US Army Corps
of Engineers®
Seattle District

Port of Grays Harbor
On Washington's Pacific Coast

Grays Harbor, Washington
Navigation Improvement Project
General Investigation Feasibility Study

FINAL Limited Reevaluation Report and Appendices

Appendix B: Engineering Analysis

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June 2014

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1. Physical Environment

The Grays Harbor Navigation Improvement Project (NIP) encompasses the Grays Harbor estuary from the cities of Westport to Aberdeen, Washington. Grays Harbor is located on the Southwest Washington coast, about 45 miles north of the Columbia River and 110 miles south of the entrance to the Strait of Juan de Fuca. A vicinity map including the federal navigation project features are shown in Figure 1. Grays Harbor is 15 miles long and 11 miles wide. The water surface area ranges from 91 square miles at mean higher high water (MWWH) to 38 square miles at mean lower low water (MLLW). The harbor broadens gradually from the river channel at the city of Aberdeen to a large, pear-shaped, shallow estuary encompassing North and South Bays. On the ocean side, two long spits enclose the estuary, Point Brown on the north and Point Chehalis on the south. Two convergent rubblemound-rock jetties, North Jetty and South Jetty, extend seaward from the sand spits at Point Chehalis and Point Brown, respectively; constricting the harbor entrance width to about 6,500 feet (Figure 1). A federally maintained navigation channel extends 27.5 miles from the outer Bar, through the Grays Harbor estuary, and terminating on the Chehalis River in Cosmopolis, WA. The navigation channel is classified between the outer harbor and inner harbor reaches. The outer harbor consists of the first 15 miles of channel and includes the Bar, Entrance, Point Chehalis, South, and Outer Crossover Reaches. The inner harbor consists of the remaining 12.5 miles of channel up to Cosmopolis, WA and consists of the Inner Crossover, North Channel, Hoquiam, Cow Point, Aberdeen, and South Aberdeen Reaches. Table 1 lists the channel stationing of each reach in the federal navigation channel.

1.1 Climatology

During late spring and summer, high-pressure centers predominate over the northeastern Pacific Ocean, sending a northwesterly flow of dry, warm air over the Chehalis Basin. The dry season extends from late spring to midsummer, with precipitation generally limited to a few light showers during this period. Average summer temperatures are in the 50’s and 60’s (°F), although hot, dry easterly winds that occasionally cross the Cascade Mountains can raise daytime temperatures into the 90’s. In fall and winter, strong winds and heavy precipitation occur throughout the basin. Storms are frequent and may continue for several days. Successive secondary fronts with variable rainfall may move onshore daily or more often. Heavy rainfall frequently is produced by these storms when warm, saturated air rises over the coastal range and west slopes of the Cascade Mountains.

Due to topographic controls, a variable weather pattern within the basin results in precipitation that ranges from an average of less than 45 inches per year near the city of Chehalis to an average of more than 200 inches per year in the upper reaches of tributary sub-basins draining the southern slopes of the Olympic Mountains.

1.2 Streamflow characteristics

The Chehalis, Humptulips, Wishkah, Elk, Johns, and Hoquiam Rivers are the major tributaries to Grays Harbor (Figure 2). The largest, the Chehalis River is approximately 125 miles long, originating in the Willapa and Doty hills southeast of Aberdeen and flowing northeast and then northwest before emptying into Grays Harbor. The Chehalis River enters at the head of the estuary and contributes approximately 80 percent of the freshwater discharge to the harbor. The Chehalis River drains 2,114 square miles into the inner harbor at Aberdeen, while the Humptulips River drains 276 square miles into North Bay. The smaller drainages include the Hoquiam River (98 sq. miles drainage area), Wishkah River (102 sq. miles drainage area), Elk River, Johns River, Newskah Creek, and Charlie Creek. South Bay has two estuaries at Elk River and Johns River, with six smaller, independent drainages (O'Leary, Stafford, Indian, Chapin, Newskah and Charley Creeks) entering Grays Harbor between Johns River and the mouth of the Chehalis River.

Table 1: Grays Harbor federal navigation project - channel reach and stationing

Channel reach	Authorized depth (feet, MLLW)	Channel Station	Within NIP
Bar Channel	-46	0+00 to 280+89	No
Entrance Channel	-44	280+89 to 342+89	No
Entrance Channel	-42	342+89 to 377+00	No
Pt. Chehalis Reach	-40	377+00 to 463+00	No
South Reach	**-38**	**463+00 to 715+93**	**Yes**
Outer Crossover Reach	**-38**	**715+93 to 795+00**	**Yes**
Inner Crossover Reach	**-38**	**795+00 to 869+00**	**Yes**
North Channel	**-38**	**869+00 to 1005+71**	**Yes**
Hoquiam Reach	**-38**	**1005+71 to 1156+02**	**Yes**
Cow Point Reach	**-38**	**1156+02 to 1227+99**	**Yes**
Aberdeen Reach	-36	1227+99 to 1315+86	No
South Aberdeen Reach	-36	1315+86 to 1448+04	No

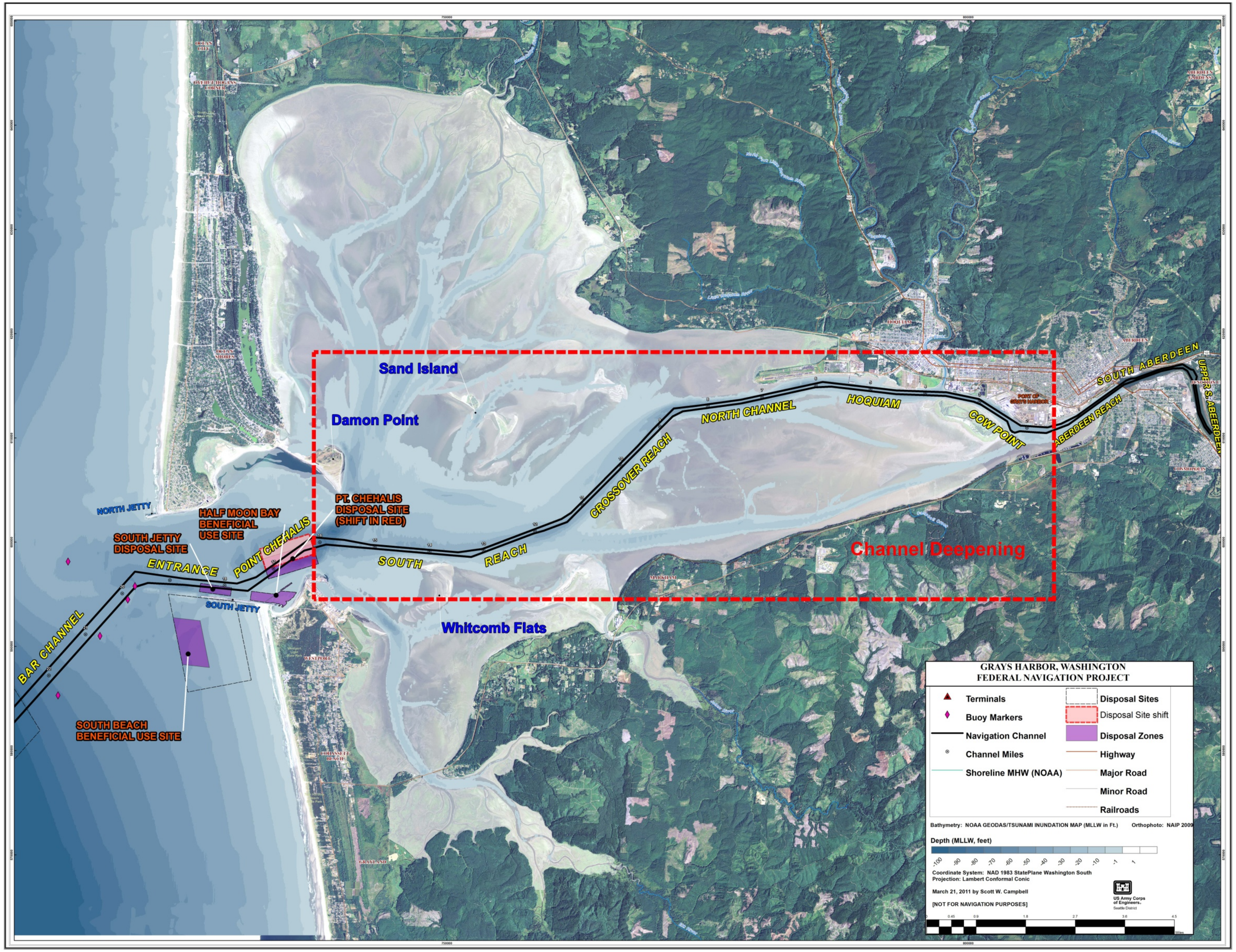

Figure 1: Grays Harbor Navigation Improvement Project and minor channel realignment

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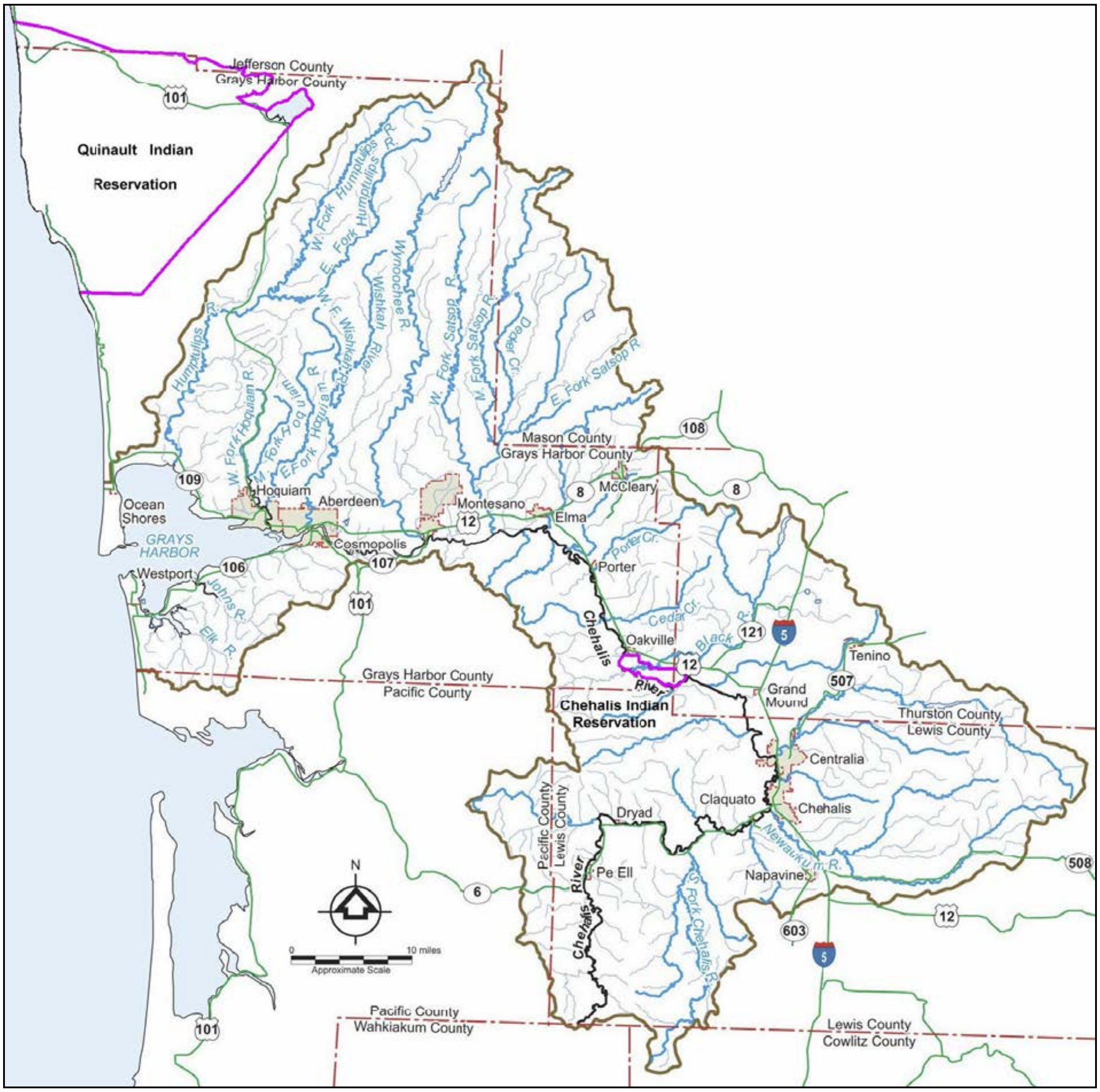

Figure 2: Chehalis River Basin tributaries (from Chehalis Basin Partnership)

1.3 Tides

Tides at in Grays Harbor have the diurnal inequality typical of the Pacific Coast of North America. Tidal datums for Westport and Aberdeen are listed in Table 2 and 3 respectively. The mean diurnal tidal range for Westport published by the National Ocean Survey is 9.15 feet. The mean diurnal tidal range for Aberdeen is 10.11 feet. The tidal phase lag at Aberdeen is approximately 1 hour later at high tide and low tide. Observed water levels are primarily a function of astronomical tide influences. However anomalies from the predicted astronomical tide occur due to factors including changes in atmospheric pressure, wind set-up, wave set-up, and river discharge.

1.4 Sea Level Change

Sea level change (SLC) is required to be considered in all USACE Civil Works projects per the guidance presented in EC 1165-2-212 (USACE 2011). The guidance states that "engineering designs should consider alternatives that are developed and assessed for the entire range of possible future rates of sea-level change". The guidelines require an active tide station with at least a 40 year record length to estimate sea level change for a project. Therefore data from NOAA tide station 9440910, Toke Point, WA was used for the analysis as data at the Westport gage has only been collected since 2006 and is of insufficient duration for developing accurate long-term sea level trends. The long-term trend line indicates an increase of 1.48 mm/yr (0.058 inches/yr) in local mean sea level. Table 4 lists the incremental (5-year) sea level change estimates calculated per the guidance for the next 100-years. The low, intermediate, and high represent different sea level rise scenarios. The low extrapolates the historic rate while the intermediate and high assume global sea level rise accelerates over time. By the end of the 50-year project lifecycle in 2065, local mean sea level is estimated to rise between 0.3 to 2.0 feet. In 100 years, local mean sea level at the project is estimated to rise between 0.5 to 5.9 feet.

1.5 Currents

Tidal currents dominate the current regime in the estuary; except during high Chehalis River flow. In general the strongest currents follow the channel thalweg1. Figure 3 and 4 display velocity magnitude (color contours) and direction (vectors) during four tidal stages (peak ebb, peak flood, low water slack, and high water slack) predicted by the CMS-FLOW two-dimensional hydrodynamic model during low flow conditions. During peak ebb flows, current speeds approach 4 knots (2 m/s) near the distal end of Damon Point. In the navigation channel at the Point Chehalis and South Reach currents are above 2 knots. Tidal currents generally diminish to less than 2 knots in the Crossover, North Channel, and Hoquiam Reaches. Near the Port of Grays Harbor terminals in the Cow Point reach these currents diminish to less than 1 knot. During peak flood, current speeds approach 3 knots (2 m/s) near the distal end of Damon Point and exceed 5 knots along the North Jetty. In the navigation channel, at the Point Chehalis and South Reach currents are above 2 knots. Tidal currents generally diminish to less than 1.5 knots in the Crossover, North Channel, and Hoquiam Reaches. Near the Port of Grays Harbor terminals in the Cow Point reach these currents diminish to less than 0.5 knots. During slack water conditions, currents throughout the navigation channel are primarily under 1 knot in the South Reach and under 0.5 knots upstream into the inner harbor reaches.

Table 2: Tidal datums at Westport, Washington, NOS Station 9441102

Datum	Water Level
Highest Observed Water Level (1 January 2010)	12.67
Mean Higher-High Water (MHHW)	9.15
Mean High Water (MHW)	8.41

[1] Thalweg. The line defining the lowest points along the length of a river bed or valley

Mean Tide Level (MTL)	4.90
Mean Low Water (MLW)	1.39
North American Vertical Datum (NAVD)	1.19
Mean Lower Low Water (MLLW)	0
Lowest Observed Water Level (7 May 2008)	-3.55

Table 3: Tidal Datums at Aberdeen, Washington, NOS Station 9441187

Datum	Water Level
Highest Observed Water Level (3 December 1982)	13.86
Mean Higher-High Water (MHHW)	10.11
Mean High Water (MHW)	9.41
Mean Tide Level (MTL)	5.44
North American Vertical Datum (NAVD)	1.64
Mean Low Water (MLW)	1.47
Mean Lower Low Water (MLLW)	0
Lowest Observed Water Level (22 July 1982)	-3.35

Table 4: Sea-level change scenarios (in feet) at Toke Point, Washington per EC 1165-2-212

Year	Low	Intermediate	High
2015	**0.00**	**0.00**	**0.00**
2020	0.02	0.05	0.12
2025	0.05	0.10	0.26
2030	0.07	0.15	0.41
2035	0.10	0.21	0.59
2040	0.12	0.28	0.78
2045	0.15	0.35	0.99
2050	0.17	0.42	1.22
2055	0.19	0.50	1.47
2060	0.22	0.58	1.74
2065	**0.24**	**0.67**	**2.02**
2070	0.27	0.76	2.33
2075	0.29	0.86	2.65
2080	0.32	0.96	2.99
2085	0.34	1.06	3.35
2090	0.36	1.17	3.73
2095	0.39	1.28	4.13
2100	0.41	1.40	4.54
2105	0.44	1.53	4.97
2110	0.46	1.65	5.43
2115	**0.49**	**1.78**	**5.90**

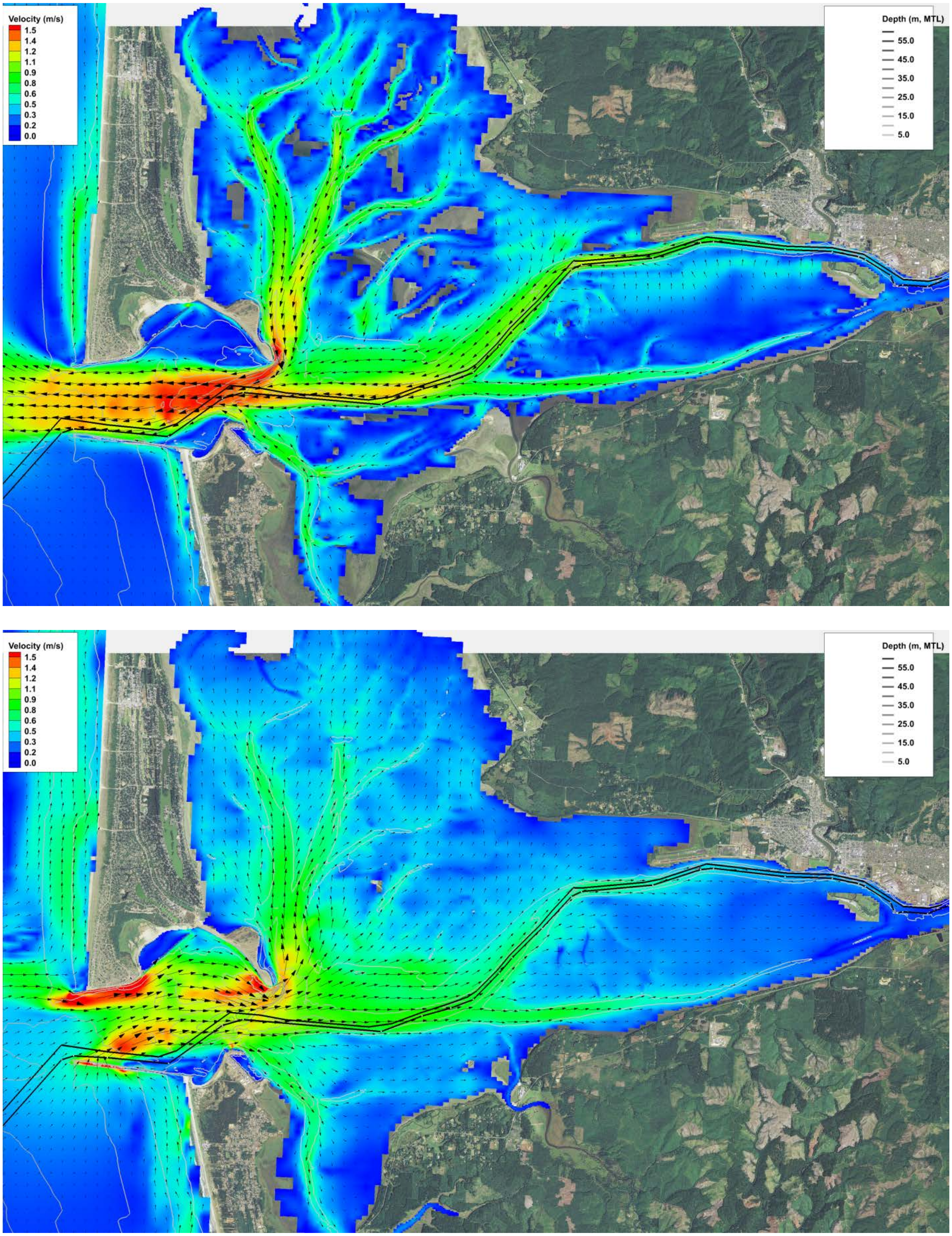

Figure 3: Peak ebb (top) and peak flood (bottom)

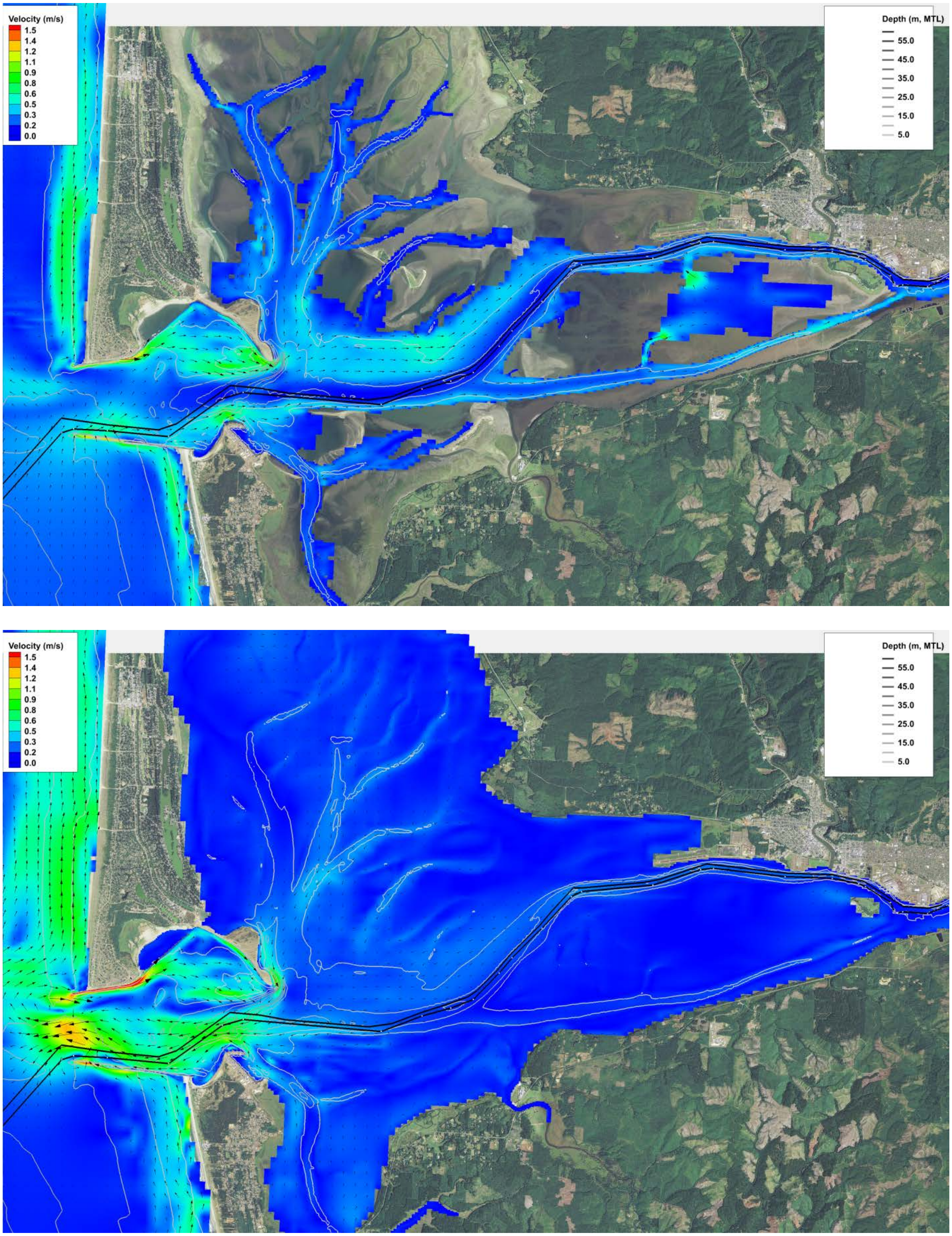

Figure 4: Low water slack (top); high water slack (bottom)

1.6 Winds

The seasonal cycle of winds over the northeast Pacific Ocean is largely determined by the circulation about the North Pacific high pressure area and the Aleutian low pressure area which drives the jet stream over the North Pacific. During the summer months, the high reaches its greatest development. In July the center of highest pressure is located near latitude 35° N., longitude 150° W. During this period, the Aleutian low is almost nonexistent. This pressure distribution causes predominantly northwest and north winds over the coastal and near offshore areas of Oregon and Washington. The high weakens with the approach of the winter season and by November is usually little more than a weak belt of high pressure lying between the Aleutian low and the equatorial belt of low pressure. These traveling depressions moving eastward cause considerable day-to-day variation in pressure, particularly in the area north of latitude 40° N.

As shown in Figure 5, at Westport the prevailing wind direction is out of the northwest. The strongest winds originate from the northwest and southerly directions and have recorded 2 minute average wind speeds exceeding 54 miles per hour. As shown in Figure 6 at Hoquiam, the prevailing wind directions are east and west as a result of the direction of the greatest fetch distances through the harbor.

