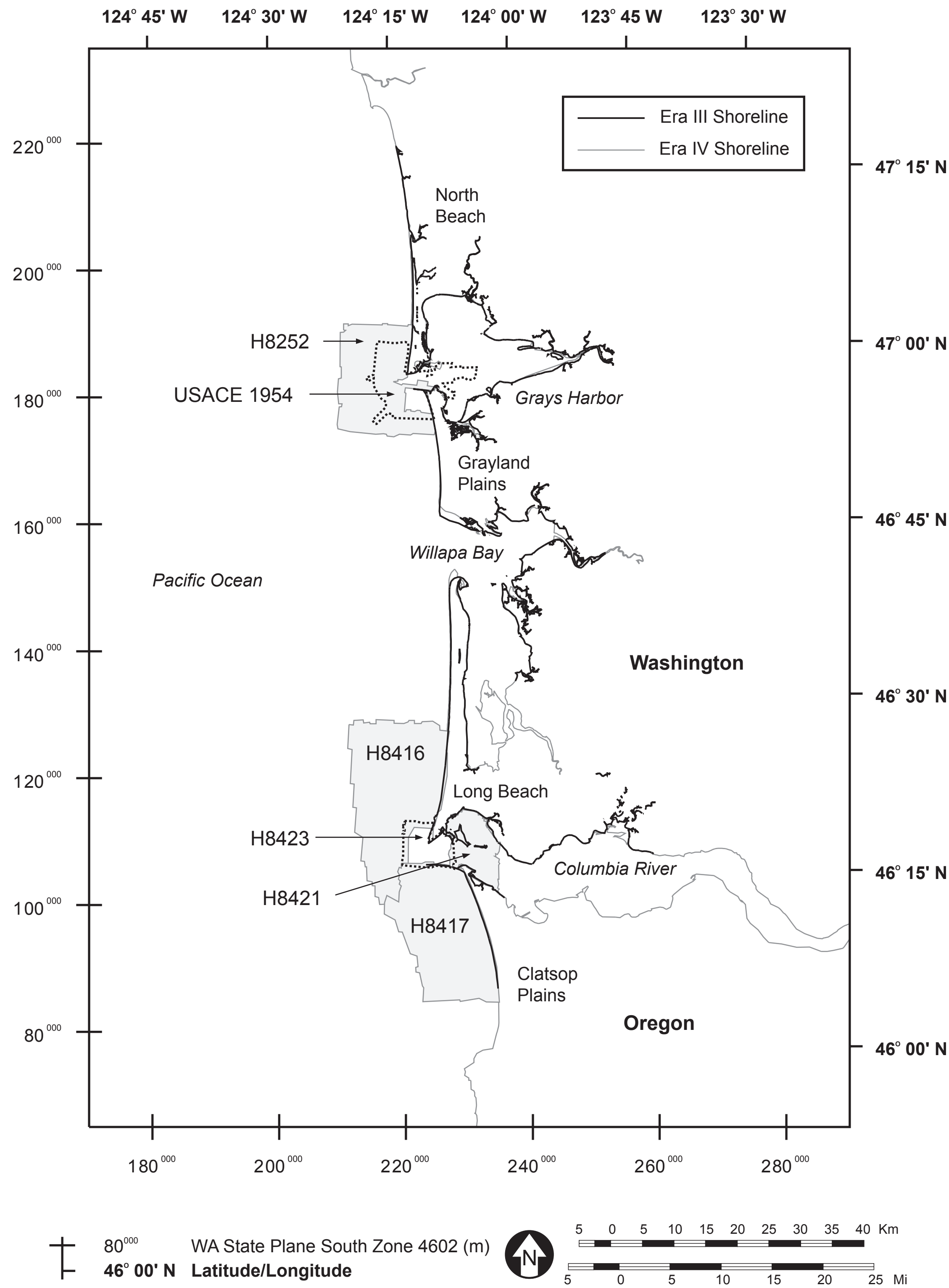


Figure 2-3. Location of the Era III bathymetric surveys and shoreline within the CRLC. The numbers refer to the surveys presented in Table 2-1 and Table 2-2. Various line styles and shading have been used to differentiate surveys.

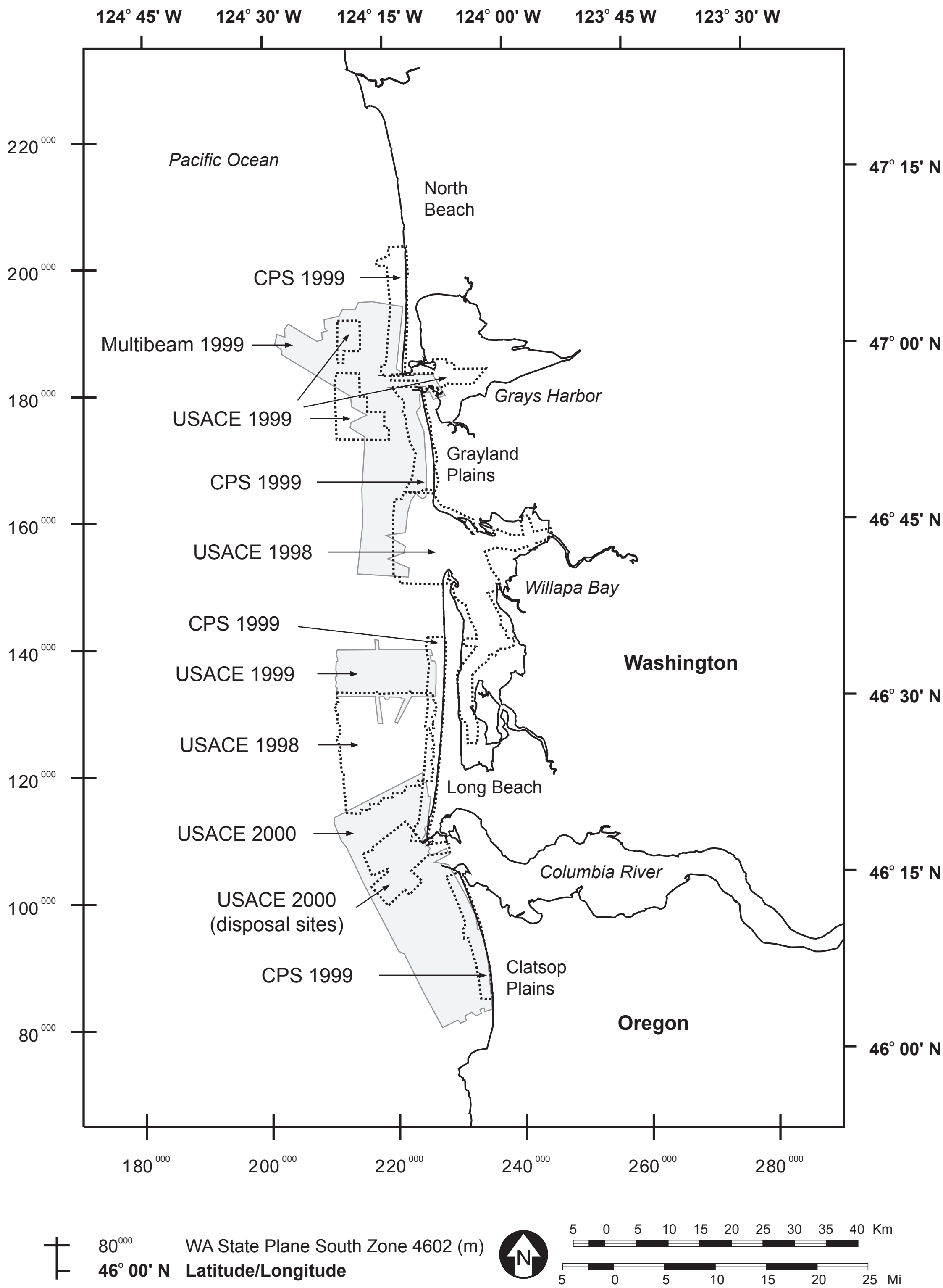


Figure 2-4. Location of the Era IV bathymetric surveys and shoreline within the CRLC. The numbers refer to the surveys presented in Table 2-1 and Table 2-2. Various line styles and shading have been used to differentiate surveys.

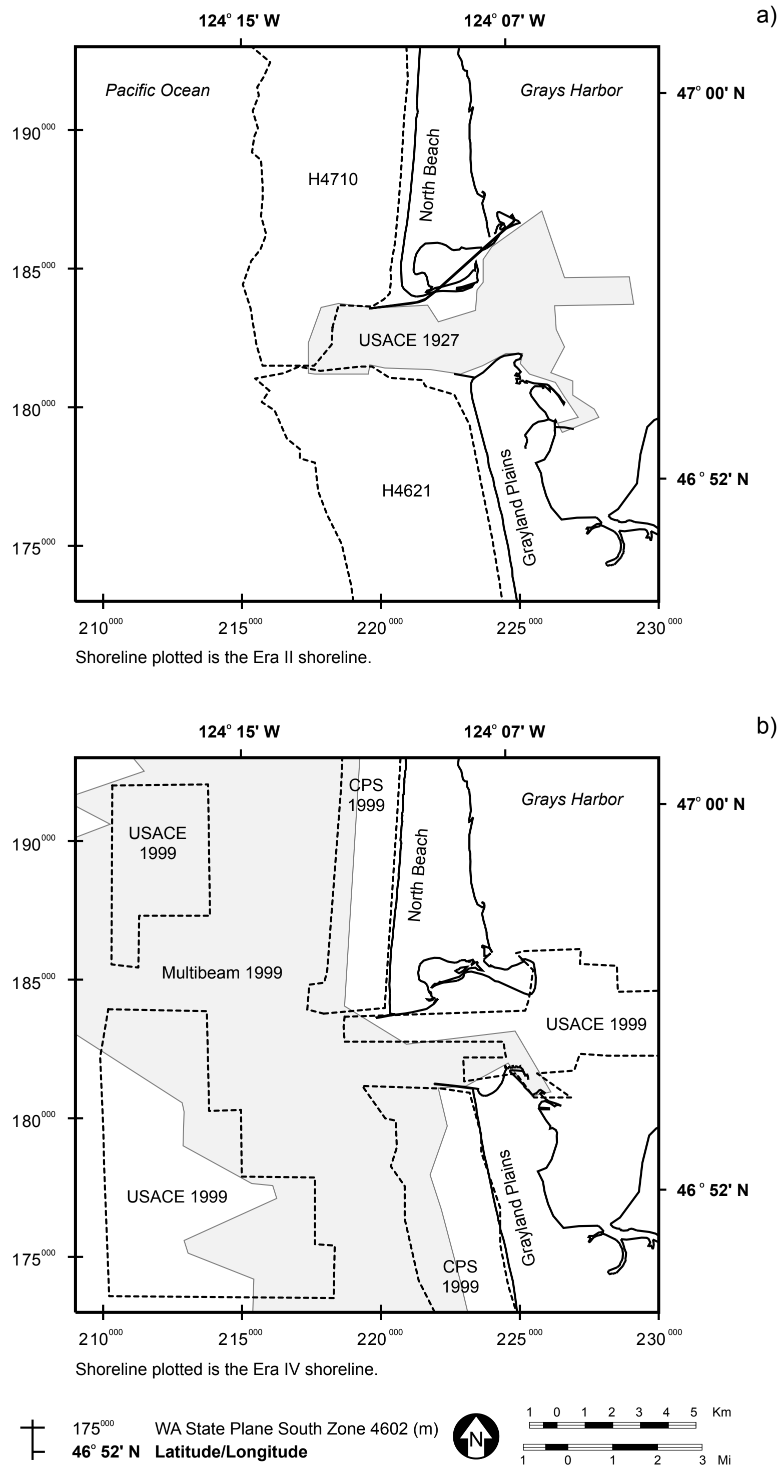


Figure 2-5. Close-up of the merged a) Era II and b) Era IV bathymetric surveys at the Grays Harbor entrance. The numbers refer to the surveys presented in Table 2-1. Various line styles and shading have been used to differentiate surveys.

2.2 Data-Collection Techniques

The data collection techniques of bathymetric surveys are extensively discussed in GIBBS and GELFENBAUM (1999) and the USC&GS Descriptive Reports of the Era II surveys. The Descriptive Reports are obtained from NOAA - NOS (SCOTT CLARK, NOS, personal communication, 1995).

Soundings performed during the Era I and Era II surveys were measured with a graduated pole in water depths less than 5.5 m (18 feet) and lead lines and Rude-Fisher pressure tubes were used in deeper water (SHALOWITZ, 1964; GIBBS and GELFENBAUM, 1999; USC&GS Descriptive Reports for Era II). Echo sounding fathometers were employed for the Era III surveys and high-precision singlebeam and multibeam echo sounders for the Era IV surveys (GIBBS and GELFENBAUM, 1999).

Horizontal positioning for the Era I surveys was by sextant angles, by theodolite angles, and by estimation of position based on the ship's speed and heading (dead reckoning). Later surveys employed both sextant angles to stations and radio acoustic ranging (SHALOWITZ, 1964; SALLENGER et al., 1975; GIBBS and GELFENBAUM, 1999). During the Era IV surveys horizontal positions were determined with Differential Global Positioning System (DGPS).

2.3 Horizontal and Vertical Control

2.3.1 Horizontal Control

All USC&GS data are obtained in the Latitude/Longitude coordinate system. Most data are referenced to the North American Datum of 1927 (NAD27), a horizontal datum based on the Clarke Ellipsoid of 1866 (NATIONAL GEODETIC SURVEY, 1986). Survey H1379 is referenced to the old North American Datum (NAD13) and H1019 to an unknown horizontal datum. Corrections for converting positions from NAD13 to NAD27 are provided in "Datum Differences, Atlantic, Gulf, and Pacific Coasts United States" (STEVE BAUMGARDNER, NOAA, written communication, 1996). Using these corrections, soundings from H1379 are shifted 39.6 m to the south and 31.0 m to the west. Survey H1019 with an unknown horizontal datum is more problematic. Typically, where geographically fixed topographic features, such as rocky headlands, are included on H-sheets, a visual best-fit shift can be performed relative to the rocky headland shoreline as mapped on NOS T-sheets of the same time interval. For survey H1019, Cape Disappointment at the entrance to the Columbia River is used to shift the soundings approximately 1067 m to the northwest so the H-sheet shorelines match the 1868 T-sheet (T1112) shoreline data.

The USACE surveys of the Grays Harbor region are acquired from the Seattle District relative to Washington State Plane South, Zone 4602 (feet), NAD83/91 coordinates. The USACE surveys of the Columbia River entrance are acquired from the Portland District relative to either

Washington State Plane South, Zone 4602 (feet), NAD83/91 coordinates or Oregon State Plane North, Zone 5076 (feet), NAD27 coordinates. NAD83/91 is the 1991 adjustment to NAD83, a horizontal datum for the United States, Canada, Mexico, and Central America based on the Geodetic Reference System of 1980 (NATIONAL GEODETIC SURVEY, 1986).

The USACE 1935 and the USC&GS H8421 surveys obtained from MARK R. BYRNES (Applied Coastal Research and Engineering, Inc., personal communication 1999) are referenced in Universal Transverse Mercator (UTM), Zone 10, NAD 27 coordinates (DEFENSE MAPPING AGENCY, 1989).

All sounding data are subsequently reprojected from their original coordinate systems into Washington State Plane South, Zone 4602 (meters), NAD83 coordinates using ArcInfo® projection routines. X coordinates are indicated as Easting (E) and y coordinates are indicated as Northing (N); for example, 100 km E, 120 km N.

2.3.2 Vertical Control

The standard vertical datum for all USC&GS and USACE sounding data is MLLW, and the standard vertical datum for the CPS and Multibeam surveys is NAVD88 (North American Vertical Datum of 1988, established in 1991; ACSM, 1992). We adjust all surveys to NAVD88, so that all data are referenced to a single vertical reference system. However, in some cases this adjustment result in implausible offsets between surveys of the same era and/or between surveys of different eras. In this section we discuss the relationship between the MLLW elevation relative to NAVD88 within the CRLC during the last century. The actual adjustments of the surveys are presented in Section 2.4.

Mean Lower Low Water (MLLW), a tide gauge dependent tidal datum, is the average of the lower low water elevations of each tidal day observed over the National Tidal Datum Epoch (NTDE). The National Tidal Datum Epoch adopted by the NOS is a 19-year period over which tide observations are taken and reduced to obtain mean values for tidal datums. In the CRLC four official tidal epoch differences have been calculated using tidal data from the Tongue Point Astoria gauge (recording since 1925): 1924 - 1942, 1941 - 1959, 1960 - 1978 (the current NTDE), and the soon to be adopted 1980 - 1998 epoch. Epoch differences have not been calculated for other gauges along the CRLC due to insufficient record length.

Temporal Change of MLLW

Tidal datums (e.g., MLLW) at a tide gauge change with sea-level rise, local land movement and the 18.6-year cycle associated with the moon's precession. In order to be consistent with the bathymetric volume-change calculations, MLLW datums need to be corrected for temporal changes relative to the land.

Changes in Mean Sea Level (MSL) and MLLW have been small (< 0.03 m) at Tongue Point, Astoria during the three tidal epochs (Table 2-5; JAMES HUBBARD and STEVE LYLES, National Ocean Service, written communication, 2001). HUBBARD and LYLES calculated the MLLW change relative to NGVD'47. The National Geodetic Vertical Datum (NGVD) is the mean sea level datum established in 1929 and adjusted in 1947 (NGVD'29; NATIONAL GEODETIC SURVEY, 1986). Between the 1924 - 1942 and 1960 - 1978 tidal epochs, MLLW and MSL both decreased by 0.01 m. The diurnal tidal range (MLLW - MHHW) has increased since 1925 by 0.002 m/yr (FLICK, et al., 1999), suggesting that the MHHW datum has increased through time. The overall magnitude for all tidal-datum changes related to tidal epochs is well within the resolution of the bathymetric change (Table 2-11 and Table 2-12). Based on the MLLW change at Astoria, we assume that the historical MLLW change at other tidal stations in the CRLC is negligible as well.

Table 2-5. Tidal epoch changes in MLLW and MSL relative to NGVD'47 at Tongue Point, Astoria, Oregon (JAMES HUBBARD and STEVE LYLES, NOS, written communication, 2001).

Tidal Epoch Interval	MLLW (m)	MSL (m)
1924 - 1942 to 1941 - 1959	0.01	0.02
1941 - 1959 to 1960 - 1978	-0.02	-0.03
1924 - 1942 to 1960 - 1978	-0.01	-0.01

Along the CRLC the vertical elevation of the land relative to NAVD88 changes as a result of uplift or subsidence. HOLDAHL et al. (1989) calculated rates of vertical land movement along the CRLC, ranging from -1 mm/yr at Toke Point, Tokeland to +1.7 mm/yr at Tongue Point, Astoria. We do not correct for vertical movement of the land, because the temporal change of the MLLW datum is known relative to the land-based NGVD datum (and thus relative to NAVD88). It should be noted that the uncertainty in the rates of vertical land movement are large, i.e., a standard deviation of approximately 1 mm/yr and that the magnitude of the vertical changes of the land are also within the uncertainty of the bathymetric change (Table 2-11 and Table 2-12).

Spatial Variability of MLLW Relative to NAVD88

The MLLW datum (1941 - 1959 and 1960 - 1978 epochs) measured at a series of tidal benchmarks within the CRLC (Table 2-6 and Table 2-7) shows an increase in elevation relative to NAVD88 from north to south. MLLW elevations relative to NAVD88 are obtained for the 1960 - 1978 epoch at four primary tidal stations using NOS Benchmark Sheets (http://co-ops.nos.noaa.gov/bench.html) and NGS Data Sheets (www.ngs.noaa.gov/cgi-bin/ds_pid.prl). The average MLLW elevations at each tidal station is calculated using all published NGS benchmarks. These elevations are listed in Table 2-6. The table includes the range of the benchmark elevations and the number of benchmarks used. The range is an indication of the uncertainty in the MLLW elevations.

Table 2-6. NAVD88 elevations of MLLW tidal datums within the CRLC based on NGS benchmark elevations.

NOS Tidal Station	Geographic Location	Northing (NAD83 m)	MLLW (NAVD88 m)	Range (m)	Number of Benchmarks
944 1102	Westport, WA	181,306	-0.46	-0.45 to -0.46	2
944 0910	Toke Point, Tokeland, WA	158,299	-0.24	-0.23 to -0.24	3
943 9040	Tongue Point, Astoria, OR	102,475	0.10	0.09 to 0.11	12
943 9008	Ft. Stevens, OR	100,054	-0.03	-0.01 to -0.04	3

DANIELS et al. (1999) checked the published NAVD88 elevations of the tidal benchmarks with Real-Time Kinematic Global Positioning System (RTK-GPS) surveying techniques using the Washington Coastal Geodetic Control network for control. DANIELS et al. also obtained unpublished tidal station and benchmark information from NOS about station 943 8478 in Seaside, OR and station 944 1627 at Pt. Grenville, WA. The MLLW datums at these stations were calculated for the 1941 - 1959 epoch. DANIELS et al. found that the benchmark elevations at the Oregon tidal stations 943 9008 (benchmarks Tidal 3 and Longitude Station) and 943 8478 (benchmark Tidal 1 B) were 0.12 m higher than the RTK-GPS elevations. The elevation of NGS benchmark Tidal 7 at Pt. Grenville was 0.17 m higher than the elevation measured by DANIELS et al.. In these cases DANIELS et al. calculated the MLLW elevation using the GPS-RTK elevations instead of the elevations published by NGS. The MLLW elevations relative to the NGS benchmarks published in DANIELS et al. (1999) are presented in Table 2-7. The table includes the published NGS and the RTK-GPS benchmark elevations.

In addition, DANIELS et al. (1999) found that leveled NAVD88 elevations at 5 other vertical benchmarks in Oregon used in the Washington Coastal Geodetic Control network differed from RTK-GPS derived orthometric elevations by approximately 0.1 m. These and the offsets between the three Oregon benchmarks mentioned above are indications of a vertical offset between the NGS leveling network in northwest Oregon and southwest Washington.

ED MCKAY and DAVE ZILKOSKY (NGS, personal communication 2001) confirmed that there is an offset between the geodetic control networks of southwest Washington and northwest Oregon. According to MCKAY and ZILKOSKY, a major cause of the offset is that it is complicated to run levels across the Columbia River and to tie the networks at both sides of the Columbia River. In addition, MCKAY and ZILKOSKY stated that the networks at both sides of the Columbia River are consistent, i.e., levels run between benchmark elevations at either side of the river agree with NGS accuracy standards. In this study we use the geodetic control network established in Washington and the RTK-GPS values for benchmarks in northwest Oregon and Pt. Grenville.

DANIELS et al. (1999) did not measure RTK-GPS elevations of the NGS benchmarks at Tongue Point, Astoria. Most likely, the benchmark elevations at Tongue Point, Astoria are approximately 0.12 m off as well. Therefore, we adjust the MLLW elevation at Tongue Point by -0.12 m to -0.02 m NAVD88.

The maximum uncertainty for all Oregon stations is approximately 0.1 m, and 0.17 m for the Pt. Grenville station. The other Washington stations have an accuracy of +/- 0.02 m (DANIELS et al., 1999). We use the MLLW elevations calculated by DANIELS et al. and the adjusted MLLW elevation at Tongue Point, Astoria. The MLLW elevations used for the bathymetric-change analysis are presented in Table 2-8.

Table 2-7. NAVD88 elevations of MLLW tidal datums within the CRLC based on NGS and RTK-GPS benchmark elevations (DANIELS et al. 1999).

NOS Tidal Station	Geographic Location	Northing (NAD83 m)	NGS Benchmark	NGS PID	Elevation (NAVD88 m)		MLLW (NAVD88 m)
					NGS	RTK-GPS	
944 1627	Pt. Grenville, WA	225,404	Tidal 4	n/a	n/a	2.29	-0.31[1)]
944 1627	Pt. Grenville, WA	225,404	Tidal 7	SD0135	3.06	2.89	-0.36[1)]
944 1102	Westport, WA	181,306	Tidal 2 Reset	SD0042	4.65	n/a	-0.46[2)]
944 0910	Toke Point, WA	158,299	Flag	SC0916	4.10	n/a	-0.24[2)]
944 0574	North Jetty, Ft. Canby, WA	110,670	A	SD0299	4.87	n/a	-0.05[2)]
943 9008	Ft. Stevens, OR	100,054	Tidal 3	SD0586	3.26	3.14	-0.15[2)]
943 9008	Ft. Stevens, OR	100,054	Longitude Station	SC0584	5.71	5.59	-0.16[2)]
943 8478	Seaside, OR	80,016	Tidal 1 B	SC1040	5.88	5.76	0.74[1)]

[1)] Calculated for the 1941 - 1959 tidal epoch.
[2)] Calculated for the 1960 - 1978 tidal epoch.

Table 2-8. NAVD88 elevations of MLLW tidal datums within the CRLC used for the bathymetric-change analysis.

NOS Tidal Station	Geographic Location	Northing (NAD83 m)	MLLW (NAVD88 m)
944 1627	Pt. Grenville, WA	225,404	-0.36
944 1102	Westport, WA	181,306	-0.46
944 0910	Toke Point, WA	158,299	-0.24
943 9040	Tongue Point, OR	102,475	-0.02
943 9008	Ft. Stevens, OR	100,054	-0.16

2.4 Adjustments of Vertical Datums

2.4.1 Methodology

The bathymetric surfaces constructed for each era consist of merged surveys, often with differing vertical datums (Table 2-1 and Table 2-2). Simple corrections from the original datums to NAVD88 (Table 2-8) can produce unrealistic offsets at survey boundaries and unlikely changes between eras. Instead of uncritically adjusting each survey to NADV88, we adjust some surveys to produce optimal results according to the following criteria. First, we minimize offsets in overlapping surveys in the same era and second, we minimize bathymetric changes (relative to Era IV) in deep water. The second criteria is based on the critical assumption that, away from the inlets, erosion and deposition at depths greater than a depth of no significant change of 14 - 30 m are small compared to both the precision of survey data and changes closer to shore or near the inlets. We use Era IV as our reference in deep water because Era IV surveys are the most modern and have the best vertical and horizontal control. We use the term “depth of no significant change” to refer to a depth below which interannual changes in nearshore bathymetry are too small to measure. In this case, our choice of 14 - 30 m is based on recent CPS observations (RUGGIERO et al., 1999) and practical considerations (depth range of overlapping surveys).

Our assumptions that bathymetric change in deep water are small can be compared to published estimates of clay, silt, and fine sand accumulation in the mid-shelf mud deposit. NITTROUER (1978) examined excess 210Pb profiles in cores taken at depths between 60 - 120 m, and estimated that accumulation rates decreased from >4 mm/yr about 20 km from the Columbia River to about 2 mm/yr near the distal edge of the deposit. These rates would produce changes ranging from 0.2 to 0.1 m in 50 years.

Individual transects and alongshore-averaged profiles are used to evaluate the fit between surveys, as will be discussed in the next section. Offsets among surveys in the same era and offsets with Era IV surfaces in deep water are minimized. In many cases where offsets appear consistent or where there are insufficient survey overlaps to identify offsets, we simply adjust the surveys to NAVD88 using the canonical differences relative to MLLW (next-to-last columns of Table 2-1 and Table 2-2). In other cases, where we do not find expected offsets (based on the difference between MLLW and NAVD88), we make no adjustments. In a few cases, we apply adjustments larger than the canonical correction for tidal datum. The following sections describe the methods we use to determine offsets and specify the adjustments made to each survey. The adjustments are summarized in the last columns of Table 2-1 and Table 2-2.

2.4.2 Transects and Alongshore-Averaged Profiles

Individual transects and alongshore-averaged cross-shore profiles of the bathymetric surfaces allow concise comparisons between surveys and are used to identify potential consistent offsets and evaluate temporal changes in the bathymetric profiles.

Exclusively for the extraction of transects and cross-shore alongshore-averaged profiles, bathymetric data are gridded at a 25-m cell size using triangulation with linear interpolation. The methods for calculating bathymetric surfaces used for the bathymetric-change analysis are further explained in Section 2.5.

Approximately 70 shore-parallel, diagonal, and cross-shore transects are extracted from the individual surveys. We use these transects to evaluate the fit between surveys of the same era. The location of these transects are plotted in Figure 2-6 and Figure 2-7. From the large number of transects, we select Transects AB, CD, and EF to be presented here (Figure 2-7 and Figure 2-8). The transects are extracted from unadjusted bathymetric data. Transects AB, CD, and EF are discussed in Section 2.4.3.

Cross-shore Transects A, B, C, and D are extracted for each era at both sides of the Grays Harbor and Columbia River inlets (Figure 2-9 and Figure 2-10). The locations of these transects are shown in Figure 2-6. Transect A at North Beach is located approximately 5 km north of the Grays Harbor North Jetty at 189 km N. Transect B along Grayland Plains is approximately 5 km south of the Grays Harbor South Jetty at 177 km N. Transect C is located at Long Beach 10 km north of the North Jetty at 118 km N. Transect D along Clatsop Plains is 7 km south of the South Jetty at 98 km N. We use the cross-shore transects in conjunction with alongshore-averaged profiles to evaluate vertical offsets between eras.

Alongshore averaging of profiles minimizes the effects of random errors in the data and facilitates comparison between surveys. Alongshore-averaged profiles are calculated between the ebb-tidal deltas, where minimal bathymetric change is expected (boxes I, II, and III shown in Figure 2-6). The boxes are as large as possible, limited only by this criterion and data coverage. Within these boxes, horizontal areas between contours are calculated, and the cross-shore distance between the contours is determined by dividing the horizontal area by the alongshore length of the box. The cross-shore positions of the contours are referenced to the Washington State Plane South, Zone 4602, NAD83 coordinate system.

Alongshore-averaged profiles are calculated along Grayland Plains in Area I (Figure 2-11), along Long Beach in Area II (Figure 2-12), and along Clatsop Plains in Area III (Figure 2-13). The coordinates of Area I are x_{min} = 215 km E, y_{min} = 167.5 km N, x_{max} = 226.2 km E, and y_{max} = 177.5 km N, coordinates of Area II are x_{min} = 211.7 km E, y_{min} = 117.3 km N, x_{max} = 227 km E, and y_{max} = 127.7 km N, and coordinates of Area III are x_{min} = 210 km E, y_{min} = 87 km N, x_{max} = 234 km E, and y_{max} = 97 km N. We do not calculate alongshore-averaged profiles along North Beach due to limited data coverage. The morphologic change we see in the cross-shore and alongshore-averaged profiles is discussed in Section 4.

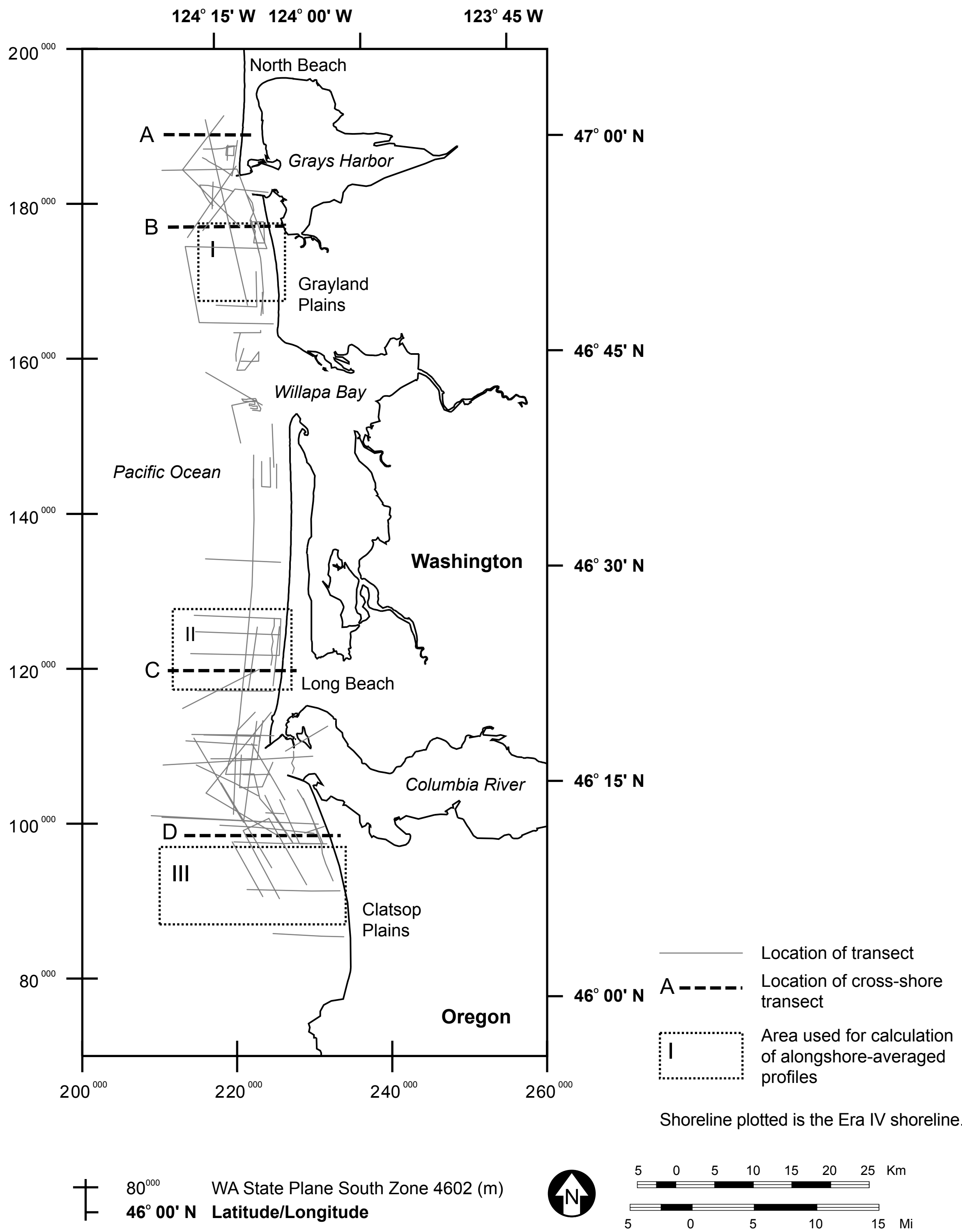


Figure 2-6. Location of transects, cross-shore transects at North Beach (A), Grayland Plains (B), Long Beach (C), and Clatsop Plains (D) and areas used for calculating alongshore-averaged profiles along Grayland Plains (I), Long Beach (II), and Clatsop Plains (III).

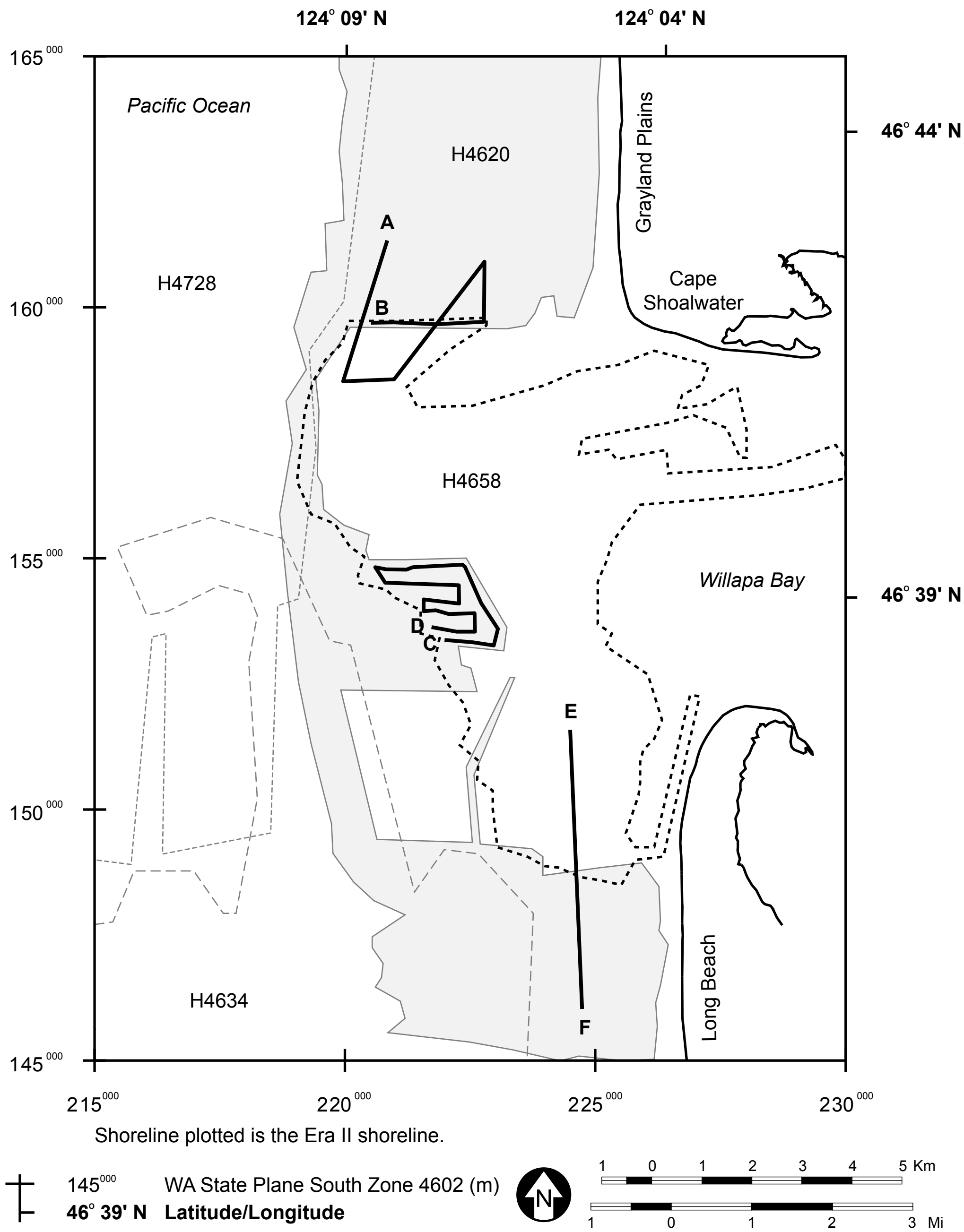


Figure 2-7. Location of Transects AB, CD, and EF across the Era II H4620 and H4658 surveys. Various line styles and shading have been used to differentiate surveys.

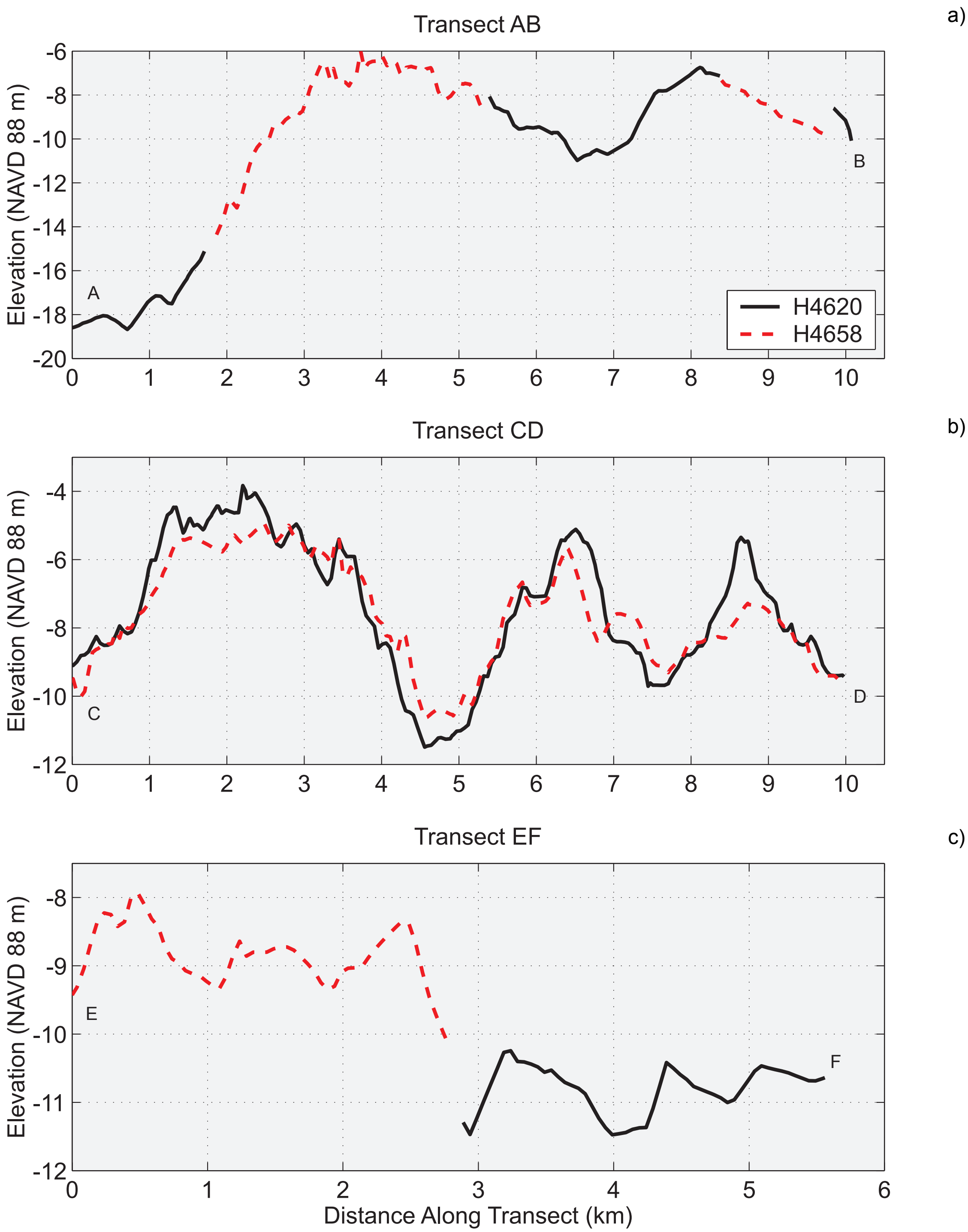


Figure 2-8. Transects a) AB, b) CD, and c) EF across the Era II H4620 and H4658 surveys.

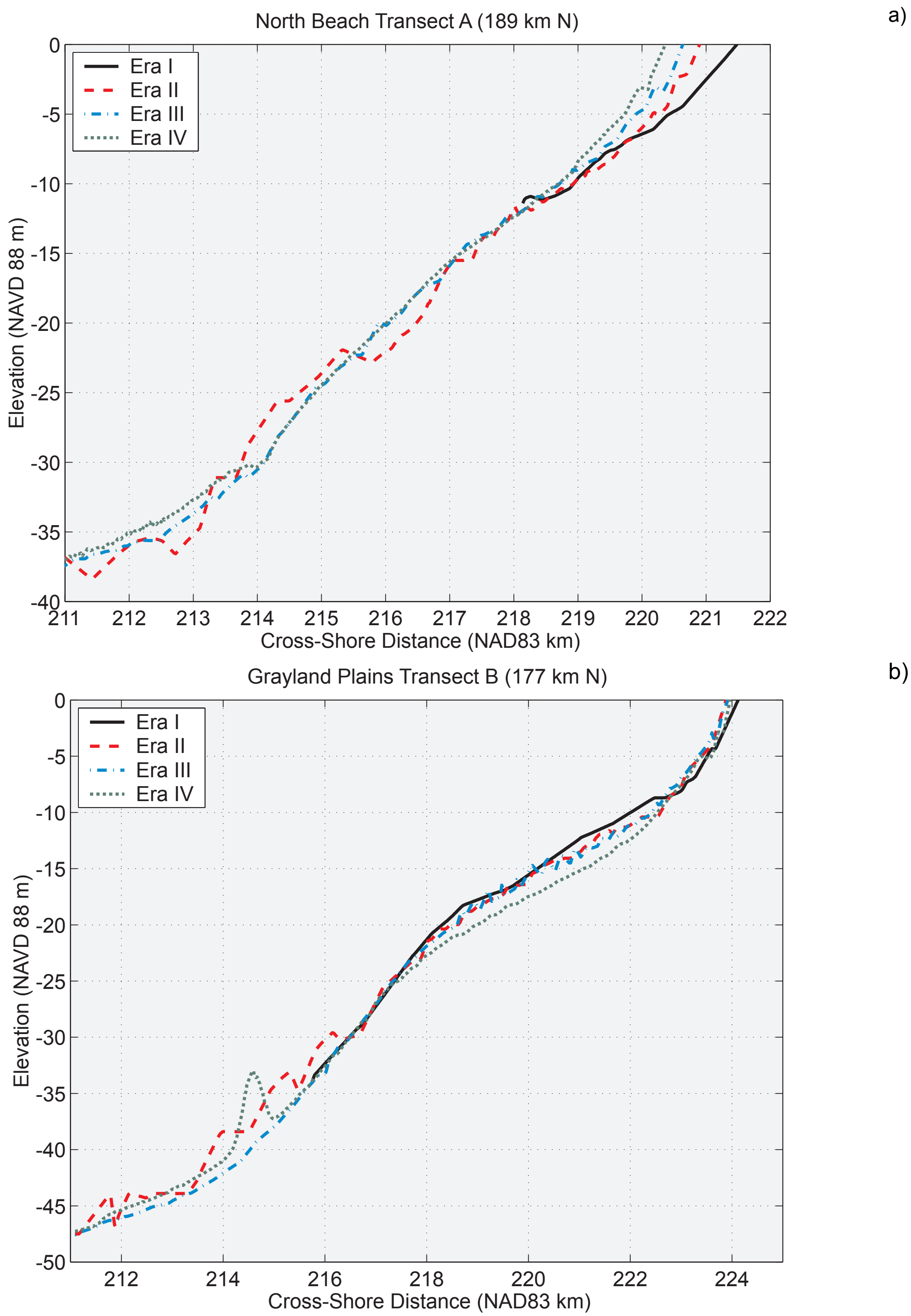


Figure 2-9. Cross-shore profiles of the unadjusted Era I, II, III and IV bathymetric surfaces a) north of the Grays Harbor entrance at 189 km N and b) south of the Grays Harbor entrance at 177 km N.

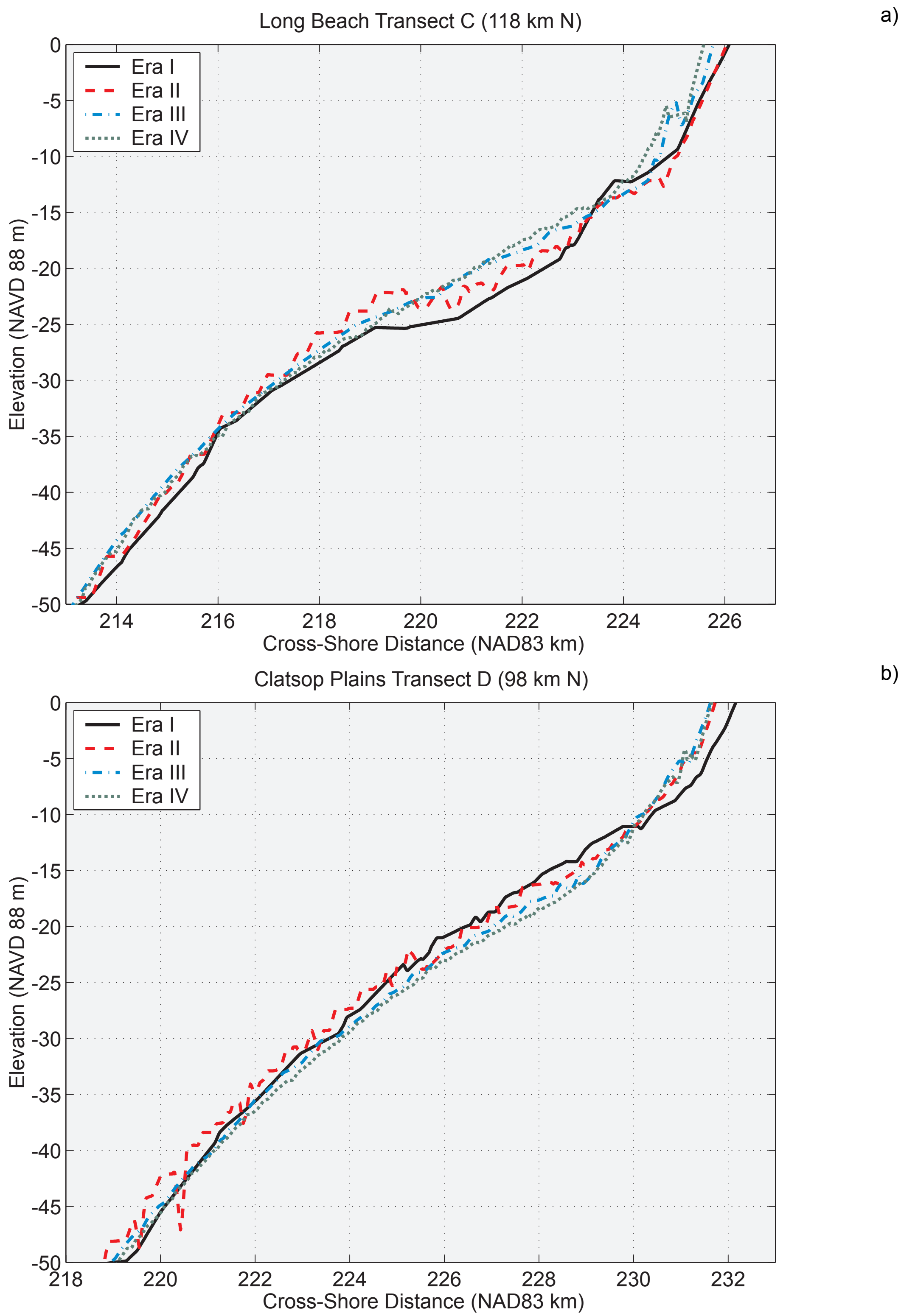


Figure 2-10. Cross-shore profiles of the unadjusted Era I, II, III and IV bathymetric surfaces a) north of the Columbia River entrance at 118 km N and b) south of the Columbia River entrance at 98 km N.

