Preprinted from Coastal Sediments '99
Proceedings of the 4th International Conference on
Coastal Engineering and Coastal Sediment Processes
American Society of Civil Engineers
June 20-24 1999, Long Island, NY

THE COLUMBIA RIVER LITTORAL CELL: A SEDIMENT BUDGET OVERVIEW

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Abstract: For the last several thousand years the Columbia River has supplied sand to nearby bays, coastal dunes, the continental shelf, and the continental slope and submarine canyons and fans. By quantifying the amount of sand that occupies these environments, we will gain a better understanding of the Columbia River dispersal system. We can use this insight to better predict the response from changes in the system, whether natural or human-induced. To help separate natural from human-induced changes in the littoral cell, the sediment budget is calculated for pre-historic periods as well as for historic and recent periods. Estimating the discharge of the Columbia River is a critical component of a sediment budget for the littoral cell. Preliminary calculations suggest an average total discharge for pre-historical time of 20×10^6 m^3/yr, compared to 8.7×10^6 m^3/yr for early historical time, and 4.3×10^6 m^3/yr since the 1950s.

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INTRODUCTION

For much of the past century, and with few exceptions, the shorelines of southwest Washington and northwest Oregon accreted at rates exceeding several meters per year. These high accretion rates have been attributed to large supplies of sand from the Columbia River. This widespread accretion resulted in new coastal lands, on which public and private infrastructure and facilities have been built. Several locations that had historically been accreting, however, are presently experiencing severe erosion (Figure 1). The erosion is a critical issue for local governments and state agencies because it threatens significant loss of public and private property (Figure 2). The causes of this reversal from accretion to erosion are not fully understood, but are speculated to be associated with human activity both in the coastal zone and within the Columbia River drainage basin (Phipps, 1990).

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The U.S. Geological Survey and the Washington Department of Ecology initiated a five-year study to address the needs of coastal communities and state and federal agencies, and: 1) understand the regional sediment dynamics, 2) determine the natural and anthropogenic influences on the littoral system, and 3) predict coastal change at management space and time scales (decades and tens of kilometers). The study is taking a whole-system approach to understanding coastal change and includes tasks to assess the evolution of the adjacent shelf and bays, in addition to the littoral cell itself. Major questions being addressed by the study include: Is recent shoreline erosion related to a decrease in sediment supply from the Columbia River? How do the natural (pre-historic) shoreline change trends compare to the anthropogenic (historic) shoreline change trends? How do seasonal and climatic variability effect beach morphology and shoreline change? Should the effects of long recurrence interval subsidence events be included in management scale predictive models?

This paper addresses these coastal change questions through a sediment-budget analysis. A sediment budget employs conservation of mass to quantify sediment sources, sinks, and pathways in a littoral cell environment (e.g. Komar, 1998). Moreover, a sediment budget can be used to quantify the effects of changing sediment supply on the coastal system and to understand the large-scale morphological responses of the coastal system (Jimenez *et al.*, 1991). Previous work has shown that throughout the last several thousand years the Columbia River has supplied sand to nearby bays (Peterson and Phipps, 1992; Gates, 1994), coastal dunes, the continental shelf (Nittrouer, 1978), and the continental slope and submarine canyons and fans (Sternberg, 1986). In the only sediment budget reported for the Washington shelf, Sternberg (1986) suggests that 84% of the annual Columbia River input can be accounted for on the shelf, slope, and deep-sea canyons and fans. Sternberg (1986) did not, however, estimate the sediment supply to the inner shelf, bays, and coastal barriers. By quantifying the amount of sand that occupies each of these environments, hope to better understand the Columbia River dispersal system and better predict the response to changes in the system, whether they are natural or human-induced. To help separate natural from human-induced changes in the littoral cell, the sediment budget is being calculated for pre-historic periods as well as for historic and recent periods. By examining the sediment budget from various time periods, we can compare the natural variability in the system to the system that is being forced by human intervention.

