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Historical changes in the Columbia River Estuary

CHRISTOPHER R. SHERWOOD[1], DAVID A. JAY[2], R. BRADFORD HARVEY[3], PETER HAMILTON[4] and CHARLES A. SIMENSTAD[5]

[1]*School of Oceanography, University of Washington, Seattle, WA 98195, USA and Battelle, Pacific Marine Sciences Laboratories, Sequim, WA 98382, USA*

[2]*Geophysics Program, University of Washington, Seattle, WA 98195, USA*

[3]*Northwest Cartography, Inc., Seattle, WA 98115, USA*

[4]*Science Applications International Corporation, Raleigh, NC 27606, USA*

[5]*Fisheries Research Institute, University of Washington, Seattle, WA 98195, USA*

Abstract – Historical changes in the hydrology, sedimentology, and physical oceanography of the Columbia River Estuary have been evaluated with a combination of statistical, cartographic, and numerical-modelling techniques. Comparison of data digitized from US Coast and Geodetic Survey bathymetric surveys conducted in the periods 1867-75, 1926-37, and 1949-58 reveals that large changes in the morphology of the estuary have been caused by navigational improvements (jetties, dredged channels, and pile dikes) and by the diking and filling of much of the wetland area. Lesser changes are attributable to natural shoaling and erosion. There has been roughly a 15% decrease in tidal prism and a net accumulation of about 68 x $10^6 m^3$ of sediment in the estuary. Large volumes of sediment have been eroded from the entrance region and deposited on the continental shelf and in the balance of the estuary, contributing to formation of new land. The bathymetric data indicate that, ignoring erosion at the entrance, 370 to 485 x $10^6 m^3$ of sediment has been deposited in the estuary since 1868 at an average rate of about 0.5cm y^{-1}, roughly 5 times the rate at which sea level has fallen locally since the turn of the century.

Riverflow data indicate that the seasonal flow cycle of the Columbia River has been significantly altered by regulation and diversion of water for irrigation. The greatest changes have occurred in the last thirty years. Flow variability over periods greater than a month has been significantly damped and the net discharge has been slightly reduced. These changes in riverflow are too recent to be reflected in the available bathymetric data.

Results from a laterally averaged, multiple-channel, two-dimensional numerical flow model (described in HAMILTON, 1990) suggest that the changes in morphology and riverflow have reduced mixing, increased stratification, altered the response to fortnightly (neap-spring) changes in tidal forcing, and decreased the salinity intrusion length and the transport of salt into the estuary.

The overall effects of human intervention in the physical processes of the Columbia River Estuary (i.e. decrease in freshwater inflow, tidal prism, and mixing; increase in flushing time and fine sediment deposition, and net accumulation of sediment) are qualitatively similar to those observed in less energetic and more obviously altered estuarine systems. A concurrent reduction in wetland habitats has resulted in an estimated 82% reduction in emergent plant production and a 15% reduction in benthic macroalgae production, a combined production loss of 51,675 metric tons of organic carbon per year. This has been at least partially compensated by a large increase in the supply of riverine detritus derived from freshwater phytoplankton primary production. Comparison of modern and estimated preregulation organic carbon budgets for the estuary indicates a shift from a food web based on comparatively refractory macrodetritus derived from emergent vegetation to one involving more labile microdetritus derived from allochthonous phytoplankton. The shift has been driven by human-induced changes to the physical environment of the estuary.

While this is a relatively comprehensive study of historical physical changes, it is incomplete in that the sediment budget is still uncertain. More precise quantification of the modern estuarine sediment budget will require both a better understanding of the fluvial input and dredging export terms and a sediment transport model designed to explain historical changes in the sediment budget. Oceanographic studies to better determine the mechanisms leading to the formation of the turbidity maximum are also needed. The combination of cartography and modelling used in this study should be applicable in other systems where large changes in morphology have occurred in historical time.

CONTENTS

1. INTRODUCTION

The papers in this volume document the present physical state of the Columbia River Estuary and analyze the functioning of the ecosystem in relation to the physical environment. An understanding of the present functioning of the system inevitably implies, however, a temporal dimension extending back through historical time and beyond. Estuaries respond to influences acting over time periods ranging from seconds (wave motions) to thousands of years (tectonic activity and glaciation). The response of circulation to human-induced changes in estuarine morphology is immediate; the subsequent natural adjustment of bathymetry to the new flow regime occurs more slowly. Biological responses, including behavioural responses of migrant species, occur on time scales which are related to those of physical processes and to the life cycles of the organisms. Meanwhile, changes in sediment supply, riverflow, or biological parameters may occur which confound analysis of the response to the first alteration. We have only historical records of the most basic physical changes (those of riverflow and bathymetry) with which to address all aspects of estuarine change induced by humans. This paper outlines a systematic approach to the evaluation of estuarine change using historical data and a judicious combination of modelling and inference. This paper is also a description of the physical and biological effects of human intervention in the Columbia River Basin and estuary.

The Columbia River Estuary ecosystem is less altered than many of the more-studied estuaries of the Atlantic seaboard, where human influence has been overwhelming. Nonetheless, substantial areas have been diked, filled, or otherwise removed from the estuary. Shorelines have been urbanized, farmed, or logged. Dredging, dredged material disposal, and pile dikes have altered the morphology and distribution of flow in the system. Jetties at the entrance have moved the mouth of the estuary and the ebb tidal delta seaward; the hydrological regime has been greatly altered by storage and diversion of water in the river basin; the enormous salmon runs that once passed through the estuary have been vastly reduced; and non-native fish and invertebrate species have been introduced. Changes in the quality of incoming water have also occurred, but water quality in the Columbia River Estuary has not become the major problem that it is in many less-dynamic estuaries.

Topics to be addressed here by examining historical trends include the relative importance of flow regulation and diversion, jetties, pile dikes, dredging, and dredged-material disposal on the sediment budget, sediment distribution, and circulation; the effects of habitat loss on the estuarine biota; the changes in the food web induced by changes in the estuary and changes in fluvial organic carbon contributions; and the effects of estuarine alterations on migratory salmonoids. More specifically:

1. historical changes in freshwater inflow will be described and analyzed;
2. morphological changes that have taken place in the estuary since 1865 will be quantitatively estimated;
3. the relative importance of navigational development of the estuary and river channel vis-a-vis alteration of the freshwater flow cycle, in causing these morphological changes will be investigated;
4. historical changes in the velocity field, salinity patterns, and location of the turbidity maximum will be examined using a two-dimensional, laterally averaged, multiple-channel model;
5. changes in the sediment budget will be assessed in qualitative terms, and;
6. a discussion of possible human-induced effects on the ecosystem caused by changes in the estuary and river will be presented.

We have attempted to combine modern cartographic and numerical modelling methods with a careful interpretation of the historical record in order to address these topics. We were fortunate in that a longer freshwater flow record exists for the Columbia River than for any other river in the western United States. As described in Section 2, monthly mean flows at the mouth are available from 1928, while daily flows from the eastern part of the drainage basin are available from 1878. These riverflow data predate most of the large human alterations caused by dams and irrigation withdrawal but not those caused by logging and agriculture in the watershed. Statistical analyses are used to examine historical trends and separate the influence of human (irrigation withdrawal and flow regulation) from long-term climate fluctuations.

The historical bathymetric database is also extensive. In addition to qualitative accounts of historical alterations and early charts from the period 1792-1860 that lack adequate geodetic control, there exists an excellent set of surveys collected by the US Coast Survey [later the US Coast and Geodetic Survey (USCGS), now the National Ocean Service (NOS)] between 1867-1877. These bathymetric data predate navigational alterations and large-scale commercial fishing (which both became significant in the 1870s; OREGON HISTORICAL SOCIETY, 1980). These and later data were exploited systematically by mapping bathymetric changes between surveys conducted at 20- to 50-year intervals between 1867 and 1981. These bathymetric changes were then analyzed (Section 4) to determine shoaling and erosion rates and, in a related study, to determine changes in shoreline and vegetative cover (THOMAS, 1983). In comparison to the freshwater flow records, the historical records of fluvial sediment load are meager (Section 3). They provide some hints, however, that flow regulation by the dam system may have substantially reduced sediment supply to the estuary.

Historical bathymetric and tidal data provided input for a two-dimensional, laterally averaged multiple-channel circulation model (HAMILTON, 1984 and 1990) that was used to determine circulation and salinity patterns prior to human alteration (Section 5). The results of these analyses and the available sediment transport information (SHERWOOD and CREAGER, 1990) were used (Section 6) to evaluate changes in suspended sediment accumulation in the turbidity maximum and to define an approximate sediment budget.

The methodology used here should be applicable to many other US estuaries where large-scale morphological changes have occurred, where USCGS surveys, which began in the early decades of the nineteenth century (SHALOWITZ, 1964), similarly predate navigational alteration if not (necessarily) extensive watershed development. Previous studies have used manually computed bathymetric differences to evaluate historical rates of shoaling and erosion (GILBERT, 1917; SMITH, 1965; KRONE, 1979); we are unaware of other attempts to use digital methods to analyze bathymetric changes over historical time scales.

The absence of quantitative information on biological resources in the estuary prior to intensive resource exploitation and human modifications of the riverflow and estuarine morphology prevents direct evaluation of historic changes in the estuary's biotic community structure and food web. Estimates of the extant production and consumption processes (SMALL, MCINTIRE, MACDONALD, LARA-LARA, FREY, AMSPOKER and WINFIELD, 1990; SIMENSTAD, SMALL and MCINTIRE, 1990) were used to extrapolate representative rates of habitats and regions to the pre-development configuration of the estuary (Section 7). In addition, using changes in the freshwater flow, estuarine circulation, and input of suspended organic matter (phytoplankton and detritus), the pathways and rates of organic matter cycling through the estuarine food web were reconstructed and evaluated relative to the system's present biotic structure and processes.

2. HISTORICAL BACKGROUND

2.1 *Jetty construction and diking*

The substantial changes that have taken place in the morphology of the estuary in historical time result from a combination of natural processes, human activity, and sedimentological responses to human activity. The natural response to the construction of permeable pile dikes and jetties, especially the jetties at the entrance, has been the largest single agent of change to the estuarine morphology. Accumulation of sediment behind dikes and jetties and the associated scour of the adjacent river channel has resulted in deeper channels, broader, shallower expanses of intertidal areas, and increased supratidal area.

Human influence on the physical environment of the Columbia River Estuary began about fifty years after the arrival of the first white settlers. Construction of salmon canneries and logging began in the 1840s and 1850s (Oregon Historical Society, 1980), but human influence on the morphology of the estuary prior to 1885 was confined to the installation of pilings and weirs and (after 1868) sporadic scrape-dredging of the bars. In 1885, construction of the South Jetty began, and a new era of significant human impact on the evolution of the estuary was inaugurated.

Several surveys made prior to 1885 demonstrated the dynamic morphology of the entrance to the estuary before the construction of the entrance jetties. Shifting shoals and channels occupied the region, forming ebb and flood tidal deltas. Early charts (collected by the Oregon Historical Society, 1980) and descriptions of the entrance region (US Army, Board of Engineers, 1903; Moore and Hickson, 1939; Hickson and Rodolf, 1951; Lockett, 1962, 1963; Borgeld, Creager, Walter and Roy, 1978) indicated that the number of channels crossing the tidal delta (the "bar") varied. The earliest survey by Admiral Vancouver in 1792 showed a single entrance channel but, by the time of the 1839 survey by Captain Belcher, two channels had formed. These were separated by Middle Sands, an intertidal sand body seaward of Clatsop Spit connected to Sand Island immediately east of the entrance. Although the entrance morphology changed continuously, two channels across the tidal delta persisted until 1880 (Fig.1). During this time, Clatsop Spit prograded north and west, forcing the southern entrance channel and Sand Island northward. In 1868, the southern entrance channel was well suited for navigation but by 1881, the continued northward migration of the southern channel had caused the two channels to merge, creating a single broad, shallow channel across the delta. Clatsop Spit was eroded and lost elevation and area during the same period. The result of these changes was that the best channel across the delta provided only 5.8m (19ft) of depth at the time of the 1881 US Army, Corps of Engineers (COE) survey.