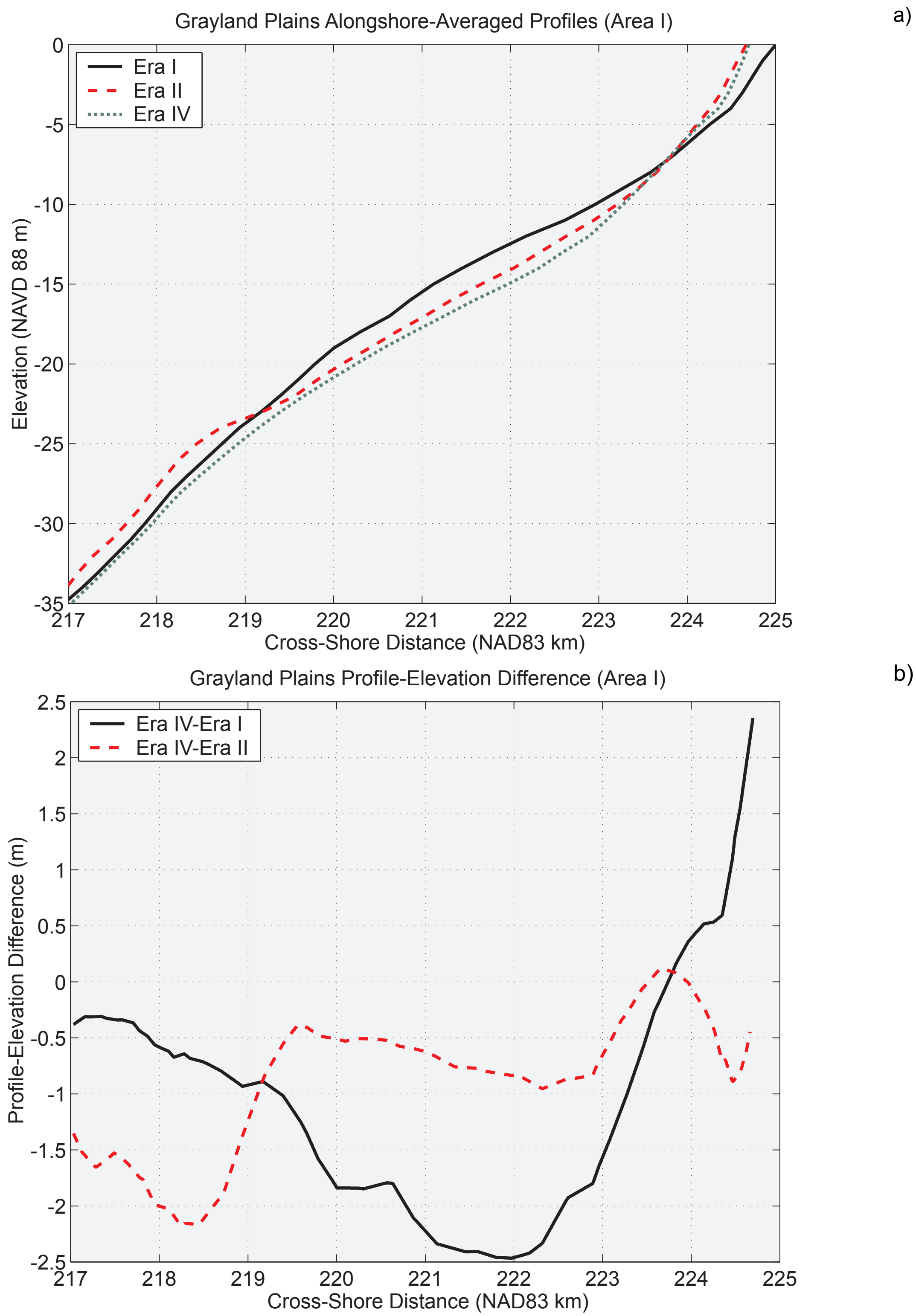
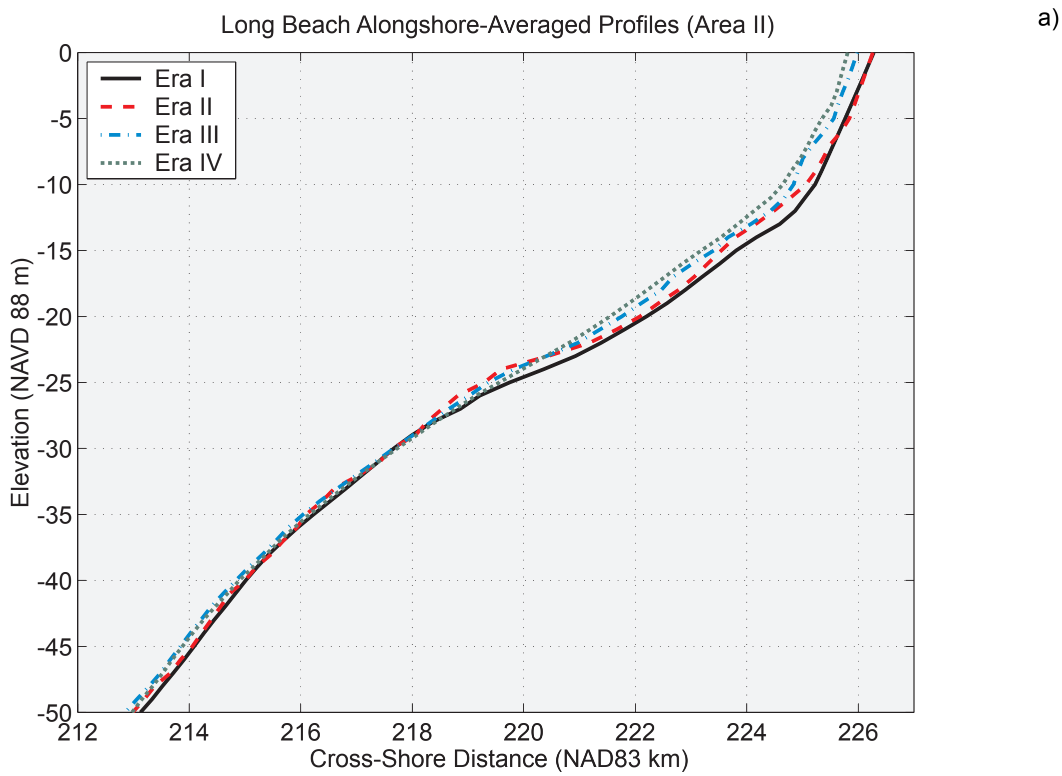


Figure 2-11. a) Unadjusted alongshore-averaged profiles along Grayland Plains (Area I) and b) the difference between Era IV and Era I and Era IV and Era II alongshore-averaged profiles.



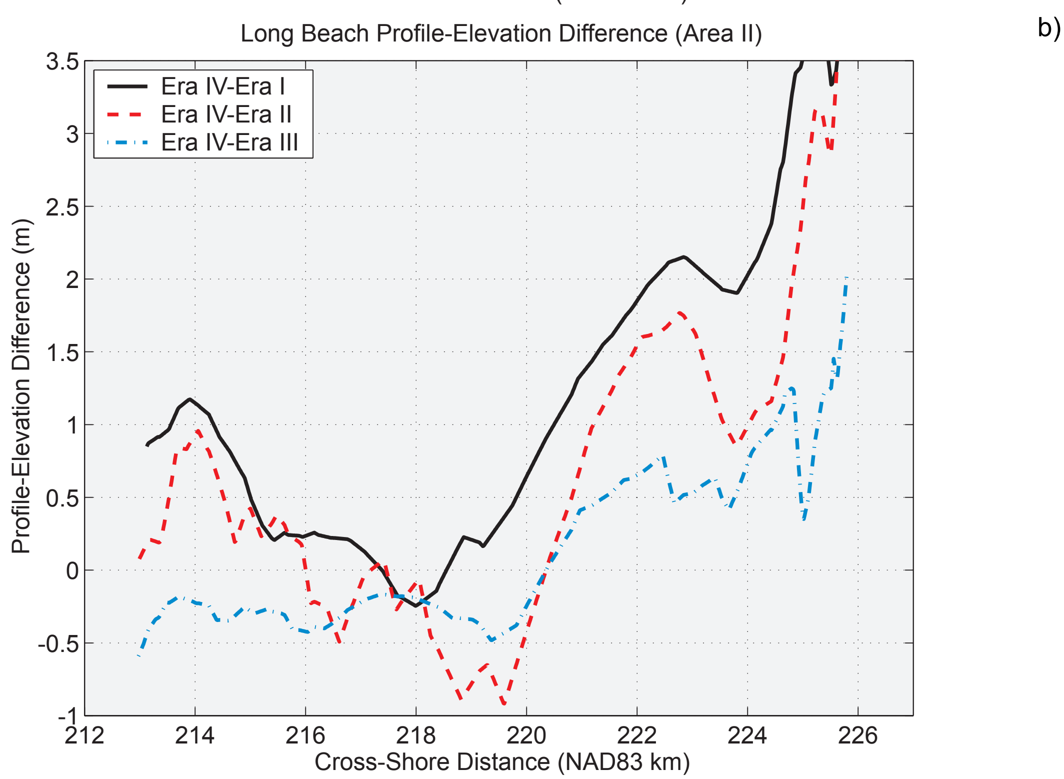


Figure 2-12. a) Unadjusted alongshore-averaged profiles along Long Beach (Area II) and b) the difference between Era IV and Era I, Era IV and Era II, and Era IV and Era III alongshore-averaged profiles.

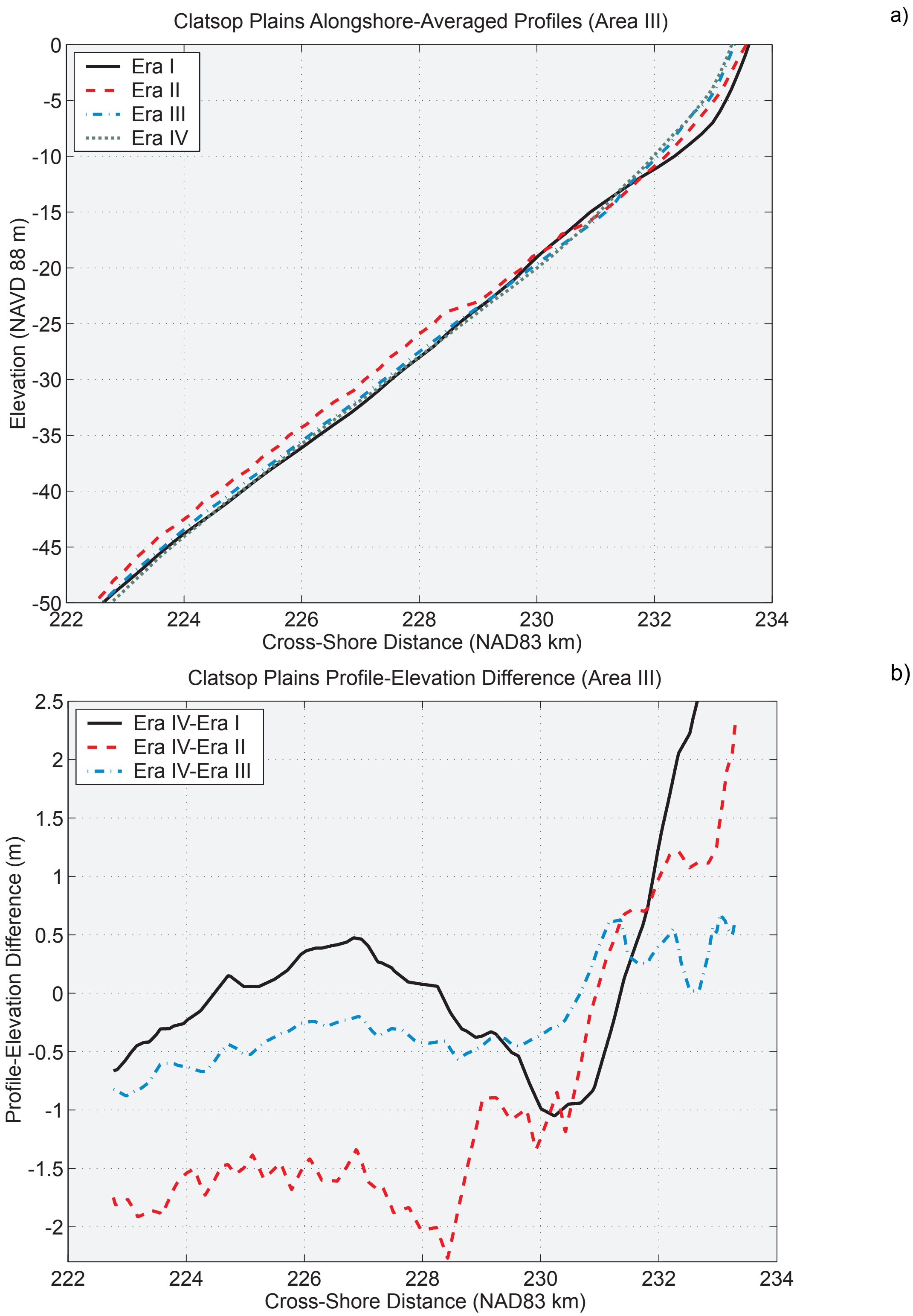


Figure 2-13. a) Unadjusted alongshore-averaged profiles along Clatsop Plains (Area III) and b) the difference between Era IV and Era I, Era IV and Era II, and Era IV and Era III alongshore-averaged profiles.

2.4.3 Vertical Adjustments

The adjustments of the vertical datums of the surveys are explained in the following section. An overview of all adjustments is presented in Table 2-1 and Table 2-2. The Adjusted cross-shore and alongshore-averaged profiles are presented in Figure 2-14, Figure 2-15, Figure 2-16, Figure 2-17 and Figure 2-18. The RMS and mean differences for various intervals calculated along these profiles are discussed in Section 2.6.1. The MLLW elevations relative to NAVD88 of the tidal stations Pt. Grenville, Westport, Toke Point, Ft. Stevens, and Astoria that are used for the adjustments are presented in Table 2-8. The geographical locations of the surveys are shown in Figure 2-1, Figure 2-2, Figure 2-3, and Figure 2-4.

Era I

Depth soundings of the Era I surveys at the Grays Harbor and Columbia River entrances were reduced to MLLW using tides measured at gauges deployed specifically for the individual surveys. Typically these gauges recorded tidal data for periods of months to years. Because these tidal records are short, the vertical datum during the survey period may have been influenced by seasonal, annual, decadal, physiographic, or wind-induced variations in the sea level. Therefore, the MLLW datum calculated during the survey may not represent the actual MLLW value for that tidal epoch.

The vertical and horizontal references of the (temporary) tidal stations of the USACE 1900 and USC&GS H1800 surveys performed during Era I at the Grays Harbor entrance are not precisely known. We assume that the USACE survey is referenced to MLLW at Pt. Chehalis (located at the south shore of the Grays Harbor entrance, near the city of Westport, Figure 1-1). The modern MLLW at Westport is -0.46 m NAVD88. On the hydrographic chart of the H1800 survey we read that the survey is referenced to “North Cove Station” (located at the north shore of the Willapa bay entrance, Figure 1-1). Toke Point is the closest tide gauge to the abandoned North Cove station, and we assume the Toke Point tides are representative of the North Cove station. The MLLW at Toke Point is -0.24 m NAVD88.

We evaluated individual trackline crossings and cross-shore transects across gridded bathymetric surfaces of the USACE 1900 and USC&GS H1800 surveys for discrepancies and offsets. The USACE 1900 and USC&GS H1800 surveys have approximately ten trackline crossings. Four crossings in 4 - 6-m water depth closest to shore exhibit large vertical differences of 1 - 2 m and are omitted. These discrepancies may have been caused by nearshore bar changes and/or sea conditions. The mean vertical difference between the other trackline crossings is approximately 0.2 m (H1800 survey is deeper). In Figure 2-9, the shoreface profiles at the Grays Harbor Transect A (north of the entrance) converge at approximately -12 m NAVD88, whereas the shoreface profiles at Transect B (south of the entrance) converge at approximately -25 m NAVD88. Note that the Era I profile along Transect A extends only to about -12 m. The shoreface along Grayland Plains shallower than this depth of no significant change eroded significantly between Era I and Era IV, but below this depth there was little change. An evaluation of the alongshore-averaged profiles in Figure 2-11 shows that not enough data coverage is available below the approximate depth of no significant change of 30 m to determine offsets with the Era IV surface. Due to the mean vertical difference between the trackline crossings of the H1800 and USACE 1900 surveys and the impossibility to determine offsets between the Era I surveys and the Era IV surveys, we adjust the USACE 1900 survey by -0.46 m and the H1800 survey by -0.24 m to match NAVD88. The adjustment of both surveys to NAVD88 reduces the mean vertical difference between the trackline crossings. The adjusted cross-shore transects and alongshore-averaged profiles are presented in Figure 2-14 and Figure 2-16.

The Era I H1018, H1019, H1378, and H1379 surveys near the Columbia River entrance are referenced to MLLW. We can not obtain information about the location of the (temporary) tide gauge of the H1018 and H1019 surveys. The only information about the plane of reference on the charts of the H1018 and H1019 surveys is "Mean of the lowest low water of each 24 hours". Additionally, we read on the H1019 chart that "The tide on the bars of the North and South Channels make nearly 50 minutes sooner than at Astoria". On the H1378 and H1379 charts we read "Tidal Station Astoria". We assume that the location of the tide gauge used for the H1018, H1019, H1378, and H1379 surveys was Astoria. The modern MLLW at Tongue Point, Astoria is -0.02 m NAVD88 (Table 2-8).

The Era I Long Beach profile along Transect C in Figure 2-10a is characterized by depressions between -15 and -25 m and below -35 m NAVD88. These features, which are not present in modern profiles, may have been caused by errors in horizontal positioning and by errors related to data-collection techniques (GIBBS and GELFENBAUM, 1999). These features are not apparent in the unadjusted alongshore-averaged profiles along Long Beach (Figure 2-12). A comparison of transects across the H1018, H1019, H1378, and H1379 surveys does not show any consistent offsets between the surveys. The Era I alongshore-averaged profiles in Figure 2-12b and Figure 2-13b deviate from the Era IV profiles, however, we can not detect any consistent offsets. We adjust all Era I surveys near the Columbia River entrance by -0.16 m to NAVD88 at Ft. Stevens. The adjusted cross-shore transects and alongshore-averaged profiles are presented in Figure 2-15, Figure 2-17 and Figure 2-18.

Era II

Information regarding tidal stations used during the Era II and Era III USC&GS surveys was obtained from USC&GS Descriptive Reports. Temporary tide gauges were typically installed on the open ocean (e.g., at the Columbia River North Jetty or Pt. Grenville) or within an estuary (e.g., Pt. Chehalis). Hourly water levels were measured and soundings were reduced to MLLW on a particular tide staff or reference station using offsets or other protocols established by USC&GS. The absolute elevation of the MLLW plane of reference at these temporary stations, however, remains unclear.

The Era II surveys at the Grays Harbor entrance comprise the USC&GS H4620, H4621, H4658, H4710, and H4728 surveys and the USACE 1927 survey. According to the Descriptive Report of the H4620 and H4621 surveys, the designated tidal station of the H4620 and H4621 surveys was Ft. Stevens, Oregon (Figure 1-1). At that time, soundings of the H4620 and H4621 surveys along the Grayland Plains were reduced to MLLW using tides measured at the North Jetty tide staff at the Columbia River entrance, only applying time corrections for tide propagation. The tides at the Columbia River North Jetty were accepted as equivalent to open-ocean conditions. Possibly, at that time it was assumed that the tides at the Columbia River North Jetty were equivalent to the tides at the Willapa Bay and Grays Harbor entrances. The open ocean tides at the Columbia River entrance might be different than those at the Grays Harbor entrance. It is not known how well the tides measured at the entrances represent the open-ocean conditions, but we infer from DANIELS et al. (1999) that the range between Mean High Water (MHW) and MLW at Westport (2.15 m) differs from the Columbia River North Jetty (1.75 m). The difference between the tide at the survey vessel and the time-shifted tide at the tide gauge can be as much as ~0.20 m. This potential error appears to be neglected in the original surveys. We read in the Descriptive Report of the H4620 and H4621 surveys that ”A simultaneous comparison was made of the Ft. Stevens staff with the staff at Tongue Point, Astoria to check MLLW at Ft Stevens and to get the value of mean tide level.” and “Another comparison was made of North Jetty with Ft. Stevens. This simultaneous comparison established the values MLLW = 1.00 foot at North Jetty.” The “simultaneous comparison” is not explained in the Descriptive Report of the H4620 and H4621 surveys. We assume that the MLLW established at the North Jetty represents the MLLW at Ft. Stevens. The modern MLLW elevation at Ft. Stevens is equal to -0.16 m NAVD88 (Table 2-8). A comparison of transects across the H4620 and H4621 surveys does not show any consistent offsets. Therefore, both surveys are adjusted by -0.16 m to NAVD88 at Ft. Stevens.

We read in the Descriptive Report of the H4710 survey that “The tidal data for the reduction of soundings on Sheet A [survey H4710 along southern North Beach] were obtained from observations taken from the automatic tide gauge at Westport. For this sheet the Westport tides were reduced by simultaneous comparison to Pt. Grenville values. These values were used directly for reduction of soundings.” This statement suggests that MLLW at Pt. Grenville (a rocky headland ~45 km north of the Grays Harbor entrance) was used for the reduction of soundings of the H4710 survey. The modern MLLW elevation at Pt. Grenville is -0.36 m NAVD88 (Table 2-8). Based on the modern MLLW elevations, the H4621 survey should be adjusted by -0.16 m and the H4710 survey should be adjusted by -0.36 m. This indicates that the H4710 survey should be shallower than the H4621 survey. Comparison of 5 pairs of data points (trackline crossings and neighbours) of the H4620 and H4710 surveys reveals that the data points of the H4710 survey average 0.15 m shallower than the H4620 survey. A comparison of transects across the H4621, H4710, and USACE 1927 surveys shows that the H4621 and H4710 surveys are approximately 0.7 m and 1 m deeper than the USACE survey, respectively. The offsets between the H4621 and H4710 surveys approximately agree with the modern MLLW elevations relative to NAVD88 at Ft. Stevens and Pt. Grenville, respectively. We can not determine any offsets between the Era II H4710 and the Era IV Multibeam surveys mainly due to the poor quality of the Era II bathymetry below the approximate depth of no significant change of 12 m along Transect A (Figure 2-9a). The nearshore profiles converge between 12-m and 15-m water depth along Transect A, and therefore, this location appears suitable for comparison. However, during Interval 2, at this location the seafloor was affected by the seaward progradation of the Grays Harbor ebb-tidal delta. As a result of the seaward progradation of the Grays Harbor ebb-tidal delta, the depth of no significant change along Transect A was deeper in Interval 4 (12 m) than in Interval 2 (8 m). Also, we can not compare the H4621 and the Era IV Multibeam surveys, because the H4621 survey does not extend deeper than 23-m water depth (which is shallower than the depth of no significant change of 25 - 30 m; Figure 2-9b and Figure 2-11). Due to the poor quality of the H4728 survey we can not compare this survey with the nearshore H4621 survey and the Era IV Multibeam survey below the depth of no significant change of 25 - 30 m (the vertical reference of the H4728 survey will be discussed later in this section). Because of these reasons, we apply the canonical relation between MLLW and NAVD88 and adjust the vertical datums of the H4710 survey by -0.36 m and the H4621 survey by -0.16 m to NAVD88. The adjusted cross-shore transects and alongshore-averaged profiles are presented in Figure 2-14 and Figure 2-16.

Most likely, the USACE 1927 survey of the Grays Harbor entrance is referenced to MLLW in Westport. The USACE used a MLLW datum that was between 0.5 and 0.9 m (1.5 to 3 feet) lower than the MLLW datum of corresponding USC&GS surveys (Eric Nelson, USACE Seattle District, personal communication, 1999). This difference was to ensure that channels were dredged deep enough. This might explain the large difference between the USACE and the H4621 and H4710 surveys. We adjust the USACE survey by -1.11 m so that it matches the adjusted H4621 and H4710 surveys.

According to the Descriptive Report of the H4658 survey, a portable automatic tide gauge was established in Tokeland during the H4658 survey of the Willapa Bay delta. However, the gauge had a defective clock and the record was incomplete. It was decided to use the tides measured at Pt. Grenville for reduction of soundings. We can not determine if only Pt. Grenville tides were used, and what corrections were applied. The Transects AB, CD, and EF across the H4658 and H4620 surveys in Figure 2-7 and Figure 2-8 show large discrepancies, however, no consistent offsets. The profiles along the northern Transect AB show that the H4620 survey is slightly shallower. The H4620 survey is approximately 0.15 m shallower than the H4658 survey along Transect CD. However, along Transect EF, at the southern boundary of the H4658 survey, the H4620 survey is approximately 1 - 2 m deeper than the H4658 survey. The H4658 survey was completed in 1928, two years later than the H4620 survey. The differences might be attributed to topography change during this period, to wave and current conditions at the delta that complicated surveying, and to the problems with the temporary tide gauge. Adjusting the H4658 survey by -0.36 m to NAVD88 at Pt. Grenville decreases the fit in northern ¾ part of the survey and improves the fit in the southern ¼ part. Therefore, we do not to apply the Pt. Grenville datum correction, but adjust the H4658 survey along with the H4620 survey by -0.16 m.

The H4728 survey extends beyond 23 - 25 m water depth and is seaward of the H4620, H4621, and H4710 surveys. We read the following in the Descriptive Report of the H4728 survey: "The tidal data for the reduction of soundings on this sheet were, with one exception, obtained from observations of an automatic tide gauge established at Westport, and these tides reduced to outside conditions as per Director's letter of September 13, 1927. The one exception was "T" day, when tides were obtained from an automatic gauge established at Pt. Grenville. On this day the tides were used direct, as per same authority." It is not clear in this case what the outside conditions were. We assume that the MLLW used resembles the modern MLLW at Pt. Grenville. The quality of the H4728 survey is not as good as the inshore surveys. The step in the Era II profile along Transect A at 23-m water depth (Figure 2-9a), the large undulations below 30-m water depth along Transects A and B (Figure 2-9), and the elevated profile between 24 - 35-m water depth of the alongshore-averaged profile along Grayland Plains (Figure 2-11) are due to errors in the H4728 survey. The offshore H4634 and H4635 surveys near the Columbia River entrance are characterized by similar undulations. An explanation for these undulations is given in the Descriptive Report of the H4728 survey. It is stated that above 27-m water depth soundings were made with lead lines and that below 27-m water depth pressure tubes were used. We read in the Descriptive Report of the H4728 survey that "In general the tubes give a shoaler depth than the vertical cast [with lead line]." Comparison of transects across the H4620, H4621, H4710, and H4728 surveys is difficult because of the large undulations, and we are not able to determine consistent offsets along Transects A and B and along the alongshore-averaged profiles of Area I. We adjust the H4728 survey by -0.36 m to NAVD88 at Pt. Grenville.

The Era II surveys performed near the Columbia River entrance are the USC&GS H4611, H4618, H4619, H4634, and H4635 surveys and the USACE 1935 survey. The H4618, H4619 surveys were performed along Long Beach and have the same tidal reference as the H4620 and H4621 surveys (i.e., MLLW at Ft. Stevens). We can not obtain Descriptive Reports of the H4611, H4634, and H4635 surveys, and therefore, we assume that these surveys are referenced to MLLW at Ft. Stevens as well. The USACE 1935 survey is obtained from MARK R. BYRNES (Applied Coastal Research and Engineering, Inc., personal communication 1999). BYRNES adjusted the vertical datum by -0.75 m from Mean Low Water (MLW) at Ft. Stevens to NGVD'29 (from http://co-ops.nos.noaa.gov/benchmarks/9439008.html; BYRNES and LI, 1999). Initially we adjusted the USACE 1935 survey by +1.1 m to MLLW at Ft. Stevens to allow for a better comparison with the USC&GS surveys, which are referenced to MLLW. We do not find significant consistent offsets between the nearshore H4611, H4618, and H4619 surveys, and we adjust these surveys by -0.16 m to NAVD88. The H4618 and the USACE 1935 surveys do not match very well. Most likely the bathymetry had changed during the 8-year period spanning the survey dates. Therefore, the USACE 1935 survey is adjusted by -0.16 m to NAVD88.

We detect significant offsets, when comparing transects across the offshore H4634 and H4635 and the nearshore H4611, H4618, and H4619 surveys. The step at 220 km E in the Era II profile along Transect C (Figure 2-10a) indicates the transition from the nearshore H4618 survey to the offshore H4634 survey. This offset is not consistent along the entire boundary of the nearshore H4618 and H4619 surveys and the offshore H4634 survey. In some places there is no offset and in other places the offset is as large as 5 m. Localized offsets are greatly reduced by alongshore averaging as shown in Figure 2-12. Figure 2-12 does not show consistent offsets between the H4634 survey and Era IV surface either. Therefore, we adjust the offshore H4634 survey to NAVD88 by -0.16 m. A comparison of transects across the H4611 and H4635 surveys reveals that the H4635 survey is between 1 and 2 m shallower than the H4611 survey. This is clearly illustrated in Figure 2-10b and Figure 2-13; notice the step in the Era II profile at 23-m water depth. RMS and mean differences between the unadjusted alongshore-averaged Era II and Era IV profiles below 26-m water depth along Clatsop Plains are 1.69 m and -1.68 m, respectively. We adjust the H4635 survey by -1.84 m (including the adjustment of -0.16 m to NAVD88 at Ft. Stevens) to make a better fit with the neighbouring USC&GS surveys and the Era IV surface.

Era III

According to the Descriptive Report of Survey H8252, the Era III USC&GS H8252 survey at the Grays Harbor entrance was referenced to MLLW by a portable automatic tide gauge at Pt. Chehalis, Westport. Most likely this gauge was employed for the duration of the survey (April-October 1955). We read in the Descriptive Reports that "No correction was applied for the distance from the gauge." The modern MLLW at Westport is -0.46 m NAVD88. We infer from the close correlation among all of the profiles, especially the most modern profiles, that very little erosion or accretion has occurred below 12-m water depth along North Beach and below 25 m along Grayland Plains (Figure 2-9). The good agreement among the Era III (H8252 survey) and Era IV profiles below these depths of no significant change indicate that no adjustment of the tidal datum of the H8252 survey is needed to compare these surveys. The mean difference between the Era IV and Era III profiles along Transect A between 214 km E and 218.5 km E is 0.03 m. Overlaps across the H8252 and USACE 1954 surveys reveal an increasing offset with increasing water depths. Solely adjusting the vertical datum of the USACE survey to NAVD88 improves the fit in shallow water, but not in deeper water. We assume that this increasing offset might be attributed to an incorrect calibration of depth soundings of the USACE survey. The fit with the H8252 survey improves significantly after increasing the USACE 1954 survey depth soundings by 5%. It is not necessary to adjust the vertical datum of the USACE survey. It is not clear why the vertical datums of both surveys do not need to be adjusted. This implies that either the vertical datum for H8252 and USACE 1954 matches NAVD88 or that consistent biases caused by Era III tidal corrections or survey methods offset the expected mismatch in the vertical datum.

We do not obtain Descriptive Reports for the Era III H8416, H8417, H8421, and H8423 surveys near the Columbia River entrance. We obtain the H8421 survey from MARK R. BYRNES (Applied Coastal Research and Engineering, Inc., personal communication 1999). BYRNES had adjusted the survey by -1.1 m from MLLW to NGVD'29 at Ft. Stevens. We adjusted the survey by 1.1 m to MLLW to allow for better comparison with the other surveys. We assume the other Era III surveys are referenced to the Ft. Stevens tide gauge as well. Transects across the H8416, H8417, H8421, and H8423 surveys do not show any significant consistent offsets. However, we calculate consistent offsets below 26-m water depth between the Era III and Era IV alongshore-averaged profiles of -0.29 m along Long Beach and -0.45 m along Clatsop Plains. The cause of the offset between the Era III and Era IV surveys remains unclear. Possibly, errors of ~1 foot were made with the vertical reference of the Era III surveys. There are no indications that the Era IV USACE surveys have a consistent error. The difference between the Era III and Era IV surveys along Clatsop Plains increases in deeper water seaward of 226 km E (Figure 2-13), and might be attributed to the survey techniques and sea conditions during the Era IV survey. We ignore this increasing offset and adjust all Era III surveys by -0.45 m (including the -0.16 m adjustment of the Era IV surveys). The adjusted profiles are presented in Figure 2-15, Figure 2-17 and Figure 2-18.

Era IV

The Grays Harbor USACE 1999 survey is referenced to MLLW at Westport (-0.46 m NAVD88), the USACE 1998 survey of Willapa Bay is referenced to MLLW at Toke Point (-0.24 m NAVD88), and the CPS surveys along North Beach and Grayland Plains are referenced to NAVD88. Transects across the 1999 USACE, 1999 Multibeam, and 1999 CPS surveys indicate that the USACE 1999 survey is ~0.46 m shallower. The fit between the CPS and Multibeam surveys along northern Grayland Plains, and southern North Beach is within +/-0.05 m. However, transects across the CPS and Multibeam surveys along the southern 8 km of Grayland Plains reveal that the Multibeam survey is ~0.25 m deeper. At two transects along the south flank of the Willapa Bay delta, the Multibeam data fits perfectly with the unadjusted USACE 1998 survey. Whereas, along one transect northwest of the delta, the Multibeam survey is ~0.25 m deeper than the USACE 1998 survey. If we correct the USACE 1998 survey by -0.24 m, the fit with the Multibeam survey (USACE 1998 deeper) along the south flank of the Willapa Bay ebb-tidal delta decreases. Seaward of the ebb channel on the terminal lobe of the Willapa Bay delta the Multibeam survey is ~1.5 m deeper than the USACE 1998 survey of Willapa Bay. This difference might be attributed to the rapid morphologic changes that occur at this side of the northward migrating Willapa Bay delta. The discrepancies between the Multibeam and the CPS and USACE surveys can be attributed to many different factors. One of them might be the problem in vertical control of the Multibeam survey. The post-processed RTK data is very noisy and has large gaps in its record, and therefore, is not used directly. Instead, the Toke Point tide record is time-shifted 45 minutes and lowered by 0.35 m to match the incomplete RTK record. This adjusted Toke Point tide curve is used for sounding corrections (ROGER D. FLOOD, Marine Sciences Research Center, Stony Brook University, personal communication, 2000). We adjust the USACE 1999 survey of Grays Harbor by -0.46 m and the USACE 1998 survey of Willapa Bay by -0.24 m. The CPS and Multibeam surveys are not adjusted. The large mound between 214 km E and 215 km E along Era IV Transect B (Figure 2-14b) is a USACE dredge disposal site.

The 1998, 1999, and 2000 Era IV surveys of USACE Portland District are referenced to MLLW of epoch 1941 - 1959 at Ft. Stevens (MLLW is -1.09 m NGVD ’47; HANS R. MORITZ, USACE Portland District, personal communication, 1999). We neglect MLLW epoch changes at Ft. Stevens and assume MLLW equal to -0.16 m NAVD88. The CPS surveys along Long Beach and Clatsop Plains are referenced to NAVD88. The detailed USACE survey of the disposal sites is approximately 0.35 m deeper than the 2000 entrance survey. We do not find significant consistent offsets across the regional USACE 1998, 1999, and 2000 surveys. A comparison of the overlaps of the regional USACE and CPS surveys reveals RMS differences of 0.60 m and mean differences of 0.01 m (CPS survey shallower) along Long Beach and RMS differences of 0.33 m and mean differences of 0.03 m (CPS survey deeper) along Clatsop Plains. However, we do not observe any consistent offsets. It should be noted that the transects were extracted in water depths between 9 and 12 m and that in these water depths interannual changes can occur of O(0.5 m) (RUGGIERO et al., 1999). We adjust the USACE surveys by -0.16 m, except the USACE 2000 survey of the disposal sites, which is adjusted by +0.19 m to match the regional 2000 USACE survey. The CPS surveys are not adjusted.

2.4.4 Summary

In the preceding sections we discuss the vertical adjustments of each individual survey used in the bathymetric-change analysis. Instead of uncritically adjusting each survey from MLLW to NAVD88 (Table 2-8), we adjust some surveys to produce optimal results according to the following criteria. First, we minimize offsets in overlapping surveys within the same era, and second, we minimize bathymetric changes (relative to the 1990s) in deep water, where we assume minimal change has occurred. Surveys with adjustments that deviate from the canonical adjustments to NAVD88 are the Era II USACE 1927, H4658, and H4635 surveys, the Era III USACE 1954, H8252, H8416, H8417, H8421, and H8423 surveys, and the Era IV USACE 2000 surveys of the disposal sites at the Columbia River entrance. An overview of the adjustments is presented in the last columns of Table 2-1 and Table 2-2. The adjusted surveys represent our best guess of reality, but may still have large uncertainties (see Section 2.5.3).

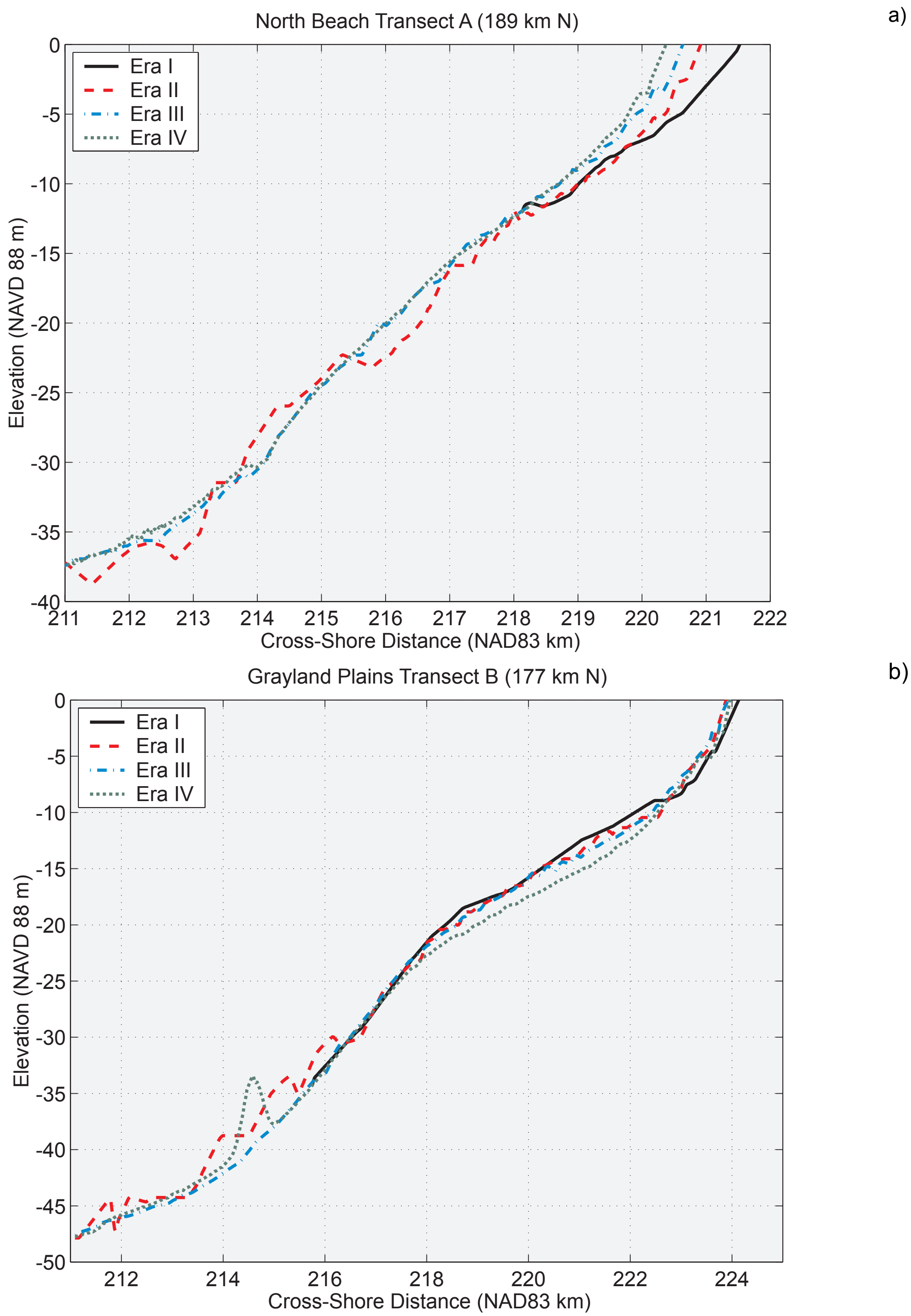


Figure 2-14. Cross-shore profiles of the adjusted Era I, II, III and IV bathymetric surfaces a) north of the Grays Harbor inlet at 189 km N and b) south of the Grays Harbor inlet at 177 km N.

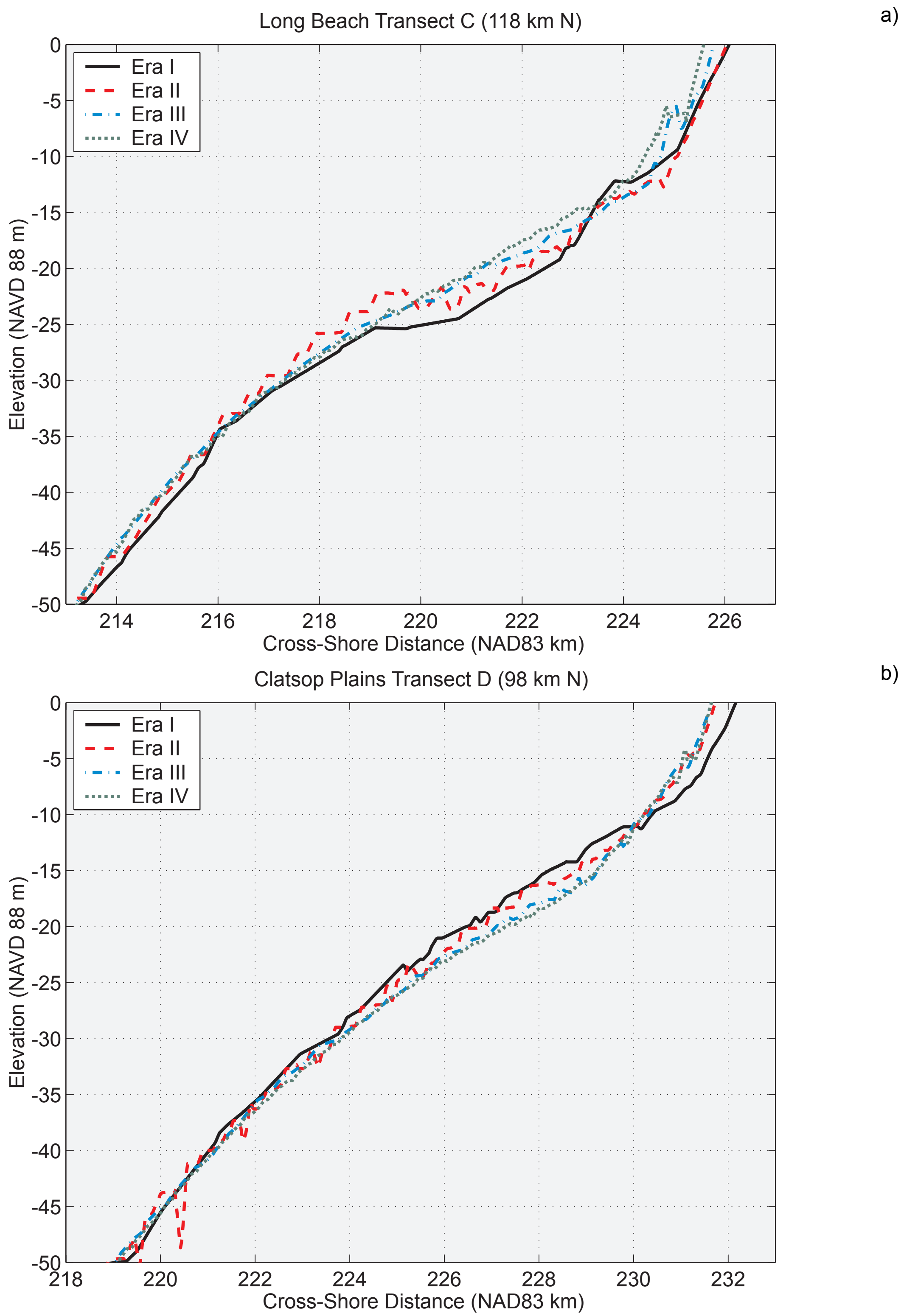


Figure 2-15. Cross-shore profiles of the adjusted Era I, II, III and IV bathymetric surfaces a) north of the Columbia River inlet at 118 km N and b) south of the Columbia River inlet at 98 km N.

