EXHIBIT J

COLUMBIA RIVER SEDIMENTATION IMPACTS ANALYSIS

(REVISED)

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43-Ft Navigation Channel Improvement
Sedimentation Impacts Analysis (Revised)

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43-FT NAVIGATION CHANNEL IMPROVEMENT
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Prepared by:
U.S. Army Corps of Engineers
Portland District

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COLUMBIA RIVER
43-FT NAVIGATION CHANNEL IMPROVEMENT
SEDIMENTATION IMPACTS ANALYSIS

EXECUTIVE SUMMARY

This sedimentation impact assessment evaluates the potential changes in sedimentation that might occur with the proposed 43-ft navigation channel. The historical sediment budgets for the lower Columbia River, estuary, and littoral cell are examined to identify system responses to past natural and human activities. The main focuses were on changes to the lower river's sand transport, estuarine sand accretion, and the movement of sand between the estuary and the mouth of the Columbia River (MCR). It is concluded that there have been declines in all three of those processes due to changes in the river flows and the changes in entrance conditions that followed the construction of the MCR jetties. Development of the Columbia River navigation channel upstream of river mile 3 has not and will not have a significant impact on those processes.

The Columbia River's average annual sand transport has declined considerably from the late 1800's to present. The declines are related to global climate variations and upstream flow regulation that have reduced the river's peak streamflows and sediment transport capacity. The reduced sand inflow from the river has contributed to the reduction in sand accretion in the estuary. The MCR jetties reduced the sand transport from the MCR into Baker Bay and across Clatsop Spit into the south channel caused by ocean waves. However, the jetties caused a large discharge of sand from the MCR and vicinity, to the ocean. The sand eroded from the inlet and south flank of the inlet following jetty construction has deposited in the outer delta, on Peacock Spit, and the shorelines along Long Beach, Washington, and Clatsop Plains, Oregon.

Over the last 120 years, navigation channel development has noticeably altered the Columbia River's channel configuration in the river, estuary, and the MCR. However, past dredging and channel modifications upstream of RM 40 have not measurably altered the available sand supply or sand transport in the river. Excluding the effects of the MCR jetties, past navigation channel development also has not altered the estuary's overall erosion/accretion or bedload transport patterns. The reduction in the Columbia River's net sand discharge to the MCR since the early 1900's is related to lower Columbia River flood discharges and not the navigation channel or the MCR jetties.

The potential channel modifications in the Columbia River and estuary from the proposed 43-ft navigation channel are similar to, but much smaller than, those caused by navigation development over the past 100 years. There will be increases in riverbed depths and slight changes in river hydraulics. Deepening will not reduce the available sand supply and the expected hydraulic changes are too small to measurably alter sand transport or erosion/accretion in the river or estuary. Sediment transport and the sediment budget at the MCR are not likely to change by the proposed 43-ft navigation channel.

COLUMBIA RIVER SEDIMENTATION IMPACTS

INTRODUCTION

The Corps' Integrated Feasibility Report for Channel Improvement and Environmental Impact Statement (FEIS) (USACE, 1999) stated that the sedimentation impacts from the proposed 43-ft deepening would be limited to increases in riverbed depths and localized increases in suspended sediment and turbidity at dredging and disposal sites during dredging operations. Since completion of that report, questions have been raised about the potential for sedimentation impacts to salmon and their habitat, adequacy of the Corps' dredging forecast, and potential changes to the river's sediment budget. All of these questions were addressed, descriptions of potential impacts refined, and concerns alleviated during preparation of the Corps' Biological Assessment (BA) completed in consultation with the NOAA Fisheries and U.S. Fish and Wildlife Service on potential impacts to threatened and endangered species (USACE, 2001, and SEI workshops, 2001).

However, questions still persist about a potential impact of the deepening on the sediment budget of the Columbia River. Those questions are largely based on the presumption that past navigation developments (dredging, disposal, pile dikes, and jetties) have already altered the river's sediment budget and those of the estuary and coast; and that further deepening will cause additional impacts to those sediment budgets. Appendix A uses the available sediment information on the river, estuary, and coast to define the system's sedimentation processes and its sediment budget since 1868. It also examines the system's response to the last 120 years of human development of the river and the entrance. The history of navigation developments in the study area is described in the FEIS (1999).

This sedimentation impact assessment supplements those in the FEIS and BA by utilizing the historic sedimentation processes and system responses described in Appendix A to predict the sedimentation responses to the proposed 43-ft channel project. This assessment relies on existing information, including new information that has become available since publication of the Corps' FEIS (1999). The impact assessment area, as shown in Figure 1, includes the Columbia River downstream of the Portland/Vancouver area, the estuary, and the mouth of the Columbia River (MCR) plus those portions of the Columbia River littoral cell (CRLC) within approximately 12 miles, north and south, of the (MCR). The Corps' 1999 study area (USACE, 1999) has been expanded to include the MCR and portions of the littoral cell to cover potential coastal impacts.

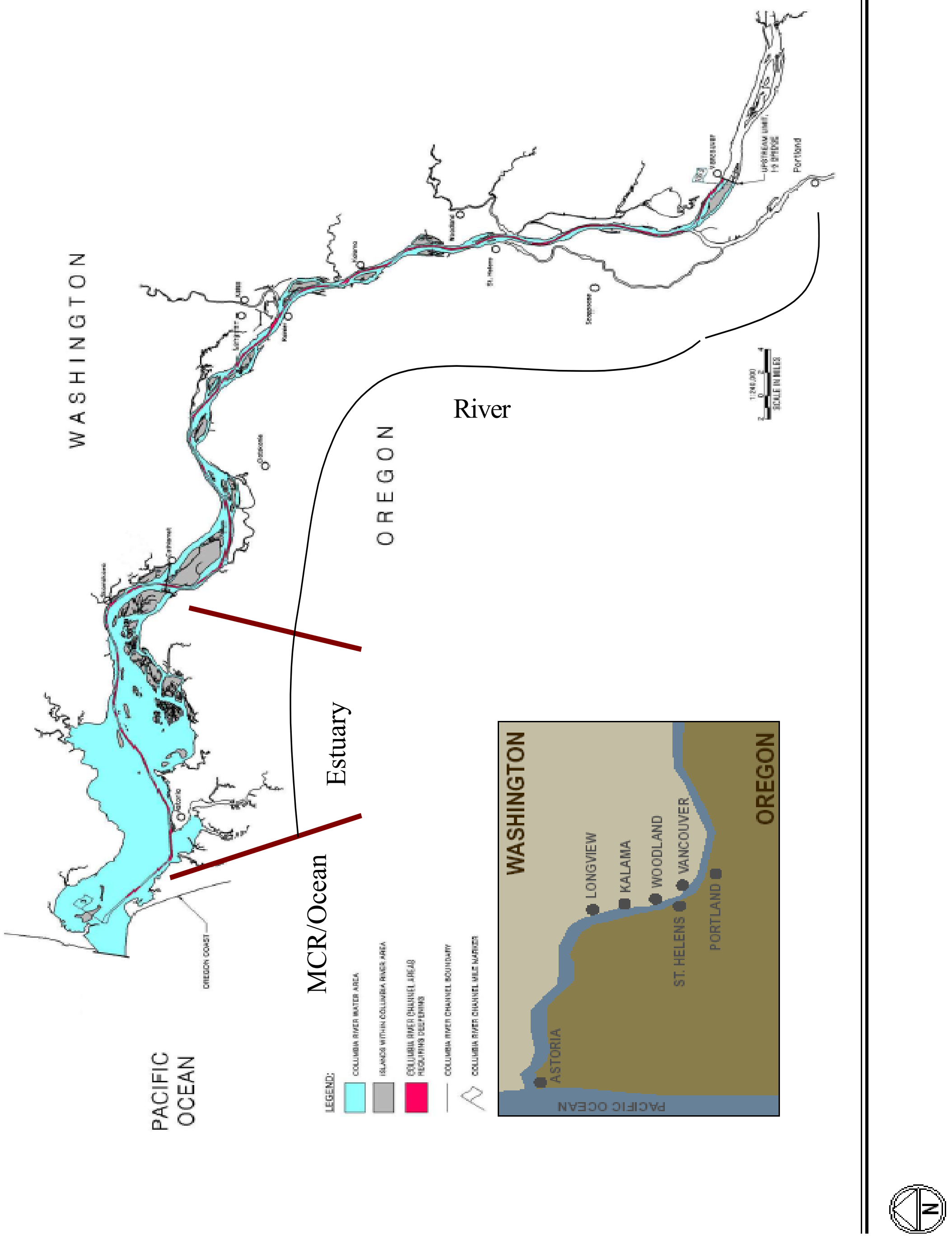


Figure 1. STUDY AREA MAP.

HISTORIC SEDIMENTATION PROCESSES

This section summarizes the significant findings from the sediment budgets and historical sedimentation processes analyses that are presented in Appendix A.

I. COLUMBIA RIVER (RM 40-106)

A. Sand Transport

The Columbia River's average annual sand transport has declined considerably, from the 6-mcy/yr in 1868-1926, to 3.6 mcy/yr for 1926-58, to 2.7 mcy/yr in 1959-72, and to 1.3 mcy/yr for 1973-99. Global scale climate variations that reduced streamflows were the primary cause of the decline in sand transport between the 1800's and 1972. Prior to 1972 the effects of flow regulation by upstream reservoirs and water diversions in the Columbia basin had caused relatively small reductions in sand transport. Since 1973, flow regulation has significantly reduced spring freshet discharges and consequently the average annual sand transport.

The relationship between river discharge and sand transport in the Columbia River has not changed since 1868. There is also no discernable change in that relationship through the river reach from RM 106 to RM 48.

B. Navigation Development Impacts

Navigation development began to noticeably alter the width and depth of the Columbia River streambed in the 1920's with the construction of the 30-ft channel and the development of pile dike fields to control flow. The riverbed continued to deepen as the navigation channel was deepened to 35-ft in 1935 and to 40-ft by 1976. Between 1900 and 1999, dredging to deepen and maintain the navigation channel between RM 40 and 106 totaled 450 mcy. Dredge material disposal utilized upland, shoreline, and in-water sites. Dredging, pile dike fields and shoreline disposal have combined to increase the depth and reduce the width of the riverbed, especially in those reaches that were naturally broad and shallow. Navigation development has not measurably altered Columbia River sand transport.

II. ESTUARY (RM 6-40)

A. Sedimentation Patterns

The 1868-1958 sediment accretion rates were comparable to those of the past 7,000 years. The average annual estuary accretion rate did decline from 5.0 mcy/yr in 1878-1926 to 3.7 mcy/yr for 1927-1958. That decline appears to be related to lower streamflows and the associated reduction in sand inflow from the river, and reduced sand inflow from the MCR. At the observed 1868-1958 accumulation rates, the estuary will not fill with sediment for 800-7,700 years.

River sand has accumulated in bays and shallows upstream of RM 15, including Cathlamet and Grays Bays, and in the south channel. There is bedload movement seaward across the central flats toward Desdemona Sands and landward transport in the north channel from the MCR to Desdemona Sands. This convergence of transport paths indicates that Desdemona Sands is an accretion zones for sand from both the estuary and the MCR. These accretions and bedload transport patterns have remained essentially unchanged since the 1930's.

B. Navigation Development Impacts

Navigation dredging had little impact on channel depths until the construction of the 30-ft channel. Depths in much of the south channel (RM 6-31) have increased as the navigation channel was deepened to 35-ft and then 40-ft. Navigation dredging totaled 230 mcy between 1900-99. In-water disposal has been by far the dominant disposal method downstream of RM 40. In-water disposal has redistributed the dredged sand along the south channel, keeping it in the active sand transport system. The exceptions to that have been the transfer of 20 mcy of sand from the south channel and the MCR to the north channel near RM 6 between 1957-87, and the placement of about 22 mcy on the Rice, Miller Sands, and Pillar Rock islands.

III. The MCR (RM 0-6)

A. Sand Transport

There was net sand discharge from the estuary to the MCR of 138 mcy in 1868-1926 and 17 mcy in 1927-1958. During both periods there was probably also sand inflow from the MCR, perhaps as much as 60 mcy in the earlier period and 5 mcy in the later period. The MCR jetties and the resulting inlet bathymetry changes reduced the sand transport into the estuary caused by ocean waves. Since the 1930's, sand entering the estuary from the MCR has been primarily transported by tidal currents through the north channel. It appears that sand discharged from the estuary to the MCR is primarily transported through the south channel during high river discharges.

B. Navigation Development Impacts

Construction of the MCR jetties changed the inlet hydraulics and sand transport. Nearly 800 mcy of sand eroded from the inlet and south flank and deposited along the coast following jetty construction. Over 100 mcy of dredged sand has been disposed of on the outer delta and over 100 mcy more has been placed near the west end of the north jetty. The jetties reduced the sand transport into Baker Bay and across Clatsop Spit into the south channel caused by ocean waves.

IV. COASTAL EROSION/ACCRETION

Since 1868, there has been erosion at the MCR inlet and south flank, and offshore along the Oregon portion of the littoral cell. The sand from the MCR area has deposited in the outer delta, on Peacock Spit, and the shorelines for approximately 12 miles north along Long Beach, Washington, and 12 miles south along Clatsop Plains, Oregon. Sand accretion along both the south and north shorelines has continued up to the present time.

43-FT CHANNEL IMPROVEMENT SEDIMENTATION IMPACTS

There has been concern about what impact the proposed 3-ft deepening of the Columbia River deep-draft navigation channel might have on the sediment budgets of the river and littoral systems. This impact assessment re-examines those issues based on the system's sedimentation processes and its response to the last 120 years of human development of the river and coast. That information is presented in Appendix A and was used to predict the sedimentation responses to the proposed 43-ft channel project that are described below. This assessment relies on existing information and incorporates new information that has become available since publication of the Corps' FEIS (USACE, 1999).

Construction and 20 years of maintenance of the proposed 43-ft navigation channel will likely remove around 70 mcy of sand from the Columbia River and place it in upland disposal sites. Approximately 40 mcy of dredged sand would be disposed of back in-water along the navigation channel or in ecosystem restoration sites in the estuary. This will cause increased riverbed depths and slight changes in river hydraulics (USACE, 1999 and 2001).

The proposed deepening would lower about 45-percent of the navigation channel in the estuary (RM 3-40) and 60-percent of the navigation channel in the river (RM 40-106) by up to 3 ft. Dredging would directly impact about 1- and 10-percent of the entire riverbed between RM 3-40 and RM 40-106, respectively. After the initial deepening the riverbed would begin to adjust to the new channel depth. Riverbeds adjacent to the deeper dredge cuts will degrade as bedload is deflected down the cut slope and into the navigation channel. This process may continue for 5-10 years before the side-slopes reach equilibrium with the channel hydraulics (USACE, 1999 and 2001). The Columbia’s riverbed is underlain by thick deposits of alluvial sand that vary in thickness from 400 ft in the estuary to 100 ft near Vancouver (Gates, 1994). The volume of sand removed by dredging and side-slope adjustment will not reduce the available sand supply in the riverbed.

The depth of bed degradation would be nearly equal to the depth of the dredge cut at the edge of the cut and reduce steadily to near zero some distance away from the cut. Side-slope adjustments may extend to the shoreline around RM’s 22, 42-46, 72, 76, 86, and 99. The resulting depth increases are expected to be less than one foot near the shore. These locations are all past shoreline disposal sites and the sandy beaches may experience 10-50 ft of lateral erosion (USACE, 2001). Sand eroded from these sites will become part of the active bedload transport on the riverbed.

The hydraulic impacts of a 3-ft channel deepening were examined in the Corps’ FEIS and BA (USACE, 1999 and 2001). The deepening would not change water surface profiles between RM 3-70. Upstream of RM 70 there is a progressive reduction in water surface elevations up to RM 106. The maximum reductions ranged from 0.12 to 0.18 ft. The water surface reductions extended upstream to Bonneville Dam at RM 146.

Flow velocities in the Columbia River change continuously due to the influence of the ocean tides. The river's cross-sectional flow area varies, but is generally around 100,000 sq ft. For most non-flood discharges, river velocities will fluctuate between 0-ft/sec and about 3-ft/sec over the course of a day. Given the general size of the river's cross-sectional flow area upstream of the project (RM 106-146), water surface reductions of 0.12-0.18 ft would cause velocity increases of about 0.1 ft/sec, or less, for any river discharge.

Downstream of RM 106, changes in velocities are similarly small, but more complex. Between RM 70-106, the changes in flow areas due to reductions in water surface elevation may be more than offset by the deepening of the riverbed in dredging areas, but not in non-dredging area. Velocity changes in this reach could range from minus 0.2 ft/sec in areas to be deepened, to plus 0.1 ft/sec, in non-dredged reaches. In the dredging reaches downstream of RM 70, velocities would tend to decrease by 0.2 ft/sec or less, but would be unchanged where there would be no dredging. The Corps' three-dimensional hydraulic modeling of the estuary (RM 0-48) indicates velocities, for a 70,000 cfs river discharge, would be unchanged over most of that reach (USACE, 2001). That modeling also showed that the bottom velocities only changed in the navigation channel and that the changes ranged from minus 0.2 ft/sec to plus 0.2 ft/sec.

To alter the Columbia River's sediment budget and/or sand discharge to the Pacific Ocean, the proposed deepening would have to reduce the sand available for transport or alter the transport capacity of the system. The project will not alter the sand inflows from the main stem upstream of the project or from tributaries. The project also will not reduce the abundant sand supply available in the riverbed within the project area. The expected hydraulic changes are very small and fluctuate between changes that would increase, decrease, and not change sand transport in the river. For these reasons, there is not likely to be a detectable change in the sediment budget or sand transport within the Columbia River.

In the estuary, the slight changes in the hydraulic conditions would be restricted to the deeper navigation channel. Hydraulic conditions in the north channel and the estuary's bays and flats would be unchanged. The estuary-wide erosion/accretion patterns also would not change. Desdemona Sands and Cathlamet Bay should remain the two areas most rapidly accumulating sand. Estuarine ecosystem features and flowlane disposal will be used for most of the sand dredged from the channel downstream of RM 40. This disposal practice will minimize changes to the estuary's sand transport and sediment accommodation space. Large floods will continue to have the potential to discharge large volumes of sand to the MCR and ocean, but flow regulation has made such floods less likely to occur. The proposed 43-ft navigation channel should cause no appreciable change in the estuary's sediment budget, sand transport, or the estimated 800-7,700 years before the estuary fills with sediment.

The 43-ft channel project does not include modification of the MCR navigation channel. The Corps' hydraulic modeling showed the deepening would not change the hydraulic conditions in the MCR (USACE, 2001). Therefore, sedimentation processes in the MCR are not likely to change and there will continue to be the transport of sand both landward and seaward at the MCR. Deepening the navigation channel in the river and estuary will not alter the sand transport through the MCR nor the sediment budget of the littoral cell.

Over the last 120 years, navigation channel development has noticeably altered the Columbia River's channel configuration in the river, estuary, and the MCR. However, past dredging and channel modifications have not measurably altered the available sand supply or sand transport in the river. Excluding the effects of the MCR jetties, past navigation channel development also has not altered the estuary's overall erosion/accretion and bedload transport patterns. The reduction in the Columbia River's net sand discharge to the MCR since the early 1900's is related to lower Columbia River flood discharges and not the navigation channel or the MCR jetties. The potential channel modifications in the Columbia River and estuary from the proposed 43-ft navigation channel are similar to, but much smaller than, those caused by navigation development over the past 100 years. The impacts to the sediment budget and sand discharge to the ocean caused by the proposed 43-ft navigation channel are thus expected to likewise be imperceptibly small.

CONCLUSIONS

Construction and 20 years of maintenance of the proposed 43-ft navigation channel will likely remove around 70 mcy of sand from the Columbia River. Another 40 mcy of dredged sand would be disposed of back in-water, mostly in the estuary. This will cause increased riverbed depths and slight changes in river hydraulics between RM 3-106. Deepening will not reduce the available sand supply and the expected hydraulic changes are too small to measurably alter sand transport or erosion/accretion in the river or estuary. There will be no measurable change in hydraulic conditions or sedimentation processes at the MCR. There will continue to be the transport of sand both landward and seaward at the MCR. Large freshets will continue to have the potential to discharge larger volumes of sand from the estuary to the MCR, however flow regulation has made such freshets less likely to occur. The proposed deepening is not expected to impact the littoral sand budgets north or south of the MCR.