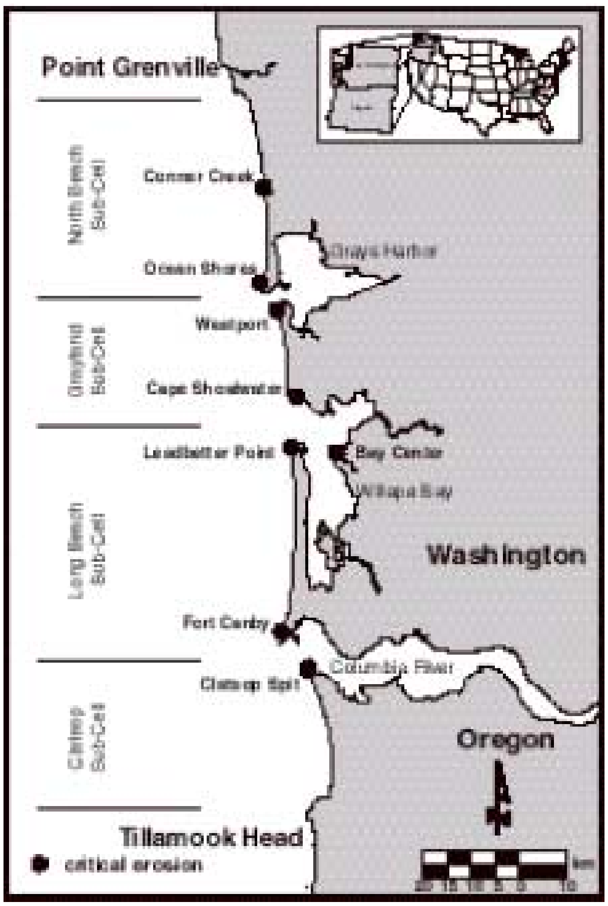
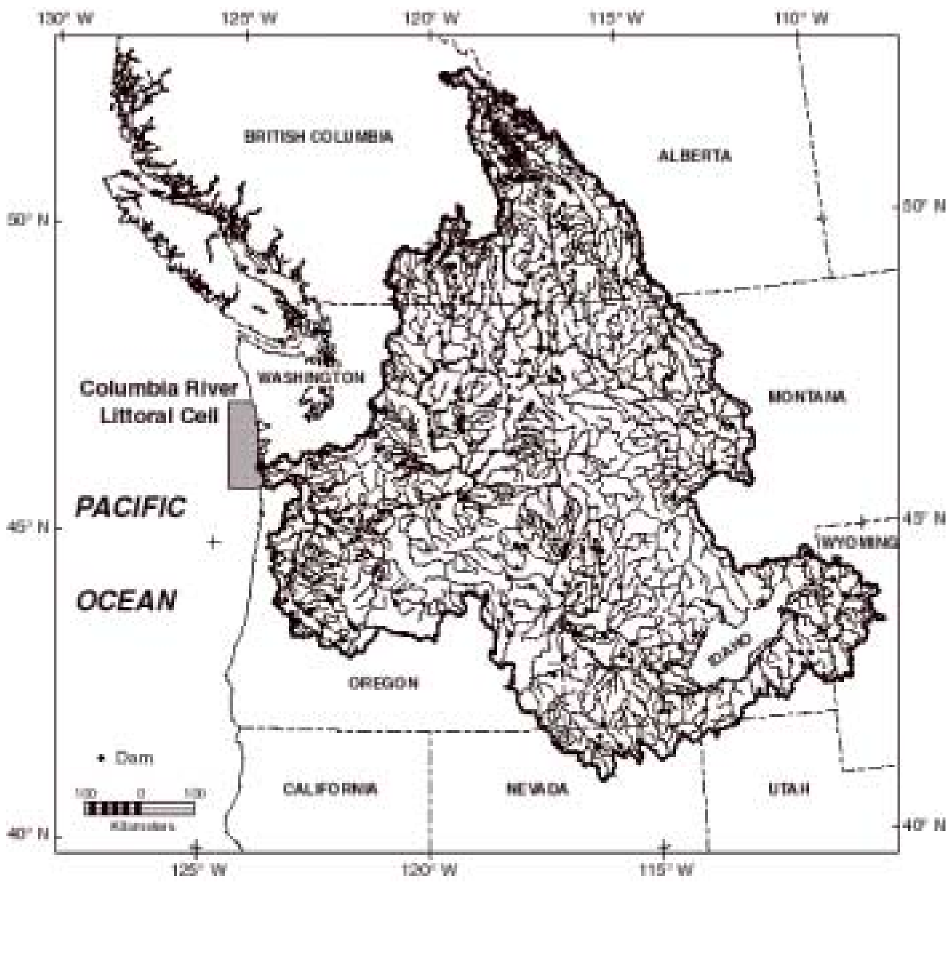


Figure 2. Study area map showing the Columbia River littoral cell, sub-cell boundaries, and the locations

The Columbia River littoral cell (CRLC) is approximately 165 km long and extends from Tillamook Head, Oregon to Point Grenville, Washington (Peterson *et al.*, 1991) (Figure 2). The cell is subdivided by three large estuaries: Grays Harbor, Willapa Bay, and the Columbia River estuary. These bays and two headlands divide the Columbia River littoral cell into four arcuate shaped sub-cells denoted as: Clatsop Plains, Long Beach Peninsula, Grayland Plains, and North Beach. The beaches are characterized by wide surf zones and large longshore sand bars. Beach sands are 0.15-0.25 mm in size, with the mean size decreasing with distance from the Columbia River (Peterson *et al*., 1994; Ruggiero *et al*., this volume).

Wave energy is high in the Pacific Northwest with monthly mean significant wave heights varying between 1.0 and 3.0 m, and wave periods varying between 8 and 12 s. Extreme winter storms produce significant wave heights of over 7 m and peak periods over 17 s (Ruggiero *et al.,* 1997). Tides are mixed semi-diurnal with a 2-4 m range driving tidal circulation on the inner shelf and large tidal exchanges at the entrances to Grays Harbor, Willapa Bay, and the Columbia River estuary. The combination of sediment supply and tidal range has produced large flood- and ebb-tidal deltas at all three estuary entrances. Freshwater discharge from Grays Harbor and Willapa Bay is small, but the Columbia River discharge is large (3rd largest in U.S.) with an annual mean flow of about 6,000 m^3/s. With the introduction of eleven major and over 200 smaller dams in the mid 1900s (Figure 3), flow regulation to prevent flooding in the Columbia River basin has had a significant impact on decreasing peak flows (Sherwood *et al*., 1990).