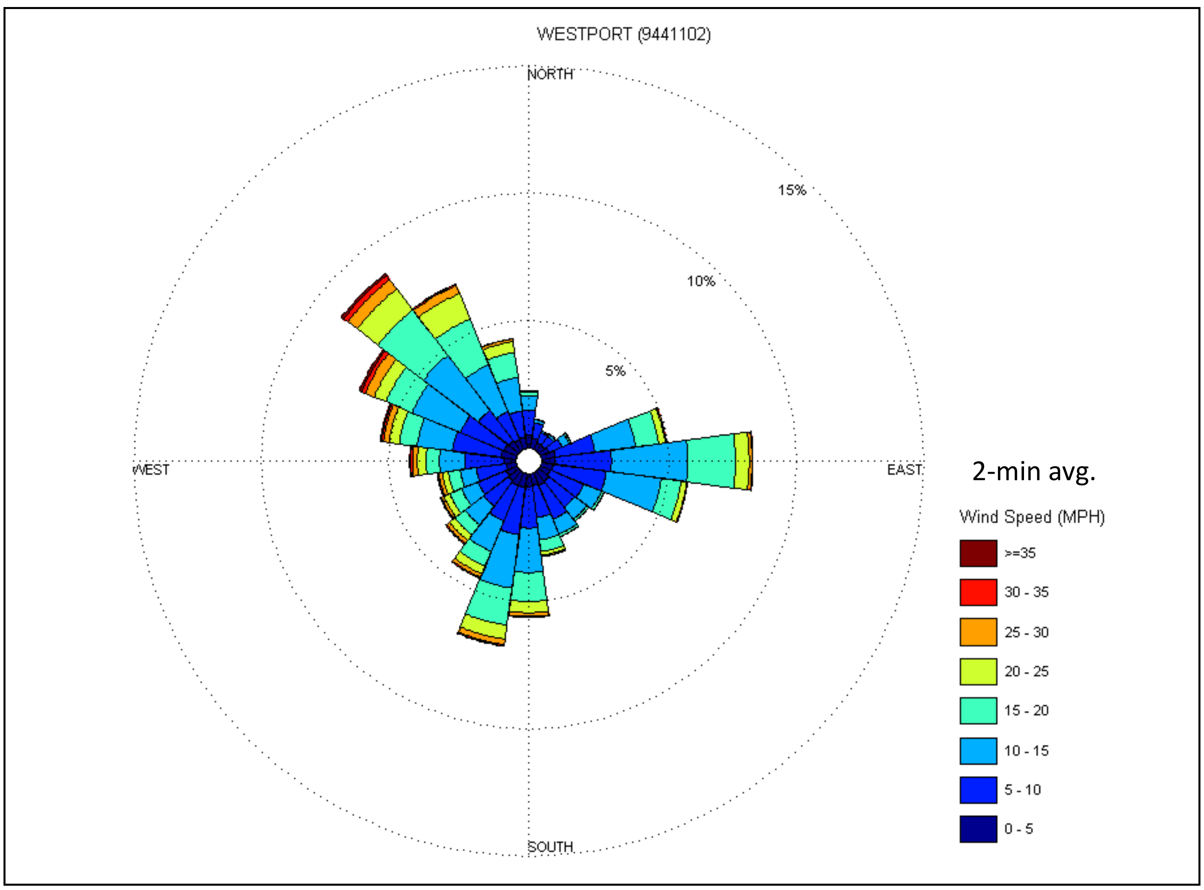

Figure 5: Wind rose at NOAA CO-OPS Station 9441102 Westport, WA. 2008-2013 (6 years)

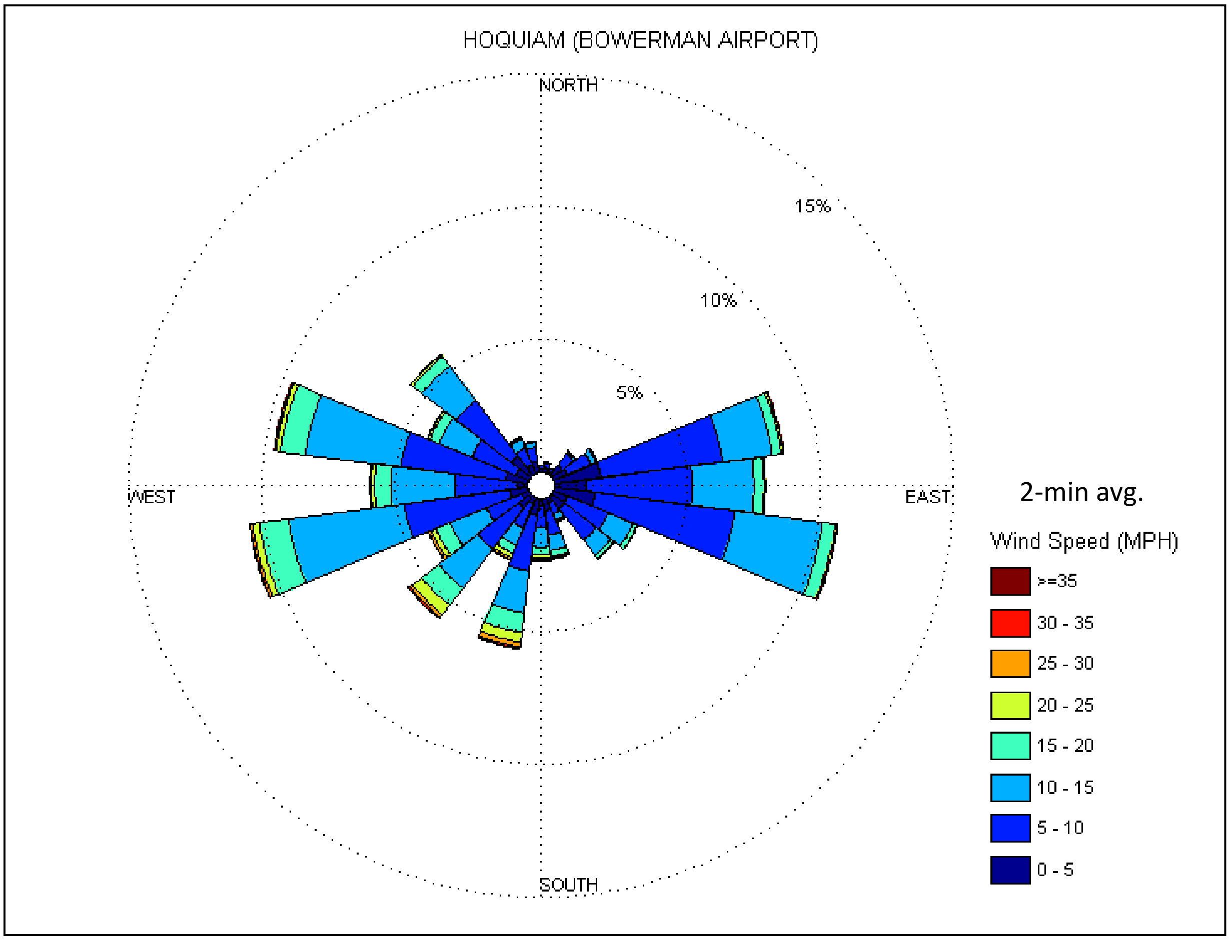

Figure 6: Wind rose at Bowerman Airport in Hoquiam, WA. 1949-1959; 1973-1990 (29 years)

1.7 Waves

Wave data has been observed at the Coastal Data Information Program (CDIP) buoy offshore of Grays Harbor in 130 feet of water since 1981. The average annual significant wave height measured at the buoy is 7 feet (2.1 meters) with a period of 11 seconds. The primary wave direction varies seasonally. The prevailing waves in the milder summer months are from the northwest. While large storms generated in the winter months have a southwesterly directionality. Weather fronts associated with maritime cyclonic storms in the Northeast Pacific can extend over the ocean for 1,000 miles and cover a latitude difference of 25 degrees. When these maritime low-pressure systems make land fall on the coast they produce hurricane-like conditions. Sustained wind speeds can be greater than 40 knots for fetches greater than 125 miles. The resulting wind stress can produce ocean waves greater than 30 feet high and a "set-up" of the mean water level of 1 to 5 feet, depending on storm evolution. An extreme wave height distribution is plotted in Figure 7. The 50-year recurrence interval (or 2% annual exceedance probability) is 37.4 feet.

As ocean swell and locally generated seas propagate into the inlet the processes of wave shoaling, refraction, diffraction, and reflection transform the waves. Wave transformation into

Grays Harbor has been investigated using the Coastal Modeling System –WAVE model (Li et al. 2013). Figure 8 and 9 plot significant wave height for three wave directions (southwest, west, and northwest). These results indicate most of the wave energy refract to toward the north and south shorelines towards shallow water as they enter the mouth. In general waves from the northwest focus more energy on Point Chehalis while waves from the west and southwest focus wave energy on the North Jetty and Damon Point.

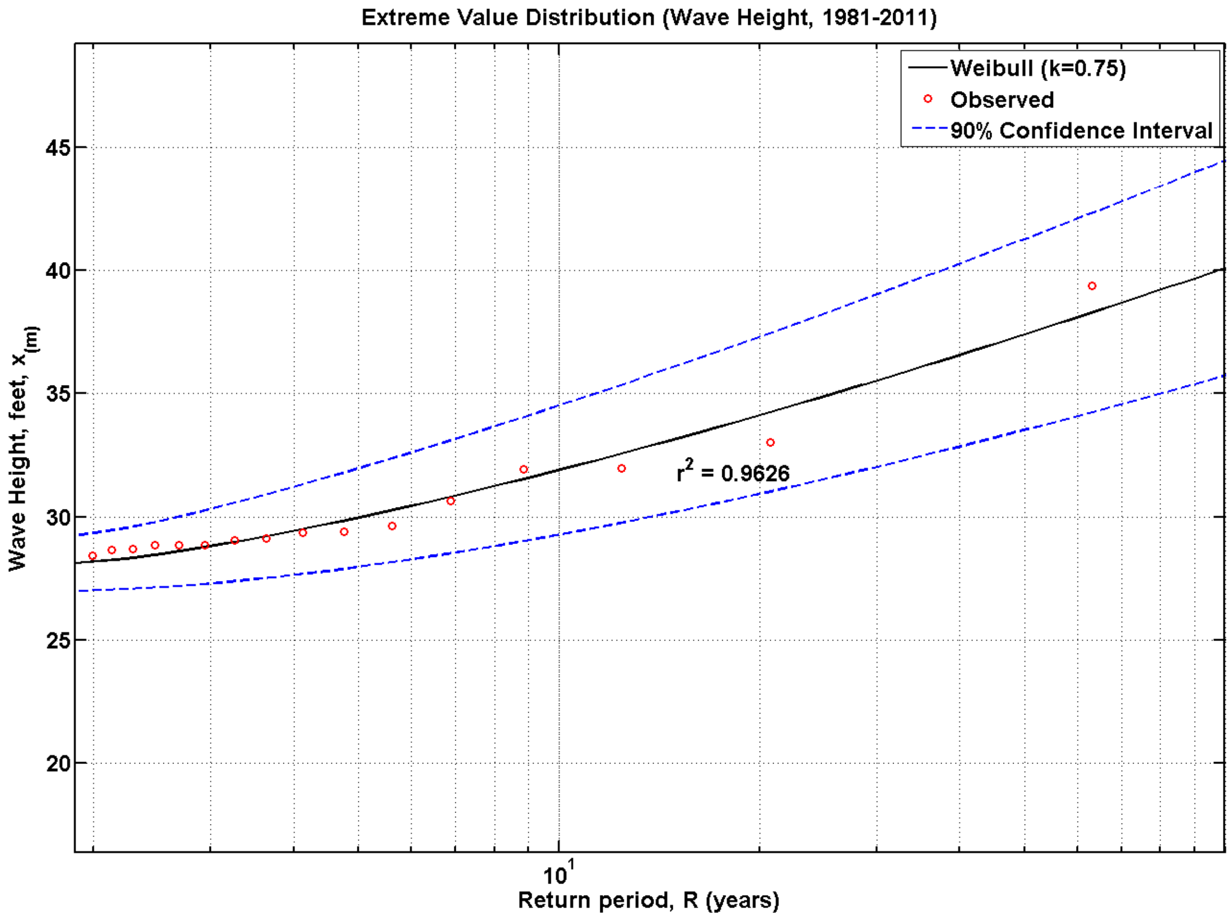

Figure 7: Extreme value distribution of significant wave heights from CDIP buoy 036 Grays harbor, WA (46.857N 124.244W) for 1981-2011.

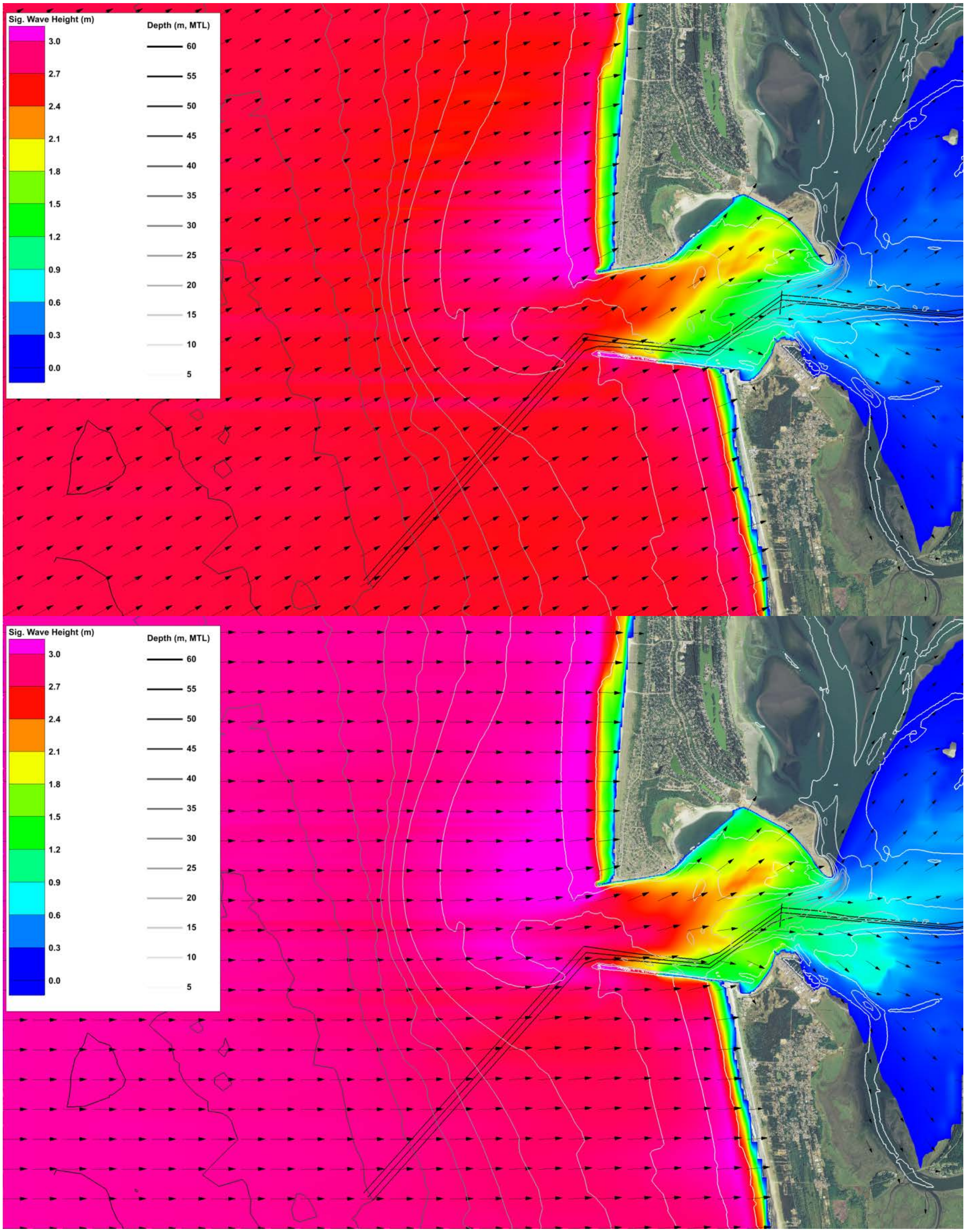

Figure 8: CMS-WAVE computed significant wave height (Hs) with a Southwest (top) and West (bottom) incident wave direction for peak wave period (Tp) = 12.5 sec.

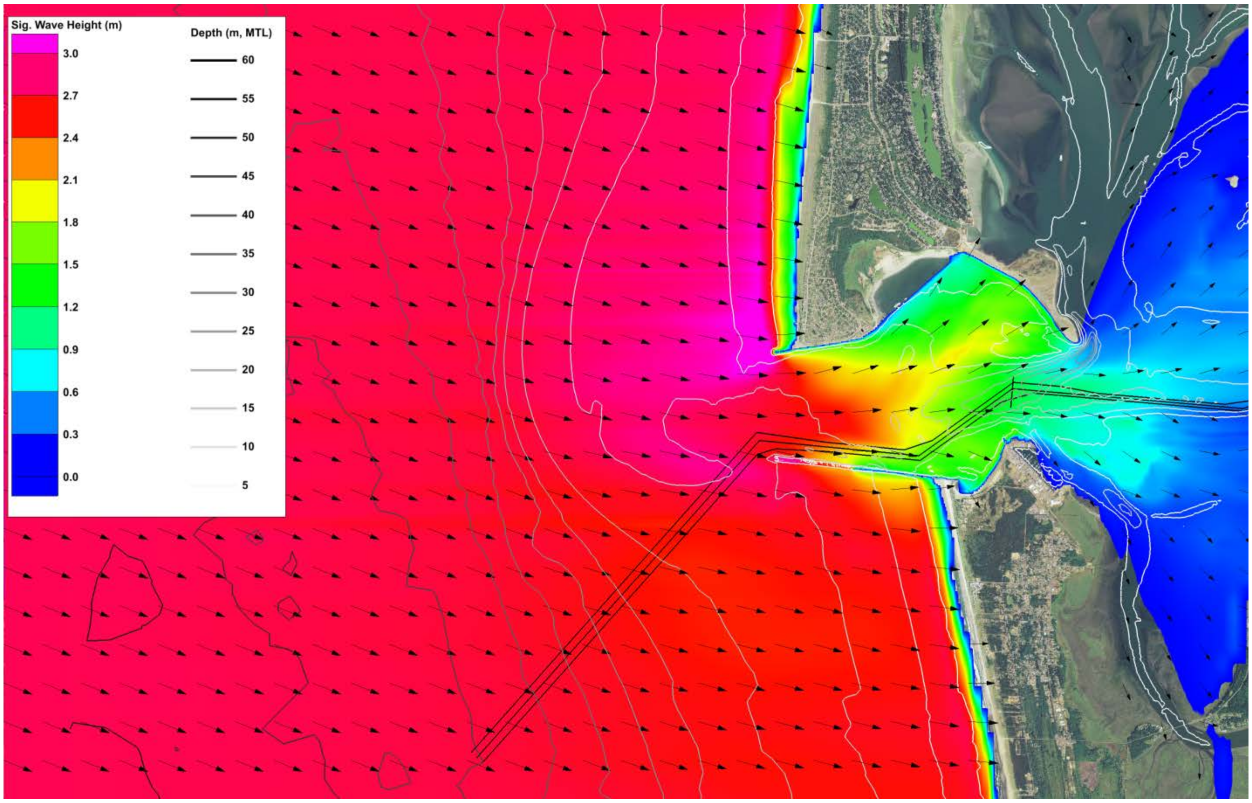

Figure 9: CMS-WAVE computed significant wave height (Hs) with a Northwest (top) incident wave direction for peak wave period (Tp) = 12.5 sec.

Ocean swells from the west and northwest generally result in more energy entering the inner harbor than from the southwest. Model results indicate the significant wave height is reduced to less than 2 feet (0.63 m) in the middle of the South Reach (Figure 10). Ocean swell is dissipated even more in the outer cross-over reach and is negligible at the inner cross-over through the remaining inner harbor channel reaches. The inner harbor reaches are also exposed to locally generated wind waves. Fetch lengths are largest during high tide and can produce waves on the order of 1 to 3 feet. Wind generated waves have shorter periods than ocean swell and seas and typically range from 2 to 4 seconds. These waves are capable of transporting fine grained materials within the inner harbor.

Vessel generated waves also occur in the inner harbor channel reaches. The waves are created by recreational craft, commercial fishing boats, barge and tugs, and deep draft ships. Vessel generated waves typically are short in wave period and typically only impact shallow regions close in proximity to the sailing line. Downstream of North Reach vessel generated waves have minimal effect on shallow areas as these as distances exceed 1500 feet from the sailing line. Shorelines adjacent to the North, Hoquiam, and Cow Point reaches may experience vessels wakes on the order of 1 to 3 feet. It is not expected the wave height will increase with future vessel traffic as the design vessel has not changed, however the frequency of the wakes may increase. However, most of the shoreline is already armored with slope protection thus additional bank erosion associated with the additional vessel traffic is not anticipated.

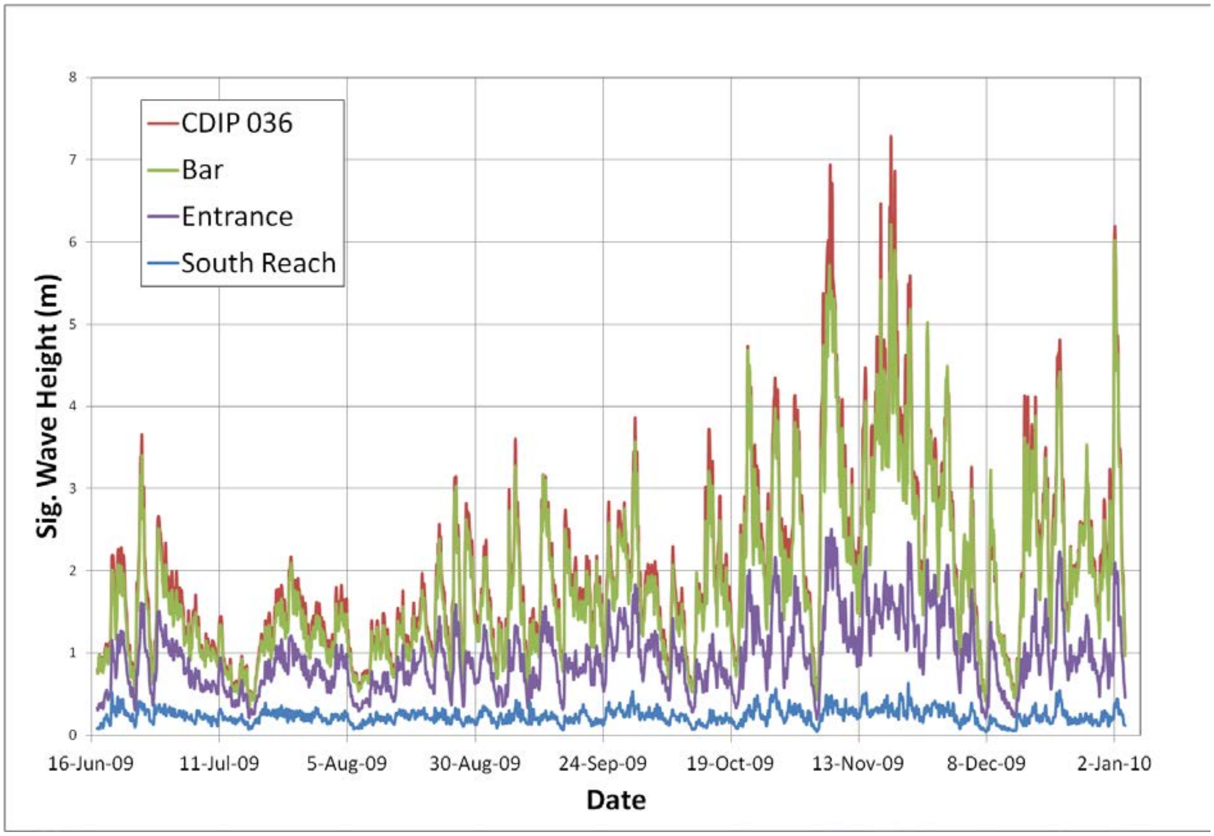

Figure 10. Significant wave height (in deepwater at CDIP 036, in Bar Channel) at mouth of harbor; in Entrance Channel inside harbor; in middle of South Reach.

2. Project History

2.1. Pre Project Condition

Like other coastal ports on the Pacific Ocean, drifting sand bars obstructed safe entrance into Grays Harbor. Only three passages existed in the early 1880s, the deepest offering transit to vessels of 21 feet draft. The need to support the booming timber industry in the Grays Harbor region sparked the Corps of Engineers to assist with engineering the inlet. Below is the description of the harbor in the 1882 Annual report of the Chief of Engineers:

> The Chehalis River becomes the eastern portion of Grays Harbor. From here two channels, one to the north and the other to the south, reach through shoals for a dozen miles toward the sea. Although broadening in its western extremity, much of the harbor is exposed at the lowest extent of tide. Grays Harbor, noted Hiram Chittenden Seattle District Engineer. "Is really a vast mud flat"...The problem at the entrance to the harbor was that the channel underwent constant and confusing relocation; it shifted to the south by an estimated thousand feet between 1862 and 1881 alone. In some seasons it was straight, in others crooked, and at all times the depth varied by several feet. Mariners had to have their sailing vessels towed to sea and could be barbound for weeks due to adverse winds and tide.

As indicated in the 1890 survey on Figure 11, the thalweg through the inner harbor to Hoquiam follows a similar alignment as the present day navigation channel. The depths in the thalweg ranged from 10 to 40 feet. However the depths through the harbor mouth varied drastically ranging from 0 feet to greater than 100 feet.

2.2. Engineering activities for navigation

Table 5 presents a chronology of major engineering activities undertaken in the construction and maintenance of the Federal Navigation Project in Grays Harbor.

South Jetty construction (1898-1902)

In order to provide a reliable channel of suitable depth a single rock jetty was proposed on the southern side of the harbor. Similar jetties at the Mouth of the Columbia and Coos Bay federal navigation projects had been undertaken by the Corps of Engineers Portland District using a timber supported railroad trestle system. The same proven methodology was utilized to construct the South Jetty at Grays Harbor. Here the trestle used to construct the South Jetty was built a distance of 10,000 feet from the oceans high water line. Rock ranging from 50 to 2000 pounds was dumped from the trestle onto a 3 foot thick woven brush mattress foundation. The brush mattress was utilized to prevent excessive erosion of sand along the line of the trestle as tidal currents were confined. This thereby reduced the quantity of stone required to secure the necessary elevation of the jetty. During the construction two channels with depths of 18 and 24 feet were crossed by the line of the jetty. Following construction of the jetties through these channels, the channels were immediately filled in with sand following the first winter season. Additionally to prevent erosion on the south of the jetty a 500 foot long groin was built at a point 11,000 feet west of the high water line (ARCE 1909; ARCE 1915). Figure 12 shows the condition of the harbor in 1909 following construction of the South Jetty. It can be seen that no clear channel across the bar was available to navigation. This led to the recommendation to the Chief of Engineers to undertake construction of a second jetty on the north side of the inlet based on the lessons learned from the construction of two-jettied systems built at the Mouth of the Columbia River and Coos Bay.

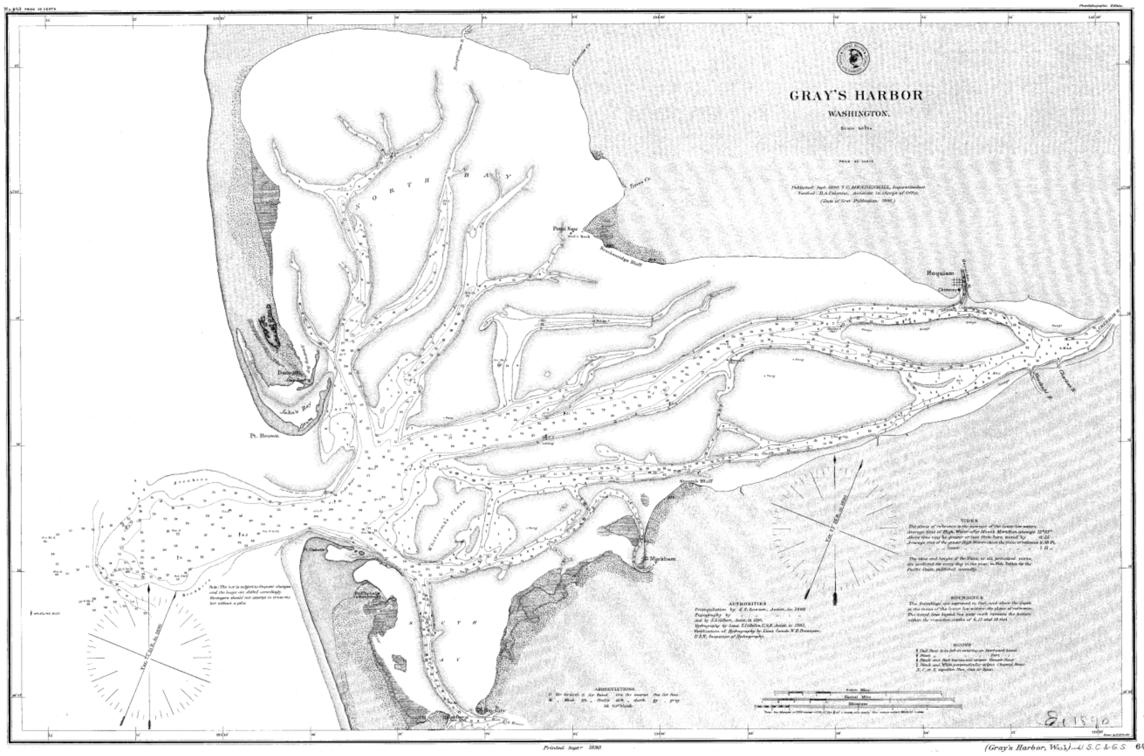

Figure 11. Grays Harbor configuration in 1890, prior to federal navigation project.