In 1882, the Board of Engineers prepared plans for an improvement project to narrow, deepen, and stabilize the channel. Construction of the original South Jetty began in 1885 (US Army, Board of Engineers, 1903; Bagnall, 1916; Hickson, 1922). During the first four years of construction, there was little change in the entrance region but, in 1889, the channel across the tidal delta began to swing north and deepen and by 1895 it reached a depth of 10.6m (35ft). However, the channel continued to migrate north and began to shoal. By 1902, the channel had broadened and bifurcated to again create two channels across the outer tidal delta. Because the best channel into the estuary was by then only 6.7m (22ft), plans for the extension of the South Jetty and construction of the North Jetty were initiated (US Army, Board of Engineers, 1903).

Construction of the South Jetty extension began in 1903 and was completed in 1914; the North Jetty, begun in 1913, was completed in 1917. Dredging of the entrance channels began in 1903.

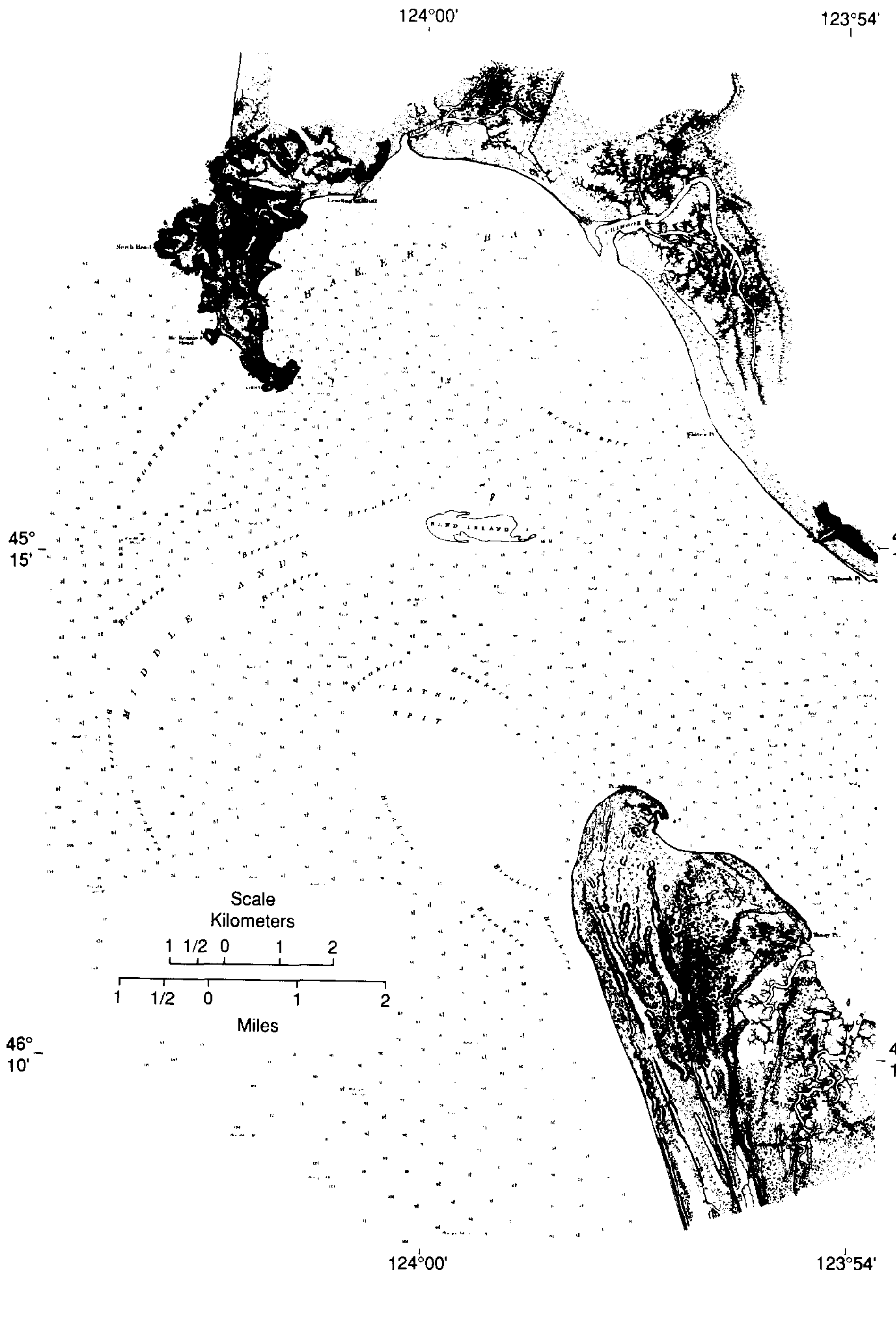

Fig. 1. US Coast Survey Office Chart of the entrance to the Columbia River in 1870, from the Oregon Historical Society (1980) collection. The survey predates jetty construction and shows two shallow channels across the Middle Sands tidal delta. Depths are in feet (1ft = 0.3048m) below mean sea level within the stippled shoals and in fathoms (1fm=1.8m) beyond the shoals.

Completion of the North Jetty reduced the cross-sectional area of entrance channel to that of the narrowest point in the lower estuary, located about 18km from the entrance near RM-11[(1)]. Rapid changes in the channel occurred as a result of jetty construction and dredging (HICKSON, 1922). Subsequent rehabilitation of the jetties during the 1930s, construction of Jetty A and the Sand Island dikes in 1939, and dredging associated with increases in the project depth of the entrance channel have resulted in further modifications to the morphology of the entrance region (LOCKETT, 1962, 1963; BORGELD, CREAGER, WALTER and ROY, 1978). The 1958 entrance configuration appears in Fig.2.

While these changes were occurring as a result of jetty construction near the entrance, the upriver channels were modified by the construction of pile dikes and by dredging; the dredging is discussed in the next section. The strategy employed by the COE in designing their "training" structures was simple: velocities would increase over troublesome bars as the channel width was artificially reduced. In the absence of salinity intrusion, the resulting increased shear stresses erode sediment from the channel bottom until the increased depth compensates for the reduced channel width. The displaced sediment moves down current to a regime of lower shear stress, where it is deposited. The system of permeable pile dikes is highly effective in the fluvial part of the system, because it narrows the channel cross section and provides a protected region of lower current velocities that receives the material displaced from the channels. Dredging efforts may then be concentrated on new projects, channel realignments, and maintenance dredging of troublesome bars.

In the upper estuary, the complex channel system was gradually replaced by a single deep navigation channel. Previously important channels like Cordell, Prairie, and Cathlamet Channels and the channels of eastern Grays Bay were isolated from the main flow by pile dikes, and bars in the main channel were removed by dredging. The greatest changes occurred during the initial development of the river for navigation; by 1935 the 10.7m (35ft) river channel had been completed.

Extensive diking and filling of marsh and swampland occurred in all four peripheral bays and along the river channel upstream of the estuary. THOMAS (1983) indicates that $1.27 \times 10^8 m^2$ (31,500 acres) of estuarine wetland (principally tidal swamps and tidal marshes) have been lost by diking and filling activities. About one quarter of this loss occurred in Youngs Bay and another quarter on Puget, Little, and Tenasillahie Islands and in the Westport area. Although diking began in the nineteenth century, the most extensive work occurred between 1936 and the early 1940s.

2.2 *Dredging activities*

Aside from jetty construction and diking, it has been channel dredging and the disposal of dredged material that has most altered the physical environment of the estuary. Substantial dredging began in 1909; since then, the COE has annually dredged some 5 to $10 \times 10^6 m^3$ of sand at the entrance and in the river-estuary system (MOORE and HICKSON, 1939; US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1975; STERNBERG, CREAGER, GLASSLEY and JOHNSON, 1977). Removal of fine material (silts and clays), gravel, and rock has been insignificant in comparison.

Historical dredging work may be divided into two phases. Between 1909 and 1939, about $145 \times 10^6 m^3$ of material was dredged from the system between the mouth and Portland while

[(1)]Locations in the estuary are identified using the local river mile (RM) convention. RM-0 is located at the entrance, and river miles increase upriver along the navigation channel (Fig.2 in SIMENSTAD, SMALL, MCINTIRE, JAY and SHERWOOD, 1990). One statute river mile equals 1.61km.

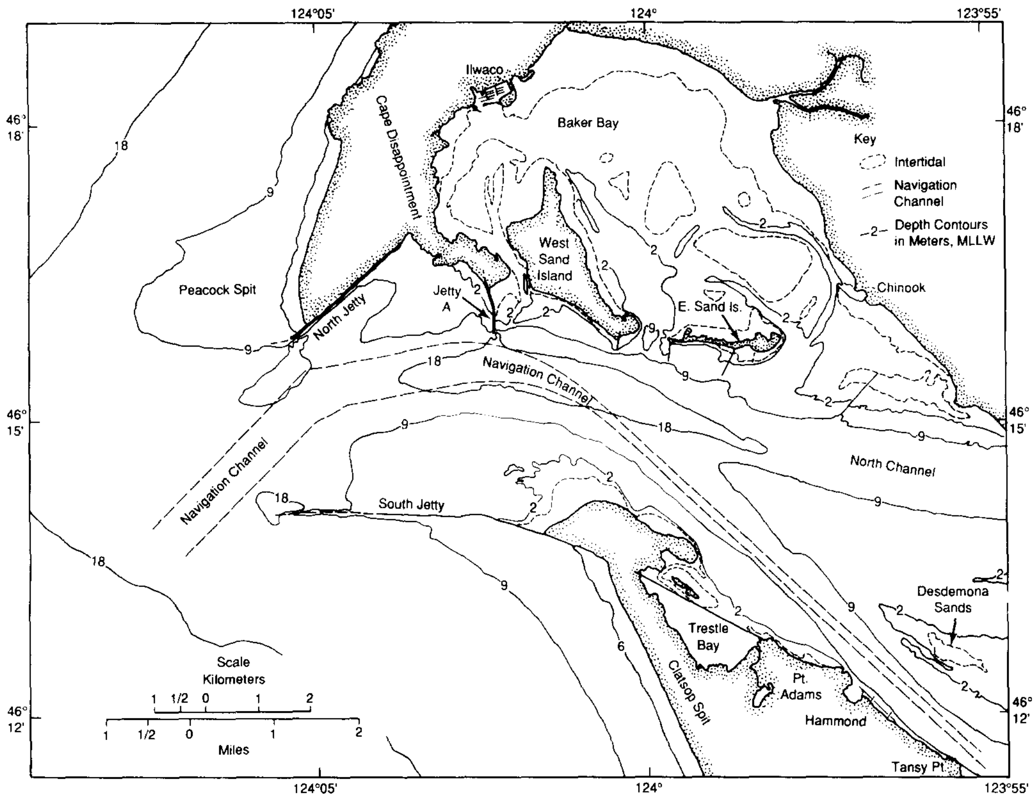

FIG.2. The entrance in 1958. Approximate depths contours in meters below mean lower-low water follow the original 6ft, 30ft, and 60ft contours from the *Bathymetric Atlas* (COLUMBIA RIVER ESTUARY DATA DEVELOPMENT PROGRAM, 1983). Jetty construction has caused substantial depth increases in the main channel and deposition on the submerged, outer (ebb) tidal delta (indicated by the 18m contour), on Clatsop Spit, and along the southern boundary of Baker Bay (see Fig.13).

constructing and maintaining the initial 9m (30ft) channel and the subsequent 10.7m (35ft) channel (MOORE and HICKSON, 1939). About 77 x $10^6 m^3$ of this material was removed by hopper dredge, most of which came "from the estuary" (boundaries undefined). Data from BAGNALL (1916) suggest that <10 x $10^6 m^3$ of the total amount was dredged at the entrance, all of it between 1909 and 1918. For comparison to shoaling and erosion volumes, we shall assume that 50 x $10^6 m^3$ was removed from the South Channel below RM-25 and that another 40 x $10^6 m^3$ was removed from the river channel in the balance of our study area (below RM-50). Unfortunately, the fate of this material was not documented. Present maintenance practice is to discharge as much as possible of the material either in the river in an area of strong scour so that it continues to move downstream (flowlane disposal) or on beaches where it erodes slowly. Consequently, the same material may be handled several times as it moves downriver. In earlier times, a large but unknown fraction went toward the creation of land.