This paper outlines a conceptual framework for evaluating a sediment budget for the CRLC and presents a preliminary budget over several time scales. This budget is based on a combination of results from ongoing geologic and shoreface-process studies (Gibbs and Gelfenbaum, this volume; Peterson *et al.*, this volume; Ruggiero *et al.*, this volume; Kaminsky *et al.*, in press; Ruggiero *et al.*, 1998) and from earlier work (Sternberg, 1986; Sherwood *et al.*, 1990; Peterson and Phipps, 1992; Gates, 1994; Wolf *et al.*, 1998; Woxell, 1998). Ultimately, a well-developed, quantitative sediment budget for this littoral system will serve as a basis for predictions of future shoreline position based on the sediment supply.

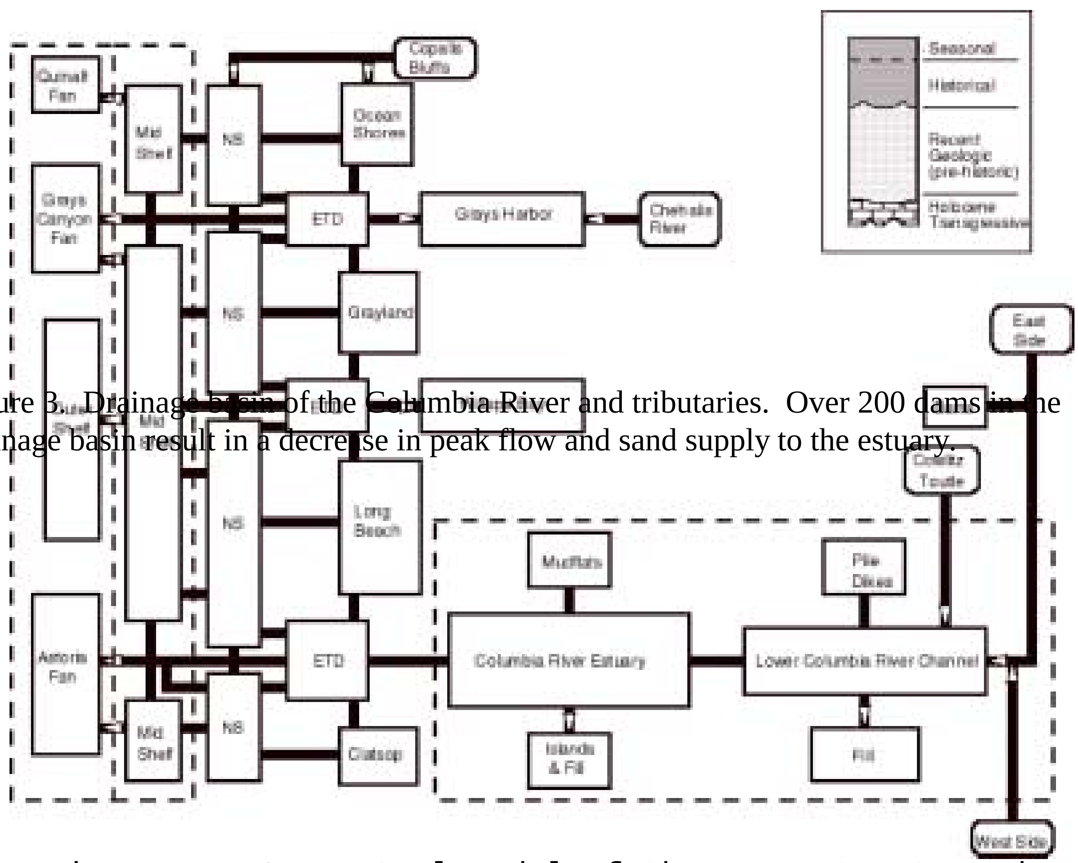


Figure 3. Drainage basin of the Columbia River and tributaries. Over 200 dams in the drainage basin result in a decrease in peak flow and sand supply to the estuary.

Figure 4. Conceptual model of the compartments and pathways for the Columbia River littoral cell sediment budget. Rounded boxes represent sources, NS=nearshore, ETD=ebb-tidal delta.

CONCEPTUAL MODEL OF COLUMBIA RIVER LITTORAL CELL SEDIMENT BUDGET

Identification of Compartments and Pathways

The southwest Washington coastal system has natural boundaries that coincide closely with the distribution of sand derived from the Columbia River (Figure 2). A proposed set of budget compartments is shown in Figure 4. Each compartment represents a generalized sedimentary environment, but most actually incorporate several sedimentary environments. Each compartment is connected with adjacent and distinct compartments by a limited number of transport pathways. When numerous sedimentary environments are grouped (e.g., islands and filled regions in the Columbia River Estuary), the objective has been to simplify the compartments to reveal the overall budget. On the other hand, some continuous environments (such as the nearshore zone) have been subdivided to correspond with adjacent beaches. In these cases, the objective has been to clarify the connections and sand exchanges among geographically adjacent compartments. To some extent, the size of the compartments must be chosen to match available budget data.

For purposes of inventory, the compartments have vertical sections that correspond to the time-stratigraphic column shown in the upper right of Figure 4. We can use stratigraphic information to relate deposits to inventory changes over various time periods.

Fluxes occur exclusively along the transport pathways indicated with thick lines in Figure 4. The pathways are, in general, bi-directional. A few of the pathways are unidirectional; these are indicated with arrows. Transport pathways include both natural phenomena and human activity (e.g., dredging).