Over the last 120 years, navigation channel development has noticeably altered the Columbia River's channel configuration in the river, estuary and the MCR. However, past dredging and channel modifications have not measurably altered sand supply or sand transport in the river or estuary. Excluding the effects of the MCR jetties, past navigation channel development also has not altered the estuary's overall erosion/accretion and bedload transport patterns. The reductions in the Columbia River's net sand discharge to the MCR since the early 1900's are related to lower Columbia River discharges caused by natural climate variations and upstream flow regulation. The potential channel modifications in the Columbia River and estuary from the proposed 43-ft navigation channel are similar to, but much smaller than, those caused by navigation development over the past 100 years. The sedimentation impacts from the proposed 43-ft navigation channel are thus expected to likewise be indiscernibly small.

APPENDIX A

COLUMBIA RIVER SEDIMENTATION PROCESSES; THE LOWER RIVER TO THE COAST

Prepared by:
U.S. Army Corps of Engineers
Portland District

January 2003

COLUMBIA RIVER SEDIMENTATION PROCESSES; THE LOWER RIVER TO THE COAST

For thousands of years, sediment carried downstream by the Columbia River has helped shape the estuary and nearby coast. Human activities have altered the river's sediment budget and those of the estuary and coast. There has been concern about what additional impact the proposed 3-ft deepening of the Columbia River deep-draft navigation channel might have on those sediment budgets.

This report examines the available sediment information in the river, estuary, and coast to define the system's sedimentation processes and its response to the last 120 years of human development of the river and coast. This report relies on existing information and incorporates new information that has become available since publication of the Corps' Integrated Feasibility Report for Channel Improvement and Environmental Impact Statement (FEIS) (USACE, 1999). The historic sedimentation processes present here provides additional background for predicting the sedimentation responses to the proposed 43-ft channel project.

STUDY AREA

The study area, as shown in Figure 1, extends from the Columbia River downstream of Bonneville Dam, to the Columbia River littoral cell (CRLC), which extends north and south of the mouth of the Columbia River (MCR). The Corps' 1999 study area (USACE, 1999) has been expanded to include the littoral cell to cover potential coastal impacts. The study area is broken into three reaches, river, estuary, and the MCR, including the adjacent coast. These divisions are based on the dominant hydraulic forces that drive the sediment transport in each reach. The history of navigation developments in the study area is described in the FEIS (USACE, 1999).

RIVER

The river reach extends from downstream of Bonneville Dam (River Mile 145) to the downstream end of Puget Island near River Mile (RM) 40. Through this reach the river occupies a single main channel with occasional small side channels around islands. Sediment transport in this reach is controlled by the river discharges, primarily those of the Columbia upstream of Bonneville and the Willamette River. Ocean tides influence water surface elevations and can create slack water conditions, but flow reversals are negligible to nonexistent.

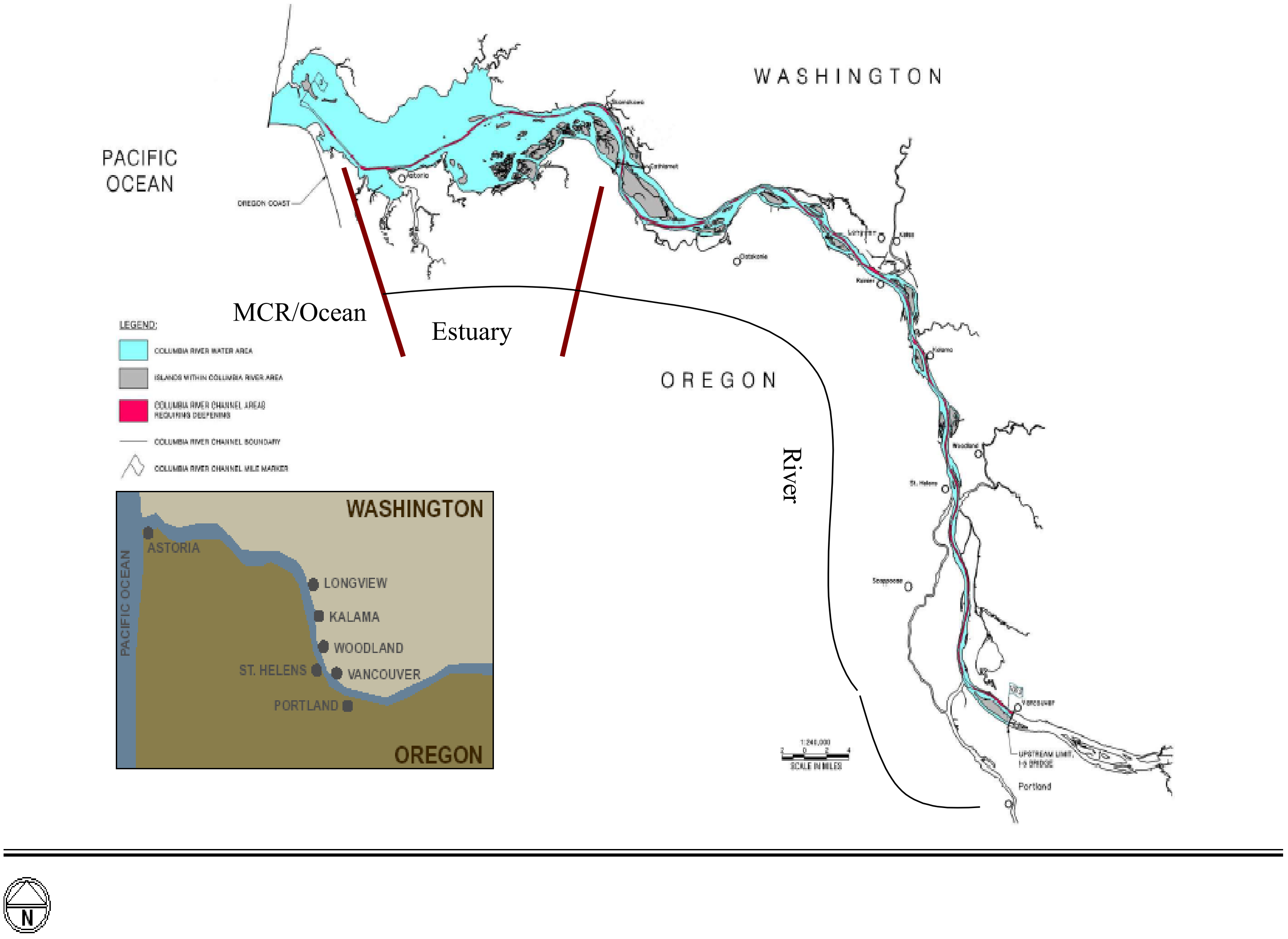


Figure 1. STUDY AREA MAP.

ESTUARY

The estuary reach extends from RM 40 to near the MCR. The Columbia River estuary is 4 to 5 miles wide and contains two main channels, the north and south channels. This reach has very complex hydraulic conditions because of the combined effects of river discharges, ocean tides and waves, and multiple side channels and flats. The main channel transitions from river dominated at the upstream end to tidally dominated near the MCR. Water and sediment are dispersed from the main channel to the estuary's side channels, bays and flats, beginning at RM 40 with flow into Cathlamet Bay.

MOUTH OF THE COLUMBIA RIVER

The MCR reach extends several miles on either side of the entrance to include Long Beach in Washington and Clatsop Plains in Oregon. The Columbia's littoral cell (CRLC) stretches from Tillamook Head on the south to Point Grenville on the north. However, the northern and southern ends of the littoral cell are not included in this report because of the lack of volume change data. The MCR is a high-energy area that extends from RM 6, excluding Baker Bay to the ebb tidal delta. Tidal flows are the dominant factor in sediment transport between the jetties; shoaling wind waves and swell, shodf-modified tidal currents, estuaring-induced currents, and wind-driven currents are the influencing morphologic changes factors along the surrounding coastline and over the ebb tidal delta. The longshore currents vary seasonally along this coast, flowing to the south in the summer and to the north the remainder of the year. Large winter storm waves come in primarily from the southwest, while summer waves come from the northwest (USACE 1999).

STUDY TIME FRAME

This report generally covers the last 130 years, but breaks those into three significant periods, 1868-1926, 1926-1958 and 1958 to present. These time periods are dictated by the time periods of the bathymetric change analysis done for the MCR and coast by Gelfenbaum, et al (2001). The 1868-1926 period includes the relatively natural conditions prior to 1885 and the initial navigation development period from 1885 to 1926. Between 1885 and 1926 the jetties at the MCR were constructed and deepening of the navigation channel began, but river discharges remained unregulated. During the 1926-58 time period, navigation channel development continued and development of the upstream reservoir system was underway, but flow regulation was still minimal. Since 1958 the MCR and river channels have been deepening and river flows have become highly regulated by the upstream reservoirs.

SEDIMENTATION PROCESSES

This study will address natural sedimentation processes and human actions in the study area that have a significant influence on the behavior of the system. Natural processes will include hydrology, transport mechanisms, sediment sources, and deposition. Human actions include dredging, disposal, flow control structures and flow regulation by upstream reservoirs. The timing of major sediment movements is important to their interaction, and is also addressed in this study.

While the sedimentation processes in the study area involve sand, silt, and clay, the emphasis of this report will be on the movement of sand. Sand is the primary material in the riverbed, ocean beaches and dredging operations, and is essential to the morphology of the study area. The natural system works to maintain a balance between transport potential and sand load such that if the transport potential is less than the incoming sand load, deposition will occur. Conversely, if transport potential exceeds the incoming sand load and there is an available source, erosion will occur (ASCE, 1977). However, transport potential varies in time and space, causing natural alluvial channels to shift and evolve. These basic processes are introduced in this section and then the specifics for the Columbia River are covered in more detail later in this report.

HYDROLOGY

The Columbia River drains 259,000 square miles, originating in Canada's Columbia Lake and flowing 1,214 miles to the Pacific Ocean. Flow from the upper basin is dominated by snowmelt, resulting in low winter discharges and large spring freshets. Heavy winter rainfall in the lower basin can cause high discharges in the study area. Since 1878, the average annual discharge at The Dalles has been 192,000 cubic feet per second (cfs). However, there has been a reduction in average annual discharge since the 1800's due to global scale climate variations, and upstream diversions and flow regulation (Jay and Naik, 2000). The 1878-1900 average annual discharge at The Dalles, was just over 220,000 cfs. For the time period before completion of any large reservoirs (1878-1935), the average annual discharge was 200,000 cfs. The period-of-record average annual discharge continued to fall until it reached approximately its current value around 1945.

Reservoirs upstream of the study area store water during the spring snowmelt and release it during the fall and winter to increase hydroelectric power generation. After completion of the large Canadian storage reservoirs in the early 1970s, the 2-year flood peak at the Dalles, Oregon, was reduced from 580,000 cfs to 360,000 cfs with regulation (USACE, 1987). Low flows, typically in the 100,000 cfs range, occur in September and October after the snowmelt runoff but before the winter rains. Flows in the study area are slightly higher due to local inflows, especially from the Willamette and Cowlitz rivers. The average annual discharge in the Willamette River at Portland is 33,000 cfs.

TRANSPORT MECHANICS

The two basic types of sediment transport of concern in this report are suspended and bedload. These two transport mechanisms occur in all three reaches of the study area; however, the hydraulic forces that drive sediment transport differ significantly between the river and the ocean. For that reason the important components of riverine and ocean transport are described separately in the following text.

Riverine Suspended Sediment

Suspended sediment is sand, silt, and clay transported within the water column. Buoyancy and turbulence within the water column support the sediment particles. Particles are carried at near the velocity of the river current and can therefore move long distances before depositing. Suspended sediment can be divided into "wash load" and "bed sediment load" (ASCE, 1977). Wash load is composed of fine sediment found in very small quantities in the bed, while the bed sediment load is composed of the larger particle sizes which are common in the bed sediments. The summation of the wash load and bed sediment load is referred to as the total suspended sediment load.

The wash load comes from outside sources, such as tributaries and local runoff, and can stay in suspension for extended periods of time. Wash load transport tends to rise and fall with river discharge but, because it is independent of the channel's bed and hydraulic conditions, it does not necessarily have a consistent relationship to discharge. The Columbia River wash load is composed of silts and clay.

Suspended bed sediment load is generally the sand portion of the suspended sediment load. Suspended sand transport is the result of the integration of the transport potential (energy) of the water, the settling properties of the sand particles, and the available sand supply. The suspended bed sediment load may originate from outside sources, but there are also erosion/deposition interactions with the riverbed that maintain the balance between suspended bed sediment load and transport potential. Because of these interactions, sand transport is dependent on both material and hydraulic properties. Important material properties include, available supply, and grain size and shape. A variety of hydraulic parameters influence transport potential, such as discharge, depth, velocity, slope, and density (ASCE, 1977).

In rivers with alluvial beds there is usually a relationship between water discharge (Q) and suspended sand discharge (Q_{ssand}). This relationship is referred to as a sediment rating curve and generally takes the form of $Q_{ssand}=aQ^b$, where a and b are variables dependent on local river conditions. Suspended sand discharge increases very rapidly with increasing water discharge because of this exponential relationship. A sediment rating curve can be combined with streamflow data, or a flood-duration curve, to estimate sand discharges for time periods without transport measurements (USACE, 1989).

The suspended sediment concentrations in the Columbia River are quite low. Measurements taken during the spring freshet in 1922, before any large dams were built, found an average suspended sediment concentration of 130 parts per million (ppm) downstream of the Willamette River (Hickson, 1961). Measurements taken in 1959 and 1960 (USACE Portland, 1961) and in the 1980's (USGS, 1980-2000) show similar suspended sediment concentration verses river discharge relationships for the two time periods. Based on observed concentrations and appropriate flow-duration curves, the Corps estimated that the average annual suspended sediment yield at Vancouver, WA, has been reduced from 12 mcy/yr pre-regulation to only 2 mcy/yr post-regulation (USACE, 1999).

Not all size classes of suspended sediment in the Columbia River are important components of the shoaling and sediment accumulation in the study area. USGS sediment data indicates around 70-90 percent of the suspended sediment is silt or clay, materials not found in significant quantities in the riverbed, estuary, or ocean beaches. Sand is generally less than 15 percent of the suspended load, increasing to over 30 percent when the discharge exceeds 400,000 cfs, but makes up about 95 percent of all the bed material in the study area. The Corps (USACE, 1999) estimated the current average suspended bed material (sand) transport into the Columbia River is only between 0.2 and 0.6 mcy/yr.

Riverine Bedload

Bedload is the movement of sand, or larger grains rolling and bouncing along the surface of the riverbed. The current velocity near the bed is slower than that of the rest of the water column, causing the bedload particles to move slower than suspended particles. Bedload particles move intermittently and when in motion tend to cover only short distances before returning to rest. This transport behavior results in bedload rates that are generally much lower than the suspended transport rates in the same stream.

In sandy riverbeds, like the Columbia's, the bedload transport shapes the bed into a series of sand waves. These waves move downstream as sediment erodes from the upstream face, deposits in the downstream trough and is then buried by additional material eroded from the upstream face. This movement occurs in a layer only a few sand grains thick. Through this mechanism, all the individual grains in a sand wave are exposed to flow, eroded, transported, deposited, buried, and then eventually exposed again as the sand wave migrates downstream.

Bedload transport varies with discharge, but is not in general directly related to discharge. Bedload movement depends on the forces exerted on the sand particles by the flowing water to cause motion. This force can be represented by the boundary shear stress (τ_b) which is a function of the density of the water (γ), the depth of flow (d), and the energy slope (S) such that $\tau_b=\lambda dS$. Bedload occurs when τ exceeds the critical shear stress (τ_c) for the bed material and the rate increases as τ increases above that value (ASCE, 1977). The actual bedload movement within a stream varies greatly because of variations in both τ_b and τ_c, and due to the effects of turbulence along the bed.

No attempt has been made to directly measure the bedload transport of the Columbia River. However, bedload estimates have been made using two independent methods (Eriksen and Gray, 1991). An empirical equation developed by the USGS was used to estimate unmeasured load for pre- and post-regulation conditions. That equation is based on the modified Einstein equation and relates unmeasured load to river discharge (USACE Portland, 1986). Applying this equation to the pre- and post-regulation flow-duration curves resulted in bedload estimates of 1.5 mcy/yr pre-regulation and 0.2 mcy/yr post-regulation.

The second estimate was made by equating bedload transport to the movement of the sand waves present on the bed. Sequential surveys were made of two sets of sand waves, one during high flow conditions and the second during average discharge conditions. The analyses of those surveys and flow conditions resulted in bedload estimates ranging from 0.1 mcy/yr to 0.4 mcy/yr. The analysis also found that large sand waves only moved several hundred feet a year.

Ocean Transport Processes

Waves and currents are the necessary elements in transporting sediment through the entrance channel as well as north and south along the coastline. Tides cause a short-term change in the direction of sediment transport, as can be seen by the flood- and ebb-tidal shoals. As waves approach a coastline, the dissipation of the wave energy causes sediment movement. The wave direction and angle determines the direction and amount of sediment transport. A wave that approaches shore-normal will tend to cause more cross-shore transport, where an oblique wave results in a majority of alongshore transport. A more long-term sediment transport pattern is seen in a seasonal timeframe, with the dominant wave direction varying. In Moritz, et al (1999) the net littoral transport is described as to the north with significant periods toward the south, because the circulation of the inner shelf region is greatly influenced by a seasonal variation. The circulation in this region is also greatly influenced by a change in wind conditions in the alongshore direction (USACE 1999). This effect is greatly decreased as the distance offshore is increased. Moritz, et al (1999) also concluded that the response of the seabed was affected primarily by wave processes and secondarily by bottom current processes.

There are three cross-shore regions for sediment transport along the Oregon-Washington continental shelf as defined by USACE 1999. The first is the outer shelf, defined as the area in depths greater than 300 ft, that is characterized by shoaling internal waves and seasonally-modified regional currents that affect the movement of bottom sediments. The next area is the mid-shelf region, in the 120 ft to 300 ft depth range, where wind-driven waves are the most important factor for sediment transport. The area in depths less than 120 ft is called the inner shelf. Wind-driven currents, estuaring-induced currents, shelf-modified tidal currents, and shoaling wind waves and swell dominate sediment transport of bottom sediment in this area. A more detailed explanation of the sediment transport processes can be found in USACE 1999.

Ocean Currents

The continental shelf of Washington and Oregon is characterized by three seasonal current regimes, fall-winter, spring, and summer (USACE 1999). The fall-winter season, which runs from November to March, marks the onset of the Davidson Current, a northward flowing current. The Davidson current develops off the Oregon and Washington coastline in the fall due to southerly winds and becomes established in January. The spring represents the transition time between the northward flowing Davidson Current integrating into the southward flowing California current by May. The California current dominates the flow offshore of the continental shelf break, more than 20 miles offshore, to a depth of 500 ft during the summer regime. The current obtains maximum strength in the summer when winds are consistently from the north-northwest. The subsurface portion of the Davidson current is believed to flow to the north throughout the year, resulting in a net flow along the bottom towards the north. A more detailed account of the ocean currents in this region is available in USACE 1999.

SEDIMENT SOURCES

Whetten et al. (1969) characterized the Columbia River as having two principal sediment sources: the upper watershed (above the Columbia/Snake confluence) that produces fine grained sediments from surfacial deposits, and the Cascades that produce sand from the erosion of volcanic material. They concluded that under average conditions, it was likely that sediments from the two sources were transported and deposited independently, the upstream sediment as suspended load and the coarser downstream sediment as bedload. Whetten et al (1969) found that sediment was not generally accumulating in the main stem Columbia River reservoirs because sediment was being scoured from those reservoirs during high flows. The Columbia River's main stem sediment discharge into the study area would thus be composed of material from both these sources.

Potential sources of coarse-grained Cascade sediments also occur throughout the study area. Tributaries such as the Sandy and Cowlitz rivers discharge volcanic sand into the Columbia River. The Willamette River was probably a sand source in historic times, but flow regulation and channel modifications have substantially reduced its sand transport. The river, estuary, and MCR beds are large potential sand sources, especially for bedload. The coastal beaches and ocean floor are also composed of sands that are potential sources for sediment transport.