During this early period, there were two other important dredging projects for which no volume estimates are available. These were (1) the east-west barge channel across Baker Bay, used primarily by barges carrying construction material for the North Jetty, and (2) the construction of the Skipanon River Channel. In both cases, most of the dredged material was deposited close to the dredged channels. In Baker Bay, the material was side-cast onto adjacent intertidal flats or pumped onto the Sand Islands. In the Skipanon River, the dredged material was used to create the twin spits at the Skipanon entrance.

The second phase of Columbia River dredging operations commenced in 1939 when hopper dredging of the entrance was resumed. Large scale operations did not, however, occur until 1953 (LOCKETT, 1959). Between 1939 and 1981, about 75 to 80 x 10^6m^3 of sediment was dredged from the entrance; about 27.4 x 10^6m^3 of this total was handled between 1939 and 1958 (LOCKETT, 1959, 1967; STERNBERG, CREAGER, GLASSLEY and JOHNSON, 1977; US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1983). Recent years have seen an increase in dredging at the entrance from about 1.7 x 10^6m^3 annually between 1958 and 1975 up to about 4.5 x 10^6m^3 annually (US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1983). The year-to-year variability of dredging activities should also be emphasized: about 11 x 10^6m^3 was removed in 1956 during the construction of the 14.6m (48ft) channel, and 7.5 x 10^6m^3 was removed in 1977 when the channel was deepened to 15.8m (52ft; LOCKETT, 1959; US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1983). Dredging records and bathymetric surveys indicate, however, that large amounts of material were handled several times in constructing the 14.6m (48ft) channel in 1956 (LOCKETT, 1959), so the dredging volume bears little relation to the amount of material which had accumulated. All of the material dredged from the entrance was removed by hopper dredge; most was dumped in the ocean just outside the entrance but still within our study area. A small but unknown fraction was deposited inside the estuary in the North Channel when rough sea conditions rendered ocean disposal hazardous. We estimate that this may have amounted to 5 x 10^6m^3 between 1939 and 1958.

Dredging of the river channels upstream of the entrance by pipeline and hopper dredges continued after 1939. Although the total amount of material moved is not available in the literature, estimates may be derived as follows. The annual average maintenance dredging for the 12.2m (40ft) channel between the entrance and Portland during 1970-74 was about 6.1 x 10^6m^3, about 48% (2.94 x 10^6m^3) of which was conducted seaward of RM-50 (US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1975; DODGE, 1976). About 1.5 x 10^6m^3 of the total below RM-50 was from the South Channel seaward of RM-25, the remaining 1.44 x 10^6m^3 from between RM-25 and RM-50. (Some of the material dredged below RM-30 was placed in a temporary storage dump near Harrington Point and then rehandled; this rehandling of material is not included in the above estimates.) Other dredging in the estuary (Baker Bay and the Skipanon River) amounted to only 0.04 x 10^6m^3 during the same period. Comparing the present volumes with those for 1951-62 (HICKSON, 1961, 1965), it appears that maintenance dredging has increased about 20% since the early 1950s. Making allowance for the cessation of dredging between 1942 and 1944, we estimate that about 22 x 10^6m^3 of material was removed from the South Channel below RM-25 during 1939-58 and that another 36 x 10^6m^3 was removed during 1959-82. The comparable figures for the river channel between RM-25 and RM-50 for the two time periods are 20 and 34 x 10^6m^3, respectively. Construction of the 12.2m (40ft) channel during the 1960s required more than 30 x 10^6m^3 of additional dredging beyond that necessary for maintenance, but not all of this dredging occurred in the study area (DODGE, 1976).

Disposal practices during 1970-74 suggest that much of the 1.5 x 10^6m^3 dredged annually below RM-25 was deposited in water, some of it outside the jetties but within the study area. Five to ten x 10^6m^3 may have been transported beyond the jetties in this manner between 1939 and 1958. More than 20 land disposal sites were in use during the 1970s, and many more have been used in the past (US ARMY CORPS OF ENGINEERS, PORTLAND DISTRICT, 1975). THOMAS (1983) states that about 1.1 x 10^6m^3 of the 2.94 x 10^6m^3 of material dredged annually in the estuary and river below RM-50 has been placed on land. If disposal practices have not varied, then perhaps 20 x 10^6m^3 of material was put on land between 1939 and 1958, and another 27 x 10^6m^3 between 1959 and 1982. Most of the material placed on land probably originates above RM-25, but the rehandling of material in the Harrington Point disposal site renders the origin of the material placed on land obscure.

The largest land disposal sites have been Rice Island and Miller Sands. Construction of these two islands removed 2.0km² (455 acres) from the intertidal system (THOMAS, 1983). Allowing for up to 6m of average fill depths, these islands could have absorbed as much as 12 x 10^6m^3 of material, most of it after 1958. The deposition of 4 to 6 x 10^6m^3 of dredged material has raised the elevation of three large bars along the river channel between RM-25 and RM-40 and converted another 1.1km² (265 acres) from intertidal flats to supratidal land. Again, most of the deposition occurred after 1958. These five sites together are large enough to have absorbed about 60% of the estimated post-1958 land disposal.

Maintenance of the navigation channel was not, however, the only source of dredged material after 1939. Additional material was moved in creating Mott and Lois Islands in Cathlamet Bay during the 1950s construction of the Tongue Point seaplane base. These islands have a total area of 1.32km² (327 acres; THOMAS, 1983). Assuming that they were filled with an average thickness of 4-5m of material, this would amount to an upper limit of about 5-6.5 x 10^6m^3 of additional material.

In summary, extensive dredging and relocation of dredged materials has occurred in the last 80 years. Dredging operations moved an estimated 300 x 10^6m^3 of mostly sand-sized material in the entrance, estuary, and river channels between 1909 and 1982. An unknown, but considerable, portion of this volume represents rehandling of the same material. About 50-100 x 10^6m^3 has been removed from the system by land disposal since 1939; land disposal prior to 1939 cannot be estimated but was also substantial. Since 1939, another 70 to 75 x 10^6m^3 of the material has been dredged from the entrance and deposited outside the jetties. An unknown portion of this material was also handled more than once. The remaining volume, representing "one-time" removal of material from the estuary, is estimated at an annual average of 4-5 x 10^6m^3 and accounts for one-third to one-half of the estimated annual fluvial sediment supply (8-12 x 10^6m^3; see Section 3), indicating that dredging and the disposal of dredged material are important terms in the sediment budget of the estuary.

3. FLUVIAL INPUTS

One goal of this investigation was to contrast the estuarine response to present-day riverflow with the response which existed prior to irrigation withdrawal and flow regulation by dams. Definition of the seasonal cycle of Columbia River freshwater flow and its historical changes is basic to the understanding of biological, geological, and circulatory processes. Determination of the fluvial sediment input and its changes is also necessary to an understanding of the estuarine sediment budget over the last century. This section reviews riverflow and sediment discharge changes in the Columbia River in historical time.

3.1 Description of the Columbia River drainage basins

The eastern and coastal subbasins of the Columbia River have different climatic, hydrological, and geological characteristics, and their flow is regulated to different degrees (Fig.1 in SIMENSTAD, SMALL, MCINTIRE, JAY and SHERWOOD, 1990). The hydrograph for the Columbia River (Fig.3) shows the contribution from the two subbasins. (This figure and other discussions of riverflow use the hydrologists' conventional "water year", which begins October 1.) The coastal subbasin contains only about 8% of the total drainage area of 660,480km^2 but contributes about 24% of the total riverflow (OREM, 1968; GOOD and JAY, 1978). The high annual runoff (2.39m; 94in; US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION, 1984) from the coastal subbasin results from mild, wet winters and a large excess of precipitation over evaporation. The major coastal basin tributaries (Willamette, Lewis and Cowlitz rivers) have winter flows that are five to ten times greater than those during other months (Fig.3). Winter freshets are brief and are caused by warm semitropical storms that not only bring heavy rains, but also cause significant snowmelt. Storage in the coastal subbasin is small relative to flow, so the effects of a winter freshet are felt within a few days of the onset of a storm.

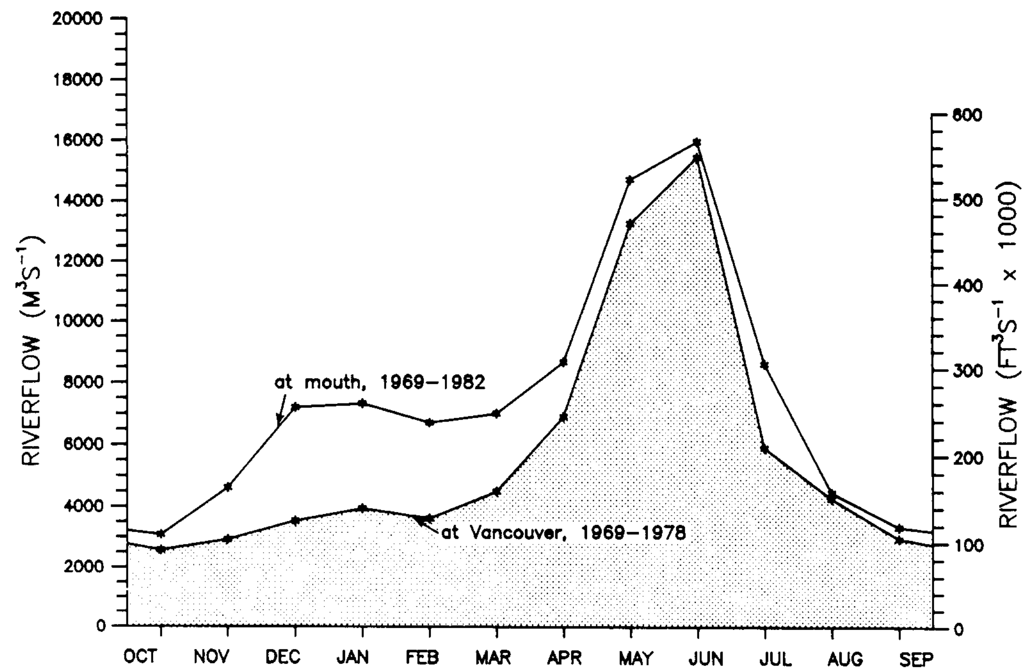

FIG.3. Modern monthly mean adjusted flow of Columbia River at Vancouver, Washington and at the mouth. Monthly flows have been averaged for the period 1969-1982 and adjusted for reservoir storage to approximate natural runoff conditions. Flows at Vancouver are from the eastern basin of the Columbia River; flows at the mouth also include the Coast Range and western basins. Data from the US Geological Survey, Portland, Oregon.