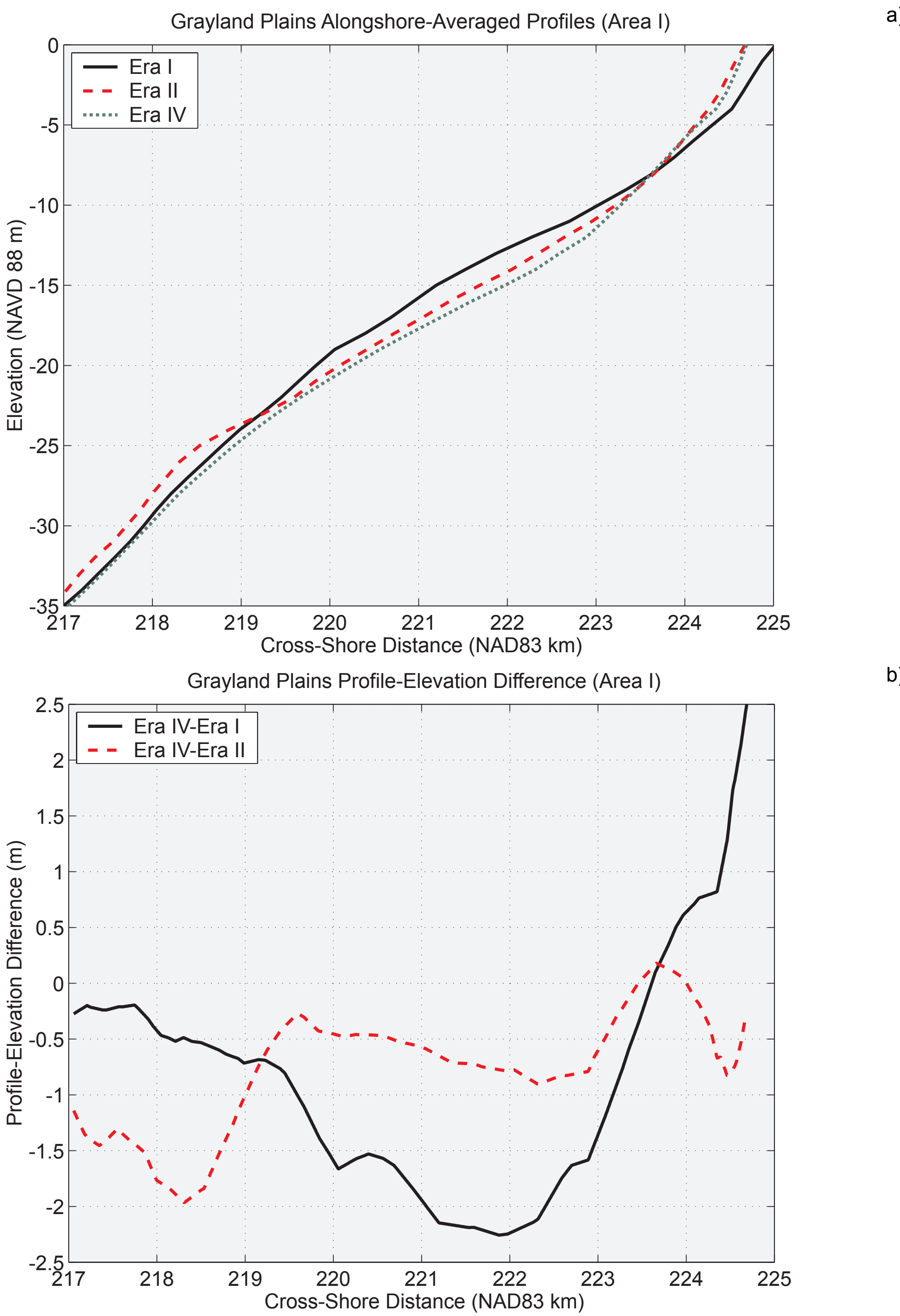


Figure 2-16. a) Adjusted alongshore-averaged profiles along Grayland Plains (Area I) and b) the difference between Era IV and Era I and Era IV and Era II alongshore-averaged profiles.

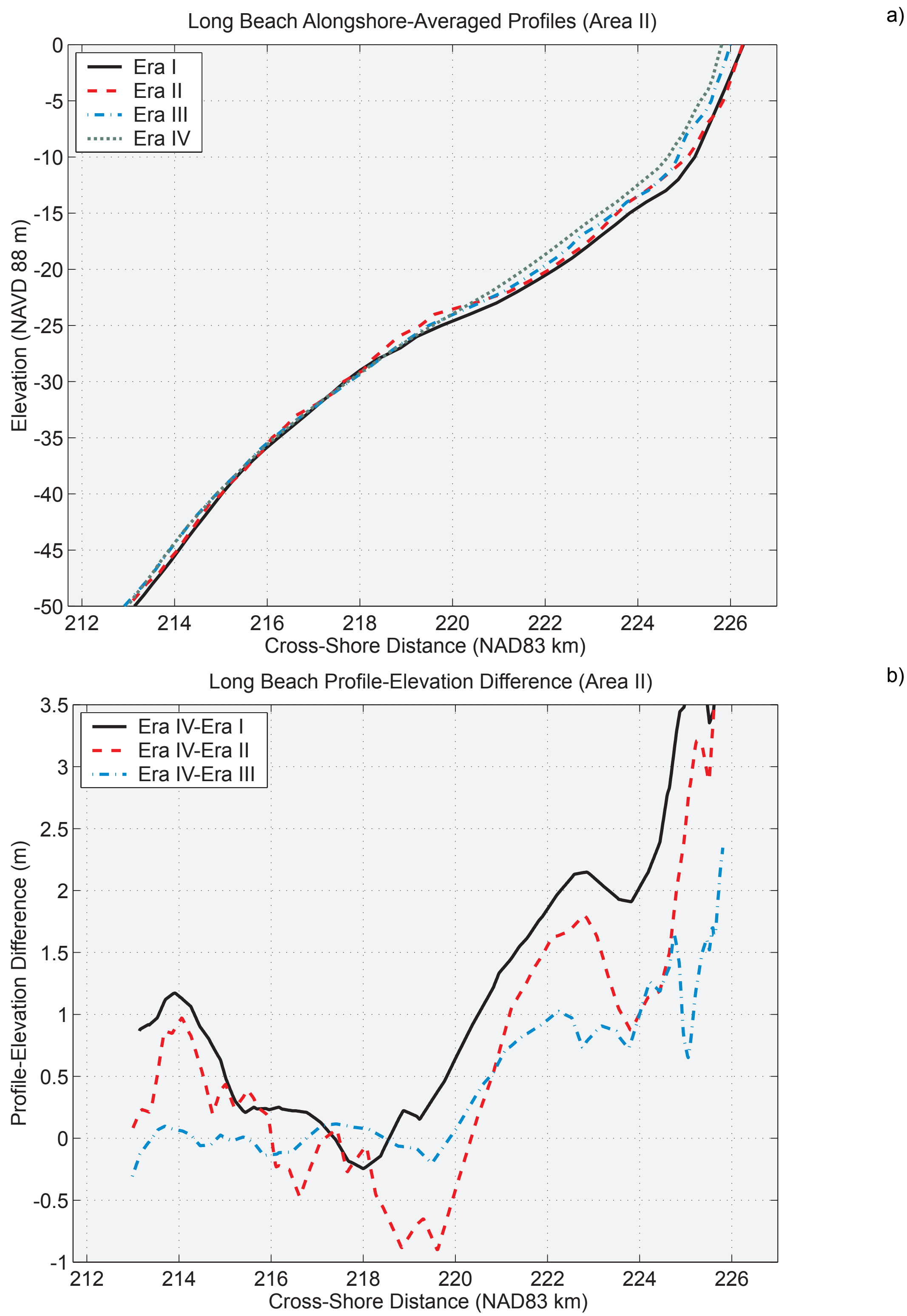


Figure 2-17. a) Adjusted alongshore-averaged profiles along Long Beach (Area II) and b) the difference between Era IV and Era I, Era IV and Era II, and Era IV and Era III alongshore-averaged profiles.

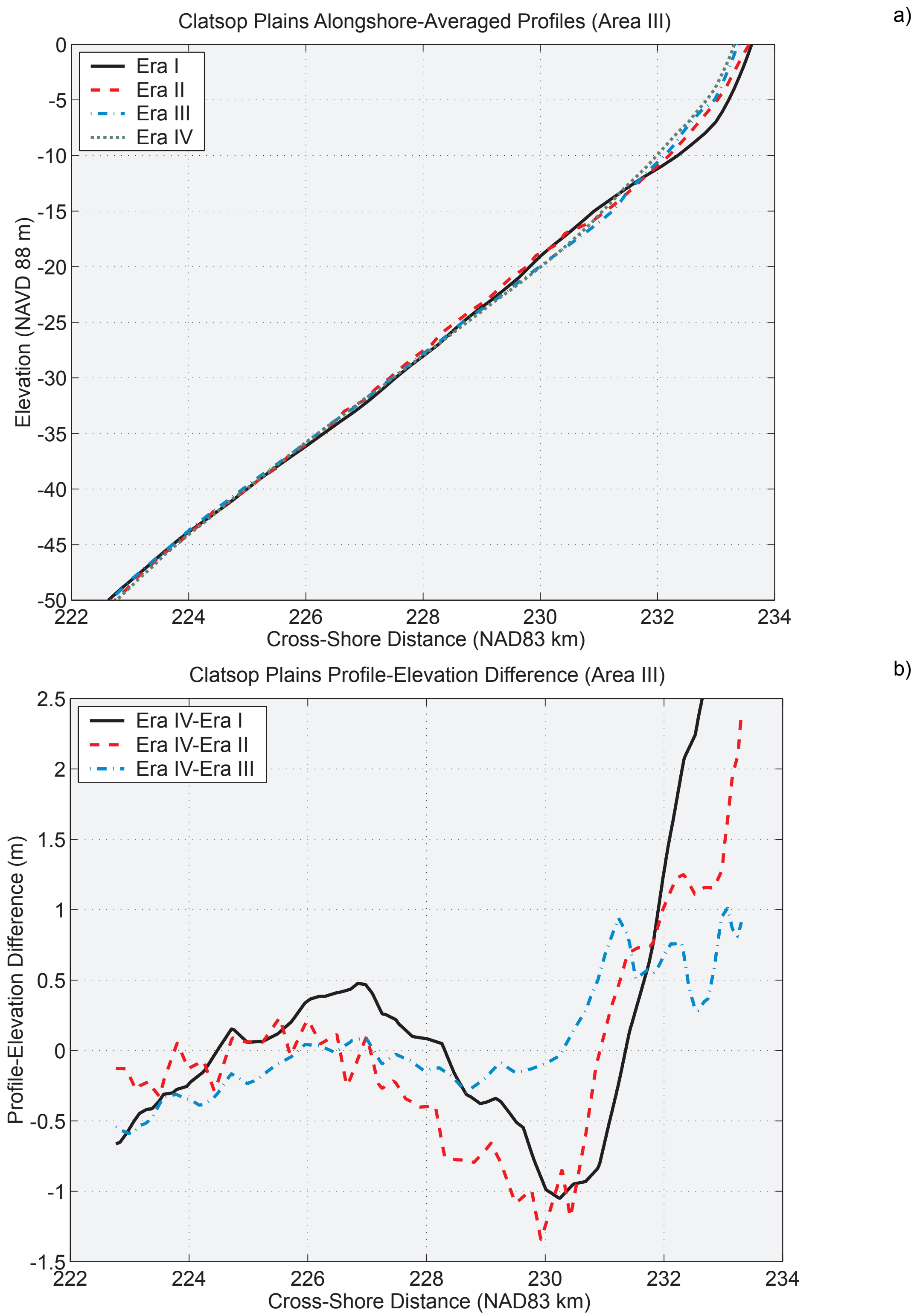


Figure 2-18. a) Adjusted alongshore-averaged profiles along Clatsop Plains (Area III) and b) the difference between Era IV and Era I, Era IV and Era II, and Era IV and Era III alongshore-averaged profiles.

2.5 Calculation of Subaerial- and Subaqueous-Volume Change

Our sediment budget analysis incorporates calculations of both subaerial and subaqueous volume changes. Topographic volumes are calculated above MHW. Along the coasts of the CRLC, MHW varies between approximately 2.7 to 3 m above NAVD88 (DANIELS et al., 2000). We assume the elevation of MHW to be 3 m above NAVD88 along the entire coastline of the CRLC. All bathymetric volumes are calculated below MHW. We assume that all bathymetric surfaces comprise of fine sand. The bathymetric change volumes calculated in the Columbia River estuary by SHERWOOD et al. (1990) are reduced to 80% to account for 20% mud and fines.

2.5.1 Calculation of Subaerial-Volume Change

The DEM used in the topographic-volume calculations is generated from LIDAR data. The 1998 LIDAR coverage extends across the entire coastal plain, from the shoreline to the landward edge of the dune complex. In an elaborate process, the LIDAR data is resampled with the ArcInfo® software package to remove trees, buildings, etc. The LIDAR data is subsequently gridded at a 5-m cell size. As a first step in creating the “bald” DEM, the raw LIDAR data is converted into a grid with a cell size of 5 m (DEM_{raw}). To reduce the number of no-data cells and to remove features like small trees or structures, a 3 by 3 cell window is passed over the DEM_{raw} and within a radius of 10.62 m of the center cell a minimum elevation is extracted (DEM_{min}). In a third step, dense vegetation and large buildings are removed from the DEM_{min}. Points are digitized at a 30 - 100-m spacing on an aerial photo mosaic that covered the extent of the LIDAR dataset. The points are located so that they provide a representative sample and avoid large trees, buildings, and other artificially high elevation points. This point coverage is then overlaid onto the DEM_{min} and spot elevations are extracted. In a final step, these elevations are adjusted with a vegetation correction factor of 1 m, 2 m, and 4 m, in the case of 1 - 2 m-tall dense brush, 2 - 4 m-tall dense brush and trees, and over 4 m-tall dense trees, respectively. This point coverage is interpolated on a 30-m grid (DEM_{BALD}) that is used for the volume calculations.

Volume changes of the prograded beach-dune complex are calculated between historical shoreline positions in compartments with an alongshore length varying between 1 - 6.3 km (Figure 2-19). The boundaries and alongshore lengths of the compartments are listed in Table 2-9. The compartment lengths are similar for all intervals, except for GLc3. The alongshore length of compartment GLc3 changed due to the northward migrating Willapa Bay North Channel (see foot notes of Table 2-9). We use the 1998 DEM_{BALD} to estimate volume changes associated with shoreline advance and retreat for all historical intervals. We assume that the contribution from vertical changes (i.e., changes in average elevation of the dune complex) is negligible compared to the contribution associated with horizontal changes related to advance and retreat of the shoreline. In the case of erosion, we calculate the volume above MHW by multiplying the eroded area by the average dune height landward of the dune crest. In addition, we assume that the beach-dune complex above MHW accreted over a beach profile with a constant shape.

In the following example we demonstrate how we calculate the volume change above MHW in the beach-dune complex during Interval 2 and Interval 3. We apply the same methodology to Interval 1 and Interval 4 as well. Figure 2-20 illustrates the volume-change calculation for a beach-dune complex prograding from the Era II to Era III and then to the Era IV shoreline positions. V_2 and V_A define the actual volume of sand accreted above MHW between the Era II and Era III shoreline positions. Due to the oblique beach profiles, it is complicated to calculate the volumes V_2 and V_A. We assume that the shape of the beach profiles of Era II and Era III (and Era I and Era IV) and the average dune heights of V_A and V_B are similar. The volume between the Era II and Era III shoreline positions are approximated by calculating the volumes V_2 and V_B. These volumes are easier to calculate because the dividing plane between the Interval 1 and Interval 2 and the Interval 2 and Interval 3 compartments is vertical instead of oblique. The actual volume of sand that accreted in Interval 3 between the Era III and Era IV shoreline positions includes V_3 and V_B. Here, we assume that the accreted volume in Interval 3 is equal to the average dune height of the area landward of the dune crest multiplied by the horizontal area between the Era III and Era IV shoreline positions.

Table 2-9. Compartment lengths and Northings of the northern and southern compartment boundaries of the compartments presented in Figure 2-19.

North Beach	Length (km)	N (km)	Grayland Plains	Length (km)	N (km)	Long Beach	Length (km)	N (km)	Clatsop Plains	Length (km)	N (km)
NBc8	1.00	226.0	**GLdn**	1.81	181.1	**LBdn**	3.32	153.2	**CPdn**	4.47	105.1
NBc7	5.00	225.0	**GLc6**	4.26	179.3	**LBc7**	5.59	149.9	**CPc5**	4.32	100.7
NBc6	5.00	220.0	**GLc5**	5.11	175.0	**LBc6**	4.26	144.3	**CPc4**	4.39	96.3
NBc5	5.00	215.0	**GLc4**	4.90	169.9	**LBc5**	4.98	140.0	**CPc3**	5.14	91.9
NBc4	5.00	210.0	**GLc3**[1)]	2.45	165.0	**LBc4**	5.02	135.0	**CPc2**	4.79	86.8
NBc3	5.00	205.0			162.6	**LBc3**	5.00	130.0	**CPc1**	4.81	82.0
NBc2	5.00	200.0				**LBc2**	5.00	125.0			77.2
NBc1	5.00	195.0				**LBc1**	6.30	120.0			
NBds	6.31	190.0				**LBds**	3.40	113.7			
		183.7						110.3			

[1)] Length of GLc3 during Interval 1 is 4600 m, during Interval 2 is 3715 m, during Interval 3 is 2100 m, and during Interval 4 is 2250 m.

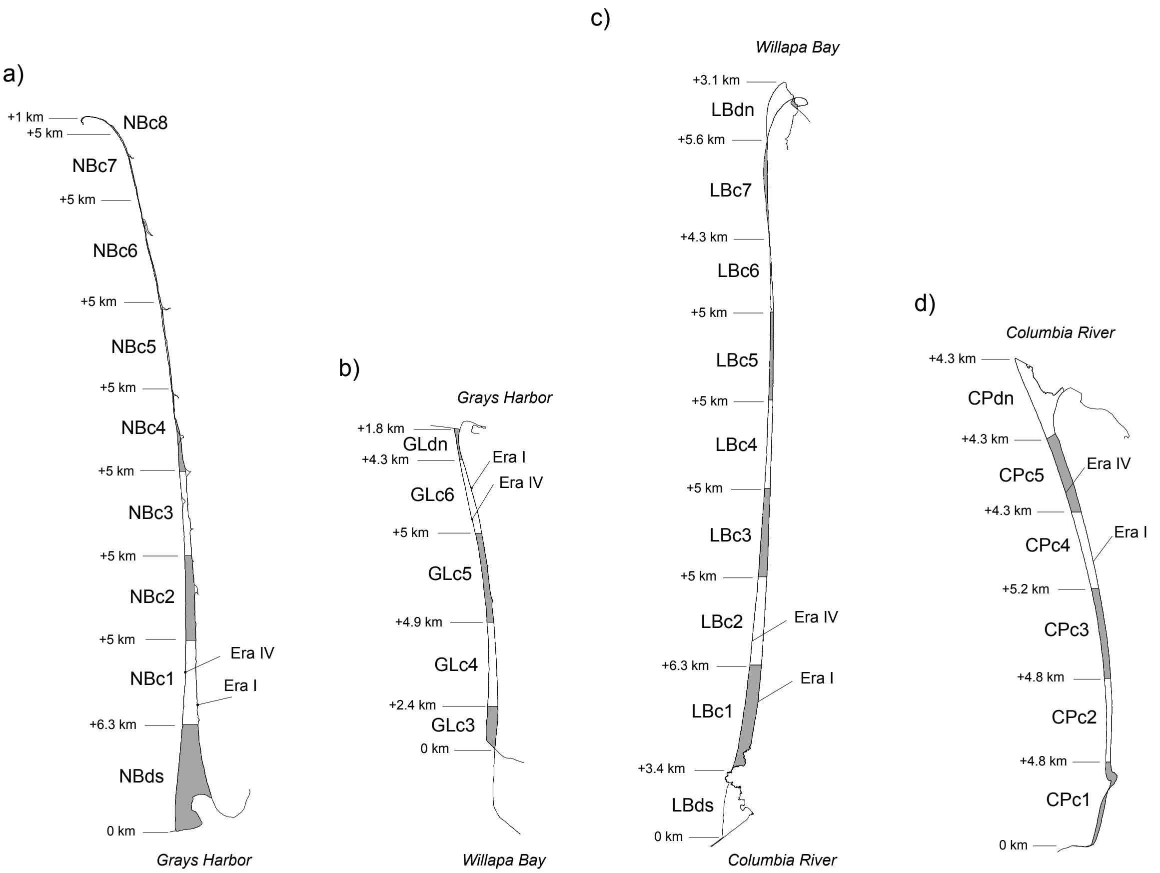


Figure 2-19. Plan view of a) North Beach (NB), b) Grayland Plains (GL) c) Long Beach (LB), and d) Clatsop Plains (CP) showing the compartments, compartment names, and compartment lengths as a function of Northing; 'c' indicates coast, 'd' delta, 'n' north, and 's' south. The landward and seaward extent of the compartments is indicated by the Era I and Era IV shorelines (Table 2-3 and Table 2-4).

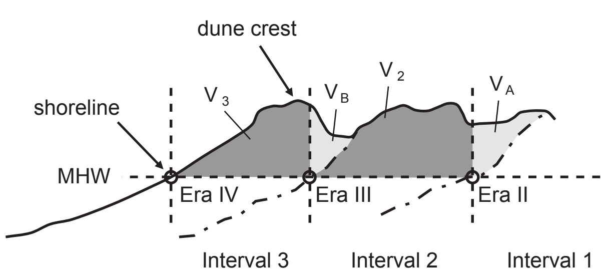


Figure 2-20. Schematic of the method used to calculate change in the volume of the prograded beach-dune complex.

2.5.2 Calculation of Subaqueous-Volume Change

Bathymetric data and shorelines are gridded at a 50-m cell size using triangulation with linear interpolation or kriging with an isotropic linear semivariogram model. To reduce error in subsequent volume calculations, the grid size is reduced to 25 m using cubic spline interpolation. We compute bathymetric-change surfaces by subtracting the bathymetric surfaces of different eras. Subsequently, we overlay polygons across the bathymetric-change surfaces and compute bathymetric-change volumes within the polygons using the average of volumes computed with the trapezoidal rule, Simpson's rule, and Simpson's 3/8 rule (GOLDEN SOFTWARE, 1997; PRESS et al., 1986).

The density of historical bathymetric data varies with water depth and survey year. Between approximately 5-m and 25-m water depth the data density is typically greatest. Seaward of 25-m depth the data density decreases. Typically, inside of about 5 m on the open coast there is little bathymetric data. In this very shallow zone the existing bathymetry was merged with the shorelines by interpolating between shoreline and bathymetry.

Figure 2-21a illustrates the method used for calculating volume change from bathymetric surfaces between Era I and Era II. We apply this method to volume calculations for Interval 2, 3, and 4 as well. V_1 is the volume above the MHW plane, calculated using the DEM_{BALD}. V_2 is calculated by subtracting the Era I bathymetry from the MHW plane out to the intersection of MHW and the Era II surface. Seaward of this point, V_3 is calculated by subtracting the Era I bathymetry from the Era II bathymetry. In some places, little or no nearshore bathymetric data is available and the nearshore volume change (V_2 and V_3) is calculated by multiplying the horizontal area between the shorelines with a value for the active depth (Figure 2-21b). The active depth is derived from nearshore areas within the same sub-cell that have good bathymetry, and is equal to the volume change (V_2 and V_3) divided by the horizontal area that accreted between the shorelines. The active depths differ for each interval and sub-cell and are listed in the tables in Section 3. It should be noted that the active depth is shallower than the depth of no significant change.

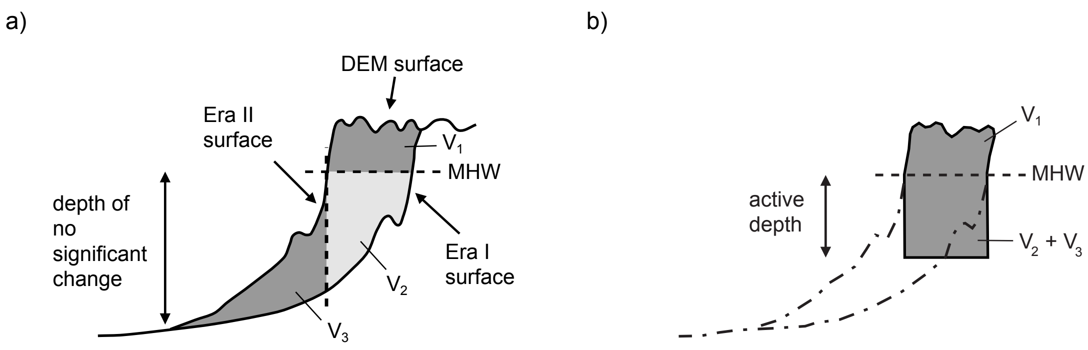


Figure 2-21. Schematic explaining the method used for calculating volume change in the case a) bathymetric surfaces are present and b) bathymetric surfaces are missing. In the latter case the volume between the Era I and Era II shorelines is calculated by assuming an active depth.

2.5.3 Calculation of Sediment Balances

To calculate net change over the study areas for each interval, we sum the bathymetric- and topographic-change volumes. We use the following sign convention: erosion or a source of sediment (e.g., Columbia River supply) is indicated with a negative (-) sign, and accretion or a sink of sediment (e.g., littoral transport leaving the study area) is indicated with a positive (+) sign. In the following we consider a fictive example. During a certain period, the Grays Harbor entrance erodes 30 million m^3 (-30 Mm^3), the beach-dune complex of North Beach accretes 50 Mm^3 (+50 Mm^3) and the littoral feeding is 5 Mm^3 (-5 Mm^3). The net bathymetric and topographic change over the Grays Harbor entrance and the beach-dune complex of North Beach is -30 + +50 = +20 Mm^3, i.e., a net gain of 20 Mm^3. If we include the littoral feeding, the net balance over the study area is a net gain of (+20 + -5 =) 15 Mm^3, i.e., the littoral feeding can only account for 5 Mm^3 of the accretion. The remaining 15 Mm^3 can be related to uncertainties in the data, insufficient bathymetric coverage, etc.

2.6 Estimates of Uncertainty

This section discusses the uncertainty of the bathymetric and topographic surveys that affect the reliability of the datasets and volume calculations.

2.6.1 Uncertainties in Bathymetric Surveys

The uncertainty in bathymetric surveys comprises random errors such as the accuracy of individual soundings, errors in horizontal positioning, errors in tide correction, and trackline crossing differences and consistent errors such as vertical datum differences.

The accuracy of the individual soundings of bathymetric surveys is discussed in GIBBS and GELFENBAUM (1999). According to GIBBS and GELFENBAUM, the first quantitative accuracy standards for bathymetric surveys are from 1883. These standards vary from the nearest tenth of a foot (0.03 m) inside the 12 foot (3.6 m) contour, the nearest quarter foot (0.08 m) between the 12 and 24 foot (2.2 - 7.3 m) curves, the nearest half foot (0.15 m) between the 4 and 10 fathom (7.3 - 18.2 m) curves, the nearest foot (0.3 m) between the 10 and 15 fathom (18.2 - 27.4 m) curves, the nearest half fathom (0.9 m) seaward of the 15 fathom (27.4 m) curve, to the nearest fathom (1.8 m) for deep sea soundings. We do not obtain standards for surveys of other eras. After examining the depth sounding records, we find that most soundings of the Era I, Era II, and Era III surveys are rounded to the nearest foot. The Era IV USACE surveys near the Columbia River entrance are rounded to the nearest tenth of a foot (0.03 m) and Era IV USACE surveys near Grays Harbor and Willapa Bay, the Multibeam, and CPS surveys are rounded to the nearest centimeter.

GIBBS and GELFENBAUM estimated potential errors for vertical datum differences, tide corrections, trackline crossings, and errors in horizontal positioning in mainly USC&GS bathymetric surveys (Table 2-10). Random errors, e.g., in horizontal positioning are clearly evident in the Era I and Era II USC&GS H1378, H1379, H4634, H4635, and H4728 surveys.

Table 2-10. Estimates of potential errors by survey period (GIBBS and GELFENBAUM, 1999).

Potential Error (m)	Era I	Era II	Era III	Era IV
Vertical Datum Differences (m)	+/-0.35	-	-	-
Tide Correction (m)	+/-0.5	+/-0.5	+/-0.5	-
Horizontal Positioning (m)	+/-0.3 - 6	+/-0.3 - 6	-	-
Trackline Crossing Differences (m)	+/-0.3 - 2[1)]	+/- 0.3 - 3 [2)]	[3)]	<0.3

[1)] Nearshore surveys only.
[2)] Average is +/-1.3 m.
[3)] Not evaluated.

We do not correct random errors, but we minimize consistent errors in vertical datum by reducing consistent offsets between surveys as discussed in Section 2.4. Deviations among the adjusted profiles are interpreted as indications of the uncertainty of the depth measurements along the profiles. If we accept the hypothesis that bathymetric changes are negligible in deeper water and assume that the Era IV data are the most accurate, we can estimate the uncertainty of a dataset as the root-mean-square (RMS) and/or mean difference between this dataset and the Era IV surface. Moreover, we calculate the uncertainty (RMS and mean difference) of the volume calculations for each bathymetric-change interval. This uncertainty is used to check the credibility of the bathymetric changes. The RMS error is determined as:

$$RMS = \sqrt{\frac{\sum_{n} (\Delta h)^2}{n}}$$

Where *RMS* = root-mean-square error, Δh = elevation difference between two data points with the same horizontal coordinates, and n = number of Δh.

We calculate RMS and mean differences below depths of no significant change for each interval and for each era relative to Era IV along the adjusted cross-shore profiles presented in Figure 2-14 and Figure 2-15 and along the alongshore-averaged profiles presented in Figure 2-16, Figure 2-17, and Figure 2-18. RMS and mean differences are not calculated below a depth of no significant change of approximately 30 m at the alongshore-averaged profiles along Grayland Plains, because of insufficient bathymetric coverage seaward of this depth. The RMS and mean differences are presented in Table 2-11 and Table 2-12. The water depths over which the calculations are performed are included in the tables. The tables show that the RMS and mean differences along the alongshore-averaged profiles are smaller than the RMS and mean differences along the transects. These results demonstrate that alongshore averaging significantly reduces the random error in the profiles.

Table 2-11. RMS and mean differences calculated along the adjusted Transects A, B, C, and D.

Location	Interval	Water Depth (m)	RMS (m)	Mean Difference (m)
North Beach (Transect A)	**Era II - Era I**	14 - 37	n/a	n/a
	Era III - Era II	14 - 37	1.38	0.49
	Era IV - Era I	14 - 37	n/a	n/a
	Era IV - Era II	14 - 37	1.46	0.65
	Era IV - Era III	14 - 37	0.35	0.16
Grayland Plains (Transect B)	**Era II - Era I**	25 - 37	n/a	n/a
	Era III - Era II	25 - 37	1.73	-1.20
	Era IV - Era I	25 - 37[1)]	n/a	n/a
	Era IV - Era II	25 - 37[1)]	1.69	-1.14
	Era IV - Era III	25 - 37[1)]	0.34	-0.24
Long Beach (Transect C)	**Era II - Era I**	23 - 50	1.31	1.12
	Era III - Era II	23 - 50	0.97	-0.22
	Era IV - Era I	23 - 50	1.02	0.70
	Era IV - Era II	23 - 50	1.13	-0.41
	Era IV - Era III	23 - 50	0.31	-0.19
Clatsop Plains (Transect D)	**Era II - Era I**	30 - 50	1.33	-0.62
	Era III - Era II	30 - 50	1.15	0.20
	Era IV - Era I	30 - 50	0.99	-0.77
	Era IV - Era II	30 - 50	1.14	-0.15
	Era IV - Era III	30 - 50	0.43	-0.35

[1)] Excluding the dredge disposal mound.

Table 2-12. RMS and mean differences calculated along the adjusted alongshore-averaged profiles for Area II and Area III.

Location	Interval	Water Depth (m)	RMS (m)	Mean Difference (m)
Grayland Plains (Area I)	**n/a**	n/a	n/a	n/a
Long Beach (Area II)	**Era II - Era I**	29 - 50	0.20	0.06
	Era III - Era II	29 - 50	0.41	0.20
	Era IV - Era I	29 - 50	0.50	0.27
	Era IV - Era II	29 - 50	0.43	0.21
	Era IV - Era III	29 - 50	0.08	0.01
Clatsop Plains (Area III)	**Era II - Era I**	28 - 50	0.28	-0.10
	Era III - Era II	28 - 50	0.28	0.20
	Era IV - Era I	28 - 50	0.29	-0.06
	Era IV - Era II	28 - 50	0.17	0.05
	Era IV - Era III	28 - 50	0.24	-0.15

2.6.2 Uncertainties in Shoreline Position and Topography

The topographic errors discussed here are the horizontal errors in shoreline position and the vertical errors associated with the DEM_{BALD}. The horizontal errors in the shoreline position (DANIELS et al., 2000; DANIELS and HUXFORD, 2001; ROBERT HUXFORD, DOE, personal communication, 2000) include the horizontal accuracy of the charts and photos (map error at the benchmark) and a horizontal interpretation error of the shoreline position in the field. In addition to these errors, the natural horizontal variability of the shorelines, at the time of survey in the summer months, was estimated to be 15 m (DANIELS et al., 2000). DANIELS et al. calculated this value assuming that the vertical position of the shoreline may vary 0.30 m due differences in wave and tide conditions on an average beach slope of 2%. An overview of shoreline position errors is presented in Table 2-13. In the following, we present an example of the relative error in shoreline position along the Long Beach sub-cell. Estimates of the square roots of the sums of the individual errors in shoreline position for Interval 1 and Interval 3 are approximately 30 m and 23 m, respectively (the landward and seaward side of the shoreline change compartment combined). The average shoreline change along central Long Beach during Interval 1 and Interval 3 was approximately 58 m and 160 m, resulting in relative errors of 52% and 14%, respectively.

Table 2-13. Horizontal errors in shoreline position (DANIELS et al., 2000; DANIELS and HUXFORD, 2001; ROBERT HUXFORD, DOE, personal communication, 2000).

Source	Map Error (m)	Interpretation Error (m)	Variability (m)
Pre-jetty NOS T-Sheets	+/-19	+/-6	+/-15
1920s and 1950s NOS T-Sheets	+/-6	+/-6	+/-15
Aerial photographs	+/-3	+/-2	+/-15

The overall accuracy of the DEM_{BALD} is affected by the removal of trees and shrubs. To study the accuracy of the DEM_{BALD}, the benchmarks that comprise the Washington Coastal Geodetic Control Network (DANIELS et al., 1999) are overlaid onto the DEM_{BALD} and 48 elevations are extracted. The RMS and mean differences between the DEM_{BALD} elevations at the benchmarks and the benchmarks elevations are 1.61 m and -1.11 m (benchmarks higher), respectively. These results show that correcting the DEM_{RAW} for vegetation generally reduces the elevation of the DEM_{BALD}. The same results are obtained when comparing the DEM_{BALD} with field data collected by the SWCES (RUGGIERO and VOIGT, 2000) and the DEM_{BALD} with the DEM_{RAW} along four transects. The field data were collected in February and March of 1998 at 199.5 km N (North Beach), 179.1 km N (Grayland Plains), 131.9 km N (Long Beach), and 92.5 km N (Clatsop Plains). The field data comprise of profiles across the dry beach and dunes and have a vertical accuracy of 4 - 5 cm. It is illustrated in Figure 2-22 at 179.1 km N at Grayland Plains that both the DEM_{RAW} and DEM_{BALD} are lower than the field data. It should be noted that this transect has the highest RMS and mean differences of the four transects. We calculate RMS and mean differences for the dry beach and dunes combined and for the dunes only. The mean difference between the DEM_{BALD} and the field data on the beach is generally within -0.3 m and the average mean difference for the beach and dunes combined for the four transects is -0.58 m. The dunes landward of the dune crest are used for the topographic volume calculations. The average RMS and mean difference between the DEM_{BALD} and the field data landward of the dune crest for the four transects are 1.28 m and -1.03 m, respectively. The RMS and mean differences for the four transects are presented in Table 2-14. The average dune heights above MHW for Interval 3 for North Beach, Grayland Plains, Long Beach, and Clatsop Plains are 2.16 m, 2.88 m, 2.67 m, and

6.79 m, respectively (Table 3-14, Table 3-15, Table 3-17, and Table 3-18). If we assume the RMS difference at the transect (DEM_{BALD}-SWCES, dunes only) is representative for the entire sub-cell, the relative errors of the dune height above MHW for Interval 3 are approximately 19%, 64%, 41%, and 26%, respectively. Based on this analysis, we conclude that the topographic volume calculations underestimate the actual topographic volumes.

Table 2-14. RMS and mean differences between the DEM_{BALD}, DEM_{RAW}, and SWCES field data for the dry beach and dunes, and for the dunes only.

Location (km N)	**DEM_{BALD}-SWCES (beach and dunes)**		**DEM_{BALD}-DEM_{RAW} (beach and dunes)**		**DEM_{BALD}-SWCES (dunes only)**		**DEM_{BALD}-DEM_{RAW} (dunes only)**	
	RMS (m)	**Mean (m)**	**RMS (m)**	**Mean (m)**	**RMS (m)**	**Mean (m)**	**RMS (m)**	**Mean (m)**
199.5	0.37	-0.13	0.30	-0.15	0.41	-0.17	0.24	-0.11
179.1	1.93	-1.22	1.27	-0.79	1.85	-1.30	1.26	-0.85
131.9	0.71	-0.33	0.57	-0.20	1.08	-0.97	0.86	-0.77
92.5	1.16	-0.64	0.79	-0.08	1.79	-1.70	1.04	-0.71
Average	**1.04**	**-0.58**	**0.73**	**-0.31**	**1.28**	**-1.03**	**0.85**	**-0.61**

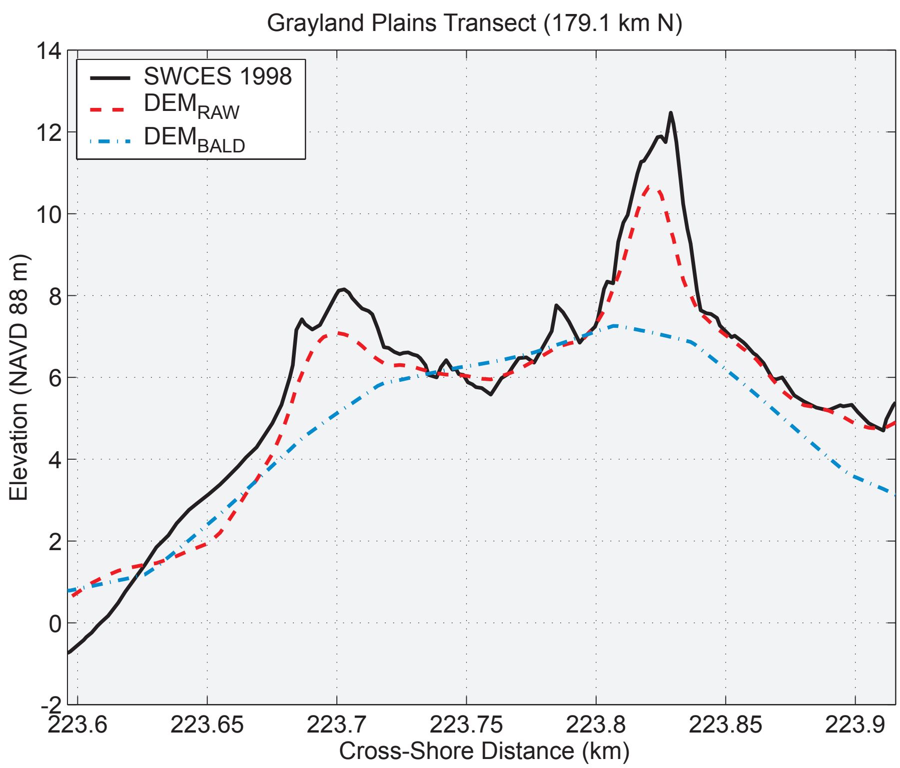


Figure 2-22. Comparison of the $\mathbf{DEM_{BALD}}$ with the DEM_{RAW}, and SWCES field data at 179.1 km N

2.6.3 Uncertainties in the Sediment Budgets

Ideally, we could use the RMS and mean differences in the bathymetry and topography to calculate the uncertainties in the sediment budgets. However, the calculated RMS and mean differences might not be representative of the entire dataset, resulting in unrealistic estimates of the uncertainties in the sediment budgets. The other drawback is that calculating the uncertainties in the sediment budgets is a time-consuming and complicated procedure, especially if we use the horizontal uncertainties in shoreline position (Table 2-13).

As an alternative for the uncertainty in the sediment budgets, we estimate the sensitivity of the sediment budgets to the adjustments in the vertical datums. The calculation of this "uncertainty" is described in the following. First, we calculate the differences between the adjustments of surveys of subsequent eras. Subsequently, we multiply these differences by the horizontal area of the bathymetric change polygons. Finally, we determine the uncertainty in the sediment budgets by summing these volumes over the study area. Basically, these uncertainties are equal to the difference between the sediment balances calculated for the adjusted surveys and the sediment balances calculated for the unadjusted surveys. These uncertainties are calculated in Section 3.

2.6.4 Unaccounted Uncertainties

Additional uncertainties that could play an important role that are not quantified are:

- Historical vertical accretion of the dunes
- Vertical error in the shoreline position
- Matching differences between bathymetry and shorelines (different years)
- Interpolation between shoreline data and bathymetry
- Gridding method
- Matching differences between the topographic and bathymetric polygons used for the volume calculations

3 TOPOGRAPHIC- AND BATHYMETRIC-VOLUME CALCULATIONS

3.1 Interval 1 (1860s - 1900 to 1920s - 1930s)

3.1.1 Grays Harbor Entrance and Adjacent Coasts

Era I and Era II Bathymetric Surfaces

The 1887 USC&GS H1800 survey (offshore Grayland) is merged with the USACE 1900 survey (Grays Harbor delta) and the 1886, 1887, 1871 T-sheet, and USACE 1900 shorelines to form the Era I bathymetric surface (Table 2-1, Table 2-3, and Figure 2-1). The spacing of the depth soundings along the tracklines of the H1800 survey is O(200 m) and the distance between the tracklines is O(600 m). The sparse data and the primitive collection methods, most likely with a large uncertainty (Section 2.6.1), result in an irregular bathymetric surface. The USACE bathymetric data and shorelines are digitized from the USACE 1900 Annual Survey data sheet. The spacing of the data points along the irregularly spaced tracklines of the USACE 1900 dataset is O(100 m). The Era I surface is presented in Figure 3-1a. The USC&GS H1589 survey from 1883 of the Grays Harbor entrance is not used, because the coverage of that survey is not sufficient. However, a comparison between the USC&GS H1589 and USACE 1900 surveys reveals that between 1883 and 1900 the Grays Harbor delta and bar channel had moved approximately 2400 m in a northward direction, whereas the deepest point of the channel at the entrance remained in place.

The Era II dataset for Grays Harbor and Willapa Bay entrances consists of the USC&GS surveys H4620 (1926, offshore Willapa Bay delta), H4621 (1926, nearshore Grayland Plains), H4658 (1928, Willapa Bay delta and entrance), H4710 (1927, nearshore North Beach), and H4728 (1927, offshore North Beach and Grayland Plains), the USACE 1927 survey of the Grays Harbor delta and entrance (digitized from the 1927 USACE Annual Survey chart), and the 1926 and 1927 T-sheet shorelines (Table 2-1, Table 2-3, Figure 2-2, and Figure 2-5). Tracklines of the nearshore USACE 1927, H4620, H4621, H4658, and H4710 surveys have a spacing of O(300 m), and data points along the tracklines have a spacing of O(100 m). Tracklines of the offshore H4728 survey have a spacing of O(500 m), and data points along the tracklines have a spacing of O(400 m). The nearshore surveys are of a higher quality than the offshore H4728 survey. Inaccuracies in the soundings of the offshore survey cause an irregular shaped bathymetric surface. Due to these large irregularities we do not calculate volume changes over the area covered by the H4728 survey, except at the Grays Harbor delta. The Era II surface is presented in Figure 3-1b.

Vertical datum adjustments are discussed in Section 2.4.3. The vertical datums of the Era I USACE 1900 and the H1800 surveys are adjusted by -0.46 m and -0.24 m to NAVD88 in Westport and Toke Point, respectively. The Era II USC&GS H4620, H4621, and H4658 surveys are adjusted by -0.16 m to NAVD88 at Ft. Stevens. The H4710 and the H4728 surveys are adjusted by -0.36 m to NAVD88 at Pt. Grenville. The USACE 1927 survey is adjusted by -1.11 m to match the adjusted USC&GS surveys.

Depth soundings that cause unrealistic distortions in the bathymetry (outliers) are removed from both the USACE 1900 and H1800 datasets. The Era I and Era II surveys are gridded at a 50-m cell size using kriging with an isotropic linear semivariogram model. To minimize errors in the volume calculations the grid size is reduced to 25 m using cubic spline interpolation.

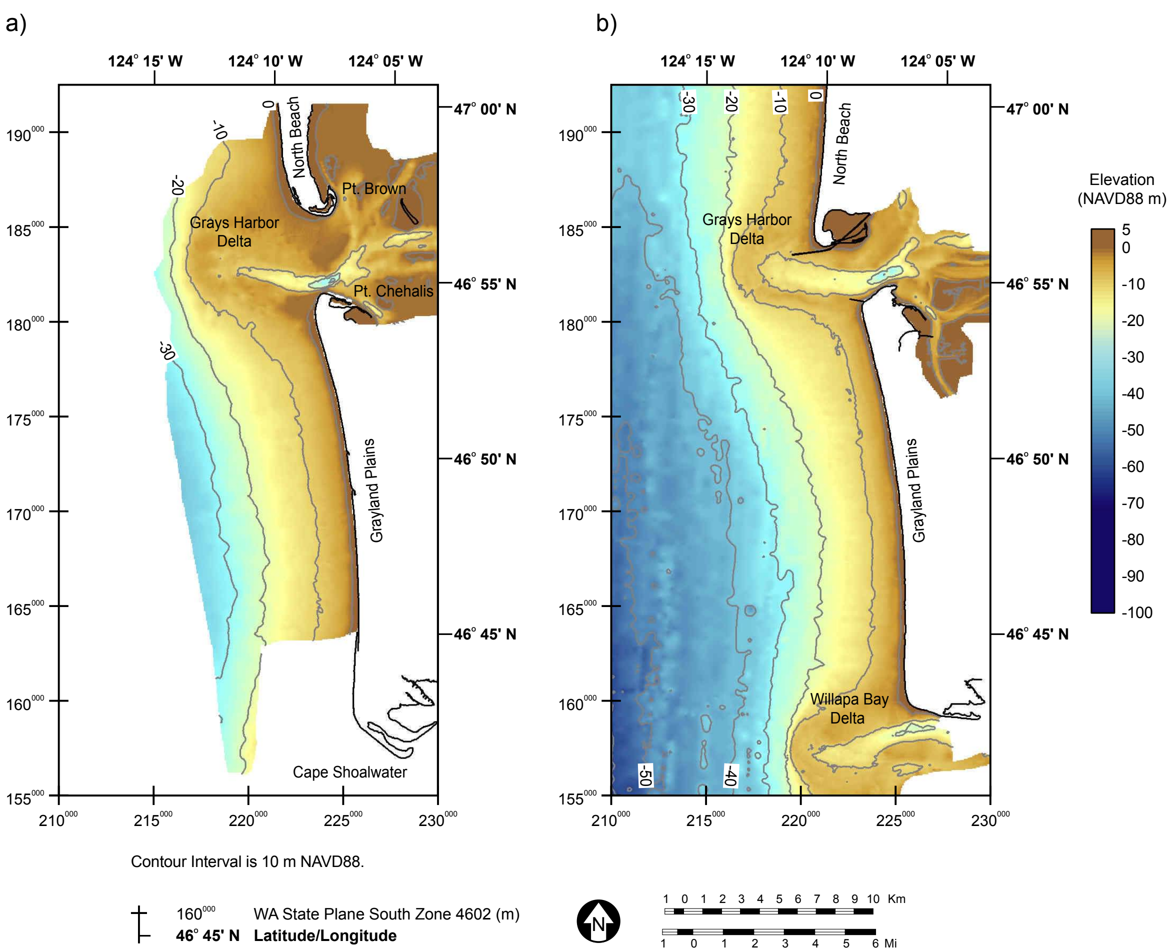


Figure 3-1. Bathymetric surface for a) Era I and b) Era II of the Grays Harbor entrance, North Beach, and Grayland Plains.

Topographic- and Bathymetric-Volume Change

The bathymetric-volume changes between Era I and Era II at the Grays Harbor entrance are shown in Figure 3-2. The bathymetric and topographic volume changes for the Grays Harbor entrance and adjacent coasts are presented in Table 3-1. The numbers in Figure 3-2 refer to the compartments in the table. In Table 3-1, Area represents the horizontal area of the compartments and ΔV the volume change of the compartments. The vertical change Δh is equal to ΔV divided by the horizontal area. Positive volumes in the table indicate accretion and negative volumes indicate erosion. The change rates ΔV and Δh are calculated for a duration of 33 years (1926 - (1887 + 1900)/2 = 33 years). The subaerial compartments (i.e., NBds (1), GLdn (10), North Beach, and Grayland Plains in Table 3-1) only comprise horizontal change, and therefore, no vertical changes and vertical-change rates are calculated for these subaerial compartments. We do not sum horizontal areas, because the freedom of movement of the subaerial compartments (horizontal) differs from the bathymetric compartments (vertical).