Compartments Identified in the Sediment Budget

Sources of Sand

The primary source of sand is the Columbia River, which provides sand with three provenances: the main basin east of the Cascade crest (East Side); the Cowlitz and Toutle River drainages (Cowlitz/Toutle), and other west-side river basins, including the Willamette, Lewis, and White Rivers (West Side) (Sherwood and Creager, 1990). Much smaller sources of sand include the Chehalis River (Chehalis River) and erosion of bluffs near Copalis Rock (Copalis Bluffs). Transport from these sources is one way. There are no other significant sources of sand for the coastal system. Erosion of pre-Holocene deposits, supply from other rivers, and littoral transport from other systems is considered negligible.

Reservoirs and Estuaries

Sand may be accumulating in reservoirs behind dams in the eastern sub-basin and along the main stem of the Columbia River (Dams). Sand transported from the East Side may be diverted to this compartment and, under some circumstances, the reservoirs might act as a source of sand contributing to supply from the West Side. The proposed framework includes several river channel and estuary compartments for sand budget estimates. The lower Columbia River channel (Lower CR Channel) includes large sand supplies associated with bar deposits and large bedforms. In general, river beds aggrade at low rates and, in the absence of human alterations to the system, most sand supplied to the upper end of the lower CR channel might transit the reach and enter the estuary. The net accumulation rate caused by permanent storage within the reach can be estimated from stratigraphic evidence. However, due to damming of the Columbia River and channel maintenance activities, recent sediment fluxes likely do not reflect longer-term Holocene rates. In particular, human activities have resulted in permanent removal of sand from the river channel, and changes in channel sand storage patterns. A compartment (Fill) has been added to specify sand permanently removed from the active channel system by dredging and filling activities, sand mining, etc., and a compartment (Pile Dikes) has been designated to represent temporary storage of sand (e.g. in accumulations behind pile dikes) in the altered river system. In the estuary proper (CR Estuary), sand may be temporarily stored in bars, shoals, estuary beaches, and mudflat (Mudflats) or permanently removed to diked islands, or spoil islands (Islands & Fill).

Compartments are also assigned to the other large estuaries in the study area (Grays Harbor) and (Willapa Bay). Note that the proposed transport is unidirectional into Willapa Bay and Grays Harbor. Although this is not strictly true, it should be sufficiently accurate for budget purposes. Also, direct exchange between the beaches and estuaries is not included.

Beaches, Nearshore Regions, and Ebb-Tidal Deltas

Compartments representing beaches flank entrances to the three estuaries. Beach compartments (Clatsop Plains, Long Beach, Grayland, and North Beach) include the foreshore and dunes. In the proposed framework, beaches only exchange sediment with adjacent nearshore compartments (NS) or with adjacent ebb-tidal deltas (ETD). This acknowledges the key role that these areas play in both temporary and long-term storage of sand. The present framework is not sufficiently detailed to address changes in erosion or deposition within a sub-cell, although that is information is becoming available.

Mid-Shelf Compartments

The mid-shelf region has been subdivided into three compartments (Mid Shelf). Compartment boundaries coincide with submarine canyons that likely interrupted alongshelf transport during lowstands of sea level. Although the mid-shelf regions play a less dynamic role in the sand budget, they are important to include because they provide long-term sand storage, and several estimates of shelf deposition rate have been made that allow the mid-shelf compartments to place useful constraints on other boxes. In particular, these offshore sinks can be used to estimate the pre-historical supply of sediment from the Columbia River.

Ultimate Sinks of Sand

Several compartments represent sinks for sand in the coastal system. These include the submarine fans and abyssal plains (Astoria Fan, Grays Harbor Fan, and Quinalt Fan) and the outer portion of the central Washington continental shelf and slope. These offshore sinks are grouped in a single dashed box in Figure 4. Also included as sink compartments are diked islands, and artificially filled areas in the estuary and along the riverbanks. Transport is one way into all of these sink compartments.

Conservation of Sand

At any given time since the onset of the Holocene, the sand budget must balance over the entire system. That is, the sum of all sand from the source compartments, must equal the amount delivered to the sink compartments plus the amount accumulating in other compartments. Long-term estimates of deposition rates in the sink compartments can be used to place lower limits on the sand supply from the various sources. Likewise, comparisons of long-term deposition in the lower Columbia River valley (shown in Figure 4 as a dashed box that encompasses the Columbia River estuary and the lower Columbia River valley) and long-term supply from the Columbia River may be used to put constraints on the supply to coastal regions beyond the estuary.

PRELIMINARY ESTIMATES OF THE CRLC SEDIMENT BUDGET

Sediment-transport pathways and patterns of sediment accumulation for the CRLC are not static, but change over geological, historical, and seasonal time scales. Some changes in the sediment budget are the result of natural cycles such as long-term changes in sea level, or of short-term fluctuations such as in wind and wave directions. Other changes in pathways and sinks in the sediment budget are the result of human influences, such as the construction of jetties, or dredging practices. By comparing the sediment budget from the period prior to human influence (over recent geological time scales) to the budget during the historical period (since about the 1870s), we can begin to understand the anthropogenic effects on the system. In addition, by examining short-term seasonal fluctuations in sediment fluxes, we can put expected limits on predictions from long-term trends. Accumulation rates discussed below are based on the in-situ volume of sediment in a particular environment that has accumulated over a particular period of time, and reported in m^3/yr.