The construction of the MCR jetties caused a large amount of sediment to accrete in the littoral zone north and south of the entrance. This “wave of sand” continues to travel away from the entrance, causing accretion along the littoral cells north and south of the entrance. Approximately 67% of the suspended sediment discharged from MCR is transported to the continental shelf off Washington; about 17% of this sediment is lost to the littoral system to submarine canyons. (USACE 1999)

DEPOSITION

Sediment deposition in the study area occurs in many different forms and has a wide range of time scales. In a geologic sense, the entire study area is a deposition zone responding to thousands of years of sea level rise (Gates, 1994). But on a more immediate time scale, the most important deposition conditions include annual shoaling in the navigation channel, and deposition and accumulation of sand in the estuary and along the coast.

Shoaling in the navigation channel through the river and estuary is primarily the result of convergence of bedload transport paths and sand wave development (USACE, 1999). This process goes on continuously, but occurs more rapidly during river discharges over 300,000 cfs. This shoaling is more a redistribution of bed sediment, rather than accumulation of sediment, since it does not change the volume of material in a river reach.

Sediment deposition and accumulation has been occurring in the Columbia estuary over the past 130 years (Sherwood et al., 1984). The bays and shallow areas accumulated most of the sediment over that time. Bed material sampling done in the early 1960's (Hubbell and Glenn, 1973) indicates that sand comprised over 80 percent of the accumulated sediment. There was a higher percentage of silt in the estuary bays, but sand was still the dominant material.

Moritz, et al (1999) and USACE (1999) both describe the deposition characterization of sediments found in the vicinity of the MCR.

HUMAN ACTIONS

Dredging and Disposal

Dredging removes material from the riverbed and disposes of it somewhere else. This discussion will summarize the dredging and disposal methods used for navigation in the study area. A detailed discussion of these methods is provided in the Columbia River Channel Improvement Project Biological Assessment (USACE, 2001).

Pipeline and hopper dredges are commonly used by the Corps in the Columbia River. A pipeline dredge uses a revolving cutter head on the end of an arm that is buried 3-6 feet deep in the riverbed. Dredged material is pumped through a pipe to the disposal site. Hopper dredges pull dragheads along the riverbed and suck sediment through the draghead and into the hold of the dredge. Large pipeline or hopper dredges have the ability to move tens of thousands of cubic yards of sediment per day.

Dredged sediments can be disposed of at upland sites, along the shoreline, in-water in deeper parts of the river channel and at ocean sites. Upland disposal sites are used by pipeline dredges and can range from a few acres to over a hundred acres in size. Upland sites generally have containment dikes and holding ponds to retain the sediments. Sediment placed in upland sites may be permanently stored at the site, or it may be removed and put to beneficial use.

Shoreline disposal along the river is done by pumping sediment directly onto a beach. The sand quickly deposits on the beach, and the water and fine sediments are allowed to return to the river. Bulldozers are then used to distribute the material along the beach, typically building river beaches out 100-150 feet. In the past, this method of disposal has been used to fill within pile dike fields. "Beach nourishment" is the use of shoreline disposal to replace beach material eroded by the currents and/or waves, and is the only type of shoreline disposal remaining in use on the Columbia River.

In-water disposal is the placement of material back into the river. In the Columbia River the most common practice is flowlane disposal. Flowlane disposal is in-water disposal within or adjacent to the navigation channel. For the 40-ft channel, flowlane disposal sites may be at depths between 35 and 65 feet deep, but are typically greater than 50 feet deep and downstream of the dredging site. Occasionally disposal depths exceed 65 feet, but only in previously agreed upon locations. Flowlane disposal is distributed along the riverbed to avoid creating mounds. These flowlane disposal practices minimize the amount of material that can return to the dredging area and also minimize the disruption to the natural downstream movement of sand.

Flow Control Structures

Pile dike fields, dredged material disposal, and stone jetties have been used in the past to construct flow control structures to improve navigation and manage sedimentation in the study area. Pile dikes and disposal have been used along the river and estuary reaches. Stone jetties were built at the MCR.

Pile dikes are rows of wooden piling constructed out into the river. There are 256 pile dikes in the study area. Pile dikes were usually built in "fields", a series of dikes spaced 1,200-1,500 feet apart, which run along the shoreline for up to four miles. When built, the two main purposes for the pile dike fields were; 1) to concentrate flow in the main channel to cause scour, and 2) to stabilize the channel and banks (Hickson, 1961 and USACE, 1987).

Flow velocities are reduced at and downstream of the pile dikes, causing more flow in the center of the channel. This reduces the sediment transport potential along the shore and increases it in the channel. Dredged material has been placed within many of the dike fields, completely eliminating the flow area and further increasing the flow in the channel. Most of the disposal material placed within pile dike fields remains in place today. Pile dikes and disposal have also been used to reduce flow into side channels and alter the alignment of the river channel.

Flow is restricted to the channel between the stone jetties at the MCR. This has caused scour in the entrance and stabilized the location of the entrance channel. The jetties also protect the entrance channel and lower estuary from large storm waves.

Flow Regulation

Many reservoirs have been built on the Columbia River and its tributaries upstream of the study area. These reservoirs provide flood control, hydropower, navigation, and irrigation water. River and sediment discharges in the study area have been permanently altered by flow regulation from those upstream reservoirs. Reservoirs upstream of the study area store water during the spring snowmelt, reducing the freshet discharges. The reduced discharges have caused large reductions in sediment transport during the spring freshet (USACE, 1999). The stored water is released during the fall and winter to increase hydroelectric power generation. Those releases cause little increase in sediment transport because the river discharges remain below critical levels.

TIMING

The timing of sedimentation processes is an important factor in how the various processes interact. The combined affect of coincident events may be much greater than the sum of the individual affects of independent events. Sedimentation processes in the study area are influenced by both natural events and human actions that range from a few hours in duration up to tens of years. Natural events include spring snowmelt freshets, large winter storms, and ocean tides. Human actions involve flow regulation, jetties, dredging and disposal, and pile dike fields.

Sedimentation in the study area is largely driven by the Columbia's hydrologic cycle. The majority of the river's sediment transport typically occurs in May and June, during the spring freshet. Infrequent (on average, less than once every ten years) winter floods can also transport high concentrations of sediment, however their sediment volumes are smaller because the flood duration may be only a few days. The Columbia's hydrology is affected by global climate events, such as El Nino/La Nina events (NOAA, 2002) and the Pacific Decadal Oscillation (Joint Institute for the Study of the Atmosphere and Ocean (JISAO), 2002), that have durations of a few years and tens of years, respectively. Jay and Naik (2000) explain the interaction between these climate cycles and how they affect sediment transport in the Columbia River.

River and sediment discharges in the study area have been permanently altered by flow regulation from upstream reservoirs. Reservoirs upstream of the study area store water during the spring snowmelt, reducing the freshet discharges. The reduced discharges have caused large reductions in sediment transport during the spring freshet (USACE, 1999). The stored water is released during the fall and winter to increase hydroelectric power generation. Those releases cause little increase in sediment transport because the river discharges remain below critical levels. Hydroelectric power releases also cause relatively minor hourly river discharge fluctuations that do not alter sedimentation.

Dredging to construct the proposed 43-ft channel would occur on a year round schedule for two years. Maintenance dredging would occur annually for the life of the project. Maintenance dredging is typically done in the May through October time period, with most work done during the summer when sediment transport is low. Dredging at any one location might range from a few days at small shoals in the river, up to a month or more at the large river shoals. Due to hazardous conditions, MCR maintenance dredging is performed in the summer.

SEDIMENT BUDGET

A sediment budget provides an accounting of sediment volumes in time and space. It can be used to help define sediment processes, detect sediment trends, identify impacts of individual events, and predict impacts of future events. Sediment budget data for the Columbia River channel, estuary, MCR, and coast were compiled from existing sources are presented in this section. The sediment budget will be used to examine questions such as; what is the net transport of sediment through the MCR, what are the long-term sediment trends, and what was the impact of jetty construction and flow regulation on sediment transport?

The usefulness of any sediment budget depends on the refinement of the available data. In the case of the Columbia River system, the available timeframes and locations for bed volume changes in the river, estuary, and ocean limit the sediment budget. There are bathymetric surveys of the river, estuary, and ocean available from the 1800's to the present (USACE, 2002). In the estuary, bathymetric differences have been mapped for 1868-1935, 1935-1958, and 1958-1982 (CREDDP, 1983), but because of differences in survey coverage, volume differences are only available for the first two time periods (Sherwood, et al, 1984). In the near- and offshore areas, bathymetric differences have been calculated for the periods 1868-1926, 1926-1958, and 1958-1999 (Gelfenbaum 2002). However, there are no bathymetric difference studies for the Columbia River upstream of RM 48. Columbia River suspended sediment loads have been estimated for the period 1878 to 1999 (Sherwood et al, 1990 and Bottom et al, 2001). Detailed records of dredging volumes are available for the MCR and river navigation channels from 1890 to 2001 (USACE, 2002). The Corps also has limited information available on the placement of dredged material disposal.

River flows and sedimentation processes have varied greatly over geologic time due to both long- and short-term events. Long-term events include glaciation, and the subsequent Missoula floods and rising sea levels. Short-term events that intensified sedimentation processes included very large floods, subduction earthquakes, landslides, and volcanic eruptions. These natural events probably had sediment impacts on the order of tens- to hundreds-of-millions of cubic yards, or in the case of the Missoula floods, unimaginable impacts. These catastrophic events are rare and unique, and will not be addressed in this report.

The focus of this report will be the last 130 years and in particular the past 115 years when human activities have had an influence on natural sedimentation processes. Major actions have included; construction of jetties at the mouth of the river, diking and filling of wetlands for urban and agricultural uses, development and maintenance of the deep-draft navigation channel from Portland/Vancouver to the Pacific Ocean, and development of a series of multi-purpose reservoirs that regulate river discharges.

GEOLOGICAL BACKGROUND

Long-term geologic processes have established the foundation for today's Columbia River river-estuary-coastal sediment system. The accumulation rate along the Columbia River Valley has decreased from 11 mcy/yr prior to 7,000 years ago, to about 5 mcy/yr, in the last 7,000 years. This indicates the total sediment accumulation volume in the lower Columbia River valley during the last 10,000 years is around 66,000 mcy (Gelfenbaum and Kaminsky, 2000).

The long-term accumulation rate for the past 10,000 years on the ocean shelf is 8.5 mcy/year. An additional 49,000 mcy of Columbia River sediment that has accumulated on the continental slopes, canyons, and fans off Washington and Oregon in the last 5,000 years (9.7 mcy/yr) (Gelfenbaum and Kaminsky, 2000). Grays Harbor and Willapa Bay have also been sinks for Columbia River sediment. Grays Harbor's accumulation rate has decreased from 0.8 mcy/yr 7,000 years ago to 0.26 mcy/yr in the last 5,000 years for a total volume of 5,800 mcy. The volume of sediment accumulation in Willapa Bay has not yet been calculated, however, the basin is about half the size of Grays Harbor, so the estimated accumulated volume is about 2,900 mcy. Accumulation rates for littoral sub-cells north and south of MCR are: Long Beach = 0.51 mcy/yr and Clatsop = 0.43 mcy/yr. The similarities between the accumulation rates north and south of MCR suggest that the net sediment transport direction is not an easy question to answer. The total accumulation of Columbia River sand for all the coastal sub-cells adjacent to MCR for the past 10,000 years is 5,300 mcy.

RIVER AND ESTUARY SEDIMENT BUDGET

A complete, indisputable sediment budget for the Columbia River and estuary is unattainable, but most of the important components can be delineated. The annual sediment transport rates and dredging volumes are the two components that can be best defined. The fate of dredged material is less well defined because of incomplete disposal records. Dredging, disposal, and natural processes have altered the river and estuary bathymetry, but only in the estuary have those changes been documented and quantified.

Sediment transport measurements have only been taken sporadically in the Columbia River. Sherwood et al. (1990) cited U.S. Geological Survey (USGS) work done in 1910-12 and 1964-70. The Corps collected a few samples in 1922 (Hickson, 1930) and conducted a field study in 1959-60 (USACE, 1961). In recent years the USGS has collected occasional measurements at Warrendale (RM 140) and Beaver (RM 55), Oregon (USGS, 1980-2000). Sherwood et al (1990) used 1964-70 USGS suspended sediment data collected at Vancouver, Washington (RM 106), USGS streamflow measurements at The Dalles (1878-1985), and empirical equations to hindcast annual total sediment and total (suspended plus bedload) sand transport for the period 1878 to 1985. Bottom et al. (2001) extended the annual total sediment discharge estimate to 1999. Unless otherwise noted, the sediment transport volumes used in this report have been derived from those two studies. (A correlation of sand/total sediment volumes from

Sherwood et al. (1990) was used to estimate sand transport from the total sediment reported by Bottom et al. (2001).) Figure 2 shows the resulting annual Columbia River sand transport hindcast for 1878-1999.

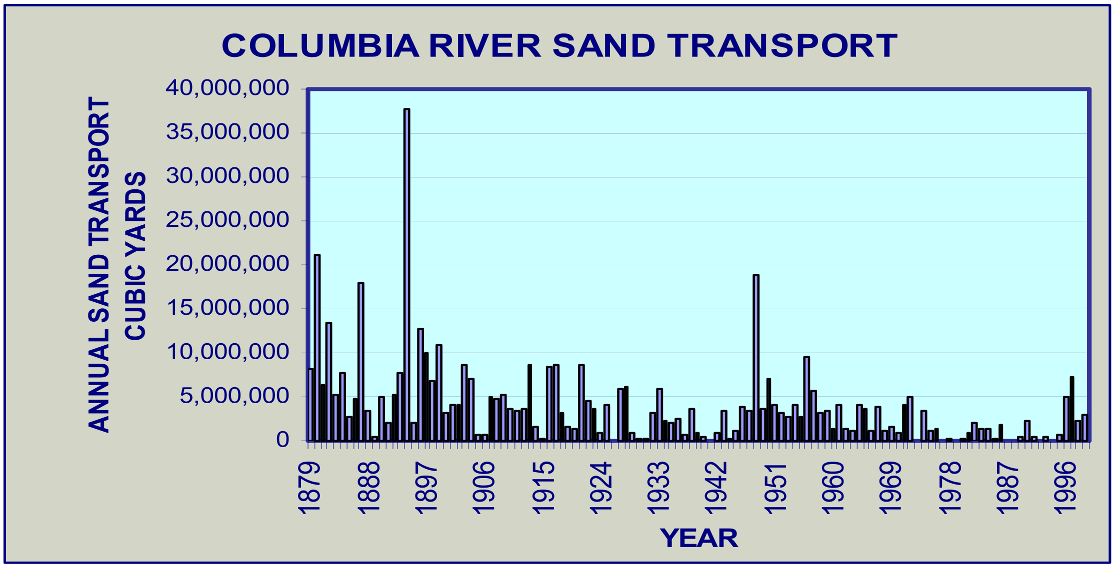


Figure 2. Columbia River total sand transport at Vancouver, Washington, upstream of the Willamette River. Derived from Sherwood et al. (1990) and Bottom et al. (2001).

While the exactness of this sand transport hindcast is limited by the available water and sediment discharge data, Bottom et al. (2001) indicate that the sand transport is nearly as accurate as the water discharge data. This is because the Columbia River has an abundant sand supply in the riverbed and sand transport is only limited by the river's transport capacity. The affects of extended periods of high river discharges on sand transport can be seen in the high transport rates in 1880, 1887, 1894, and 1948. The large winter floods of 1964 and 1996 produced high daily transport rates, but were of limited duration and did not result in high annual sand transport quantities. Sand transport from those floods may be underestimated because much of the 1964 and 1996 flood discharges came from tributary streams not included in the discharge data from The Dalles.

Sediment inflows from tributary streams, such as the Willamette, Sandy, and Cowlitz rivers, are generally unavailable. It is likely that these streams contribute only minor amounts of sand directly to the navigation channel except during very large winter storms and following the eruption of Mount St. Helens (USACE, 1985). The Willamette River's average annual suspended sediment load is estimated to be 1.7 mcy per year. Less than 20 percent, or about 0.3 mcy per year, of that material is sand and the rest is silt or clay.

The eruption of Mount St. Helen's produced extremely high levels of suspended sediment in the Toutle and Cowlitz Rivers between 1980 and 1987. From 1982 through 1987 the Cowlitz River delivered 40 mcy of sand to the Columbia River. Toutle and Cowlitz

Rivers' sediment yield dropped significantly since the completion of the Toutle River Sediment Retention Structure in 1987. The current average sand yield from the Cowlitz River is estimated to be less than one mcy per year.

Navigation channel dredging records are available from 1890 to the present (USACE, 2002). Those records indicate that 680 mcy of sediment has been dredged from the river and estuary (RM 3-106) between 1900 and 1999. Figure 3 compares those annual dredging volumes to the river's annual sand transport volumes. Dredging has exceeded sand transport in all but seven years since 1910, and four of those years were prior to completion of the 35-ft channel.

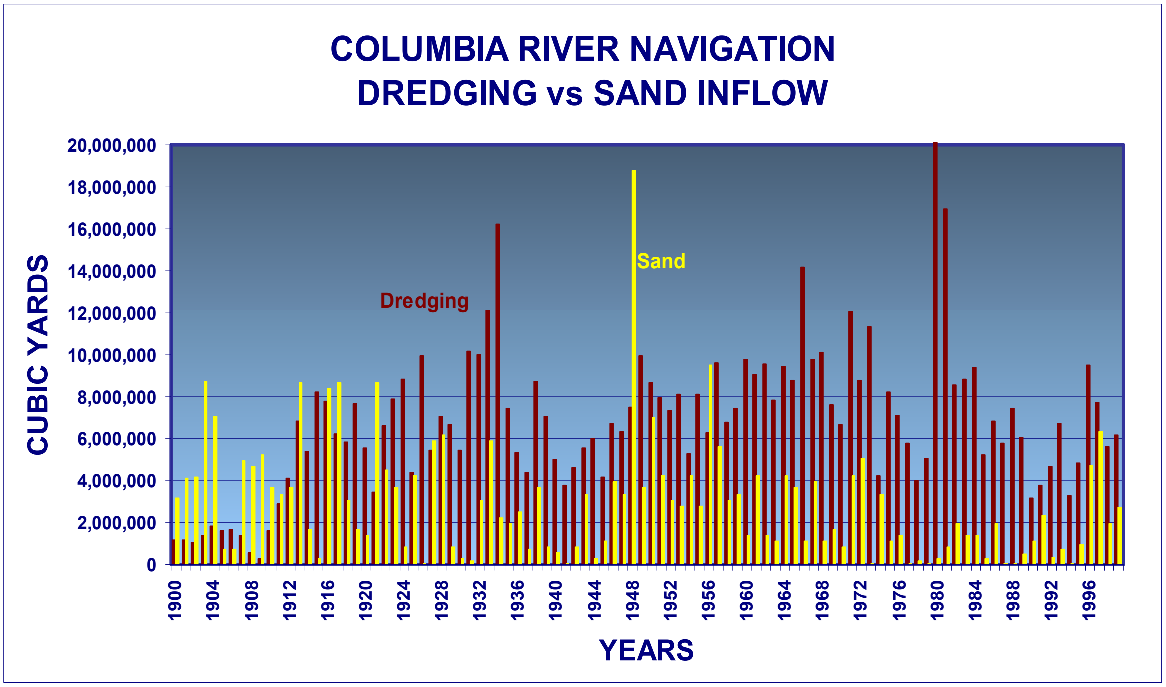


Figure 3. Comparison of dredging and sand transport in the Columbia River.