The small sizes of the drainage basins of the coastal subbasin tributaries emptying directly into the estuary below RM-50 prevent local runoff from being important in the circulation, except locally in the peripheral bays and perhaps briefly throughout the estuary during winter storms. On an annual basis, local tributary inflow amounts to about $290 m^3 s^{-1}$ ($10 \times 10^3 ft^3 s^{-1}$) or 3.5% of the total inflow to the estuary (GOOD and JAY, 1978). About two-thirds of this inflow normally occurs between December and March, while less than 5% occurs between July and September (OCEAN ENGINEERING PROGRAMS, OREGON STATE UNIVERSITY, 1975).

The eastern subbasin, which contains about 92% of the total drainage basin area, has a relatively arid, continental climate and hence a lower annual runoff (0.71m; 28in; US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION, 1984) because the Cascade Range separates the cold inland air masses from the warmer maritime air masses to the west. Most (73%) of the runoff occurs as the snow melts in the months of April to July, during which period virtually the entire riverflow comes from the east side of the Cascades (measured at Vancouver, Fig.3). Winter freshets in the eastern subbasin are comparatively rare, are no more than half as intense (at peak flow) as the largest spring freshets, and are of much shorter duration. Flows from the eastern subbasin are more strongly regulated than those from the coastal subbasin; therefore eastern subbasin freshets presently follow a different time history than they would in the absence of flow regulation.

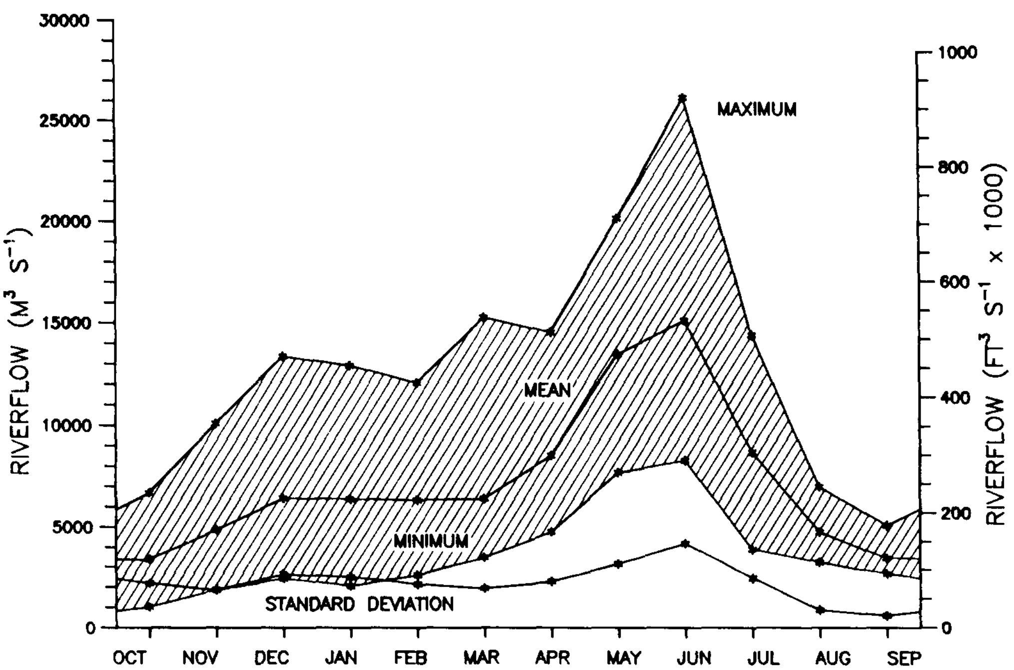

FIG.4. Monthly adjusted flow, Columbia River at the mouth, 1928-1982. Shown are mean, standard deviation, maximum, and minimum monthly flows, adjusted for reservoir storage to reflect natural conditions. Maximum flows for each month occurred in the preregulation years (prior to 1969) except in January, February, and March. Minimum flows shown also occurred prior to regulation, except during the spring runoff months of April, May and June. Mean riverflow is weighted toward the pre-regulation conditions; the present-day hydrograph is much flatter (see Fig.7).

3.2 Definition of preregulation and modern flow regimes.

Riverflow variation occurs primarily on monthly and seasonal time scales (Jay, 1984), so monthly mean flows were used to differentiate historic flow conditions and modern conditions. As no direct measurements are made of riverflow at the mouth, the best estimate of actual riverflow at the mouth is the "estimated observed flow" (hereafter observed flow) defined in Orem (1968) and calculated by the US Geological Survey. Orem (1968) also defines an "estimated adjusted flow" (hereafter adjusted flow) which accounts for storage in the reservoir system and travel time from gaging stations to the mouth. The adjusted flow at the mouth between 1928-1982 is presented in Fig.4; it represents an estimate of the flow that would have occurred in the absence of regulation. Comparison of the observed and adjusted flows at the mouth for the period 1928-1982 provides an indication of the effect of flow regulation (Fig.5). Examination of Fig.5 shows that the standard deviation of the flow difference greatly increased in the late 1960s and that year-to-year transfers of flow became significant for the first time in about 1968. This corresponds to the construction of several of the largest reservoirs in the Columbia River system. Between 1967 and 1975, reservoir capacity in the Columbia River Basin rose from about

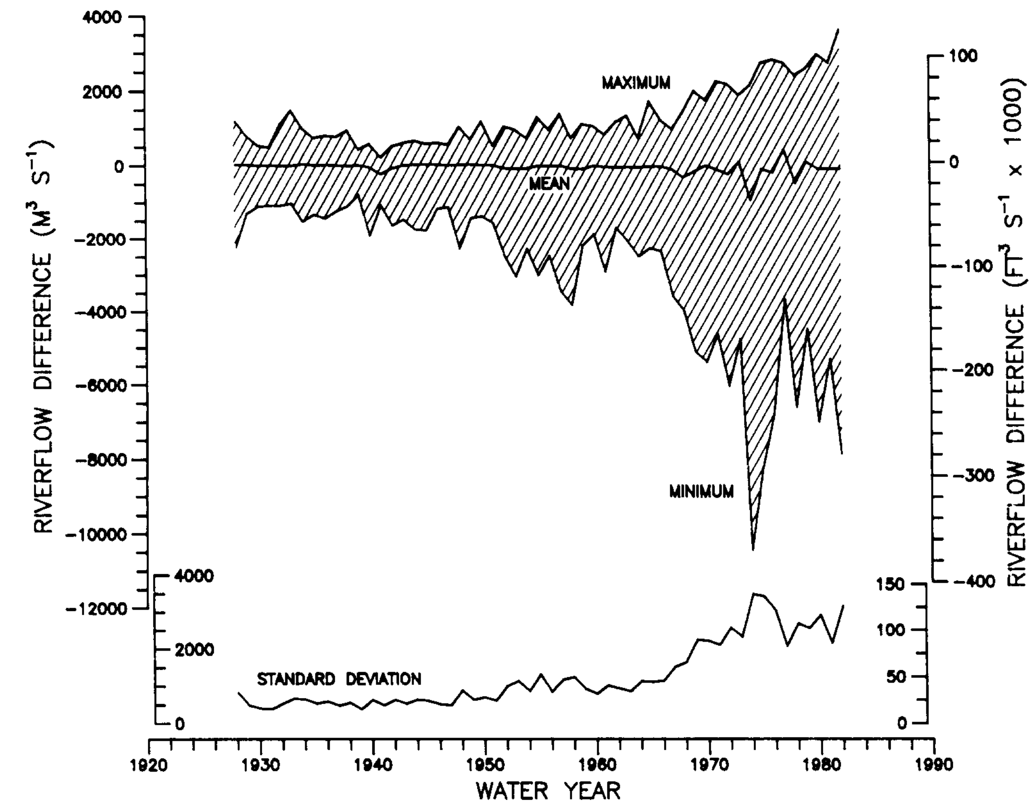

Fig.5. Observed minus adjusted monthly flows, Columbia River at the mouth, 1928-1982. Shown are the annual mean, minimum, maximum, and standard deviation of the monthly difference between observed riverflow and riverflow adjusted for storage effects. Regulation effects became increasingly significant in the late 1960s.

35 x $10^9 m^3$ (28.4 x 10^6 acre-feet) to 69.9 x $10^9 m^3$ (56.7 x 10^6 acre-feet) and is now about 77.7 x $10^9 m^3$ (63 x 10^6 acre-feet; US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION, 1984). Our analysis of the daily riverflow from the eastern subbasin at The Dalles has highlighted a dramatic reduction in seasonal variability which occurred between the late 1960s and 1975. For these reasons, we consider the period prior to 1969 as the "preregulation" condition and the period since 1969 as the "modern" condition. The differences between estimated and observed flow, calculated on a monthly basis for the preregulation and modern periods (Fig.6a,b), confirm that flow regulation has increased radically in the modern period. As a result, the observed-flow hydrograph now shows relatively little seasonal variation (Fig.7).

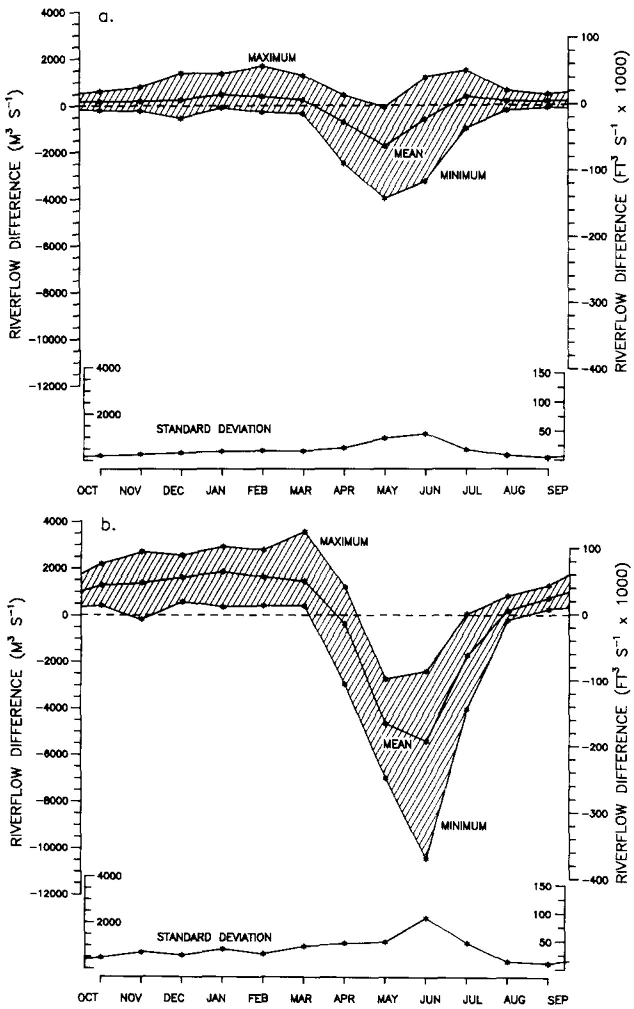

FIG.6. Observed monthly minus adjusted monthly flows, Columbia River at the mouth, for a) 1928-1968 and b) 1969-1982. The mean for each month is the average difference, for that month over the entire peirod, between observed riverflow and riverflow adjusted for storage effects. The minima and maxima are the extreme differences in the period for each month. Prior to regulation, relatively small differences are observed. Since 1969, much larger differences and the appearances of differences in the annual mean reflect storage during high runoff months and irrigation releases over the summer.