Table 3-2 and Table 3-3 present the volume changes of the beach-dune complex along North Beach and Grayland Plains, respectively. In these tables, Area is the horizontal area that accreted between the shorelines, ΔV is the sum of $\Delta V_{>MHW}$ and $\Delta V_{<MHW}$, $\Delta V_{>MHW}$ is the topographic volume change calculated above MHW using the $DEM_{\mathbf{BALD}}$ (volume V_1 in Figure 2-21), $\Delta V_{<MHW}$ is the volume calculated below MHW (volumes V_2 and V_3 in Figure 2-21), and the vertical heights h_{active}, $h_{>MHW}$, and $h_{<MHW}$ are obtained by dividing ΔV, $\Delta V_{>MHW}$, and $\Delta V_{<MHW}$ by Area, respectively. The change rates of Area, ΔV, and $\Delta V_{>MHW}$ are obtained by dividing by the interval duration (33 years) and the alongshore length of the compartments. These change rates are visualized in Figure 3-5 and Figure 3-6.

Due to the limited data coverage in deeper water we can not calculate RMS and mean differences along the alongshore-averaged profiles at Grayland Plains and along the cross-shore Transects A and B for Interval 1 (Sections 2.4.2 and 2.6.1). We use the difference between the Era I and Era II tidal-datum adjustments of 0.1 m along North Beach (-0.36 m - -0.46 m), -0.64 m at the inlet (-1.11 m - -0.46 m), 0.3 m at the South Flank (-0.16 m - -0.46 m), and 0.08 m along Grayland Plains (-0.16 m - -0.24 m) as an estimate of the uncertainty of bathymetric change.

We assume that compartments NBds (1) and GLdn (10) in Table 3-1 are part of the ebb-tidal-delta complex and only comprise volumes V_1 and V_2 (Figure 2-21). These compartments are not included in the area- and volume-change values for North Beach and Grayland Plains in Table 3-1. North Beach and Grayland Plains include compartments NBc1 - NBc8 and GLc3 - GLc6, respectively. These compartments comprise the subaerial and subaqueous volumes V_1, V_2, and

V_3. Compartments GLc6_near (15), GLc5_near (16), GLc4_near (17) and GLc3_near (18) are part of compartment Grayland Plains in Table 3-1.

There is no bathymetric coverage north of compartment NBds_near (2) and south of GLc3_near (18). The volume of the beach-dune complex along North Beach (NBc1 - NBc7) above MHW is calculated using the $DEM_{\mathbf{BALD}}$ and below MHW applying an active depth of 11.77 m. This depth is based on volume change calculated for Interval 4.

NBds_near (2) does not extend to the northern boundary of NBds at 190 km N. To get a complete estimate of the volume change of the beach-dune complex of North Beach the area of NBds_near (2) is extrapolated to match the northern boundary of NBds (dashed line in Figure 3-2). This compartment is called NBds_near_corr. We calculate the bathymetric change volume of NBds_near_corr using a proportional relation between the volume and area of NBds_near and the area of NBds_near_corr. The volume change of NBds_near_corr is included in the sand balance in Table 3-1.

Compartment GLc3_near (18) does not extend to the southern boundary of GLc3 at 160.4 km N. We estimate $V_{<MHW}$ of GLc3 (V_2 and V_3) using a proportional relation between the horizontal area of GLc3 (0.97 km^2), the area of GLc3* (0.48 Mm^3, Figure 3-2), and the volume of GLc3_near (2.46 Mm^3). The estimated volume $V_{<MHW}$ of GLc3 (6.36 Mm^3) is included in the volume change of the Grayland Plains compartment in Table 3-1.

Compartments NBc7 and/or NBc8 do not have shoreline coverage, and therefore, volume changes are not calculated. However, there was no significant shoreline change along northern North Beach, and neglecting volume changes of compartments NBc7 and NBc8 does not impact the sediment budget.

The volume change of compartment 5 (Oyhut) is estimated by subtracting the Era I bathymetry from the 2-m plane. In Era II Oyhut was a marshy bay, with most of its area below 3 m (MHW). We assume that 2 m is a good estimate of the average height of the marshes. Point Brown (6) and Point Chehalis (8) were sandy spits, and we assume that their sandy crests approximated MHW. Their volume change is calculated by subtracting the Era I surface from the MHW plane.

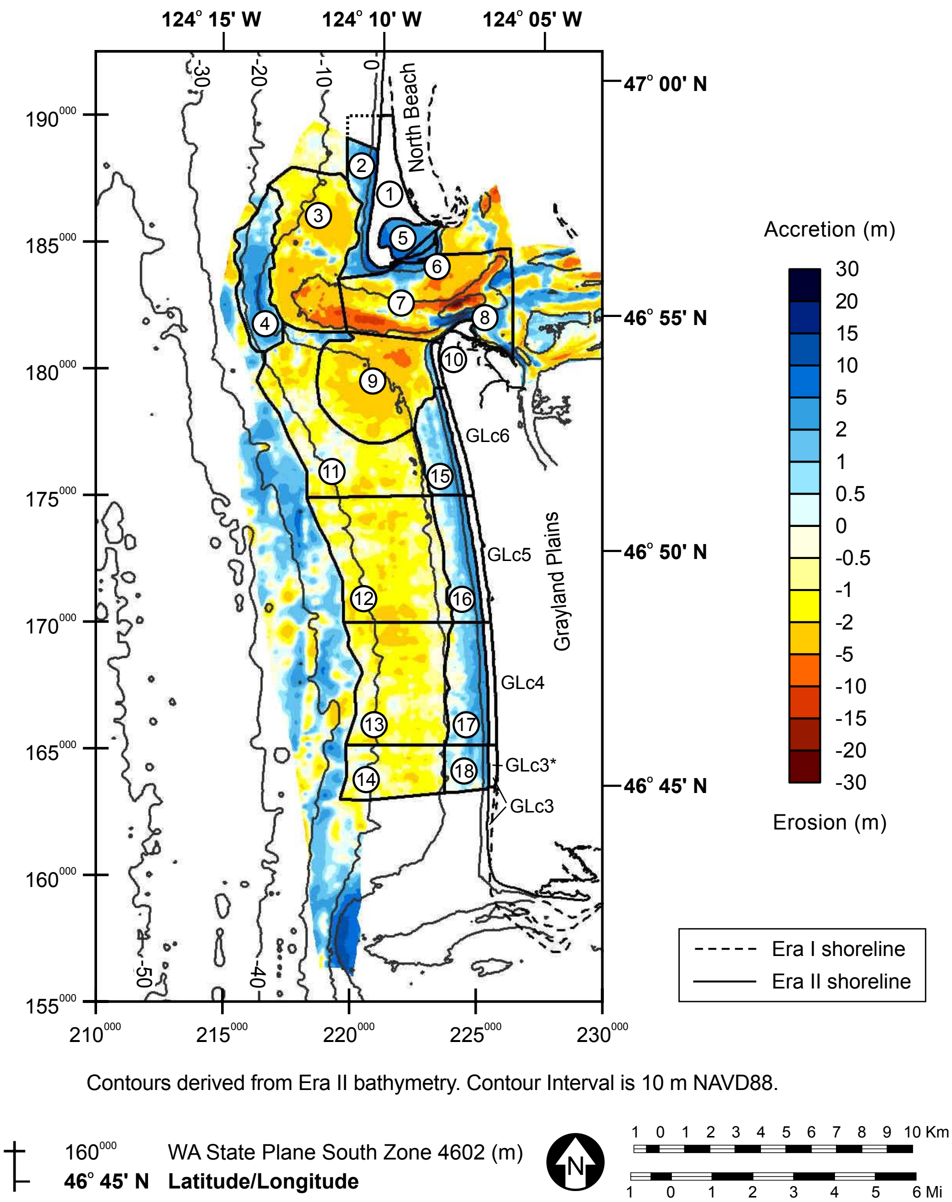


Figure 3-2. Bathymetric and topographic change for Interval 1 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Table 3-1. Bathymetric and topographic change for Interval 1 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Interval 1 ~33 yr	Area (km^2)	ΔV (Mm^3)	Δh (m)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
NBds (1)	5.04	29.81	n/a	0.90	n/a
NBds_near_corr[3)]	5.78	16.96	2.94	0.51	0.089
Inner Delta (3)	17.98	-44.73	-2.49	-1.36	-0.075
Outer Delta (4)	7.60	14.97	1.97	0.45	0.060
Oyhut (5)	2.60	9.19	3.53	0.28	0.107
Point Brown (6)	0.45	2.51	5.53	0.08	0.168
Inlet (7)	19.75	-39.45	-2.00	-1.20	-0.061
Point Chehalis (8)	0.39	2.18	5.55	0.07	0.168
South Flank (9)	15.99	-35.96	-2.25	-1.09	-0.068
GLdn (10)	0.47	1.57	n/a	0.05	n/a
Sum	**n/a**	**-42.95**	**n/a**	**-1.30**	**n/a**
North Beach[1)]	1.23	17.62	n/a	0.53	n/a
Subtotal	**n/a**	**-25.33**	**n/a**	**-0.77**	**n/a**
Grayland Plains[2) 4)]	5.53	55.12	n/a	1.67	n/a
Glc6_off (11)	20.10	-17.60	-0.88	-0.53	-0.027
Glc5_off (12)	21.67	-26.91	-1.24	-0.82	-0.038
Glc4_off (13)	17.88	-20.28	-1.13	-0.61	-0.034
Glc3_off (14)	7.89	-7.06	-0.89	-0.21	-0.027
Sum	**n/a**	**-16.73**	**n/a**	**-0.51**	**n/a**
Net Change	**n/a**	**-42.05**	**n/a**	**-1.27**	**n/a**
Glc6_near (15)	4.89	6.35	1.30	0.19	0.039
Glc5_near (16)	6.17	8.83	1.43	0.27	0.043
Glc4_near (17)	7.45	10.31	1.38	0.31	0.042
Glc3_near (18)	3.00	2.46	0.82	0.07	0.025
NBds_near (2)	4.39	12.88	2.94	0.39	0.089

[1)] Includes compartments NBc1 - NBc8.
[2)] Includes compartments GLc3 - GLc6 and GLc3_near - GLc6_near.
[3)] Based on the extrapolated volume of NBc1_near.
[4)] Based on the extrapolated volume $V_{<MHW}$ of GLc3*.

Table 3-2. Bathymetric and topographic change for Interval 1 at North Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
NBc8	1000	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
NBc7	5000	0.00	-0.04	0.00	-0.03	13.39	1.62	11.77	-0.02	-0.23	-0.03
NBc6	5000	-0.08	-1.09	-0.11	-0.98	13.06	1.28	11.77	-0.51	-6.60	-0.65
NBc5	5000	0.07	0.91	0.11	0.80	13.39	1.62	11.77	0.41	5.52	0.67
NBc4	5000	-0.08	-1.15	-0.16	-0.98	13.72	1.95	11.77	-0.51	-6.96	-0.99
NBc3	5000	0.04	0.65	0.12	0.53	14.39	2.61	11.77	0.27	3.91	0.71
NBc2	5000	0.25	3.95	1.01	2.93	15.83	4.06	11.77	1.51	23.91	6.13
NBc1	5000	1.04	14.39	2.14	12.25	13.83	2.06	11.77	6.31	87.22	12.97
Sum[1)]	**n/a**	**1.23**	**17.62**	**3.10**	**14.52**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
NBds	6307	5.34	29.81[2)]	8.02	21.79[2)]	n/a	1.50	n/a	25.63	n/a	38.52

[1)] Excluding NBds.
[2)] Based on the extrapolated volume of NBds_near.

Table 3-3. Bathymetric and topographic change for Interval 1 at Grayland Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
GLdn	1807	0.47	1.57	0.96	0.62	n/a	2.05	n/a	7.81	26.37	16.04
GLc6	4259	1.33	12.40	4.11	8.29	9.31	3.08	6.22	9.48	88.21	29.23
GLc5	5105	1.71	16.84	5.39	11.45	9.87	3.16	6.71	10.13	99.96	32.01
GLc4	4895	1.52	16.99	4.43	12.55	11.19	2.92	8.27	9.40	105.15	27.45
GLc3	4600	0.97	8.90	2.54	6.36	9.15	2.61	6.54	6.41	58.60	16.73
Sum[2)]	**n/a**	**5.5**	**55.1**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

[1)] Based on the extrapolated volume $V_{<MHW}$.of GLc3*.
[2)] Excluding GLdn.

Analysis

In the pre-jetty era, the shallow Grays Harbor bar (ebb-tidal delta) complicated navigation of commerce to the port of Aberdeen. To overcome this problem Congress approved the construction of the South Jetty and North Jetty at the Grays Harbor entrance (COMMITTEE ON TIDAL HYDRAULICS, 1967). The 4.2-km long South Jetty was constructed between 1898 and 1902 across the sub-tidal shoal attached to Point Chehalis. The North Jetty was constructed between 1908 and 1916 across the broad, shallow tidal flats south of Point Brown, featuring a length of 5.2 km.

Jetty construction reduced the width of the entrance channel from approximately 3.7 km to 2.5 km. As a result, the confined tidal currents scoured the entrance channel and pushed the ebb-tidal delta farther offshore. Figure 3-2 reveals erosion of the Inlet (compartment 7) by 39 Mm^3 and Inner Delta (compartment 3) by 45 Mm^3. Sand was transported offshore to accrete the Outer Delta (compartment 4) by 15 Mm^3 and onshore and northward to accrete the North Beach coast.

The North Jetty reduced southerly sand transport into the inlet channel. As a result, the North Beach sub-cell prograded rapidly along its southern end, accreting approximately 8 km^2 of land within 6 km of the Grays Harbor North Jetty, with decreasing rates of accretion over tens of kilometers toward Point Grenville (Table 3-2 and Figure 3-5). Compartment NBds (1) accreted 30 Mm^3 (V_1 and V_2) and the northern compartments of North Beach accreted 18 Mm^3.

Sand from the South Flank (compartment 9) eroded by 36 Mm^3, some of which likely moved onshore to contribute to the accretion of Grayland Plains (55 Mm^3) and some of which moved northward to accrete the Outer Delta. Along Grayland Plains, shoreline progradation rates increase from approximately 1 m/yr, (pre-jetty) to 6 - 10 m/yr (post-jetty) (WOXELL, 1998; Table 3-3 and Figure 3-5). The accretion of the beaches along Grayland Plains during Interval 1 is fairly uniform and might be related to the erosion of the seafloor along Grayland Plains (72 Mm^3, compartments 11 - 14; Figure 2-16). In subsequent intervals the accretion of Grayland Plains coast and the erosion offshore of Grayland Plains are significantly smaller. The seafloor within compartments 11 - 14 lowered by 0.03 m/yr during Interval 1.

Dredging and disposal of sediment at the Grays Harbor entrance is described in Appendix C. The first dredging of the Bar and Entrance channel occurred in 1916 and comprises 0.044 Mm^3. Between 1916 and 1942 the channels were dredged annually, except in 1918 and 1919. The total quantity removed during Interval 1 is approximately 5 Mm^3 (0.619 Mm^3/yr). The dredged material was disposed on the southwest flank of the delta off the end of the dredged channel. The small volumes of dredged and disposed sediments do not affect the sediment balance of Interval 1.

The net balance over all volume changes is 42 Mm^3 erosion, suggesting an export of sediment out of the Grays Harbor entrance sub-region. Without the tidal-datum adjustments of -0.16 m, -0.24 m, -0.36 m, -0.46 m, and -1.11 m, i.e., using MLLW as the vertical reference, the net erosion only increases by 5 Mm^3. Obviously, the volume changes due to the adjustments cancel.

We use 0.8 Mm^3/yr as an estimate of the northward sediment flux at southern Grayland Plains and 1.4 Mm^3/yr as an estimate of the northward sediment flux at northern Long Beach (see Section 3.1.2). These values are based in part on bathymetric- and topographic-change analyses (KAMINSKY et al., 2000) that precede this analysis. In this bathymetric- and topographic-change analysis, we update the bathymetric- and topographic- change volumes that were used by KAMINSKY et al. (2000) to calculate the sediment fluxes. We assume that the order of magnitude of these fluxes is correct and continue using these fluxes in this report.

If we account for the sediment influx at the southern boundary of Grayland Plains of 0.8 Mm^3/yr (26 Mm^3) the export of sediment increases from 42 Mm^3 to 68 Mm^3. It should be noted that the sediment balance is affected by uncertainties in the data and the incomplete data coverage of the Grays Harbor tidal basin, the shelf along North Beach, and the Willapa Bay entrance.

3.1.2 Columbia River Entrance and Adjacent Coasts

Era I and Era II Bathymetric Surfaces

The USC&GS H1018, H1019, H1378, and H1379 surveys are merged with the 1860s and 1870s T-sheet shorelines to form the Era I dataset (Table 2-2, Table 2-4, and Figure 2-1). The coverage of the offshore H1378 and H1379 surveys is very sparse. The distance between the tracklines is O(3000 m), and the distance between the data points along the tracklines is O(500 m). The coverage of the H1018 and H1019 surveys at the Columbia River entrance and estuary is substantially better. The distance between the tracklines is O(500 m), and the distance between the data points along the tracklines is O(100 m). Inaccuracies and large data gaps in the H1378 and H1379 surveys result in irregular bathymetric surfaces as depicted by large wiggles in the contourlines along Clatsop Plains and Long Beach. These irregularities also yield unrealistic patches of erosion and accretion in the Interval 1 bathymetric change. These patches are excluded from the volume-change analysis. The pre-jetty Era I bathymetry is presented in Figure 3-3a.

The Era II dataset consists of the USC&GS H4611, H4618, H4619, H4634, H4635 and USACE 1935 surveys and 1926 T-sheet shorelines (Table 2-2, Table 2-4, and Figure 2-2). The data-coverage of the Era II dataset is better than the Era I dataset. Tracklines of the nearshore surveys H4611, H4618, and USACE 1935 have a spacing of O(300 m), and the distance between the data points along the tracklines is O(100 m). Tracklines of the offshore surveys H4634 and H4635 have a spacing of O(500 m), and the spacing between the data points along the tracklines is O(500 m). Inaccuracies in the offshore surveys H4634 and H4635 result in an irregular Era II surface. The Era II bathymetry is presented in Figure 3-3b.

The Era I MLLW datums are adjusted by -0.02 m to NAVD88 in Astoria. The vertical reference of the Era II surveys was MLLW at Ft. Stevens. We adjust all Era II surveys by -0.16 m to NAVD88, except the H4635 survey, which is adjusted by -1.84 m (Section 2.4.3).

Both the Era I and Era II datasets are gridded at a 50-m cell size using kriging with an isotropic linear semivariogram model. To minimize errors in the volume calculations the grid is reduced to 25 m using cubic spline interpolation.

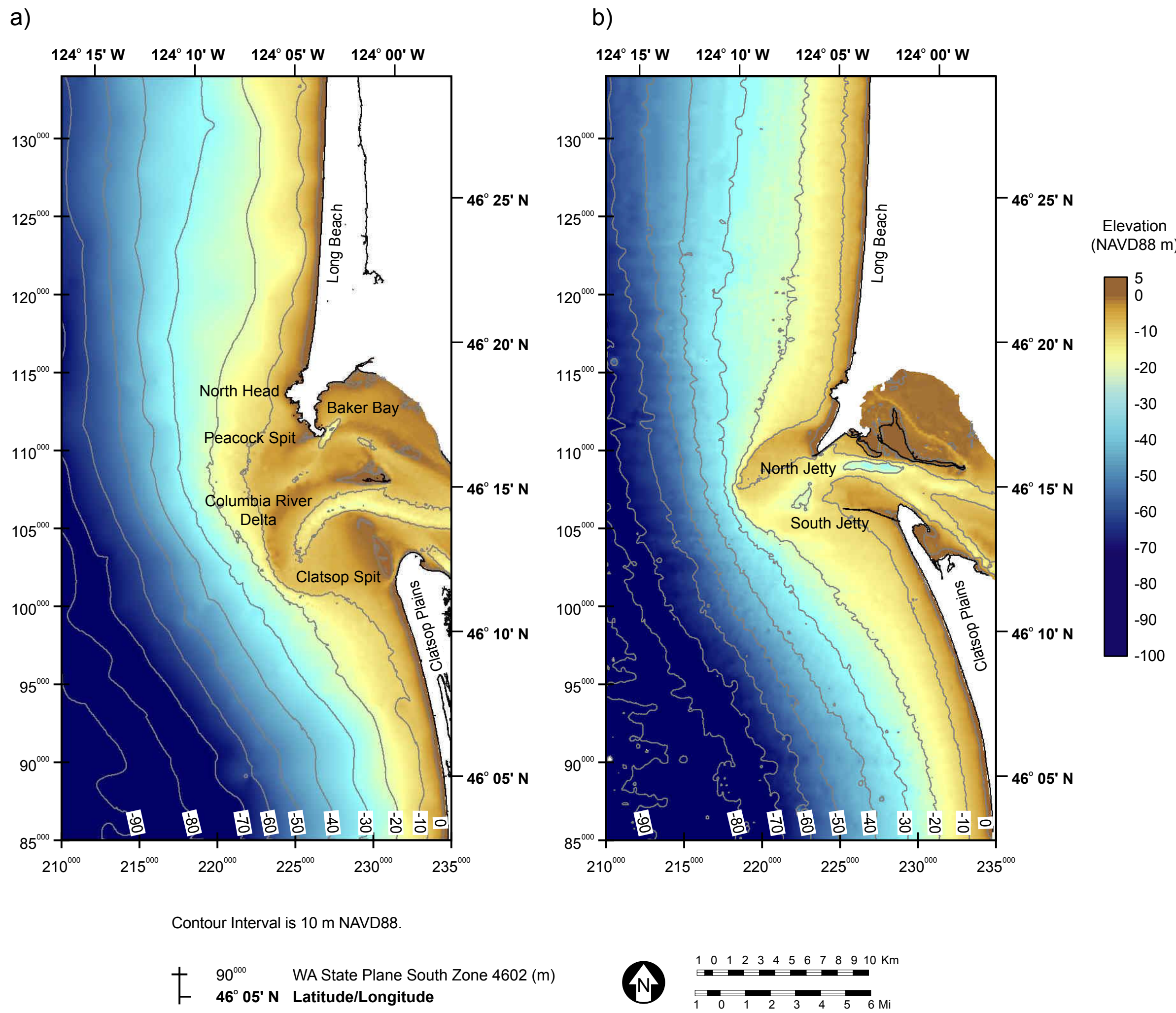


Figure 3-3. Bathymetric surface for a) Era I and b) Era II of the Columbia River entrance, Long Beach, and Clatsop Plains.

Topographic- and Bathymetric-Volume Change

Volume calculations for Interval 1 are made for the entrance area, the ebb-tidal delta and the adjacent beach-dune complexes of Long Beach and Clatsop Plains. The bathymetric changes are shown in Figure 3-4, and the results for the volume-change calculations of the entrance and adjacent coasts are presented in Table 3-4. The volume-change calculations of the Columbia River estuary east of the Inlet (6) are taken from SHERWOOD et al. (1990). In Table 3-4, ΔV represents the uncorrected volume changes. The surveys in the estuary date from 1935, 1936 and 1937, and volume changes are linearly interpolated for the period 1868 - 1926 (ΔV_{time}). The residuals of these volumes (1926 - 1935) were added to the bathymetric change volumes of the estuary for Interval 2 (Section 2.1). We assume that in the estuary about 80% of the unadjusted bathymetric-volume change ΔV comprised sand (ΔV_{sand}). The 6th column shows volume changes corrected for both time and sand ($\Delta V_{time,sand}$). The vertical change Δh, the volume-change rate, and the vertical-change rate are based on $\Delta V_{time,sand}$ and to indicate this relation the last four columns are shaded. The volumes $\Delta V_{time,sand}$ are used for the sediment budget analysis. The change rates are based on a period of 58 years (1926 - 1868 = 58 years).

Table 3-5 and Table 3-6 present the volume changes of the beach-dune complex for Long Beach and Clatsop Plains, respectively. The format of these tables is explained in Section 3.1.1. The change rates in Table 3-5 and Table 3-6 for Interval 1 are based on a period of 58 years and are presented in Figure 3-5, and Figure 3-6.

Uncertainties in bathymetric change are discussed in Section 2.6.1 and RMS and mean differences are presented in Table 2-11 and Table 2-12. The RMS and mean differences along the alongshore-averaged profiles for Interval 1 at Long Beach are 0.20 m and 0.06 m, respectively. The RMS and mean differences along the alongshore-averaged profiles at Clatsop Plains are 0.28 m and -0.10 m, respectively. These differences are mainly derived from the offshore Era I H1378 and H1379 and Era II H4634 and H4635 surveys and are not representative of the uncertainty of the nearshore bathymetric change. We use the difference between the Era I and Era II tidal-datum adjustments of 0.14 m (-0.02 m - -0.16 m) as an estimate of the uncertainty of bathymetric change of the seafloor, excluding the estuary.

Due to the large irregularities in the bathymetric surface, no bathymetric volumes are calculated along the coast of Long Beach. To estimate the volume that accreted along Long Beach, $\Delta V_{<MHW}$ (V_2 and V_3, Figure 2-21) is calculated by multiplying the area that accreted between the shorelines by an active depth of 12.19 m below MHW. This depth is based on bathymetric change below MHW along Long Beach for Interval 2. The nearshore area off the northern tip of Long Beach (LBdn) is part of the Willapa Bay ebb-tidal delta. The volume $\Delta V_{<MHW}$ of LBdn is estimated by applying an active depth of 5.1 m (derived from the USACE Annual Survey charts of the Willapa Bay entrance from 1928 to 1948). The volume below MHW ($\Delta V_{<MHW}$) of compartments CPc1, CPc2 and CPc3 (Figure 2-19) is calculated by applying a depth of 8.7 m below MHW of compartment CPc5. The depth below MHW of CPc4 of 19.59 m seems unrealistic and is not used to calculate the volume below MHW of the other compartments.

The volume ΔV of Peacock Spit (LBds) and Clatsop Spit (CPdn) in Table 3-4 only includes the volume landward of the shoreline (volume V_1 and V_2, Figure 2-21). The volume $\Delta V_{<MHW}$ of LBds and CPdn in Table 3-5 and Table 3-6 only includes volume V_2. In both cases volume V_3 is part of the morphologic change at the Columbia River ebb-tidal delta (compartments 3 and 4). In Table 3-4, Long Beach includes compartments LBc1 - LBc7 and LBdn and Clatsop Plains includes compartments CPc1 - CPc5. These compartments comprise the subaerial and subaqueous

volumes V_1, V_2, and V_3. Compartments CPc5_near (10) and CPc4_near (11) are part of the volume of Clatsop Plains in Table 3-4.

The flood-tidal delta in the Columbia River estuary consists of the compartments Baker Bay, Trestle Bay, North Channel, South Channel, and Desdemona Sands (Appendix A; SHERWOOD et al., 1990). The largest changes in the estuary following jetty construction occurred at the flood-tidal delta, therefore, we divide the estuary into two compartments, the Flood-tidal Delta and the Upper Estuary. SHERWOOD et al. calculated the area of land that was omitted from the surveyed area. We assume that the height of the omitted land was 2 m, i.e., the difference between MLLW and MHHW.

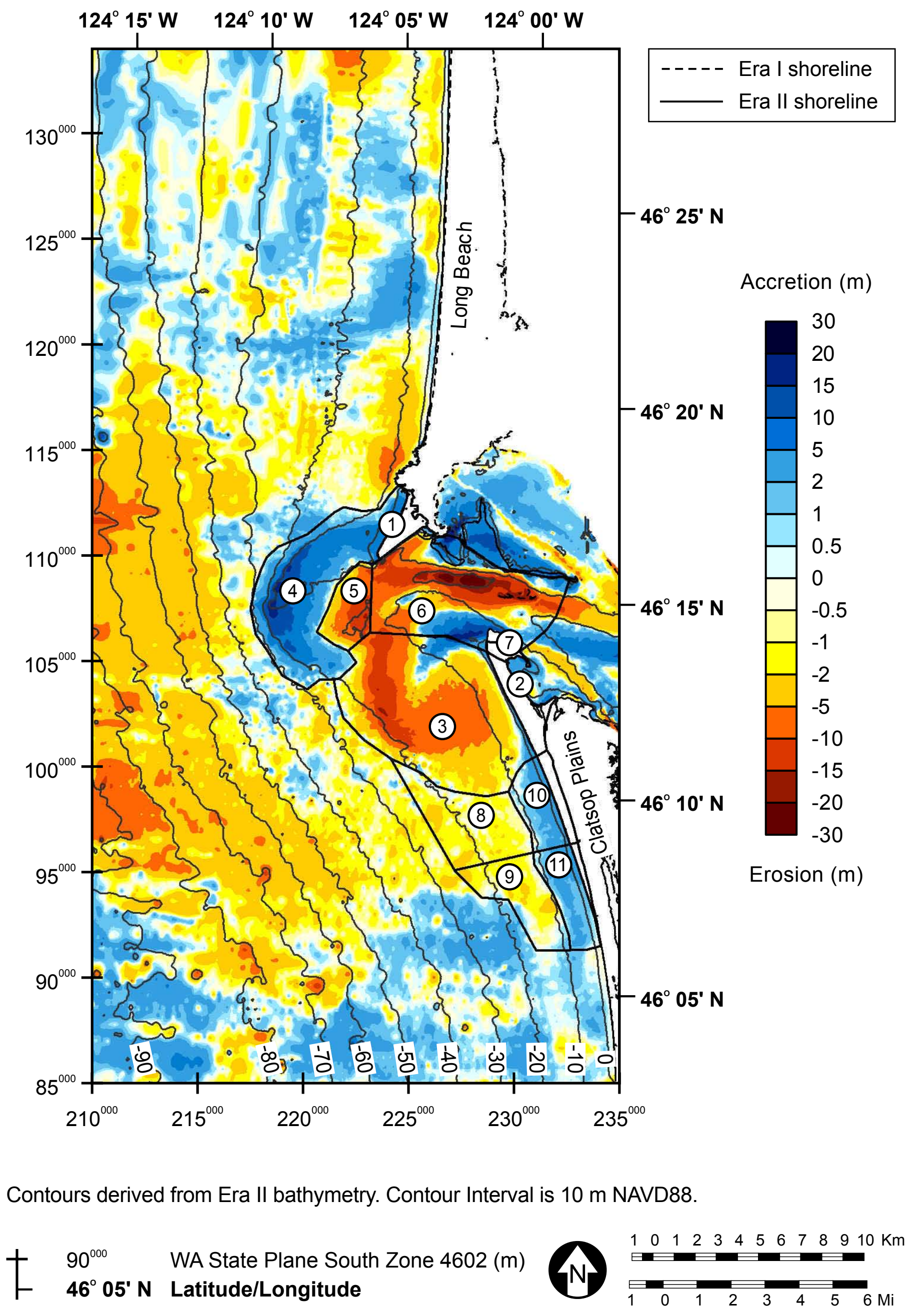


Figure 3-4. Bathymetric and topographic changes for Interval 1 at the Columbia River entrance and estuary, Long Beach, and Clatsop Plains.

Table 3-4. Bathymetric and topographic change for Interval 1 at the Columbia River entrance, estuary, Long Beach, and Clatsop Plains.

Interval 1 ~58 yr	**Area (km^2)**	**ΔV (Mm^3)**	**ΔV_{time} (Mm3)**	**ΔV_{sand} (Mm^3)**	**$\Delta V_{time,sand}$ (Mm^3)**	**Δh (m)**	**Rate $\Delta V_{time,sand}$ (Mm^3/yr)**	**Rate Δh (m/yr)**
Peacock Spit (1)	2.35	21.68	21.68	21.68	21.68	n/a	0.37	n/a
Clatsop Spit (2)	4.34	25.99	25.99	25.99	25.99	n/a	0.45	n/a
South Flank (3)	49.64	-217.48	-217.48	-217.48	-217.48	-4.38	-3.75	-0.076
Outer Delta (4)	31.31	171.53	171.53	171.53	171.53	5.48	2.96	0.094
Inner Delta (5)	6.85	-47.49	-47.49	-47.49	-47.49	-6.94	-0.82	-0.120
Inlet (6)	35.40	-134.47	-116.41	-134.47	-116.41	-3.29	-2.01	-0.057
Clatsop Spit Inlet (7)	1.06	5.90	5.18	5.90	5.18	n/a	0.09	n/a
Subtotal	**n/a**	**-174.34**	**-157.01**	**-174.34**	**-157.01**	**n/a**	-2.71	**n/a**
Long Beach[1)]	1.74	26.56	26.56	26.56	26.56	n/a	0.46	n/a
Subtotal	**n/a**	**-147.78**	**-130.45**	**-147.78**	**-130.45**	**n/a**	-2.25	**n/a**
Clatsop Plains[2)]	2.74	48.04	48.04	48.04	48.04	n/a	0.83	n/a
CPc5_off (8)	11.41	-10.44	-10.44	-10.44	-10.44	-0.92	-0.18	-0.016
CPc4_off (9)	15.99	-19.30	-19.30	-19.30	-19.30	-1.21	-0.33	-0.021
Sum	**n/a**	**18.31**	**18.31**	**18.31**	**18.31**	**n/a**	0.32	**n/a**
Subtotal	**n/a**	**-129.48**	**-112.14**	**-129.48**	**-112.14**	**n/a**	-1.93	**n/a**
Flood tidal-delta[3)]	202.15	132.47	114.68	105.98	91.74	0.45	1.58	0.008
Subtotal	**n/a**	**2.99**	**2.53**	**-23.50**	**-20.40**	**n/a**	-0.35	**n/a**
					0.00			
Upper Estuary[3)]	493.10	123.55	106.95	98.84	85.56	0.17	1.48	0.003
Omission	9.57[3)]	-19.14	-16.57	-15.31	-13.26	-1.39	-0.23	-0.024
Sum	**n/a**	**104.41**	**90.38**	**83.53**	**72.31**	**n/a**	1.25	**n/a**
Subtotal Estuary	**n/a**	**236.88**	**205.06**	**189.50**	**164.05**	**n/a**	2.83	**n/a**
Net Change	**n/a**	**107.40**	**92.92**	**60.03**	**51.91**	**n/a**	0.89	**n/a**
CPc5_near (10)	6.89	14.68	14.68	14.68	14.68	2.13	0.25	0.037
CPc4_near (11)	7.76	14.50	14.50	14.50	14.50	1.87	0.25	0.032

1) Includes compartments LBc1 - LBc7, LBdn.
2) Includes compartments CPc1 - CPc5, CPc5_near, and CPc4_near.
3) From SHERWOOD et al. (1990).

Table 3-5. Bathymetric and topographic change for Interval 1 at Long Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
LBdn	3320	0.18	1.27	0.35	0.92	7.08	1.95	5.13	0.93	6.58	1.81
LBc7	5589	-0.44	-5.73	-0.41	-5.32	13.14	0.95	12.19	-1.35	-17.68	-1.28
LBc6	4261	0.17	2.37	0.24	2.13	13.59	1.40	12.19	0.71	9.59	0.99
LBc5	4980	0.50	8.09	1.97	6.12	16.12	3.93	12.19	1.74	28.01	6.83
LBc4	5020	0.36	5.69	1.34	4.35	15.94	3.75	12.19	1.23	19.54	4.60
LBc3	5000	0.24	3.85	0.98	2.87	16.34	4.15	12.19	0.81	13.27	3.37
LBc2	5000	0.27	4.25	0.93	3.32	15.62	3.43	12.19	0.94	14.66	3.22
LBc1	6300	0.46	6.78	1.23	5.55	14.88	2.69	12.19	1.25	18.55	3.36
Sum	**n/a**	**1.74**	**26.56**	**6.63**	**19.93**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
LBds[1)]	3403	2.48	21.68	7.75	13.93	n/a	3.13	n/a	12.56	n/a	39.27

1) Excluding LBds.

Table 3-6. Bathymetric and topographic change for Interval 1 at Clatsop Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
CPdn	4471	4.33	25.99	9.78	16.21	n/a	2.26	n/a	16.70	n/a	37.71
CPc5	4318	2.19	30.30	11.16	19.14	13.82	5.09	8.73	8.76	120.99	44.57
CPc4	4388	0.79	20.29	4.82	15.47	25.69	6.10	19.59	3.10	79.72	18.93
CPc3	5140	0.05	0.77	0.34	0.43	15.52	6.80	8.73	0.17	2.59	1.13
CPc2	4788	-0.08	-1.21	-0.53	-0.68	15.57	6.84	8.73	-0.28	-4.37	-1.92
CPc1	4812	-0.21	-2.11	-0.24	-1.87	9.85	1.12	8.73	-0.77	-7.56	-0.86
Sum[1)]	**n/a**	**2.74**	**48.04**	**15.54**	**32.50**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

1) Excluding CPdn.

Analysis

In the pre-jetty era, the Columbia River entrance was characterized by a broad and shallow ebb-tidal delta complex with one to three dynamic inlet channels, flanked by shallow shoals of Peacock Spit and Clatsop Spit. The dynamic pre-jetty entrance was a hazard to in- and outgoing commerce. To improve navigation, Congress approved the construction of the South Jetty at the Columbia River entrance (BAGNALL, 1916; MOORE AND HICKSON, 1939). The South Jetty was constructed across Clatsop Shoal between 1885 and 1895 featuring a length of approximately 6.8 km. Initially, the jetty confined the tidal currents, deepening the entrance channel. The jetty deteriorated under influence of the waves and currents, and the entrance channel shoaled and moved to the northwest. Further improvement was authorized by the River and Harbor Act of 1905. The act provided for a 4-km extension of the South Jetty, construction of the North Jetty, and bar dredging. The South Jetty was extended between 1903 and 1913. The North Jetty was built across the large shoal of Peacock Spit between 1913 and 1917, featuring a length of 3.8 km.

Jetty construction reduced the width of the river mouth from approximately 9.6 to 3.2 km. As a result, the confined tidal currents eroded the entrance channel 159 Mm^3 (compartments 5, 6, and

7) during Interval 1. Part of this sand was transported seaward and deposited in a new ebb-tidal delta offshore (172 Mm^3, compartment 4). The South Flank (3) south of the South Jetty, which was no longer affected by the ebb-jet, eroded 217 Mm^3. Waves and currents transported part of this sand to the northwest to accrete in the outer lobe of the ebb-tidal delta and part of the sand was transported onshore to accrete Clatsop Spit (compartment 2) by 26 Mm^3 and Clatsop Plains by 48 Mm^3. Clatsop Spit accreted over 7 km^2 of land within 5 km of the South Jetty. Along Clatsop Plains, shoreline progradation rates increase from 0.5 - 1 m/yr prior to jetty construction (WOXELL, 1998) to up to 17 m/yr following jetty construction (Figure 3-6). Offshore Clatsop Plains (CPc5_off (8) and CPc4_off (9)) eroded by a total of 30 Mm^3, possibly contributing to the accretion of Clatsop Plains. Peacock Spit (compartment 1), a pocket beach between the Columbia River North Jetty and North Head accreted 22 Mm^3 (nearly 4 km^2 of land). The coast of Long Beach north of North Head accreted little during this interval (27 Mm^3). Sand from the entrance may have moved into the Columbia River estuary, contributing to the accretion of the Flood-tidal Delta by 92 Mm^3. The Upper Estuary, including Omission, accreted 72 Mm^3.

The amount of sand dredged out of the estuary and disposed on land between Era I and Era III was estimated to be 50 - 70 Mm^3 (SHERWOOD et al., 1990). However, it is not known how much sand was dredged during Interval 1 or Interval 2. Between the initial project authorization in 1885 and 1945 about 6.3 Mm^3 of sand was dredged from the Columbia River entrance channel. We estimate that about 70% (4.4 Mm^3) was placed in the vicinity of present disposal site A and the remaining 30% (1.9 Mm^3) was placed in estuarine disposal sites (see Appendix D). These numbers are small compared to the morphologic changes, and we neglect the effects of the dredging and disposal on the sediment budget.

All bathymetric changes are much larger than the uncertainties, and therefore, the order of magnitude of these changes is correct. The net change for the Delta, Inner Delta, Inlet, Clatsop Spit Inlet and the adjacent coasts of Long Beach and Clatsop Plains combined is 112 Mm^3 erosion. The net change for the Flood-tidal Delta and Upper Estuary, including Omission, is 164 Mm^3 accretion. The net change over all topographic- and bathymetric-change volumes is 52 Mm^3 accretion. Estimates of the northward sediment flux at Leadbetter Point of 81 Mm^3 (1.4 Mm^3/yr; KAMINSKY et al., 2000) and the Columbia River sand supply to the estuary of 249 Mm^3 (4.3 Mm^3/yr, Appendix B) amount to a net influx of 168 Mm^3. This net influx accounts for the net accretion of 52 Mm^3 and increases the export of sediment out of the Columbia River entrance sub-region by 116 Mm^3. The balance for the change volumes in the third column in Table 3-4 is 107 Mm^3 accretion, excluding fluxes, and 61 Mm^3 "net erosion" (i.e., an increased export), including fluxes. If we neglect the vertical datum adjustments of -0.02 m and -0.16 m of all ocean surveys, i.e., compare the surveys to MLLW, the net erosion from the sediment balance decreases by approximately 30 Mm^3.

3.1.3 Regional Barrier-Change Rates

Regional ΔV-, $\Delta V_{>MHW}$-, and Area-change rates of Interval 1 are presented in Figure 3-5 and Figure 3-6. The volume- and area-change rates for North Beach, Grayland Plains, Long Beach, and Clatsop Plains are presented in Table 3-2, Table 3-3, Table 3-5, and Table 3-6 as well. All change rates are relative to the compartment length. Volumes ΔV of the compartments adjacent to the Grays Harbor and Columbia River ebb-tidal deltas are not calculated - the nearshore changes are part of the ebb-tidal deltas - and are not presented in the figures. The duration of Interval 1 at North Beach and Grayland Plains is approximately 33 years and the duration at Long Beach and Clatsop Plains is approximately 58 years. If we assume that most changes occurred as a result of jetty construction, and reference our calculations to 1885, the change rates will be higher.

Following construction of the Grays Harbor South Jetty (1898-1902) and North Jetty (1908-1916) the southern part of North Beach (6 - 26 m/yr) and the entire coast of Grayland Plains (6 -10 m/yr) accreted rapidly. Most likely sand from the Grays Harbor ebb-tidal delta caused the accretion of southern North Beach and Grayland Plains. The results show consistent erosion offshore Grayland Plains, and this sand may have contributed to the accretion of Grayland Plains coast. Construction of the South Jetty (1885-1895) and the North Jetty (1913-1917) at the Columbia River entrance resulted in similar behaviour. Sand from the ebb-tidal delta moved onshore, resulting in shoreline advance along Clatsop Spit (17 m/yr), CPc5 (8 m/yr), CPc4 (3 m/yr) and Peacock Spit (13 m/yr), whereas the remainder of Clatsop Plains (CPc3 - CPc1, -1 - 0 m/yr) and Long Beach (LBc1 - LBc7 and LBdn, -1 - 2 m/yr) hardly accreted. The area-change rates in Figure 3-6 show similar trends as the volume-change rates. In Figure 3-6 it is evident that the accretion rates adjacent to the jetties following jetty construction, except at GLdn, are largest.

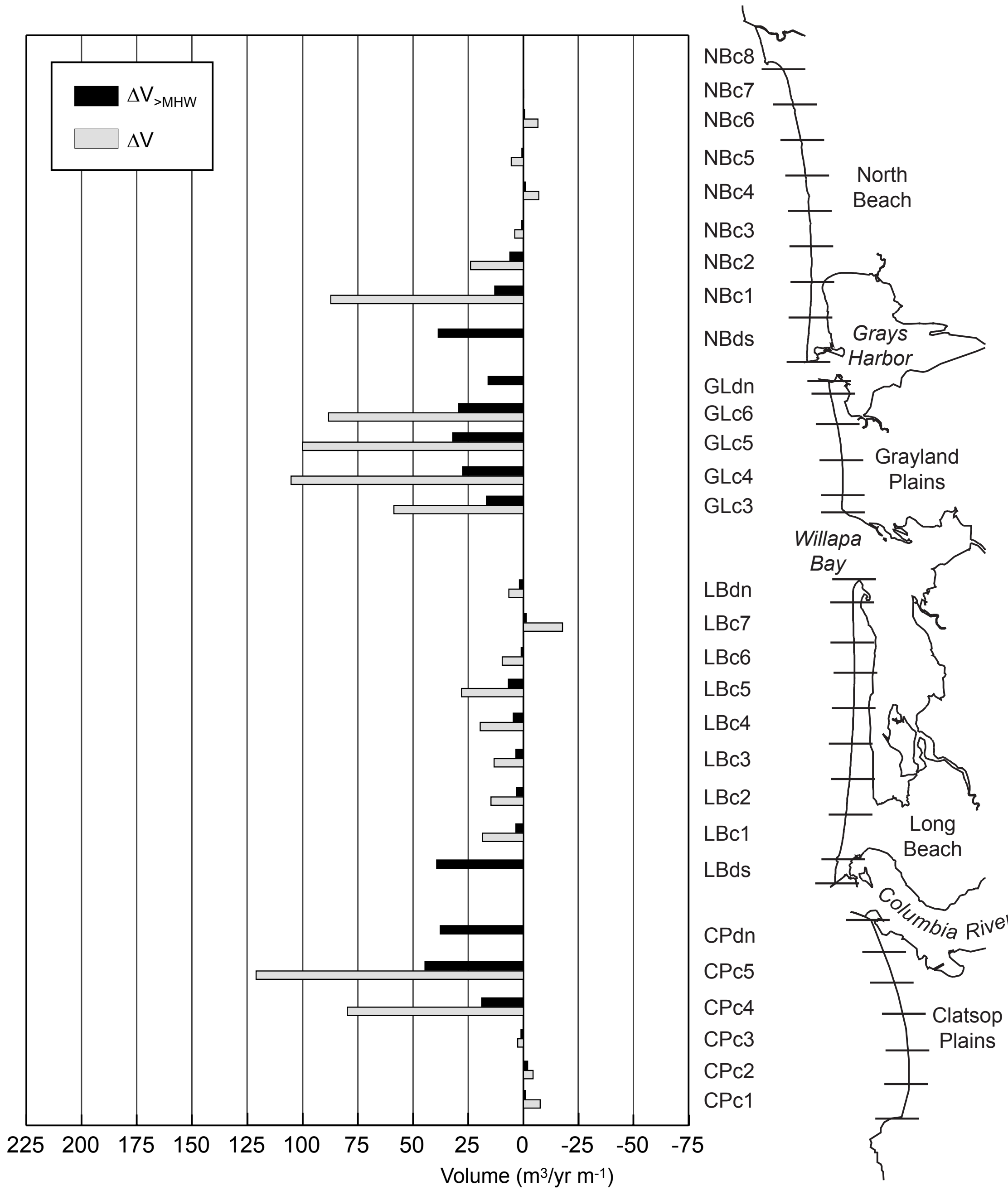


Figure 3-5. Bathymetric and topographic volume-change rates per compartment normalized by compartment length for Interval 1 along the CRLC. The duration of Interval 1 at North Beach and Grayland Plains is approximately 33 years, and the duration of Interval 1 at Long Beach and Clatsop Plains is approximately 58 years. ΔV represents the total volume change of the barrier compartments and $\Delta V_{>MHW}$ represents the volume change above MHW.