Geological Time Scales

During the last 10,000 years, Columbia River sediment accumulated seaward of the shelf edge, on the continental shelf, in the bays, and on the barriers. During this time, the local rate of sea-level rise decreased substantially (Peterson and Phipps, 1992). From 10,000 to 8,000 years ago, sea level rose from about 55 to 23 m below present mean sea level (msl), at an average rate of 1.6 cm/yr. From 8,000 to 5,000 years ago, sea level rose from 23 to 9 m below present msl, at a slower rate of 0.47 cm/yr. In the last 5,000 years sea level rose to its present stage at an average rate of only 0.16 cm/yr. When sea level was lower, the Columbia River extended further across the shelf and sediment moved directly into Astoria Canyon. As sea level rose rapidly from 10-5,000 years ago, shelf and bay accommodation was large and sand accumulated rapidly on the shelf and in the bays. Preliminary calculations of sediment volumes accumulating since the rise of sea level (based on analysis of high-resolution seismic data) show 65 x 10^9 m^3 of sediment on the shelf with the greatest amount near the mouth of the Columbia River and decreasing toward the north and south. From the Columbia River south to Tillamook Head, 21 x 10^9 m^3 of sediment has accumulated on the shelf. From the Columbia River north to Willapa Bay, 36 x

10^9 m^3 of sediment has accumulated; from Willapa Bay to Grays Harbor, 8 x 10^9 m^3 has accumulated; and from Grays Harbor to Point Grenville, 6 x 10^9 m^3 of sediment has accumulated on the shelf. These volumes include sand-size and finer material. Averaged over the past 10,000 years, they indicate a mean long-term accumulation rate of 6.5 x 10^6 m^3/yr. Sternberg (1986) and Wolf *et al.* (in press) suggest that an additional 37 x 10^9 m^3 of Columbia River sediment has accumulated on the continental slopes, canyons, and fans off Washington and Oregon in the last 5,000 years.

Grays Harbor, Willapa Bay and the lower Columbia River basin have been significant sinks of Columbia River sediment as well. Seismic data in Grays Harbor show a 60-70 m deep basin prior to filling by a combination of locally-derived sediment and by Columbia River sand (Peterson and Phipps, 1992). We estimate that accumulation rates of Columbia River sand in Grays Harbor decreased from 0.6 x 10^6 m^3/yr 7,000 years ago to 0.2 x 10^6 m^3/yr in the last 5000 years. The total volume of Columbia River sand that has accumulated in Grays Harbor is 4.4 x 10^9 m^3. Accumulation in Willapa Bay is not yet calculated, but seismic data suggest its basin was one-half the depth of Grays Harbor (Wolf *et al.*, 1998); thus we assume it has less Columbia River sediment in it than Grays Harbor. Stratigraphic evidence indicates that the lower Columbia River valley accumulated sediment at a rate of 8.5 x 10^6 m^3/yr prior to 7,000 years ago, and at a rate of 3.6 x 10^6 m^3/yr in the last 7000 years (Gates, 1994). The total volume of accumulated sediment in the Columbia River valley during the last 10,000 years is 50 x 10^9 m^3.

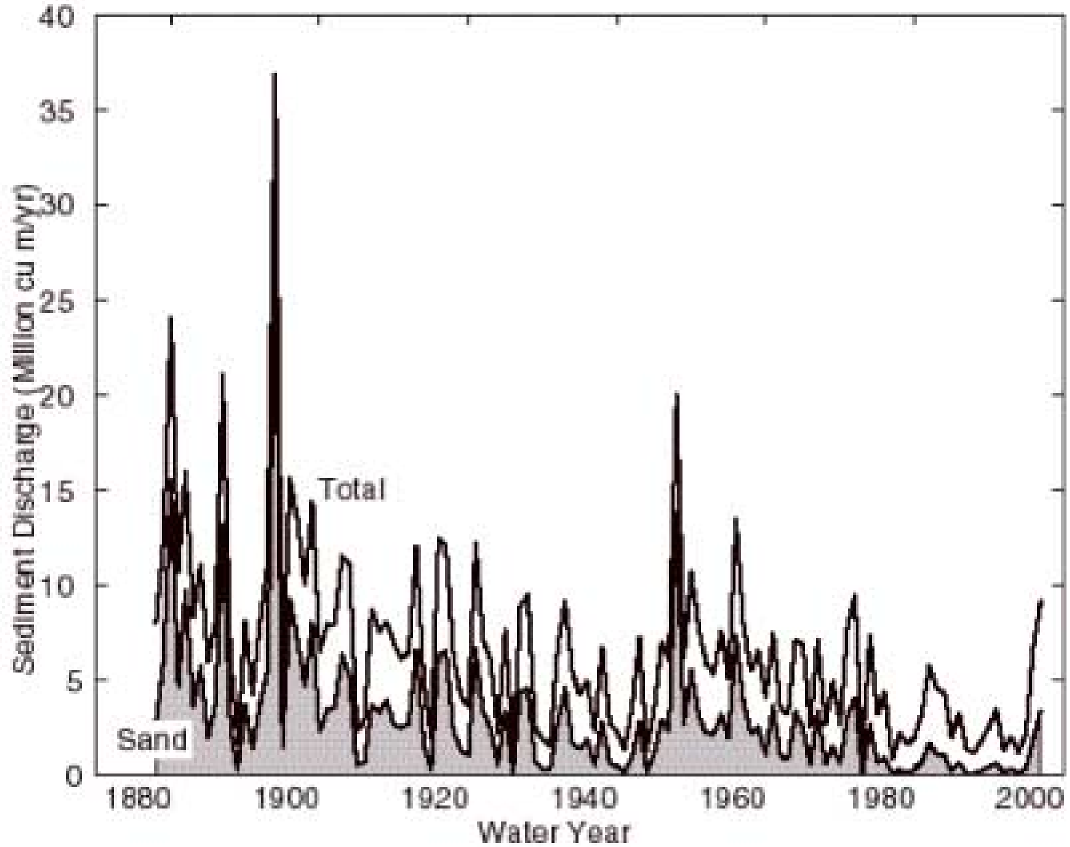
As the rate of sea-level rise slowed around 4-5,000 years ago, the barriers adjacent to the Columbia River, at Long Beach and Clatsop, began accumulating sediment and prograded seaward (Woxell, 1998; Peterson *et al.*, this volume). The barriers furthest away from the Columbia River, Grayland and North Beach, began prograding seaward around 2,000 and 1,500 years ago, respectively. Barrier progradation was relatively uniform within each of the sub-cells, whereas among the sub-cells, the pre-historic accumulation rates decreased away from the Columbia River source. Accumulation rates for each of the sub-cells were calculated using the total cell length times the mean progradation rate times the thickness, where the thickness is the average elevation of the barrier above a vertical datum plus the closure depth below that datum. We chose a mean elevation of the dunes of +5 m and a depth of closure of –15 m for a total thickness of 20 m. Accumulation rates were highest for the Long Beach sub-cell at 0.39 x 10^6 m^3/yr and Clatsop sub-cell at 0.33 x 10^6 m^3/yr and decreased to 0.22 x 10^6 m^3/yr for the Grayland sub-cell and 0.24 x 10^6 m^3/yr for the North Beach sub-cell. Total pre-historical volume accumulation of Columbia River sand for all the barriers in the CRLC was 4.07 x 10^9 m^3.