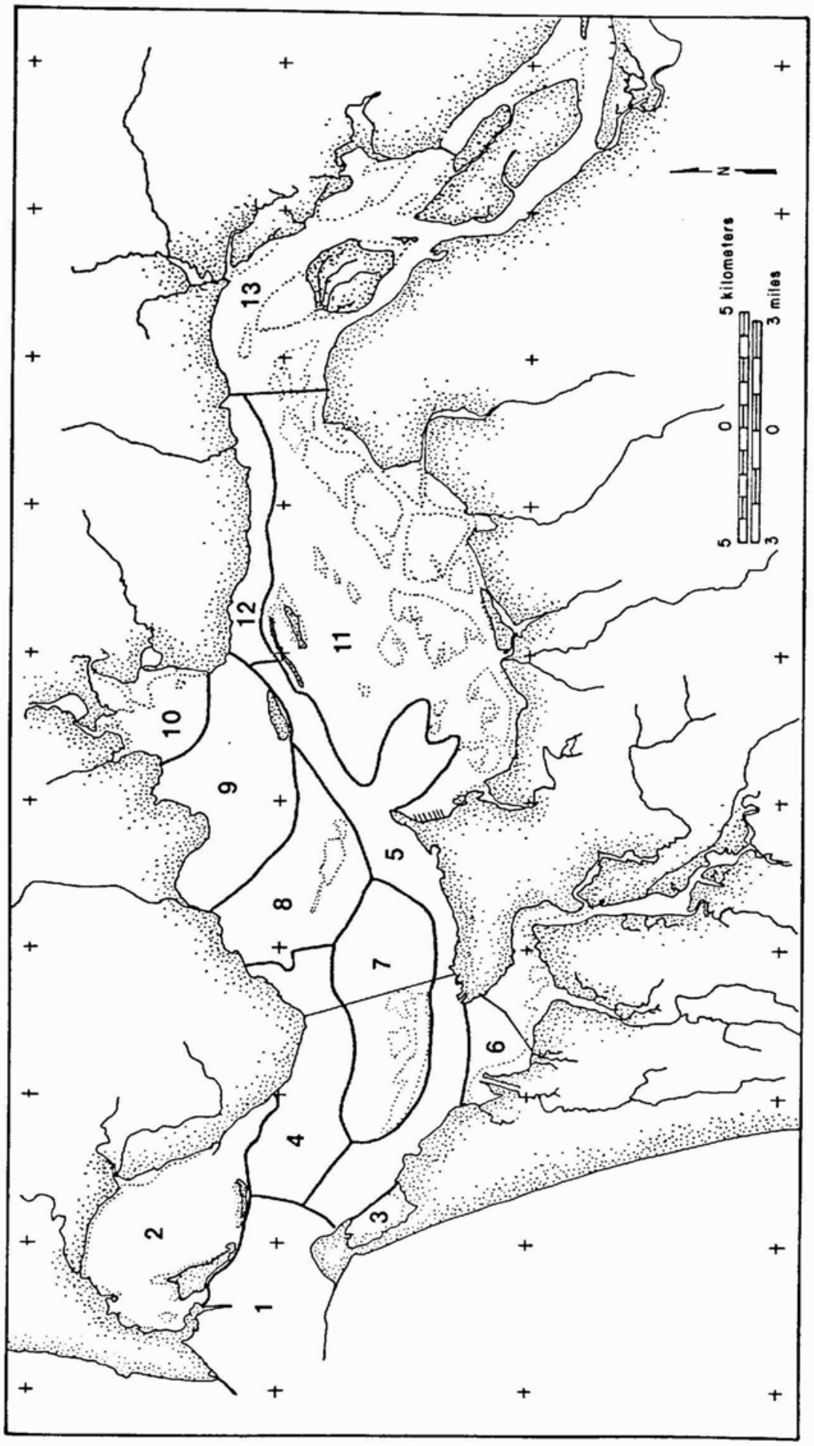
The dredging records identify the location, volume, and type of dredge used for each action. Table 1 summarizes the dredging volumes for four reaches in the river and estuary for the time periods of interest in this report. Unfortunately, the disposal locations were not as carefully recorded and most are not available. It is known that downstream of Puget Island (RM 40), most disposal has been in-water, because most of the dredging has been done by hopper dredges. The only significant removal of sand downstream of RM 40 has been at the Miller Sands-Pillar Rock reach (RM's 21-28) where about 22 mcy of sand has been placed on three islands. About 5 mcy of the island disposal occurred in 1934-35 and the remainder has been since 1970. Dredging upstream of RM 40 has been by a combination of hopper and pipeline dredges, with in-water, shoreline, and upland disposal being used. Shoreline and upland disposal sites can be identified from historical aerial photographs and bathymetric surveys (USACE, 2002). Even in this upstream reach it is likely that more than half of the disposal has been placed directly in-water, or has eroded from shoreline disposal sites and returned to the active river.

Table 1. Columbia River Dredging and Sediment Transport in MCY.

DREDGING REACH	1868-1926	1927-1958	1959-1978	1979-1999	1900-1999
South Channel (RM 6-23)	31	52	41	29	153
Lower River Channel (RM 23-31)	6	19	11	12	48
Upper River Channel (RM 31-48)	12	21	26	32	91
Main River Channel upstream of RM 48	69	143	93	83	388
Total River Dredging	118	235	172	156	680
Sand Transport	355	113	43	30	541
Total Sediment Transport	710	290	130	113	1243

Sand and total sediment transport volumes are based on Sherwood et al. (1990) and Bottom et al. (2001).

Navigation channel construction and maintenance has altered the Columbia's riverbed. The river has been deepened, narrowed, and re-aligned by dredging, disposal, and pile dike fields. The changes have been greatest upstream of Puget Island (RM 40) and smallest in the estuary. These changes can be seen in aerial photographs and bathymetric surveys of the river taken over the past 100 years (USACE, 2002), but the riverbed volume changes have only been documented for the river and estuary downstream of RM 48. Sherwood et al. (1984) calculated volume changes for the time periods 1868-1935, 1935-1958, and 1868-1958, for the estuary and river reaches shown on Figure 4. Table 2 presents their results and shows that the largest volume changes occurred in the estuary's bays and shallow flats. Volume changes in the main channels were relatively small. The 67 years of the first period encompasses a number of important natural and human actions, such as the shift of the north channel out of Baker Bay prior to 1885 (USACE, 1938), construction of the MCR jetties (1885-1917), and construction of the 25-ft (1910-1911), 30-ft (1915-1919) and 35-ft (1934-1935) navigation channels.



Map of the Columbia River Estuary showing 13 subareas used in volume and area calculations: 1) Entrance, 2) Baker Bay, 3) Trestle Bay, 4) North Channel, 5) South Channel, 6) Youngs Bay, 7) Desdemona Sands, 8) Mid-Estuary Shoals, 9) Grays Bay, 10) Brix Bay, 11) Cathlamet Bay, 12) Lower River Channel, 13) Upper River Channel.

Figure 4. Map of Columbia River Estuary sub-areas from Sherwood et al., 1984.

Table 2. Columbia River Estuary Shoaling and Erosion Rates

ESTUARY SUBAREA	1958 Surface Area in Acres	1868-1935 Volume Change in MCY	1935-1958 Volume Change in MCY	1868-1958 Volume Change in MCY
Baker Bay	14,700	119.6	-6.3	113.3
North Channel (RM 6-14)	8,200	-4.5	-7.4	-11.9
Trestle Bay	1,500	11.9	5.2	17.1
Youngs Bay	9,900	41.4	5.1	46.5
Desdemona Sands	8,500	60.4	17.0	77.4
Mid-Estuary Shoals	6,700	1.7	-0.4	1.3
Brix Bay	10,900	8.1	-0.8	7.4
Grays Bay	8,300	30.4	-5.3	25.2
Cathlamet Bay	35,300	64.9	35.3	100.3
South Channel (RM 6-23)	17,100	-13.1	23.2	10.1
Lower River Channel (RM 23-31)	7,300	-9.4	1.2	-8.2
Upper River Channel (RM 31-48)	16,600	25.4	10.8	36.3
ESTUARY TOTALS	145,000	336.9	77.8	414.7

From Sherwood, et al, 1984.

The CREDDP bathymetric maps (1983) show the sediment accumulations in the bays and shallow flats of the estuary that are the net results of processes that include the gradual accumulation of sediments on flats, shifting channels, and the filling and abandonment of large channels. Deposition in the 1868 river channel through Baker Bay accounts for a third of the total estuary sediment accumulation between 1868 and 1935. Baker Bay became a minor source of sand in the 1935-58 time period. Desdemona Sands experienced sand accumulation in both periods, but switched from a pattern of shifting channels prior to 1935, to one of gradual accumulation that continued up to 1982. Cathlamet Bay experienced a steady accumulation of sand, which was the result of continuously shifting of channels and gradual accumulation on the shallow flats. The changes in the main north and south channels are generally the net results of shifting channels with intermittent areas of erosion and deposition. Bed elevation changes of up to plus or minus 30-ft were fairly common in those channels over the 67-year period between 1868 and 1935. Sherwood et al. (1984) estimated that at the observed rates of sediment accumulation, the estuary would fill in 800 years, but that it would take over 7,700 years to fill the estuary and the MCR.

Table 3 presents a summary of the Columbia River and estuary sediment budget. The timeframes and volume changes in the estuary on this table are those of Sherwood et al.

(1990). The table shows that the volume changes in the main channel downstream of RM 31 are much smaller than the corresponding navigation channel dredging volumes. This is a result of using hopper dredges and in-water disposal, as this would just redistribute sand within the river channel and have little impact to the net volume of sediment in a reach. The north channel had a net loss of material during both time periods, even though it likely received a portion of the in-water disposal from dredging downstream of RM 14.

Table 3. Sediment budget summary for the Columbia River and estuary. Positive values indicate accumulation of sediment.

AREA	1868-1935		1935-1958		1868-1958	
	Volume Change in MCY	Dredging Volumes in MCY(1)	Volume Change in MCY	Dredging Volumes in MCY	Volume Change in MCY	Dredging Volumes in MCY
Estuary bays and shallow flats	339	(2)	50	(2)	389	(2)
North Channel (RM 6-14)	-5	0	-7	0	-12	0
South Channel (RM 6-23)	-13	50(3)	23	33(3)	10	83(3)
Lower River Channel (RM 23-31)	-9	17(3)	1	8(3)	-8	25(3)
Upper River Channel (RM 31-48)	25	19(3)	11	14(3)	36	33(3)
River Channel upstream of RM 48	N/A	113	*-140*(4)	99	N/A	212
Total Sand Transport	380		88		468	
Total Sediment Transport	800		200		1,000	

1 Only minor amounts of dredging occurred before 1900 when the 25-ft channel construction began.

2 Insignificant dredging volumes in small side channels.

3 All dredging downstream of Puget Island (RM 40) was done by hopper dredges with in-water disposal except for 5.5 mcy of pipeline dredging at Miller Sands in 1934-35.

4 This is a rough estimate of erosion outside the navigation channel between 1920 and 1960 (Hickson, 1961). It covers the entire study area, including the reach from Vancouver to Bonneville Dam, but it is estimated that most of the change occurred between RM's 48 and 106. It does not account for shoreline fills created with disposal material that would probably offset much of the volume lost.

Sand Discharge to the MCR

The final component of a sediment budget for the river and estuary is the sediment discharge, and more importantly the sand discharge, to the MCR. This has been a critical unknown in the sedimentation analysis of the Columbia River and coastal systems.

Given the available data, the sand discharge to the MCR cannot be calculated with a high degree of certainty, but reasonable estimates of total sand discharge can be made for the 1868-1926 and 1927-58 time periods.

One necessary hypothesis for estimating the sediment discharge to the MCR is the sand behavior in the river upstream of RM 48. This reach could be a sand source, a sink for inflowing sand, or simply a sand transport reach. The detailed data on riverbed volume changes, sand transport rates and disposal placement, necessary to calculate the sand behavior in this reach does not exist. It is therefore necessary to draw conclusions about sediment processes from theory and the limited data that is available.

As Table 3 shows, the only estimate of river channel volume changes is Hickson's (1961) 140-mcy of erosion between Bonneville and the estuary, between 1920 and 1960. Hickson explained this 140-mcy loss (an average of 3.5 mcy per year for 40 years) as erosion caused by the construction of pile dike fields along the navigation channel. He also concluded that because there were no apparent increases in estuary dredging, this material was discharged to the ocean. Hickson's conclusion that the 140 mcy was discharged to the ocean is probably wrong. To transport that volume of sand to the ocean would have required a doubling of the river's sand transport rates and a nearly ten-fold increase in sand discharge from the estuary to the ocean, based on the rates calculated by Sherwood et al. (1990) for this time period. While sand transport rates may have increased locally around the pile dike fields, it is very unlikely that there would have been any overall increase in transport capacity in the relatively unaltered reaches of the lower river or estuary. Also as Tables 3, 4, and 5 show, there was not a large increase in estuary or ocean deposition between 1926-58 as would be expected from such a large inflow of sand. Therefore, it is very unlikely that this sand was actually eroded from the river and transported through the estuary to ocean.

Based on the Corps' latest analysis of navigation channel shoaling processes (USACE, 1999), and an examination of disposal practices and channel changes, it appears that the 140 mcy was dredged from the river and disposed of along the shorelines. The pile dike fields would have cause sand to have been transported into the adjacent navigation channel as bedload, causing shoaling that was then dredged and disposed of along the shoreline within those same pile dike fields. The riverbed's adjustment to the pile dike fields and the progressively deeper navigation channels would have been comparable to the side-slope adjustments expected to follow the proposed 43-ft channel deepening (USACE, 1999 and 2001). The side-slope adjustment occurs because bedload movement, which is generally directed downstream, has a small displacement towards deeper water caused by the side-slopes of the riverbed. The steep side-slopes of the dredge cuts cause bedload to be deflected into the channel, forming new shoals. Over a period of years this action would cause the side-slope adjacent to a dredge cut to degrade until an equilibrium slope is re-established. This side-slope adjustment often produces very flat slopes that extend from the navigation channel to the riverward end of the pile dike fields. The estimated 140-mcy of material removed from the riverbed is compatible with the 205 mcy of dredging that occurred between RM's 40 and 105, during that same time period.

Disposal within the pile dike fields was a common practice during that time. For these reasons, it is concluded that the 140 mcy was not transported to the ocean, but actually migrated into the navigation channel and was then removed by dredging. This indicates that the riverbed upstream of RM 48 was not a net supplier of sand to the estuary or ocean.

While the lower Columbia River has been a sand sink in past geologic times (Gates, 1994), there are no indications that it has been a significant sink during the last 100 years. It would be expected that the natural river would have been at or near a state of dynamic equilibrium (sand inflow equals sand outflow, with a balance between erosion and deposition) until it reached the depositional environment of the estuary. Sherwood et al. (1990), Bottom et al. (2001), Whetten et al. (1969), and Hickson, (1961) use river sand transport and sand delivery to the estuary as interchangeable values. The Corps' shoaling analysis also supports a conclusion of dynamic equilibrium. Navigation channel shoaling was found to be the result of bedload processes that redistribute sand already present in the riverbed and not from deposition of inflowing sand (USACE, 1999). Thus, the river upstream of RM 48 will be treated as a sand transport reach, with no net change in transport volumes.

After setting the sand transport estimates by Sherwood et al. (1990) and Bottom et al. (2001) shown in Figure 2 as the delivery to RM 48, the next step in estimating the sand discharge to the MCR is to determine how much sand was deposited or eroded between RM 48 and the MCR during each time period. The resulting total net sand volume changes would then be combined with the sand inflows from the river to determine the sand discharges to the MCR.

To provide consistent time period comparisons, the estuary sub-area volume changes in Table 2 were adjusted to match time periods used for the MCR and coastal volume changes reported in Gelfenbaum et al. (2002). This adjustment was made for each sub-area by using the average annual volume change for 1935-1958 to calculate a volume change for 1926-35. For each sub-area, the 1926-1935 volume changes were subtracted from the 1868-1935 volume changes to arrive at 1868-1926 volume changes and added to the 1935-58 volume changes to arrive at 1926-58 volume changes. This method was chosen because the 1935-58 river and estuary conditions more closely resemble the 1926-35 conditions than do the 1868-1935 conditions. This is especially true of the pre-1900 conditions, which are remarkably different than the 1926-35 conditions.

The bed material gradations measured by Hubbell and Glenn (1973) were then applied to the appropriate sub-area volume changes to calculate the fine sediment and sand volume changes in each sub-area that are shown in Table 4. The volume changes from all the sub-areas were then totaled for each material size class to arrive at the total net volume change for both fine sediments and sand. The total net volume changes for 1868-1926 and 1926-58 were subtracted from the corresponding sediment inflows to get the sediment discharges to the MCR for both fine sediment and sand. As shown in Table 4, these calculations determined net sand discharges from the estuary into the MCR inlet of 138 mcy for 1868-1926 and 17 mcy for 1926-58.

The average annual rates of sand inflow, accumulation, and discharge all declined from the first to second time period. However, the relative proportion of deposition to river sand entering the estuary was higher in the 1926-58 period, 85% verses 61%. The sand discharges of 138 mcy between 1868 and 1926 and 17 mcy between 1926 and 1958 should not be viewed as uniform average annual sand discharges of about 2- and 0.5-mcy per year, respectively. The sand discharges from the estuary to the MCR are probably driven by high river discharges just like the river's sand transport. Sherwood et al. (1990) suggest that the largest freshets discharged more sand to the MCR than they transported into the estuary from upstream. The sand discharges would thus follow an annual pattern similar to that shown in Figure 2 for the river's sand transport, with most sand discharge to the MCR occurring during just a few high streamflow years.

Table 4. Columbia River Estuary and Lower River Shoaling and Erosion Rates

ESTUARY SUBAREA	Volume Change in MCY					
	1868-1929			1927-1958		
	Total	Fines	Sand	Total	Fines	Sand
Baker Bay	122.2	61.1	61.1	-8.9	-4.4	-4.4
North Channel(RM 6-14	-1.4	0.0	-1.3	-10.5	0.0	-10.3
Youngs Bay	39.2	5.1	34.1	7.2	0.9	6.3
Desdemona Sands	53.4	0.5	52.8	24.1	0.2	23.8
Mid-Estuary Shoals	1.8	0.0	1.8	-0.5	0.0	-0.5
Brix Bay	8.4	0.1	8.4	-1.1	0.0	-1.1
Grays Bay	32.6	0.3	32.3	-7.5	-0.1	-7.4
Cathlemet Bay	50.2	10.5	39.7	50.1	10.5	39.6
South Channel (RM 6-23)	-22.8	-0.2	-22.5	32.9	0.3	32.6
Lower River Channel (RM 23-31)	-9.8	-0.1	-9.7	1.6	0.0	1.6
Upper River Channel (RM 31-48)	20.9	0.2	20.7	15.4	0.2	15.5
Estuary Totals	304.5	77.6	217.2	110.2	7.7	95.7
Sediment Inflow from Upstream in MCY		355	355		177	113
Deposition as a Percent of Sediment Inflow		22%	61%		4%	85%
Sediment discharge to the MCR in MCY		277	138		169	17

The above sand discharges to the MCR are net values. They do not give any indication of the magnitude of the interactions between the river, estuary, and littoral sand systems. It can not be determined if the sand being discharged flowed continuously through the river and estuary, or if it had once deposited and was later scoured from somewhere in the estuary. There probably was sand inflow to the estuary from the MCR during these time periods, especially into Baker Bay prior to jetty construction. However, the volumes of sand inflow from the MCR cannot be specifically determined from the available data. If the volume of sand inflow from the MCR could be defined, the sand discharge to the

MCR would increase by an equal amount to maintain the sediment budget balance and the calculated net sand discharges to the MCR would be unchanged.

MCR SEDIMENT BUDGET

In 1868, prior to jetty construction, at least two channels existed through MCR, with an average depth over the ebb tidal delta about 25 ft (USACE 1999). The location of the channels varied from year to year. As can be seen in Figure 5, Peacock Spit, Clatsop Spit, Sand Island, and what was once called Middle Sands, were very dynamic prior to the construction period. Prior to construction of the jetties, the ebb-tidal delta off MCR was over 6 miles wide located close to MCR in very shallow water. After jetty construction, the ebb-tidal delta moved more than 10,000 ft offshore from MCR into deeper water (USACE 1999). The MCR jetties were built to maintain a single, stable navigation channel. The south jetty was initially built to stabilize Clatsop Spit, but Peacock Spit still meandered into the channel, as can be seen in Figure 6, so the north jetty was authorized. Jetty A, inside the channel was then built to keep the channel from migrating too far to the north.

Prior to jetty construction, there was more accumulation found on the south beaches than the beaches to the north of MCR. After construction, during the 1926-1950s period, Clatsop Spit began to erode, Peacock Spit accreted at a slower rate than immediately post-construction, and the southern portion of the Long Beach sub-cell prograded rapidly. Accretion rates within the entire littoral cell generally slowed after the 1926-1950s period, as did erosion rates in some areas.

Preliminary modeling results indicate that the areas near the jetties have the highest sediment transport rate (Gelfenbaum and Kaminsky, 2000). There is also an indication that some of the sand-sized sediment within the estuary may have been transported through MCR from adjacent nearshore and shelf regions of the Oregon and Washington coasts.

GeoSea Consulting Ltd. performed a Sediment Trend Analysis (STA) and Acoustic Bottom Classification (ABC) (GeoSea 2001) to develop sediment transport patterns related to grain-size distributions. The net transport pathways derived from over 1200 sediment samples can be seen in Figure 7. The flow pattern shows a definite separation between the river sediment transport and the transport within the entrance channel and along the coastline. There is one accretion pattern that shows sediment moving from the estuary towards the north jetty. The rest of the sediment flowing from the estuary appears to flow into Baker Bay and then flow back through a north channel into the estuary.