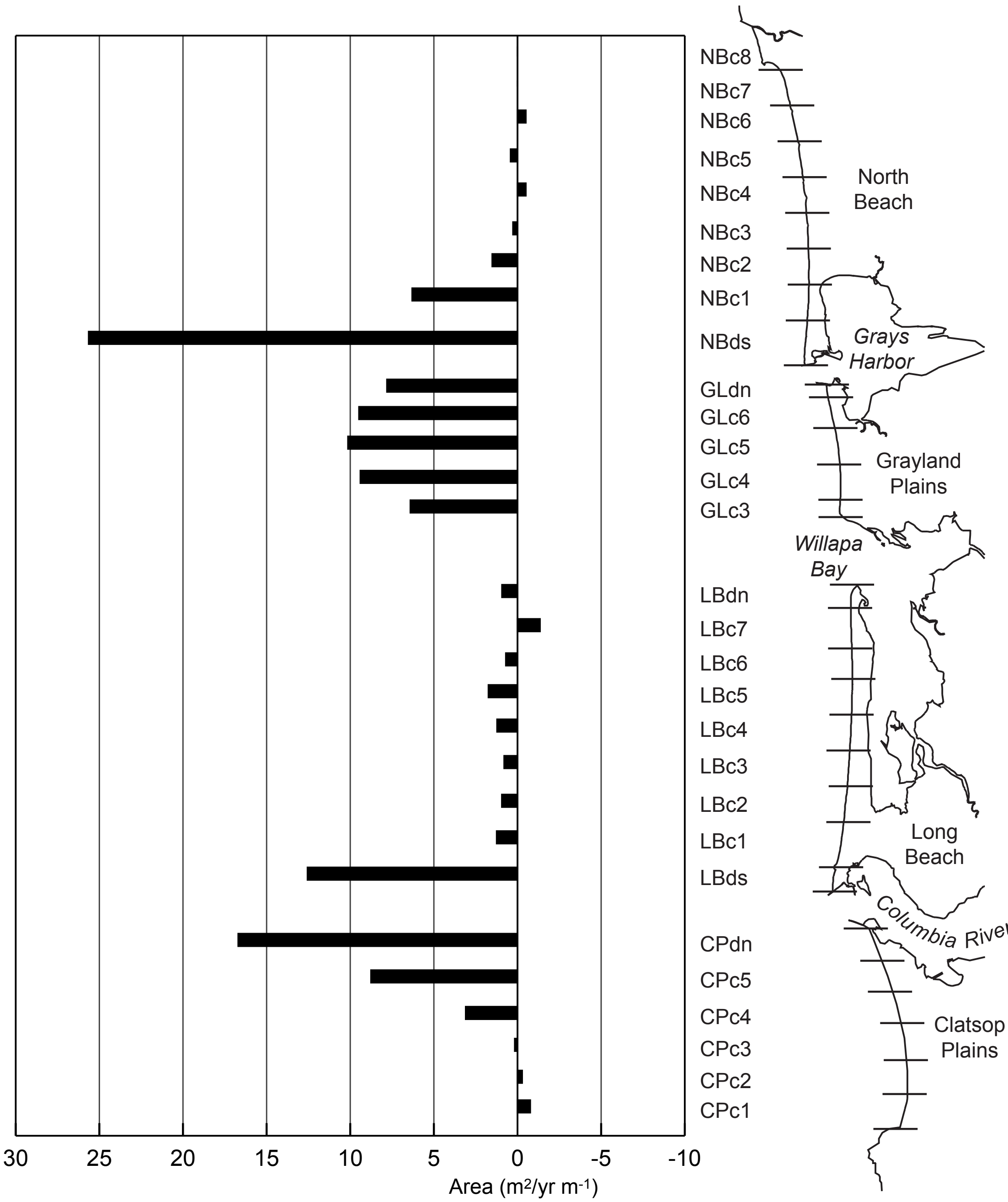


Figure 3-6. Area-change rates per compartment normalized by compartment length for Interval 1 along the CRLC. The duration of Interval 1 for North Beach and Grayland Plains is approximately 33 years, and the duration of Interval 1 for Long Beach and Clatsop Plains is approximately 58 years.

3.2 Interval 2 (1920s - 1930s to 1940s - 1950s)

3.2.1 Grays Harbor Entrance and Adjacent Coasts

Era III Bathymetric Surface

The Era III bathymetric surface consists of the 1955 USC&GS H8252 (surrounding the Grays Harbor ebb-tidal delta), the USACE 1954 Annual Survey (entrance and delta) and the 1950 and 1951 T-sheet shorelines (Table 2-1, Table 2-3, and Figure 2-3). The USACE survey is digitized from the 1954 Annual Survey chart. The USACE survey extends to 20-m water depth. The spacing of the data points along the tracklines of the USC&GS survey is O(200 m) and the distance between the tracklines is O(300 m). Both the distance between and the spacing along the tracklines of the USACE survey are O(300 m).

Vertical datum adjustments are discussed in Section 2.4.3. We do not adjust the vertical MLLW datums of the USACE and USC&GS surveys to NAVD88 at Westport. To improve the fit with the H8252 survey, the depth soundings of the USACE 1954 survey are increased by 5%.

To minimize irregularities in the bathymetric surface, nearshore USC&GS H8252 tracklines that overlapped the USACE 1954 tracklines are removed. The Era III data are gridded at a 50-m cell size using kriging with an isotropic linear semivariogram model. To minimize errors in the volume calculations the grid size is reduced to 25 m using cubic spline interpolation. The Era III surface is presented in Figure 3-7.

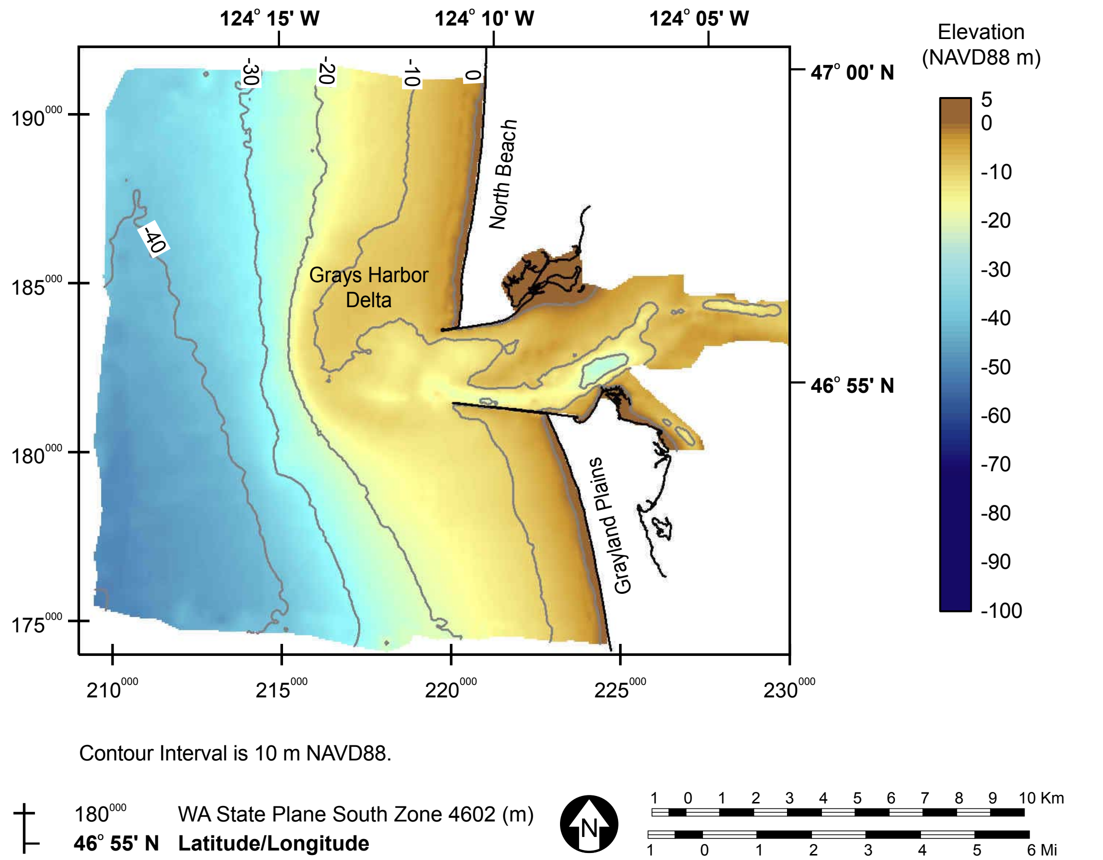


Figure 3-7. Era III bathymetric surface of the Grays Harbor entrance, North Beach, and Grayland Plains.

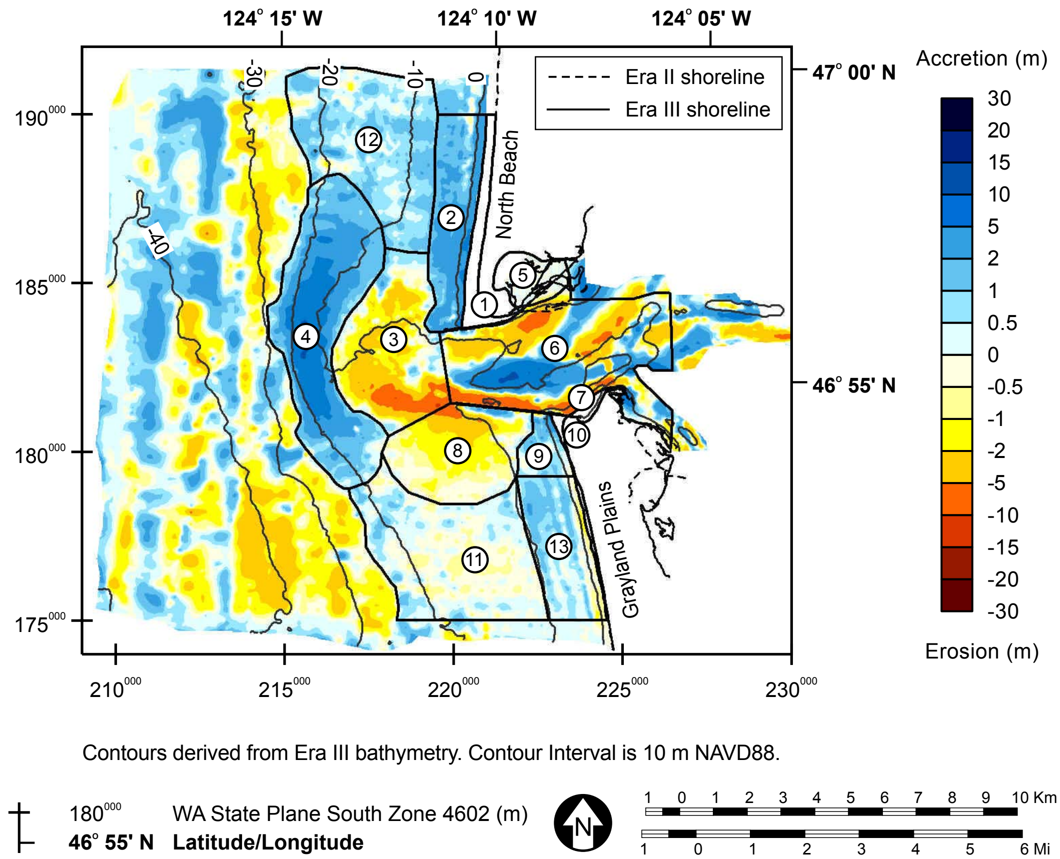


Figure 3-8. Bathymetric and topographic change for Interval 2 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Topographic- and Bathymetric-Volume Change

The bathymetric and topographic volume changes are presented in Figure 3-8, Table 3-7, Table 3-8, and Table 3-9. The format of these tables is explained in Section 3.1.1. The change rates in Table 3-7, Table 3-8, and Table 3-9 are calculated for a period of 28 years (1954 - 1926 = 28 years). The ΔV-, $\Delta V_{>MHW}$-, and Area-change rates in Table 3-8 and Table 3-9 are visualized in Figure 3-11 and Figure 3-12.

Due to the limited data coverage in deeper water, we can not calculate RMS and mean differences along the alongshore-averaged profiles at Grayland Plains (Sections 2.4.2 and 2.6.1). The RMS and mean differences calculated along cross-shore Transects A and B for Interval 2 (Table 2-11) are biased by irregularities in the USC&GS H4728 survey, and they are not a good representation of the uncertainties in the volume changes. Similar to Interval 1, we use the difference between the Era II and Era III tidal-datum adjustments as an indication of the uncertainty. The uncertainty along North Beach is 0.36 m (0 m - -0.36 m), along Grayland Plains 0.16 m (0 m - -0.16 m), and at the inner delta and inlet 1.11 m (0 m - -1.11 m).

NBds (1) and GLdn (10) in Table 3-7 only comprise volume V_1 and V_2 (Figure 2-21). The volume below MHW ($\Delta V_{<MHW}$) of NBds (Table 3-8) and GLdn (Table 3-9) only comprise volume V_2. North Beach and Grayland Plains in Table 3-7 comprise compartments NBc1 - NBc8 and GLc3 - GLc6, respectively. In Table 3-7, compartment GLc6_near (13) is part of the volume of Clatsop Plains.

There is no bathymetric coverage north of NBds and south of GLc6. The volume below MHW (representing V_2 and V_3, Figure 2-21) of compartments NBc1 - NBc8 are calculated applying an active depth of 11.77 m below MHW, which is calculated for Interval 4. The volume below MHW of compartments GLc3 - GLc5 are calculated using $h_{<MHW}$ calculated in Interval 1.

We assume that Oyhut (5) accreted to MHW. The volume of compartment 5 is calculated by subtracting the 2-m plane from the MHW plane. Compartment Pt. Chehalis (7) is calculated by subtracting the Era III surface from the 3-m plane.

Table 3-7. Bathymetric and topographic change for Interval 2 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Interval 2 ~28 yr	Area (km^2)	ΔV (Mm^3)	Δh (m)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
NBds (1)	2.50	11.51	n/a	0.41	n/a
NBds_near (2)	7.75	18.98	2.45	0.68	0.087
Inner Delta (3)	12.59	-24.41	-1.94	-0.87	-0.069
Outer Delta (4)	18.48	59.72	3.23	2.13	0.115
Oyhut (5)	2.55	2.54	1.00	0.09	0.036
Inlet (6)	19.56	-3.19	-0.16	-0.11	-0.006
Pt. Chehalis (7)	-0.37	-1.82	4.94	-0.07	0.176
South Flank (8)	9.71	-11.17	-1.15	-0.40	-0.041
GLdn_near (9)	2.11	1.85	0.88	0.07	0.031
GLdn (10)	0.19	0.83	n/a	0.03	n/a
Sum	**n/a**	**54.83**	**n/a**	**1.96**	**n/a**
North Beach[1)]	5.21	73.62	n/a	2.63	n/a
Subtotal	**n/a**	**128.45**	**n/a**	**4.59**	**n/a**
Grayland Plains[2)]	0.31	9.07	n/a	0.32	n/a
Subtotal	**n/a**	**137.52**	**n/a**	**4.91**	**n/a**
Glc6_off (11)	17.55	1.16	0.07	0.04	0.002
NBds_off (12)	16.64	12.21	0.73	0.44	0.026
Sum	**n/a**	**13.37**	**n/a**	**0.48**	**n/a**
Net Change	**n/a**	**150.90**	**n/a**	**5.39**	**n/a**
GLc6_near (13)	7.40	4.01	0.54	0.14	0.019

[1)] Includes compartments NBc1 - NBc8.
[2)] Includes compartments GLc3 - GLc6 and GLc6_near.

Table 3-8. Bathymetric and topographic change for Interval 2 at North Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
NBc8	1000	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
NBc7	5000	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
NBc6	5000	0.26	3.39	0.35	3.04	13.14	1.36	11.77	1.84	24.20	2.51
NBc5	5000	0.41	5.46	0.68	4.78	13.45	1.67	11.77	2.90	39.03	4.86
NBc4	5000	0.59	7.72	0.73	6.99	13.01	1.23	11.77	4.24	55.14	5.23
NBc3	5000	0.99	13.50	1.90	11.61	13.70	1.92	11.77	7.04	96.46	13.55
NBc2	5000	1.44	21.20	4.27	16.92	14.75	2.97	11.77	10.27	151.40	30.51
NBc1	5000	1.52	22.35	4.40	17.95	14.66	2.89	11.77	10.89	159.65	31.45
Sum[1)]	**n/a**	**5.21**	**73.62**	**12.34**	**61.29**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
NBds	6307	2.50	11.51	5.87	5.64	4.60	2.34	n/a	14.18	n/a	33.23

1) Excluding NBds.

Table 3-9. Bathymetric and topographic change for Interval 2 at Grayland Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
GLdn	1807	0.19	0.83	0.39	0.44	4.33	2.05	n/a	3.78	n/a	7.76
GLc6	4259	-0.35	2.80	-1.07	3.87	-8.09	3.08	-11.17	-2.90	23.47	-8.95
GLc5	5105	-0.03	-0.33	-0.10	-0.22	9.87	3.16	6.71	-0.23	-2.28	-0.73
GLc4	4895	0.14	1.54	0.40	1.14	11.19	2.92	8.27	1.00	11.23	2.93
GLc3	3715	0.55	5.06	1.44	3.61	9.15	2.61	6.54	5.31	48.60	13.87
Sum[1)]	**n/a**	**0.31**	**9.07**	**0.67**	**8.39**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

[1)] Excluding GLdn.

Analysis

Compared to Interval 1, the erosion offshore Grayland Plains and the accretion of the beach-dune complex of Grayland Plains decrease during Interval 2, whereas the accretion of the outer ebb-tidal delta and the beach-dune complex of North Beach increases.

Most likely, sand that eroded (29 Mm^3) from the Inlet (6), Inner Delta (3), and Pt. Chehalis (7) combined moved offshore to contribute to the accretion of the Outer Delta (compartment 4) by 60 Mm^3. The erosion of the South Flank (11 Mm^3) may have contributed to the accretion of the Outer Delta and the beach-dune complex of Grayland Plains.

In comparison to Interval 1, the beaches of Grayland Plains did not accrete significantly (9 Mm^3, GLdn not included) (see Table 3-9, Figure 3-5, and Figure 3-11). Compared to Interval 1, the accretion along North Beach increases in Interval 2. North Beach accreted with shoreline change rates between 2 m/yr and 14 m/yr (Table 3-8, KAMINSKY et al., 1999a), amounting to a total volume change of 74 Mm^3 (NBds not included).

Dredging and disposal of sediments at Grays Harbor is discussed in Appendix C. The material dredged from the Bar and Entrance channels between 1926 and 1942 is approximately 10 Mm^3. This material was disposed on the southwest flank of the Grays Harbor ebb-tidal delta. Due to the scouring of the jetties no dredging was required in the Bar and Entrance channels between 1942 and 1988.

The erosion of the Inlet, Inner Delta, Pt. Chehalis and the South Flank combined can not balance the accretion of the Outer Delta, Oyhut and the beach-dune complexes of North Beach and Grayland Plains combined. The net change over the study area is 151 Mm^3 more accretion than can be accounted for. The sediment flux at the southern boundary of Grayland Plains of 0.8 Mm^3/yr (KAMINSKY et al., 2000) might account for 22 Mm^3 of the observed accretion. However, the budget remains unbalanced with a net accretion of 129 Mm^3. The lack of accurate estimates of sediment fluxes at the southern boundary, the incomplete coverage of the shoreface along North Beach and Grayland Plains and the Grays Harbor estuary might contribute to this net accretion. In addition, these results might be biased by the datum corrections. If we do not adjust the Era II surveys by -0.16 m, -0.36 m, and -1.11 m, the net accretion decreases by approximately 60 Mm^3.

3.2.2 Columbia River Entrance and Adjacent Coasts

Era III Bathymetric Surface

The Era III bathymetric surface presented in Figure 3-9 consists of the USC&GS H8416, H8417, H8421, H8423 surveys and the 1948, 1950, 1951, 1955, and 1957 T-Sheet and aerial photograph shorelines (Table 2-2, Table 2-4, and Figure 2-3). The spacing between the tracklines varies between O(50 m) and O(500 m), and the spacing between the depth soundings along the tracklines varies between O(50 m) and O(150 m). Data from the Era III survey cover shallow water depths up to 3 m and reveal shore-parallel bar features. The Era II survey covers part of the surf zone as well, however, no significant bar features can be seen. As discussed in Section 2.4.3 we adjust the USC&GS Era III surveys by -0.16 m and by an extra -0.29 m to minimize offsets with the Era IV surveys.

The datasets are gridded at a 50-m cell size using kriging with an isotropic linear semivariogram model. To minimize errors in the volume calculations the grid size is reduced to 25 m using cubic spline interpolation. The Era III surface is presented in Figure 3-9.

Topographic- and Bathymetric-Volume Change

Bathymetric and topographic change at the Columbia River entrance and adjacent coasts for Interval 2 are presented in Figure 3-10, Table 3-10, Table 3-11, and Table 3-12. The format of the tables is explained in Section 3.1.1. The volume-change calculations of the Columbia River estuary east of the Inlet (compartment 4) between 1935 and 1958 are from SHERWOOD et al. (1990). These volumes (ΔV) are adjusted by adding the residuals calculated for Interval 1 (ΔV_{time}). The change rates in the tables are based on a period of 32 years (1958 - 1926 = 32 years). The change rates in Table 3-11 and Table 3-12 are relative to the compartment length and are presented in Figure 3-11 and Figure 3-12.

The RMS and mean differences are presented in Table 2-11 and Table 2-12 in Section 2.6.1. The RMS and mean differences along the alongshore-averaged profiles for Interval 2 at Long Beach are 0.41 m and 0.20 m, respectively. The RMS and mean differences along the alongshore-averaged profiles at Clatsop Plains are 0.28 m and 0.20 m, respectively. These differences are mainly calculated for the offshore USC&GS H4634 and H4635 surveys and are not representative of the nearshore volume changes. We use the adjustment of -0.29 m of the Era III surveys and the adjustment of -1.68 m of the Era II H4635 survey as an indication of the uncertainty.

At Clatsop Plains, the Era III bathymetry and shoreline does not extend farther south than the southern boundary of compartment CPc3 (or compartment 21 in Figure 3-10). The nearshore and topographic volumes (volumes V_1, V_2, and V_3 in Figure 2-21) of CPc1 and CPc2 are estimated based on a proportional relation between CPc3, CPc2, and CPc1 for the volume change of Clatsop Plains between the 1920s and 1990s. We assume that the volume change between the 1920s and 1990s is proportional to the volume change of Interval 2. The volume change between the 1920s and 1990s is estimated by multiplying the horizontal area by the average height landward of the dune crest (Appendix E).

At Long Beach no bathymetric change coverage of Interval 2 is available north of compartment LBc2 (or compartment 17). The active depth of 12.19 m below MHW calculated at LBc2 is used to estimate the volume change below MHW (V_2 and V_3, Figure 2-21) of compartments LBc3 - LBc7. The active depth below MHW of LBdn is estimated to be 5.1 m (Section 3.1.2). Volumes ΔV of Peacock Spit (LBds) in Table 3-10 and Table 3-11 and Clatsop Spit (CPds) in Table 3-10 and Table 3-12 only include volumes V_1 and V_2. In contrast to Interval 1, the (nearshore) volume changes at Clatsop Spit in Interval 2 (and Interval 3) were less affected by changes at the Columbia River entrance and delta. Therefore, Clatsop Spit is grouped with the compartments along Clatsop Plains coast in Table 3-10.

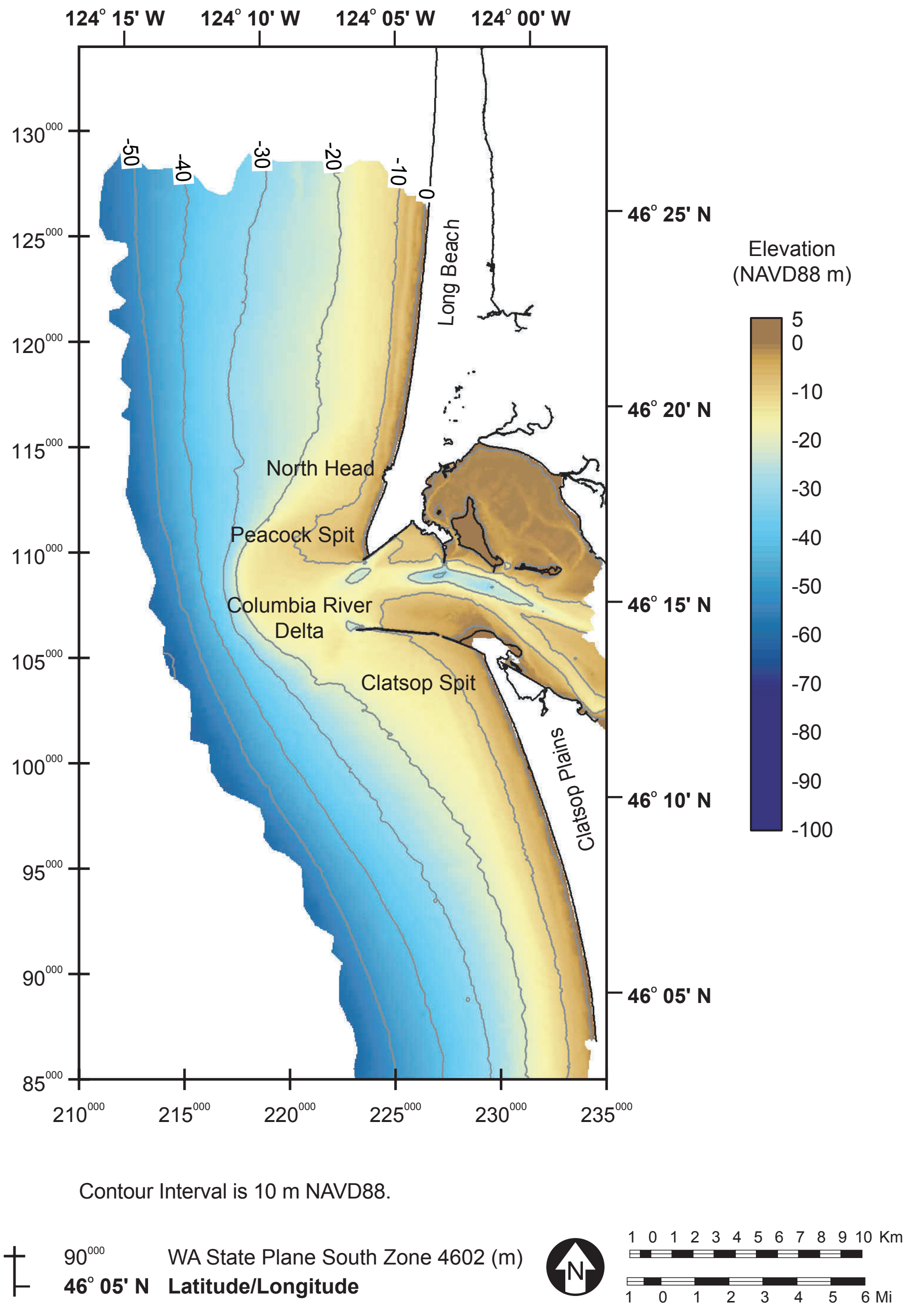


Figure 3-9. Era III bathymetric surface of the Columbia River entrance, Long Beach, and Clatsop Plains.

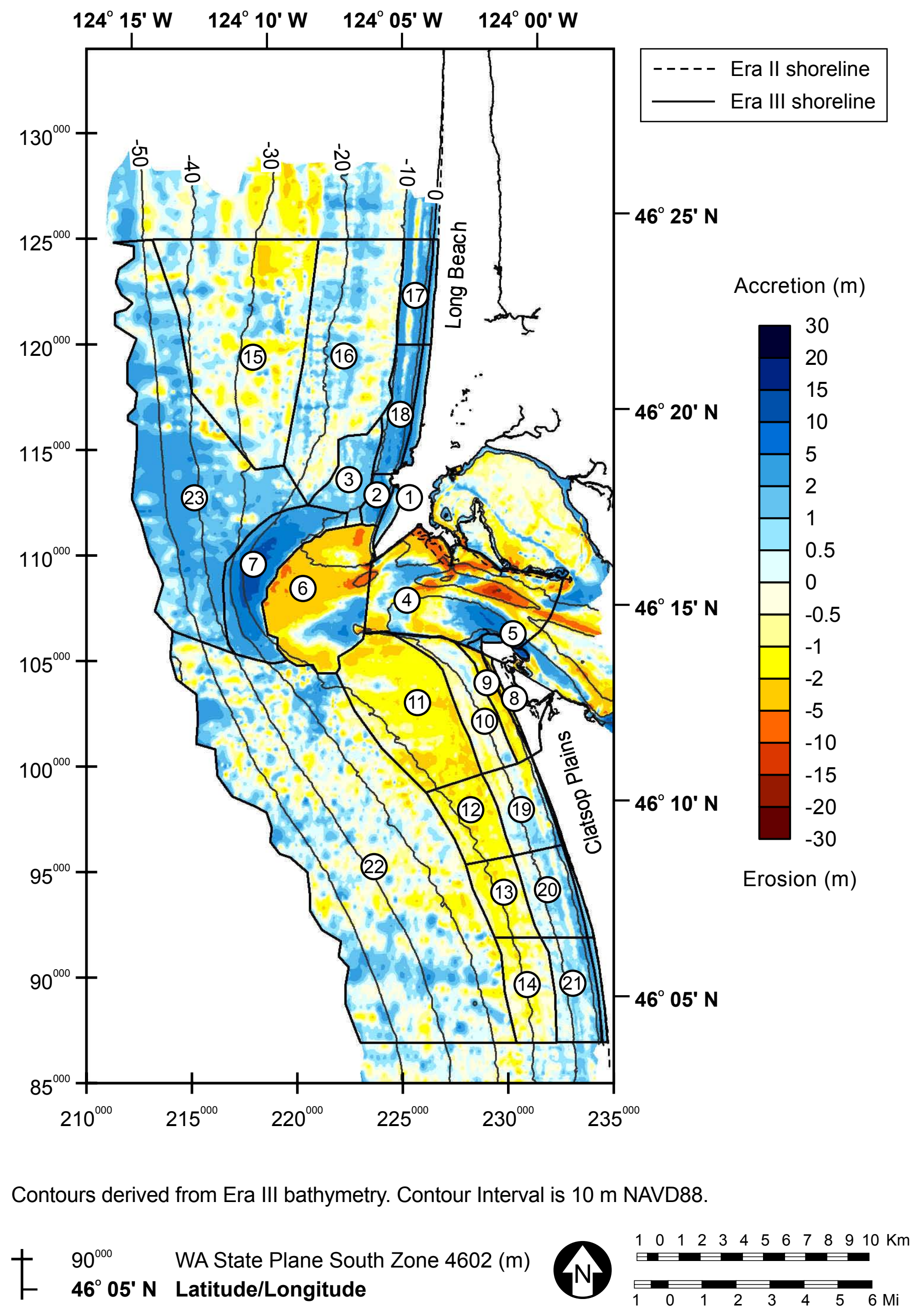


Figure 3-10. Bathymetric and topographic change for Interval 2 at the Columbia River entrance and estuary, Long Beach, and Clatsop Plains.

Footnotes of Table 3-10.

1) Includes compartments LBc5 - LBc7 and LBdn.
2) Includes compartments LBc1 - LBc4, LBc1_near and LBc2_near.
3) Includes compartments CPc1 - CPc5 and LBc3_near - LBc5_near.
4) From SHERWOOD et al. (1990).

Table 3-10. Bathymetric and topographic change for Interval 2 at the Columbia River entrance, estuary, Long Beach, and Clatsop Plains.

Interval 2 ~32 years	Area (km^2)	ΔV (Mm^3)	ΔV_{time} (Mm3)	ΔV_{sand} (Mm^3)	$\Delta V_{time,sand}$ (Mm^3)	Δh (m)	Rate $\Delta V_{time,sand}$ (Mm^3/yr)	Rate Δh (m/yr)
Peacock Spit (1)	1.33	5.58	5.58	5.58	5.58	n/a	0.17	n/a
LBds_near (2)	2.37	8.77	8.77	8.77	8.77	3.71	0.27	0.116
LBds_off (3)	7.90	8.26	8.26	8.26	8.26	1.05	0.26	0.033
Inlet (4)	34.63	-35.71	-53.77	-35.71	-53.77	-1.55	-1.68	-0.049
Clatsop Spit Inlet (5)	0.92	3.01	3.74	3.01	3.74	n/a	0.12	n/a
Inner Delta (6)	26.45	-54.19	-54.19	-54.19	-54.19	-2.05	-1.69	-0.064
Outer Delta (7)	17.92	101.30	101.30	101.30	101.30	5.65	3.17	0.177
Subtotal	**n/a**	**37.02**	**19.69**	**37.02**	**19.69**	**n/a**	**0.62**	**n/a**
Long Beach[1)]	-2.20	-24.31	-24.31	-24.31	-24.31	n/a	-0.76	n/a
Long Beach[2)]	4.79	76.01	76.01	76.01	76.01	n/a	2.38	n/a
Sum	**n/a**	**51.70**	**51.70**	**51.70**	**51.70**	**n/a**	**1.62**	**n/a**
Subtotal	**n/a**	**88.72**	**71.39**	**88.72**	**71.39**	**n/a**	**2.23**	**n/a**
Clatsop Plains[3)]	4.57	61.17	61.17	61.17	61.17	n/a	1.91	n/a
Clatsop Spit (8)	-0.98	-4.64	-4.64	-4.64	-4.64	n/a	-0.14	n/a
CPdn_near (9)	3.43	-6.14	-6.14	-6.14	-6.14	-1.79	-0.19	-0.056
CPdn_near_w (10)	11.23	-3.20	-3.20	-3.20	-3.20	-0.28	-0.10	-0.009
South Flank (11)	29.82	-42.76	-42.76	-42.76	-42.76	-1.43	-1.34	-0.045
CPc5_off (12)	9.80	-13.18	-13.18	-13.18	-13.18	-1.35	-0.41	-0.042
CPc4_off (13)	8.37	-9.05	-9.05	-9.05	-9.05	-1.08	-0.28	-0.034
CPc3_off (14)	10.88	-7.30	-7.30	-7.30	-7.30	-0.67	-0.23	-0.021
Sum	**n/a**	**-25.09**	**-25.09**	**-25.09**	**-25.09**	**n/a**	**-0.78**	**n/a**
Subtotal	**n/a**	**63.64**	**46.30**	**63.64**	**46.30**	**n/a**	**1.45**	**n/a**
Flood-tidal Delta[4)]	202.15	24.13	41.92	19.30	33.54	0.17	1.05	0.005
Subtotal	**n/a**	**87.77**	**88.23**	**82.94**	**79.84**	**n/a**	**2.50**	**n/a**
Upper Estuary[4)]	493.10	34.99	51.59	27.99	41.27	0.08	1.29	0.003
Omission[4)]	24.15	48.30	45.73	38.64	36.58	n/a	1.14	n/a
Sum	**n/a**	**83.29**	**97.32**	**66.63**	**77.85**	**n/a**	**2.43**	**n/a**
Subtotal Estuary	**n/a**	**107.42**	**139.24**	**85.94**	**111.39**	**n/a**	**3.48**	**n/a**
Subtotal	**n/a**	**171.06**	**185.54**	**149.57**	**157.69**	**n/a**	**4.93**	**n/a**
LB_off_m (15)	57.02	-5.37	-5.37	-5.37	-5.37	-0.09	-0.17	-0.003
LB_off_e (16)	44.68	12.79	12.79	12.79	12.79	0.29	0.40	0.009
CP_off_w (22)	145.73	32.04	32.04	32.04	32.04	0.22	1.00	0.007
LB_off_w (23)	70.12	113.45	113.45	113.45	113.45	1.62	3.55	0.051
Sum	**n/a**	**152.91**	**152.91**	**152.91**	**152.91**	**n/a**	**4.78**	**n/a**
Net Change	**n/a**	**323.97**	**338.45**	**302.48**	**310.60**	**n/a**	**9.71**	**n/a**
LBc2_near (17)	6.56	15.55	15.55	15.55	15.55	2.37	0.49	0.074
LBc1_near (18)	7.64	25.19	25.19	25.19	25.19	3.30	0.79	0.103
CPc5_near (19)	9.91	1.01	1.01	1.01	1.01	0.10	0.03	0.003
CPc4_near (20)	9.91	6.20	6.20	6.20	6.20	0.63	0.19	0.020
CPc3_near (21)	10.08	7.72	7.72	7.72	7.72	0.77	0.24	0.024

Table 3-11. Bathymetric and topographic change for Interval 2 at Long Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
LBdn	3320	-0.73	-4.44	-0.67	-3.77	6.04	0.91	5.13	-6.91	-41.77	-6.30
LBc7	5589	-0.89	-11.70	-0.84	-10.86	13.14	0.95	12.19	-4.98	-65.44	-4.72
LBc6	4261	-0.40	-5.49	-0.57	-4.93	13.59	1.40	12.19	-2.96	-40.29	-4.15
LBc5	4980	-0.17	-2.67	-0.65	-2.02	16.12	3.93	12.19	-1.04	-16.75	-4.09
LBc4	5020	0.13	2.00	0.47	1.53	15.94	3.75	12.19	0.78	12.43	2.93
LBc3	5000	0.71	11.57	2.86	8.71	16.20	4.01	12.19	4.46	72.29	17.88
LBc2	5000	1.50	23.34	5.03	18.32	15.54	3.35	12.19	9.39	145.90	31.41
LBc1	6300	2.45	39.10	7.15	31.95	15.95	2.92	13.03	12.16	193.94	35.48
Sum[1)]	**n/a**	**2.60**	**51.70**	**12.78**	**38.92**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
LBds	3403	1.33	5.58	3.53	2.05	n/a	2.66	n/a	12.18	n/a	32.43

[1)] Excluding LBds.

Table 3-12. Bathymetric and topographic change for Interval 2 at Clatsop Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
CPdn	4471	-0.98	-4.64	-2.50	-2.13	n/a	2.55	n/a	-6.85	n/a	-17.49
CPc5	4318	0.35	3.66	2.37	1.29	10.41	6.75	3.66	2.54	26.47	17.16
CPc4	4388	0.94	14.33	7.08	7.25	15.19	7.50	7.69	6.72	102.05	50.40
CPc3	5140	1.38	20.00	10.53	9.47	14.51	7.64	6.87	8.38	121.57	64.02
CPc2[2)]	4788	n/a	16.46	n/a	n/a	n/a	n/a	n/a	n/a	107.44	n/a
CPc1[2)]	4812	n/a	6.72	n/a	n/a	n/a	n/a	n/a	n/a	43.66	n/a
Sum[1)]	**n/a**	**n/a**	**61.17**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

[1)] Excluding CPdn.
[2)] CPc1 and CPc2 are based on a proportional relation between CPc3, CPc2, and CPc1 (Appendix E).

Analysis

During Interval 2 the readjustment of the morphology due to jetty construction at the Columbia River entrance continued. The estuary, the outer ebb-tidal delta, the beach-dune complexes of Long Beach and Clatsop Plains accreted, whereas the Inner Delta, Inlet, and the shoreface along Clatsop Plains eroded.

The inlet (compartments 4 and 5) and the Inner Delta (6) eroded by 104 Mm^3. Sand from the Inlet may have contributed to the accretion of the Outer Delta (101 Mm^3).

The regions of greatest accumulation along the coast shifted away from the Columbia River entrance. Clatsop Spit started to erode and the central part of the Clatsop Plains sub-cell prograded significantly with shoreline change rates of 7 - 8 m/yr (Table 3-12 and Figure 2-11). The inner shoreface along Clatsop Plains (compartments 11, 12, 13, and 14), Clatsop Spit (8), CPdn_near (9), and CPdn_near_w (10) eroded 86 Mm^3 and this sand may have moved southward and onshore, contributing to the accretion of Clatsop Plains (61 Mm^3).

North of the Columbia River entrance, Peacock Spit continued to accumulate sand (6 Mm^3), but at a slower rate of 0.17 Mm^3/yr (0.37 Mm^3/yr during Interval 1). North of North Head, the southern 20 km of Long Beach prograded 76 Mm^3, whereas the northern 20 km of Long Beach eroded 24 Mm^3. The total accumulation of Long Beach, excluding Peacock Spit, is 52 Mm^3. It is not clear if the sand that eroded at northern Long Beach contributed to the accretion at southern Long Beach. We hypothesize that the erosion at northern Long Beach is related to processes at the Willapa Bay entrance, e.g., channel migration.

The Flood-tidal Delta and Upper Estuary continued to accumulate, 34 Mm^3 and 41 Mm^3, respectively. Compared to Interval 1, the vertical change rates of the Flood-tidal Delta decrease from 0.008 m/yr to 0.005 m/yr, whereas the vertical change rates of the Upper Estuary remain 0.003 m/yr during both intervals. About 24 km^2 of land (37 Mm^3) was omitted in Interval 2. Approximately a quarter of the infilling and diking occurred in Youngs Bay, and another quarter on Puget, Little, and Tenasillahie Islands (SHERWOOD et al., 1990). The net change in the estuary, excluding Columbia River sediment supply, is equal to 111 Mm^3 more accretion than can be accounted for.

Compartment LB_off_w (23) may represent deposition from a plume of fine sediments released by the Columbia River. The maximum of daily riverflows of the Columbia River at The Dalles, Oregon (SHERWOOD et al., 1990) shows a peak in 1948. This peak in discharge could have caused the release of these fines.

The amount of sand dredged out of the estuary and disposed on land between Era I and Era III was estimated to be 50 to 70 Mm^3 (SHERWOOD et al., 1990). However, it is not known how much was dredged in Interval 1 or Interval 2. The volumes for dredging and disposal at the Columbia River entrance during Interval 2 are not exactly known. However, they are small compared to the volume changes (Appendix D).

The vertical changes of the offshore compartments LB_off_m (15), LB_off_e (16), and CP_off_w (22) are small, because we minimize offshore bathymetric change as discussed in Section 2.4.3. Bathymetric changes of these compartments are within the uncertainty.

The net change over the inlet, ebb-tidal delta, and adjacent coasts (excluding compartments 15, 16, 22, and 23) is 46 Mm^3 accretion (6th column in Table 3-10). The net change for the estuary is 111 Mm^3 more accretion than erosion (excluding the estimates for dredging). The net change for all compartments (including the estuary and excluding compartments 15, 16, 22, and 23) is 158 Mm^3 more accretion than erosion. The supply of Columbia River sand to the estuary of 2.6

Mm^3/yr (Appendix B) might account for 83 Mm^3 of the observed accretion. However, the budget remains unbalanced with 75 Mm^3 accretion. If we account for the estimates of the northward sediment flux at the northern tip of Long Beach of 45 Mm^3 (1.4 Mm^3/yr; KAMINSKY et al., 2000) and dredging of 70 Mm^3 in the Columbia River estuary, the influx of sand increases by 115 Mm^3, i.e., the net accretion on the sediment balance increases by 115 Mm^3.

Uncertainties in the bathymetric volume-change calculations, sediment fluxes, and the lack of bathymetric coverage along northern Long Beach might have contributed to the net accretion of 158 Mm^3. In these volume calculations we adjust the Era III surveys by an extra -0.29 m to minimize the apparent offset with the Era IV surface. If we neglect this adjustment, the net accretion over the study area increases by either approximately 60 Mm^3 (excluding the shelf along Long Beach and Clatsop Plains, compartments 15, 16, 22, and 23), or by approximately 135 Mm^3 (including compartments 15, 16, and 22 and excluding compartment 23). If we neglect both the -0.29-m adjustment of the Era III surveys and the -1.68-m adjustment of the H4635 survey, the net accretion decreases by approximately 65 Mm^3 (including compartments 15, 16, and 22 and excluding compartment 23).

3.2.3 Regional Barrier-Change Rates

Regional ΔV-, $\Delta V_{>MHW}$-, and Area-change rates of Interval 2 normalized by compartment length are presented in Figure 3-11 and Figure 3-12. The volume- and area-change rates for North Beach, Grayland Plains, Long Beach, and Clatsop Plains are presented in Table 3-8, Table 3-9, Table 3-11, and Table 3-12. No Era III shorelines are available for the southern compartments CPc1 and CPc2. The volumes ΔV of these compartments are estimated based on the shoreline progradation between Era II and Era IV. The duration of Interval 2 at North Beach and Grayland Plains is approximately 28 years and the duration at Long Beach and Clatsop Plains is approximately 32 years.

During Interval 2, the centers of net deposition moved away from the entrances. The shoreline-progradation rates at the spits decrease or reverse to erosion: at NBds from 26 m/yr to 14 m/yr, at GLdn from 8 m/yr to 4 m/yr, at LBds from 13 m/yr to 12 m/yr, and at CPdn from 17 m/yr to -7 m/yr. The uniform accretion along Grayland Plains in Interval 1 (6 - 10 m/yr) does not continue during Interval 2 (-3 - 5 m/yr). Grayland Plains accreted in the south, most likely due to the northerly migration of the Willapa Bay ebb-tidal delta. In the north, Grayland Plains eroded and accreted at GLc6 and GLdn, possibly as a result of South Jetty deterioration and rehabilitation (1935 - 1940), respectively. Massive shoreline progradation occurred at North Beach (2 - 14 m/yr) and southern Long Beach (LBc1 - LBc4, 1 - 12 m/yr). It is not clear why northern Long Beach (LBc5 - LBc7 and LBdn, -1 - -7 m/yr) eroded during this interval. The center of deposition along Clatsop Plains shifted towards the south, and the shoreline retreated along northern Clatsop Plains.

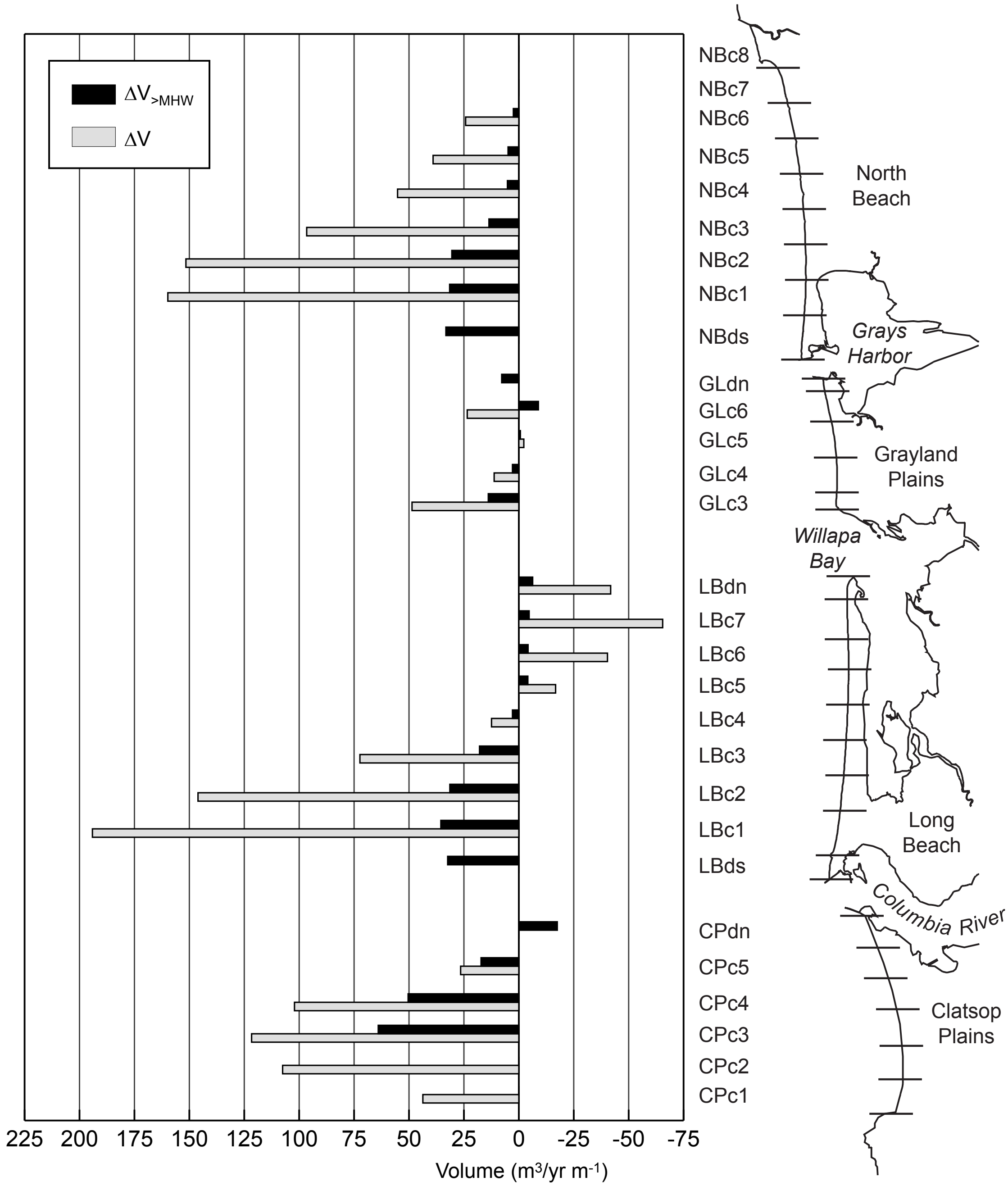


Figure 3-11. Bathymetric and topographic volume-change rates per compartment normalized by compartment length for Interval 2 along the CRLC. The duration of Interval 2 for North Beach and Grayland Plains is 28 years, and the duration of Interval 2 for Long Beach and Clatsop Plains is 32 years. ΔV represents the total volume change of the barrier compartments, and ΔV_{MHW} represents the volume change above MHW.