The long-term pre-historical sediment supply over the last 10,000 years from the Columbia River can be estimated by summing the weighted accumulation rates for the different time intervals in the various sedimentary environments of the CRLC. Using the above estimates of sediment accumulation throughout the CRLC, and assuming Willapa Bay filled at half the rate of Grays Harbor, the long-term supply rate of Columbia River sediment to the lower river valley was about 20 x 10^6 m^3/yr, and sediment left the estuary at a long-term rate of 15 x 10^6 m^3/yr. These supply rates are for total sediment load, including sand, silt, and clay. Further work will allow us to partition the sand from the silt and clay components.

Historical Time Scales

The Columbia River is the predominant source of sediment for the continental shelf and littoral zones of southwest Washington, but the actual sediment load of the Columbia River has not been adequately measured. Sherwood *et al*. (1990) used a rating curve (based on USGS measurements at Vancouver, WA in water years 1964–1970) to hindcast sediment discharge from daily riverflow measured since 1878 at The Dalles, OR. That estimate has been updated with riverflow data through water year 1997 (Figure 5). The updated estimate, as well as others (Van Winkle, 1914a,b; Judson and Ritter, 1964; Sherwood *et al*., 1990) differ by as much as 30% for comparable periods. The relationship between riverflow and sediment discharge is simplistic, does not explicitly account for sediment from the Willamette and Toutle-Cowlitz drainages, and has probably changed over the last century as dam construction, modifications of the river channel, the 1981 eruption of Mt. St. Helens, and changes in land-use practices have altered the fluvial environment and sediment supply. With these caveats, the hindcast calculations indicate that the mean annual sediment (sand) supply to the estuary for 1878-1997 is 6.6 x 10^6 (3.0 x 10^6) m^3/yr. However, with the construction of over 200 dams in the Columbia River drainage basin, regulation of peak river flows has greatly reduced the transport capacity of the Columbia River. Sediment (sand) supply has decreased from 8.7 x 10^6 (4.3 x 10^6) m^3/yr (for the period 1878–1934, prior to significant flow modification by dams) to 4.3 x 10^6 (1.4 x 10^6) m^3/yr (for the period 1958–1997), a decrease by a factor of 3 during historical times.

Not all of the sediment supplied in historical times to the Columbia River Estuary has reached the Pacific Ocean. Approximately 1.8 x 10^6 m^3/yr of fine sand, silt, and clay accumulated in peripheral bays, and upriver channels between 1868 and 1958 (subareas 4-6 and 8-13 in Sherwood *et al*., 1990); probably 80% of this is sand (Sherwood and Creager, 1990), so it accounts for 48% of the mean annual sand supply, but only about 10% of the finer fraction. This estimate, based on bathymetric changes from 1868–1958 (Sherwood *et al*., 1990), excludes sands that once occupied the flood- and ebb-tidal delta complex. Examinations of historical changes of the entrance region (Lockett, 1963; CRDDP, 1983; Sherwood *et al*., 1990) indicate that this sand has been eroded from the main channel and deposited in several regions. Depositional regions include the adjacent Clatsop and Peacock Spits, a deeper offshore ebb-tidal bar, and several shoals and emergent islands immediately inside the entrance (Baker Bay, Trestle Bay, Sand Island, and Desdemona Sands. By combining data of Sherwood *et al*., 1990 with bathymetric-difference calculations of Byrnes and Li (1999), we estimate that the historical accumulation rate in the ebb/flood-tidal delta complex is only about 0.3 x 10^6 m^3/yr.