North Jetty construction (1907-1916)

The original project for the improvement of the entrance to Grays Harbor contemplated securing depths of 24 feet at mean lower low water by the construction of one jetty on the south side of the harbor entrance. However these depths were only secured for a short periods and were not permanent due to the shifting nature of sands to the north of the entrance. During the latter part of 1906 the Bar channel had seriously deteriorated without a reliable channel across the ebb shoal as indicated in Figure 12. As a result the project authorization was modified to include construction of a second jetty approximately 9,000 feet long on the north side of the entrance. The inner 7,000 feet of jetty were constructed from 1907-1910. At this time it was clear that the jetty needed to be extended to meet its intended function. In 1910 Congress authorized a 7,000 foot extension of the jetty. By 1913 the North Jetty was constructed to its fully authorized length. The period from 1913 to 1916 involved continuous repairs of the North Jetty to mean high water. The morphological feedback of the shoals and channels at the entrance during jetty construction highlight the fact that initial designs of the jetty configuration required adaptive management during construction to meet the intended project purpose. Figure 13 shows the condition of the project in 1916 following completion of the North Jetty.

Outer harbor channel improvement (1916 to 1942)

Construction of the north and south jetties were authorized to provide a 500 foot wide and 24 feet deep channel across the Bar. The 1916 condition survey indicated project depth of 24 feet was achieved. From 1916 to 1922 dredging of the Bar was performed intermittently but could not hold a consistent depth of 24 feet. In the summer of 1924 was the first time a dredge was available for an entire work season from June to October; a total of 652,781 cubic yards were dredged and on completion a channel 32 feet deep was secured across the bar (H. Doc No. 582, 69th Cong). However surveys in the following months indicated the Bar continued to shoal heavily with controlling depths varying from 22.5 to 26 feet. In 1925, dredging removed approximately 1.1 million cubic yards securing a Bar channel depth of 36 feet but surveys in the following winter indicated shoaling depths up to 25 feet. From 1928 to 1932 the minimum depth maintained over the Bar generally exceeded 28 feet. Between 1916 and 1942, dredging of the outer bar amounted to about 22 million cubic yards (USACE 1974).

Inner Harbor channel improvement (1905-1934)

The River and Harbor Act of June 13, 1902 provided continued authority for improvement of the inner harbor portion between the Bar and Aberdeen. In 1905, a channel 100 feet wide and 15 feet deep at low water was obtained by dredging through the shoal between Hoquiam and Aberdeen (Hoquiam Reach).

The River and Harbor Act of March 2, 1907 provided a channel 200 feet wide and 18 feet at mean lower low water from Cosmopolis (South Aberdeen Reach) to deep water below Hoquiam (Hoquiam Reach) a distance of about 15 miles; and a 6 feet and 150 feet wide channel between Cosmopolis and Montesano, Washington. This construction was completed in 1910 and required approximately 1.8 million cubic yards of dredging. The maximum draft that could be carried in 1910 over the shoals below Aberdeen at mean lower low water was 18 feet. (H. Doc. No. 53, 73rd Cong.).

In 1919 the Port of Grays Harbor Commission agreed to undertake maintenance dredging of the inner harbor reaches to a depth commensurate with that obtained on the outer bar; this dredging amounted to approximately 6.2 million cubic yards in 1919. Under this agreement the Port deepened 8.5 miles of the inner harbor to 26 feet over a channel width ranging from 200 to 350 feet. The natural depths from Aberdeen to Cosmopolis were nearly 26 feet thus no maintenance dredging was required to these channel reaches (H. Doc. No. 53, 73rd Cong.).
The River and Harbor Act of July 3, 1930 provided a 150 foot wide 16 feet deep channel from Cosmopolis to Montesano, a distance of 10.75 miles subject to the condition that local interests pay half the initial cost and assume the maintenance (H. Doc No 315, 70th Cong.). In 1931 a

channel 12 feet deep and 100 to 150 was constructed. Soon after, dredging this channel reach became classified as inactive.

In 1932, the Port of Grays Harbor was financially unable to continue maintenance dredging of the channel through the inner harbor to Aberdeen. The Board of Engineers for Rivers and Harbors and Chief of Engineers recommended the Corps take over maintenance dredging responsibilities in the inner harbor in order to secure the federal investments already made at the Bar (H. Doc. No. 53, 73rd Cong.).

South Jetty reconstruction (1935-1939)

From 1904 to 1933, the South Jetty subsided to elevations varying from +6 feet MLLW, on the shore end, to -10 feet MLLW at the seaward end. Between 1935 and 1939, 12,656 feet of the South Jetty was reconstructed to an elevation of +20 feet MLLW.

North Jetty reconstruction (1941-1942)

From 1941 to 1942 an 8,828 foot section between the seaward end and the high water line was reconstructed to +20 feet MLLW. Sediment transport over the jetty created shoaling within the harbor and progressively forced the Bar channel to migrate south toward the South Jetty. This resulted in considerable scour forces along the channel side of the South Jetty. After the North Jetty crest height was restored shoreline accretion from 1942 to 1959 north of the North Jetty on North Beach amounted to approximately 2 million cubic yards per year (USACE 1975).

Point Chehalis and Westhaven Cove construction (1950-1957)

The Port of Grays Harbor constructed a harbor at Westhaven Cove on Point Chehalis in 1929. The Cove which had been formed naturally a few years earlier was enlarged by dredging. Reconstruction of the South Jetty between 1935 and 1939 was a contributory cause of erosion of Point Chehalis by its effect upon wave and current action in the vicinity of the Point. Seven groins, three timber pile breakwaters, and a 2,880-foot rock revetment along the north and west shoreline were constructed from 1950 to 1957 to stabilize the shoreline and secure the boat basin in Westhaven Cove.

Inner Harbor Channel Improvement (1954)

In 1954 the following modifications (H. Doc. No. 412, 83rd Cong) were made to the navigation project:

- Provide a 30 feet deep and 350 feet wide channel from the Port of Grays Harbor Terminal 1 upstream to Cow Point (e.g. Cow Point Reach).
- Provide a 30 feet deep and 200 foot wide channel to Aberdeen, approximately 13,700 feet upstream of the Union Pacific Railroad Bridge (e.g. Aberdeen and South Aberdeen Reaches).
- Provide a turning basin 550 feet wide at Cosmopolis (e.g. Elliott Slough Turning Basin).

South Jetty rehabilitation (1966)

Between 1939 and 1962, the outer 4,400 feet of the jetty was destroyed leaving less than 5,000 feet of the jetty near grade (USACE 1965). In 1966, approximately 600,000 tons of new rock was placed to rehabilitate 4,000 feet of destroyed jetty (Sta. 110+00 to 150+00). Due to the excessive scouring forces on the channel side of the jetty the structures alignment was shifted approximately 35 feet south at the shoreward end and 133 feet south on the seaward end. Following rehabilitation, this left approximately 7,000 feet of the original jetty 1902 in a destroyed condition.

North Jetty rehabilitation (1976)

In the 1941-1942 reconstruction the remainder of the North Jetty landward of the high water line was not restored. Additionally by 1961 only 2,100 feet of the 1941-1942 reconstructed section was at or near grade. Similar to the prior rehabilitation significant littoral transport from north to south over the North Jetty was beginning to create impacts to O&M dredging of the navigation channel. Thus in 1976, approximately 200,000 tons of new rock was placed to rehabilitate the outer 6,000 feet of the jetty (Sta. 100+00 to 160+00).

South Reach (Sand Island) Channel Realignment (1976)

As the North Jetty deteriorated from 1942 to 1975 sediment entered the harbor from North Beach and resulted in increased shoaling rates in the navigation channel as well as the growth of the spit at Damon Point. This resulted in accretion in the Sand Island Reach of the navigation channel which historically followed the thalweg into the inner harbor adjacent to Sand Island. In effort to minimize adverse impacts to annual maintenance dredging costs, the Corps conducted a 4.5 mile channel realignment which shifted the navigation approximately 1 mile south of the former Sand Island Reach alignment (Figure 17). The initial volume to dredge the new South Reach channel to its authorized depth of -30 feet MLLW was approximately 3 million cubic yards (USACE 1976).

Navigation Improvement Project (1990-1991)

The 1990 channel deepening and widening began in April 1990 and concluded in February 1991. The project was completed using three separate contracts. Manson Construction Company and Great Lakes Dredge & Dock were awarded the contracts which dredged approximately 8.2 million cubic yards of sediment from the navigation channel from the Bar to Cow Point (USACE 1989; USACE 1990). The first contract was awarded to Manson for Outer harbor dredging of the Bar, Entrance, and South Reach using the Newport and Westport hydraulic hopper dredges. The second contract was awarded to Manson for dredging of the Crossover and North Channel with the Newport hopper dredge. The construction period of the first two contracts was from early May 1990 to February 1991. The third contract was awarded to Great Lakes Dredge & Dock and consisted of clamshell dredging of North Channel and Cow Point Reaches and hydraulic pipeline dredging of Cow Point Reach. Upland placement of sediment from the Cow Point Reach was performed with a pipeline dredge. The period of construction of this contract ranged from June to September 1990.

There were a few of changes from the recommended plan presented in the General Design Memorandum (USACE 1989) to what was eventually implemented during construction which was primarily due to the declining timber industry in the early 1990s. The primary deviations being, (1) The channel deepening of the Aberdeen Reach to -36 feet MLLW went only to an upstream Station of 1252+00. (2) The South Aberdeen Reach was not deepened to -36 feet MLLW. The South Aberdeen Reach was most recently dredged to a project depth of -32 feet MLLW in 1999. (3) The Elliott Slough Turning Basin was never widened to 750 foot width and still maintains a 550-foot width. (4) The recommended bridge modifications to the Union Pacific Railroad Bridge were never implemented and were later removed from the project.

Breach Fill (1994)

From 1954 to 1999, South Beach (the nearshore area south of the South Jetty) experienced a cumulative erosion or nearly 72.3 million cubic yards (Buijsman et al. 2003). Additionally, erosion in Half Moon Bay caused the shoreline to continue to recede. In December 1993, the beach and dune adjacent to the South Jetty become low and narrow enough that during a winter storm in a breach channel formed connecting the Pacific Ocean to Half Moon Bay. The channel widened and deepened over the course of the winter and was eventually filled with 600,000 cubic yards of dredged material in August 1994.

Point Chehalis Revetment Extension (1998-1999)

In June 1997, the Corps completed an Evaluation Report (USACE 1997) that recommended construction of a jetty extension to minimize the probability of a breach and the potential consequences to navigation. The planned solution consisted of:

- Extending the South Jetty eastward 4,300 feet. The first phase would include a 1,000 foot extension to the existing South Jetty alignment (Segment 1) and a 2,300 foot extension to the Point Chehalis revetment (Segment 2). The second phase would connect Segment 1 and 2 at project year 25 with a remaining 1,000 foot section of jetty.
- Beach nourishment for toe protection of the jetty extension at four-year intervals.

The Point Chehalis revetment was extended by 1,900 feet during the period November 1998 to March 1999. However, the South Jetty extension was never implemented. As a mitigation agreement with the resource agencies, nearshore placement of dredged material within the Half Moon Bay Beneficial Use Site is required to maintain a stable beach slope (1 vertical on 60 horizontal slope) within Half Moon Bay (USACE 1998).

South Jetty rehabilitation (1999-2002)

The steepening of the South Beach nearshore area resulted in larger waves attacking the South Jetty which resulted in more damages along the structure. By 1999 blowouts in the jetty crest allowed wave transmission and tidal currents through the jetty and threatened the reliability of navigation into the harbor. Thus in 1999 to 2002, the landward 3,300 feet (Sta. 87+00 to 110+00) of the South Jetty was rehabilitated (USACE 1999).

North Jetty rehabilitation (2000-2001)

From 1976 to 1996 the seaward reach of the jetty had lowered to +14 feet MLLW. Overtopping waves created large amounts of water to be deposited on the north side of the jetty root which formed two swash channels on the east and west end of the peninsula the North Jetty is attached. Drainage through and adjacent to the jetty became inadequate to convey this volume of water and threatened the stability of the jetty. From 2000 to 2001, 5,000 feet of the North Jetty were rehabilitated to +23 feet MLLW (Sta. 95+00 to 145+00). A 30 foot rock blanket (splash apron) was constructed to the north of the jetty crest to prevent scour along the north of the jetty from the swash channel (USACE 2000).

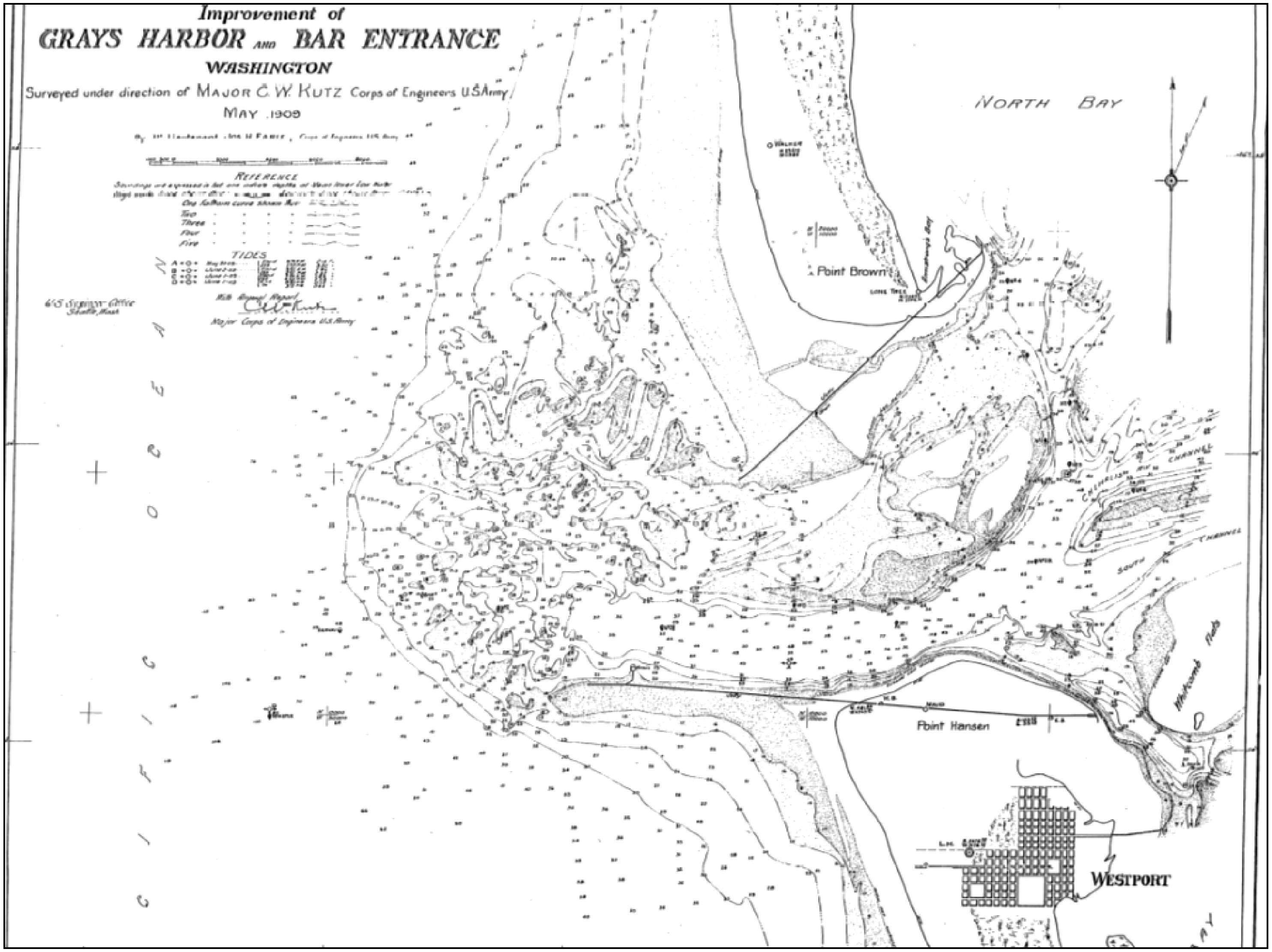

Figure 12: Condition survey from 1909 following original construction of the South Jetty and during construction of the North Jetty. Note no clear channel across ebb tidal shoal indicating unreliable conditions for navigation.

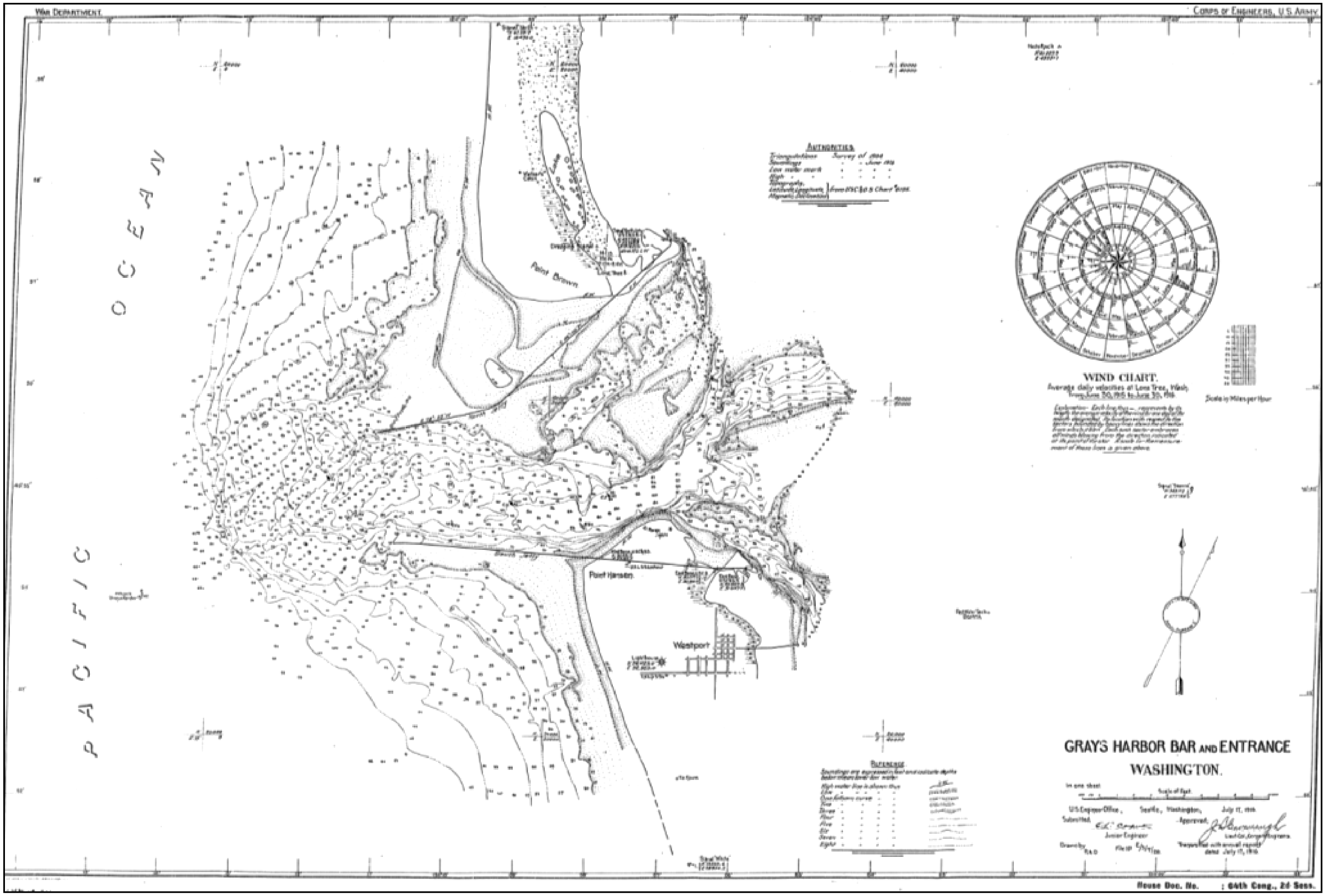

Figure 13: Condition survey from 1916 following original construction of the North jetty. Note ewith presence of the two jetties a clear channel across ebb tidal shoal now exists.

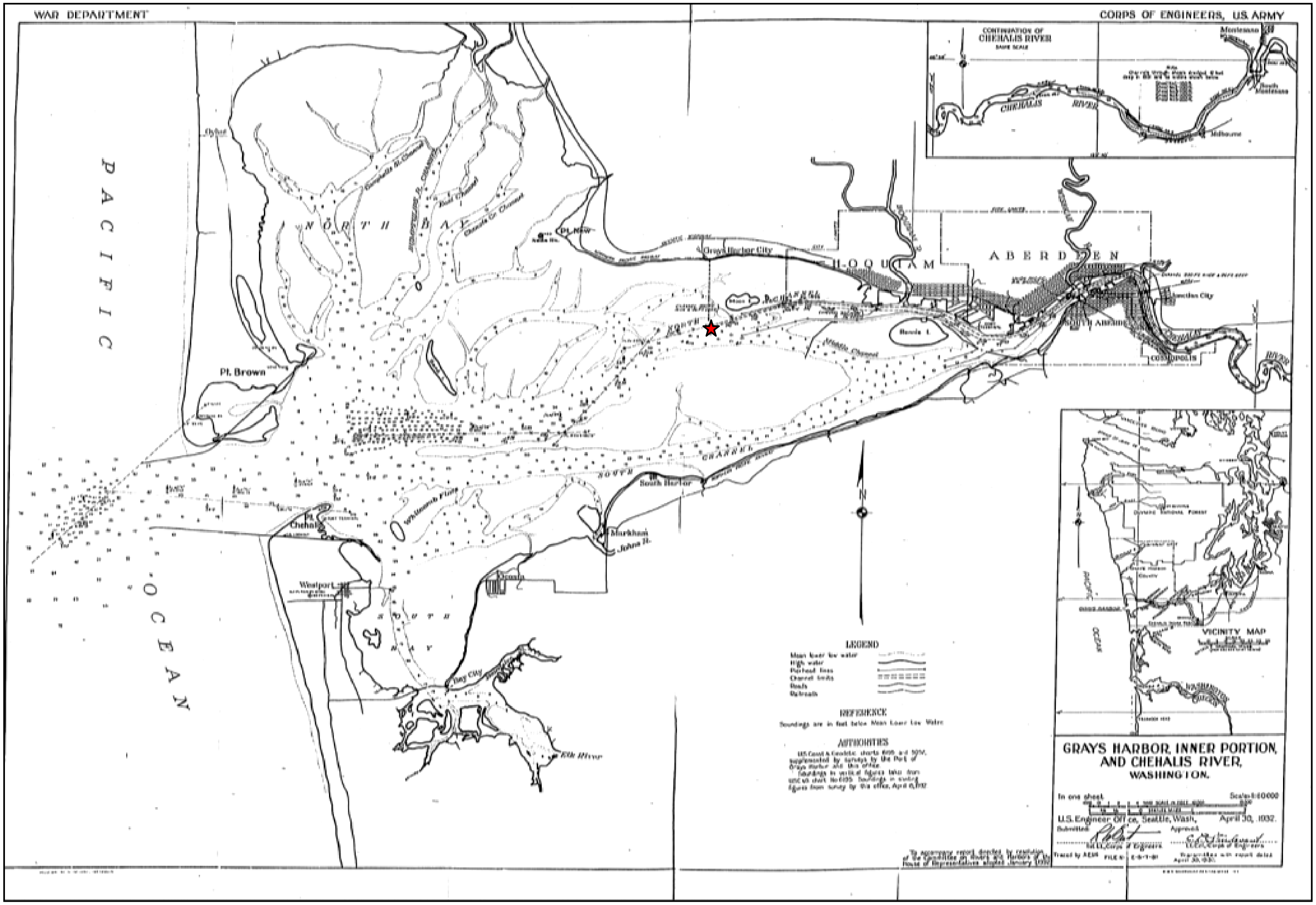

Figure 14: Condition of Grays Harbor in 1932. Star denotes downstream limit of channel maintained by Port of Grays Harbor until 1934 (North Channel).

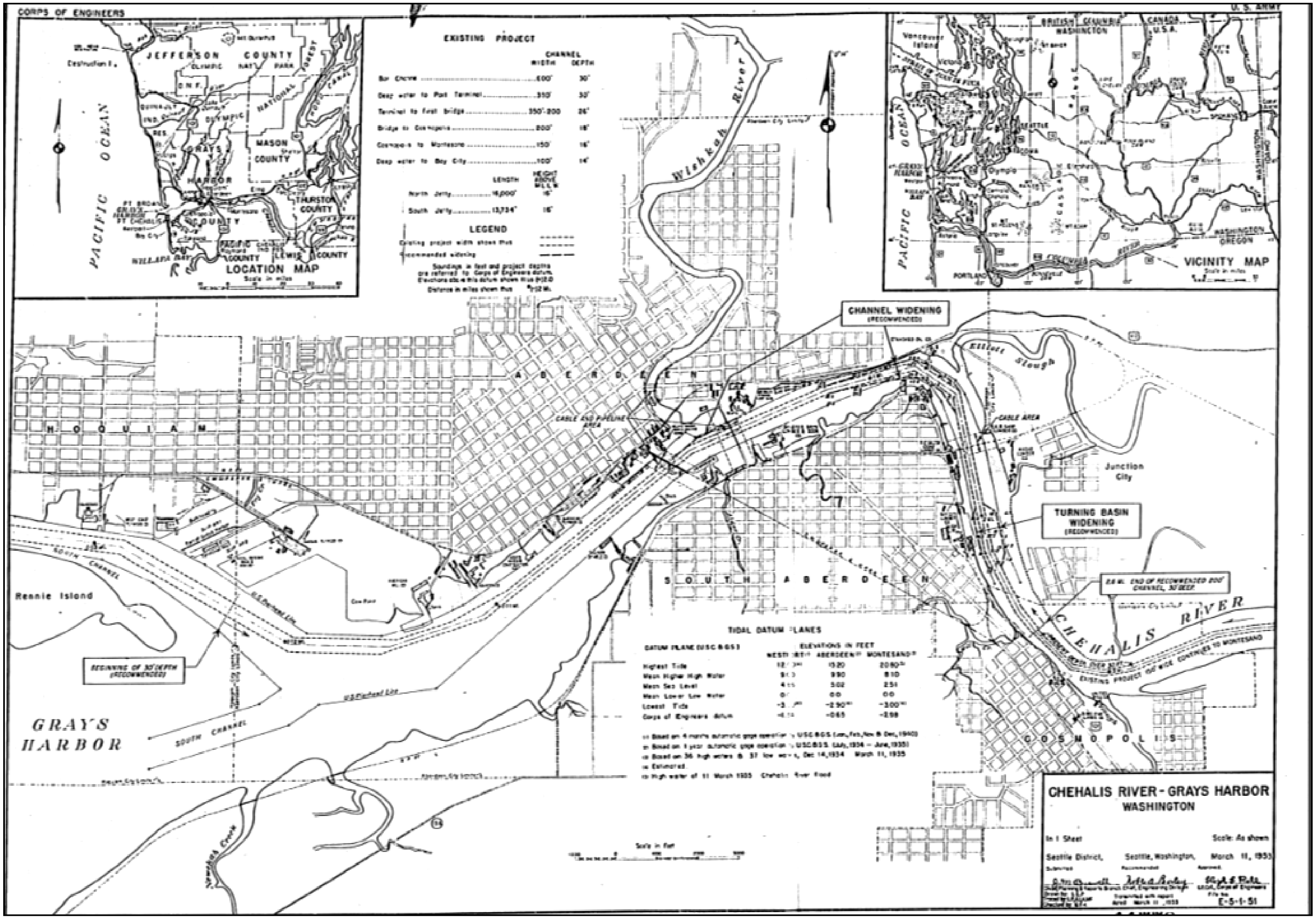

Figure 15: Channel Improvements from Cow Point to South Aberdeen and widening of Elliott Slough Turning Basin