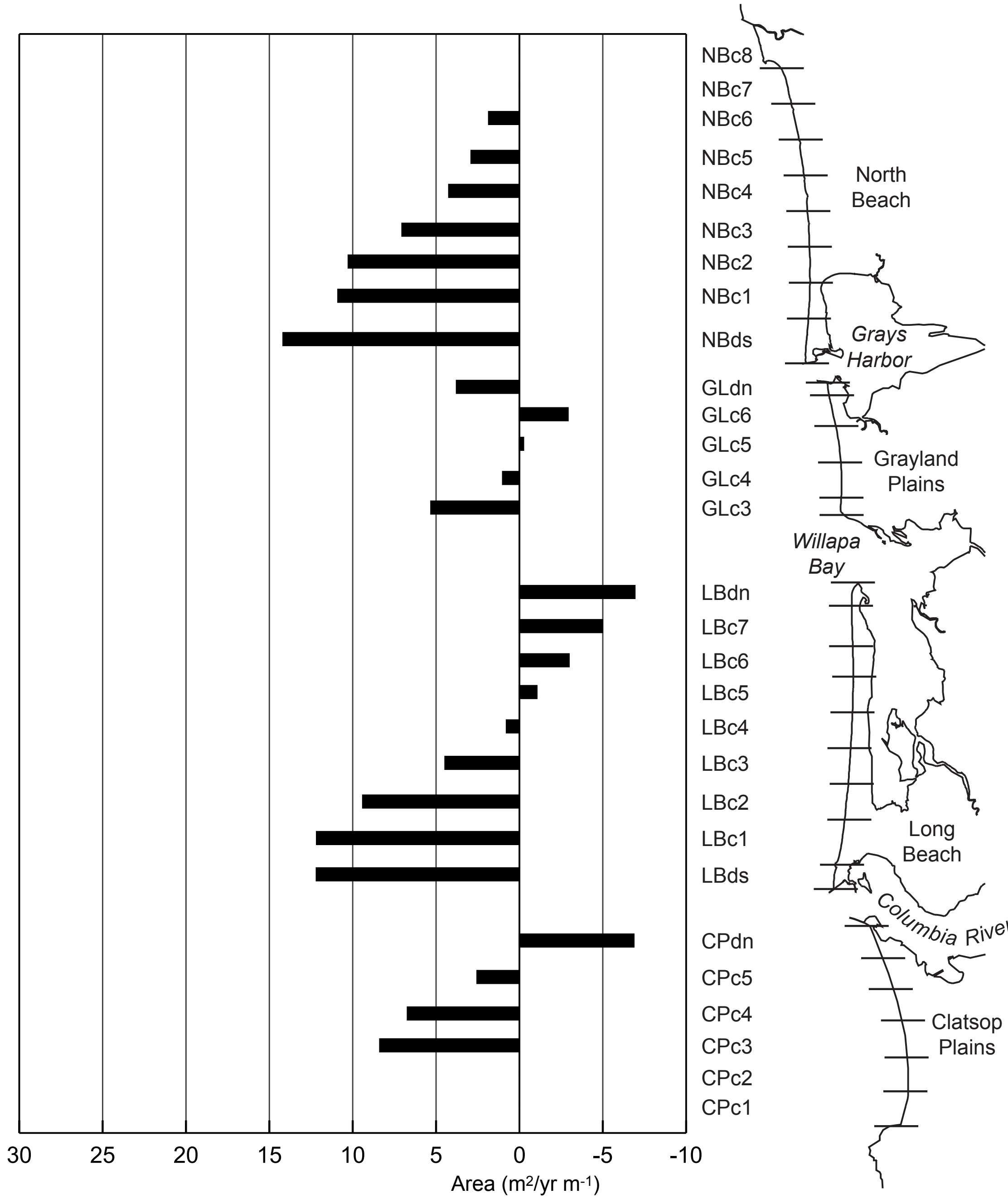


Figure 3-12. Area-change rates per compartment normalized by compartment length for Interval 2 along the CRLC. The duration of Interval 2 at North Beach and Grayland Plains is 28 years, and the duration of Interval 2 at Long Beach and Clatsop Plains is 32 years.

3.3 Interval 3 (1940s - 1950s to 1990s - 2000)

3.3.1 Grays Harbor Entrance and Adjacent Coasts

Era IV Bathymetric Surface

The Era IV bathymetric surface incorporates the 1999 Multibeam sonar data (Grays Harbor entrance and nearshore Grayland Plains) collected by USGS/DOE, the USACE 1999 Annual Survey (Grays Harbor delta), the 1999 USGS/DOE Coastal Profiling System (CPS) data (nearshore North Beach and Grayland Plains), the USACE 1998 survey (Willapa Bay delta and Willapa Bay), and the 1995 shoreline derived from aerial photographs (Table 2-1, Table 2-3, Figure 2-4, and Figure 2-5). The use of the 1995 shoreline causes some minor matching problems near Cape Shoalwater, because of erosion of Cape Shoalwater between 1995 and 1998. Therefore, portions of the 1995 shoreline along Cape Shoalwater are excluded. The data density of the multibeam sonar data is very high: there are many data points within a square meter. The data is resampled to a 50 x 50 m^2 grid, which is used in this analysis. The CPS data spacing along the tracklines is O(1 m), and the spacing between the tracklines varies between 200 to 1000 m. The data spacing along the tracklines of the USACE Grays Harbor survey is O(10 m), and the spacing between the tracklines is O(100 m). The USACE Willapa Bay survey comprises over 600,000 survey points collected with various techniques, such as synoptic sounding and laser altimetry (LIDAR). The resolution along the tracklines of the CPS data and the resolution of the LIDAR data of USACE 1998 survey is very high. We minimize the resolution to make these datasets more manageable, without loosing significant accuracy.

The MLLW datum of the USACE 1998 survey is adjusted by -0.24 m to NAVD88 at the Toke Point tide gauge. The USACE 1999 Annual Survey is adjusted by -0.46 m to NAVD88 at Westport. The Multibeam and CPS surveys are not adjusted.

The Era IV surveys are gridded at a 50-m cell size using triangulation with linear interpolation. To minimize errors in the volume calculations the grid size is reduced to 25 m using cubic spline interpolation. The Era IV bathymetric surface used for the Interval 3 and Interval 4 volume calculations is presented in Figure 3-13.

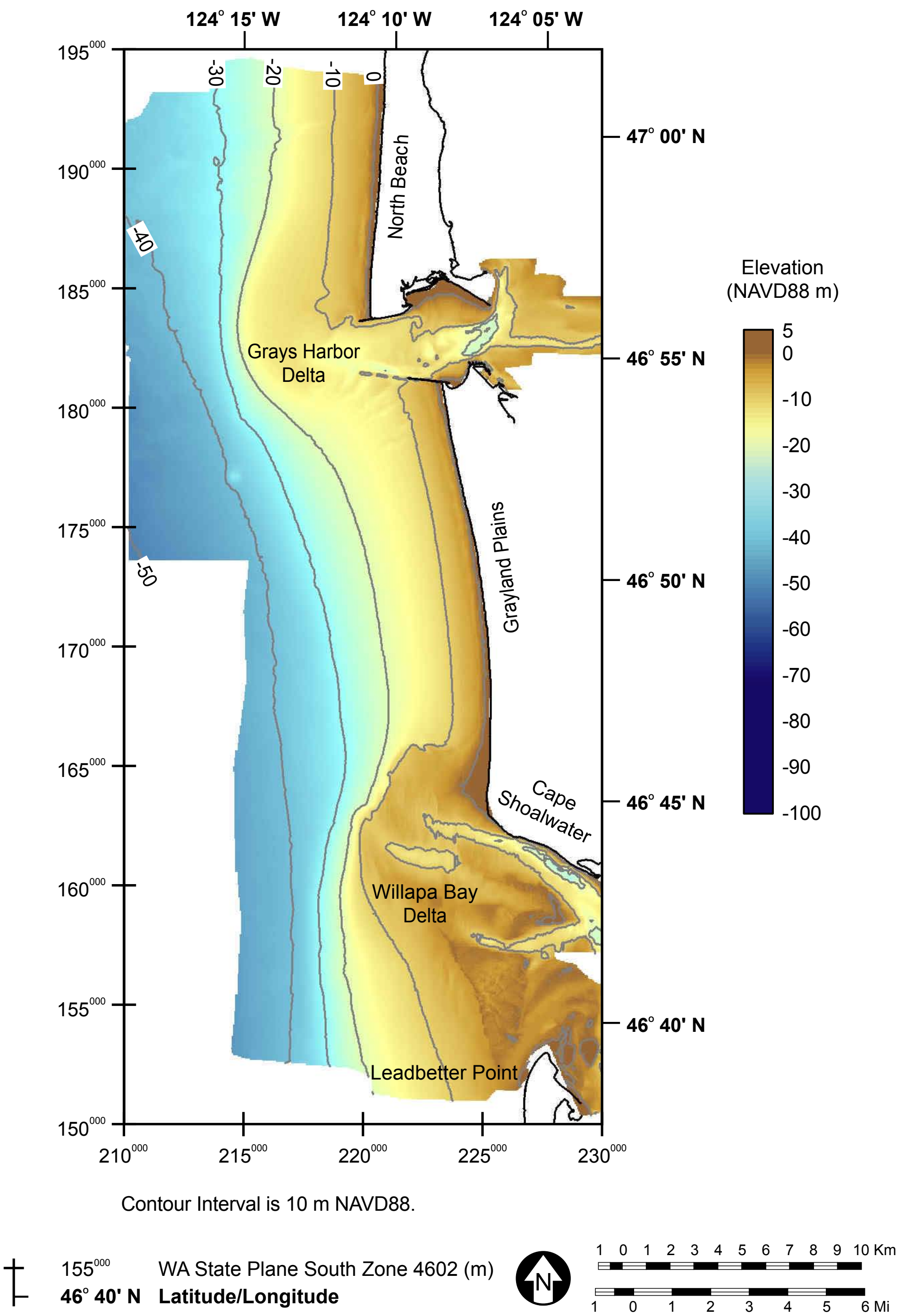


Figure 3-13. Era IV Bathymetric surface of the Grays Harbor entrance, North Beach, Grayland Plains, and Willapa Bay entrance.

Topographic- and Bathymetric-Volume Change

The results of the bathymetric volume-change analysis for Interval 3 are presented in Figure 3-14, Table 3-13, Table 3-14, and Table 3-15. The format of these tables is explained in Section 3.1.1. The change rates in Table 3-13, Table 3-14, and Table 3-15 are calculated for a period of 45 years (1999 - 1954 = 45 years). The ΔV-, $\Delta V_{>MHW}$-, and Area-change rates in Table 3-14 and Table 3-15 are visualized in Figure 3-17 and Figure 3-18.

Due to the limited data coverage in deeper water we can not calculate RMS and mean differences along the alongshore-averaged profiles at Grayland Plains for Interval 3 (Sections 2.4.2 and 2.6.1). We calculate RMS and mean differences between the Era IV and Era III surveys along Transect A of 0.35 m and 0.16 m, respectively and along Transect B of 0.35 m and -0.24 m, respectively (Table 2-11). In addition, we use the (ignored) adjustment of -0.46 m of the Era III surveys as an estimate of the uncertainty in the sediment balance.

Compartments NBds (1) and GLdn (13) in Table 3-13 only comprise volumes V_1 and V_2 (Figure 2-21). The volume below MHW ($\Delta V_{<MHW}$) of NBds (Table 3-14) and GLdn (Table 3-15) only comprise volume V_2. In Table 3-13, North Beach and Grayland Plains comprise compartments NBc1 - NBc8, and GLc3 - GLc6, respectively. The volumes of these compartments consist of the subaerial and subaqueous volumes V_1, V_2, and V_3. Compartment GLc6_near (15) is part of the volume of Clatsop Plains in Table 3-13. Compartment 7 is a dredge disposal mound used by the USACE.

There is no bathymetric coverage of the Era II survey north of NBds and south of GLc6, and therefore we can not calculate bathymetric change for these areas. The volume below MHW (represented by V_2 and V_3 in Figure 2-21) of compartments NBc1 - NBc8 is calculated applying an active depth of 11.77 m below MHW, which is calculated for Interval 4. The volume below MHW of compartments GLc3 - GLc5 is calculated using active depths based on Interval 1.

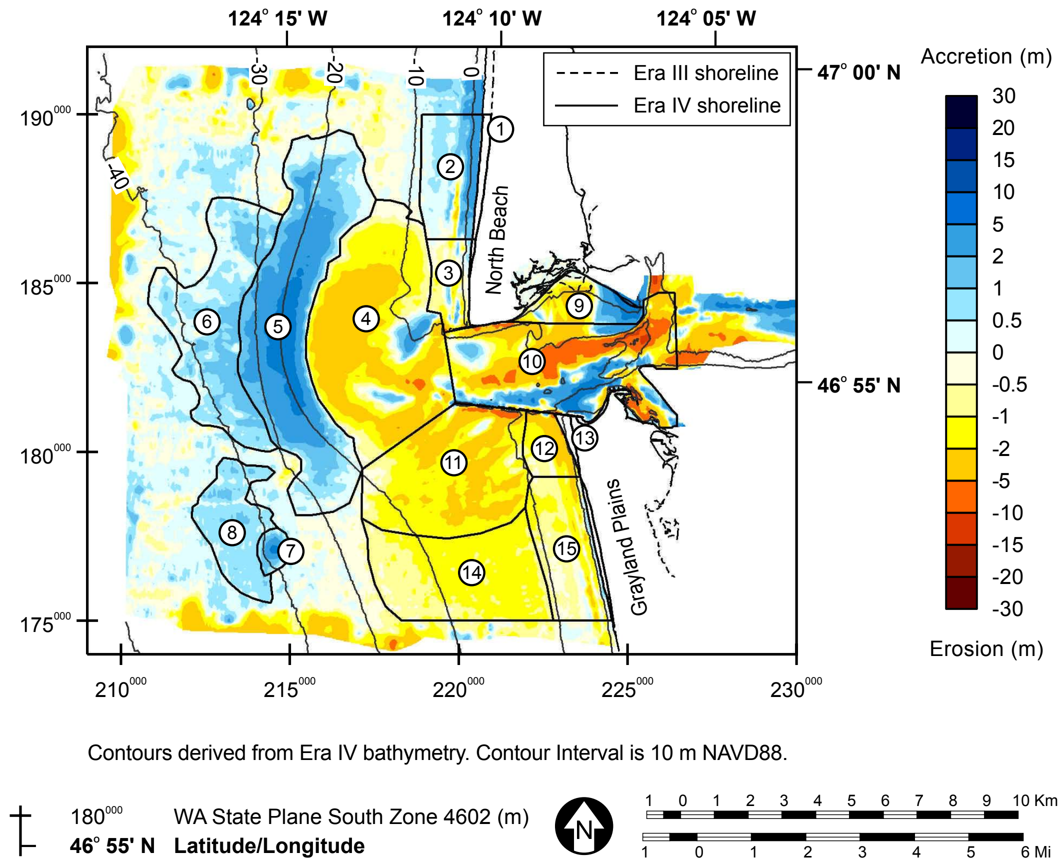


Figure 3-14. Bathymetric and topographic change for Interval 3 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Table 3-13. Bathymetric and topographic change for Interval 3 at the Grays Harbor entrance, North Beach, and Grayland Plains.

Interval 3 ~45 yr	Area (km^2)	ΔV (Mm^3)	Δh (m)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
NBds (1)	0.90	3.09	n/a	0.07	n/a
NBds_near_n (2)	6.08	5.73	0.94	0.13	0.021
NBds_near_s (3)	2.93	-1.63	-0.55	-0.04	-0.012
Inner Delta (4)	22.95	-40.56	-1.77	-0.90	-0.039
Outer Delta (5)	23.01	52.52	2.28	1.17	0.051
Outer Delta West (6)	13.75	9.93	0.72	0.22	0.016
Disposal Site (7)	0.96	1.83	1.90	0.04	0.042
Disposal_west (8)	5.98	4.18	0.70	0.09	0.016
Inlet_north (9)	3.55	0.12	0.03	0.00	0.001
Inlet (10)	17.29	-30.57	-1.77	-0.68	-0.039
South Flank (11)	15.22	-28.92	-1.90	-0.64	-0.042
GLdn_near (12)	2.35	-4.77	-2.03	-0.11	-0.045
GLdn (13)	-0.31	-1.45	n/a	-0.03	n/a
Sum	**n/a**	**-30.50**	**n/a**	**-0.68**	**n/a**
North Beach[1)]	2.83	39.16	n/a	0.87	n/a
Subtotal	**n/a**	**8.66**	**n/a**	**0.19**	**n/a**
Grayland Plains[2)]	1.59	7.28	n/a	0.16	n/a
Subtotal	**n/a**	**15.93**	**n/a**	**0.35**	**n/a**
GLc6_off (14)	12.98	-14.27	-1.10	-0.32	-0.024
Net Change	**n/a**	**1.66**	**n/a**	**0.04**	**n/a**
GLc6_near (15)	7.20	-5.92	-0.82	-0.13	-0.018

1) Includes compartments NBc1 - NBc8.
2) Includes compartments GLc3 - GLc6.

Table 3-14. Bathymetric and topographic change for Interval 3 at North Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$ΔV_{>MHW}$ (Mm^3)	$ΔV_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $ΔV_{>MHW}$ ($m^3/yr\ m^{-1}$)
NBc8	1000	-0.05	-0.60	-0.06	-0.53	13.14	1.36	11.77	-1.01	-13.24	-1.37
NBc7	5000	0.00	0.00	0.00	0.00	13.14	1.36	11.77	0.00	0.00	0.00
NBc6	5000	-0.01	-0.15	-0.02	-0.13	13.14	1.36	11.77	-0.05	-0.65	-0.07
NBc5	5000	-0.11	-1.50	-0.18	-1.32	13.39	1.62	11.77	-0.50	-6.67	-0.81
NBc4	5000	0.20	2.66	0.25	2.41	13.01	1.23	11.77	0.91	11.84	1.12
NBc3	5000	0.82	10.68	0.98	9.70	12.96	1.19	11.77	3.66	47.48	4.36
NBc2	5000	0.94	13.06	1.96	11.10	13.85	2.08	11.77	4.19	58.05	8.70
NBc1	5000	1.02	14.99	2.95	12.04	14.66	2.89	11.77	4.54	66.64	13.13
Sum[1)]	**n/a**	**2.83**	**39.16**	**5.89**	**33.27**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
NBds	6307	0.90	3.09	2.12	0.98	n/a	2.34	n/a	3.18	n/a	7.46

1) Excluding NBds.

Table 3-15. Bathymetric and topographic change for Interval 3 at Grayland Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
GLdn	1807	-0.31	-1.45	-0.64	-0.81	n/a	2.05	n/a	-3.84	n/a	-7.88
GLc6	4259	0.47	-4.24	1.45	-5.69	-9.03	3.08	-12.12	2.45	-22.12	7.55
GLc5	5105	0.16	1.60	0.51	1.09	9.87	3.16	6.71	0.71	6.96	2.23
GLc4	4895	0.58	6.46	1.69	4.77	11.19	2.92	8.27	2.62	29.31	7.65
GLc3	2100	0.38	3.46	0.99	2.47	9.15	2.61	6.54	4.00	36.63	10.45
sum[1)]	**n/a**	**1.59**	**7.28**	**4.63**	**2.64**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

[1)] Excluding GLdn.

Analysis

The compartments at the entrance, excluding North Beach and Grayland Plains eroded by 31 Mm^3 . The Inner Delta (4) and Inlet (10) combined eroded 71 Mm^3. The South Flank (11) of the Grays Harbor delta eroded 29 Mm^3. Sand that eroded from these compartments most likely contributed to the accretion of the Outer Delta (5), Outer Delta West (6) and the adjacent coasts of North Beach and Grayland Plains. The Outer Delta and Outer Delta West accreted by 53 Mm^3 and 10 Mm^3, respectively.

North Beach, excluding NBds, accreted at a slower rate of 0.9 Mm^3/yr (39 Mm^3) compared to 2.6 Mm^3/yr (74 Mm^3) for the previous interval. Since the 1950s, the beach within 2 km north of the North Jetty has remained stable, whereas the coast to the north has continued to accrete. Grayland Plains, excluding NBds, accreted about 7 Mm^3. The shoreline within 1700 m south of the South Jetty retreated -4 m/yr (GLdn), whereas a 3000-m stretch of shoreline to the south (GLc6) advanced 2 m/yr. Although the shoreline advanced, the nearshore area (GLc6_near) eroded 6 Mm^3, resulting in net erosion of 4.2 Mm^3 in compartment GLc6 (Table 3-15). Most of the accretion along Grayland Plains occurred in the south, most likely related to the northward migrating Willapa Bay ebb-tidal delta. It is not clear if compartment 8 is comprised of material that dispersed from the dredge disposal mound (compartment 7).

Dredging and disposal of sediment at the Grays Harbor entrance is described in Appendix C. No dredging was required in the Bar and Entrance channels between 1942 and 1988. Between 1988 and 2000, 2.6 Mm^3 was dredged from both the Bar and Entrance channels. This sediment was placed in the Pt. Chehalis, South Jetty or Half Moon Bay disposal sites. Material that was dredged from the Bar channel was placed in nearshore berms at the South Beach disposal site or in the Southwest Ocean disposal site in deep water. The total amount disposed since 1988 in the Southwest Ocean disposal site, Westport beach fill, South Beach, Breach Fill, and Half Moon Bay was 4.4 Mm^3. The largest disposal occurred in the South Jetty and Pt. Chehalis disposal sites. Between 1977 and 2000, 9 Mm^3 and 25.4 Mm^3 was disposed in the South Jetty and Pt. Chehalis disposal sites, respectively. Most of the sediment disposed here came from the bay channels east of Pt. Chehalis. The impact of the disposal of sediment in the Pt. Chehalis disposal site on the sediment budget is small, since most material placed here comprise fine-grained sediments with an estimated sand fraction of 10% (BURCH and SHERWOOD, 1992).

Most bathymetric changes are larger than the estimated uncertainties. The net balance over the entrance area and adjacent coasts is approximately 2 Mm^3 accretion. The northward sediment flux of 0.8 Mm^3/yr (KAMINSKY et al., 2000) at southern Grayland Plains accounts for the observed accretion of 2 Mm^3 and increases the export of sand out of the Grays Harbor entrance sub-region by 34 Mm^3. In addition, the sand balance of Interval 3 relies on incomplete bathymetric coverage of the shoreface along North Beach and Grayland Plains and within the Grays Harbor tidal basin. Adjusting the vertical datums of the H8252 and USACE 1954 surveys by -0.46 m increases the observed accretion by approximately 60 Mm^3.

3.3.2 Columbia River Entrance and Adjacent Coasts

Era IV Bathymetric Surface

The Era IV bathymetric surface of the Columbia River entrance and the adjacent coasts consists of the USACE 1998 (offshore Long Beach), USACE 1999 (northern Long Beach), USACE 2000 (dredge disposal sites), and the USACE 2000 (entrance and offshore Clatsop Plains) surveys, the 1999 Coastal Profiling System (CPS) data, and the 1995 shorelines (Table 2-2, Table 2-3, and Figure 2-4). The spacing between the tracklines of the USACE surveys along Long Beach and Clatsop Plains is O(500 m), and the spacing between the depth soundings along the tracklines is O(50 m). The spacing between the tracklines of the USACE 2000 survey of the disposal sites varies between O(50 m) and O(200) m, and the spacing between the depth soundings along the tracklines is O(50 m). The spacing between the tracklines of the CPS data varies between O(100 m) and O(1000 m), and the spacing between the depth soundings along the tracklines is O(1 m). To make the CPS data more manageable, the resolution of the data is reduced by a factor 5 to a spacing of O(5 m). The inlet has only a partial coverage, and there is no recent complete coverage available of the Columbia River estuary.

The CPS surveys are referenced to NAVD88 and are not adjusted. The USACE surveys are adjusted by -0.16 m to NAVD88 at Ft. Stevens, except for the USACE 2000 survey of the disposal sites, which is adjusted by +0.19 m to fit the surrounding USACE surveys.

The datasets are gridded at a 50-m cell size using triangulation with linear interpolation with an anisotropy ratio of 0.7. To minimize errors in the volume calculations the grid size is reduced to 25 m using cubic spline interpolation. The Era IV surface is presented in Figure 3-15.

Topographic- and Bathymetric-Volume Change

Bathymetric and topographic change at the Columbia River entrance and adjacent coasts for Interval 3 are presented in Figure 3-16, Table 3-16, Table 3-17, and Table 3-18. Table 3-16 presents the area and volume changes and change rates of all bathymetric compartments, including the beach-dune complexes of Long Beach and Clatsop Plains. Table 3-17 and Table 3-18 present the bathymetric and topographic change of the beach-dune complexes of Long Beach and Clatsop Plains by compartment. The volume- and area-change rates in Table 3-17 and Table 3-18 are visualized in Figure 3-17 and Figure 3-18. The change rates in the tables are based on a duration of 41 years (1999 - 1958 = 41 years). The format of the tables is explained in Section 3.1.1.

The RMS and mean differences are presented in Table 2-11 and Table 2-12 in Section 2.6.1. The RMS and mean differences along the alongshore-averaged profiles for Interval 3 at Long Beach are 0.08 m and 0.01 m, respectively. The RMS and mean differences along the alongshore-averaged profiles at Grayland Plains are 0.24 m and -0.15 m, respectively. In addition, we use the -0.29-m adjustment of the Era III surveys as an estimate of the uncertainty in the sediment balance.

The volume of the Long Beach compartment in Table 3-16 includes the topographic- and bathymetric-volume change of compartments LBc1 - LBc7 and LBdn (volumes V_1, V_2, and V_3 in Figure 2-21). Along Long Beach only the nearshore areas of LBc1 and LBc2 have bathymetric coverage. The average depth below MHW ($h_{<MHW}$) of LBc1 and LBc2 is about 16.71 m and is used to calculate volume changes below MHW of the northern compartments without bathymetric coverage (LBc3 - LBc7). The active depth below MHW for LBdn is estimated to be 5.1 m. The Peacock Spit compartment (LBds) comprises volumes V_1 and V_2 (Figure 2-21).

The volume of the Clatsop Plains compartment in Table 3-16 consists of compartments CPc1 - CPc5. CPdn (Clatsop Spit) comprises volumes V_1 and V_2. Compartment CPdn_near represents the nearshore volume of CPdn (volume V_3). The Era III shoreline and bathymetry does not extend farther south along Clatsop Plains than compartment CPc3. The nearshore and topographic volumes of Interval 3 (the sum of V_1, V_2, and V_3) of CPc1 and CPc2 are estimated based on a proportional relation between CPc3, CPc2, and CPc1 for the volume change of the beach-dune complex of Clatsop Plains between the 1920s and 1990s (Appendix E).

Compartments LBc1_near (16), LBc2_near (15), CPc3_near (19), CPc4_near (18), and CPc5_near (17) are included as volume V_3 in the volumes of LBc1, LBc2, CPc3, CPc4, and

CPc5, respectively and are mentioned in Table 3-16 for reference. Due to the lack of data, we do not calculate volume changes for the inlet and estuary.

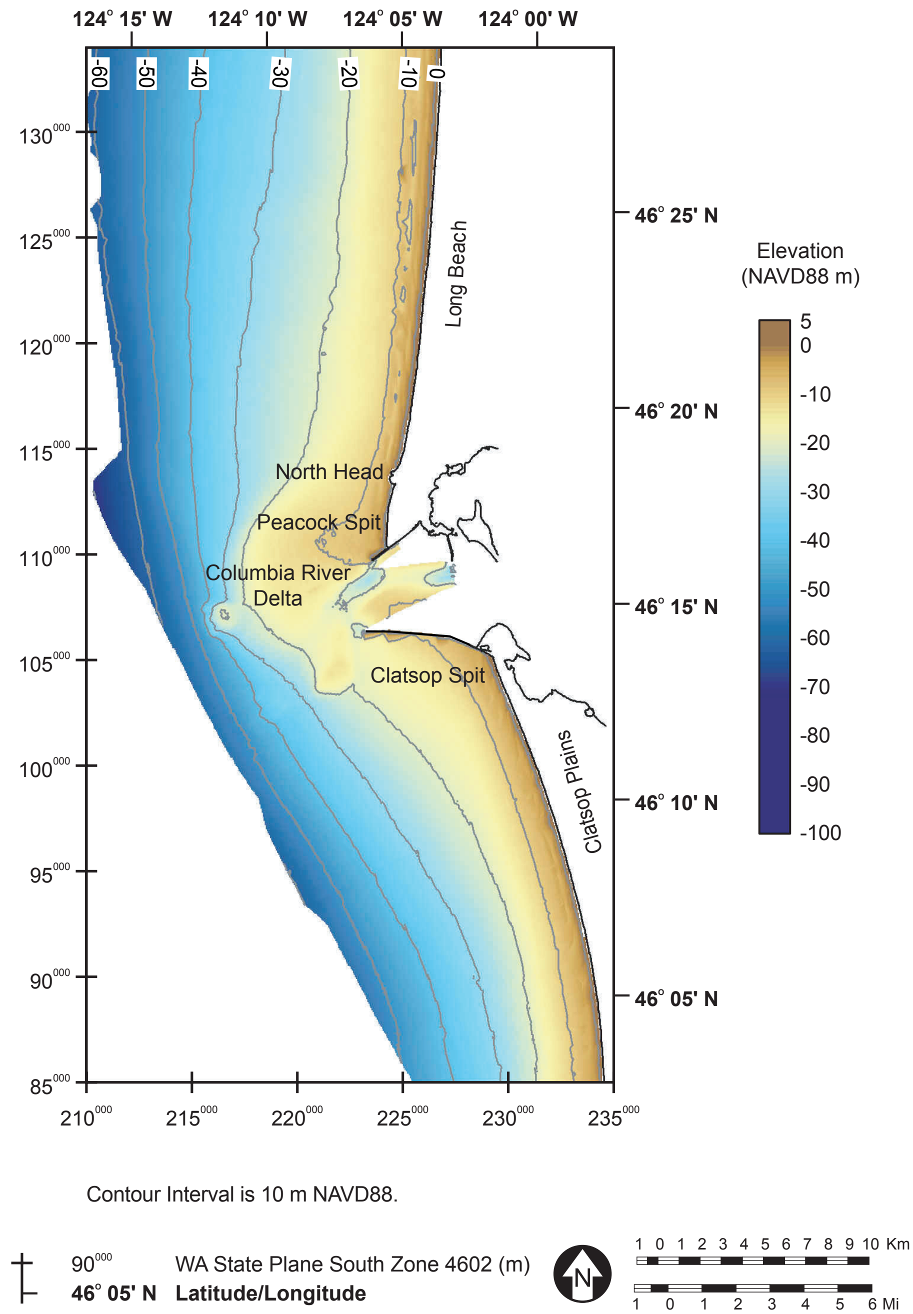


Figure 3-15. Era IV bathymetric surface of the Columbia River entrance, Long Beach, and Clatsop Plains.

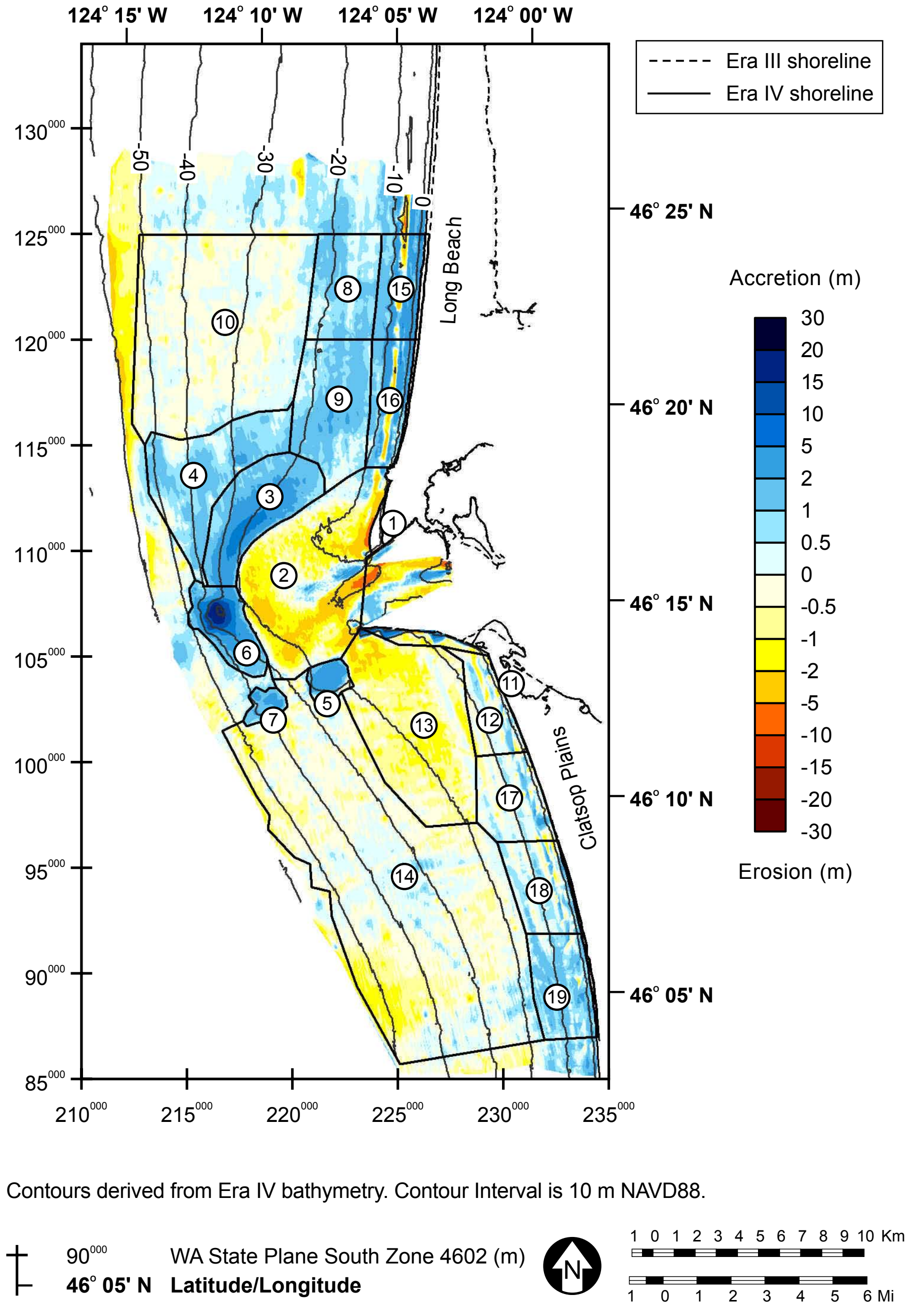


Figure 3-16. Bathymetric and topographic change for Interval 3 at the Columbia River entrance, Long Beach, and Clatsop Plains.

Table 3-16. Bathymetric and topographic change for Interval 3 at the Columbia River entrance, estuary, Long Beach, and Clatsop Plains.

Interval 3 ~41 years	Area (km^2)	ΔV (Mm^3)	Δh (m)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
Peacock Spit (1)	-1.05	-7.48	n/a	-0.18	n/a
Inner delta (2)	43.47	-47.07	-1.08	-1.15	-0.026
Outer delta (3)	18.41	45.13	2.45	1.10	0.060
North Delta (4)	24.23	22.02	0.91	0.54	0.022
Disposal site A (5)	3.01	6.57	2.19	0.16	0.053
Disposal site B (6)	9.53	45.79	4.80	1.12	0.117
Disposal site F (7)	2.35	3.85	1.63	0.09	0.040
Subtotal	**n/a**	**68.81**	**n/a**	**1.68**	**n/a**
Long Beach[1)]	7.70	127.04	n/a	3.10	n/a
LBc2_off (8)	15.22	13.38	0.88	0.33	0.021
LBc1_off (9)	21.54	22.64	1.05	0.55	0.026
Sum	**n/a**	**163.05**	**n/a**	**3.98**	**n/a**
Subtotal	**n/a**	**231.86**	**n/a**	**5.66**	**n/a**
Clatsop Spit (11)	0.02	0.03	n/a	0.00	n/a
CPdn_near (12)	9.27	0.34	0.04	0.01	0.001
Clatsop Plains[2)]	n/a	50.48	n/a	1.23	n/a
South flank (13)	41.35	-30.27	-0.73	-0.74	-0.018
Sum	**n/a**	**20.57**	**n/a**	**0.50**	**n/a**
Subtotal	**n/a**	**252.44**	**n/a**	**6.16**	**n/a**
LB_off (10)	72.54	-5.13	-0.07	-0.13	-0.002
CP_off (14)	130.43	-25.84	-0.20	-0.63	-0.005
Sum	**n/a**	**-30.97**	**n/a**	**-0.76**	**n/a**
Net Change	**n/a**	**221.46**	**n/a**	**5.40**	**n/a**
LBc2_near (15)	9.97	17.71	1.78	0.43	0.043
LBc1_near (16)	10.44	14.10	1.35	0.34	0.033
CPc5_near (17)	12.59	2.52	0.20	0.06	0.005
CPc4_near (18)	11.93	5.18	0.43	0.13	0.011
CPc3_near (19)	13.31	13.55	1.02	0.33	0.025

[1)] Includes compartments LBc1 - LBc7 and LBdn.
[2)] Includes compartments CPc1 - CPc5.

Table 3-17. Bathymetric and topographic change for Interval 3 at Long Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
LBn	3320	1.92	11.33	1.49	9.84	5.91	0.78	5.13	14.10	83.26	10.94
LBc7	5589	0.68	12.61	1.29	11.33	18.60	1.90	16.71	2.96	55.04	5.61
LBc6	4261	0.54	10.50	1.51	8.99	19.51	2.80	16.71	3.08	60.08	8.63
LBc5	4980	0.60	12.41	2.36	10.05	20.64	3.93	16.71	2.95	60.78	11.58
LBc4	5020	0.85	17.47	3.20	14.26	20.46	3.75	16.71	4.15	84.88	15.57
LBc3	5000	1.09	22.65	4.38	18.26	20.71	4.01	16.71	5.33	110.47	21.37
LBc2	5000	1.10	22.68	3.69	18.99	20.55	3.35	17.20	5.39	110.66	18.02
LBc1	6300	0.91	17.39	2.65	14.74	19.13	2.92	16.21	3.52	67.33	10.27
sum	**n/a**	**n/a**	**127.04**	**20.58**	**106.46**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
LBds	3403	-1.05	-7.48	-3.19	-4.29	n/a	3.05	n/a	-7.49	n/a	-22.84

1) Excluding LBds.

Table 3-18. Bathymetric and topographic change for Interval 3 at Clatsop Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
CPdn	4471	0.02	0.03	0.03	0.00	n/a	1.65	n/a	0.09	n/a	0.15
CPc5	4318	0.07	2.89	0.38	2.52	39.62	5.18	34.45	0.41	16.35	2.14
CPc4	4388	0.46	8.46	2.99	5.47	18.36	6.49	11.87	2.56	47.01	16.62
CPc3	5140	0.58	18.12	4.28	13.84	31.43	7.42	24.02	2.73	85.97	20.29
CPc2[2)]	4788	n/a	14.91	n/a	n/a	n/a	n/a	n/a	n/a	75.98	n/a
CPc1[2)]	4812	n/a	6.09	n/a	n/a	n/a	n/a	n/a	n/a	30.87	n/a
Sum[1)]	**n/a**	**n/a**	**50.48**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

1) Excluding CPdn.
2) CPc1 and CPc2 are based on a proportional relation between CPc3, CPc2, and CPc1 (Appendix E).

Analysis

The adjustment of the morphology at the Columbia River entrance due to jetty construction continued in Interval 3. The Inner Delta, Inlet, and South Flank continued to erode, whereas Long Beach and Clatsop Plains continued to accrete.

The Outer Delta (3) continued growing westward, accumulating 45 Mm^3, and an additional 56 Mm^3 accumulated at dredge disposal sites A, B, and F (compartments 5, 6, and 7, respectively). During this interval, approximately 3.4 Mm^3/yr of mostly sand was removed from the entrance channel by dredging (Appendix D). Approximately 88 Mm^3 was placed in disposal sites A, B, and F, suggesting that approximately 33 Mm^3 (0.8 Mm^3/yr) dispersed. The Inner Delta (2) and Peacock Spit (1) continued to erode, loosing approximately 55 Mm^3.

The beach-dune complex of Long Beach accreted 127 Mm^3. The combined compartments LBc2_off (8) and LBc1_off (9) accreted 36 Mm^3. The prevailing transport directions are northward, suggesting that the majority of the sand that accreted along Long Beach came from the south.

During Interval 3, the shoreline at Clatsop Spit (CPdn, compartment 11) stabilized, and CPdn_near (12) accreted 0.3 Mm^3. The beach-dune complex of Clatsop Plains (CPc1 - CPc5) accreted by 50 Mm^3. South of the South Jetty, the South Flank (13) lost 30 Mm^3. Sand from the South Flank might have moved onshore and southward to contribute to the accretion of Clatsop Plains. The net change along Clatsop Plains (CPc1 - CPc5 and compartments 11, 12, and 13) is 21 Mm^3 more accretion than erosion. The erosion of CP_off (26 Mm^3) is within the uncertainty of the bathymetric change. However, the net accretion of 21 Mm^3 along Clatsop Plains can be balanced with sand supplied from compartment CP_off.

The net change over the study area (including compartments 10 and 14) is 221 Mm^3 accretion. It is not possible to balance the budget along Long Beach with sand that eroded from the Columbia River entrance and/or the shelf along Clatsop Plains. These volume calculations include the adjustment of the Era III surveys by an extra -0.29 m. If we neglect this adjustment, the observed net accretion decreases by approximately 95 Mm^3 (excluding the shelf along Long Beach and Clatsop Plains, compartments 10 and 14), or by approximately 150 Mm^3 (including compartments 10 and 14). Without the adjustment of -0.29 m, the active depth of 16.7 m below MHW along Long Beach, based on the bathymetric change of compartments LBc1_near and LBc2_near, decreases to 13.1 m below MHW. If we use 13.1 m instead of 16.7 m, the volume change of the beach-dune complex of Long Beach is 106 Mm^3 instead of 127 Mm^3. In addition, the imbalance in the sand budget might be due to the incomplete bathymetric coverage of the inlet, Columbia River estuary, and shelf along northern Long Beach and southern Clatsop Plains. In the sediment balance, we do not include losses due to the northward littoral drift at northern Long Beach of 57 Mm^3 (1.4 Mm^3/yr; KAMINSKY et al., 2000) and gains to the estuary due to Columbia River sand supply of 57 Mm^3 (1.4 Mm^3/yr, Appendix B).

3.3.3 Regional Barrier-Change Rates

Regional ΔV-, $\Delta V_{>MHW}$-, and Area-change rates of Interval 3 normalized by compartment length are presented in Figure 3-17 and Figure 3-18. The volume- and area-change rates for North Beach, Grayland Plains, Long Beach, and Clatsop Plains are presented in Table 3-14, Table 3-15, Table 3-17, and Table 3-18 as well. No Era III shoreline data is available for the southern compartments CPc1 and CPc2. The volumes ΔV of these compartments are estimated based on the shoreline progradation between Era II and Era IV. The duration of Interval 3 at North Beach and Grayland Plains is approximately 45 years and the duration at Long Beach and Clatsop Plains is approximately 41 years.

In comparison to Interval 2, the shoreline-progradation rates are generally smaller in Interval 3. The shoreline progradation rate at NBds decreases from 14 m/yr in Interval 2 to 3 m/yr in Interval 3. The shoreline along GLdn advanced 4 m/yr in Interval 2, but receded 4 m/yr in Interval 3. The shoreline advance at LBds of 12 m/yr in Interval 2 reverses to a recession of 7 m/yr in Interval 3. Northern Clatsop Plains deviates from this trend; the shoreline at CPdn receded 7 m/yr in Interval 2 and advanced little by 0.09 m/yr in Interval 3. The retreat at northern Long Beach (LBc5 - LBc7 and LBdn) of -1 - -7 m/yr reverses to progradation of 3 - 14 m/yr, resulting in more net accretion of the entire Long Beach sub-cell than in Interval 2. The high shoreline progradation rates of 14 m/yr at Leadbetter Point (LBdn) are due to the northward expansion of the spit. Central Grayland Plains remains stable, with shoreline retreat in the north up to 3 m/yr and shoreline advance in the south up to 4 m/yr as a result of the northward migrating Willapa Bay ebb-tidal delta.

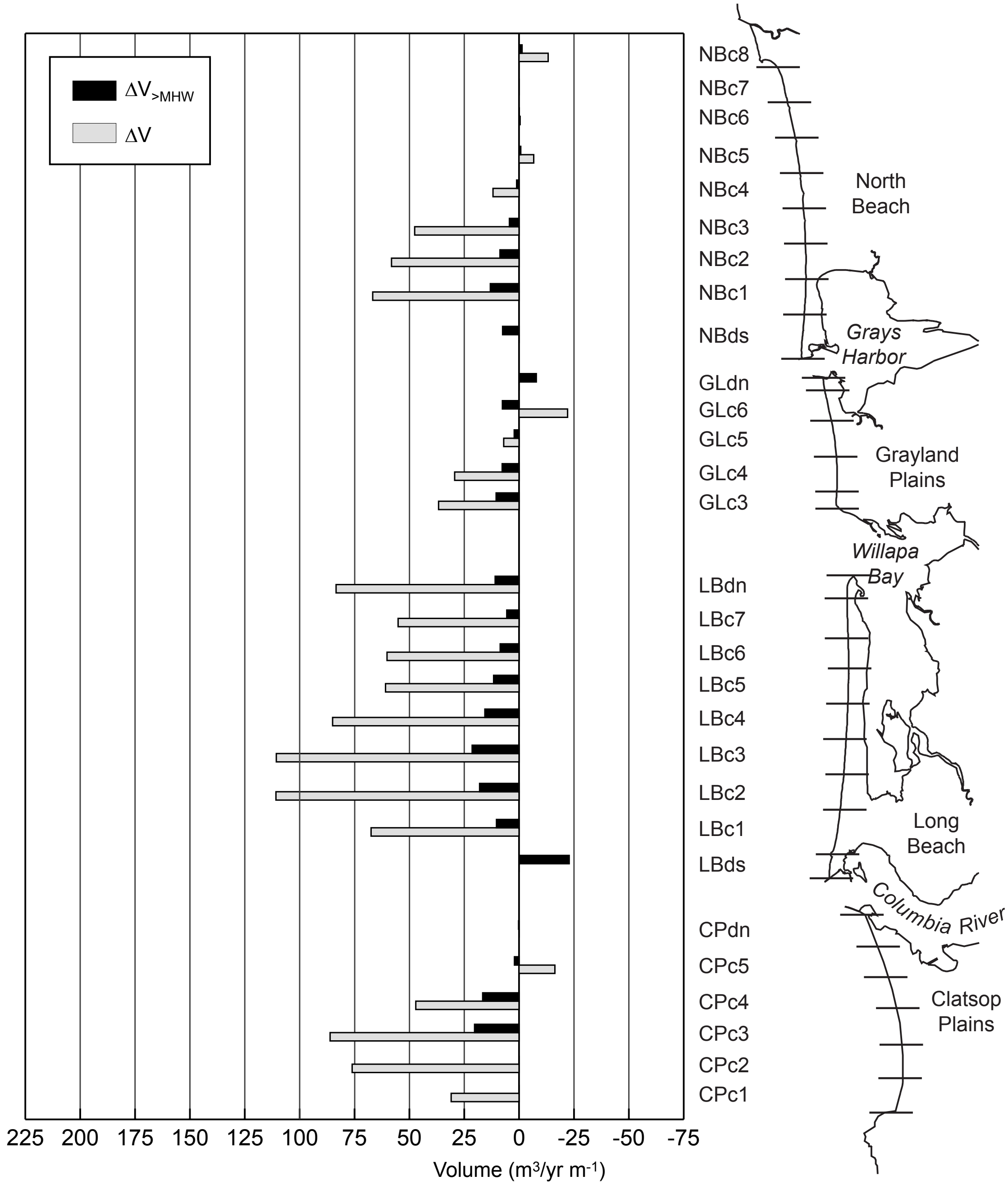


Figure 3-17. Bathymetric and topographic volume-change rates per compartment normalized by compartment length for Interval 3 along the CRLC. The duration of Interval 3 at North Beach and Grayland Plains is 45 years, and the duration of Interval 3 at Long Beach and Clatsop Plains is 41 years. ΔV represents the total volume change of the barrier compartments, and ΔV_{MHW} represents the volume change above MHW.