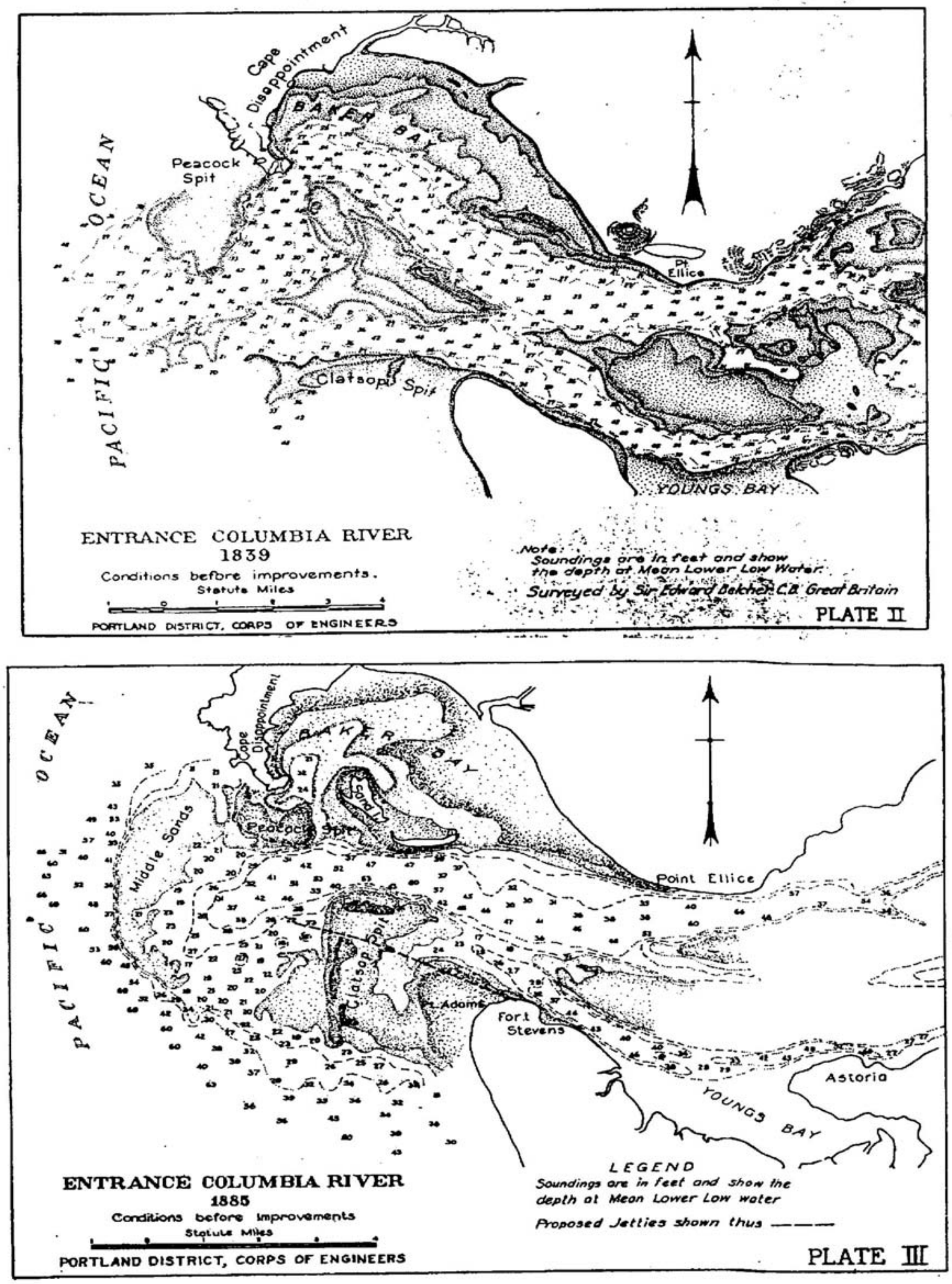


Figure 5. Historical view of MCR prior to jetty construction. MCR was constantly changing prior to improvement. In 1839, a spit, Middle Sands, is present in the middle of the entrance. The south jetty was initially built to stop Clatosop Spit from entering the channel, as seen in 1885.

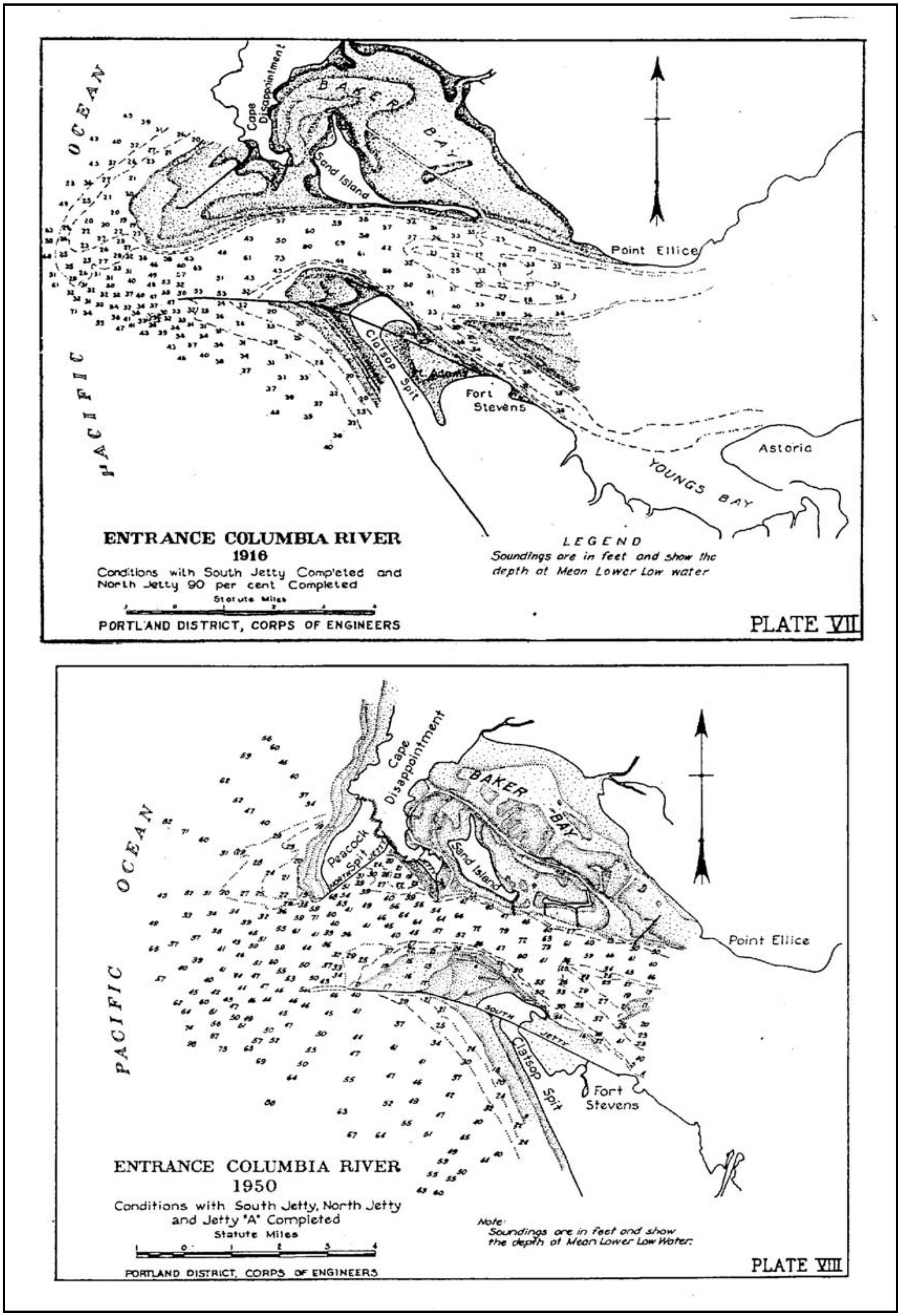


Figure 6. Historical view of MCR after jetty construction. The development of beaches adjacent to both jetties can be seen in 1950.

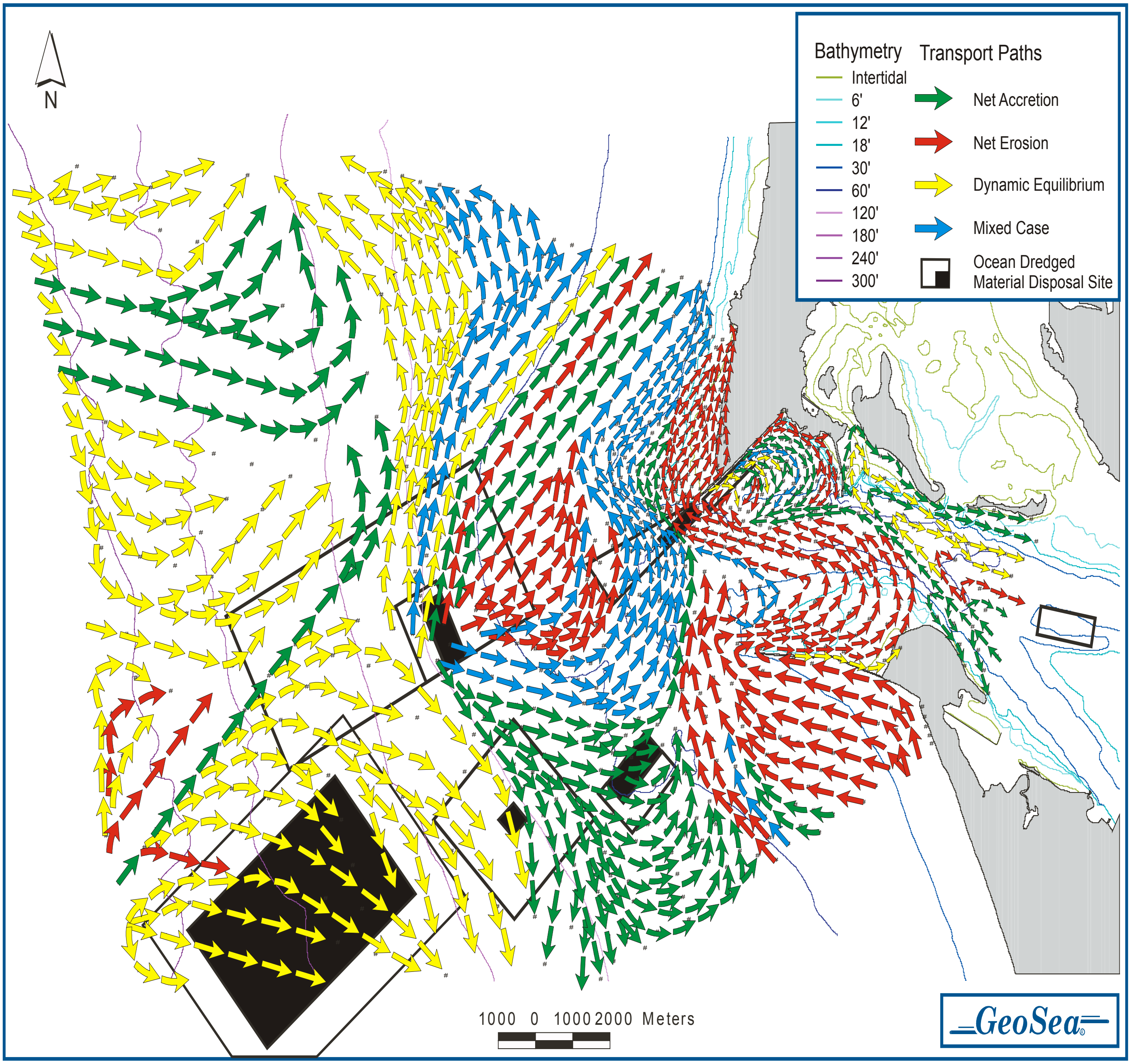


Figure 7 Sediment transport around MCR. From GeoSea, 2001.

Buijsman, et al (2002) made some conclusions based on a study of the volumetric changes within the CRLC (Figure 8). He concluded that sand that eroded from the MCR inlet and inner delta, moved offshore and northward to supply sand to the outer delta and northern beaches. Eroded sand from the south side of the Columbia River delta and shelf along Clatsop Plains was the source of accreted sand to the beach-dune complex of Clatsop Plains and the Columbia River outer delta. Between 1868 and 1928, Long Beach and Clatsop Plains both steepened, due to erosion offshore and accretion in the nearshore. Table 5 shows the overall volume change calculations from Gelfenbaum, et al (2001). There are large uncertainties in the numbers due to vertical datum changes, tide corrections, horizontal errors in historical shoreline positions, and vertical errors in the DEM.

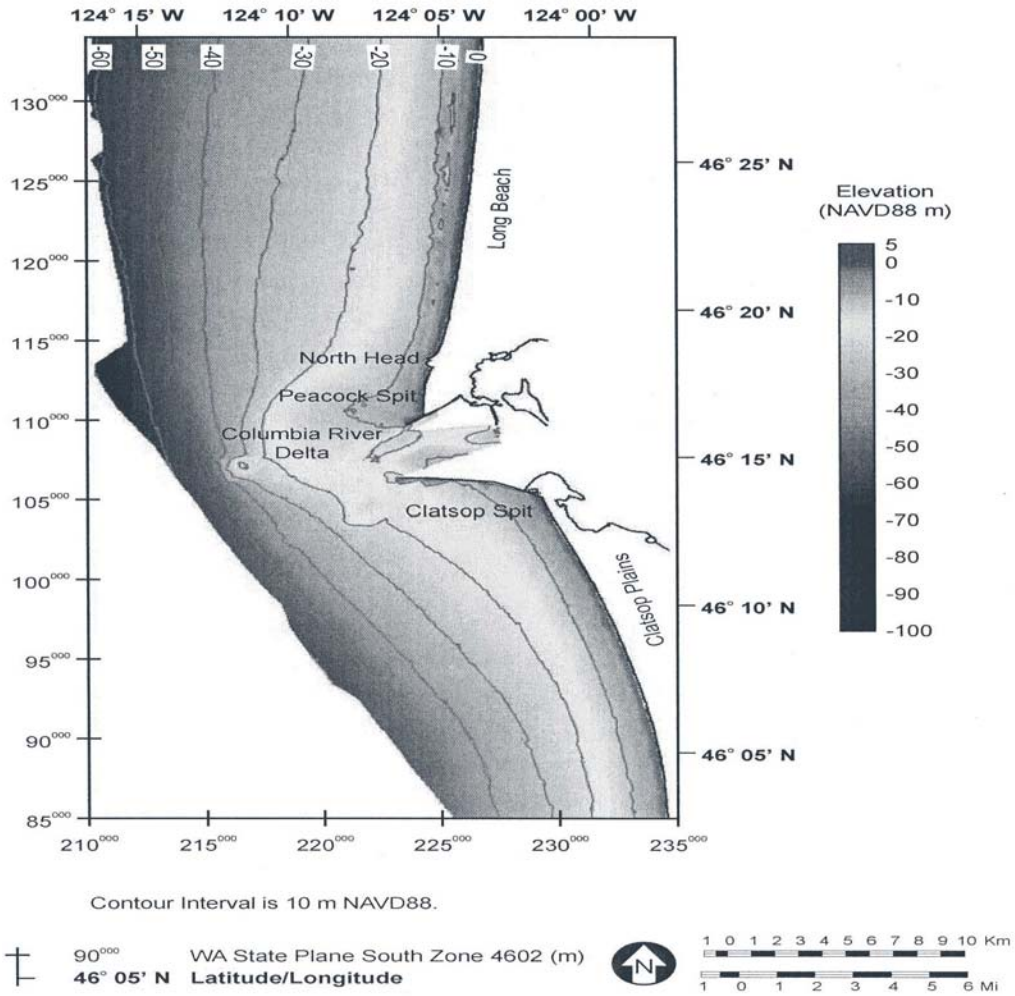


Figure 8 Sub-cells of CRLC adjacent to MCR from Buijsman, et al (2002)

Table 5 Volume Changes (mcy)

	1868-1926	1926-1958	1958-1999
Long Beach and Peacock Spit	66	71	130
Long Beach inner shelf/offshore		48	-1.3
Inlet	-202	-113	-75
Outer Delta	231	140	122
South Flank	-275	-45	-56
Clatsop Plains	102	83	56
Clatsop Plains inner shelf	-31	-34	
Clatsop Plains offshore		-128	-83
Net Volume Change	**-109**	**22**	**93**
Sand Yield from CR	138	17	N/A

Figure 9 (USACE 1999) shows the volume of sediment dredged from MCR. Prior to 1945, dredging was performed intermittently, with an average volume dredged of 0.75 mcy/yr to maintain a 30-foot channel. From 1945 to 1955, regular maintenance

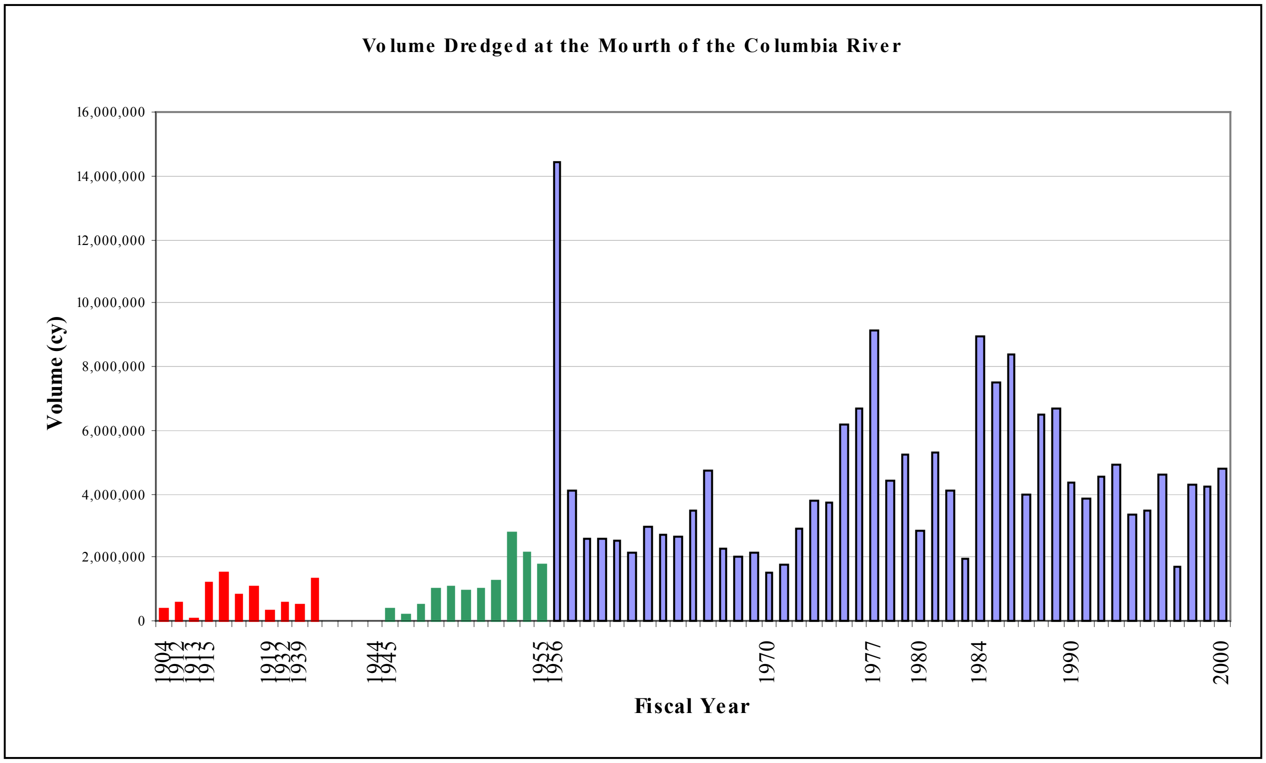


Figure 9 Volume Dredged at MCR

dredging was performed at MCR, with an average volume dredged of 1.2 mcy/yr. As the demand for a deeper and better-defined channel increased due to deeper-draft vessels, the entrance channel was deepened in 1956 to 48 ft. The full authorized channel dimensions and a 5 ft advanced maintenance depth was maintained beginning in 1977. A new authorized depth of 55 ft below MLLW was obtained in 1985. The average volume dredged since the deepening to 48 ft is shown in Table 6.