Analysis of historical shoreline positions shows that beach accretion rates increased substantially during early historical periods over pre-historical periods (Woxell, 1998; Kaminsky *et al.*, this volume). The total volume of sand lost or gained due to shoreline change was calculated using a Digital Elevation Model (DEM). The shape of the beach profile is assumed to be constant over time, so any loss or gain of sand moves the entire profile from closure depth up to the height of the dune. Closure depth was estimated as –15 m msl using Birkemeier (1985). Accumulation rates for the early historical period from the 1870s to the 1950s vary from 1.21 x 10^6 m^3/yr for the Grayland sub-cell to 2.48 x 10^6 m^3/yr for the North Beach sub-cell (Table 1). As with the shoreline-change rates reported in Kaminsky *et al.* (this volume), the accumulation rates are not uniform within the sub-cells. More sand accumulated on the barriers near the entrance to Grays Harbor and the Columbia River than in the center of the sub-cells during the pre-dam historical period. This time period includes the construction of the jetties at the entrances to the Columbia River Estuary and Grays Harbor, and is prior to significant modification of the Columbia River drainage basin due to dams. More recently (1950s to 1995), accumulation rates vary from 0.26 x 10^6 m^3/yr for the Grayland sub-cell to 2.10 x 10^6 m^3/yr for Long Beach. Except for the Long Beach sub-cell, where the early and recent historical accumulation rates have stayed about the same, accumulation rates decreased in recent historical time for the Clatsop, Grayland, and North Beach sub-cells. Accumulation rates during the early historical period are 5 to 10 times greater than the long-term pre-historical rates of accretion (Table 1).

Table 1. Accumulation rates of Columbia River sand on the barrier of each sub-cell.

Barrier Sub-Cell	Sediment Accumulation Rate (x 10^6 m^3/yr)		
	Pre-Historical* (since start of barrier accretion)	Historical	
		(1870s-1950s)	(1950s-1995)
Clatsop	0.33	2.01	0.57
Long Beach	0.39	1.98	2.10
Grayland	0.22	1.21	0.26
North Beach	0.24	2.48	1.43

* based on pre-historical shoreline change rates from Woxell (1998).

We know that the middle and inner shelf of the CRLC has accumulated enormous amounts of Columbia River sediment (~65 x 10^9 m^3) since the last transgression. Sternberg (1986) sites evidence from Nittrouer (1978) that the modern accumulation rate in the mid-shelf silt deposit is similar to the rate estimated for the last 3,000-7,000 years. There is less evidence of regional accumulation of sand for the inner shelf during historical time. In fact, regional bathymetric change studies conducted by differencing historical hydrographic surveys from the 1870s and the 1920s suggest that some areas of the inner shelf may have lost sand (Gibbs and Gelfenbaum, this volume). For example, the inner shelf off Grayland was acting as a source of sediment between the 1870s and 1920s, losing 0.81 x 10^6 m^3/yr of sand. Off Long Beach, however, the inner shelf gained sand at a rate of 1.09 x 10^6 m^3/yr. The last regional bathymetric survey was in the 1920s, so it is unknown how the inner shelf has responded over the last 70 years.

Estimates of the sediment budget of the CRLC during historical times must consider direct human-induced transport of sand. The U.S. Army Corps of Engineers dredges an average of 3.41 x 10^6 m^3/yr of sand from the lower estuary (Table 2) (U.S. Army Engineer District, Portland, 1998). The dredged sand is placed in disposal sites inside the estuary (Inside), in the entrance (Entrance), and offshore (Outside). Dredging records since 1956 reveal that the majority of sand, approximately 2.1 x 10^6 m^3/yr are moved to offshore disposal sites. These offshore sites are on various parts of the ebb-tidal delta in water depths ranging from 15 to 55 m. An unknown amount of the sand placed on the ebb-tidal delta may be transported back into the estuary. The amount of dredged material that stays in the active littoral zone is unknown. Although side-scan sonar records taken in the mouth of the Columbia River estuary (Sherwood and Creager, 1990) reveal both upstream and downstream oriented bedforms, net transport at the mouth has not been directly measured.

Table 2. Mean annual volume of dredged material disposed near the mouth of the Columbia River* (x 10^6 m^3/yr)

Period	Outside	Entrance	Inside	Total
1956 to 1976	1.86	0.44	0.64	2.97
1977 to 1985	2.01	2.59	0.11	4.71
1986 to 1998	2.93	0.93	0	3.85
1956 to 1998	2.11	0.97	0.33	3.41

* Source: U.S. Army Engineer District, Portland (1998).

Seasonal Time Scales

In order to understand the natural variability that exists around the long-term averages discussed above, it is important to quantify short-term variations in transport. Transport of sand along the shelf and in the littoral zone along the beaches changes magnitude and direction seasonally. Summer conditions result in southerly shelf currents with little transport capacity and weak southerly-directed littoral transport. Winter conditions result in stronger northerly shelf currents (Gross *et al.*, 1969) and large northerly-directed littoral drift. Simple longshore transport calculations for a single location using 20 years of hindcast waves suggest nearly constant monthly mean southward sand transport of between 5-10 x 10^6 m^3/yr (Figure 6). Monthly mean northward longshore transport varies from 0.5-45 x 10^6 m^3/yr with the largest transport occurring during November, December, January, and February. For these hindcast wave data, net littoral transport was northerly directed each year from 1956-1975 and varied between 2-12 x 10^6 m^3/yr. The inter annual and annual variations in wave direction may be well represented by the hindcast wave data, but because the wave heights are over-estimated by 45% as compared to buoy data, the magnitude of the transport will be over-estimated by as much as a factor of 2. Moreover, longshore transport will vary across the CRLC as shoreline angles vary.