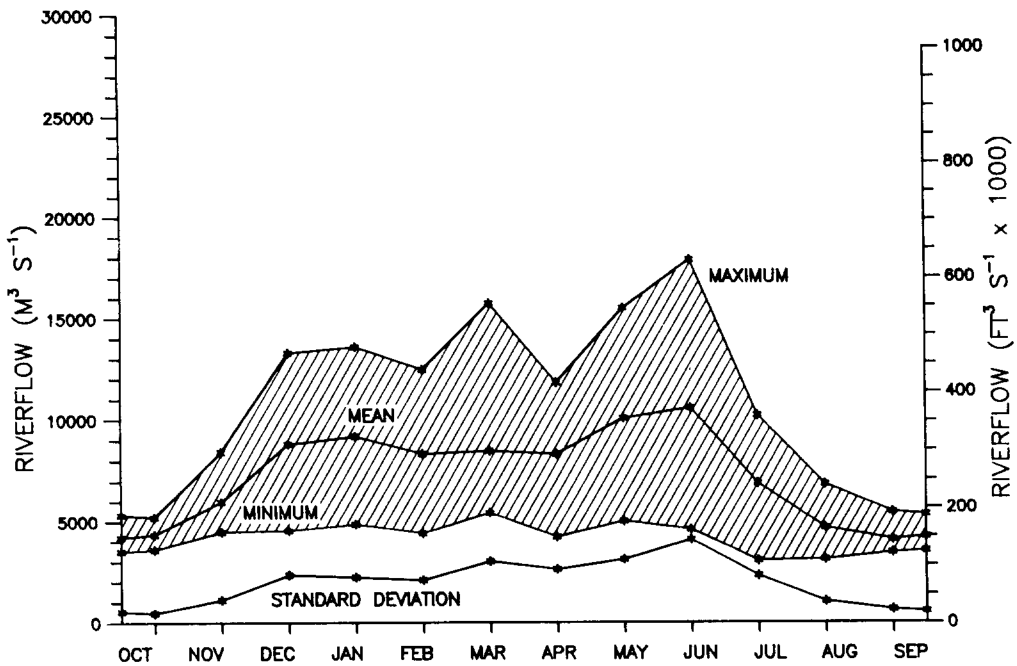

FIG.7. Modern observed mean flows, Columbia River at the mouth (1969-1982). The modern hydrograph has less seasonal variation than the hydrograph prior to 1968 (Fig.4). Minimum riverflow has been increased during the dry summer and fall months, and maximum riverflow during the spring freshet has been dramatically reduced.

3.3 Flow regulation

Regulation of riverflow to prevent flooding has been highly successful. The last flood to inflict serious damage on a basin-wide scale occurred in 1948, when peak riverflow at The Dalles exceeded 28,600m^3s^{-1} (1.0 x $10^6ft^3s^{-1}$). In the absence of regulation, the freshets of 1972 and 1974 would have been as large, but they were reduced by 12,318 and 11,864m^3s^{-1}, respectively (435 and 419 x $10^3ft^3s^{-1}$) to less than 17,600m^3s^{-1} (620 x $10^3ft^3s^{-1}$), thus preventing an estimated 500 x 10^6 dollars in damage (US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION, 1984; COLUMBIA RIVER WATER MANAGEMENT GROUP, 1977). In general, the maximum monthly mean flows at the mouth during the spring freshet have been curtailed by an average of 3,900m^3s^{-1} (140 x $10^3ft^3s^{-1}$), and now seldom exceed 17,000m^3s^{-1} (600 x $10^3ft^3s^{-1}$). The probability of large freshets having important sedimentological effects has been greatly reduced. The US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION (1984) estimated maximum flow at The Dalles during the "Standard Project Flood" to be 44,174 m^3s^{-1} (1,560 x $10^3ft^3s^{-1}$); at 1969 levels of regulation, this flood would have been regulated to 24,070m^3s^{-1} (850 x $10^3ft^3s^{-1}$) and would be even smaller under present-day regulation.

The decrease in spring freshet magnitude is probably somewhat larger than indicated by comparison of Figs.4 and 7 because (1) two large freshets (1972 and 1974) are included in the latter figure, and (2) Fig.4 includes the modern period. The typical difference is closer to 5,200m^3s^{-1} (185 x $10^3ft^3s^{-1}$). The decreases in spring freshet flows have been accompanied by increases in observed flows throughout the rest of the year (Fig.7). In particular, minimum monthly mean flows in the fall have been increased from about 1,840m^3s^{-1} (65 x $10^3ft^3s^{-1}$) to about 2,970m^3s^{-1} (105 x $10^3ft^3s^{-1}$).

3.4 Long-term variability: climate change and depletion

Long-term variations in the total mean riverflow of the Columbia River have been caused by both climate change and by human influences, principally irrigation depletion. Long-term variations may be defined by examining the annual-mean flows. The adjusted annual-mean flow at the mouth (OREM, 1968) from 1928 to 1982 varied by about a factor of 2.7 between approximately 3,960m^3s^{-1} (140 x $10^3ft^3s^{-1}$; 1977) and 10,800m^3s^{-1} (382 x $10^3ft^3s^{-1}$; 1974). The annual-mean observed flows at the mouth ranged from about 4,330m^3s^{-1} (153 x $10^3ft^3s^{-1}$; 1977) to about 9,830m^3s^{-1} (347 x $10^3ft^3s^{-1}$; 1974). Three years between 1880 and 1894 were probably wetter than 1974, but data for flows at the mouth prior to 1928 are not available. However, riverflow data for the eastern subbasin are available for 1879 to date from a gaging station at The Dalles, Oregon (RM-189; US GEOLOGICAL SURVEY, 1958, 1963, subsequent Water Supply Papers, and C. ALEXANDER, personal communication). These data (Fig.8a,b) indicate that long-period fluctuations in riverflow have occurred in the period of record. Between 1920 and 1940, annual-mean riverflow declined by approximately 25% compared to previous years. There was a small increase in riverflow between 1940-55, which has since then been followed by a slight decline.

The primary human influence on annual mean riverflow has been losses associated with irrigation. To separate human influence from long-term climate changes, we investigated estimates of irrigation depletion. Irrigation in the Columbia River Basin began in about 1849 (DEPLETIONS TASK FORCE, 1983). The area of land irrigated rose from about 2,000km^2 in 1900, to about 9,300km^2 in 1910, to about 14,600km^2 in 1928, and to about 31,600km^2 in 1980. Because irrigation practices have become more efficient and because other variables are involved, a direct correlation between irrigated land area and depletion is not possible. However, the DEPLETIONS TASK FORCE (1983) concluded that the annual-mean discharge volume of the Columbia River has been reduced from 241 x 10^9m^3 (196 x 10^6 acre-feet) to 223 x 10^9m^3 (181 x 10^6 acre-feet) by irrigation depletion. This represents an annual-mean riverflow reduction of nearly 563m^3s^{-1} (20 x $10^3ft^3s^{-1}$), about 10% of the long-term mean riverflow. A slightly different estimate published by the US ARMY CORPS OF ENGINEERS, NORTH PACIFIC DIVISION (1984) indicates that the average net depletion is about 11.5 x 10^9m^3 (9.3 x 10^6 acre-feet), suggesting an annual-mean riverflow reduction of about 363m^3s^{-1} (12.8 x $10^3ft^3s^{-1}$), or 7%.

There is an annual cycle of irrigation withdrawal and return flow. Withdrawal is typically greatest in June and July, and return flows are highest in July, August, and September. Net depletion (withdrawal minus return flow) is greatest in May, June and July, while net return flow is greatest in November and December (DEPLETIONS TASK FORCE, 1983). Irrigation may reduce the spring freshet by as much as 1,130 to 1,700m^3s^{-1} (40 to 60 x $10^3ft^3s^{-1}$) in some years.

The decrease in annual-mean riverflow at The Dalles between twenty-year averages for 1881-1900 (about 6,200m^3s^{-1}; 219 x $10^3ft^3s^{-1}$) and 1961-1980 (about 5,150m^3s^{-1}; 182 x $10^3ft^3s^{-1}$) was about twice the irrigation depletion and indicates that long-term climatic changes are at least as large as human-induced changes in the last century. Year-to-year weather variations and variations over periods of five to twenty years cause riverflow fluctuations that are much larger than human influences over the same time scale.

Monthly mean flows show stronger variations than the yearly flows. Monthly mean adjusted flows at the mouth range from about 1,840m^3s^{-1} (65 x $10^3ft^3s^{-1}$; January 1937) to about 26,100m^3s^{-1} (921 x $10^3ft^3s^{-1}$; June 1974); the monthly mean flow for June 1894 at The Dalles alone (without

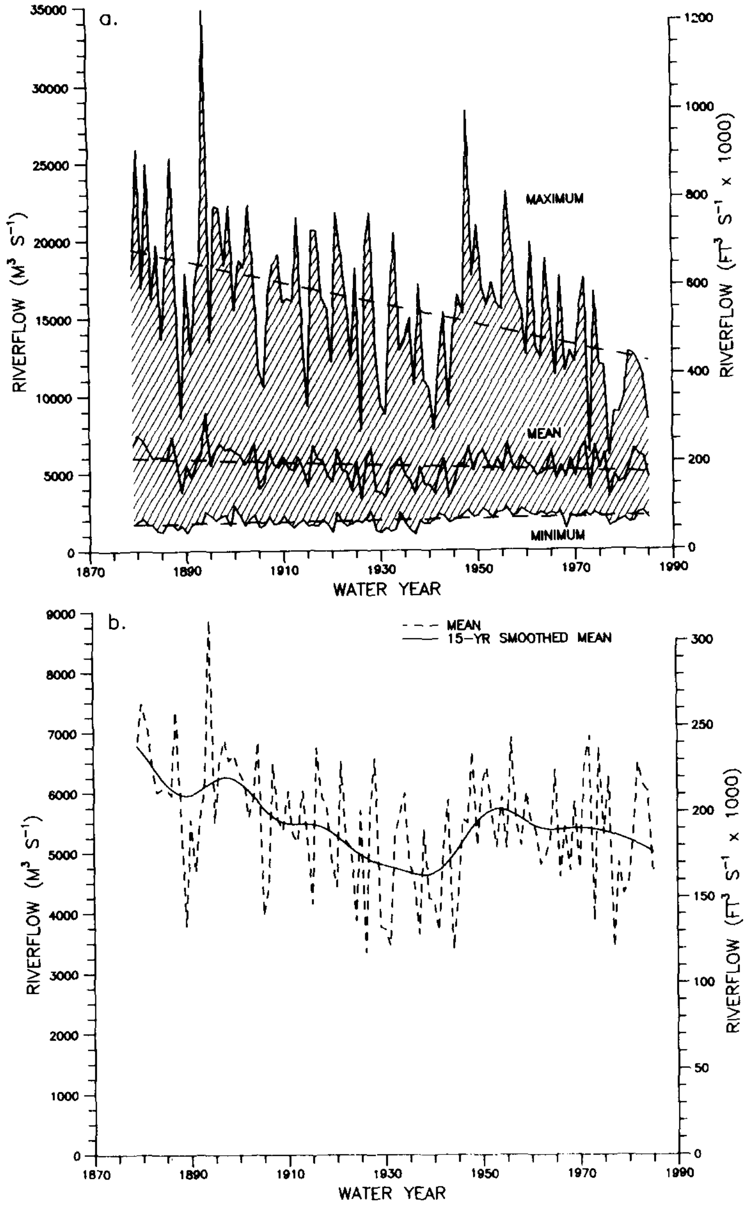

FIG.8a. Annual mean, minimum, and maximum of daily riverflows, Columbia River at The Dalles, Oregon for water years 1878-1985. These data form one of the longest recorded time series of riverflow in the western US. Maximum riverflows have been reduced and minimum riverflows have been increased by regulation. The largest flood on record occurred in 1894 when riverflow peaked at 35,100m^3s^{-1}.