Table 6 Volume Sediment dredged from MCR

Period	Average Vol. Dredged (cy/yr)
1956-1976	3,696,071
1977-1985	5,478,748
1986-1989	6,375,070
1990-1998	3,887,378

Disposal of material dredged at MCR has been placed in 7 Ocean Dredged Material Disposal Sites (ODMDS) (Figure 10E) since dredging commenced in the late 1800's. Figure 11 shows the volumes placed in each site. "Between 1904 and 1997, approximately 61% of the material dredged from MCR has been placed in the vicinity of ODMDS A and E or estuarine disposal sites" (USACE 1999). The estimated vertical erosion rates at sites A and E is greater than 3 and 4 ft/yr, respectively, with average water depths at these sites of 45 and 55 ft, respectively. In USACE 1999, the maximum water depth for littoral transport to occur at MCR was determined to be about 59 ft. This is an important depth to consider when determining locations for dredge material placement that will be beneficial to the sediment transport within the entire littoral cell; in other words, disposal locations that will keep the sediment moving within the littoral cell.

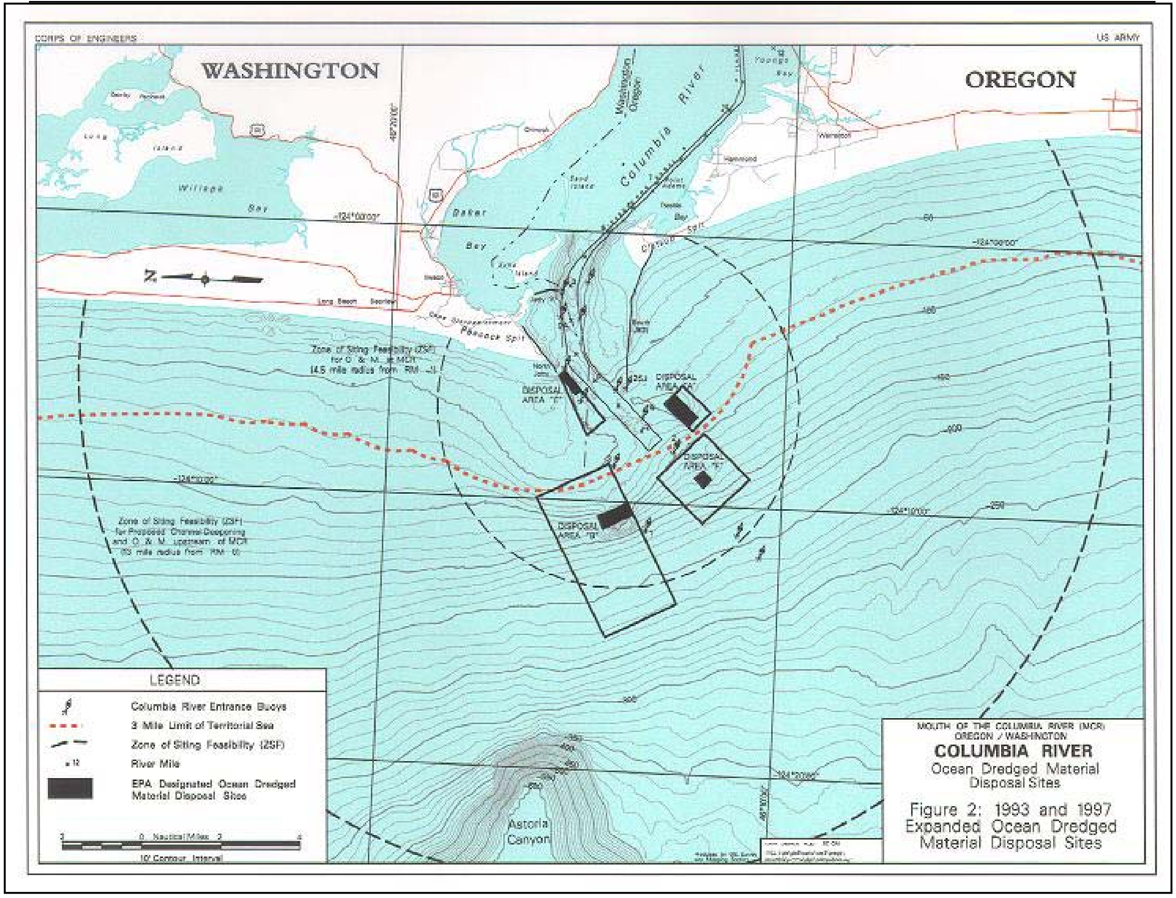


Figure 10 Disposal sites at MCR.

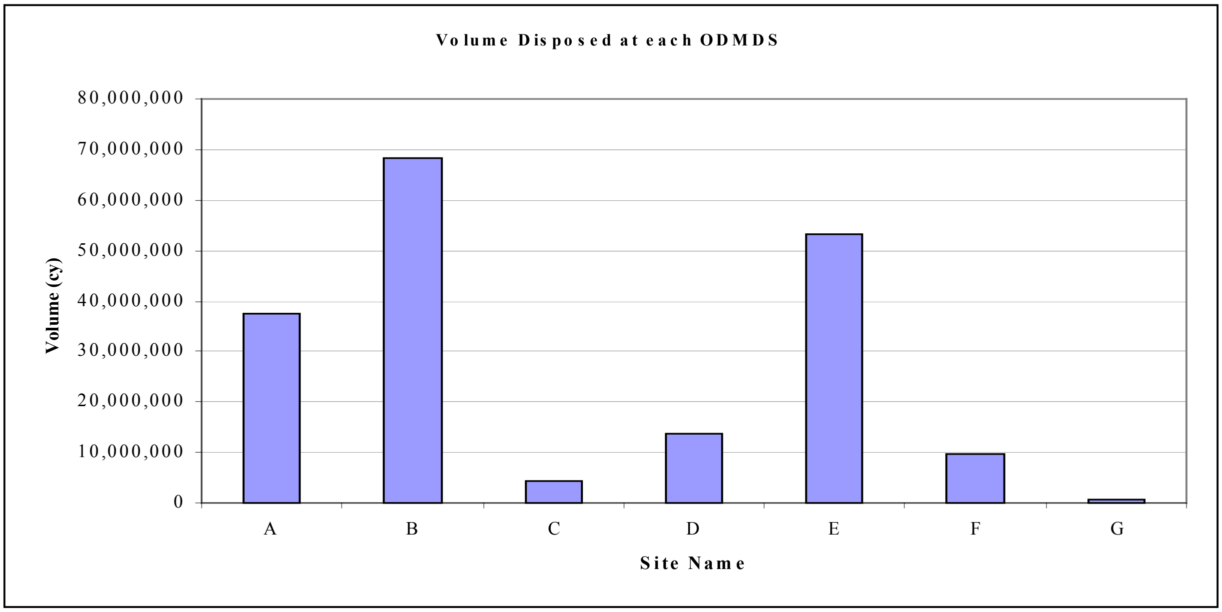


Figure 11 Volume Disposed

1868-1926 SEDIMENTATION

RIVER

Prior to 1926, the Columbia basin was largely undeveloped and there is little specific information on sediment processes. The sediment supply was probably similar to that described by Whetten et al. (1969), with the upper basin producing most of the silt and clay and the Cascades tributaries producing most of the sand. The Columbia River valley was already filled with deep alluvial deposits of sand, with some silt and gravel (Gates, 1994). The bed of the main river channel was composed of deep deposits of mostly fine and medium sand (0.125-0.50 mm). The results of five sediment samples collected between RM's 60-100 indicate very fine sand and finer sediments made up only 0.1-2.3 percent of the bed material in the main river channel (Park, 1924). The natural riverbanks consisted of basalt or erosion resistant sand, silt, and clay deposits. The location of the river channel had been stable for 6,000 years (USACE, 1986).

The natural sand transport in the lower Columbia River was highly variable, mirroring the rise and fall of the river discharges. Available streamflow data allowed Sherwood et al. (1990) to hindcast total sand transport as far back as 1878. The sand transport in Figure 2, shows the annual variability, with annual sand transport ranging from about 0.1 mcy in 1926 to over 37 mcy in 1894. The 1894 spring freshet had an estimated peak discharge of 1,260,000 cfs, with a maximum stage of 33 feet at Portland (Hickson, 1930). The average annual sand transport during this period was near 6 mcy/yr and there were seven years with 10 mcy or more. Bedload transport made up only a fraction of the total sand transport, but was an important factor in navigation channel shoaling. Hickson (1930) explained that shoaling in the navigation channel was the result of transport, or "drift", along the river bottom. He also noted the existence of 8-10 ft high sand waves migrating downstream in the navigation channel. Park (1924) also identified the role of bedload when he reported the downstream movement of a sand bar caused shoaling of the 30-ft navigation channel along Puget Island.

Prior to navigation channel development, much of the main river channel already had natural thalweg (deepest line) depths in the 35- to 45-foot range. However, the controlling depth (minimum depth available anywhere along the navigation channel) was only 12-15 feet (Hickson, 1961). The thalweg of the sandy riverbed repeatedly shifted alignment. Because of the naturally occurring depths, only minor dredging was conducted in the river to maintain the 25-ft channel. As Figure 12 shows, annual dredging increased sharply in 1914, when work began on the 30-ft deep by 300-ft wide navigation channel. An ambitious river control program was implemented between 1912 and 1926 (Park, 1924). Numerous pile dikes and in-water fills were built along the river to constrict the channel, decrease flow into some of the side channels, and to stabilize the navigation channel alignment. Pile dikes were usually built in "fields", a series of dikes spaced 1,200-1,500 feet apart, which run along the shoreline for up to four miles. Those measures combined with dredging began to lower bed elevations in the shallow reaches of the river channel. Figure 13 shows examples of channel constrictions and the resulting channel changes that occurred between 1909 and 1924.

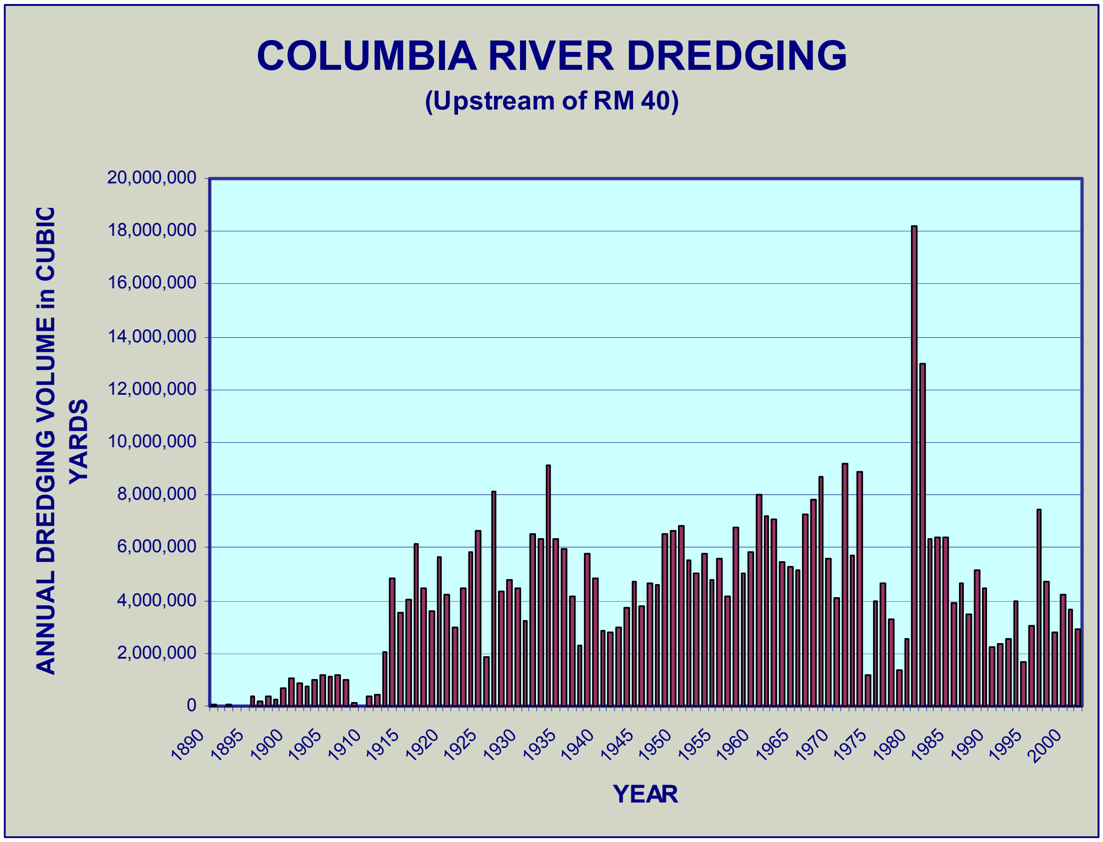
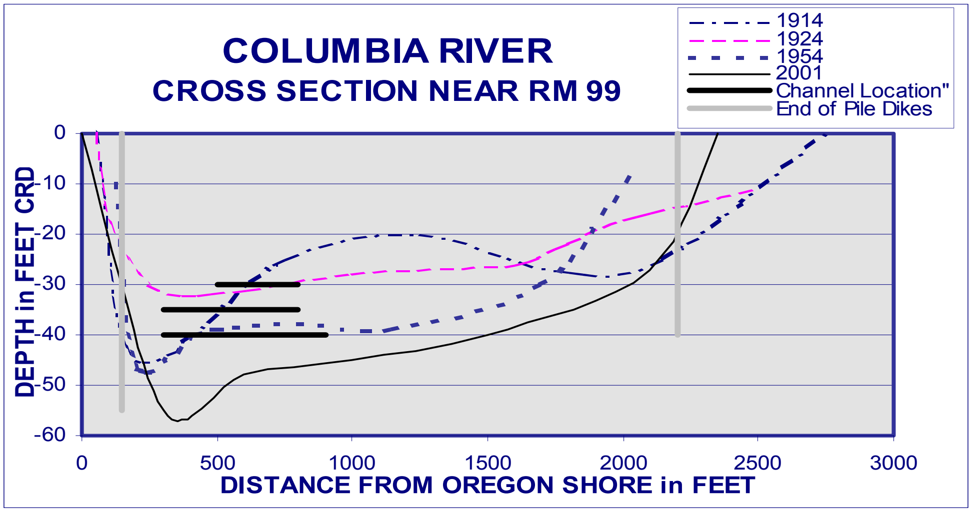
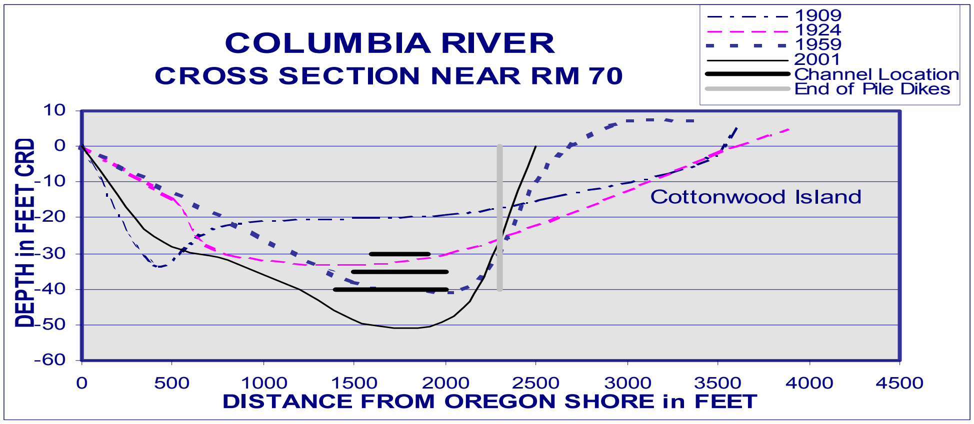


Figure 12. Annual Columbia River dredging between RM 40-106.

The CREDDP atlas (1983) shows large changes in the bathymetry in both channels around Puget Island between 1868 and 1935. Based on the work of Sherwood et al. (1984), about 20 mcy of sediment accumulated between RM's 31-48 (including portions of Cathlamet Bay) between 1868 and 1935. Park (1924) noted local sediment accumulation when he reported that dredging was not required at the upstream end of Puget Island until 1921.





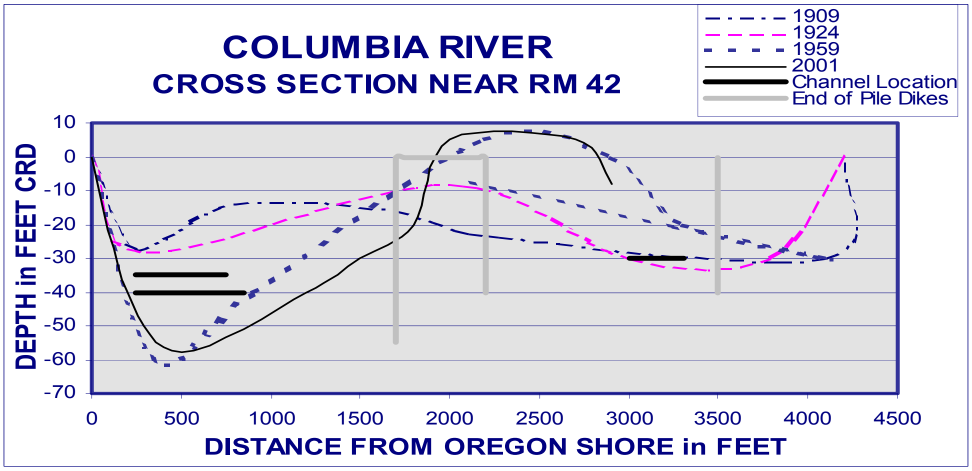


Figure 13. Changes in Columbia River cross-sections at constricted reaches.

ESTUARY

During this 1868-1926 time period, the estuary was a depositional area with several large unstable channels (Sherwood et al, 1984 and CREDDP, 1983). At the beginning of the time period, there was a sizeable channel along the north side of the estuary that flowed from Harrington Point (RM 23) across Grays Bay and through the southern portion of what is now Baker Bay. By 1885, the channel no longer passed through Baker Bay. By then, Sand Island had formed and occupied a portion of the old channel. A University of California (UC-B) report (1936a) also refers to a "Chinook Spit" that migrated from the Sand Island location, east through Baker Bay between 1874 and 1989. Between 1868-89, Baker Bay was just inside the MCR and exposed to ocean waves form the southwest. Ocean waves likely pushed sand into and across Baker Bay. The UC-B study found that after completion of the MCR jetties in 1917, sand movement from the MCR into Baker Bay due to ocean waves was greatly reduced. The pre-1885 changes probably account for most of the 120 mcy of accretion that occurred in Baker Bay between 1868 and 1926. During that time, the river channel downstream of RM 6 shifted south out of Baker Bay. (Sherwood et al. 1984, included the river channels downstream of RM 6 in the entrance sub-area, this report uses those same sub-area delineations as shown in Figure 4.) The north channel (RM 6-14) also experienced large changes in channel geometry. The deep-water channel shifted north, with erosion up to 30 ft deep and accretion of up to 20 ft along the south side of the channel (CREDDP Atlas, 1983). Despite the large geometry changes there was only slightly more than 1 mcy of net erosion during this time period.

The remainder of the estuary bays and shallows were also accumulating sand during this time period. By 1926, Grays Bay (Figure 4) had an estimated 33 mcy of accumulation, much of it in the old north channel which was no longer directly connected to the river channel at Harrington Point. During this period there were three or four distinct, but interconnected, channels that flowed through Cathlamet Bay and joined at Tongue Point. Downstream of Tongue Point, there were two channels, one passed south to north through Desdemona Sands, near RM 15, and the other followed the Oregon shore. The CREDDP atlas (1983) shows all these channels were actively shifting around. Cathlamet Bay and Desdemona Sands both experienced about 50 mcy of deposition during this period.

The south channel eroded around 33 mcy downstream of RM 31. The channel deepened over most of this length. The south channel erosion may have been triggered by flow being concentrated in that channel due to the deposition in Cathlamet Bay, Grays Bay, and Desdemona Sands reducing flow in the channels in those areas. The channel would have eroded until a balance was reached with the increased flow conditions.