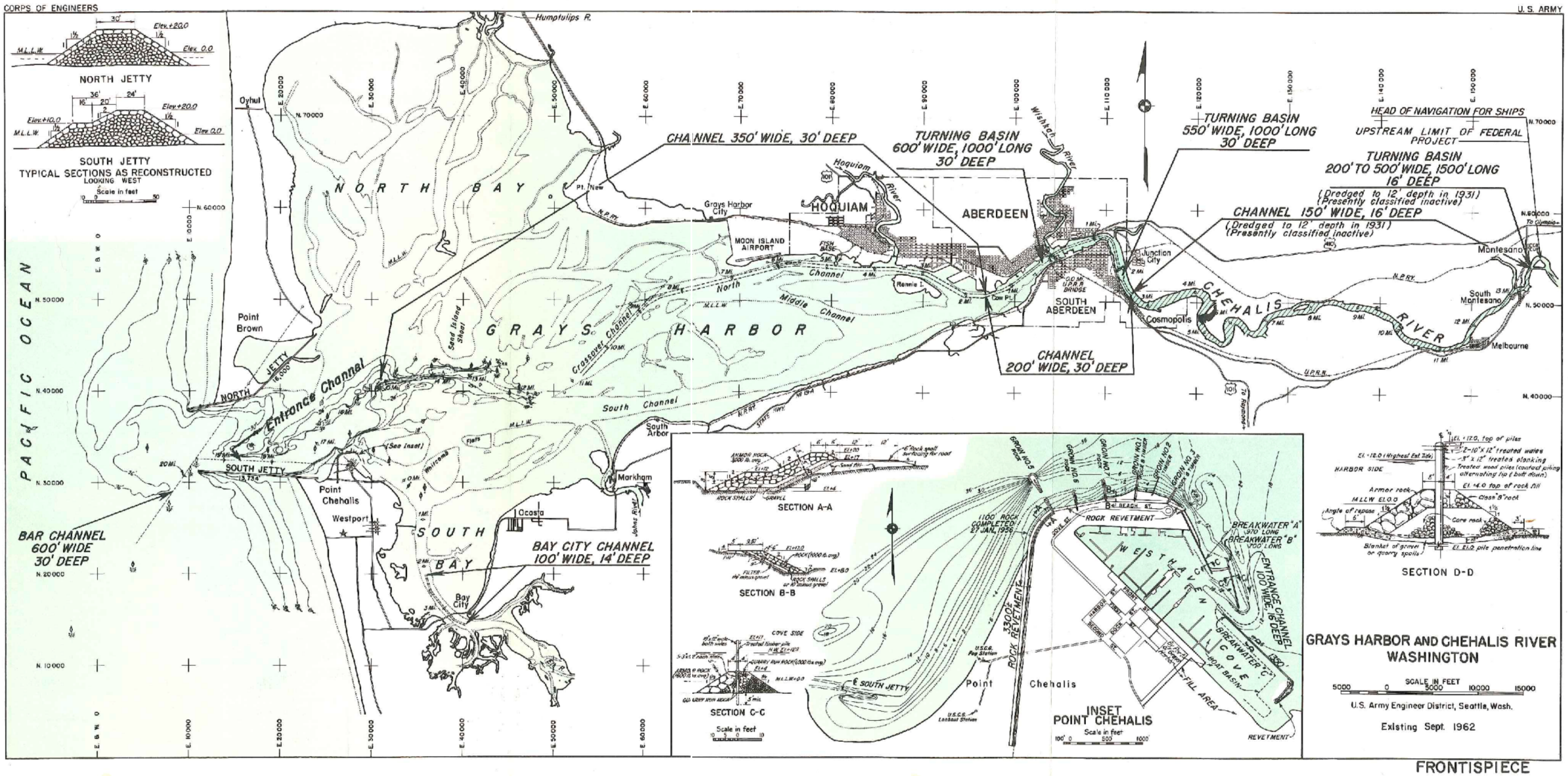

Figure 16: Channel condition after 1954 channel improvements

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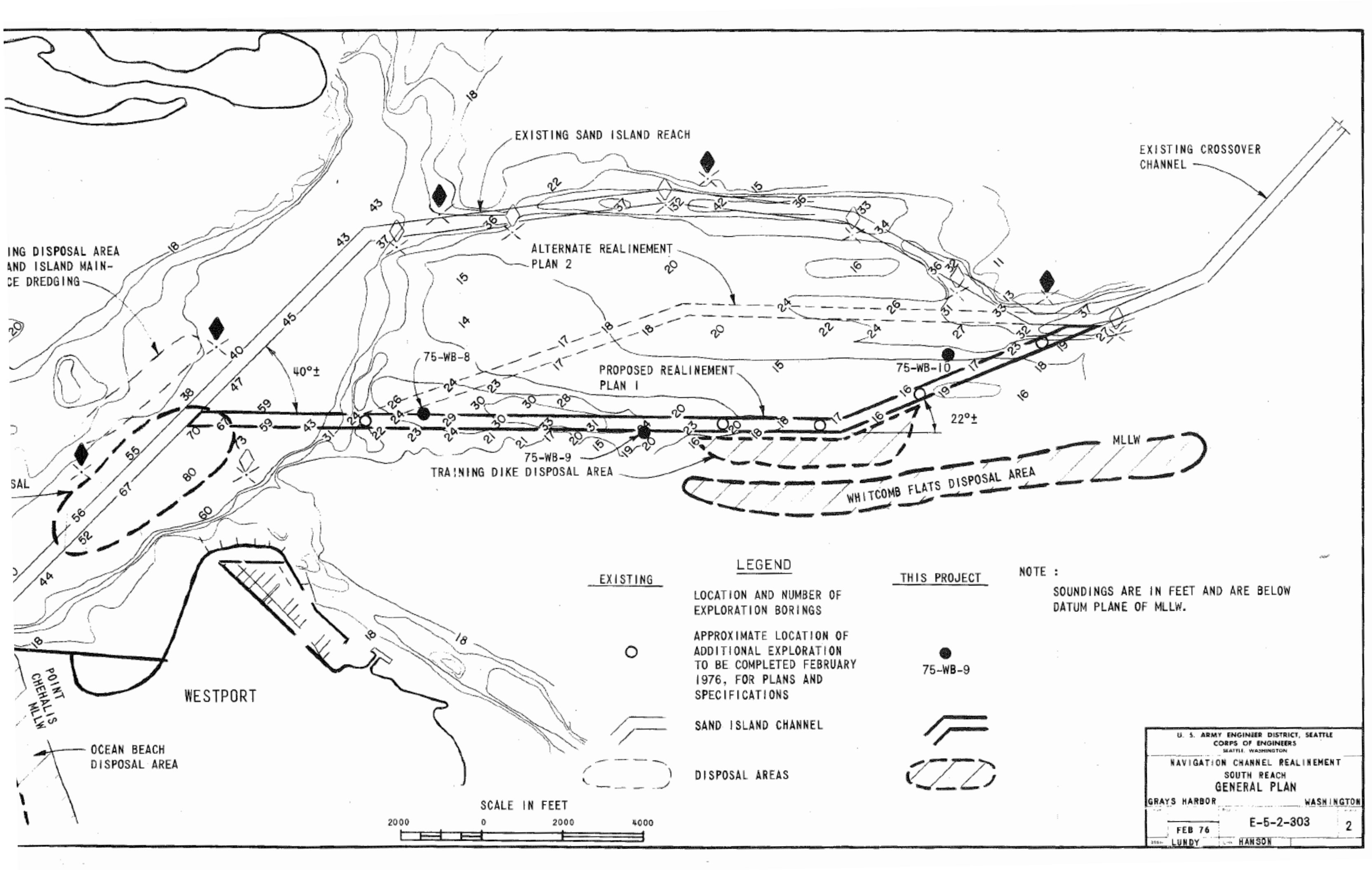

Figure 17: South Reach Channel Realignment in 1976.

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Table 5: Construction and Rehabilitation History, Grays Harbor, Washington (modified from Kraus and Arden 2003)

3 June 1896	The River and Harbor Act authorized the original Grays Harbor navigation project, including a channel across the bar (self-scouring to a depth of about 18 feet mean lower low water (MLLW) and construction of a single jetty extending 18,154 feet seaward from Point Hansen (now called Point Chehalis) peninsula along the southern margin of the entrance to Grays Harbor. At this time, predominant longshore transport was determined to be from south-to-north, and the South Jetty was considered responsible for preventing shoaling in the navigation bar channel (USACE1965).
1898 – 1902	The South Jetty was constructed between May 1898 and September 1902. It was completed to a height of +8 feet MLLW and a total length of 13,734 feet, of which 11,950 feet extended seaward of the high-water line in 1902. During construction, the channel adjacent to the jetty undermined the structure causing material overruns that depleted project funds before the design length of 18,154 feet could be reached. A groin (spur) pointing into the channel was constructed 11,952 feet from the high-water line in 1902.
1902 – 1906	Between 1898 and 1904, depth over the ebb-shoal increased from 12 to 22 feet MLLW as a result of jetty construction, meeting the stated purpose of the project. In addition, the beach south of the jetty accreted, creating a 3,000-feet seaward progradation of the high-water shoreline. However, deterioration of the jetty began around 1904. By 1906, the South Jetty had settled due to scour, and the bar channel began to widen and shoal. This unfavorable shoaling led to construction of the North Jetty
2 March 1907	The River and Harbor Act authorized construction of the North Jetty 9,000 feet long from the ordinary high-water line to an elevation of +5 feet MLLW and 18-foot deep navigation channel.
1907 – 1910	Construction of 10,000 feet of the North Jetty completed to +5 feet MLLW.
25 June 1910	The River and Harbor Act authorized an extension of 7,000 feet to the North Jetty.
1910 – 1913	The North Jetty was completed to a project length of 16,000 feet and an elevation of +5 feet
1913 – 1916	The North Jetty was reconstructed to +8 feet MLLW and extended to a length of 17,204 feet. Construction period for the entire jetty extends from May 1907 to January 1916. After reconstruction of the North Jetty, the channel adjacent to the South Jetty shoaled, and a new wider and deeper channel developed north of the old channel to about -24 feet MLLW. Depth over the bar was again about -22 feet MLLW, and it remained that way until about 1924.
8 August 1917	River and Harbor Act authorized dredging of the bar channel.
1916	As jetties continued to deteriorate and were inadequate to maintain project dimensions in the bar channel, dredging commenced (57,000 cu yd) and continued at regular intervals until 1926 (except for 1918 and 1919).
1926 - 1942	The bar channel required almost continuous dredging between 1926 and 1942. The total quantity dredged from the entrance between 1916 and 1942 was approximately 22×10^6 cu yd; maximum dredging occurred between 1934 and 1936. The minimum quantity dredged in a year was 22,000 cu yd, and the maximum was 1,964,000 cu yd (USACE 1967).
1933	By 1933, the South Jetty had subsided to an average depth of 5 to 10 feet below MLLW (+6 feet MLLW at the high-water shoreline and -10 feet MLLW at the outer end).
1934	The outer 8,000 feet of the North Jetty, between the high water shoreline and the tip of the jetty, subsided to approximately -1.5 feet MLLW.
30 August 1935	River and Harbor Act authorized reconstruction of the north and south jetties and maintenance of a 26-foot deep channel below Aberdeen.
1935 – 1939	A 12,656-feet section of the South Jetty (about Sta. 80+00 to 220+00) was reconstructed to an elevation of +20 feet MLLW. Jetty reconstruction blocked the supply of sand to Point Chehalis, causing serious erosion of Point Chehalis. A 32-foot section of the jetty was removed to try to restore the supply of sand, but it was quickly blocked by accretion south of the jetty.
1939 – 1946	The outer 900 feet of the South Jetty was destroyed, and crest rock was displaced to +2 feet MLLW over the next 2,656 feet.
1940	The inner 7,300 feet of the North Jetty, shoreward of the high-water shoreline, was impounded with sand.
1941 - 1942	The North Jetty was reconstructed between February 1941 and May 1942 to +20 feet MLLW for 7,700 feet seaward of the high-water shoreline, then +30 feet MLLW for an additional 528 feet. A 412 feet segment seaward of the reconstructed section was at MLLW and was not restored. The structure landward of the high-water shoreline was not rebuilt.
1942	Maintenance dredging of the bar and entrance channels was no longer required due to scouring effects of the jetties.

[1] Reconstructed refers to major changes in jetty dimensions along the length of the structure.
[2] Rehabilitated refers to changes implemented to maintain a portion of the jetty and its general dimensions.

Table 5 (Concluded)	
1942 – 1949	The outer 325 feet of the North Jetty was leveled, and about 400 feet of the reconstructed section was lowered 4 feet below grade.
1946 – 1951	An additional 900 feet of the South Jetty was destroyed, and the next 4,100 feet subsided to 0 to +10
1946	Half Moon Bay begins to form east of the South Jetty root
1950-1956	Construction of Point Chehalis Revetment and Groins to serve as shore protection for marina at Westport due to erosion associated with South Jetty reconstruction.
1951 – 1953	An additional 900 feet of the outer South Jetty was destroyed, and the next 4,500 feet subsided to 0 to 2 feet MLLW. The next 2,400 feet subsided to +4 feet MLLW.
1949 - 1953	An additional 325 feet of outer end of the North Jetty was leveled, and more than 1,000 feet of the remaining section subsided to +10 feet MLLW.
1952 - 1954	More than 300 feet of the South Jetty (between Sta. 70+00 and 80+00) was dismantled, and the rock used for construction of the Point Chehalis revetment.
1959	An additional 30 x 10^6 cu yd of sand had accumulated north of the North Jetty as a result of jetty reconstruction completed in 1942.
1961	Only 2,100 feet of the reconstructed portion of the North Jetty remained at or near grade (+20 feet MLLW).
1962	By April 1962, average elevation of the South Jetty between 135+00 and 198+00 (6,300 feet) was about MLLW; seaward of this point from 198+00 to 220+00 (2,200 feet), crest elevation ranged from -6 feet MLLW to -48 feet MLLW. The landward section from about 88+00 (high-water shoreline) to 135+00 (4,700 feet) was near grade.
1966	A 4,000-feet section of the South Jetty (from Sta.110+00 to 150+00) was rehabilitated to +20 feet MLLW, leaving the outer 7,000 feet in a degraded condition (-10 feet MLLW or deeper).
1970-1973	Extensive groin replacement , revetment repair, and timber breakwater construction along Point Chehalis (including timber pile closure of Westport Marina entrance between breakwaters A and B)
1974	A section of the North Jetty, about 1,300 feet seaward of the high-water shoreline, ranged from +3 to +14 feet MLLW. The jetty seaward of this point was below MLLW.
1975 - 1976	A 6,000-feet section of the North Jetty, from the high-water shoreline seaward, was rehabilitated to an elevation of +20 MLLW.
1990	Construction of outer harbor navigation channel improvements including deepening of bar and outer entrance channel to 46 feet MLLW, widening of bar channel to 1000 feet, and entrance channel to 600 feet. Deepening of inner harbor reaches and turning basins from 30 feet MLLW to 36 feet.
1991	Maintenance dredging of the bar and entrance channel reactivated.
December 1993	A breach occurred between the ocean and Half Moon Bay adjacent to the South Jetty. The breach was filled with 600,000 cu yd of sand dredged from the channel in 1994.
1993	Rehabilitate southern portion (800 feet) of the Point Chehalis revetment.
March 1999	Storm lowered a 200 feet section of the South Jetty to about +9 feet MLLW and damaged the jetty where it intersected the shoreline.
Dec 1998 – Mar 1999	Pt. Chehalis Revetment Extension Project. Corps extends the Pt. Chehalis Revetment 1900’ south along Half Moon Bay.
2000	South Jetty Repair Project. Reinforce South Jetty from Sta. 81+00 to 87+50 to 40 foot crest width. Contract wave diffraction mound at landward root of South Jetty including placement of 17,400 tons of 12” minus gravel/cobble on Half Moon Bay to slow erosion.
1999-2000	A 3,500-feet section of the South Jetty seaward of the high-water shoreline was raised to an elevation of +23 feet MLLW.
2000	North Jetty Major Maintenance Rehabilitation, Sta. 95+00 to 145+00, top el. +23 feet MLLW.
2002-present	Dredged material or upland materials are used to periodically renourish sediment to the dune/beach on Half Moon Bay and South Beach to minimize risk of a breach reoccurring adjacent to the South Jetty. Four Nourishments placing a total of 166,000 cu yd. of sediment have taken place in 2002, 2004, 2010, and 2012.
2010	Repaired two sections (total of 300 feet) of the Point Chehalis Revetment which had been damaged by wave overtopping
2013	Repaired another 300 foot section of the Point Chehalis Revetment which had been damaged by wave overtopping

Operations and Maintenance Dredging (2000 to present)

The Corps of Engineers annually performs O&M dredging of the federal navigation channel using two different dredge types for the outer harbor and inner harbor reaches. These dredged volumes are related to funding allocated to the project in a given year versus the volume available to maintain the navigation channel to the authorized depth. The historic dredging volumes from 2000 to 2012 in the Grays Harbor navigation channel are listed by reach in Table 6.

The outer harbor reaches from the Bar to the Outer Crossover are dredged with a hydraulic hopper dredge which can operate in harsher conditions. The Corps typically operates two government hopper dredges, the Yaquina and the Essayons, in the outer harbor; howeve,r private hopper dredges have been utilized in the past. The load capacity of these dredges ranges from 1,000 to 6,000 cubic yards with an average daily production ranging from 10,000 to 30,000 cubic yards per day. The timing of hopper dredging has historically been in the months of April and May. This is typically due to the scheduling of the government dredges which are shared among the Corps Districts on the West Coast. O&M dredged material from the outer harbor is placed at four different open water placement sites: the Point Chehalis Site, South Jetty Site, South Beach Beneficial Use Site, and the Half Moon Bay Beneficial Use Site. The average annual volume dredged from the outer harbor from 2000 to 2012 was 887,600 cubic yards. The maximum dredged was 1.24 million cubic yards in 2000.

Historically the inner harbor reaches from the Inner Crossover to Cow Point has been dredged via clamshell dredge which is a mitigation requirement for juvenile crabs. The Outer Crossover may be dredged via hopper or clamshell dredge; clamshell dredging is the preferred method however hopper dredges have historically dredged this reach due to the timing of the clamshell dredging which typically requires more exposure to adverse weather conditions. Clamshell dredging is performed with a private Contractor dredge within the fish window extending from 15 July to 14 February. Dredged material is transported by a tug from the dredge area and placed at the Point Chehalis or South Jetty open water placement site by a bottom dump scow barge. Recently the Contract dredge has utilized a 35 cubic yard clamshell bucket with 2 bottom dump barges and has achieved an average daily production of approximately 12,000 cubic yards per day. The average annual volume dredged from the inner harbor from 2000 to 2012 was 997,500 cubic yards, while the maximum dredged was 1.62 million cubic yards in 2004.

	Clam Shell Dredging (Inner Harbor) Volume (yd^3)							Hopper Dredging (Outer Harbor) Volume (yd^3)				Total Volumes (yd^3)	
Dredge Year	S. Aberdeen	Elliot Slough Turning Basin	Cow Point / Aberdeen	Cow Point Turning Basin	Hoquiam	North Channel	Inner Crossover	Outer Crossover	South Reach	Entrance / Pt Chehalis	Bar Channel	Inner Harbor	Outer Harbor
2000	-	-	443,518	-	54,376	200,000	218,163	295,837	198,000	537,000	209,000	916,057	1,239,837
2001	-	-	271,303	-	42,777	-	-	162,654	191,209	359,000	227,000	314,080	939,863
2002	-	61,279	705,114	-	115,901	126,780	158,838	22,129	135,706	605,459	144,031	1,167,912	907,325
2003	-	-	549,026	-	128,874	146,794	301,819	-	135,634	246,792	137,689	1,126,513	520,115
2004	-	35,619	784,950	-	135,863	113,633	545,896	175,968	177,529	443,470	291,195	1,615,961	1,088,162
2005	-	-	657,352	-	141,746	143,760	223,542	107,432	-	622,771	217,909	1,166,400	948,112
2006	-	27,869	638,343	-	37,863	93,825	200,488	163,730	59,931	379,513	55,170	998,388	658,344
2007	-	-	418,564	-	-	-	-	117,560	94,868	497,795	-	418,564	710,223
2008	-	-	694,536	208,069	-	-	198,471	-	-	800,258	-	1,101,076	800,258
2009	-	-	626,247	200,000	-	-	268,179	-	-	684,107	246,873	1,094,426	930,980
2010	-	-	716,449	171,295	150,000	150,000	198,529	-	67,102	580,218	118,182	1,386,273	765,502
2011	-	-	521,646	83,853	122,288	104,765	-	-	46,670	459,840	298,163	832,552	804,673
2012	-	-	451,291	177,185	96,846	103,598	-	-	27,475	1,056,333	141,655	828,920	1,225,463
Sum	**-**	**124,767**	**7,478,339**	**840,402**	**1,026,534**	**1,183,155**	**2,313,925**	**1,045,310**	**1,134,124**	**7,272,556**	**2,086,867**	**12,967,122**	**11,538,857**
Average	**-**	**9,600**	**575,300**	**64,600**	**79,000**	**91,000**	**178,000**	**80,400**	**87,200**	**559,400**	**160,500**	**997,500**	**887,600**
Max	**-**	**61,279**	**784,950**	**208,069**	**150,000**	**200,000**	**545,896**	**295,837**	**198,000**	**1,056,333**	**298,163**	**1,615,961**	**1,239,837**

Table 6: Annual Grays Harbor Navigation Channel Paid Dredge Volumes (FY 2000 - FY 2012)

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2.3. Harbor morphology

Grays Harbor is located within the Columbia River littoral cell which extends over 100 miles of shoreline between two rock headlands; Tillamook Head in Northwest Oregon to Point Grenville in Southwest Washington. The majority of sediments within the littoral cell derive from the Columbia River. The net direction of longshore (littoral) transport in the cell is from south to north. Construction of two rock jetties at the Mouth of the Columbia River and at Grays Harbor near the turn of the 20th century significantly changed littoral transport patterns within the Columbia River littoral cell. At Grays Harbor, jetty construction resulted in inlet narrowing and deepening to sustain safe and reliable navigation into the harbor. As the inlet was constricted, sediments from the mouth of the inlet were scoured and transported offshore resulting in an offshore migration of the ebb tidal delta and massive accretion of the shorelines flanking the jetties. Subsequently, the physical barrier of the jetty and the migration of the ebb tidal delta offshore, the once connected shoal on the updrift (southern) side of the inlet lost connection to the ebb tidal delta and altered the process which historically bypassed sediment across the inlet. As a result the sediment exchange across adjacent shorelines within the littoral cell diminished (Kaminsky et al. 2010). As shown in Figure 18, construction of the north and south jetties from 1898 to 1916 resulted in over 30 feet (~10 m) of scour in portions of the entrance channel between the jetties (erosion denoted by hot colors) as the entrance was confined. Accretion was experienced offshore of the convex shaped ebb tidal delta, Point Chehalis, Damon Point, to the South Beach nearshore region, and to the North Beach nearshore region (accretion is denoted by cool colors). This resulted in significant shoreline advances on North Beach and South Beach shorelines which is discussed in more detail in Section 2.3.1.1.

The jetties were originally constructed to high water using materials which were eventually displaced by currents and waves. On the south side of the inlet, deterioration of the South Jetty resulted in transport of sands over and through the jetty which and fed the growth of the spit at Point Chehalis to the north. However following reconstruction of the South Jetty in 1939 tidal currents were strengthened and the sediment over and through the South Jetty was blocked. As a result this initiated severe erosion of Point Chehalis and the formation of Half Moon Bay. On the north side of the inlet, deterioration of the North Jetty resulted in southern littoral transport over and through the jetty and resulted in the formation and growth of Damon Point inside the harbor. Following reconstruction of the North Jetty in 1942, analogous to Point Chehalis on the south, erosion of the spit at Damon Point occurred once the southerly sediment transport over and through the North Jetty was cutoff. This continued until the North Jetty again began to deteriorate allowing southerly sediment transport back into the harbor. At the same time the North Beach shoreline had advanced seaward enough to begin bypassing sediment around the terminus North Jetty during flood tides further supplementing the sediment source to Damon Point. This led to the progressive advancement of Damon Point to the southeast and resulted in increased shoaling in the Bar, Entrance, and Sand Island Reaches of the navigation channel. As a result this forced the thalweg to the south of the harbor away from the historic position which was adjacent to Sand Island. In 1976, this prompted the Corps of Engineers to rehabilitate the North Jetty and realign the navigation channel from the former position adjacent to Sand Island to a location adjacent to Whitcomb Flats.

In 1990, the channel deepening and widening project deepened the navigation channel across the Bar and Entrance reaches from -36 feet MLLW to -46 feet MLLW. The result of this activity has resulted in increased O&M dredging in these channel reaches since construction. Additionally, the deeper channel depths have resulted in larger wave energy transmitted into the harbor. This has had influence on the wave climate experienced at Point Chehalis and the morphology of the flood tidal shoals (Whitcomb Flats) which is discussed in more detail in Section 2.3.1.2.

From 1954 to 1999 the accretion to the South Beach nearshore reversed and began to erode. Persistent recession to South Beach and Half Moon Bay shorelines culminated with a breach which disconnected to South Jetty from land in December 1993. The Corps filled the breach in 1994 with approximately 600,000 cubic yards of dredged materials. Since, 1994 the Corps has utilized nearshore placement of dredged material and direct beach and dune nourishment to mitigate the erosive trends and reduce the risk of long-term impacts to the navigation channel.

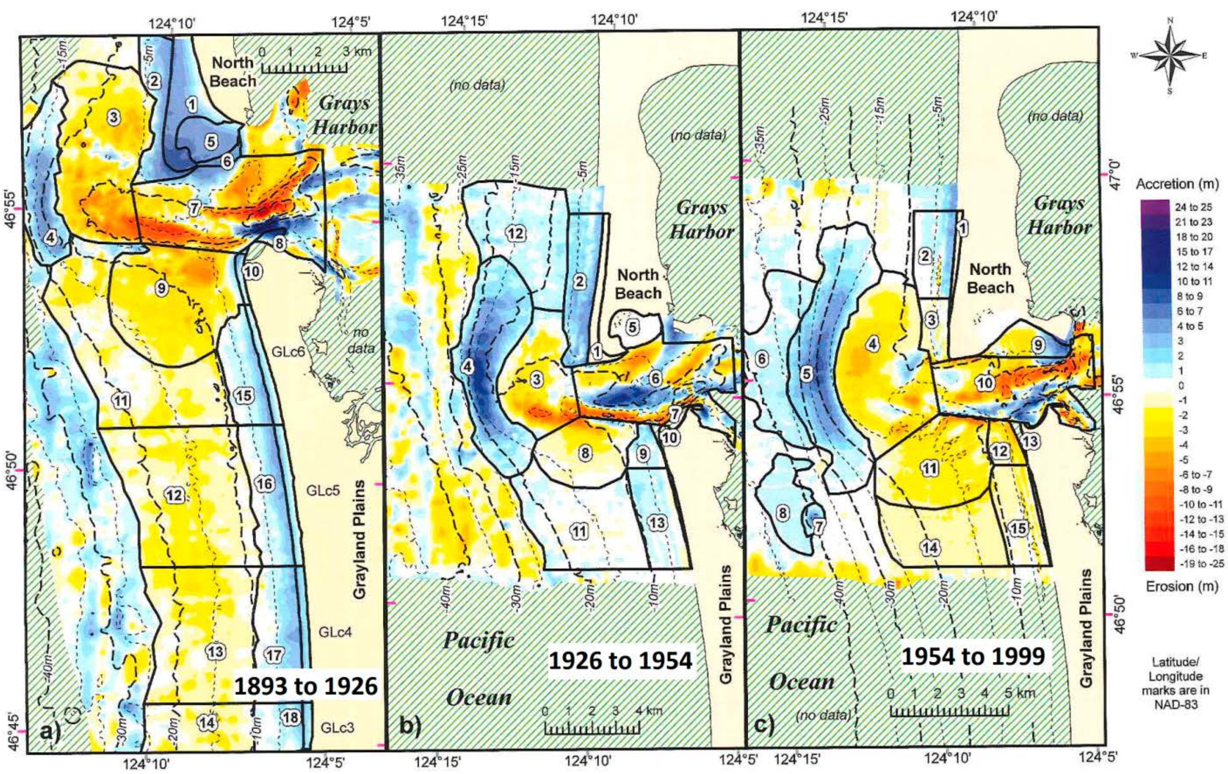


Figure 18: Grays Harbor bathymetric changes from 1893 to 1999 (from Kaminsky et al. 2010)

2.3.1.1. Shoreline change

The shoreline on both the north and south sides of the entrance to Grays Harbor have undergone major changes since the Corps constructed the North and South Jetties between 1898 and 1916 in an effort to minimize dredging requirements for the deep-draft Federal Navigation Channel. Construction of the jetties constricted the inlet to Grays Harbor, which increased the tidal currents in the entrance channel and moved the ebb-tidal delta offshore (Kraus and Arden 2003; Buijsman et al. 2003). As shown in Figure 19a and Figure 20a, by 1916 the South Beach shoreline had witnessed 2,190 feet and by 1942 North Beach had witnessed 7,640 feet of accretion oceanward as a result of entrance materials introduced into the nearshore system.