FIG.8b. Annual mean riverflow (dashed) of Fig.8a plotted on an expanded scale. Annual mean riverflow has decreased over the 108-year period. Loss due to irrigation has caused a 7-10% reduction and the remaining decrease is presumably due to climatic effects. The smoothed curve (solid line) averages over about fifteen years and highlights low flows that occurred during drought years in the late 1930s.

the coastal subbasin) was about 28,400m^3s^{-1} (1,002 x $10^3ft^3s^{-1}$). Daily mean flows are yet more variable. Daily flows at the mouth are not available but the US GEOLOGICAL SURVEY (USGS) has published daily flows at The Dalles from 1878 to date and yearly maximum flows from 1858 to date (US GEOLOGICAL SURVEY 1958, 1963 and subsequent Water Supply Papers). The highest recorded daily flow was during June 1894 (by far the wettest year in the last century); it was about 35,100m^3s^{-1} (1,240 x $10^3ft^3s^{-1}$; US GEOLOGICAL SURVEY, 1958). The freshet of spring 1849 is believed to have been almost this large (HENSHAW and DEAN, 1915). Daily flows in excess of 28,300m^3s^{-1} (1,000 x $10^3ft^3s^{-1}$) at The Dalles are known to have occurred on only one other occasion (1948; 28,600m^3s^{-1} or 1,010 x $10^3ft^3s^{-1}$). Daily flows at The Dalles in excess of 24,100m^3s^{-1} (850 x $10^3ft^3s^{-1}$) occurred on seven occasions betwen 1858 and 1900 but only once in the twentieth century; such high flows would have occurred in 1972 and 1974 in the absence of regulation. The lowest flow at The Dalles occur during periods of prolonged winter cold in the interior (HENSHAW and DEAN, 1915); the minimum recorded daily average flow was about 990m^3s^{-1} (35 x $10^3ft^3s^{-1}$) in January 1937.

Before regulation, spring freshets were the largest freshets in the system, both in terms of instantaneous flow and total flow. The largest spring freshets occur after wet, snowy winters with cold springs, when the weather warms suddenly and melting is accompanied by heavy rains throughout the basin (PAULSEN, 1949). Most winter freshets originate primarily from the coastal subbasin. They are occasionally (e.g. in water years 1935 and 1965) augmented by very large flows from the eastern subbasin. Present winter freshets achieve instantaneous flows as large as most regulated spring freshets, but are of shorter duration. In years with small spring freshets, one or more winter freshets may exceed the regulated spring freshet (e.g. 1979-80) though they do not approach the magnitude of the larger historical spring freshets.

3.5 *Fluvial sediment input*

Quantification of the sediment carried by the river to the estuary is a more difficult problem than quantification of riverflow. Availability of silts and clays for fluvial transport is influenced by soil type and land-use practices in the river subbasins. When fine material is present, the flow velocity in the river above the estuary is normally sufficient to transport the material through the system (JAY, GIESE and SHERWOOD, 1990). Different tributaries contribute various suspended loads to the river. In contrast, sand transport in the alluvial channels is generally thought to be capacity limited; sands are usually available on the bottom of the Columbia River and will move as bedload or even in suspension whenever the boundary shear stress is sufficient. Thus, there is no consistent causal relationship between riverflow and sediment discharge.

In the absence of any long-term direct measurements of the sediment load of the Columbia River, we summarize several estimates of sediment discharge (Table 1). Early estimates of VAN WINKLE (1914a,b) and JUDSON and RITTER (1964) range from 6.7 to 13.7 x 10^6metric tons (mt) y^{-1}, but are based on only a few years of measurements at one or two locations. Measurements in 1969 of suspended load only, at the upriver end of the estuary (RM-53) produced an estimate of 7.7 x 10^6mt y^{-1}. The most complete set of measurements of suspended sediment transport, made by the USGS (HAUSHILD, PERKINS, STEVENS, DEMPSTER and GLENN, 1966; D. HUBBELL, personal communication) at Vancouver provide one estimate of annual sediment transport rates from the eastern subbasin. That estimate, based on seven years of data (1964-1970) and after correction for "unmeasured" transport below the sampler, is 11.2 x 10^6mt y^{-1}. We have used an estimate of the Willamette River contribution (1.2 x 10^6mt y^{-1}; based on USGS measurements during WY 1963-1964) to arrive at an estimate of annual sediment discharge of 12.4 x 10^6mt y^{-1} for this period.

USGS observations from 1968-1970, when sampling was conducted at both Vancouver and RM-53, suggest that winter freshets in the coastal subbasin tributaries can contribute an additional 30% to the daily sediment load that is not included in the estimate. The contribution of this discrepancy over the course of a year is normally small.

Table 1. Sediment discharge estimates from the Columbia River

Estimate (10^6 metric tons y^{-1})	Water Year	Reference
6.7, 13.7*	1910, 1911-1912	VAN WINKLE, 1914a,b
10.1*(a)	1950-1952	JUDSON and RITTER, 1964
7.7*(b)	1969	USGS, unpublished data(f)
11.2(c)	1964-1970	USGS, unpublished data(f)
12.4(d)	1964-1970	This paper
12.5(e)	1878-1981	This paper

(a)Snake and Columbia Rivers at Pasco, based on 2 years of incomplete data.
(b)Based on measurements at Beaver Army Terminal (RM-53)
(c)Includes estimate of "unmeasured" suspended load and bedload, omits contribution of Willamette, Toutle-Cowlitz, and other tributaries below Vancouver.
(d)Same as (c), corrected for Willamette River contribution using average total load of 1.2 million tons y^{-1} (based on USGS, unpublished data, WY 1963-1964).
(e)Based on hindcast 1878-1981; Fig.10.
(f)D. HUBBELL, personal communication.
*Suspended load only.

An heuristic model for predicting sediment discharge from riverflow was developed in an attempt to refine estimates of the fluvial sediment supply. Weekly suspended sediment discharge and riverflow measurements made by the USGS at Vancouver between 1964 and 1970 (D. HUBBELL, personal communication, and HUBBELL, GLENN and STEVENS, 1971) were used to develop a linear regression of the log-transformed variables to evaluate of suepended sediment load as a function of riverflow. To this estimate was added a correction for "unmeasured" bedload and sediment transport occurring below the lowest sampler. The correction, based on the modified Einstein total load procedure (COLBY and HEMBREE, 1955; COLBY and HUBBELL, 1961), was suggested by D. HUBBELL (personal communication) and provided us with an estimate of total sediment discharge as a function of riverflow (Fig.9). The amount of sand-sized material (coarser than 0.062mm) in transport as a function of riverflow was estimated from a relationship provided as Fig.15 in HAUSHILD, PERKINS, STEVENS, DEMPSTER and GLENN (1966). It is difficult to estimate the errors in this procedure. The sediment discharge-riverflow relationship is based on data from the years 1964-1970; different relationships might apply to the earlier preregulation years or to more recent years. Although no change in the sediment discharge-riverflow relationship was found after construction of several dams in the Green River Basin (ANDREWS, 1986), VAN WINKLE's early (1914a,b) data from the Columbia River Basin do not show the clear relationship we found in the USGS data. The installation of pile dikes and other navigational training structures has locally increased the ability of the river to transport sediment and may also have increased the availability of material for transport. Increased irrigation, logging, and other land-use changes have affected the fine sediment supply. Finally, sediment transport data are not available for a large spring freshet, so transport estimates for riverflows in excess of 18,400m^3s^{-1} are based on extrapolation.

We have used the sediment discharge-riverflow relationship and daily riverflow records collected by the USGS at The Dalles (beginning in 1879 and kindly provided in digital form by C. ALEXANDER, personal communication) to hindcast the sediment discharge of the Columbia River (Fig.10). Using data from 1879-1899 to extrapolate back to 1868 and breaking the data into periods corresponding to those of the bathymetric surveys (Table 2), we estimate that the period-average sediment discharge decreased nearly 50% between the first period (14.9 x 10^6mt y^{-1}; 1868-1934) and the most recent period (7.6 x 10^6mt y^{-1}; 1958-1981). The dramatic decrease in estimated sediment supply to the estuary is clearly related to the decrease in peak riverflow caused by regulation. The same phenomenon has been more fully documented by ANDREWS (1986) in the Green River Basin of Colorado and Utah.

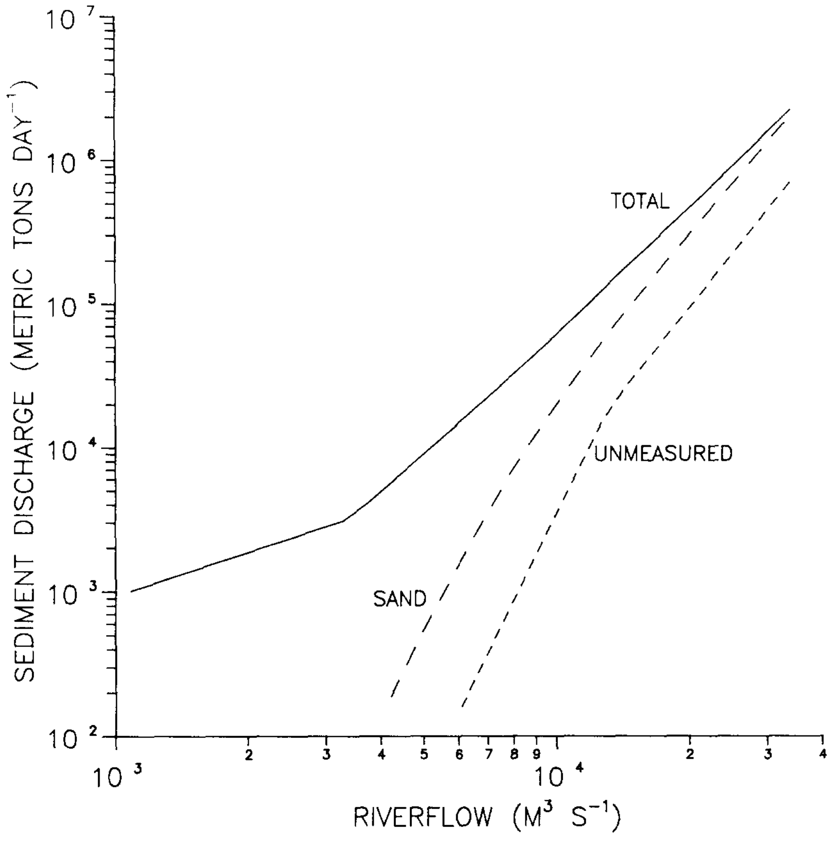

FIG.9. Heuristic relationship between sediment discharge and riverflow. The total sediment load is the sum of the suspended load and the "unmeasured" transport occurring below the bottom sampler (see text). Sand content in the total load is estimated from data of HAUSHILD, PERKINS, STEVENS, DEMPSTER and GLENN (1966). The curves were derived empirically from several years of USGS suspended sediment data measured at Vancouver, Washington (D. HUBBELL, personal communication).