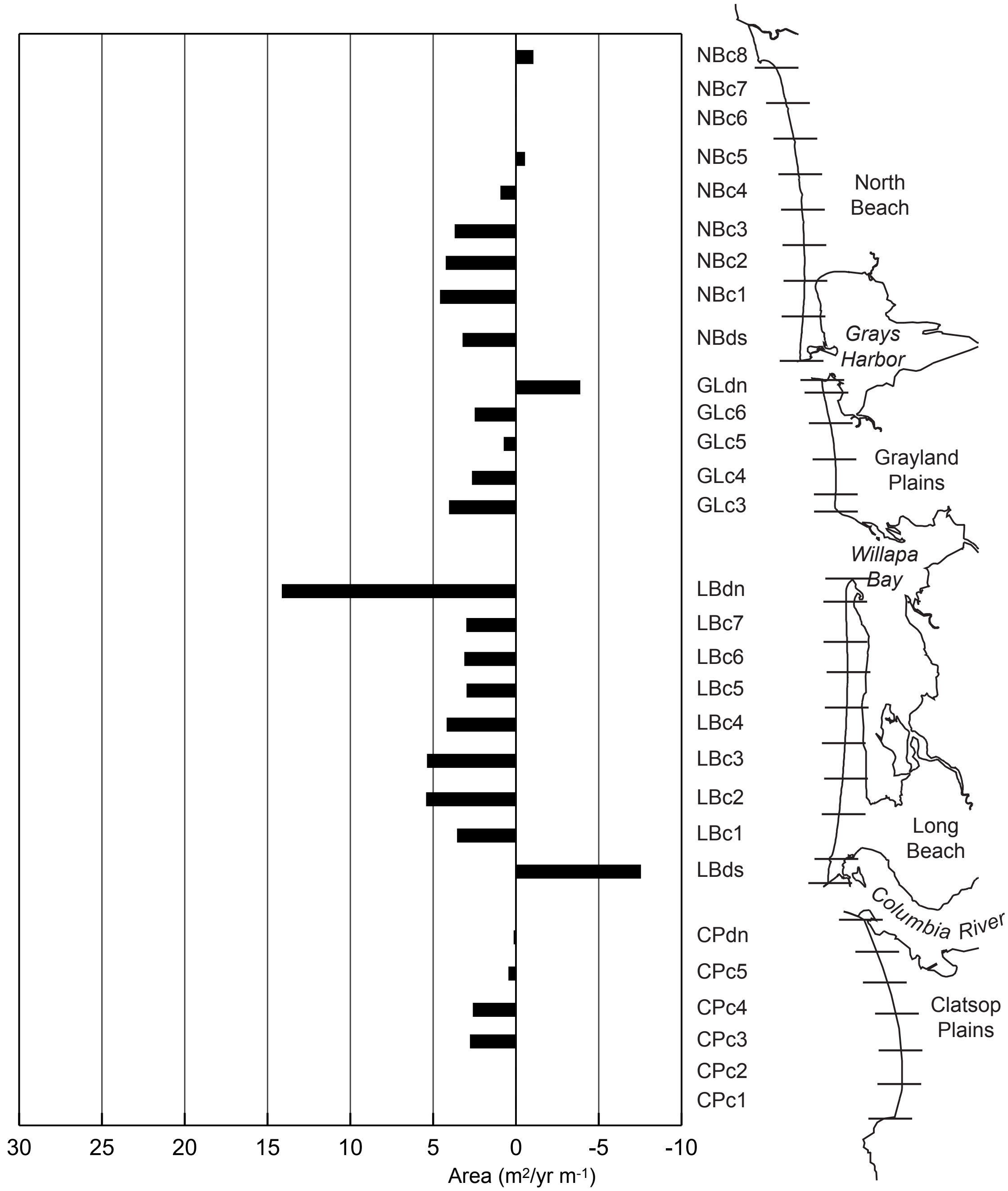


Figure 3-18. Area-change rates per compartment normalized by compartment length for Interval 3 along the CRLC. The duration of Interval 3 at North Beach and Grayland Plains is 45 years, and the duration of Interval 3 at Long Beach and Clatsop Plains is 41 years.

3.4 Interval 4 (1920s to 1990s)

3.4.1 Grays Harbor and Willapa Bay Entrances and Adjacent Coasts

Topographic- and Bathymetric-Volume Change

Interval 4 comprises bathymetric change between Era II and Era IV at southern North Beach, Grayland Plains, and the entrances to Grays Harbor and Willapa Bay. We do not calculate bathymetric change at the location of the H4728 survey (except at the Grays Harbor delta) due to the poor quality of this survey. The results for the Interval 4 bathymetric-volume change are presented in Figure 3-19, Table 3-19, Table 3-20, and Table 3-21. The format of these tables is explained in Section 3.1.1.

Due to the limited data coverage in deeper water, RMS and mean differences along the alongshore-averaged profiles at Grayland Plains are not calculated (Sections 2.4.2 and 2.6.1). The RMS and mean differences calculated along cross-shore Transects A and B for Interval 2 (Table 2-11) are biased by the irregularities in the USC&GS H4728 survey, and they are not a good representation of the uncertainties of the volume changes. We use the difference between the Era II and Era IV adjustments as an estimate of the uncertainty. The uncertainty along North Beach is 0.1 m (0.46 m - 0.36 m), along Grayland Plains 0.30 m (0.46 m - 0.16 m), and at the inner delta and inlet -0.65 m (0.46 m - 1.11 m).

We assume that the compartments NBds (1), GLdn (11), and GLc3 (15) were part of the Grays Harbor and Willapa Bay ebb-tidal delta complexes during Interval 4. Therefore they are grouped with the volume changes at the Grays Harbor and Willapa Bay ebb-tidal deltas in Table 3-19. Compartments NBds, GLdn, and GLc3 only comprise volumes V_1 and V_2 (Figure 2-21). The volume below MHW ($\Delta V_{<MHW}$) of NBds, GLdn, GLc3 and in Table 3-14 and Table 3-15 only include volume V_2. North Beach and Grayland Plains in Table 3-19 comprise compartments NBc1 - NBc8, and GLc4 - GLc6, respectively. The volumes of these compartments consist of the subaerial and subaqueous volumes V_1, V_2, and V_3.

Compartment NBc1_near (22) does not extend to the northern boundary of NBc1 (195 km N). We calculate the volume below MHW of NBc1 (29.99 Mm^3) using the proportional relation between the horizontal area of NBc1 (2.55 km^2), the horizontal area of NBc1* (1.91 km^2), and the sum (22.47 Mm^3) of the volume of NBc1_near (16.95 Mm^3) and the volume of NBc1* below MHW (volume V_2, 5.53 Mm^3). The subaerial compartment NBc1* is smaller than NBc1 and is shown in Figure 3-19. The calculated volume of NBc1 below MHW is presented in Table 3-20 and is included in the volume of the North Beach compartment in Table 3-19. We use the active depth of 11.77 m below MHW of NBc1 to estimate the volumes below MHW of compartments NBc2 - NBc8 for this and all previous intervals.

The volume of Oyhut (5) is calculated by subtracting the 3-m plane from the Era II surface and the volume of Pt. Chehalis (8) is calculated by subtracting the Era IV surface from the 3-m plane. We estimate the erosion of Cape Shoalwater (18) by summing the volume change between the 3-m plane and the Era IV surface and the horizontal area multiplied by an assumed dune height of 3 m above the 3-m plane.

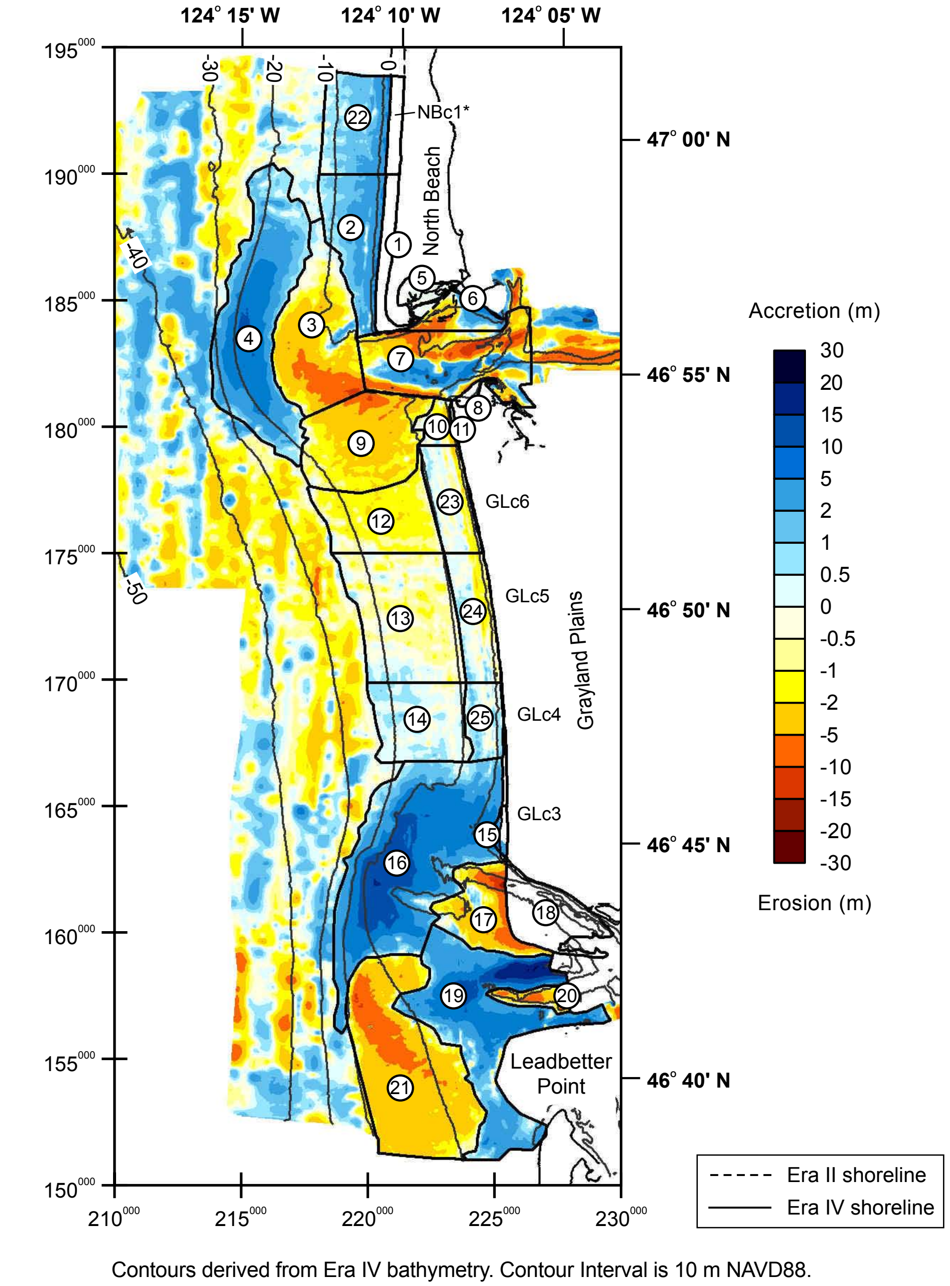


Figure 3-19. Bathymetric and topographic change for Interval 4 at the Grays Harbor and Willapa Bay entrance, North Beach, and Grayland Plains.

Table 3-19. Bathymetric and topographic change for Interval 4 at the Grays Harbor and Willapa Bay entrance, North Beach, and Grayland Plains.

Interval 1 ~73 yr	Area (km^2)	ΔV (Mm^3)	Δh (m)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
NBds (1)	3.41	17.16	n/a	0.24	n/a
NBds_near (2)	10.72	24.02	2.24	0.33	0.031
Inner Delta (3)	17.49	-47.09	-2.69	-0.65	-0.037
Outer Delta (4)	26.15	95.53	3.65	1.31	0.050
Oyhut (5)	1.79	1.89	1.06	0.03	0.014
Inlet_north (6)	3.96	-1.41	-0.36	-0.02	-0.005
Inlet (7)	17.24	-29.30	-1.70	-0.40	-0.023
Pt. Chehalis (8)	-0.50	-2.65	5.34	-0.04	0.073
South Flank (9)	15.97	-41.57	-2.60	-0.57	-0.036
GLdn_near (10)	2.05	-2.20	-1.07	-0.03	-0.015
GLdn (11)	-0.18	-0.53	n/a	-0.01	n/a
Sum	**n/a**	**13.85**	**n/a**	**0.19**	**n/a**
North Beach[1) 3)]	8.03	112.76	n/a	1.54	n/a
Subtotal	**n/a**	**126.61**	**n/a**	**1.73**	**n/a**
Grayland Plains[2)]	0.97	1.46	n/a	0.02	n/a
Subtotal	**n/a**	**128.07**	**n/a**	**1.75**	**n/a**
GLc6_off (12)	11.84	-13.87	-1.17	-0.19	-0.016
GLc5_off (13)	20.19	-7.76	-0.38	-0.11	-0.005
GLc4_off (14)	11.12	2.85	0.26	0.04	0.004
Sum	**n/a**	**-18.78**	**n/a**	**-0.26**	**n/a**
Subtotal	**n/a**	**109.28**	**n/a**	**1.50**	**n/a**
GLc3 (15)	0.84	5.06	n/a	0.07	n/a
WB_delta_north (16)	36.87	219.63	5.96	3.01	0.082
WB_chan_north (17)	8.46	-28.74	-3.40	-0.39	-0.047
Cape Shoalwater (18)	-8.01	-123.94	n/a	-1.70	n/a
WB_chan_west (19)	26.31	134.85	5.13	1.85	0.070
WB_chan_south (20)	2.12	-5.59	-2.63	-0.08	-0.036
WB_delta_south (21)	28.03	-95.56	-3.41	-1.31	-0.047
Sum	**n/a**	**105.71**	**n/a**	**1.45**	**n/a**
Net Change	**n/a**	**215.00**	**n/a**	**2.95**	**n/a**
NBc1_near (22)	10.06	16.95	1.69	0.23	0.023
GLc6_near (23)	6.66	-1.68	-0.25	-0.02	-0.003
GLc5_near (24)	7.40	-2.00	-0.27	-0.03	-0.004
GLc4_near (25)	4.21	1.83	0.43	0.03	0.006

[1)] Includes compartments NBc1 - NBc8.
[2)] Includes compartments GLc3 - GLc6.
[3)] Based on the extrapolated volume of NBc1*.

Table 3-20. Bathymetric and topographic change for Interval 4 at North Beach.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
NBc8	1000	-0.05	-0.60	-0.06	-0.53	13.14	1.36	11.77	-0.62	-8.16	-0.85
NBc7	5000	0.00	0.00	0.00	0.00	13.14	1.36	11.77	0.00	0.00	0.00
NBc6	5000	0.25	3.24	0.34	2.91	13.14	1.36	11.77	0.68	8.88	0.92
NBc5	5000	0.29	3.94	0.48	3.46	13.39	1.62	11.77	0.81	10.79	1.30
NBc4	5000	0.80	10.38	0.99	9.40	13.01	1.23	11.77	2.19	28.45	2.70
NBc3	5000	1.81	24.19	2.88	21.31	13.36	1.59	11.77	4.96	66.27	7.89
NBc2	5000	2.38	34.26	6.23	28.03	14.39	2.62	11.77	6.52	93.86	17.06
NBc1	5000	2.55	37.34[2)]	7.36	29.99[2)]	14.66[2)]	2.89	11.77[2)]	6.98	102.31[2)]	20.16
Sum[1)]	**n/a**	**n/a**	**112.76**	**18.20**	**94.56**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
NBds	6307	3.41	17.16	7.99	9.18	n/a	2.34	n/a	7.40	37.27	17.34

[1)] Excluding NBds.
[2)] Based on the extrapolated volume of NBc1*.

Table 3-21. Bathymetric and topographic change for Interval 4 at Grayland Plains.

Comp.	Length (m)	Area (km^2)	ΔV (Mm^3)	$\Delta V_{>MHW}$ (Mm^3)	$\Delta V_{<MHW}$ (Mm^3)	h_{active} (m)	$h_{>MHW}$ (m)	$h_{<MHW}$ (m)	Rate Area ($m^2/yr\ m^{-1}$)	Rate ΔV ($m^3/yr\ m^{-1}$)	Rate $\Delta V_{>MHW}$ ($m^3/yr\ m^{-1}$)
GLdn	1807	-0.2	-0.5	-0.4	-0.2	n/a	2.1	n/a	-1.34	n/a	-2.76
GLc6	4259	0.1	-1.3	0.4	-1.7	-10.4	3.1	-13.4	0.40	-4.11	1.22
GLc5	5105	0.1	-1.6	0.4	-2.0	-12.4	3.2	-15.5	0.35	-4.27	1.09
GLc4	4895	0.7	4.3	2.1	2.2	6.1	2.9	3.1	2.00	12.12	5.84
Sum[1)]	**n/a**	**n/a**	**1.5**	**2.9**	**-1.4**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
GLc3	2250	0.8	5.1	2.2	2.8	n/a	2.6	n/a	5.14	n/a	13.43

[1)] Excluding GLdn and GLc3.

Analysis

The morphologic changes in Interval 4 have similar trends as the changes in Interval 2 and 3. The outer ebb-tidal delta, the beach-dune complexes of North Beach and Grayland Plains accreted, whereas the inlet, inner delta and shoreface along Grayland Plains eroded.

Compartments 5, 6, 7, and 8, Inner Delta (3), and South Flank (9) eroded 120 Mm^3, contributing to the accretion of 96 Mm^3 of the Outer Delta (4) and 113 Mm^3 of North Beach (excluding NBds). Although nearshore Grayland Plains eroded, the shoreline prograded, resulting in a net gain of 1.5 Mm^3 of Grayland Plains (GLdn and GLc3 not included). The shoreface offshore Grayland Plains (compartments 12 and 13) eroded 22 Mm^3. We assume that this sand was transported northward and contributed to the accretion of the Outer Delta and North Beach. The net change over the study area north of the Willapa Bay entrance is an observed accretion of 109 Mm^3.

Due to the northern migration of the Willapa Bay North Channel, the ebb-shoal of the Willapa Bay ebb-tidal delta accreted 225 Mm^3 at the north flank (compartments 15 and 16) and eroded 96 Mm^3 at the South Flank (compartment 21). In addition, the channel eroded 153 Mm^3 to the north (compartments 17 and 18) and accreted 135 Mm^3 to the south (compartment 19). The Cape Shoalwater (18) shoreline retreated northward approximately 3 km. The net change over all compartments at the Willapa Bay entrance is 106 Mm^3 accretion.

Dredging and disposal of sediment at the Grays Harbor entrance during Interval 4 is discussed in Section 3.2.1, Section 3.3.1, and Appendix C. The effect of dredging and disposal of sediment on the sediment budget of Interval 4 is small and is neglected.

The majority of the bathymetric changes are larger than the estimated uncertainties. The net balance for the study area is 215 Mm^3 accretion. If we ignore all Era II tidal-datum adjustments, the net accretion of 109 Mm^3 of the study area north of the Willapa Bay entrance decreases by approximately 15 Mm^3, and the net accretion of 106 Mm^3 of the Willapa Bay entrance decreases by approximately 15 Mm^3. If we reduce both the Era II and Era IV surveys to MLLW, the net accretion increases by approximately 10 Mm^3. The sediment input at the southern boundary of 1.4 Mm^3/yr (KAMINSKY et al., 2000) might account for 102 Mm^3 of the observed accretion. Thus, even if all possible adjustments are met, the budget remains unbalanced with an observed net accretion of 83 Mm^3. Possible explanations for this are the incomplete coverage of the tidal basins of Grays Harbor and Willapa Bay and the seafloor offshore North Beach and Grayland Plains.

4 DISCUSSION

In this section we discuss the temporal and spatial scales of the morphologic and bathymetric changes, sediment balances, sediment transport pathways, and the uncertainty of the volume changes.

4.1 Temporal and Spatial Scales of Morphologic Changes

4.1.1 Shoreline Change

We calculate shoreline-change rates by dividing the horizontal-area change of each sub-cell (including the spits adjacent to the entrances) by the alongshore distance and the interval duration and compare these rates to pre-jetty accretion rates based on WOXELL (1998) (Table 4-1). The alongshore lengths used for the calculation of the shoreline-change rates vary per interval, and the lengths of the Grayland Plains and Clatsop Plains sub-cells in Table 4-1 are not representative for all intervals. WOXELL measured the accretion between the earthquake-erosion scarps resulting from the 1700 Cascadia subduction zone earthquake event (SATAKE et al, 1996) and the Era I shoreline positions along all sub-cells. Following jetty construction, the average accretion rates soared along North Beach, Grayland Plains, Long Beach, and Clatsop Plains. The average accretion rates along Grayland Plains and Clatsop Plains are highest during Interval 1 and the accretion rates along North Beach are highest during Interval 2. Long Beach deviates from this trend and has the highest accretion rates during Interval 3.

Table 4-1. Shoreline-change rates for each sub-cell.

Sub-cell	Sub-cell Length (km)	1700 - Era I[1) 4)] (m/yr)	Interval 1[3)] (m/yr)	Interval 2[3)] (m/yr)	Interval 3[3)] (m/yr)	Interval 4[3)] (m/yr)
North Beach	42.31	0.98[2)]	4.70	6.51	1.96	3.70
Grayland Plains	19.54[6)]	0.98	8.79	0.91	1.56	1.22
Long Beach	42.87	0.28	1.70	2.86	3.78	n/a
Clatsop Plains	27.92[7)]	0.54	4.37	2.89[5)]	1.50[5)]	n/a

[1)] From WOXELL (1998).
[2)] Calculated for the southern 29 km.
[3)] Including spits NBds, GLdn, LBds, and CPdn.
[4)] Duration along North Beach, Grayland Plains, Long Beach, and Clatsop Plains is 186 years, 186 years, 172 years, and 185 years, respectively.
[5)] Calculated along compartments CPdn, CPc5, CPc4, and CPc3.
[6)] Length averaged over Intervals 1 - 3 ; length changes due to northward erosion of GLc3.
[7)] Length calculated for Interval 1.

The temporal and spatial scales of the morphologic changes along the CRLC for Interval 1, 2, and 3 are reflected in the area- and volume-change rates in Figure 4-1 and Figure 4-2, respectively. The area and volume changes of the beach-dune complex are normalized by alongshore compartment length and interval duration. Following jetty construction, in Interval 1, the largest morphologic changes occurred directly adjacent to the entrance jetties at North Beach, Long Beach, and Clatsop Plains. Grayland Plains, however, accreted along its entire coastline with shoreline-change rates between 6 m/yr and 10 m/yr.

During Interval 2, along North Beach, Long Beach, and Clatsop Plains, the regions of greatest accumulation shifted away from the Grays Harbor and Columbia River entrances. The accretion rates decrease at the spits NBds, GLdn, and LBdn and reverse to erosion at CPdn, whereas the accretion rates of the central coasts of North Beach, Long Beach, and Clatsop Plains increase. We hypothesize that the erosion at northern Long Beach during Interval 2 is related to processes at the Willapa Bay entrance, e.g., channel migration.

The morphologic behaviour of Grayland Plains during all intervals differs from the other sub-cells (see Section 4.3). In comparison to Interval 1, the accumulation rates along Grayland Plains are significantly smaller during Intervals 2, 3, and 4. During these three intervals, the shoreline along southern Grayland Plains advanced due to the northward migration of the Willapa Bay delta. During the late 1920s and 1930s the shoreline along northern Grayland Plains receded as a result of jetty deterioration and advanced as a result of jetty rehabilitation (1935 - 1940) and local sand supply. Along the central Grayland Plains (GLc5), very little shoreline change occurred during Intervals 2, 3 and 4.

During Interval 3, the net accumulation along North Beach, southern Long Beach, and Clatsop Plains decreases. Peacock spit (LBds) eroded, and Clatsop spit (CPdn) stabilized.

4.1.2 Bathymetric Change

In this section, we discuss the vertical-change rates of the bathymetric compartments. Table 4-2 and Table 4-3 present volume changes and (vertical) change rates for compartments at the Grays Harbor and Columbia River entrances, respectively. The compartment numbers in these tables refer to the approximate locations of the compartments shown in Figure 4-3. The numbers in these tables are compiled from tables presented in Section 3. Most of the compartments (e.g., the North Beach Shelf (1), Outer Delta (3), and Inlet Spits and Bays) in Table 4-2 and Table 4-3 consist of multiple compartments. “Subtotal” in Table 4-2 and Table 4-3 is similar to “Net Change” in the tables in Section 3. In Table 4-2, “Input from South“ represents an estimate of the northward sediment flux at southern Grayland Plains of 0.8 Mm^3/yr (Section 3.1.1; KAMINSKY et al., 2000). In Table 4-3, “Loss out North” is an estimate of the northward sediment flux at northern Long Beach of 1.4 Mm^3/yr (Section 3.1.1; KAMINSKY et al., 2000), “Omission Estuary” represents the volume of the area of land that was omitted from the surveyed area (Sections 3.1.2 and 3.2.2; SHERWOOD et al., 1990), “Dredging Estuary” represents the volume of sediment dredged from the Columbia River estuary as estimated by SHERWOOD et al. (1990) (Sections 3.1.2 and 3.2.2), and the "Columbia River Supply" is the supply of sand to the Columbia River estuary (Appendix B; SHERWOOD et al. (1990). In Table 4-2 and Table 4-3, "Net Change" is the sum of the bathymetric and topographic changes, losses and gains. A negative (-) value of the "Net Change" indicates net erosion, i.e., export of sand. A positive (+) value indicates net accretion, i.e., import of sand.

During the last century, the morphologic changes at both the Grays Harbor and Columbia River entrances are similar in form and of the same order of magnitude. Following jetty construction, the vertical-change rates at the entrances are largest in either Interval 1 or Interval 2 and decrease during Interval 3 and Interval 4.

At the Grays Harbor entrance, the Inner Delta (compartment 4), Inlet (5), South Flank (6), and Grayland Plains Shelf (9) lowered by 0.075 m/yr, 0.061 m/yr, 0.068 m/yr, and 0.032 m/yr, respectively, during Interval 1, and these rates decrease to 0.037 m/yr, 0.023 m/yr, 0.036 and 0.006 m/yr, respectively, during Interval 4. The difference in lowering of the bathymetric surfaces within these compartments over these two intervals represents a decrease in rates of change between 48% and 81%. The largest vertical accretion of the Outer Delta (3) occurs during Interval 2 by 0.115 m/yr, and decreases in Interval 3 by 67% to 0.038 m/yr.

The majority of the changes at the Columbia River entrance happened following construction of the South Jetty in 1885. Old USACE surveys of the entrance (HANS R. MORITZ, USACE, personal communication, 1999) do not show major morphologic change during the 17-year period from 1868 to 1885, and therefore, the change rates can be biased by the long interval duration of 58 years. During Interval 1, the Inner Delta (compartment 14) and South Flank (19) lowered by 0.12 m/yr and 0.057 m/yr, respectively, and during Interval 3, these rates decrease to 0.026 m/yr and 0.018 m/yr, respectively. The difference in lowering of the bathymetric surfaces within these compartments over these two intervals represents a decrease in rates of change of 78% and 76%, respectively. Similar to the Grays Harbor entrance, the largest vertical accretion of the Outer Delta (13) occurs during Interval 2 by 0.177 m/yr, and decreases in Interval 3 by 66% to 0.06 m/yr.

The vertical-change rates at the Flood-tidal Delta (17) in the Columbia River estuary are 0.008 m/yr in Interval 1 and decrease by 34% to 0.005 m/yr in Interval 2. Following jetty construction, sand from the inlet may have moved to the flood-tidal delta, producing the higher accretion rates observed in Interval 1. The accretion rates of the more river-dominated Upper Estuary (18) remain constant at 0.003 m/yr in Interval 1 and Interval 2. If we include Omission in both intervals and Dredging in Interval 2, the Upper Estuary accretes by approximately 0.003 m/yr during Interval 1 and 0.009 m/yr during Interval 2.

4.1.3 Summary

We summarize that the shoreline-change rates as well as the vertical-change rates in the bathymetric surfaces are largest during either Interval 1 or Interval 2, except at Long Beach, and that these rates (significantly) decrease during Interval 3 and Interval 4. This response to jetty construction of the coastal system (i.e., the shelf and back barriers) of the CRLC suggests the system is approaching dynamic equilibrium.

4.2 Sediment Balances and Transport Pathways

In this section, we use the bathymetric- and topographic-volume changes (Table 4-2 and Table 4-3) to infer sediment transport pathways in the CRLC. Qualitative transport pathways averaged over bathymetric-change Intervals 1, 2, and 3 along the CRLC are presented in Figure 4-4.

4.2.1 Grays Harbor Entrance and Adjacent Coasts

Sand in the northern most portion of the CRLC (North Beach to Pt. Grenville) has as its source the Columbia River (PETERSON et al., 1991). Bedrock is exposed on the inner shelf off North Beach, and is only covered by a thin veneer of sand with a thickness < 10 m (WOLF et al., 1997), making it unlikely that sand for the accelerated accretion along North Beach following jetty construction at the Grays Harbor entrance came from offshore. Thus, we infer that sand that accreted along North Beach came from the south. The accretion of North Beach and the Outer Delta in all intervals can not be compensated for by the erosion of the Inlet and Inner Delta at the Grays Harbor entrance. This implies that sand either came from the south and bypassed the Grays Harbor delta, or it came from the Grays Harbor tidal basin.

During Interval 1, the South Flank of the Grays Harbor delta and the Grayland Plains Shelf eroded by 3.27 Mm^3/yr (108 Mm^3), possibly accreting the beach-dune complex of Grayland Plains by 1.73 Mm^3/yr (57 Mm^3). The remainder may have been transported northward to contribute to the accretion of the Outer Delta and North Beach sub-cell by 79 Mm^3 (2.4 Mm^3/yr). The net change over all bathymetric changes is 42 Mm^3 erosion. If we account for the estimate of the northward sediment flux at southern Grayland Plains of 0.8 Mm^3/yr (26 Mm^3) the net balance amounts to erosion of 68 Mm^3 (Table 4-2).

The sand budget does not balance in Intervals 2 and 3. The volume change in interval 2, including the sediment influx at southern Grayland Plains, is 129 Mm^3/yr (4.59 m/yr) net accretion. The balance over Interval 3 for all bathymetric changes, including the influx of 0.8

Mm^3/yr at southern Grayland Plains is 34 Mm^3 (0.76 Mm^3/yr) net erosion. Possibly, the net accretion in Interval 2 and the net erosion in Interval 3 are due to the lack of bathymetric coverage, mainly of the shelf along Grayland Plains. Or it may be due to the Era III tidal-datum adjustments (see Section 4.4). However, the sediment balances of Intervals 2 and 3 do not cancel, leaving a net accretion of 60 Mm^3, which must represent an extra influx of sand from the shelf, the south, and/or from Grays Harbor tidal basin.

The accretion at the Outer Delta (3) and the beach-dune complex of North Beach by 3.4 Mm^3/yr (249 Mm^3) can not be compensated for by sand that eroded from the Inlet (5), Inner Delta (4), South Flank (6) and Grayland Plains Shelf (9) by 1.9 Mm^3/yr (140 Mm^3) during Interval 4. To balance the budget, an influx of 1.5 Mm^3/yr (109 Mm^3) is needed. The Willapa Bay North Channel started its northward movement in late 1800s to early 1900s (TERICH and LEVENSELLER, 1986), resulting in the erosion of Cape Shoalwater beginning in the early 1900s and the northward migration of the Willapa Bay ebb-tidal delta. During Interval 4, the Willapa Bay Delta, including Cape Shoalwater accreted by 106 Mm^3 (1.45 Mm^3/yr). Possibly, the erosion of Cape Shoalwater contributed to the accretion of the north flank of the Willapa Bay ebb-tidal delta. The balance over the volume changes at the Grays Harbor and Willapa Bay entrances, including a southerly influx of 1.4 Mm^3/yr (102 Mm^3) at northern Long Beach is 1.55 Mm^3/yr (113 Mm^3) net accretion. Unfortunately, there is insufficient bathymetric coverage of the shelf along North Beach, the Grays Harbor tidal basin, and Willapa Bay.

4.2.2 Columbia River Entrance and Adjacent Coasts

During the last century, the morphologic changes and transport pathways at the Columbia River entrance are similar to those at the Grays Harbor entrance. The erosion of the Inlet (15), Inlet Spits, and Inner Delta (14) of 2.74 Mm^3/yr (159 Mm^3) in Interval 1, can not account for the combined accretion of Long Beach and the Outer Delta (13) of 3.79 Mm^3/yr (220 Mm^3), implying that sand came from the estuary and/or from the South Flank (19) and the Clatsop Plains Shelf (21). The South Flank and Clatsop Plains Shelf combined eroded by 4.26 Mm^3/yr (247 Mm^3), and part of this sand moved onshore to accrete the beach-dune complex of Clatsop Plains by 1.28 Mm^3/yr (74 Mm^3) and the remainder moved to the northwest to accrete the Outer Delta. As a result of jetty construction, sand from the inlet may have moved into the Columbia River estuary to accrete the Flood-tidal Delta (17) by 1.58 Mm^3/yr (92 Mm^3). The balance over all bathymetric changes is 65 Mm^3 net erosion (Table 4-3). Including omission, losses due to northward sediment transport, and gains due to Columbia River sediment supply the balance is 2 Mm^3/yr (116 Mm^3) net erosion.

In Interval 2 and Interval 3 the changes are a net accretion of 229 Mm^3 and 221 Mm^3, respectively. The inferred sediment flux patterns are similar during these intervals. In Interval 2, the erosion of the South Flank and the Clatsop Plains Shelf balances the accretion of the beach-dune complex of Clatsop Plains, i.e., the net change is 0.22 Mm^3/yr (7 Mm^3) more accretion than erosion. The net balance over the entrance (compartments 12 - 16), the estuary (compartments 17 and 18) and Long Beach is an observed accretion of 4.8 Mm^3/yr (154 Mm^3). If we include the estimates for Omission Estuary, Dredging Estuary, and losses due to northward sediment transport the net accretion increases from 154 Mm^3 to 305 Mm^3. In Interval 3, the change over the South Flank, Clatsop Plains Shelf and the beach-dune complex of Clatsop Plains is 0.13 Mm^3/yr (5.26 Mm^3) erosion. The balance for the Outer Delta, Long Beach Shelf, and the beach-dune complex of Long Beach is 5.49 Mm^3/yr (225 Mm^3) net accretion. Although the Inlet and estuary are not included in this balance, we do not expect these compartments to be a significant source of sand to balance the accretion.

We infer from littoral transport calculations along Long Beach (KAMINSKY et al., 2000; BUIJSMAN et al., 2001) and the net accretion of Long Beach Shelf that the beach-dune complex of Long Beach during mainly accreted in Intervals 2 and 3 due to sand supply from the south (i.e., the Columbia River entrance). However, we can not balance the erosion of the Inlet and Inner Delta with the combined accretion of the Outer Delta, the beach-dune complex of Long Beach, and Long Beach Shelf. In addition, the erosion of the South Flank and the Clatsop Plains Shelf balances the accretion of the beach-dune complex of Clatsop Plains, suggesting that no significant volume of sand was transported northward from the region south of the Columbia River entrance during Interval 2 and 3. We conclude that the net observed accretion during Intervals 2 and 3 is due to uncertainties in the bathymetric data, and/or the supply of sand from the Columbia River estuary was higher than estimated.

4.2.3 Columbia River Littoral Cell

The net volume change over Intervals 1, 2, and 3 (approximately 120 years) for all bathymetric and topographic changes, excluding the Willapa Bay entrance and, including sediment inputs and losses at the Grays Harbor and Columbia River entrances is 3 Mm^3/yr (359 Mm^3). The time-averaged transport directions for the CRLC for all intervals are presented in Figure 4-4. The fluxes at the Grays Harbor and Willapa Bay entrances are unknown and are indicated with a double-headed arrow. It is difficult to estimate the flux at the Columbia River estuary. If we want to balance the volume changes at the Columbia River delta and adjacent coasts in Interval 2 and Interval 3, an extra influx of sand is needed, possibly from the estuary. However, to balance the sum of the Columbia River sediment supply and the volume changes in the estuary during these intervals, an extra supply of sand is needed as well, possibly from the ocean. Therefore, we use a double headed arrow at the Columbia River entrance to represent the sediment flux in both directions and the unknown net direction.

4.3 Barrier Progradation and Shoreface Rotation

During all intervals, the behaviour of the shorefaces along North Beach and Long Beach is similar, as is the behaviour of the shorefaces along Grayland Plains and Clatsop Plains.

4.3.1 Barrier Progradation

Along North Beach and Long Beach, the beach-dune complex has mainly prograded (Figure 2-14a, Figure 2-15a, and Figure 2-17a). Profile changes above the depth of no significant change of approximately -12 m NAVD88 north of Grays Harbor (Figure 2-14a) indicate that the barrier has been prograding and the shoreface has steepened. These trends of progradation and shoreface steepening have occurred continually since the construction of the North Jetty, but the rate of change has diminished with time and distance from the jetty (Figure 3-5, Figure 3-11, and Figure 3-17). Along Long Beach, the beach-dune complex has prograded and the shoreface has steepened above the depth of no significant change of approximately -24 m NAVD88 during all intervals (Figure 2-17a). Interestingly, the largest progradation occurs during Interval 3.

4.3.2 Shoreface Rotation

Along Grayland Plains and Clatsop Plains, the beach-dune complex prograded and the shelf lowered, i.e., shoreface rotation, with the largest lowering occurring adjacent to the entrances of Grays Harbor and Columbia River (Figure 2-14b, Figure 2-15b, Figure 2-16a, and Figure 2-18a). During Interval 1, south of Grays Harbor, there has been significant progradation of the shoreline, accompanied by lowering of the shelf between depths of 10 m and 30 m (Figure 2-16a). It is tempting to associate the apparent shelf lowering and the rapid progradation of the beach-dune complex with jetty construction at the Grays Harbor entrance. It is unclear however, why the shelf lowering along Grayland Plains is so uniform at 0.03 m/yr (except for the South Flank, where the lowering is 0.07 m/yr). The trend of barrier progradation extended southward along all of Grayland Plains and continued (albeit at much slower rates) in Interval 2 - 4. Some evidence of shoreface lowering appears as far south as 170 km N in the bathymetric change map for Interval 4 (Figure 3-19). Along Clatsop Plains the shoreface eroded between ~35-m and ~12-m water depth, whereas above 12 m the beach prograded . Directly south of the Columbia River South Jetty the shoreface lowering is significant (Figure 2-15b), whereas farther south (Figure 2-18a) the changes are smaller. The rates of shoreface lowering are largest following jetty construction and decrease through time.

4.4 Uncertainties

4.4.1 Overview of the Uncertainties

There are many uncertainties related to this bathymetric-change analysis. The most important uncertainties are:

Tidal datums. The tidal datums and the vertical adjustments (Section 2.4.1) cause the largest uncertainties in the bathymetric-volume change calculations. We will discuss these uncertainties in more detail below.

Incomplete coverage. There is insufficient coverage of bathymetric data along North Beach, Grayland Plains, northern Long Beach, southern Clatsop Plains, the Grays Harbor and Willapa Bay tidal basins, the Willapa Bay ebb-tidal delta, and the Columbia River estuary. This lack of data coverage complicates the bathymetric- and topographic volume change analysis. Although the largest changes occurred at the ebb-tidal deltas, inlets, and adjacent coasts, exclusion of large areas with little vertical change can still affect the sediment balances. Therefore, the balances presented here should be regarded as estimates.

Inconsistencies in the data. Inconsistencies in the data are uncertainties that can not be related to consistent offsets. Examples are surveys with bathymetric surfaces that seem warped or tilted, surveys with sections that are consistently shallower or deeper, etc. In contrast to offsets, these uncertainties are hard to correct. The USC&GS Era I H1379 and H1378 and the Era II H4634, H4635, H4628, and H4728 surveys have many inconsistencies. The effect of these inconsistencies on the bathymetric volume-change calculations can be large.

Elevation of the DEM_{BALD}. A comparison of the DEM_{BALD} with the field data collected by the SWCES shows that the DEM_{BALD} averages 1.03 m lower than the field data. This difference is a direct result of the methods used to filter buildings, trees, shrubs, and tall grasses. If this difference applies to the entire DEM_{BALD}, the topographic-volume changes are underestimated, and the net accretion of the beach-dune complex for the entire CRLC over all intervals increases by approximately 50 Mm^3.

Columbia River sediment supply. The estimates of sediment supply to the estuary by SHERWOOD et al. (1990) (see Appendix B) are too low to balance the net accretion in the CRLC, and may be in error.

In the following we discuss the sensitivity of the sediment budgets to the adjustments of the tidal datums (see Section 0). This so-called uncertainty of the sediment budget is defined as the difference between the sediment budgets (or balances) of the adjusted surveys and the sediment balances of the unadjusted surveys (i.e., surveys reduced to MLLW). In this report, we estimate these uncertainties by subtracting the vertical adjustments of surveys of subsequent eras, multiplying these differences by the horizontal areas of the compartments, and summing these volumes.

4.4.2 Grays Harbor Entrance and Adjacent Coasts

The net balance over all bathymetric- and topographic-volume changes during Interval 1 is approximately 42 Mm^3 more erosion than accretion. Without the tidal-datum adjustments the net erosion increases slightly by approximately 5 Mm^3. Obviously, the adjustments nearly cancel.

The net balance over all bathymetric and topographic changes for Interval 2 is an observed accretion of 151 Mm^3. Without all tidal datum adjustments, the net accretion on the sediment balance decreases by approximately 60 Mm^3. The fit between the unadjusted Era III surveys and Era IV surveys is good, and therefore, we do not adjust the Era III surveys to NAVD88. However, if we adjust both the Era III surveys and the Era II surveys to NAVD88, the net accretion on the sediment balance decreases by approximately 50 Mm^3. Thus, it seems that net accretion of at least 90 Mm^3 occurred during Interval 2.

The net balance over the Grays Harbor entrance and adjacent coasts for Interval 3 is approximately 2 Mm^3 more accretion than can be accounted for. If we adjust al Era IV surveys by 0.46 m to MLLW (or all Era III surveys by -0.46 m to NAVD88), the net accretion increases by approximately 60 Mm^3.

If we reduce the Era II and Era IV surveys to MLLW, the net observed accretion of 109 Mm^3 for Interval 4 at the Grays Harbor entrance (excluding the Willapa Bay Delta, compartment 10 in Figure 4-3) increases by approximately 15 Mm^3, and the net observed accretion of 106 Mm^3 at the Willapa Bay Delta increases by approximately 10 Mm^3.

Reducing all surveys to MLLW only improves the sediment balances for Intervals 2 and 3. The net erosion and net accretion on the balances of Intervals 1 and 4 increase by maximally 5 Mm^3 and 25 Mm^3, respectively. Adjusting the Era III surveys by -0.46 m to NAVD88 improves both the Interval 2 and Interval 3 sediment balances. In this case, the balances for Intervals 2 and 3 have a net accretion of 78.5 Mm^3 (2.8 Mm^3/yr) and 26 Mm^3 (0.58 Mm^3/yr) respectively. However, this adjustment decreases the fit between the Era III and Era IV surveys.

4.4.3 Columbia River Entrance and Adjacent Coasts

The sand balance for Interval 1 over the volume changes of the Columbia River entrance and adjacent coasts is 112 Mm^3 net erosion (excluding the Columbia River estuary and losses due to littoral transport). If we neglect the vertical datum adjustments of all Era I and Era II surveys, (excluding the surveys at the estuary) the net observed erosion of 112 Mm^3 on the sediment balance decreases by approximately 30 Mm^3.

In Interval 2, the balance is 229 Mm^3 net accretion. If we neglect the -0.29-m adjustment of the Era III surveys, the net accretion over all bathymetric-volume changes, excluding the estuary, increases by either approximately 60 Mm^3, excluding the shelf along Long Beach and Clatsop Plains (compartments 15, 16, 22, and 23 in Figure 3-10), or by approximately 135 Mm^3, including compartments 15, 16, and 22 and excluding compartment 23. If we neglect both the -0.29-m adjustment and the -1.68-m adjustment of the Era II H4635 survey along Clatsop Plains (compartment 22 in Figure 3-10) the net accretion decreases by approximately 65 Mm^3.

The balance over the Columbia River entrance for Interval 3 is 221 Mm^3 net accretion. If we reduce all Era III and Era IV surveys to MLLW, the net accretion decreases by either approximately 95 Mm^3, excluding the shelf along Long Beach and Clatsop Plains (compartments 10 and 14 in Figure 3-16), or by approximately 150 Mm^3, including compartments 10 and 14.

As presented in the above, if we reduce all surveys to MLLW and neglect the offsets of the Era II H4635 and the Era III surveys, both the net erosion of Interval 1 and the net accretion of Interval 2 decreases. However, the offset between the Era II H4635 survey and the Era IV surface in Figure 2-13 is evident, and therefore can not be ignored. If we include the -1.68-m adjustment of the H4635 survey, the net accretion on the Interval 2 balance increases. If we ignore the -0.29-m offset between the Era III and Era IV surveys (Figure 2-12 and Figure 2-13), the erosion of the shelf along Clatsop Plains increases. We conclude that ignoring both the offsets of -0.29 m and -1.68 m increases the erosion of Clatsop Plains Shelf and decreases the net accretion on the sediment balances. If we correct for these offsets we need to account for the net accretion with sand from external sources.

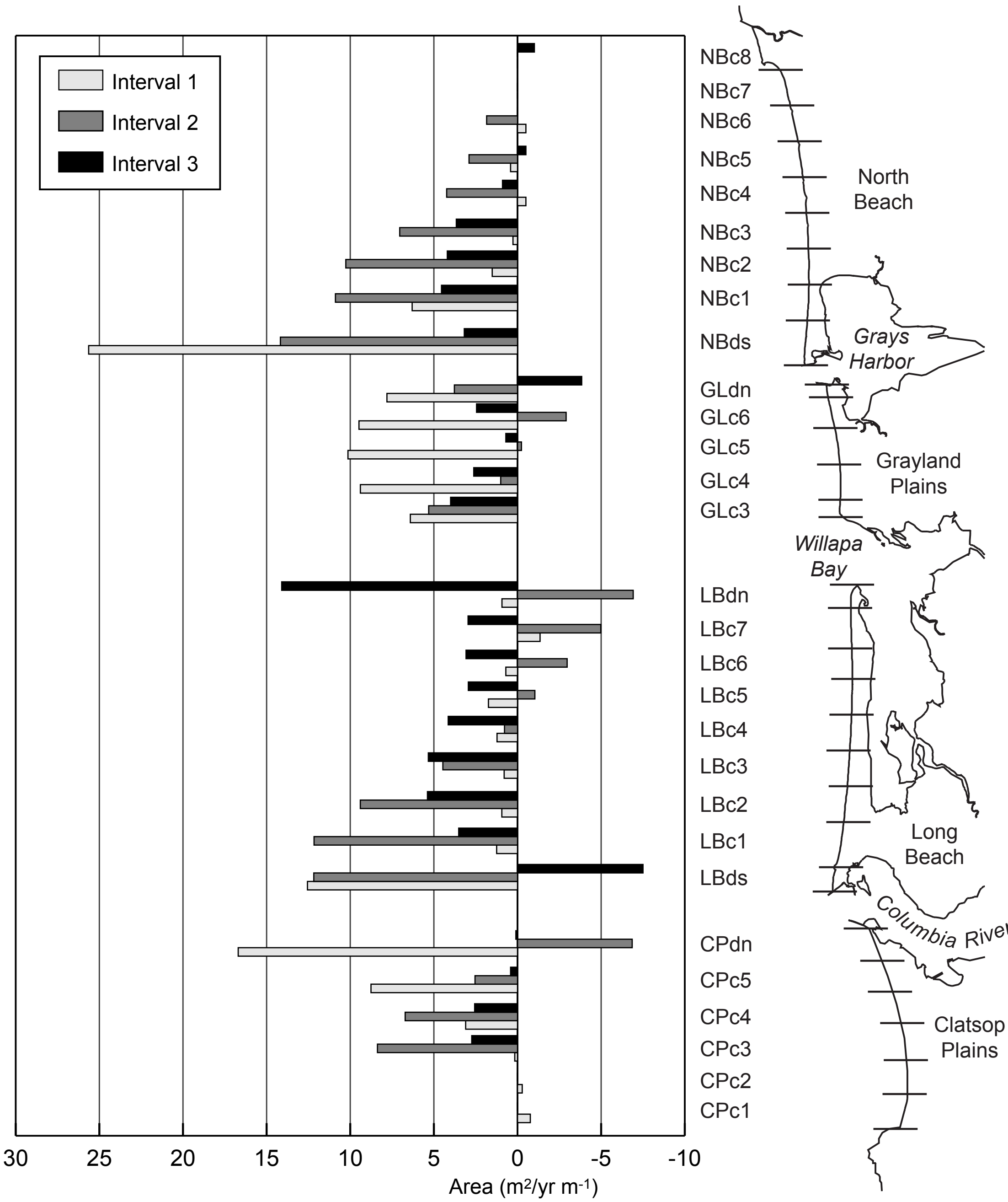


Figure 4-1. Shoreline-change rates per compartment for Interval 1, 2, and 3 along the CRLC. Due to the lack of Era III shoreline data along CPc1 and CPc2, we do not calculate the Interval 2 and 3 area-change rates.