The sediment budget indicates 138 mcy of sand were discharged from the estuary to the MCR. This represents an apparent estuary trap efficiency for river sands of 61 percent. However, the trap efficiency for river sands may have been even lower. As noted above, much of the Baker Bay accumulation may have been caused by sediment pushed landward by ocean waves and shifting entrance channels. Sherwood et al. (1984)

concluded that Baker Bay and other areas near the MCR were filled by ocean sediment that accounted for half of the total estuary accumulation since 1868. Crediting just the Baker Bay sand accumulation to ocean sources would increase the discharge of river sands to the MCR to 199 mcy for this time period and lower the estuary's trap efficiency for river sands to 44 percent.

Navigation channel development played a limited role in the estuary changes between 1868 and 1926. The MCR jetties, while causing large bathymetric changes in the entrance and ocean, may actually have reduced some of the sediment instabilities in the lower estuary. The jetties reduced incoming wave energy and cut off the sand supply from Clatsop Spit (UC-B, 1936a). Those changes would help to stabilize the lower estuary by reducing sand transport and supply. Navigation dredging had little impact until construction of the 30-ft channel in 1915-1919. Even then, much of the south channel was naturally over 35 ft deep and only seven miles between RM's 3 and 31 had to be dredged for the 30-ft channel (Park, 1924). Figure 14 shows that only 15 mcy were dredged for navigation from 1893 through 1914 and then 24 mcy were dredged to construct and maintain the 30-ft channel from 1915 through 1926. While this dredging altered channel depths, it did not influence the volume of material in the main channels because hopper dredges did the work. The hopper dredges used in-water disposal, simply moving sand from the navigation channel to other locations within the river channel. Disposal may have transferred some sand between channel reaches, such as from the south channel to the north channel

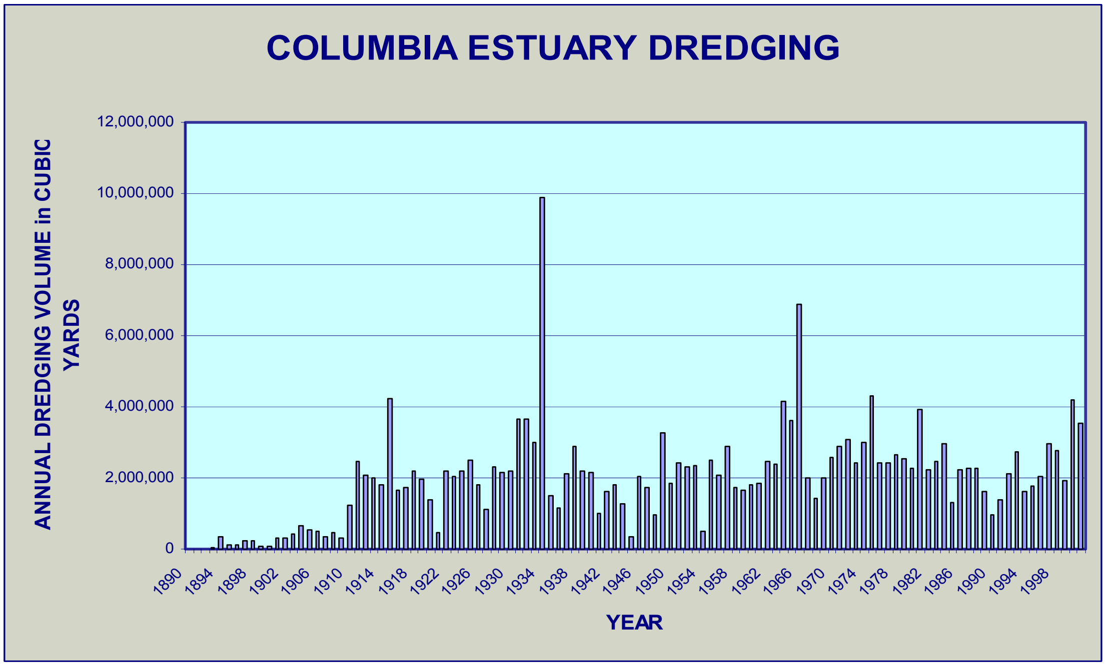


Figure 14. Annual Columbia Estuary (RM 3-40) dredging volumes.

in the vicinity of RM 6. However, the bathymetry of the estuary would not have allowed the hopper dredges to operate outside the boundaries of the main channels. The only notable flow control structure in the estuary prior to 1922 was the Snag Island jetty, built prior to 1871. That jetty was not on the present south channel, but was in Cathlamet Bay, where it directed flow away from Cordell Channel and into Woody Island channel.

MCR: 1868-1926

The Columbia River entrance, prior to jetty construction, consisted of a "broad and shallow ebb-tidal delta complex with up to three dynamic inlet channels, flanked by shallow shoals of Peacock and Clatsop Spit" (Buijsman, et al, 2002). The natural channel had an average depth of 25 ft and shifted on a seasonal and annual basis, as seen in Figure 5. The ebb tidal shoal complex was symmetric on the ocean side of MCR, prior to entrance modifications, which strongly suggests a dynamic equilibrium north and south sediment transport around MCR. After jetty construction, the inlet narrowed, and a single deeper channel with a depth over 33 ft formed. The south jetty was initially built, 1886-1913, to stabilize Clatsop Spit, but Peacock Spit still meandered into the channel, so the north jetty was authorized in 1917. Jetty construction reduced the width of the mouth from 6 to 2 miles.

Work by Gelfenbaum and Kaminsky (2000) and Gelfenbaum, et al (2001), calculated volume changes within different sub-areas around the MCR between 1868 and 1926. During that period, a total of 202 mcy of sand eroded from the entrance channel. This sand migrated to the new ebb-tidal delta, which accreted 231 mcy. The south flank, section 3 in Figure 15, eroded 275 mcy due to the absence of the ebb jet from the entrance traversing this area. The south flank material was transported to the ebb-tidal delta.

Peacock Spit accreted 29 mcy (an area of 960 acres), while the entire Long Beach sub-cell only accreted 37 mcy. This indicates a great imbalance in the areas of accretion on Long Beach, with Peacock Spit receiving a greater portion of sediment than the rest of the cell.

The area south of MCR, Clatsop Spit and Clatsop Plains, also accreted during this period. The shoreline of Clatsop Plains moved seaward, with a rate that increased from 2-3 ft/yr prior to jetty construction, to up to 56 ft/yr after construction (Buijsman 2002). While Clatsop Plains and Clatsop Spit accreted 102 mcy and 34 mcy, respectively, the area offshore of Clatsop Plains eroded 39 mcy.

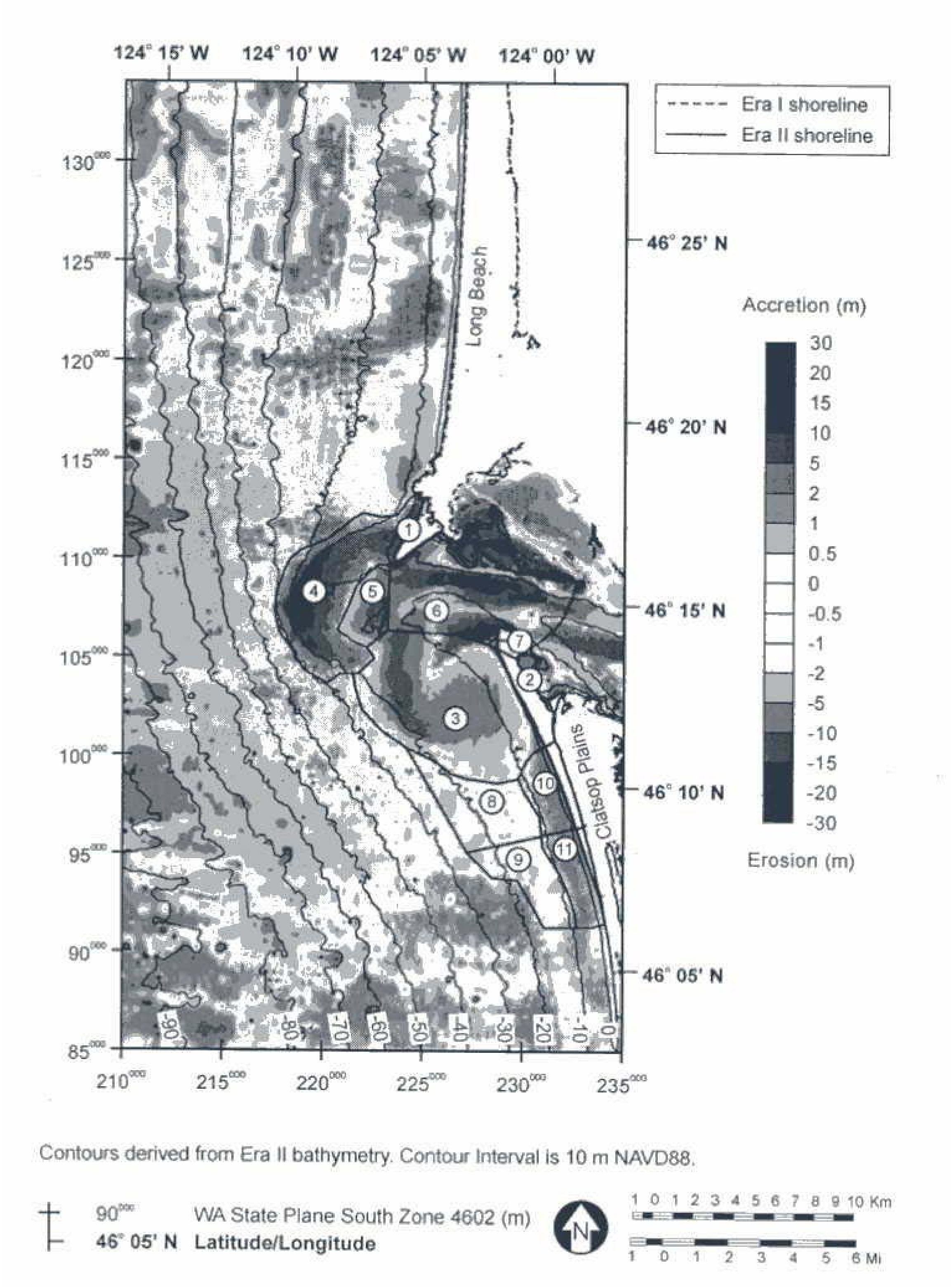


Figure 15. Volume change analysis (Buijsman 2002).

As can be seen in Table 5, there is a large volume imbalance within the MCR area. The total unaccounted for loss of material amounts to 247 mcy, between the amount of sediment being supplied from the Columbia River (138 mcy) and an apparent loss of sediment (-109 mcy) in the areas surrounding MCR. Some of this sediment could be accounted for in the amount of sediment dredged from the entrance channel, but that only amounts to about 6 mcy for the entire period. The material may have moved into areas further north and south along the coast, areas still within the CRLC but that are not accounted for in Table 5. The volume changes further offshore are also difficult to evaluate due to lack of sufficient survey data.

1927-1958 SEDIMENTATION

RIVER

There was a marked decline in annual streamflows during this time period compared with the earlier period. The hydrologic analysis of Bottom et al. (2001) indicates that because of regional climate trends, annual runoff tended to be below normal between 1927 and 1944 and then returned to a more normal pattern for 1945-58. Water resource development was ongoing throughout the Columbia basin during this time period, but only had a small impact on annual streamflows. Bonneville (1937), The Dalles (1957), McNary (1953), Chief Joseph (1955), and Grand Coulee (1941) dams were constructed on the main stem of the Columbia River. These dams have run-of-river reservoirs with little capacity to store water, except Grand Coulee, which is a storage project. Because of the limited storage capacity, these dams had only minor impacts on Columbia River discharges. Upper basin irrigation withdrawals did cause a slightly reduction in streamflows throughout this time period.

Figure 2 shows the reduced sand transport resulting from the decreased streamflows. The average annual sand transport for this period was 3.6 mcy/yr, or 60 percent of the 1878-1926 average of 6 mcy/yr. The occurrence of very high annual sand discharges in the river declined even more, as only one year exceeded 10 mcy, which was 1948 with 19 mcy. Other than the effects due to streamflow changes, the upstream reservoirs did not noticeably affect sand transport or supply. Whetten et al. (1969) found no sand accumulations in the Columbia River reservoirs. They reported that sediment deposited in Columbia River reservoirs during low flows was eroded and transported by subsequent high flows. Sand waves were reported migrating downstream in the Bonneville pool at rates of around 1-2 feet per day during the 1964 spring freshet. They also noted that sand waves covered over 80 percent of the riverbed downstream of the Willamette River. They estimated that downstream of Bonneville, the Columbia River's bedload transport was less than 1 mcy/yr. While those observations were made in the 1960's, they would also be indicative of sand movement in the 1927-58 time period.

Navigation development had a larger impact on the river during this time period. The channel was expanded to 35-ft deep by 500-ft wide and adjustments to channel alignment that brought the channel to approximately its current location. Navigation dredging remained steady, with 158 mcy dredged from upstream of RM 41 during this period. The channel impacts were largest in those naturally shallow reaches where channel constrictions were built. The lowering of the riverbeds and reduction in widths shown in Figure 13 are typical of the riverbed changes in the constricted reaches. The increased depths across the riverbed are due to the deflection of bedload into the deeper navigation channel and the subsequent removal of the resulting shoal by maintenance dredging (Eriksen and Gray, 1991). In these areas, much of the sand was disposed of within the pile dike fields, producing the sediment accumulations shown in Figure 13.

ESTUARY

The estuary continued to accumulate sediment, however there was a clear change in the accumulation pattern. In the earlier period (1868-1926), all parts of the estuary downstream of RM 31 accumulated sediment except for the main channels. During 1926-58, the north side of the estuary lost sediment and the south side, including Desdemona Sands and the south channel, accumulated sediment. The CREDDP atlas shows shifting channels and mixed erosion/deposition over the flats throughout the estuary.

The sediment losses from the north side of the estuary were relatively small, only 28.5 mcy (23 mcy of sand), but losses occurred in all sub-areas, as shown in Table 4. Baker Bay was protected from ocean waves by the MCR jetties and Sand Island. The bay, which had accumulated over 120 mcy in the earlier time period, lost nearly 9 mcy of sediment during this period.

The sediment accumulations on the south side were nearly five times greater than the north side losses. The sand accumulations in Cathlamet Bay and the main south channels totaled 90 mcy, nearly equal to the 113 mcy of sand inflow from the river. Overall, the net sand accumulations in the estuary amounted to 85 percent of the 113 mcy of total Columbia River sand inflow during this period.

In another 1936 report, UC-B (1936b) used a physical model to look at bedload movement in the estuary downstream of RM 30. The study examined bedload transport over the course of a tidal cycle for an "average" river discharge of 196,000 cfs and a "freshet" discharge of 556,000 cfs. The transport rates calculated in that study were very small, but the bedload transport patterns give an indication of the estuary's behavior in the 1930's.

The UC-B model results for "average" conditions showed the bedload changing direction with the tide as far upstream as Harrington Point (RM 23). The net transport for average flow conditions was downstream everywhere in the estuary, except for the reach downstream of RM 5. Under freshet conditions the model showed net downstream bedload transport throughout the estuary, including downstream of RM 5. The daily transport rates for the freshet condition were 4 to 35 times higher than the daily rates for average conditions at the same locations.

The UC-B model showed that under average flow conditions, the net upstream bedload transport near Sand Island (RM 4-5) resulted from transport in the northern and central portions of the channel. Under freshet conditions the net bedload transport was downstream in this reach. However, over the course of a year, the sum of the average conditions would prevail and there would be net upstream bedload transport in the channel at RM 4-5. It is noteworthy that the model results also showed a very small net bedload discharge from the MCR to the ocean under both average and freshet conditions.

These model results indicate net movement away, in both directions, from the RM 4-5 reach, an area that actually did erode considerably between 1926-58.

Both average and freshet conditions showed sand being transported northwest away from the south channel between Tongue and Harrington Points (RM 17-23) and into Grays Bay and the mid-estuary shoal. The transport paths indicate sand would move seaward through Grays Bay and the mid-estuary shoal, and into the north channel and Desdemona Sands (UC-B, 1936b). These downstream transport paths converge at Desdemona Sands with the upstream paths in the RM 4-5 reach. This would indicate an area of sand accumulation and suggests that much of the sand lost from the north channel, Grays Bay, and the mid-estuary shoal was accumulated on Desdemona Sands.

The UC-B model results for "average" conditions for the south channel showed little or no upstream bedload transport during the flood tide and only low rates of downstream transport during ebb flows. With all the pathways leading away from the south channel in the estuary, the only source for the sand accumulation in the south channel (RM 6-31) and Cathlamet Bay would have been the inflowing sand from the Columbia River.

Lockett (1967), citing another model study and prototype measurements, presented the map of bottom sediment transport shown in Figure 16. The pattern is very similar to the bedload patterns reported by UC-B in 1936. Both studies show sand moving landward in the north channel near Sand Island, sand moving northwest away from the south channel between RM's 17-23, and sand transport following the south channel to the MCR. Locket identifies net transport paths and no transport volumes were reported. Lockett cites observed bed sediment characteristics and sand wave patterns as the prototype information supporting this transport pattern.

The transport patterns presented by UC-B and Lockett, and the lower streamflows and sand inflow from the river during this time period can also be used to explain the changes in estuary sedimentation trends, as described below.

With lower discharges and less sand transport in the river, there would have been less sand diverted from the south channel, between RM 17-23, to the north side of the estuary. The lower supply would reduce deposition in Grays Bay and the mid-estuary shoal. Erosion, being more dependent on tidal currents, would not have been influenced as much by the reduced river flows. The large reduction in deposition, coupled with continued erosion resulted in a shift to net erosion in those areas.

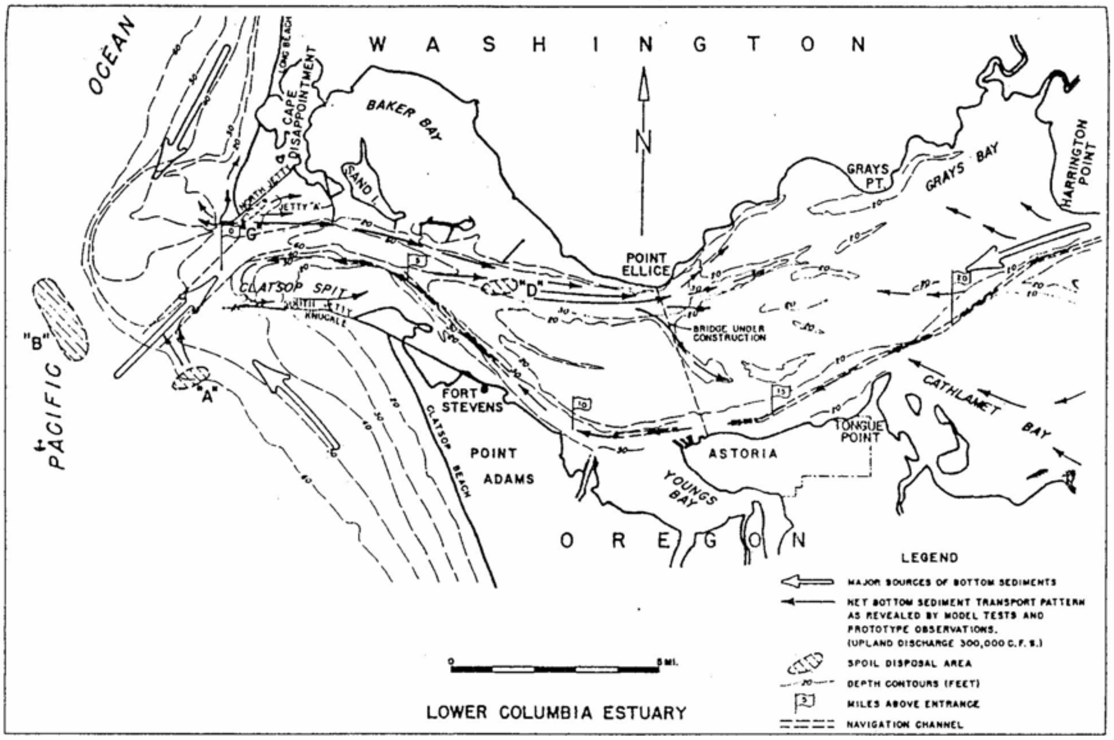


FIG. 1.—LOWER COLUMBIA ESTUARY

Figure 16. Sand transport paths from Lockett, 1967.