As shown in Figure 21, prior to 1954 the shoreline adjacent to the jetty (GLdn) had accreted at a rate of over 10 feet (3 m) per year. This was primarily in response to the large influx of sediments introduced into the nearshore region following jetty construction. After 1954, this trend reversed and the shoreline began receding at a rate of approximately 10 feet per year. This reversal is attributed to changes in littoral drift patterns and steepening of the nearshore area. On the north side of the harbor the North Beach shoreline has experienced continuous accretion between 1700 and 1999. The shoreline adjacent to the North Jetty (NBds) experienced a shoreline accretion rate of approximately 100 feet (30 m) per year in the interval from 1885 to 1926, which is during the time frame the jetties were originally constructed. This accretion rate has decreased to approximately 13 feet (4 m) per year from 1951 to 1999.

Inside the harbor between 1898 and 1936 a substantial volume of sediment was transported over and through the South Jetty. This was a result of a low crest height and progressive deterioration of the South Jetty. The sediment deposited just north of the South Jetty resulted in the northward growth of the Point Chehalis shoreline (Figure 20b). With this newly accreted peninsula, the Port of Grays Harbor constructed a small boat basin on the east side of Point Chehalis in 1929, named Westhaven Cove. However, reconstruction of the South Jetty in 1935-1939 raised the height of the jetty and eliminated this sediment source to Point Chehalis. After this sediment source was cut off this resulted in considerable erosion of the west and north sides of the Point Chehalis by tidal currents and wave action. By 1946 the shoreline formation of present day Half Moon Bay had been established (Figure 20c). In 1952 in effort to protect Westhaven Cove, shoreline recession at Point Chehalis was stopped through measures which included deconstructing the outer 1800 feet of the South Jetty and constructing a rock revetment and groins on the shoreline of Point Chehalis. However, erosion still continued near the landward root of the South Jetty resulting in a progressive narrowing of the dune separating the Pacific Ocean with Half Moon Bay.

Damon Point is a long low relief sand spit which presently extends 1.9 miles southeast from the landward root of the Grays Harbor North Jetty. The formation of the spit was a direct result of construction of the North Jetty. The North Jetty was originally constructed in 1916 to a height of +8 feet above mean lower low water (MLLW), or approximately to mean higher high water. During high water levels the jetty was submerged and allowed sediment to be transported through and over the structure. Over time the prevailing northwesterly waves transported this sediment over and through the North Jetty and served as the original source of sediment which initially formed the sand spit at Damon Point. The rate of growth of Damon Point accelerated as the North Jetty deteriorated from wave attack. By 1942, Damon Point extended approximately 1 mile east from the North Jetty (Figure 19b).

The first major rehabilitation of the North Jetty was completed in 1942 and the jetty was raised to +20 feet MLLW. This rehabilitation effectively cut off the sediment source which historically supplied sediment to Damon Point. As a result the spit began to migrate eastward and became less prominent in area and eventually culminated in a breach separating the spit from the root of the North Jetty in 1944 (Figure 19c).

By 1950 the shoreline north of the jetty advanced seaward to a position which allowed sand to be transported around the jetties seaward terminus and bypassed sediment eastward back into the harbor. This process renewed the sediment source to Damon Point and again began to grow the spit to the southeast. This process has continued up until about 1998. Currently the rate of longshore transport along the Damon Point spit is presently greater than the supply of sediment from the shoreline north of the jetty. This has resulted in gradual elongation and narrowing of the spit (Figure 22 and Figure 23). The narrowing of the spit eventually led to two overwash events in 1997 and 1998 and was at that time speculated to be the precursor of a future breach of Damon Point (Kaminsky et al. 1999). During a storm in December 2007 the narrowest section of Damon Point was overwashed again and resulted in the ultimate closure of the State Park road along Damon Point.

Since 2006 the erosion to the northwest shoreline of Damon Point has been significant. Over 500 feet of shoreline retreat occurred between 2006 and 2011 and 150 feet of shoreline retreat has occurred between 2009 and 2011 adjacent to the root of the North Jetty. The average shoreline retreat along the 7,200 feet southeast of the jetty where erosion was observed was calculated at 384 feet (Figure 23). Over this period, this computes to approximately 1.5 million cubic yards of erosion (or 300,000 cubic yards per year).

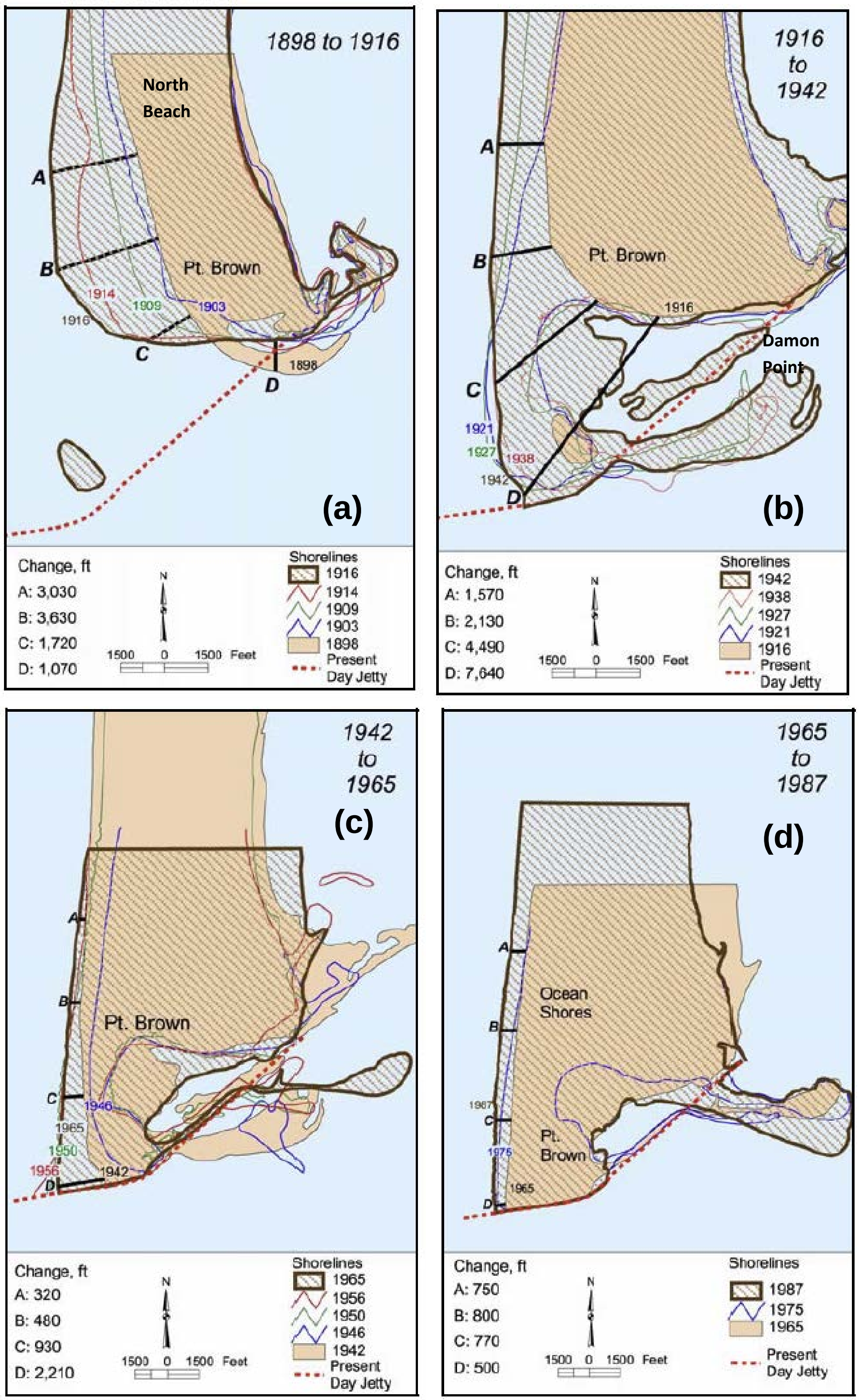


Figure 19: North Beach and Damon Point Shoreline change near the Grays Harbor North Jetty from 1898 to 1987 (from Kraus et al 2003)

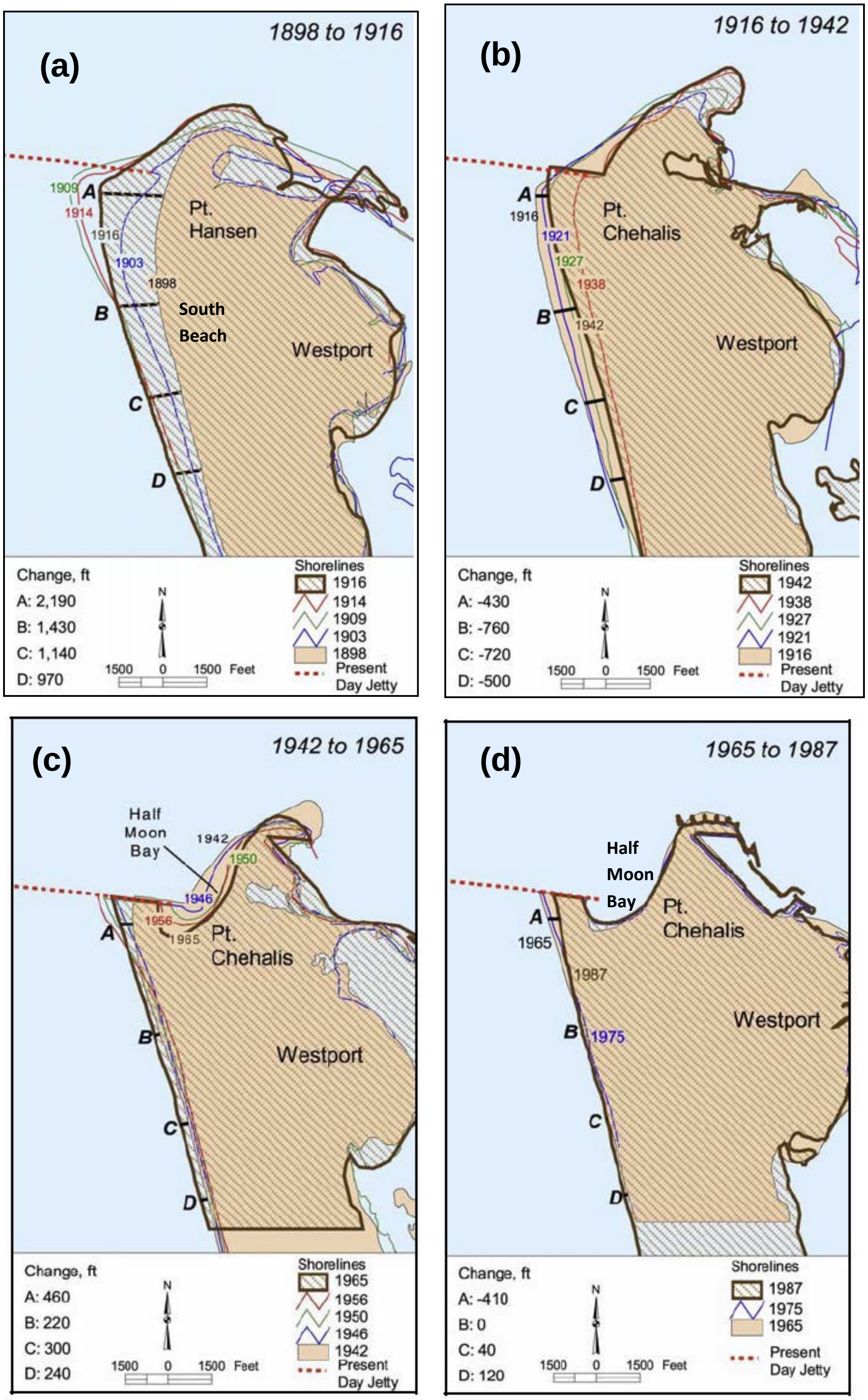


Figure 20: South Beach, Point Chehalis, and Half Moon Bay shoreline change from 1898 to 1987 initial shoreline advancement during jetty construction and equilibrium period immediately following, respectively (from Kraus and Arden 2003)

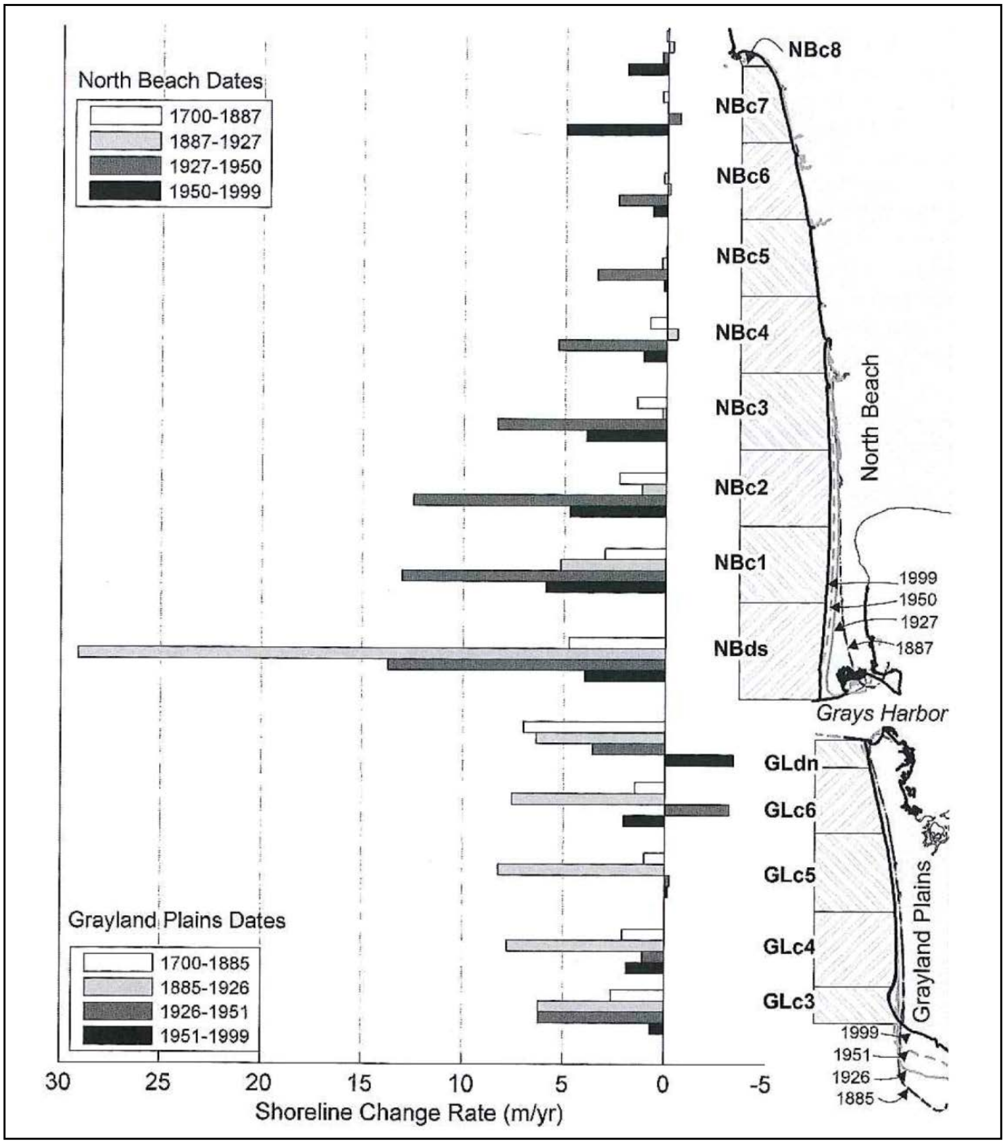


Figure 21: Grays Harbor shoreline change rates over time (from Kaminsky et al. 2010)

Figure 22: Damon Point shoreline position from 1968 to 2009.

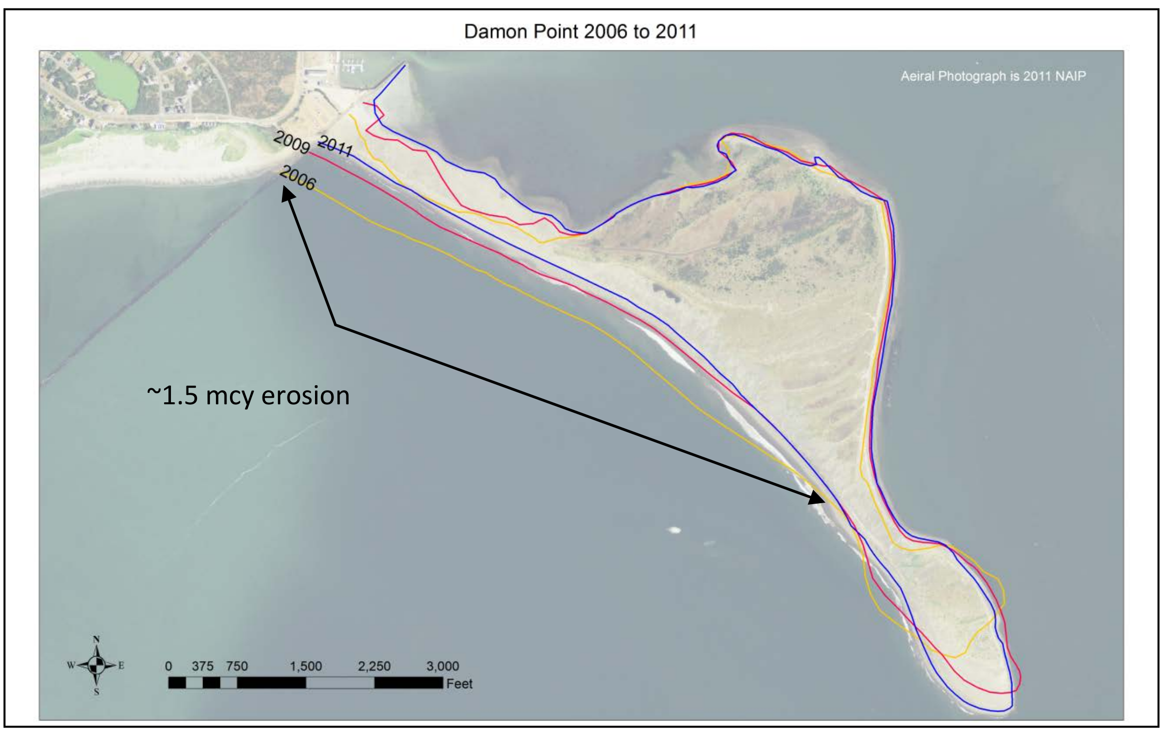


Figure 23: Damon Point shoreline position from 2006 to 2011

2.3.1.2. Flood tidal shoal morphology

Whitcomb Flats

Whitcomb Flats is a flood tidal shoal complex located approximately 1 mile east of Point Chehalis (Figure 1). Its sediments are composed of sand derived of marine origins which were deposited by tidal flood currents and wave-induced transport. The flood shoal has been a long standing land feature within Grays Harbor which predates the navigation project; Whitcomb Flats was mapped in the 1890 condition survey prior to jetty construction in 1898 (Figure 11). Osborne (2003) conducted a geomorphology study on the evolution of Whitcomb Flats using georectified aerial photographs from 1962 to 2001. Figure 24 shows Whitcomb Flats has experienced a net eastward migration over this time period. This migration is tied closely with the morphology of the inlet throat. As discussed in Section 2.2, the deteriorated condition of the North Jetty resulted in significant sediment transport from North Beach over and through the North Jetty. This caused the distal end of Damon Point to grow toward the southeast which is a trend that has continued up until present time (Figure 23). This has in turn constricted the throat of the inlet between Damon Point and Point Chehalis resulted in a net erosion of 40 million cubic yards of sediment from the seabed since 1954 (Figure 18c – polygon 10). The pathways of sediment scoured from the inlet throat have been primarily directed offshore due to the strength of the ebb currents on outgoing tide (Figure 3) and have resulted in a diminished sediment supply to Whitcomb Flats over time. Additionally, as Damon Point continued to grow southeast this also forced the southward migration of the channel thalweg away from the historic Sand Island Reach of the navigation channel (Figure 17). As the thalweg migrated south, the wave transmission into the inner harbor was also altered. Wave model results (Figures 8 and 9) indicate moderate wave transmission into the harbor near Whitcomb Flats for west and northwesterly offshore waves. Thus deepwater wave energy transmitted into the harbor through the inlet throat eventually refracts into the shallows near Whitcomb Flats. The geomorphology analysis suggests these waves can overwash the low-relief sand flat and cause the eastward migration of Whitcomb Flats.

Sand Island

The Sand Island flood tidal shoal complex also predates the navigation project at Grays Harbor. However, unlike Whitcomb Flats the subaqueous shoal fronting Sand Island has been accreting sediment. Between 1987 and 2002 a net deposition of 6.6 million cubic yards was measured (Kraus and Arden 2003). The stability of Sand Island itself can be attributed to the sheltering effect of Damon Point and the Sand Island shoal from wave energy and a well established network of tidal channels in the vicinity of Sand Island.

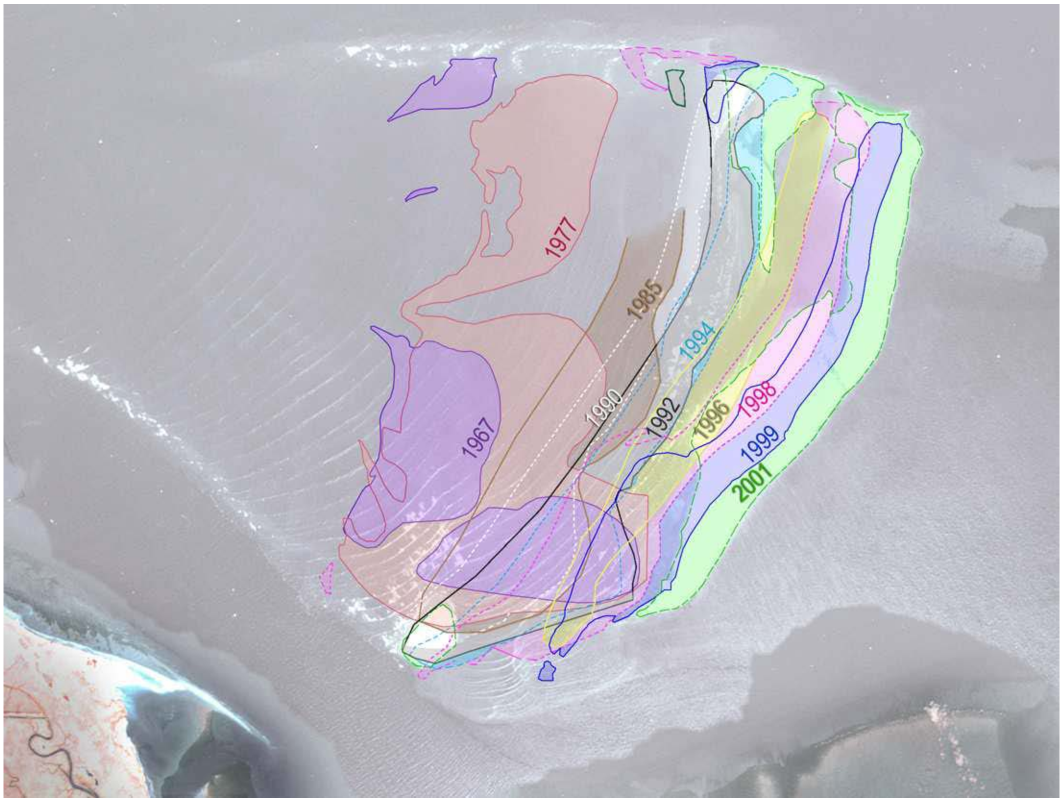


Figure 24: Eastward migration of Whitcomb Flat from 1967 to 2001 (from Osborne 2003)

3. Geology and Soils

General

Development of the present topographic configuration and features in the Grays Harbor area has resulted mainly from drowning of a major coastal river valley and subsequent erosion and deposition of coastal sediments by wave action, tidal and alongshore currents. A geologic history of this area begins with the origin of the regional bedrock. Oscillatory crustal earth movement caused periodic advance and retreat of seas across the plains which were present in western Washington prior to development of the Coast and Cascade Ranges. Both continental and marine sediments were deposited, sometimes associated with volcanic flows. These rocks were later warped and uplifted, and the Olympic Mountains and Willapa Hills were formed. In the present Grays Harbor area, a major stream valley system, the beginning of the present Chehalis Valley, developed on the uplifted land surfaces. Glaciers did not reach this area during the Pleistocene, but a lowering of sea level occurred which resulted in the erosion and deepening of this valley system. As the continental ice retreated, a re-advance of the sea, possibly accompanied by some coastal subsidence, drowned the valley.

Soft sedimentary rock of the headlands north and south of the Grays Harbor embayment was attacked by the sea, and barrier beaches were developed. Detritus, mostly sand with a few gravels, moved along the coast by alongshore currents developed spits extending into the embayment entrance both north and south, Point Brown and Point Chehalis respectively. Tidal currents have maintained a channel between the bay and the sea, and redistributed the fluvial sediments (sand and silt) being deposited within the bay by numerous tributary drainages. The present spit and harbor bottom are, therefore, mostly sand with silty sand and rare gravels. A general description of estuary sediments is shown on Figure 25 by Scheidegger and Phipps (1976).

Subsurface exploration and rippability of sediment in Cow Point Reach

Extensive subsurface explorations have been performed in the channel reaches of the proposed channel improvement in 1975, 1985, and 2012 using vibracores and wash boring cores. All of the subsurface coring results indicated dredgeable soils within authorized depth to -38 feet MLLW from South Reach to Cow Point Reach. However dredging to the maximum allowable depth (i.e. authorized + advanced maintenance + overdepth tolerance) in the Cow Point Reach may be more challenging. USACE (1989) indicates in the Cow Point Beach “gravels are underlain by sandstone bedrock”. The highest bedrock surface, elevation -36 feet, was found at Sta. 1231+06 on the channel centerline which is upstream of the project limit of Sta. 1227+99.

Three foundation explorations from 1985 were found to have refusal above the maximum allowable depth of -42 feet MLLW within the project limits. The only channel reaches where sandstone refusal was observed to occur above the authorized depth of -38 feet MLLW is upstream of 1227+99. Test hole locations 85-VC-18, 85-VC-17, and 85-WB-21 observed refusal in depths ranging from -39.9 to -41.5 feet MLLW, and were located between Sta.

1212+00 to 1223+00 adjacent to the Port of Grays Harbor Terminal 4 (Figure 26). In these test holes a top layer of silts was underlain by sandy gravel prior to refusal on the sandstone. Recent explorations from 2012 indicate refusal of the vibracore above -42 feet MLLW from Sta. 1200+00 to 1215+00 (Figure 27).

The sandstone unit is part of the Miocene Montesanso Formation (Laprade and Robinson 1989). The sandstone is classified as soft and “almost soil-like” and has previously been quarried for foundation fill in the Grays Harbor area. Geophysical logs (Brocher and Christensen 2001) of the Montesano formation collected north of Aberdeen, Washington indicate average sonic velocities of 2.4 km/s and an average density of 2230 kg/m3 (140 pcf). Rippability graphs published (Caterpillar 2010) show seismic velocities between 2.1 and 2.9 km/s with marginal rippability for sandstone.

A clamshell dredge cannot rip, but an excavator or hydraulic cutter head dredge can rip. Thus attaining the 2 feet of advanced maintenance dredge allowance from Station 1200+00 to 1223+00 may require the use of an excavator or hydraulic cutterhead dredge. Dredge productivity was measured by the Corps at 10 test pits in areas of hard sandstone in the Arthur Kill Channel within New York Harbor (Murphy et al. 2011). The seismic velocity through the sandstone formation exceeded 2.7 km/s in the dredge area. Test pits were dredged to depths of -53.5 feet MLLW with an excavator and production varied from 2.6 to 35.9 cubic yards per hour using a 1 cubic yard bucket.

At Grays Harbor, the seismic velocities are lower suggesting better rippability and production of sandstone present within the dredge prism between -40 and -42 feet MLLW. In order to gather site specific data, a test dredge to -42 feet MLLW using a clamshell bucket is being pursued through the O&M dredging program. This data will determine whether additional equipment may need to be mobilized during the construction of the channel improvement project.