Table 3. Seasonal and annual beach changes (x 10^6 m^3/yr). Negative values are erosion.

Sub-Cell	Summer 97-Winter 98	Summer 97-Summer 98
North Beach	-2.75	-0.03
Grayland	-4.08	-0.48
Long Beach	-10.59	-0.47
Clatsop	-0.96	1.67

In addition to seasonal variations in longshore transport directions, there is a seasonal signal in the cross-shore transport as well. Beach volumes were calculated between the 1.0 m and 4.0 m contours as determined from the summer 1997 surveys. The volume change over this cross-shore distance was calculated between the summer 1997 profiles and the winter 1998 profiles, and then again between the summer 1997 profiles and the summer 1998 profiles. During winter months, large waves and elevated sea-levels result in the offshore transport of beach sand. Conversely, during the summer season, sand is moved onshore, back on to the beaches by smaller waves. Table 3 summarizes the volume changes for each sub-cell over the past year from beach profiles.

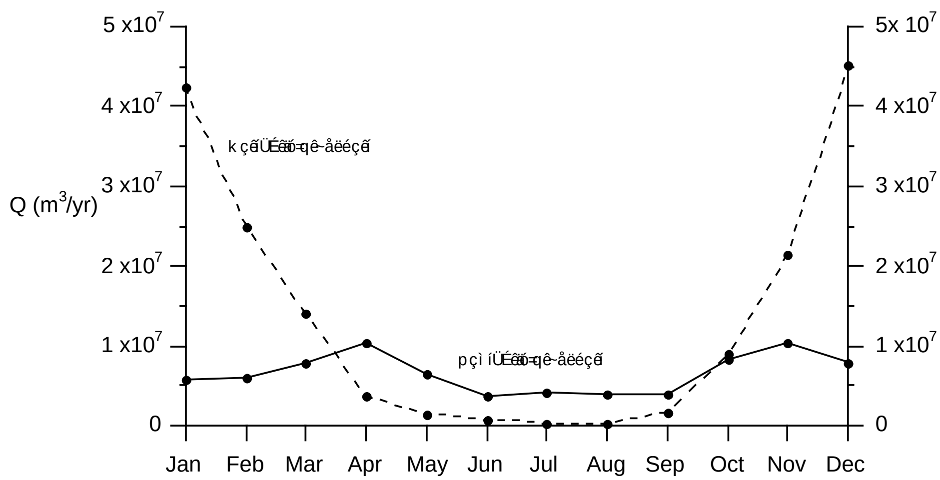


Figure 6. Monthly mean longshore transport using 20 years of hindcast wave data.

CONCLUSION

Although the sediment budget presented here is preliminary and much work is needed to quantify all the compartments and pathways of the CRLC, several observations can be drawn from our analysis.

1. The majority of Columbia River sediment has accumulated on the continental shelf, in the deep sea, and in the estuaries. The amount in the beaches, by comparison, is smaller.
2. Average sediment supply from the Columbia River was apparently much greater for the last 10,000 years than it is now, possibly reflecting the contribution of several unmitigated volcanic eruptions, erosion of glacial deposits, and extreme floods.
3. Early historical shoreline accretion rates are much greater than pre-historical rates, and in general, greater than recent accretion rates. The timing of

the rapid accretion in the early part of the century and the longshore variation in the accretion suggest changes in the ebb-tidal deltas after jetty construction as the primary cause.

4. Ebb-tidal deltas and the inner shelf may act as temporary sources of sediment to the beaches.
5. Sediment supply from the Columbia River to the estuary has likely been reduced over the last several decades due to reduction in transport capacity resulting from flow regulation, and possible direct trapping behind dams.
6. The volume of dredged material placed at the mouth of the Columbia River is large compared to long-term changes in the tidal-delta complex.
7. Seasonal fluxes of sand on the inner shelf and on the beaches are large compared to long-term averages, therefore it may take several years to resolve changes in shoreline position trends.
8. Extrapolating short-term sediment fluxes to long-term trends can be misleading.

Questions remaining to be resolved:

1. What is the exchange of sediment, if any, between the inner shelf and the beaches?
2. Are Grays Harbor and Willapa Bay presently accumulating Columbia River sediment or have they reached equilibrium?
3. Is the inner shelf still accumulating Columbia River sediment as it has in the past, or is it stable, or perhaps a source to another sedimentary environment in the CRLC?
4. How much of the dredged material disposed near the mouth of the Columbia River is available to the littoral cell?
5. Has the supply of sediment from the Columbia River stabilized, and how long does it take the littoral system to adjust to changes in supply?

ACKNOWLEDGEMENTS

The Southwest Washington Coastal Erosion Study is jointly funded by the U.S. Geological Survey and the Washington State Department of Ecology. The participation and support of our local partners is greatly appreciated. Numerous people have assisted in the collection, and analysis of data that were used in this study, and their contributions are greatly appreciated. The authors thank Larry Phillips and Walter Barnhardt for their critical reviews of an early version of this manuscript.

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