The lower streamflows would have had the most impact on sand transport capacity in the main channel and Cathlamet Bay. The smaller freshet flows would have reduced the annual sand transport capacity through the south channel to the MCR. Lower streamflows potentially could allow tides to transport sand upstream from the MCR into the south channel, but the UC-B and Lockett reports both indicate this did not happen and that net transport, though much smaller, remained in the downstream direction to the MCR. The lack of large freshets to carry river sand out of the estuary would explain the increase in the estuary's trap efficiency (based on inflowing river sand) from 61 percent for 1878-1926 to 85 percent for 1927-1958.

Utilizing the theories that converging transport pathways indicate an area of deposition and that of mass balance, the estuary’s transport paths and sediment volume changes can be used to make an estimate of the volume of sand that may have entered the estuary from the ocean. Both UC-B and Locket indicate there is net upstream sand transport in the north channel but not in the south channel in the vicinity of RM 4-5. The reports also show that the landward transport in the north channel converges around Desdemona Sands with downstream transport from the north side of the estuary. Therefore, if there were any inflow of sand from the MCR, it would be part of the 24-mcy accumulation on

Desdemona Sand. As described above, the 19 mcy of sand eroded from the north channel, mid-estuary shoal, Grays Bay, and Brix Bay was the likely source of much of the Desdemona Sands accumulation. The additional 5 mcy of sand accumulated on Desdemona Sand could have come from the river, the MCR, or the ocean. Based on Lockett's conclusions that there was ocean sand moving upstream in the north channel, that additional 5 mcy would have come from the MCR or ocean. This amounts to an average annual sand inflow from the MCR through the north channel of less than 0.2 mcy/yr.

Navigation developments in the estuary included increasing the channel depth to 35 ft, realigning the channel at Miller Sands (RM's 22-25), and construction of pile dikes around Sand Island and at Miller Sands. All the dredging was done by hopper dredges using in-water disposal, except the Miller Sands realignment. As in the earlier period, the in-water disposal would have been along the navigation channel near the dredging sites. The dredging and disposal would not have changed the sediment volumes along the channel, except for some material that may have been transferred from the south channel to north channel near RM 6.

The Miller Sands realignment was constructed in 1934-35 by a pipeline dredge and the 5.5 mcy of disposal created the main island at Miller Sands. Pile dikes were built to reduce flow through the old channel at Miller Sands. This action, combined with the 35-ft channel and deposition in Grays Bay, essentially established the south channel as the dominant estuary channel.

The pile dikes at Sand Island were built in 1933-34 to stop the northward migration of the north channel. The CREDDP bathymetric maps show the pile dikes did stop the migration and some sediment accumulated around the upstream dike near Chinook Point.

MCR: 1927-1958

The erosion/accretion pattern around the MCR was similar to the earlier period. Accretion continued in the outer ebb-tidal delta, and the beach-dune complexes of Long Beach and Clatsop Plains. The area of greatest coastal accumulation shifted away from MCR during this period, as seen in Figure H from Gelfenbaum, et al. (2001). The inner portion of the ebb tidal delta, the inlet, and Clatsop Plains shoreface (Figure I) experienced erosion during this period.

The inlet and inner portion of the ebb-tidal delta eroded 113 mcy. This deepened the channel and the seafloor west of Clatsop Spit, which caused erosion. While the inlet and inner delta eroded, there was 140 mcy of accretion in the deeper water on the eastern edge of the outer delta.

Peacock Spit accumulated 33 mcy of sand, but accumulation was at a slower rate than in the previous time period (Gelfenbaum, et al., 2001). The southern end of Long Beach, including Peacock Spit, accreted 102 mcy, while the northern portion eroded 31 mcy.

Buijsman, et al (2002) suggests that the erosion at the northern end is related to sediment transport processes around Willapa Bay.

The middle of the Clatsop Plains sub-cell began to prograde significantly with the shoreline moving seaward at rates of 23-26 ft/yr and a volume change of +83 mcy. The inner shelf, just offshore of Clatsop Plains, eroded 34 mcy, and may have acted as a sediment source for Clatsop Plains. Further offshore, the area eroded 128 mcy.

Annual maintenance dredging has been performed at the MCR since 1945. Dredging was conducted only intermittently prior to 1945. More than 36 mcy of sediment was dredged from the entrance channel during this time period, with 14 mcy dredged in 1956 for a 48-ft channel-deepening project. Dredging amounts to about a third of the volume loss from the inlet. Disposal was offshore about 1 to 2 miles southwest of the south jetty in water depths of 60 ft (USACE 1999).

1958-1999 SEDIMENTATION

RIVER

This is a long time period, with a substantial change in the Columbia River's annual streamflow pattern and sediment transport occurring in the middle of the period. Additional hydropower and flood control projects were completed in the basin, including the four lower Snake River dams and large storage reservoirs in Canada. Flow regulation of the spring freshet became effective in 1973, reducing the 2-year peak discharge from 560,000 cfs to 360,000 cfs (USACE, 1987). The navigation channel downstream of Portland/Vancouver was deepened to 40-ft between 1968 and 1972.

Because of the exponential relationship between sand transport and river discharge, the annual sand transport declined sharply after flow regulation became fully operational in 1973, as shown in Figure 2. The average annual sand transport for the entire period was 1.8 mcy/yr, half that of the 1926-58 period. However, the pre-regulation period (1959-72) had an average annual sand transport of 2.7 mcy/yr, compared to a post-regulation (1973-99) average of 1.3 mcy/yr. The high streamflow years of 1996 and 1997 accounted for nearly half of the 1973-99 sand transport. Prior to 1996, the post-regulation total sand transport averaged only 0.8 mcy/yr; comfortably within the 0.4-1.0 mcy/yr range of total sand transport used in the Corps' channel improvement FEIS (USACE, 1999a).

While sand transport has declined significantly since the late 1800's, a sand supply has remained readily available in the riverbed from Bonneville Dam to the MCR. A comparison by Jay and Naik (2000) of pre-1970 and post-1990 sediment transport data from the Columbia River at Beaver, Oregon (RM 53) found the best-fit sediment load curves for the two periods were not statistically distinguishable. They concluded that sand is and always has been available in the riverbed and that of the human actions; flow regulation has had the greatest impact on sediment transport. The conclusions of Jay and Naik are consistent with the Corps' conclusions that the reductions in sand transport are the result of flow regulation and that there has been no substantial change in the river's sand supply (USACE, 1999 and 2001).

Navigation development continued to have an impact on main channel depths. The navigation channel was deepened to 40-ft and additional pile dikes were built between 1968 and 1972. By the 1999, thalweg depths had increased to near 50 feet throughout most of the river downstream of Portland/Vancouver. Upstream of Portland/Vancouver the navigation channel is maintained to 17 ft deep and the riverbed has changed relatively little in the last 130 years.

The riverbed's side-slopes have remained flat and depths across the entire channel have increased in response to navigation dredging. Navigation channel shoaling continued to be caused by bedload transport (USACE, 1999), as originally noted by Park in 1924 and Hickson in 1930. The time periods in the sediment transport analysis by Jay and Naik cited above spanned the construction and 20-25 years of maintenance of the 40-ft navigation channel. While they did not specifically comment on the influence of the navigation channel, the lack of change in sediment transport that they identified would indicate that channel related actions also had no detectable impact on sand supply or transport rates in the river.

ESTUARY

Bathymetric difference maps of the estuary were prepared by CREDDP (1983) for the period 1958-82, but limited survey coverage prevented calculation of the volume changes (Sherwood, 1984). The most recent changes around the estuary cannot be identified because there has not been a complete survey of the estuary since 1982. However, the Corps has repetitive surveys along the navigation channel and of the lower 7 miles of the north channel.

The CREDDP atlas shows shifting channels and mixed erosion/accretion over the flats throughout the estuary, very similar to the 1935-58 sedimentation patterns. The south channel appears to have expanded, but shows a mix of erosion and accumulation over the length of its course. The cross estuary channels continued to dwindle in size as sediment accumulated on the south side of the estuary flats. There was erosion along both sides and accumulation in the center of the north channel near Sand Island, RM 5-8. Eriksen (2001) identified continued active sedimentation in the north channel with erosion at RM 5 and sediment accumulation around RM 6-7 between 1980 and 2001.

In addition to the reports by Locket (1959, 1963, and 1967) from the beginning of this time period, there have been two other studies that address estuary sediment transport during this period. Sherwood et al. (1984) conducted an extensive study of sediment processes downstream of RM 48 that is the source of the sediment volume changes used in this analysis. That study also examined suspended and bedload transport in the estuary. The other study, done by McLaren and Hill in 2001, primarily looked at sediment transport patterns in the MCR and ocean, but included the area just inside the MCR at the confluence of the north and south channels.

The Sherwood et al. (1984) study used the CREDDP bathymetric atlas, grain size analysis, suspended sediment measurements, and side-scan sonar to evaluate sediment transport and erosion/accretion patterns in the estuary. Their detailed analysis found much spatial and temporal variation in the sediment processes. They concluded that upstream of Tongue Point the estuary functioned as a fluvial system, with tidal hydraulics and ocean waves becoming more important closer to the MCR.

Sediment processes were found to vary at time scales ranging from the daily tidal cycle to monthly spring/neap cycles, to the seasonal streamflow pattern. Figure 17 is Sherwood et al's summary of estuary sediment transport and deposition that integrates those temporal variations. With only some minor differences, the overall sedimentation patterns shown in Figure 16 (Locket, 1967) and Figure 17 (Sherwood et al., 1984) match closely. The minor differences are in the extent of upstream bedload transport in lower reaches of the south and north channels. The time period between these two studies includes the construction of the 40-ft navigation channel in 1968-72 and the implementation of greater flow regulation by upstream reservoirs in 1973.

In the south channel Locket concluded that net transport was seaward through this entire reach to the MCR. Sherwood et al. found a complex pattern below RM 14, with transport direction changing with location and season. They concluded there was net seaward transport upstream of RM 14 and downstream of RM 8, but net landward transport, mainly on the south side of the channel, at RM 9-10.

In the north channel, Locket extended net landward transport upstream to about RM 16, while Sherwood et al. stopped it at about RM 13. Both studies show transport paths converging in the vicinity of Desdemona Sands, suggesting that sand from the river and the MCR will continue to accumulate there. They also both show sediment moving from the ocean through the MCR and into the north channel.

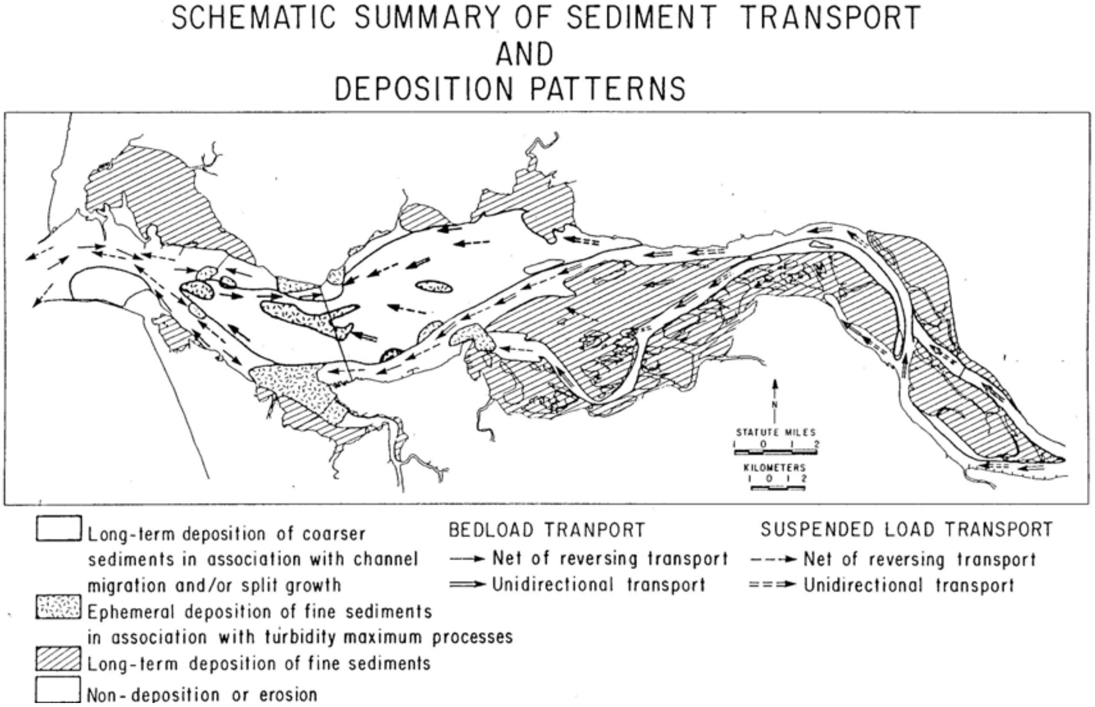


Figure 17. Sediment transport paths from Sherwood et al., 1984.

The minor differences between the two studies are indicative of the complexity of the bedload transport processes in the heavily tidally influenced reach downstream of RM 16.

Sherwood et al. identified that transport varied with changing river flows and the different patterns are likely the result of different flow conditions during the two observation periods.

In the estuary, the 2001 study by GeoSea includes only the confluence of the north and south channels downstream of RM 6 (Figure 7). This study used grain size statistics from bed material samples collected in August and September 2000, to determine sediment transport paths and the trend toward erosion, accumulation, or equilibrium. The results show seaward transport and net accumulation in the south channel between RM 4-6 and then the paths turning landward into the north channel. The results indicate erosion on the south side and deposition on the north side of the north channel. It is notable that this study differs from all the studies discussed above in that it does not indicate a transport path that would move sand from the MCR into the estuary. This study again demonstrates the complexity of bedload transport near the MCR and the differences may also be the result of flow conditions at the time of the study.

Navigation developments in the estuary included increasing the channel depth to 40 ft and construction of pile dikes at Miller Sands and Pillar Rock. Changes in dredging and disposal practices probably contributed to the apparent expansion of the south channel and to sediment accumulation in the north channel near Sand Island.

Hopper dredges using in-water disposal did most of the 113 mcy of estuary dredging during this period. Upstream of RM 15 the in-water disposal would have been along the navigation channel near the dredging sites, as it had been in the past. However, downstream of RM 15 there was a significant change in the in-water disposal practices. It was a common practice between 1957-87 to dispose of sand from the south channel, RM 5-13, at "Area D" in the north channel near RM 6. During that time, over 12 mcy was dredged from the south channel and disposed of in Area D (Beeman and Shapiro, 1987). An additional 8 mcy of sand from the MCR dredging was also disposed at Area D during that time. This disposal could very well have been the cause of the sediment accumulation in the center of the north channel between RM 5-8. The removal of sand from the south channel would have contributed to its enlargement between RM 5-13.

Pipeline dredges were used frequently between RM 19-29 and 37-39. Much of the pipeline disposal was placed along the shorelines and eventually eroded back into the river. There is about 17 mcy of disposal that was placed on Rice Island, Miller Sands Spit, and Pillar Rock Island that remains in place. Perhaps another 1-2 mcy remains at shoreline sites located between RM 29-40. Pile dikes were built to protect the disposal at Rice and Pillar Rock islands.

MCR: 1958-1999

The erosion/accretion pattern for the MCR area for 1959-99 is similar to the earlier two periods, however there are is a large increase in the MCR dredging that may have altered the sediment budget for the inlet sub-area. During 1959-75 annual dredging at the MCR averaged 2-3 mcy/yr and then from 1976 to 1999 it averaged 4-5 mcy/yr. Over 175 mcy of sediment was dredged from the entrance channel during this time period. Of that total, the 69 mcy that was disposed of on the outer ebb-tidal delta and the remainder was placed near the west end of the north jetty. While during the earlier time periods dredging and disposal volumes were small compared the inlet volume losses, during 1959-99 the 69 mcy of dredged sand transferred to the outer ebb-tidal delta is nearly equal to the 75 mcy of sediment lost from the inlet. The 69 mcy also is over half of the 122 mcy accreted on the outer ebb-tidal delta during that time period.

Along Long Beach, north of MCR, the accretion pattern from the previous period continued, with the northern areas accreting faster than previously and the southern portion decreasing its accumulation rate. Peacock Spit, at the extreme southern end of Long Beach, eroded 9 mcy (Gelfenbaum, et al 2001), while the rest of Long Beach continued to accrete at a moderate rate (Figure 18). The sediment supply to Peacock Spit and adjacent nearshore areas was augmented by the Corps' placement of MCR disposal material in Area E at the west end of the north jetty and Site B.

The areas to the south of MCR all experienced decreased accumulation rates, with Clatsop Spit appearing to stabilize. Central Clatsop Plains prograded at a slower rate than the previous time period, with an accretion of 56 mcy, augmented by sediment disposal at Site A.

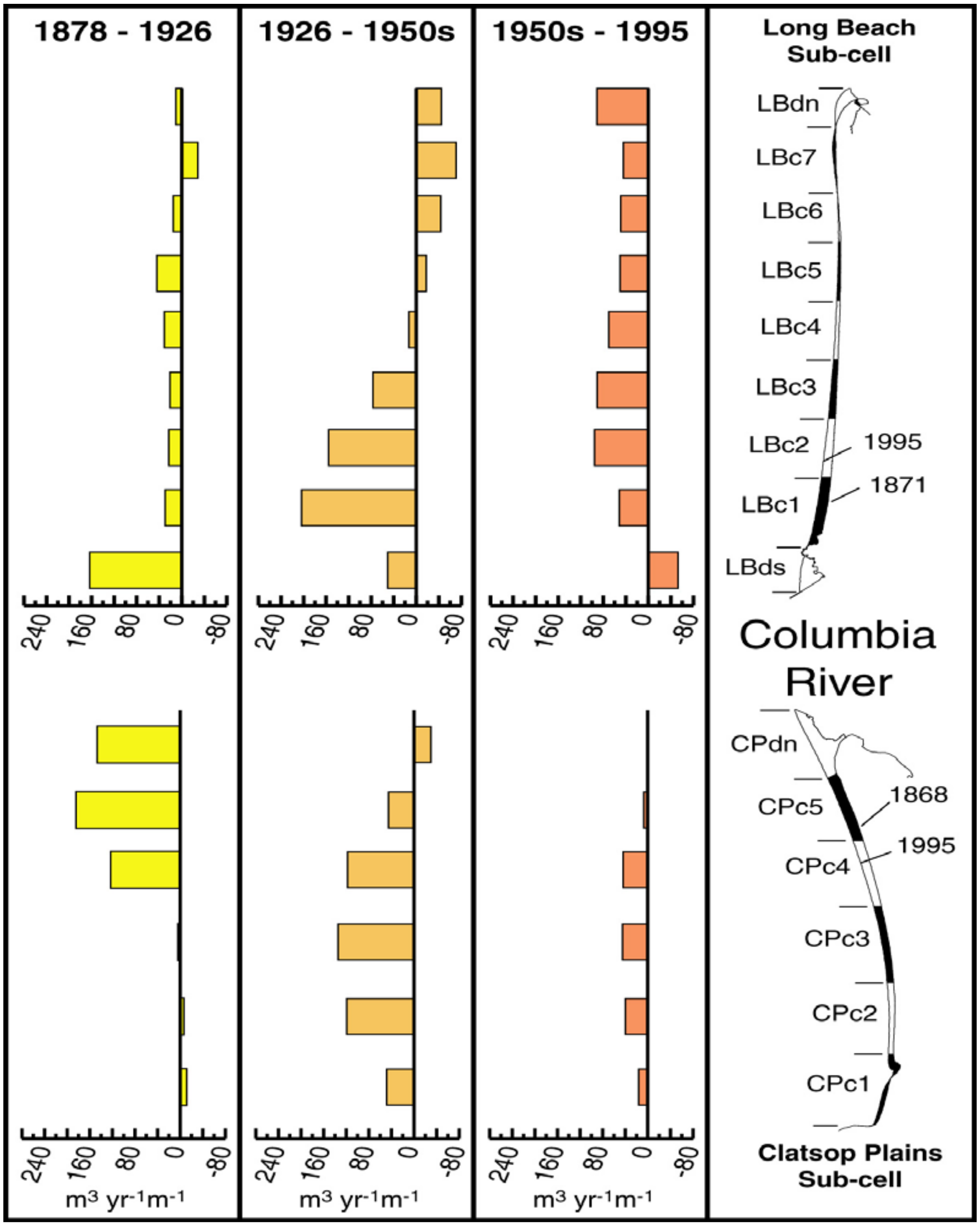


Figure 18 Volume changes along the CRLC (Gelfenbaum and Kaminsky et al, 2000)

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