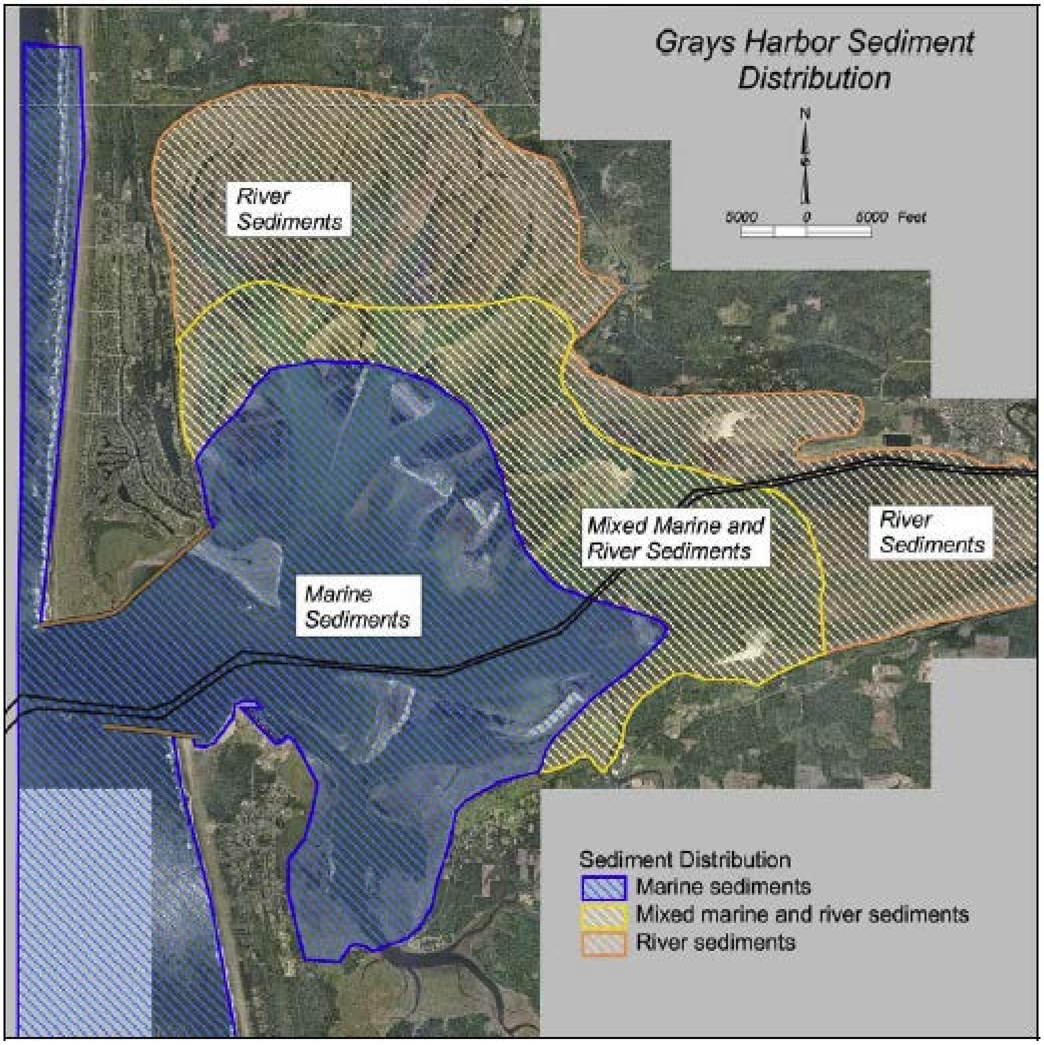


Figure 25: Distribution of sediments within Grays Harbor (from Kraus and Arden 2003; originally depicted by Scheidegger and Phipps (1976)

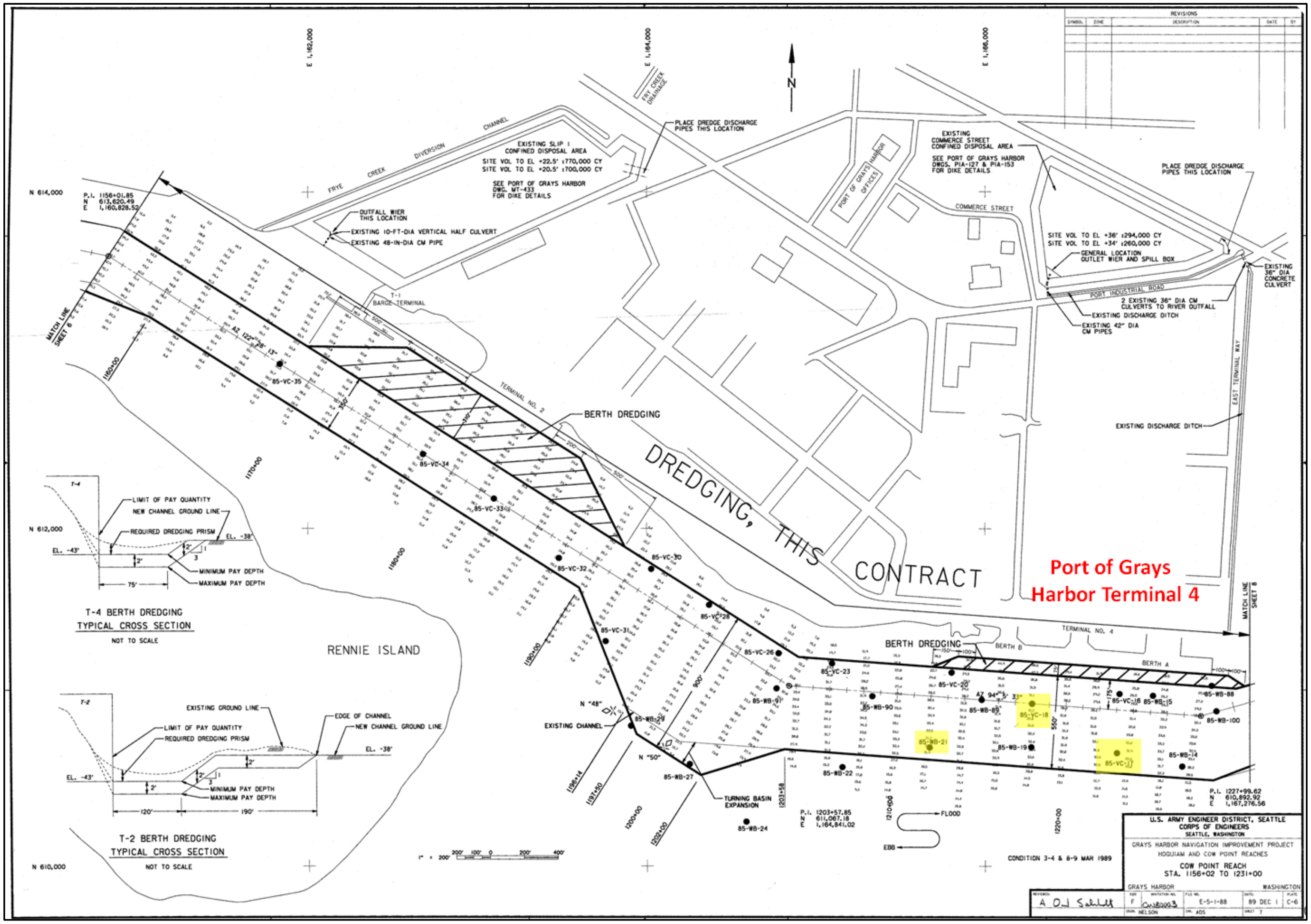


Figure 26: 1985 vibracore and wash-boring test hole locations

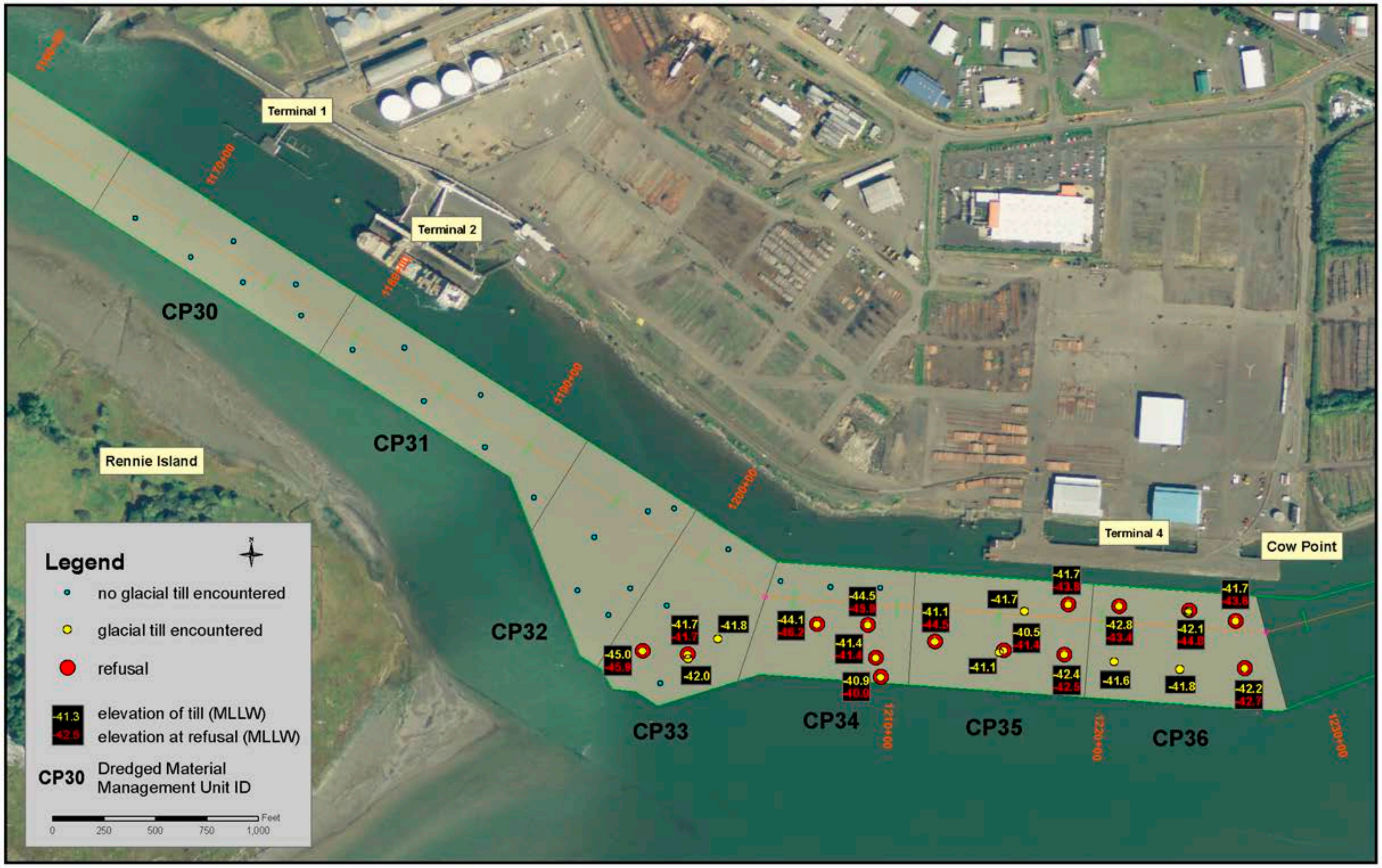


Figure 27**: 2012 Vibracore test hole locations and refusal depths.**

4. Design Considerations

4.1. Vessel Traffic

Vessel traffic has changed since completion of the 1990 Navigation Improvement Project. Historically, deep-draft vessels calling at Grays Harbor were generally limited to foreign export timber carriers. However within the last decade, the Port made a strategic decision to move away from timber exports and diversify to include liquid/bulk and automobile exports. Figure 28 shows a breakout of commodities by vessel draft using the Waterborne Commerce Database[2] (2005-2009). Presently, deep draft vessels calling the Port of Grays Harbor are classified into three main categories; Tanker, Bulker, and Roll On Roll Off (Ro-Ro). In 2012, the Port of Grays Harbor called 83 of these types of vessels. Port arrivals had an average draft of 24.7 feet and a maximum draft of 36.4 feet. Departing vessels from the Port had an average draft of 31.5 feet and a maximum draft of 40.5 feet. This indicates departing vessels (exports) continue to be the design condition for the navigation channel serving the Port.

4.2. Design Vessel

USACE (1989) determined the design vessel for two channel segments within Grays Harbor. At Cow Point Reach and downstream this was determined to be a 37-foot draft, 625-foot length, and 100-foot beam vessel. Upstream of Cow Point this was a 37-foot draft, 600-foot length, and 100-foot beam (note this project does not include any dredging upstream of Cow Point Reach). This design vessel was defined as the size of vessel which carried the majority of cargo versus the maximum-sized vessel that the channel could accommodate. EM 1110-2-1613 (USACE 2006) recommends the designer utilize information on the type of traffic to select the design ship, which is usually the largest ship of the major commodity movers expected to use the project improvements on a frequent and continuing basis.

Deep draft vessels presently calling at Grays Harbor range in size from 10,000 to 75,000 deadweight ton (DWT), with an average of 40,000 DWT. The range in vessels is broader than in 1990 which were listed as 20,000 to 40,000 DWT. Still the present average vessel calling Grays Harbor is approximately 40,000 DWT. Figure 29 shows the vessel dimensions from 2012 versus the USACE (1989) defined design vessel. Note from these figures the previous design vessel captures most of the Ro-Ro and Tanker vessel types. The Bulker vessel type represents the only vessel outside this range. However as these data indicate it is possible to compensate for larger draft vessels by transiting the channel during higher tides. The majority of the vessels with length greater than 625 feet are less than 660 feet, and beams wider than 100 feet are less than 107 feet. The the forecasted vessel fleet is projected to be of the same size as existing conditions. The largest reported vessel leaving the harbor occurred in 2012 and was 75,617 DWT, L = 738 feet, B = 106 feet, D = 40.5 feet. The existing channel width which ranges from 350 to 450 feet meets the recommended guidance of B*3.25 for trench type channel in the 0.5 to 1.5 knots current range per EM 1110-2-1613. The recent channel re-alignment has widened

[2] Waterborne Commerce Statistics Center.
http://www.iwr.usace.army.mil/About/TechnicalCenters/WCSCWaterborneCommerceStatisticsCenter.aspx

three channel bends adding new cutoff turns in the North Channel and Hoquiam Reaches and apex turn in the Inner Crossover Reach. These minor adjustments will better accommodate longer vessels. Vessels with drafts greater than the original design vessel of 37 feet represent less than 4% of the total vessel traffic. These vessel departures all occurred on outgoing tides above +5 feet MLLW. This indicates that the vast majority of cargo transiting the harbor will fall within the present design vessel criteria. Given this information no reason has been found to modify the 1989 design vessel assumptions used for navigation channel design.

4.3. Channel Design

Depth

The inner harbor channel design specified in USACE (1989) included 2.5 feet for minimum safe clearance, 0.5 feet for trim, 0.5 feet for freshwater sinkage, and 1.0 feet for squat. This translates into a design under keel clearance of 4.5 feet. Presently the harbor pilots use a minimum underkeel clearance of 3.5 feet during transits. In this scenario an underkeel clearance of 3.5 feet will suffice as the pilot can reduce the speed of the vessel to negate the effect of squat. Thus the design underkeel clearance remains valid for the current project. In the South Reach, the wave model results presented in Section 1.7 confirm the previous assumption that operational waves in the South Reach are less than two feet in height. Thus no additional depth is necessary to account for ship motion due to waves.

Historic practice at Grays Harbor is for departing vessels to leave the Port terminal near mid tide on an incoming tide. This allows fully loaded vessels to reach the Bar near high tide and safely exit the harbor. Vessel bow movements crossing the Bar have been observed to be on the order of 4 to 14 feet below the water still water line as a result of wave action. Thus vessels crossing the bar must occur near high tide (i.e. mean higher high water). The transit time from Aberdeen to the Bar Reach is approximately 3 hours. Data from the Port indicates the average tide a departing vessel leaving Aberdeen is approximately +6.0 feet MLLW. During transits of vessels with loaded drafts above 37 feet MLLW, this average departure tide was +8.0 feet MLLW.

Width and alignment

A ship simulation study (USACE 1991) was performed to confirm a 350 foot wide channel through the inner harbor reaches was still sufficient for the design vessel. In April 2012, discussions with the Port of Grays Harbor Bar Pilots and the ship simulation manager at the USACE Coastal Hydraulics Laboratory determined the current channel width was sufficient to accommodate the forecasted vessel traffic and a supplemental ship simulation was not necessary for an incremental deepening of 2 feet (USACE 2012).

Through the Operations and Maintenance (O&M) program the Corps initiated a minor re-alignment of the federal navigation channel from South Reach to North Channel ; Sta. 660+00 to 1014+00 (USACE 2013a). The intent of channel realignment was to more appropriately align the channel with the natural thalweg through the inner harbor in effort to reduce annual O&M dredging. This was determined the most sustainable solution as O&M funding has not historically matched the dredging needed to maintain the channel to its fully authorized width and depth in its present location. Channel realignment saves approximately 1 million cubic yards of dredging to obtain a full channel width and depth, and thus also reduces the burdens of dredging and disposal on the ecosystem. Minor adjustments to turns in the channel at Sta. 860+00, 943+00, and 998+00 are required to accommodate the design vessel beam of 100 feet (Figure 30 to 32). These adjustments include modifying an angle turn to a cutoff turn at Sta.

943+00 and modifying a cutoff turn to an apex turn at Sta. 860+00 as required by EM 1110-2-613 (USACE 2006).

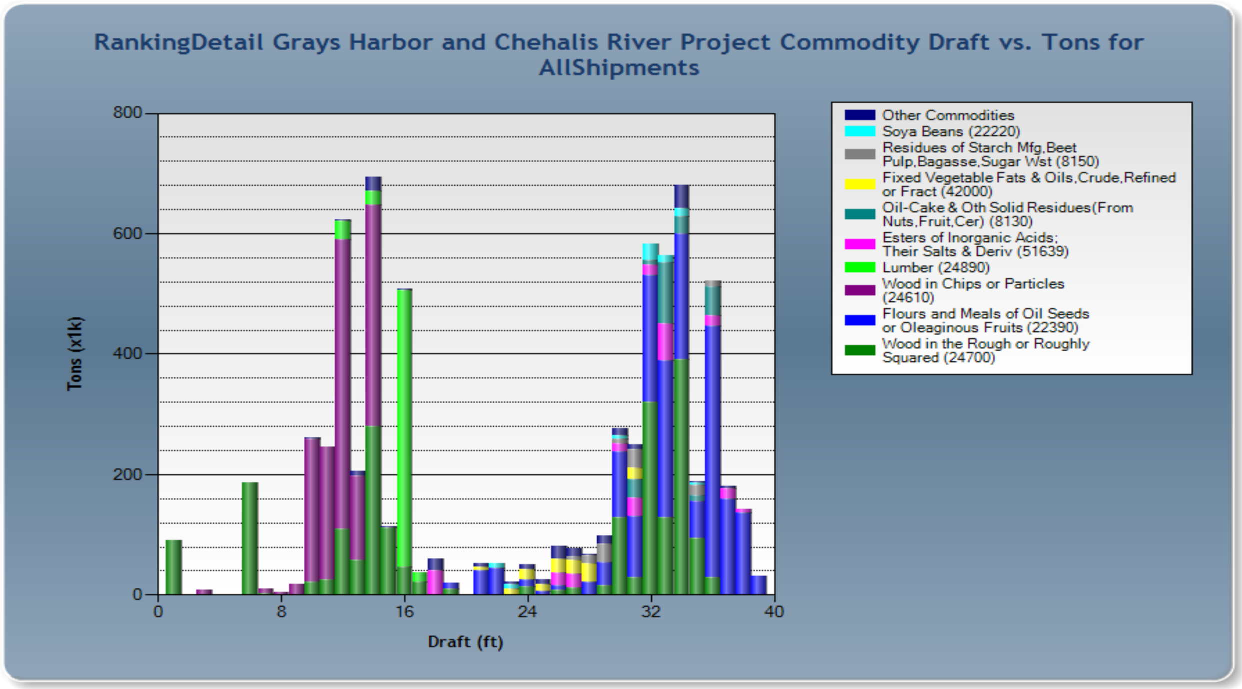
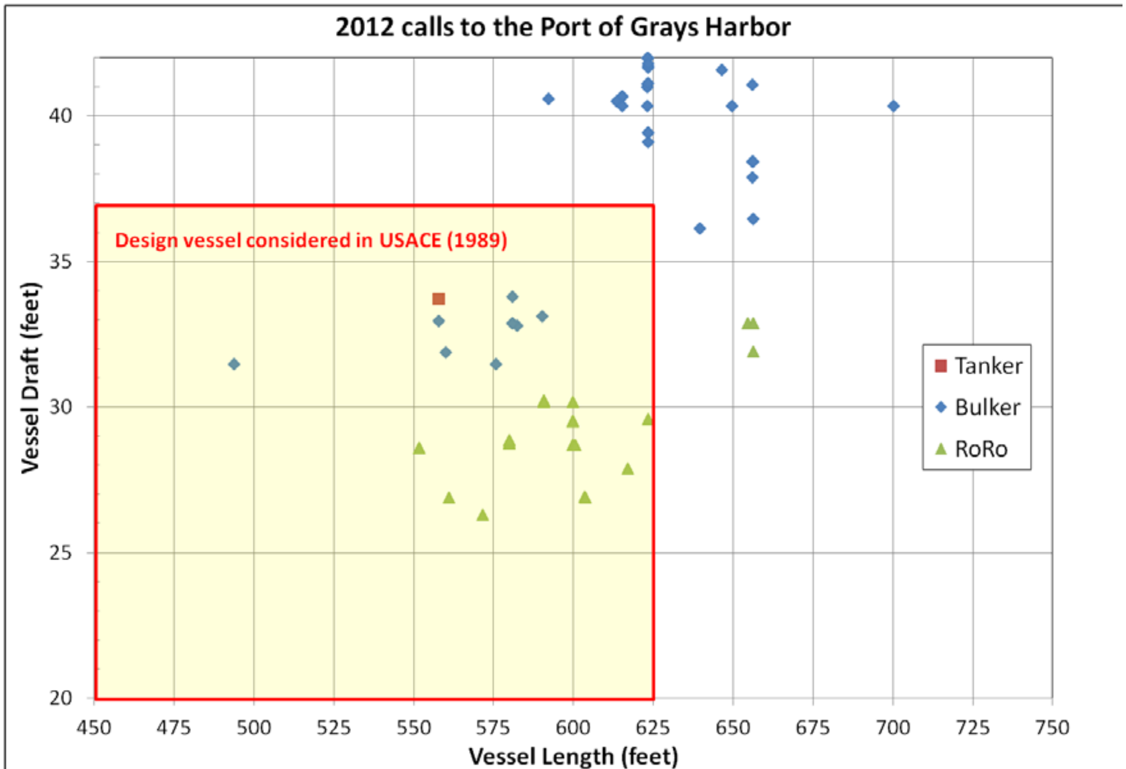


Figure 28: Tonnage by draft at Grays Harbor (2005-2009). Source: Waterborne Commerce Database



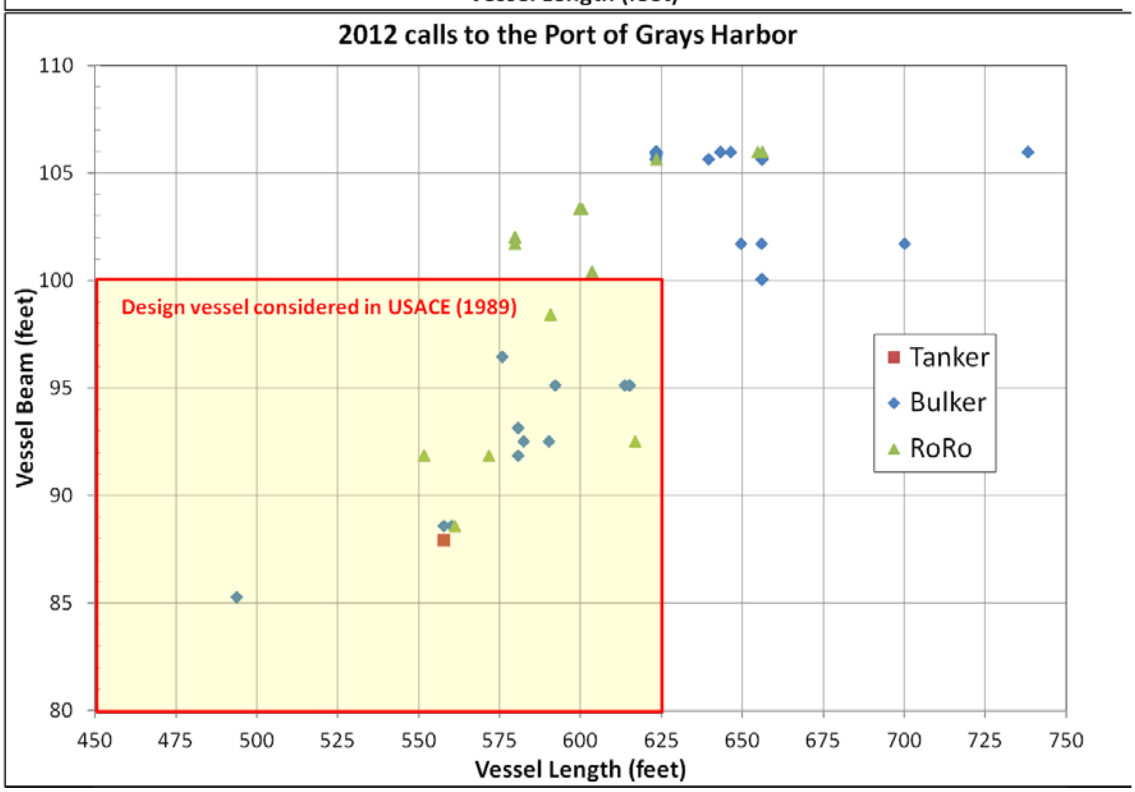


Figure 29: 2012 calls to PGH relative to the USACE (1989) design vessel (a) length/draft (b) length/beam

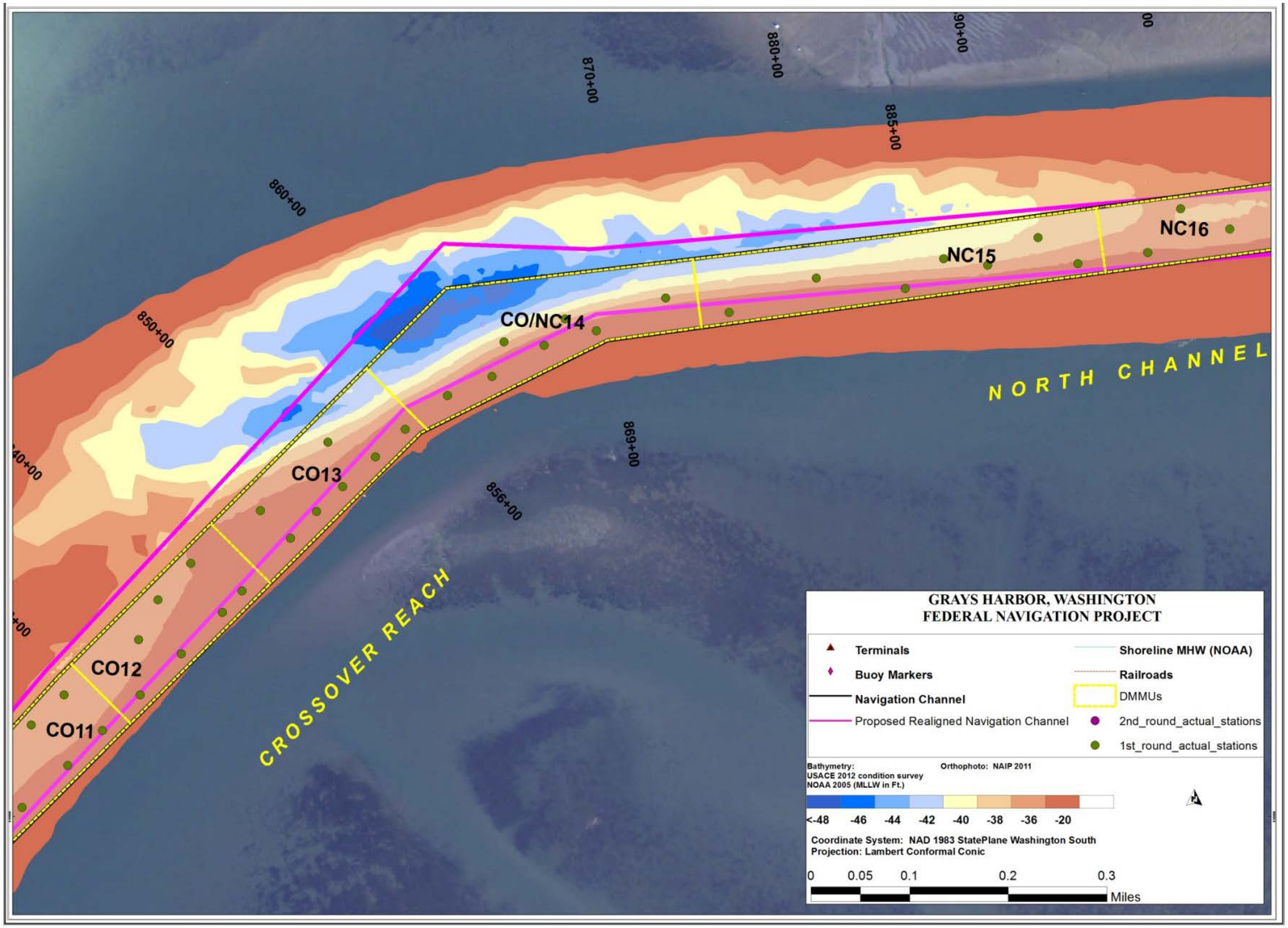


Figure 30: Minor channel re-alignment channel turn modification (in pink) at Sta. 860+00.