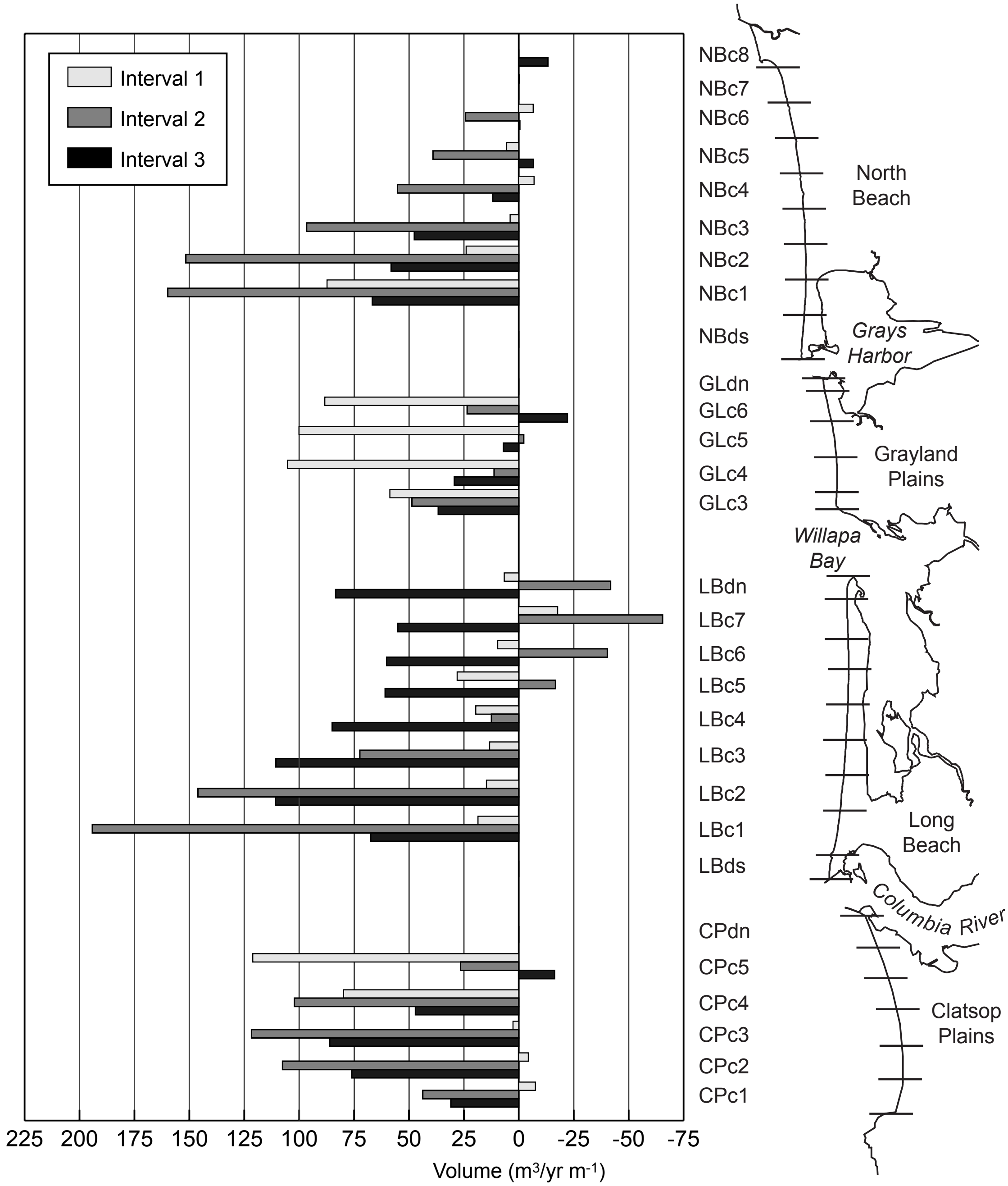


Figure 4-2. Bathymetric and topographic volume-change rates per compartment (volumes V_1, V_2, and V_3 in Figure 2-21) normalized by compartment length for Interval 1, 2, and 3 along the CRLC. Volume changes at the spits NBds, GLdn, LBds, and CPdn were not included.

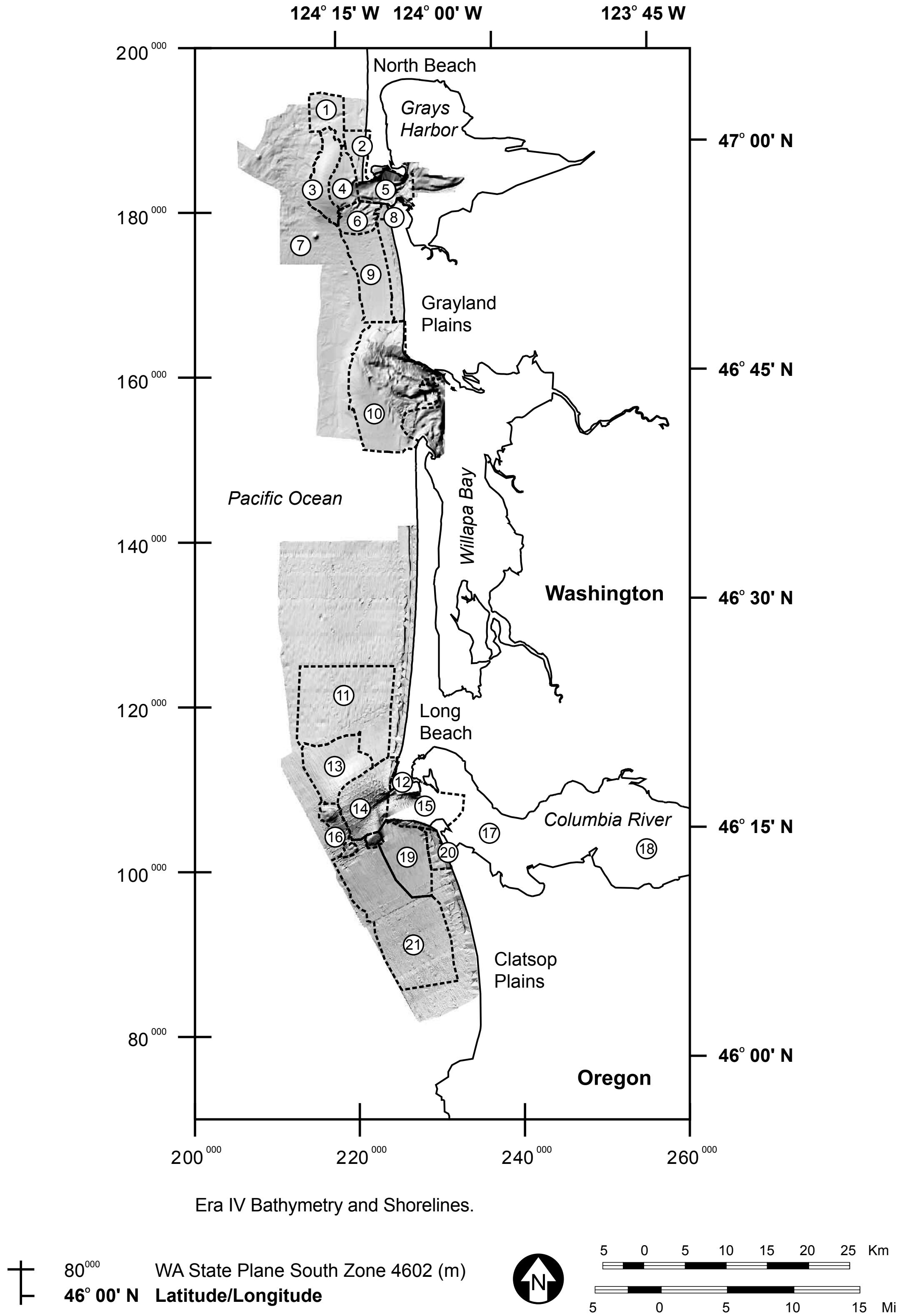


Figure 4-3. Approximate locations of the compartments used in the bathymetric and topographic volume-change calculations. Numbers refer to the compartments in Table 4-2 and Table 4-3.

Table 4-2. Volume changes and change rates at the Grays Harbor and Willapa Bay entrances.

Grays Harbor Entrance	Interval 1		Interval 2		Interval 3		Interval 4	
	Area (km^2)	Volume (Mm^3)	Area (km^2)	Volume (Mm^3)	Area (km^2)	Volume (Mm^3)	Area (km^2)	Volume (Mm^3)
North Beach Shelf (1)	n/a	n/a	16.64	12.21	n/a	n/a	n/a	n/a
North Beach	1.23	17.62	5.21	73.62	2.83	39.16	8.03	112.76
NBds (2)[1)]	10.81	46.77	10.25	30.49	9.92	7.20	14.12	41.18
Outer Delta (3)	7.60	14.97	18.48	59.72	36.76	62.45	26.15	95.53
Inner Delta (4)	17.98	-44.73	12.59	-24.41	22.95	-40.56	17.49	-47.09
Inlet (5)	19.75	-39.45	19.56	-3.19	17.29	-30.57	17.24	-29.30
Inlet Spits and Bays	3.45	13.88	2.18	0.72	3.55	0.12	5.26	-2.17
South Flank (6)	15.99	-35.96	9.71	-11.17	15.22	-28.92	15.97	-41.57
Disposal Mount (7)	n/a	n/a	n/a	n/a	6.94	6.01	n/a	n/a
GLdn (8)[1)]	0.47	1.57	2.30	2.68	2.04	-6.22	1.87	-2.73
Grayland Plains	5.53	55.12	0.31	9.07	1.59	7.28	0.97	1.46
Grayland Plains Shelf (9)	67.55	-71.85	17.55	1.16	12.98	-14.27	43.15	-18.78
Willapa Bay Delta (10)	n/a	n/a	n/a	n/a	n/a	n/a	94.62	105.71
Subtotal	**n/a**	**-42.05**	**n/a**	**150.90**	**n/a**	**1.66**	**n/a**	**215.00**
Input from South[2)]	n/a	-26.40	n/a	-22.40	n/a	-36.00	n/a	-102.20[3)]
Net Change GH	**n/a**	**-68.45**	**n/a**	**128.50**	**n/a**	**-34.34**	**n/a**	**112.80**

Grays Harbor Entrance	Interval 1[4)]		Interval 2[4)]		Interval 3[4)]		Interval 4[4)]	
	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
North Beach Shelf (1)	n/a	n/a	0.44	0.026	n/a	n/a	n/a	n/a
North Beach	0.53	n/a	2.63	n/a	0.87	n/a	1.54	n/a
NBds (2)[1)]	1.42	n/a	1.09	n/a	0.16	n/a	0.56	n/a
Outer Delta (3)	0.45	0.060	2.13	0.115	1.39	0.038	1.31	0.050
Inner Delta (4)	-1.36	-0.075	-0.87	-0.069	-0.90	-0.039	-0.65	-0.037
Inlet (5)	-1.20	-0.061	-0.11	-0.006	-0.68	-0.039	-0.40	-0.023
Inlet Spits and Bays	0.42	n/a	0.03	n/a	0.00	n/a	-0.03	n/a
South Flank (6)	-1.09	-0.068	-0.40	-0.041	-0.64	-0.042	-0.57	-0.036
Disposal Mount (7)	n/a	n/a	n/a	n/a	0.13	0.019	n/a	n/a
GLdn (8)[1)]	0.05	n/a	0.10	n/a	-0.14	n/a	-0.04	n/a
Grayland Plains	1.67	n/a	0.32	n/a	0.16	n/a	0.02	n/a
Grayland Plains Shelf (9)	-2.18	-0.032	0.04	0.002	-0.32	-0.024	-0.26	-0.006
Willapa Bay Delta (10)	n/a	n/a	n/a	n/a	n/a	n/a	1.45	n/a
Subtotal	**-1.27**	**n/a**	**5.39**	**n/a**	**0.04**	**n/a**	**2.95**	**n/a**
Input from South[2)]	-0.80	n/a	-0.80	n/a	-0.80	n/a	-1.40[3)]	n/a
Net Change GH	**-2.07**	**n/a**	**4.59**	**n/a**	**-0.76**	**n/a**	**1.55**	**n/a**

[1)] Including nearshore.
[2)] From KAMINSKY et al. (2000).
[3)] Input at Leadbetter Point.
[4)] Duration of Interval 1 is 33 years, Interval 2 is 28 years, Interval 3 is 45 years, and Interval 4 is 73 years.

Footnotes of Table 4-3.
[1)] Including nearshore.
[2)] From SHERWOOD et al. (1990).
[3)] From KAMINSKY et al. (2000).
[4)] See Appendix B.
[5)] Duration of Interval 1 is 58 years, Interval 2 is 32 years, and Interval 3 is 41 years.
[6)] Includes all changes at the Grays Harbor and Columbia River entrances for Interval 1, 2, and 3.

Table 4-3. Volume changes and change rates at the Columbia River entrance.

Columbia River Entrance	Interval 1		Interval 2		Interval 3	
	Area (km^2)	Volume (Mm^3)	Area (km^2)	Volume (Mm^3)	Area (km^2)	Volume (Mm^3)
Long Beach Shelf (11)	n/a	n/a	109.60	15.67	133.53	52.90
Long Beach	1.74	26.56	2.60	51.70	7.70	127.04
LBds (12)[1)]	2.35	21.68	3.69	14.36	-1.05	-7.48
Outer Delta (13)	31.31	171.53	17.92	101.30	18.41	45.13
Inner Delta (14)	6.85	-47.49	26.45	-54.19	43.47	-47.07
Inlet (15)	35.40	-116.41	34.63	-53.77	n/a	n/a
Inlet Spits	1.06	5.18	0.92	3.74	n/a	n/a
Disposal Sites A, B, F (16)	n/a	n/a	n/a	n/a	14.89	56.21
Flood-tidal Delta (17)[2)]	202.15	91.74	202.15	33.54	n/a	n/a
Upper Estuary (18) [2)]	493.10	85.56	493.10	41.27	n/a	n/a
South Flank (19)	49.64	-217.48	29.82	-42.76	41.35	-30.27
CPdn (20)[1)]	4.34	25.99	13.68	-13.97	9.29	0.37
Clatsop Plains	2.98	48.04	4.57	61.17	n/a	50.48
Clatsop Plains Shelf (21)	27.39	-29.73	174.77	2.52	130.43	-25.84
Subtotal	**n/a**	**65.16**	**n/a**	**160.57**	**n/a**	**221.46**
Loss out North[3)]	n/a	81.20	n/a	44.80	n/a	57.40
Omission Estuary[2)]	9.57	-13.26	24.15	36.58	n/a	n/a
Dredging Estuary[2)]	n/a	n/a	n/a	70.00	n/a	n/a
Columbia River Supply[4)]	n/a	-249.40	n/a	-83.20	n/a	-57.40
Net Change CR	**n/a**	**-116.29**	**n/a**	**228.76**	**n/a**	**221.46**
Net Change CRLC[6)]	**n/a**	**-184.75**	**n/a**	**357.25**	**n/a**	**187.13**

Columbia River Entrance	Interval 1[5)]		Interval 2[5)]		Interval 3[5)]	
	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)	Rate ΔV (Mm^3/yr)	Rate Δh (m/yr)
Long Beach Shelf (11)	n/a	n/a	0.49	0.004	1.29	0.010
Long Beach	0.46	n/a	1.62	n/a	3.10	n/a
LBds (12)[1)]	0.37	n/a	0.45	n/a	-0.18	n/a
Outer Delta (13)	2.96	0.094	3.17	0.177	1.10	0.060
Inner Delta (14)	-0.82	-0.120	-1.69	-0.064	-1.15	-0.026
Inlet (15)	-2.01	-0.057	-1.68	-0.049	n/a	n/a
Inlet Spits	0.09	n/a	0.12	n/a	n/a	n/a
Disposal Sites A, B, F (16)	n/a	n/a	n/a	n/a	1.37	0.092
Flood-tidal Delta (17)[2)]	1.58	0.008	1.05	0.005	n/a	n/a
Upper Estuary (18) [2)]	1.48	0.003	1.29	0.003	n/a	n/a
South Flank (19)	-3.75	-0.076	-1.34	-0.045	-0.74	-0.018
CPdn (20)[1)]	0.45	n/a	-0.44	n/a	0.01	n/a
Clatsop Plains	0.83	n/a	1.91	n/a	1.23	n/a
Clatsop Plains Shelf (21)	-0.51	-0.019	0.08	0.000	-0.63	-0.005
Subtotal	**1.12**	**n/a**	**5.02**	**n/a**	**5.40**	**n/a**
Loss out North[3)]	1.40	n/a	1.40	n/a	1.40	n/a
Omission Estuary[2)]	-0.23	-0.024	1.14	0.047	n/a	n/a
Dredging Estuary[2)]	n/a	n/a	2.19	n/a	n/a	n/a
Columbia River Supply[4)]	-4.30	n/a	-2.60	n/a	-1.40	n/a
Net Change CR	**-2.01**	**n/a**	**7.15**	**n/a**	**5.40**	**n/a**
Net Change CRLC[6)]	**-4.06**	**n/a**	**11.91**	**n/a**	**4.35**	**n/a**

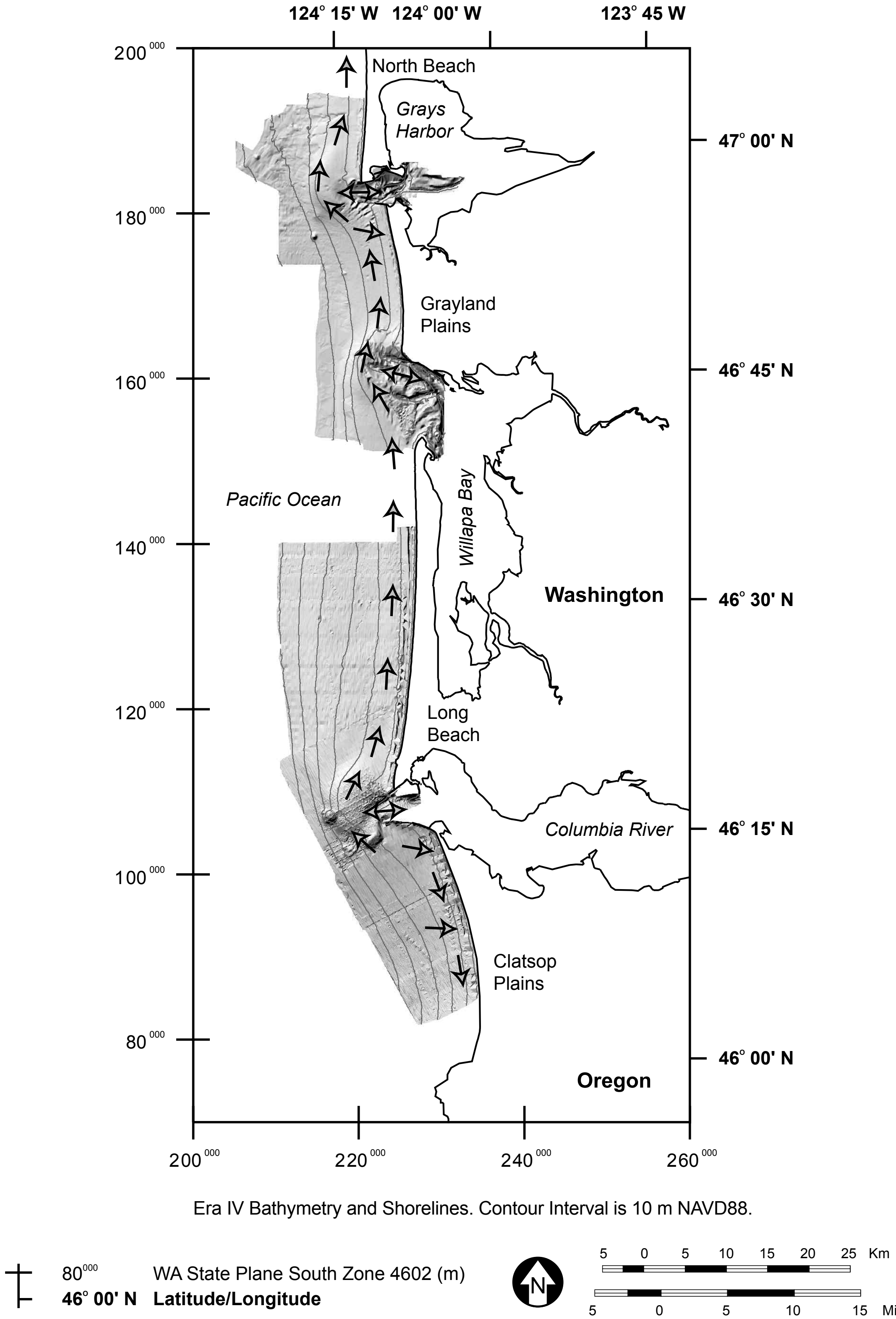


Figure 4-4. Integrated sediment-transport pathways along the CRLC averaged over Interval 1, 2, and 3. Arrows do not represent quantitative volumes.

5 CONCLUSIONS

Table 5-1. Sediment balances at the Grays Harbor, Willapa Bay, and Columbia River entrances.

Net Change (Mm^3)	Interval 1	Interval 2	Interval 3	Total
GH and WB	-68[1)]	128[2)]	-34[1)]	**26**[2)]
CR	-116[1)]	229[2)]	221[2)]	**334**[2)]
Total	**-185**[1)]	**357**[2)]	**187**[2)]	**360**[2)]
Change Rate (Mm^3/yr)	**-4**[1) 3)]	**12**[2) 3)]	**4**[2) 3)]	**3**[2) 4)]

1) Negative value suggests export out of study area, e.g., offshore transport.
2) Positive value suggests import into study area, e.g., onshore transport and CR sand supply.
3) Approximate duration of Intervals 1, 2, and 3 is 46 years, 30 years, and 43 years, respectively.
4) Approximate duration of all intervals combined is 116 years.

This is one of the first studies to provide an extensive bathymetric- and topographic-change analysis of the Grays Harbor, Willapa Bay, and Columbia River entrances and adjacent coasts within the Columbia River littoral cell between the late 1800s and the 1990s. The primary goals of this analysis are to calculate historical volume changes of the seafloor and beach-dune complex, to establish sediment transport pathways, and to lay the groundwork for further research (e.g., numeric modeling) and scientific papers.

This analysis is performed for four time intervals: pre-jetty - 1920s (Interval 1), 1920s - 1950s (Interval 2), 1950s - 1990s (Interval 3), and 1920s - 1990s (Interval 4). Topographic data is obtained from a joint project by the USGS, NOAA, NASA, and DOE and bathymetric data is obtained from the USC&GS, USACE, USGS, and DOE. Shoreline data are digitized from T-Sheets and aerial photographs obtained from the USC&GS and NOS. Bathymetric and topographic data are gridded using kriging and triangulation algorithms. Subsequently, bathymetric-change surfaces are computed by subtracting bathymetric surfaces of different eras. Volume changes are calculated within polygons that are overlaid on the bathymetric- and topographic-change surfaces. Sediment balances are established over the bathymetric- and topographic-change volumes, external gains and losses are calculated, and sediment transport pathways are inferred.

The morphologic changes at the deltas, inlets, and adjacent coasts of the Grays Harbor and Columbia River entrances are similar following the construction of the South Jetty (1898 - 1902) and North Jetty (1908 - 1916) at the Grays Harbor entrance and the South Jetty (1885 - 1895) and North Jetty (1913 - 1917) at the Columbia River entrance. At both entrances, the inlets and inner deltas eroded, contributing to the accretion of the outer deltas. Sand from the inner deltas and south flanks of the ebb-tidal deltas moved onshore. The jetties trapped sand, and the coasts adjacent to the inlets accreted at rates much higher than the pre-jetty accretion rates.

In the decades following jetty construction the centers of deposition along the adjacent coasts migrated farther from the entrances. The shoreline advance along the beaches adjacent to the jetties decreases or reverses to erosion during Intervals 2, 3, and 4.

The accretion and erosion rates of the coastal system (the deltas, inlets and adjacent coasts) are highest either during Intervals 1 or 2, and decrease during Intervals 3 and 4, suggesting the system is approaching dynamic equilibrium. An exception is the beach-dune complex of Long Beach: the shoreline along Long Beach continued to advance during Interval 3 at rates that were 1250% larger than the pre-jetty rates and 122% larger than the Interval 1 rates.

During the last decade, the shelf along North Beach and Long Beach is characterized by upper shoreface steepening and barrier progradation, whereas the shelf along Grayland Plains and Clatsop Plains is characterized by shoreface lowering and barrier progradation, i.e., shoreface rotation.

We infer the following from the sediment balances:

- The net transport pathways were directed offshore from the eroding inlets and inner deltas to the accreting outer deltas at both the Grays Harbor and Columbia River entrances.

- The net transport pathways along the sub-cells North Beach, Grayland Plains, and Long Beach were directed northward and the net transport pathway along Clatsop Plains was directed southward.

- Sand that eroded from the south flank of the Grays Harbor delta and the shelf along Grayland Plains could have moved onshore to contribute to the accretion of Grayland Plains as well as northward to contribute to the accretion of the outer delta and North Beach during Interval 1.

- To account for the accretion of North Beach coast and the Grays Harbor outer delta during Interval 4, sand that eroded from the south flank and the shelf along Grayland Plains had to be transported northward.

- To balance the accretion along Clatsop Plains coast, sand had to be transported onshore from the eroding south flank of the Columbia River delta and shelf along Clatsop Plains and towards the south during all intervals.

- During Intervals 2 and 3, the erosion of the south flank and the shelf was nearly equal to the accretion of the beach-dune complex along Clatsop Plains, implying that there was no significant net northward transport around the Columbia River delta to contribute to the accretion of the outer delta and Long Beach.

There are many uncertainties associated with this bathymetric and topographic change analysis, the most important are: tidal-datum adjustments, incomplete bathymetric coverage, inconsistencies in the bathymetric data, elevation of the DEM_{BALD}, and the Columbia River sediment supply. However, many of the calculated bathymetric and topographic changes are greater than the uncertainties, suggesting that the order of magnitude is correct.

The sand budget calculated over the entire CRLC for the historical period does not balance (Table 5-1). The sediment budgets of Intervals 1 and 3 at the Grays Harbor entrance and the sediment budget of Interval 1 at the Columbia River entrance have net erosion, whereas the other sediment budgets have net accretion. The net accretion on the sediment balances suggest that the external sediment input, e.g., from the Columbia River, the Grays Harbor and Willapa Bay tidal basins, and/or the shoreface should have been higher.

At the Grays Harbor entrance, the net accretion in Interval 2 and the net erosion in Interval 3 can be attributed to not adjusting the Era III surveys to NAVD88. However, due to the goodness of fit between the Era III and Era IV surveys below the depth of no significant change, we do not to adjust the Era III surveys.

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APPENDIX A COLUMBIA RIVER ESTUARY COMPARTMENTS

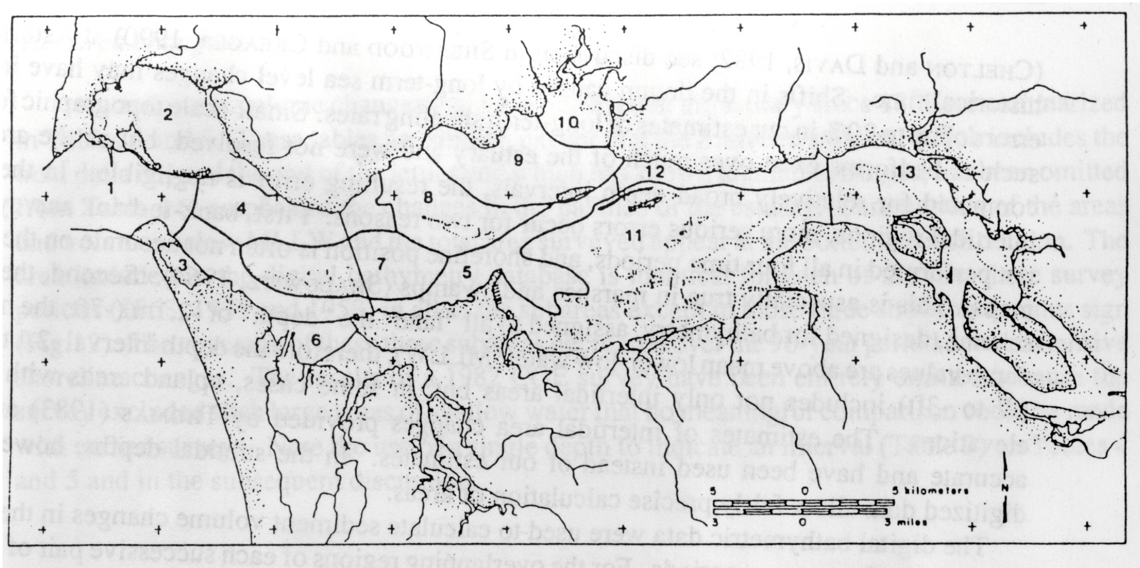

Figure A-1. Columbia River estuary compartments (SHERWOOD et al., 1990): 1) Entrance; 2) Baker Bay; 3) Trestle Bay; 4) North Channel; 5) South Channel; 6) Youngs Bay; 7) Desdemona Sands; 8) Mid-estuary shoals; 9) Grays Bay; 10) Brix Bay; 11) Cathlamet Bay; 12) Lower River Channel; 13) Upper River Channel.

APPENDIX B COLUMBIA RIVER SEDIMENT SUPPLY

A rating curve, based on suspended sediment discharge and riverflow measurements between 1964 and 1970 at Vancouver is used to hindcast Columbia River sediment discharge (SHERWOOD et al., 1990; GELFENBAUM et al., 1999). The rates are calculated incorporating 40% porosity and a density of 2650 kg/m^3. The rates are presented in Table B-1.

Table B-1. Estimates of transport rates of sand and fines at VANCOUVER (SHERWOOD et al., 1990; GELFENBAUM et al., 1999).

Interval	Sand (Mm^3/yr)	Silt and clay (Mm^3/yr)	Total (Mm^3/yr)
1878-1935	4.3	4.4	8.7
1935-1958	2.6	2.8	5.3
1958-1997	1.4	2.9	4.3
1878-1997	3.0	3.6	6.6

APPENDIX C DREDGING AND DISPOSAL AT THE GRAYS HARBOR ENTRANCE

The information about dredging and disposal at the Grays Harbor entrance is obtained from various sources and is not complete.

Following jetty construction the Grays Harbor jetties were not able to maintain an authorized water depth of 5.5 m (18 ft) and the first dredging of the Bar channel across the southwestern part of the Grays Harbor ebb-tidal delta (Figure C-1) occurred in 1916 of 0.044 Mm^3 (USACE, 1967). Between 1916 and 1942 the Bar channel was dredged annually, except in 1918 and 1919. The total quantity removed in this 27-year period is 16.8 Mm^3 (0.619 Mm^3/yr). The dredged material was disposed in deep water off the end of the dredged channel. Due to the scouring of the jetties no dredging was required in either the Bar channel or entrance channel between 1942 and 1988 (USACE, 1997; USACE, 2001). In 1945 the channel between Sand Island West (northeast of Pt. Chehalis) and Cosmopolis was dredged 1.34 Mm^3 (USACE, 1967). The material was disposed in Grays Harbor at undocumented locations. The South Reach channel (the channel east of Pt. Chehalis) has been dredged since its realignment in 1979 (USACE, 1997).

In 1990, as part of the Grays Harbor Navigation Improvement Project, the Bar channel was dredged to a water depth of 14 m (46 ft) below MLLW. A total of 1.225 Mm^3 was dredged from the Bar channel and Entrance channel. Between 1991 and 2000 the annual maintenance dredging requirements for the Bar channel, Entrance channel, and South Reach channel average 0.232 Mm^3, 0.249 Mm^3, and 0.268 Mm^3, respectively. No dredging of the Bar channel and Entrance channel was required in 1995, and no dredging of the Bar channel was required in 1996 and 1997. The total amount dredged between 1988 and 2000 from the Bar channel and Entrance channel is 2.57 Mm^3 and 2.586 Mm^3, respectively. The total amount dredged between 1977 and 2000 from the South Reach channel and Crossover channel is 10.577 Mm^3 and 9.070 Mm^3, respectively. The quantities dredged since 1977 from the channels are presented in Table C-1.

Between 1992 and 1995, material that was dredged from the Entrance channel and South Reach channel was placed in the Pt. Chehalis disposal site, the South Jetty disposal site, or in Half Moon Bay (USACE, 1997). Material that was dredged from the Bar channel in 1993 and 1994 was placed in nearshore berms at the South Beach disposal site or at the Southwest Ocean disposal site in deep water if nearshore placement was not possible due to bad weather (USACE, 1997).

The locations of the disposal sites are presented in Figure C-1. The Pt. Chehalis Disposal site is located in the navigation channel, north of Pt. Chehalis. The South Jetty disposal Site is located at a deep area at the north toe of the South Jetty approximately 1500 m seaward from the shoreline. The Half Moon Bay disposal site includes the nearshore berm and the beach. The South Beach disposal site is located south of the South Jetty between 7 and 15-m water depth. The Southwest Ocean disposal site is located approximately 7 km southwest of the entrance (Figure C-1, compartment 7 in Figure 3-14).

The Pt. Chehalis disposal site was the most heavily used disposal site; over 25 Mm^3 of material has been placed here since 1977 (USACE, 1997; USACE, 2001). The majority of the material placed at this site was fine-grained sediment (sand fraction possibly 10%) dredged from the channels east of Pt. Chehalis (BURCH and SHERWOOD, 1992). The quantities disposed since 1977 are presented in Table C-2.

The dredge and disposal volumes are not equivalent; since 1977 the total volume dredged and disposed is 24.8 Mm^3 and 38.8 Mm^3, respectively. The other dredge sites are located in the harbor and comprise the North Channel, Hoquiam Channel, Cow Point Reach, and Aberdeen Reach. These dredge volumes are not published here.

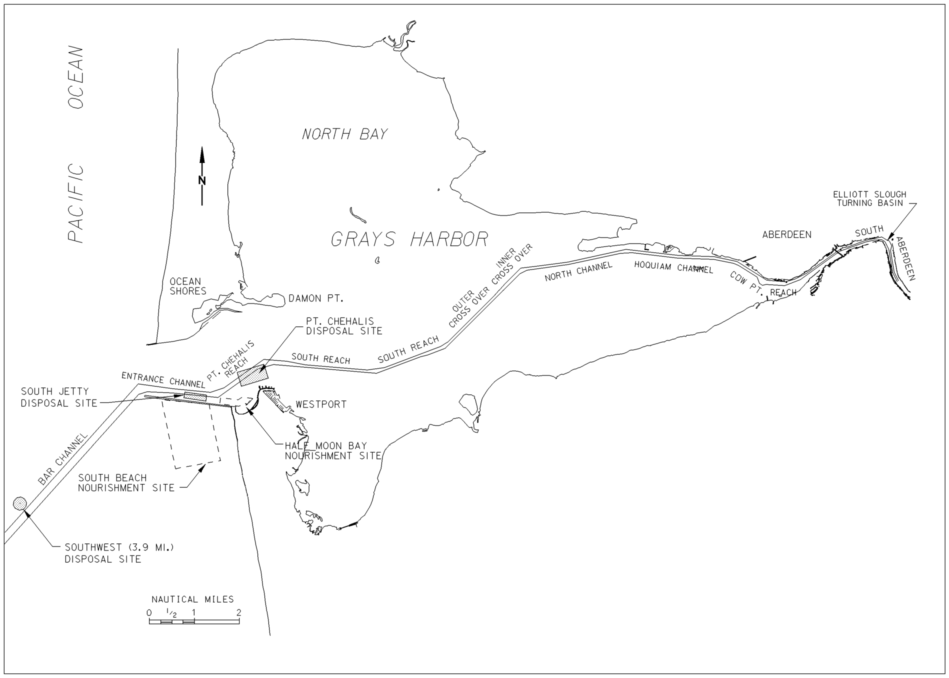

Figure C-1. Dredge and disposal sites at the Grays Harbor entrance (USACE, 2001).

Table C-1. Channel dredge quantities in Mm^3 at the Grays Harbor entrance (USACE, 2001).

Year	Bar	Entrance	South Reach	Crossover	Sum
1977			0.050	0.489	**0.540**
1978			1.341	0.092	**1.433**
1979			1.440	0.308	**1.749**
1980			0.523	0.313	**0.836**
1981			0.358	0.310	**0.667**
1982			0.334	0.357	**0.691**
1983			0.356	0.378	**0.734**
1984			0.414	0.555	**0.969**
1985			0.390	0.398	**0.787**
1986			0.434	0.447	**0.880**
1987			0.368	0.273	**0.641**
1988	0.022	0.046	0.447	0.336	**0.852**
1989			0.159	0.288	**0.447**
1990	0.922	0.303	1.287	1.421	**3.933**
1991	0.346	0.346	0.365	0.044	**1.099**
1992	0.487	0.276	0.522	0.321	**1.606**
1993	0.285	0.248	0.122	0.436	**1.090**
1994	0.212	0.123	0.696	0.202	**1.232**
1995			0.248	0.359	**0.607**
1996		0.235	0.089	0.325	**0.649**
1997		0.104	0.132	0.300	**0.537**
1998	0.079	0.203	0.176	0.427	**0.885**
1999	0.058	0.292	0.175	0.299	**0.824**
2000	0.160	0.411	0.151	0.393	**1.115**
Sum	**2.570**	**2.586**	**10.577**	**9.070**	**24.803**

Table C-2. Dredge disposal quantities in Mm^3 at the Grays Harbor entrance (USACE, 2001).

Year	South-west Ocean	Westport Fill	South Beach	Breach Fill	South Jetty	Half Moon Bay Nearshore	Half Moon Bay Beach	Pt. Chehalis	Sum
1977								0.540	**0.540**
1978								1.433	**1.433**
1979								2.004	**2.004**
1980								1.096	**1.096**
1981								1.075	**1.075**
1982								1.293	**1.293**
1983								1.106	**1.106**
1984								1.417	**1.417**
1985								1.342	**1.342**
1986								1.524	**1.524**
1987								1.135	**1.135**
1988					0.068			1.190	**1.258**
1989								0.937	**0.937**
1990	0.922				0.739			3.179	**4.840**
1991	0.346				0.848			0.543	**1.736**
1992	0.487				1.239	0.153		0.757	**2.636**
1993			0.285		0.856			0.522	**1.664**
1994	0.009		0.203	0.459	0.680	0.112		0.538	**2.000**
1995		0.230			0.300			0.903	**1.433**
1996					1.280	0.210		0.226	**1.716**
1997					0.733	0.236		0.442	**1.412**
1998					0.916	0.322		0.544	**1.782**
1999			0.058		0.454	0.175	0.175	0.884	**1.746**
2000					0.918			0.731	**1.649**
Sum	**1.764**	**0.230**	**0.546**	**0.459**	**9.031**	**1.207**	**0.175**	**25.361**	**38.772**

APPENDIX D DREDGING AND DISPOSAL AT THE COLUMBIA RIVER ENTRANCE

The purpose of the jetties at the Columbia River Entrance was to maintain minimum water depths over the bar of 9.1 m (30 ft) (USACE, 1999). However, at the Columbia River entrance, dredging was required to maintain project water depths. Most of the sand dredged at the entrance seaward of River Mile 3 was disposed at ocean disposal sites. Between the initial project authorization in 1885 and 1945 about 6.3 Mm^3 was dredged from the Columbia River entrance channel. Approximately 70% (4.4 Mm^3) of the dredged material was placed in the vicinity of present disposal site A (Figure D-1), and the remaining 30% (1.9 Mm^3) was placed at estuarine disposal sites. Between 1945 and 1955 approximately 10 Mm^3 was dredged from the entrance. Approximately 70% (~7 Mm^3) was placed near disposal site A, 10% (~1 Mm^3) was placed in the vicinity of ocean disposal site B, and 20% (~2 Mm^3) was placed at estuarine disposal sites.

Between 1956 and 1998 the sites A, B, C, D, E, F, and G were used for disposal of sand dredged from the entrance (Figure D-1). Disposal sites C and D are estuarine disposal sites and are not shown in the figure. Disposal site G is not shown in the figure and is located directly south of A and was used only once. The total volume placed in the sites during this period is approximately 28.8, 52.1, 3.3, 10.4, 40.7, 7.5, and 0.5 Mm^3, respectively (USACE, 1999). Between 1956 and 1998 the total amount placed is 143.3 Mm^3, and the amount placed excluding the estuarine disposal site D is 132.8 Mm^3. The volume of sand deposited in disposal sites A, B, and F is about 88 Mm^3. A comparison between the 1958 and 2000 seafloor surveys reveals that about 56 Mm^3 remained in these sites, suggesting that approximately 33 Mm^3 dispersed.

The project water depth of the river upstream of River Mile 3 was initially authorized in 1878 to a water depth of 6.1 m (20 ft). Gradually the water depth was increased and in 1962 the Project was authorized to a water depth of 12.2 m (40 ft). The required water depths were obtained by a combination of dredging and hydraulic control works. Dredged material was disposed by flow lane disposal, placed on the beaches along the river, placed on land or placed on artificially created sand islands. We can not find exact numbers on dredging and disposal in literature. Between 1909 and 1982, dredging operations moved approximately 220 Mm^3 in the estuary and river channels between the estuary and Portland (excluding the entrance area) (SHERWOOD et al. 1990). An unknown portion of the dredged material was rehandled more than once.

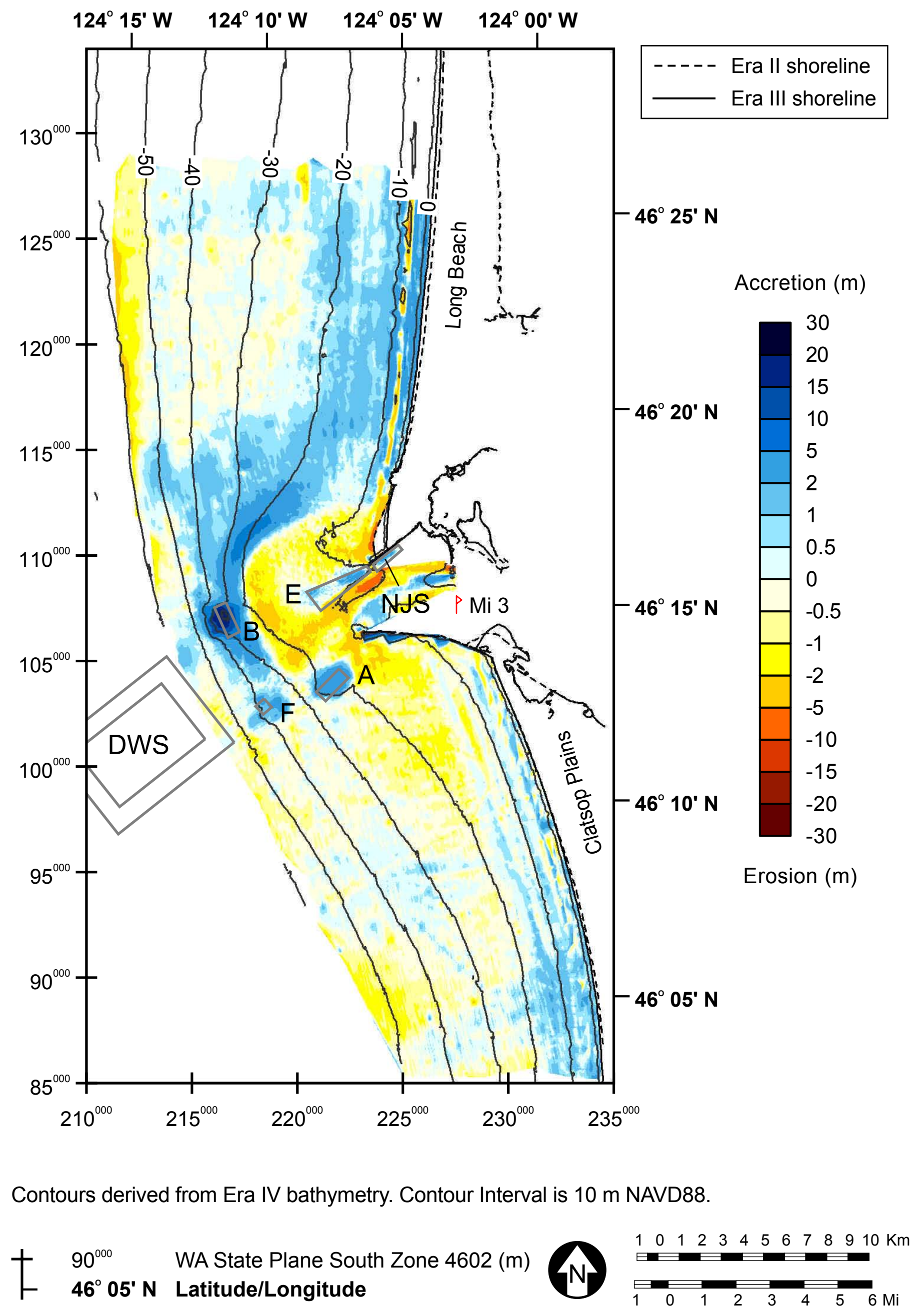

Figure D-1. Overview of the dredge disposal sites of the USACE at the Columbia River entrance. Bathymetric difference map is from Interval 3. DWS is the proposed disposal site in the Columbia River Channel Improvement Study (USACE, 1999). NJS is the North Jetty disposal site.

APPENDIX E ESTIMATING VOLUME CHANGE AT CPC1 AND CPC2

There is no Era III shoreline data along southern Clatsop Plains (CPc1 and CPc2). In order to calculate the Interval 2 and Interval 3 CPc1 and CPc2 volumes we assume that the accretion rate between the 1920s and 1990s (Interval 4) is equal to the rates of Interval 2 and Interval 3. We calculate the total volumes ΔV (V_1, V_2, and V_3) for Interval 2 and Interval 3 using the proportional relation between the known total volumes of CPc3 of Interval 2 and Interval 3 and the volume above NAVD88 of Interval 4 ($\Delta V_{>NAVD88\ Interval\ 4}$) (Table E-1). We calculate $\Delta V_{>NAVD88\ Interval\ 4}$ by subtracting the Interval 1 volumes from the post-jetty-1990s volumes. We calculate the post-jetty-1990s volumes by multiplying the horizontal accreted area with the average dune height above NAVD88.

Table E-1. Volume change at southern Clatsop Plains 1920s-1990s.

	Area Interval 4 **(km^2)**	**$h_{>MHW}$ (m)**	**$\Delta V_{>NAVD88}$** Interval 4 **(Mm^3)**	**$\Delta V_{>NAVD88}$** Interval 1 **(Mm^3)**	**$\Delta V_{>NAVD88}$** Interval 4 **(Mm^3)**	**$\Delta V_{Interval\ 2}$ (Mm^3)**	**$\Delta V_{Interval\ 3}$ (Mm^3)**
CPc3	2.00	10.42	20.83	0.49	20.34	20.00	18.12
CPc2	1.45	11.01	15.98	-0.77	16.74	16.46	14.91
CPc1	0.94	6.33	5.95	-0.88	6.84	6.72	6.09