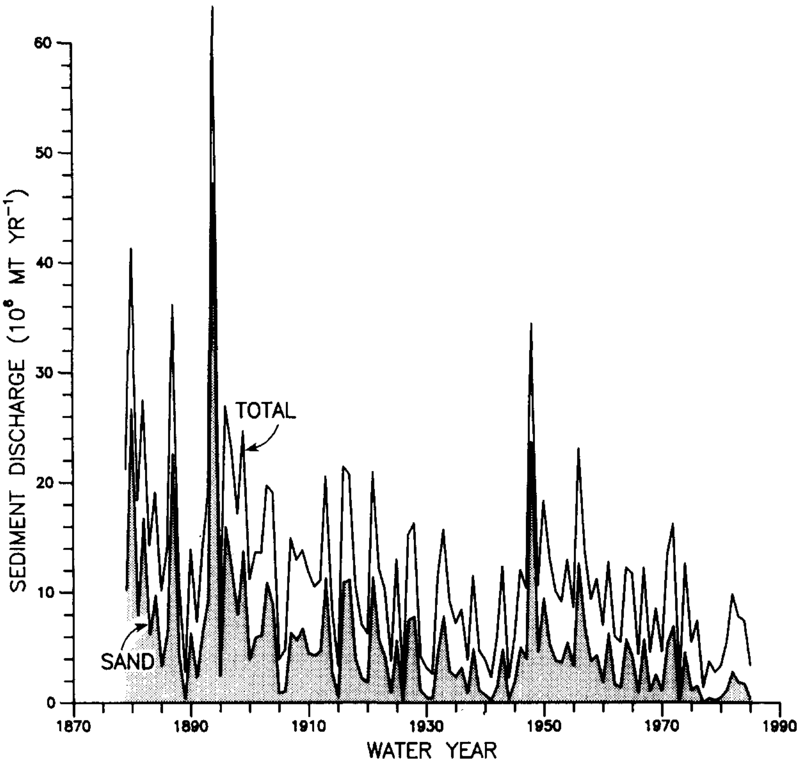

FIG.10. Time series of hindcast annual sediment discharge of the Columbia River at Vancouver, Washington, resulting from application of the sediment discharge - riverflow relationship (Fig.9) to daily discharge data from The Dalles.

TABLE 2. Hindcast sediment discharge rates of Vancouver, Washington, by historical period, based on time series presented in Fig.10

	Sand (>0.062mm)		Silt and Clay (<0.062mm)		Total	
	10^6metric tons y^{-1}	10^6m^3 y^{-1}	10^6metric tons y^{-1}	10^6m^3 y^{-1}	10^6metric tons y^{-1}	10^6m^3 y^{-1}
1868-1934	7.4	(7.0)	7.5	(7.1)	14.9	(14.0)
1935-1957	4.8	(4.5)	5.7	(5.5)	10.4	(10.0)
1958-1981	2.5	(2.5)	5.1	(4.8)	7.6	(7.2)
Entire Period	5.9	(5.5)	6.7	(6.3)	12.5	(11.8)

Volume estimates assume uniform density of 2,650kg m^{-3} and 40% porosity.

In summary, average annual sediment supply to the estuary has been about 8 x 10^6mt y^{-1} for the 1958-1981 period, but was probably substantially higher before regulation. The relationship between sediment discharge and riverflow has probably changed in response to dam construction, alteration of the river channel, and development in the drainage basins, but no data are available to evaluate the nature of the changes. Reduction in peak riverflows has had an important effect in reducing sediment supply to the estuary, but several important questions remain unanswered. How much sediment has accumulated behind the dams? Is only sand trapped behind the dams, or have the dams also affected the supply of fine sediment? How have changes in land use affected the relationship between riverflow and sediment discharge? What is the present relationship? Additional work is required to answer these questions.

4. CHANGES IN THE MORPHOLOGY OF THE ESTUARY

4.1 Measurements of bathymetric changes

The digitized bathymetric information compiled in the preparation of the Columbia River Estuary Data Development Program (1983) *Bathymetric Atlas* was used to quantitatively analyze historical bathymetric changes. Surveys from three periods were chosen for analysis:

1. 1868: USCGS charts made between 1867 and 1877, before jetty construction.
2. 1935: USCGS surveys made between 1926 and 1937; post-dating jetty construction and coincident with construction of numerous pile dikes and changes in channel alignments, and;
3. 1958: USCGS surveys made between 1949 and 1958, post-dating the completion of the 14.6m (48ft) entrance channel but pre-dating the initiation of the 12.2m (40ft) river channel and much of the flow regulation.

Calculations of surface area in each of several depth regimes were made utilizing the digitized bathymetric data. The estuary was subdivided into 13 subareas (Fig.11) on the basis of physical, geological, and biological criteria. The surface areas (projected onto a level plane) within each of 14 depth intervals (Table 3) were calculated for each of the subareas. The precision of the calculated surface areas is limited by the density of soundings in the surveys and by the interpolation used in obtaining digitized bathymetry. Bathymetric data used in the analysis were interpolated onto a latitude-longitude grid which contained one bathymetric data point every 29m along the north-south axis and every 21m along the east-west axis. Areas calculated from this grid cannot be considered precise to more than 1,000m^2 (generally much less than 0.1% of the total area of the depth interval). Inaccuracies may be present in the original data as a result of discrepancies in geodetic control encountered during compilation of the historical bathymetric series and biases introduced by undersampling. Considering all sources of error, the contours and shoreline are believed to be accurate to within about 50m. Although errors of up to 30% in the measurement of a 100,000m^2 area could occur with uncompensated boundary displacements of 50m, this is considered the maximum error involved in the calculations. The much larger area of many of the polygons and internally consistent comparisons are, however, likely to produce fairly precise values.

Vertical control on the bathymetric data is considered reliable to within about 3cm (0.1ft) in the estuary proper but could degrade to as much as 0.5m (1.5ft) in the upriver areas due to seasonal runoff effects on river stage. Seasonal effects have been properly considered in the definition of reference datum and, although we are unable to quantify the error induced in our estimates by seasonal effects, we believe them to be small. Sea level has been falling 0.01 to 0.11cm y^{-1}

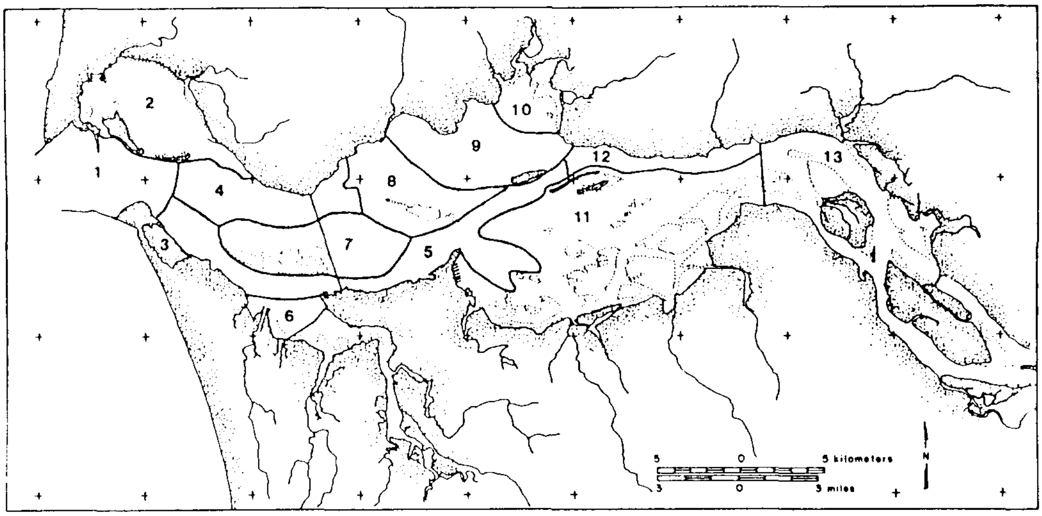

FIG. 11. Map of the Columbia River Estuary showing 13 subareas used in sedimentation calculations: 1) Entrance; 2) Baker Bay; 3) Trestle Bay; 4) North Channel; 5) South Channel; 6) Youngs Bay; 7) Desdemona Sands; 8) Mid-estuary shoals; 9) Grays Bay; 10) Brix Bay; 11) Cathlamet Bay; 12) Lower River Channel;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

TABLE 3. Depth intervals used in area calculations relative to mean lower-low water (MLLW). Depths above MLLW are negative

Nominal Interval (m)	Nominal Interval (ft)	Applicable Depth Range (ft)
-2.1	-7.0	$-7.0 \leqslant z < -3.0$
-0.9	-3.0	$-3.0 \leqslant z < 0.0$
0.0	0.0	$0.0 \leqslant z < 3.0$
0.9	3.0	$3.0 \leqslant z < 6.0$
1.8	6.0	$6.0 \leqslant z < 12.0$
3.7	12.0	$12.0 \leqslant z < 18.0$
5.5	18.0	$18.0 \leqslant z < 24.0$
7.3	24.0	$24.0 \leqslant z < 30.0$
9.1	30.0	$30.0 \leqslant z < 36.0$
11.0	36.0	$36.0 \leqslant z < 42.0$
12.8	42.0	$42.0 \leqslant z < 60.0$
18.3	60.0	$60.0 \leqslant z < 80.0$
24.4	80.0	$80.0 \leqslant z < 100.0$
36.5	100.0	$100.0 \leqslant z$

(CHELTON and DAVIS, 1982; see discussion in SHERWOOD and CREAGER, 1990) at Astoria over historical time. Shifts in the datum caused by long-term sea level changes may have induced errors of up to 20% in our estimates of long-term shoaling rates. Small-scale topographic features such as bedforms exist over much of the estuary and were not resolved, but as the areas are computed for relatively broad depth intervals, the resulting error is negligible. In the upper intertidal regions, more serious errors occur for two reasons. First, bank-to-bank surveys were not performed in all four time periods, and shoreline position is often not accurate on the survey maps. This is especially true in marshes and swamps (SHALOWITZ, 1964). Second, the digital scheme, designed for bathymetry, assigned to all "land" the "depth" of -2.1m (-7ft; the negative depth values are above mean lower-low water: MLLW); therefore the depth interval -2.1 to -0.9m (-7 to -3ft) includes not only intertidal areas but, in some cases, upland areas with greater elevations. The estimates of intertidal area changes provided by THOMAS (1983) are more accurate and have been used instead of our estimates. In the subtidal depths, however, the digitized data allow fairly precise calculation of areas.

The digital bathymetric data were used to calculate sediment volume changes in the estuary between the four survey periods. For the overlapping regions of each successive pair of surveys, the change in volume of each triangular prism defined by three adjacent bathymetry data points was summed over each subarea, providing an estimate of the change in sediment volume of that subarea between the survey periods. The sediment volume change estimates are sensitive to area changes and more sensitive than the area calculations to errors in depth measurements. It is difficult to assign error estimates to the sediment volume change calculations; although a systematic error (e.g. a datum error) in depth could cause large errors if multiplied over a large area, errors in depth are thought to be largely random. These errors should not bias the sediment volume change calculations. It is believed that the important errors are those of omission. Several dredged-material disposal sites and the broad expanses of beach near the entrance jetties accreted rapidly from intertidal or subtidal depths to "depths" above -2.1m (-7ft) between survey periods. In the subsequent survey these areas were either (1) considered land and were assigned depths of -2.1m, or, (2) omitted from the survey. In the first instance, the sediment volume differences presented underestimate the amount of shoaling occurring in the estuary. In the second case, no comparison between the two areas is made because only the overlapping regions of consecutive surveys are compared. Although in this case the error can fall in either direction, the accumulation of sediment is again usually underestimated. Therefore, the sediment volume differences presented here are conservative in the sense that they provide a minimum estimate of the amount of material that has accumulated in the estuary since the 1868 survey period.