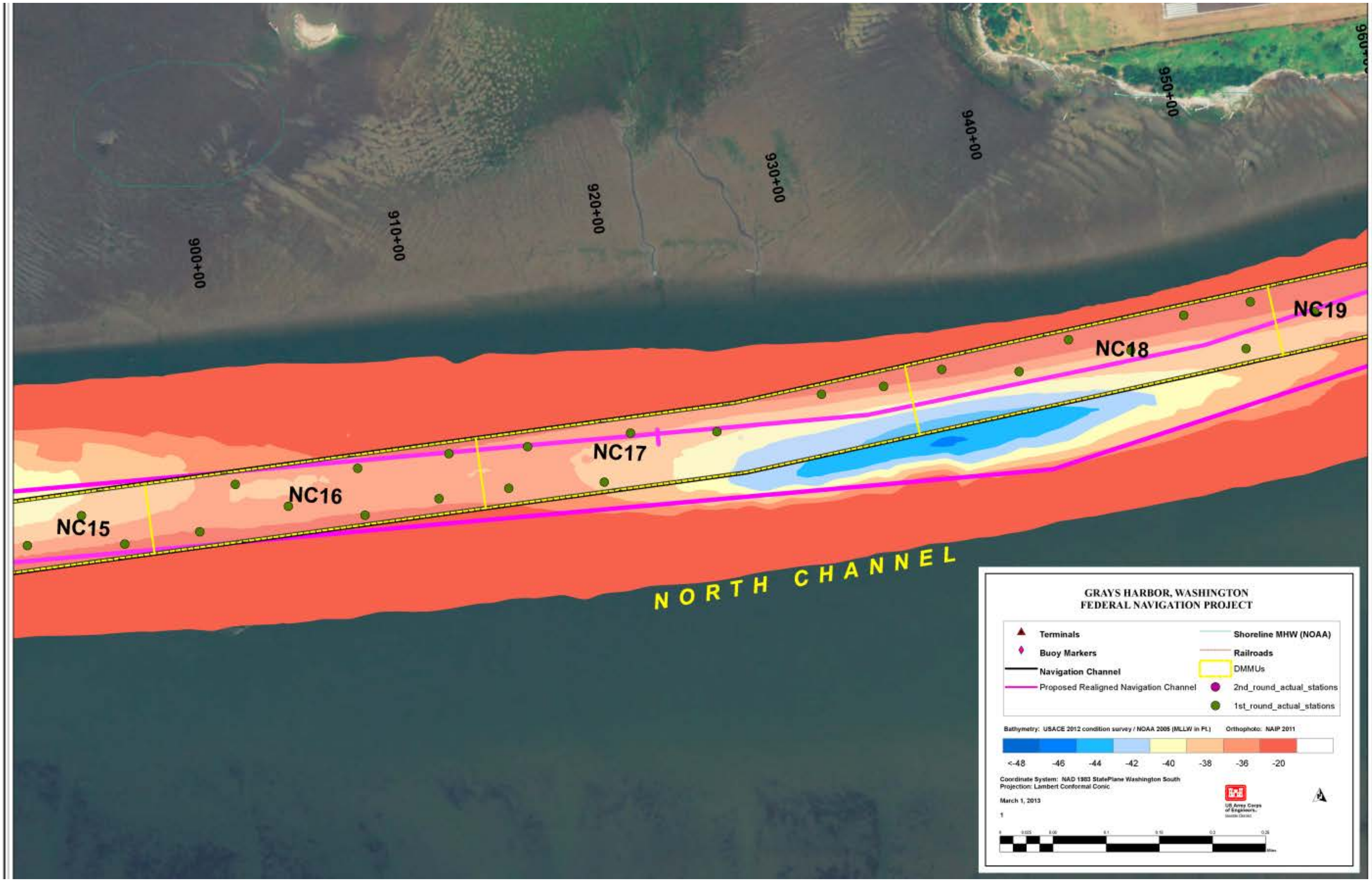


Figure 31: Minor channel re-alignment channel turn modification (in pink) at Sta. 943+00.

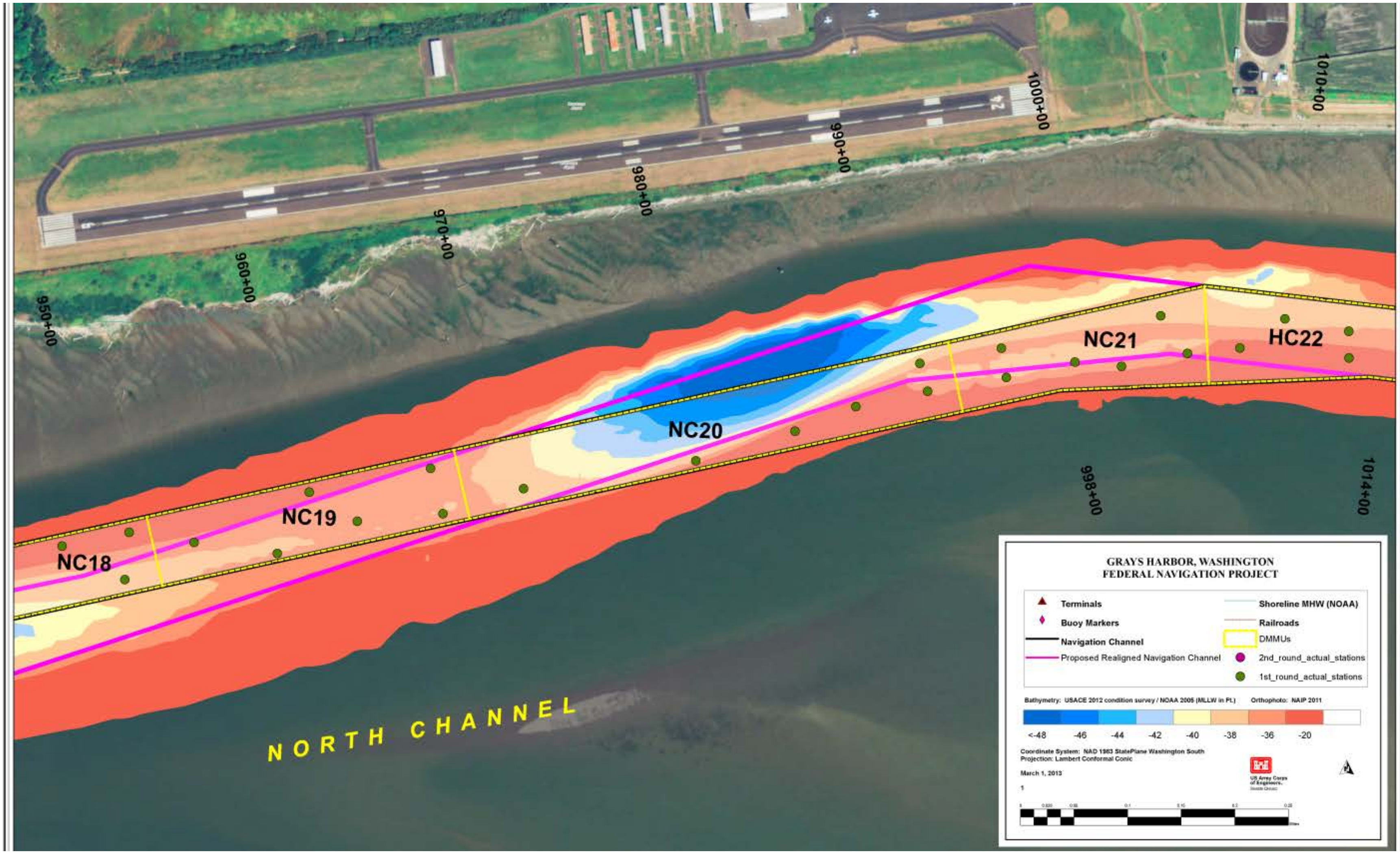


Figure 32: Minor channel re-alignment channel turn modification (in pink) at Sta. 998+00.

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4.4. Dredging and placement of dredged materials

Three alternatives are considered in the Limited Revaluation Report.

- Alternative 1: No Action – maintain current project depth of -36 feet MLLW
- Alternative 2: Deepen project depth 1 foot to -37 feet MLLW
- Alternative 3: Deepen project depth 2 foot to -38 feet MLLW

The maximum allowable dredging depth for each alternative includes 2 feet of advanced maintenance dredging and 2 feet of allowable overdepth tolerance. For each alternative it is assumed the channel would be dredged to its maximum allowable depth and width. It is also assumed that deepening would be performed concurrently with O&M dredging and would be performed in one dredge year. Thus the open water dredged material placement sites require sufficient capacity to accept all O&M and deepening material in one dredging year.

4.4.1. Dredged material quantities

Table 7 lists dredged volumes to obtain the maximum allowable dredge depth for each of the three alternatives. This volume ranges from 2.5 to 4.2 million cubic yards (including both O&M and channel improvement dredging, as applicable). Of this quantity the incremental volume representing only channel deepening represents 0.8 million cubic yards for Alternative 2 and 1.8 million yards for Alternative 3.

4.4.2. Dredging schedule and production

For the inner harbor dredging in order to meet a one year construction schedule it is assumed the daily production will be increased by mobilizing a second clamshell dredge and two additional bottom dump scow barges to dredge the Inner Harbor reaches to their maximum allowable depth. Based on the September 2012 condition survey, the maximum allowable clamshell dredging volume for Alternative 2 is 3.07 million cubic yards and 3.87 million cubic yards for Alternative 3..

There are 214 available work days in the work window from July 15 to February 14. Thus a daily production of 16,000 cubic yards is required to complete construction in one year.

Recent O&M dredging production in the inner harbor has averaged 12,000 cubic yards per day. This includes a 35 cubic yards clamshell bucket and 2 bottom dump barges (1 – 1800 cubic yard and 1 – 4000 cubic yard scow) for open water placement at the Point Chehalis and South Jetty estuarine placement sites. In order to estimate the daily production of new material associated with deepening, production rates from the 1990 deepening project and the 2006 O&M clamshell dredging were reviewed. The 1990 Channel Deepening project removed 2.2 million cubic yards from the Crossover and North Channel Reaches with an average daily production of 16,628 cubic yards per day. The 2006 O&M dredging removed material below -40 feet MLLW throughout the inner harbor reaches using a 26 cubic yard clamshell bucket and 2 – 7,200 cubic yard scows). The average daily production across all reaches was 13,127 cubic yards per day and is considered to be a representative estimate of the combined O&M and new work dredging. Thus it is assumed by mobilizing a second dredge and 2 additional scows daily production would increase to approximately 24,000 cubic yards per day. This translates to 128 dredging days for Alternative 2 and 162 dredging days for Alternative 3.

The outer harbor dredging in South Reach will be dredged with a hydraulic hopper dredge. The maximum allowable hopper dredging volume for Alternative 2 is 0.17 million cubic yards and 0.32 million cubic yards for Alternative 3. Typically the government hopper dredges maintain these channel reaches. At Grays Harbor, historically the production of the *Essayons* is approximately 30,000 cubic yards per day and the *Yaquina* is 10,000 cubic yards per day. For each hopper dredge this would translate to an additional 5 dredging days for Alternative 2 and an additional 8 dredging days for Alternative 3.

4.4.3. Placement of dredged materials

All dredged material was found to be suitable for open water placement except for one dredged material management subunit in the Cow Point Reach. This volume is approximately 22,400 cubic yards (USACE 2013b) for Alternative 3 and will be placed in a designated upland site. The remaining dredged materials will be placed at the Point Chehalis and South Jetty open water placement sites (Figure 33).

4.4.3.1. Open water placement sites and capacity

O&M and channel improvement dredged materials will be placed at the Point Chehalis Site (PCS) and South Jetty Site (SJS). The PCS and SJS are dispersive open water estuarine sites managed by Washington State Department of Natural Resources (WSDNR). As listed in Table 8, on average the Corps places 960,300 cubic yards at the PCS and 576,400 cubic yards at the SJS each year. The maximum cumulative quantity placed at both sites in one year was 2.2 million cubic yards. For comparison, for Alternative 3 the total O&M and deepening dredged volume is 4.2 million cubic yards in the single construction year, or almost two times this amount.

Due to the dispersive nature and amount of sediment transported outside of the site boundaries as suspended sediment during placement, both the PCS and SJS have a larger capacity than the volume released from the bottom dump barge. Incorporating this dispersive nature into the management of a site is typically referred to as dynamic capacity of a site. Analysis of historic open water placement of O&M sediments from the channel indicate at the dynamic capacity at each site can be as large as three times the static capacity, or in other words 67% of the sediments placed at a site are transported outside of the site boundaries in one year, either as suspended load during placement or as bedload following its placement. Currently open water placement of O&M dredged materials are limited to the northern half of the PCS as material placed in the southern half results in a significant amount of sediment that re-enters the navigation channel which would require re-dredging.

Based on sediment transport modeling and Sedflume analysis conducted (Demirbilek et al. 2010; Hayter et al. 2012) it was determined placing all dredged material within the current PCS boundaries may pose an adverse risk to navigation and O&M dredging costs. The federal navigation channel passes through the site and mounding of material can result in loss of channel depth and width without proper site management. This conclusion was made by modeling multiple placement scenarios representing different volumes of dredge material, different fractions of sediment clumps (i.e. consolidated sediments which form large clumps), and different placement site boundaries (the current site and a modified site). As shown in Figure 34, model results indicate that larger sediment clump fractions have a significant impact on mounding at the placement sites. For instance as shown in Figure 34a, the maximum computed mound height in the Point Chehalis site was 8.5 feet for a 10-percent clumping fraction. This height increases to 20.7 feet for a 50-percent clumping fraction (Figure 34b). As channel deepening sediments are likely more consolidated than newer O&M sediments it is likely that the transport rate at each of the sites will be slower than historically observed during placement of O&M dredged material. Model results suggest that utilizing current placement practices at the Point Chehalis site, more than half the navigation channel width would shoal in above the authorized depth when a 50% sediment clumping fraction is assumed for the sediments placed at the site. Thus, solely using the northern half of the Point Chehalis Site as currently managed is likely to create adverse shoaling in the Point Chehalis Reach of the federal navigation channel. In order to safely accommodate both the O&M dredged material and the channel deepening material, it is necessary to shift the Point Chehalis placement site boundaries 1,000 feet northwest for the single construction year. This shift would provide greater static capacity (i.e. deeper depths) as well as preferential transport pathways which minimize the amount of sediments re-entering the navigation channel. Figure 35 shows the computed mound heights for the same quantity with the shifted site boundaries. In this scenario the shifted boundaries alone, reduced the loss of authorized depth in the navigation channel to only 8% of the channel width. The modeling simulations assumed uniform placements over the entire placement area. Therefore it is speculated that impacts to navigation could be further reduced by concentrating more placements in the eastern sector of the site where depths are greater.

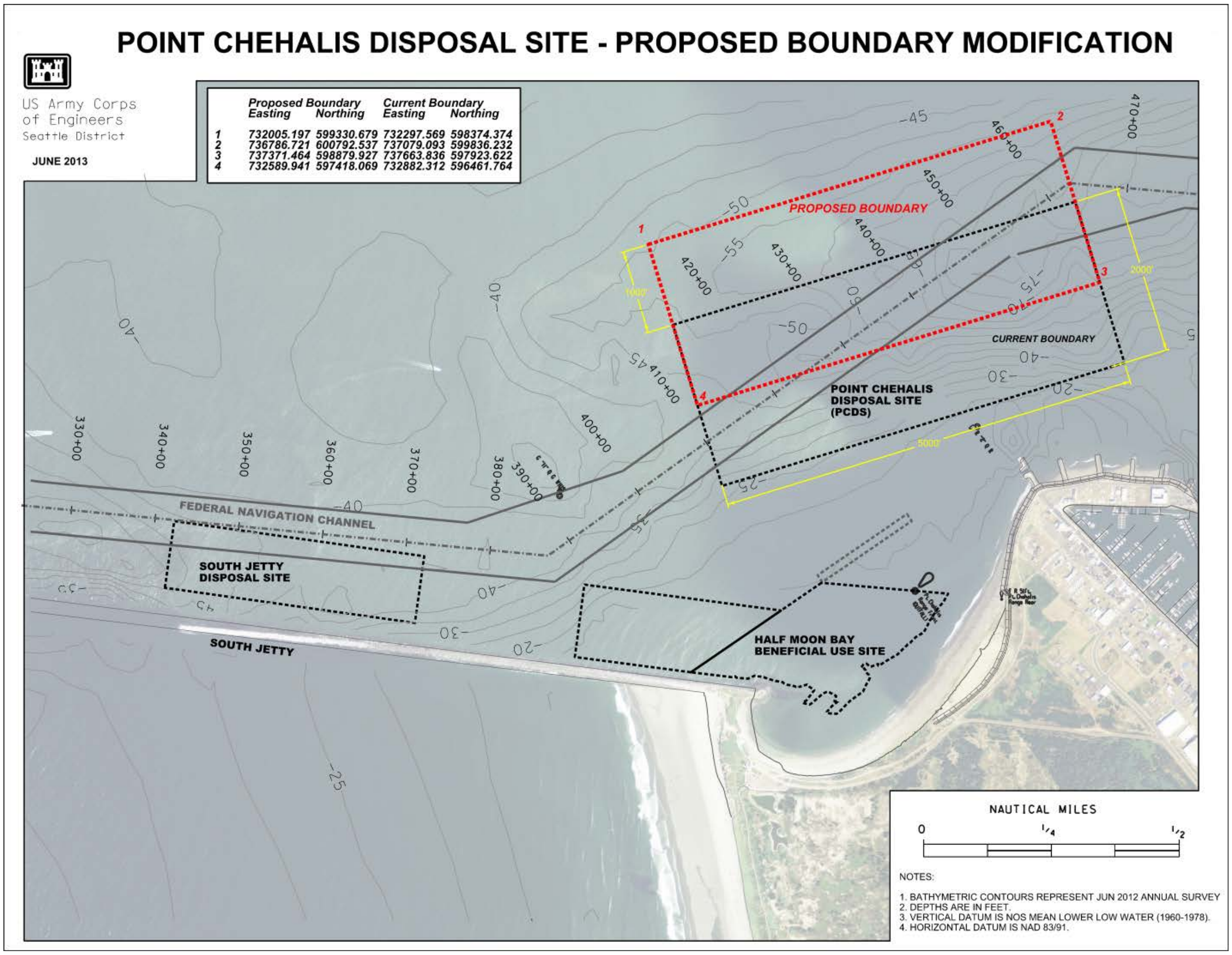

Figure 33: South Jetty Site (SJS) and Point Chehalis Site (PCS) with boundary modification (in red)

Table 7: Grays Harbor Navigation improvement Project Dredge Volumes to maximum allowable dredging depth

Channel Reach	Stationing	Side Slope	Alt 1 (-40' MLLW) Volume (cubic yards)[3,4]	Alt 2 (-41' MLLW) Volume (cubic yards)[2,3]	Alt 3 (-42' MLLW) Volume (cubic yards)[2,3]
South Reach	463+00 to 716+88	1:5	78,674	163,874	318,332
Outer Crossover	716+88 to 795+00	1:5	208,325	310,865	451,485
Inner Crossover	795+00 to 871+12	1:5	393,042	528,381	662,640
North Channel	871+12 to 1009+24	1:3	282,401	432,068	599,140
Hoquiam Channel	1009+24 to 1159+50	1:3	622,144	799,609	986,417
Cow Point	1159+50 to 1231+48	1:3 / 1:1.5	856,766	994,891	1,168,614
TOTAL			**2,441,352**	**3,229,688**	**4,186,628**

[3]Assumes minor channel realignment initiated from South Reach to Hoquiam Reach (channel stationing 660+00 to 1014+00)

[4]Volumes are computed relative to the Seattle District September 2012 condition hydrosurvey and supplemented with NOAA 2005 hydrosurvey in areas without coverage; volumes include 15% contingency

Table 8: Placement Volumes (2000-2012)

	Pt. Chehalis (open water)	South Jetty (Open water)	HMB (Nearshore)	South Beach (nearshore)	Pt Chehalis Stockpile mitigation (upland)	Total
2000	956,700	1,200,248	0	0	0	2,156,948
2001	667,943	358,873	0	0	0	1,026,816
2002	942,310	475,199	378,441	75,219	705	2,006,874
2003	355,139	824,694	329,107	125,388	0	1,634,328
2004	957,186	1,166,089	289,652	262,176	-45,000	2,675,103
2005	1,054,086	740,970	102,194	217,909	0	2,115,159
2006	1,277,837	196,833	126,892	55,170	0	1,656,732
2007	599,254	389,127	140,406	0	0	1,128,787
2008	1,288,726	707,080	171,352	0	0	2,167,158
2009	1,223,159	21,088	144,975	214,502	0	1,603,724
2010	977,282	91,720	91,720	118,182	-30,000	1,278,904
2011	702,650	1,000,925	177,150	298,251	0	2,178,976
2012	1,481,714	320,985	111,205	142,313	0	2,086,217
TOTAL	12,483,986	7,493,831	2,063,094	1,509,110	-74,295	23,715,726
AVG. ANNUAL	**960,300**	**576,400**	**158,700**	**116,100**	**-5,700**	**1,896,000**

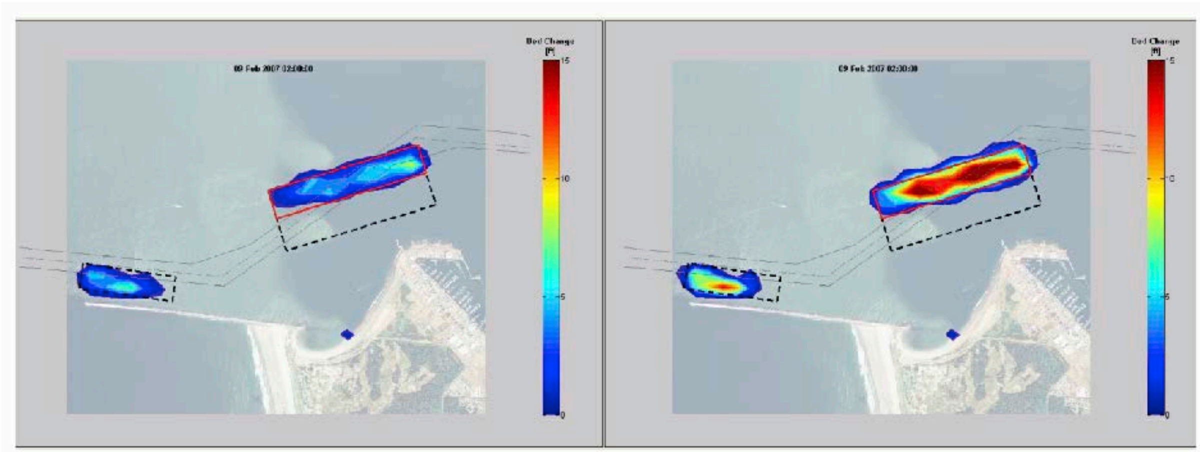

Figure 34: Dredge material mound heights following 10 month simulation for (a) 10 percent and (b) 50 percent clumping fractions for Scenario 1 which assumes 4.5 million cubic yards of dredged material is placed using *current* Point Chehalis site placement practices (from Hayter et al. 2012).

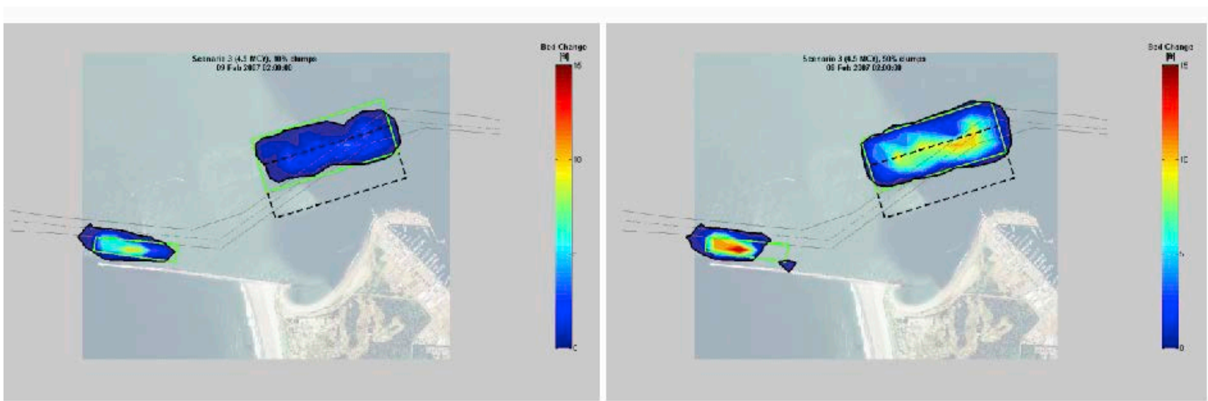

Figure 35: Dredge material mound heights afeeter 10 month simulation for (a) 10 percent and (b) 50 percent clumping fractions for Scenario 3 which assumes 4.5 Mcubic yards of dredged material is placed using a *modified* Point Chehalis site boundary.

4.4.3.2. Beneficial Use Sites

During construction of the navigation improvement project, O&M dredged materials from the outer harbor reaches will be placed in the Half Moon Bay and South Beach Beneficial Use Sites which will help to maximize capacity of the PCS and SJS. Beneficial use sites have annually received 158,700 cubic yards and 116,100 cubic yards respectively since 2000. The South Beach Beneficial Use Site (SBBUS) has significantly more capacity to receive dredged material than what has been historically placed here. The static capacity computed in March 2013 at the SBBUS is over 1.5 million cubic yards with a dynamic capacity of over 3.0 million cubic yards. Thus during the year of construction of the deepening project, over 90% of all O&M dredged materials from the Bar, Entrance, and Point Chehalis reach will be directed for placement at the SBBUS or HMBBUS. Additionally deepening material from South Reach is suitable for placement at the South Beach or Half Moon Bay beneficial use sites; however in the capacity analysis it is assumed to all be placed at the Point Chehalis (PCS) or South Jetty Site (SJS).

4.4.3.3. Upland placement

Chemical analysis conducted in 2012 found subunit CP32a in the Cow Point reach to be unsuitable for open water placement. The quantity of material is estimated to be approximately 22,400 cubic yards. This material will need to be placed in a designated upland placement site. The Port of Grays Harbor has identified a location with sufficient capacity to accept this material in the former waste water treatment lagoons near Port Terminal 3 in Hoquiam. The lagoons already have berms constructed around the site and are pursuing additional fill material,. Real estate has acquired easements for this site as shown in Figure 37. The methodology for placing the material is assumed to be via clamshell and barge with mechanical rehanding of material. During dredging the barge would be lined with geotextile fabric to prevent leakage. The barge would be dewatered through a sump pump with a geofabric bag surrounding the discharge pipe to contain sediments.

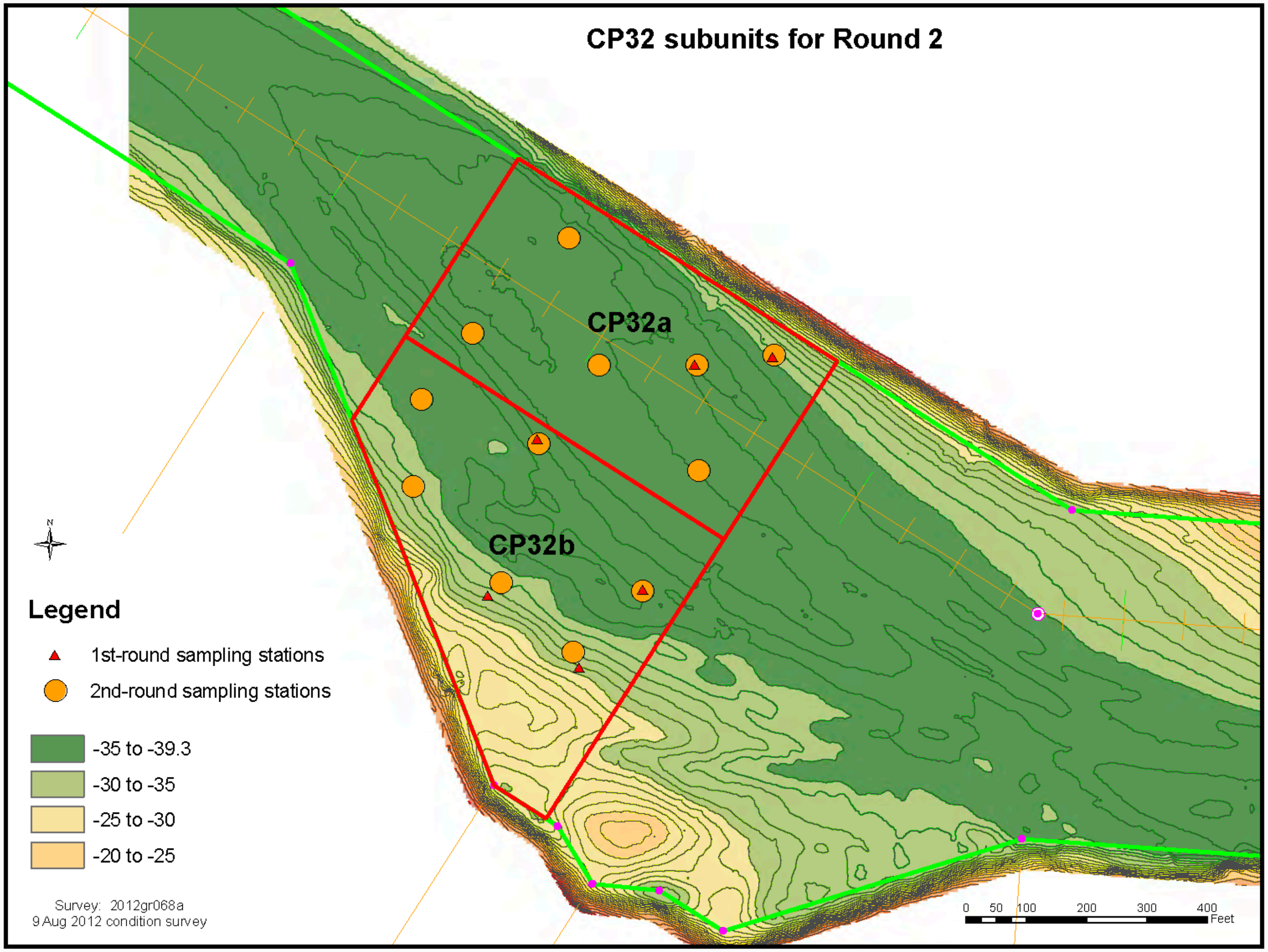

Figure 36: Unsuitable dredged material in Cow Point Reach (sub-unit CP32a; volume = 22,400 cubic yards)

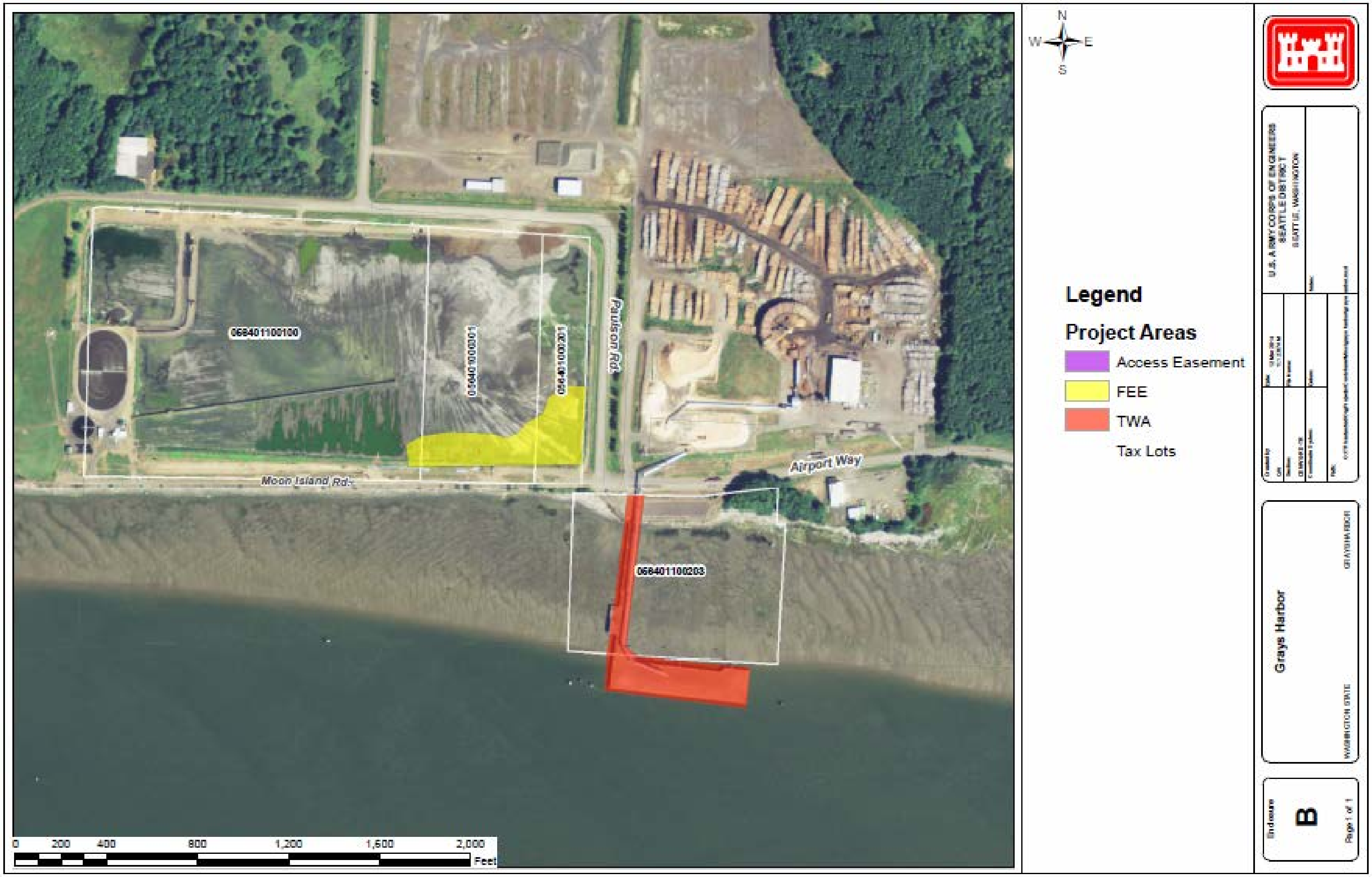

Figure 37: Upland placement location (in yellow)

5. Operations and Maintenance

Historically channel deepening and widening projects result in a net increase in O&M dredging requirements. This has been well documented by Rosati (2005) which shows a net increase in O&M dredging over six historic deepening and widening projects. An empirical relationship was also developed which relates the volume deficit, or the volumetric difference between the dredged and natural equilibrium channel geometry. A linear regression using historic data indicates the annual increase in dredging is approximately 6% of the volume deficit. Thus for this project the volume deficit would be increased by approximately 1.75 million cubic yards for Alternative 3. Using this relationship the predicted increase in O&M dredging associated with the project would be 0.0613*1.75 = 106,985 cubic yards per year. Table 9 presents this by channel reach. This assumption assumes linear shoaling across the entire channel length which is not necessarily the case at Grays Harbor, but serves as a first level estimate for project planning.

Table 9: Grays Harbor Navigation Improvement Project Alternatives - Dredge Volumes to maximum allowable dredging depth

Channel Reach	Stationing	Side Slope	Alt. 2. Volume deficit (cubic yards)	Alt. 2 Increase in O&M dredging (Rosati 2004) (cubic yards)	Alt. 3. Volume deficit (cubic yards)	Alt. 3 Increase in O&M dredging (Rosati 2004) (cubic yards)
South Reach	463+00 to 716+88	1:5	85,200	5,223	239,658	14,691
Outer Crossover	716+88 to 795+00	1:5	102,540	6,286	243,160	14,906
Inner Crossover	795+00 to 871+12	1:5	135,339	8,296	269,598	16,526
North Channel	871+12 to 1009+24	1:3	149,667	9,175	316,739	19,416
Hoquiam Channel	1009+24 to 1159+50	1:3	177,465	10,879	364,273	22,330
Cow Point	1159+50 to 1231+48	1:3 / 1:1.5	138,125	8,467	311,848	19,116
TOTAL			788,336	48,325	1,745,276	106,985

5.1. Outer Harbor Channel Reaches

O&M dredging in the South Reach and Outer Crossover reaches are primarily influenced by bank encroachment and deposition of sediments as sediment is transported across the channel. Thus dredging is typically focused on one side of the channel. Historic O&M dredging has focused on dredging the sideslopes of the channel to minimize bank encroachment. At the South Reach bank encroachment occurs on the north side of the channel as discussed in Section 2.3. The minor channel realignment which will have been implemented by the time of the channel improvement project will significantly reduce dredging in the South and Outer Cross-over reaches.

5.2. Inner Harbor Channel Reaches

O&M dredging in the inner harbor reaches is a result of both bank encroachment and deposition of sediments resulting from the sediment load from the Chehalis River. Shoaling is heaviest in the Cow Point Reach of the federal navigation channel. The channel widens from 350 feet to 950 feet in the turning basin. This effectively increases the cross-sectional area of the channel and thereby reduces the velocity of flows transporting sediments from the Chehalis River and in turn creates deposition in the channel. Additionally the confluence of the south channel immediately south of the turning basin is capable of capturing flow which further dissipates velocity. The intensity of shoaling in the Cow Point Reach and turning basin has historically been correlated with the annual sediment load from the Chehalis River. It is not uncommon to experience shoaling rates of greater than 10 feet between dredge cycles in the turning basin and navigation channel adjacent to the Port of Grays Harbor Terminal 4 (Figure 38). Figure 39, displays the intensity of shoaling in feet in the Cow Point reach between the post dredge survey conducted in February 2013 and the pre-dredge condition survey conducted in August 2013.

Figure 40, displays the intensity of shoaling in feet in the Cow Point Turning Basin which is influenced primarily by deposition from sediment coming from the Chehalis River. Deposition in the southern portion of the turning basin exceeded 7 feet in the 2013 dredge year. It is assumed this area will capture more of the sediment load when the channel improvement project is implemented.

6. Implications of Sea Level Change

The project covers 14.5 miles of the existing channel. The range of sea level change scenarios identified in Section 1.4 varies between 0.24 and 2.0 feet by 2065. The project area does not have any bridge crossings within the reaches being deepened and thus clearance issues associated with sea level rise are not a factor. Existing bridges are located upstream in the navigation channel in the Aberdeen Reach. These include the Union Pacific Railroad Bridge and the WA Route 101 Bridge. Deck heights at the Port of Grays Harbor Terminals are above 18 feet MLLW, thus will not be impacted by sea level change. The greatest impact from sea level change is likely the morphology near the inlet throat. As discussed in Section 2.3, the growth of Damon Point has constricted the inlet throat which has forced the thalweg into the inner harbor to maintain a position where the South Reach channel currently is aligned. Diminishing sediments feeding Damon Point coupled with sea level rise could result in breaches through Damon Point opening new channels into the inner harbor. Should a breach through Damon Point result in a permanent channel into the inner harbor, this could result in greater O&M dredging requirements in the South Reach.

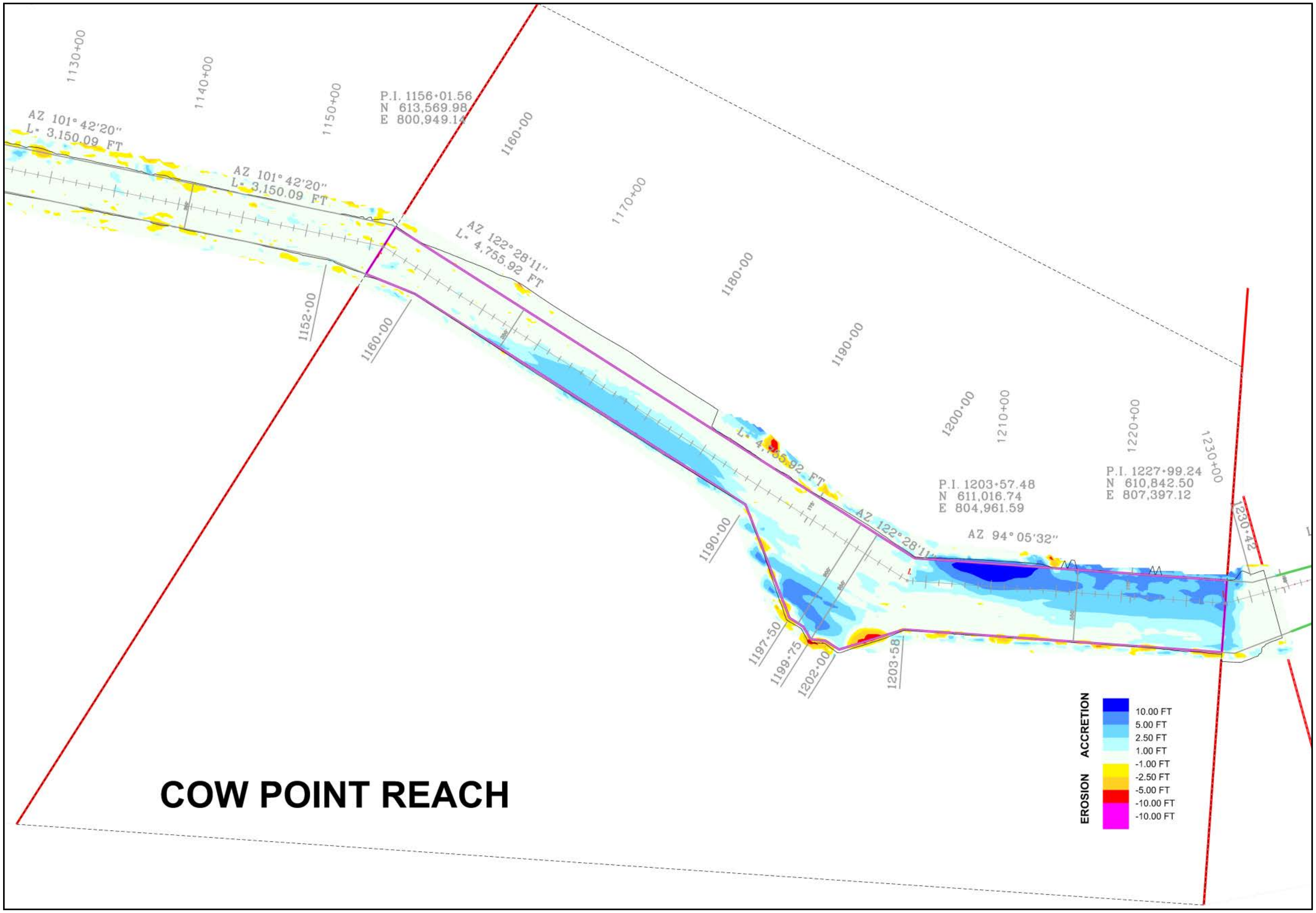

Figure 38: Shoaling (in feet) in Cow Point Reach from February 2013 to August 2013. Net shoaling volume = 212,132 cubic yards

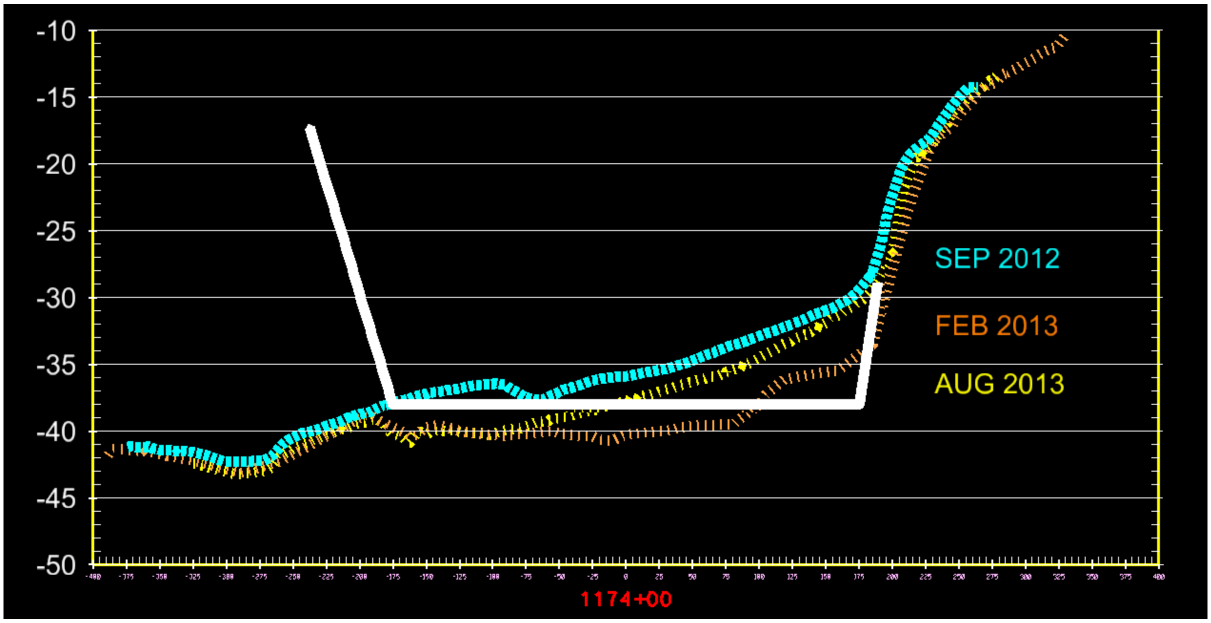

Figure 39: Example of dredging and shoaling in Cow Point Reach over one dredge year. Note after-dredge survey (FEB 2013) indicating bank encroachment from the right bank and up to 5 feet of deposition in the channel at the time of the following pre-dredge survey (AUG 2013).

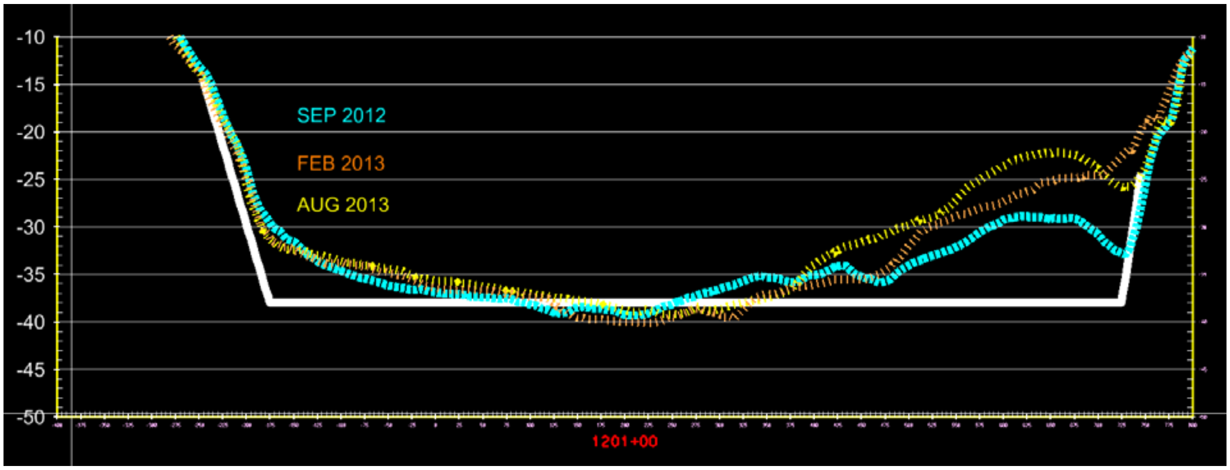

Figure 40: Example of deposition in the Cow Point Turning Basin over one dredge year. Comparing pre-dredge survey (SEP 2012) to following pre-dredge survey (AUG 2013) up to 7 feet of deposition occurred in the turning basin.

7. References

Annual Report to Chief of Engineers (ARCE). 1909. House Document No. 111, 61st Congress, 2nd Session. 2246-2247.

Annual Report to Chief of Engineers (ARCE). 1915. House Document No. 91, 64t Congress, 1st Session. 2246-2247.

Buijsman, M.C., Sherwood, C.R., Gibbs, A.E., Gelfenbaum, G., Kaminsky, G., Ruggiero, P., Franklin, J. 2003. Regional Sediment Budget of the Columbia River Littoral Cell, USA – Analysis of Bathymetric- and Topographic-Volume Change. United States Geological Survey and Washington State Department of Ecology. Open –File Report 02-281. March 2003.

Brocher, T.M. and Christensen, N.I. 2001. Density and Velocity Relationships for Digital Sonic and Density Logs from Coastal Washington and Laboratory Measurements of Olympic Peninsula Mafic Rocks and Greywackes. U.S. Geological Survey. Open-File Report 01-264.

Caterpillar Performance Handbook. 2010. Edition 36, Caterpillar, Peoria, IL.

Demirbilek, Z., Lin, L., Smith, J., Smith, E., Hayter, E., Smith, E, Gailani, J., Norwood, G., and Michalsen, D.R. 2010. Waves, hydrodynamics and sediment transport modeling at Grays Harbor, WA. Technical Report ERDC/CHL TR-10-13, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Gelfenbaum, G. Kaminsky, G.M. 2010. Large-scale coastal change in the Columbia River littoral cell: An overview. *Marine Geology*. 273. 1-10.

Hayter, E.J., Smith, J, Michalsen, D.R., Demirbilek, Z., and Lin, L. 2012. Dredged material placement site capacity analysis for navigation improvement project at Grays Harbor, WA. Technical Report ERDC/CHL TR-12-18, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Kraus, N.C. and Arden H.T. 2003. North Jetty Performance and Entrance Navigation Channel Maintenance, Grays Harbor, Washington. U.S. Army Corps of Engineers Engineering Research and Development Center Coastal Hydraulics Laboratory. ERDC/CHL TR-03-12

Kaminsky, G.M., Ruggiero, P., McCandless, D. Lindstrum, E., McInnis J., and Daniels, R. 1999. Road wash-outs and shoreline change at Damon Point, Washington, Report to the Washington State Parks and Recreation Commission, Olympia, WA.

Kaminsky, G.M., Ruggiero, P. Buijsman, M.C., McCandless, D., and Gelfenbaum, G. 2010. Historical evolution of the Columbia River littoral cell. *Marine Geology*. 273. 96-126.

Laprade, W.T. and Robinson, R.A. 1989. *Foundation and Excavation Conditions in Washington*. Bulletin 78, Volume I, Division of Geology and Earth Resources. Washington State Department of Natural Resources.

Li, H., Sanchez, A., Brown, M.E., Watts, I.E., Demirbilek, Z., Rosati, J.D., Michalsen, D.R. 2013. A Modeling Study of Coastal Sediment Transport and Morphology Change. Accepted to the 23rd International Offshore and Polar Engineering Conference. Anchorage, Alaska.

Murphy III, W.F., Ward, W.B., Boyd, B., Murphy IV, W.F., Nolen-Hoeksema, R., Art, M., Rosales-R, D.A. 2011. Geophysical, geological, geotechnical, and mechanical testing of rock. Proceedings of the Western Dredging Association (WEDA XXXI). Technical Conference and Texas A&M University (TAMU 42) Dredging Seminar, Nashville, Tennessee, June 5-8, 2011.

Osborne, P. D. Dynamics of Whitcomb Flats, Grays Harbor. July 10, 2003.

Scheidegger, K.F., and Phipps, J.B. 1976. Dispersal patterns of sands in Grays Harbor estuary., Washington. *Journal of Sedimentary Petrology*. 46(1), 163-166.

Rosati, J.D. Coastal Inlet Navigation Channel Shoaling with Deepening and Widening. US Army Corps of Engineers, Coastal Hydraulics Laboratory. ERDC/CHL CHETN-IV-64. June 2005.

US Army Corps of Engineers, Seattle District (USACE). 1965. South Jetty Rehabilitation – Station 110 to 150. General Design Memorandum. February 1965.

US Army Corps of Engineers, Committee on Tidal Hydraulics (USACE). 1967. Grays Harbor, Washington. 24 pages.

US Army Corps of Engineers, Seattle District (USACE). 1974. North Jetty Rehabilitation. Design Memorandum. August 1974.

US Army Corps of Engineers, Seattle District (USACE). 1976. Navigation Channel Realignment – South Reach (Sand Island). Design Memorandum. February 1976.

US Army Corps of Engineers, Seattle District (USACE). 1989. Grays Harbor Navigation Improvement Project. General Design Memorandum. February 1989.

US Army Corps of Engineers, Seattle District (USACE). 1990. Grays Harbor Navigation Improvement Project – Supplemental Construction Data and Current Schedule. Memorandum from Raymond G. Schmitz, P.E. (Chief of Operations Division). June 6, 1990.

US Army Corps of Engineers, Seattle District (USACE). 1991. Ship Simulation Study of Grays Harbor Navigation Project, Grays Harbor, Washington. Technical Report HL-91-18.

US Army Corps of Engineers, Seattle District (USACE). 1997. Evaluation Report – Long-term Maintenance of the South Jetty at Grays Harbor, Washington.

US Army Corps of Engineers (USACE). 1998. Final Environmental Assessment. Point Chehalis Revetment Extension Project. Westport, Grays Harbor County, Washington. October 5, 1998.

US Army Corps of Engineers, Seattle District (USACE). 1999. South Jetty Rehabilitation – Station 87+00 to 120+00. Design Analysis. July 1999.

US Army Corps of Engineers, Seattle District (USACE). 2000. North Jetty Major Maintenance – Station 95+00 to 145+00. Design Analysis. January 2000.

US Army Corps of Engineers, (USACE). (2006) EM 1110-2-1613. Engineering and Design – Hydraulic design of deep draft navigation projects. 31 May 2006. http://140.194.76.129/publications/eng-manuals/EM_1110-2-1613_sec/toc.htm

US Army Corps of Engineers (USACE). 2011. Water Resource Policies and Authorities. Sea Level Change Considerations for Civil Works Program – Engineering Circular No. 1165-2-212.

US Army Corps of Engineers (USACE). 2012. Grays Harbor Navigation Improvement Project. Memorandum for the Record. Purpose: To discuss and determine path forward regarding a ship simulation study. April 3, 2012.

US Army Corps of Engineers, Seattle District (USACE). 2013a. Conceptual Design for Federal Deep Draft Channel Realignment in South Reach to Hoquiam Reach, Grays Harbor, Washington. Memorandum for Record, prepared by David R. Michalsen, P.E. March 5, 2013.

US Army Corps of Engineers, Seattle District (USACE). 2013b. Determination Regarding the Suitability of Dredged Material from the Grays Harbor Navigation Improvement Project, Evaluated Under Section 404 of the Clean Water Act, for Open-Water Disposal at the South Jetty or Point Chehalis Dispersive Sites, or for Beneficial Use. Memorandum for Record. CENWS-OD-TS-DMMO.