A second, slightly different, estimate of volume changes in the estuary was calculated from the area estimates. "Water volume" estimates were calculated using the midpoint of the depth interval times the normal area in that interval and summing over each subarea. The water volume estimates tend to be systematically too large because there is generally more shallow water area than deep water area in a given depth interval. In the absence of these and other errors, changes in the water volume between survey periods should equal the changes in sediment volume and be opposite in sign. Despite their inherent bias, water volume estimates were useful as a check on the sediment volume estimates based on the bathymetry in those cases where shoreline changes had occurred. The following discussion focuses on area changes and sediment volume differences.

4.2 *Area changes*

Area and water volume changes that have occurred in the estuary since 1868 are summarized in Tables 4 and 5. These tables are similar, except that the Entrance subarea, which includes the tidal delta beyond the end of the jetties and which has shown dramatic changes, has been omitted from Table 4 to emphasize the changes in the balance of the estuary. Summations of the areas and volumes below MLLW and the total area surveyed appear at the bottom of each column. The area included in the digital bathymetry database is identical for each of the first three survey periods (1868, 1935 and 1958) in all of the subareas except in those three showing a minus sign (Fig.12). The coverage of these three subareas decreased over the 90-year period due to extensive shoreline changes. The results of a 1982 COE survey have been entirely omitted because the survey excluded such large areas of shallow water that no meaningful comparison could be made with earlier surveys. Note the use of a single depth to indicate an interval (Table 3) on Tables 4 and 5 and in the subsequent discussion.

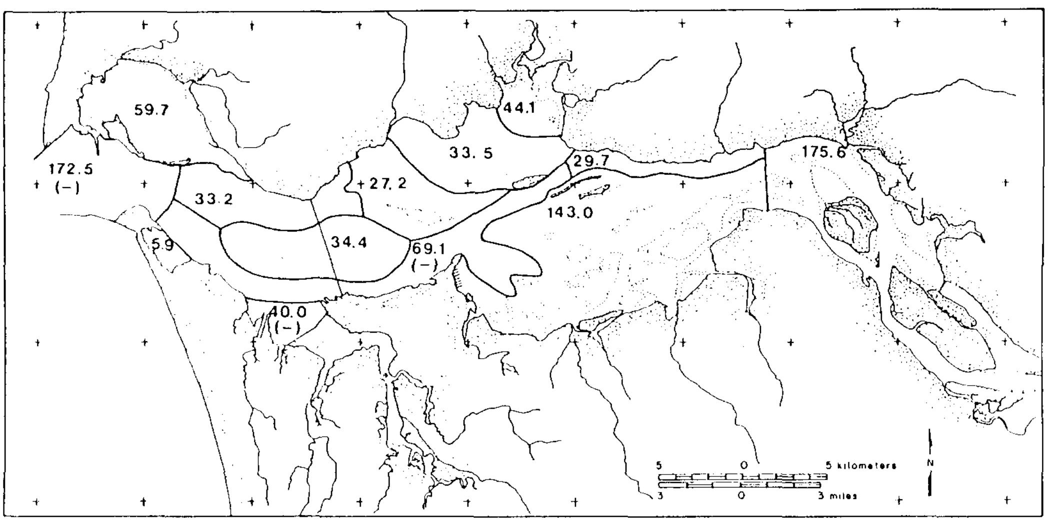

FIG.12. Map of the Columbia River Estuary showing the 1958 surveyed area ($10^6 m^2$) in each of the 13 subareas labelled in Fig.11. Areas marked with a minus (-) were larger in 1868, but much of these areas became intertidal or supratidal over the intervening years and portions were omitted in the 1958 survey.

TABLE 4. Areas, volumes, volume changes, and area changes by depth regime for 1868, 1935, and 1958 (including Entrance subarea)

Depth[a] Interval (m)	(ft)	Area (km²) 1868	Area (km²) 1935	Area (km²) 1958	Water Volume[b](10⁶m³)1868- 1868	1935	1958	Volume changes (10⁶m³) 1935- 1935	1868- 1958	1868- 1958	Area changes (km²) 1935- 1935	1868- 1958	1958
-2.1	-7.00	294.22	339.33	326.31	-448.39	-517.14	-497.15	-68.75	19.99	-48.76	45.11	-13.12	31.99
-0.9	-3.00	38.05	54.46	50.91	-17.40	-24.90	-23.27	-7.60	1.62	-5.88	16.41	-3.55	12.86
0.0	0.00	113.85	69.48	65.11	52.05	31.77	29.77	-20.28	-2.00	-22.28	-44.36	-4.37	-48.74
0.9	3.00	47.65	50.23	48.66	65.36	68.90	676.75	3.54	-2.15	1.38	2.58	-1.57	1.01
1.8	6.00	104.43	74.19	75.72	286.47	203.52	207.72	-82.95	4.20	-78.74	-30.24	1.53	-28.71
3.7	12.00	70.71	53.33	55.39	323.31	342.85	253.25	-79.46	9.40	-70.06	-17.38	2.06	-15.32
5.5	18.00	61.63	43.36	38.65	394.50	277.51	247.37	-116.98	-30.14	-147.13	-18.28	-4.71	-22.99
7.3	24.00	45.41	35.62	31.48	373.72	293.13	259.91	-80.59	-33.22	-113.81	-9.79	-4.04	-13.83
9.1	30.00	28.82	33.56	33.30	289.85	337.59	334.96	47.74	-2.63	45.11	4.75	-0.26	4.49
11.0	36.00	21.42	32.33	30.87	254.58	384.31	366.98	129.73	-17.33	112.41	10.91	-1.46	9.46
12.8	42.00	44.93	62.38	66.19	698.36	969.68	1028.94	271.32	59.26	330.59	17.45	3.81	21.27
18.3	60.00	24.63	22.16	25.86	525.51	472.88	551.83	-52.63	78.95	26.32	-2.47	3.70	1.23
24.4	80.00	17.98	13.79	11.51	493.16	378.33	315.79	-114.83	-62.54	-177.37	-4.19	-2.28	-6.47
36.5	100.00	8.52	9.19	7.81	285.71	308.27	261.90	22.56	-46.37	-23.81	0.67	-1.38	-0.71
Total		922.24	893.43	867.78	4042.57	3969.74	3925.17	-72.83	-44.57	-117.40	-28.82	-25.64	-54.46
Summed Depth Interval[c] (m)	(ft)												
-0.9≤0.90	-3≤03	151.89	123.94	116.01	69.45	56.66	53.04	-12.78	-3.62	-16.40	-27.96	-7.92	-35.88
0.9≤5.50	3≤18	222.80	177.76	179.78	675.13	516.26	527.71	-158.87	11.45	-147.42	-45.04	2.02	-43.02
5.5≤12.8	18≤42	157.28	144.87	134.40	1312.64	1292.54	1209.22	-20.10	-83.02	-103.42	-12.41	-10.46	-22.87
>12.8	>42	96.06	107.53	111.38	2002.75	2129.16	2158.47	126.42	29.30	155.72	11.47	3.85	15.32
Total below -3		628.02	554.09	541.57	4059.96	3994.63	3948.44	-65.33	-46.19	-111.52	-73.93	-12.52	-86.45

[a]See Table 3. Depths above MLLW are negative.
[b]Volumes above MLLW are expressed as negative.
[c]Volume sums do not include volume above depths of -0.9m (-3ft).

TABLE 5. Areas, volumes, volume changes, and area changes by depth regime for 1868, 1935 and 1959 (excluding Entrance subarea).

Depth[a] Interval		Area (km^2)			Water Volume[b] (10^6m^3)			Volume Changes (10^6m^3)			Area Changes (km^2)		
(m)	(ft)	1868	1935	1958	1868	1935	1958	1868-1935	1935-1958	1868-1958	1868-1935	1935-1958	1868-1958
-2.1	-7.00	285.44	323.82	310.67	-435.01	-493.50	-473.45	-58.50	20.05	-38.45	38.39	-13.16	25.23
-0.9	-3.00	36.40	50.76	48.66	-16.64	-23.21	-22.25	-6.56	0.96	-5.60	14.35	-2.09	12.26
0.0	0.00	74.12	67.50	63.28	33.89	30.86	28.93	-3.02	-1.93	-4.96	-6.62	-4.22	-10.84
0.9	3.00	45.34	48.29	46.68	62.18	66.23	64.03	4.05	-2.20	1.85	2.95	-1.61	1.35
1.8	6.00	88.21	69.56	70.56	241.97	190.81	193.57	-51.16	2.77	-48.39	-18.65	1.01	-17.64
3.7	12.00	58.19	48.18	49.22	266.06	220.27	225.05	-45.80	4.78	-41.01	-10.02	1.05	-8.97
5.5	18.00	45.04	35.88	31.43	288.28	229.66	201.20	-58.61	-28.47	-87.08	-9.16	-4.45	-13.60
7.3	24.00	29.30	26.61	22.09	241.15	219.00	181.78	-22.15	-37.22	-59.36	-2.69	-4.52	-7.21
9.1	30.00	17.12	21.42	21.79	172.18	215.41	219.17	43.23	3.76	46.99	4.30	0.37	4.67
11.0	36.00	10.35	14.17	16.18	123.07	168.39	192.38	45.32	23.99	69.31	3.81	2.02	5.83
12.8	42.00	17.79	11.25	12.89	276.55	174.88	200.44	-101.67	25.56	-76.11	-6.54	1.64	-4.90
18.3	60.00	2.17	1.83	1.68	46.25	39.07	35.88	-7.18	-3.19	-10.37	-0.34	-0.15	-0.49
24.4	80.00	0.41	0.11	0.19	11.28	3.08	5.13	-8.20	2.05	-6.15	-0.30	0.07	-0.22
36.5	100.00	0.04	0.11	0.00	1.25	3.76	0.00	2.51	-3.76	-1.25	0.07	-0.11	-0.04
Total		709.91	719.48	695.33	1764.11	1561.42	1547.56	-202.69	-13.85	-216.54	9.57	-24.14	-14.58
Summed Depth Interval[c]													
(m)	(ft)												
-0.9≤0.90	-3≤03	110.52	118.26	111.94	50.53	54.07	51.18	3.54	-2.89	0.65	7.74	-6.32	1.42
0.9≤5.50	3≤18	191.74	166.02	166.47	570.21	477.30	482.65	-92.91	5.35	-87.56	-25.71	0.45	-25.27
5.5≤12.8	18≤42	101.81	98.07	91.50	824.67	832.46	794.53	7.79	-37.93	-30.14	-3.74	-6.58	-10.32
>12.8	>42	20.41	13.31	14.76	335.34	220.79	241.45	-114.55	20.67	-93.88	-7.10	1.46	-5.64
Total below -3		424.47	395.66	384.67	1780.75	1584.62	1569.81	-196.13	-14.81	-210.94	-28.82	-10.99	-39.80

[a]See Table 3. Depths above MLLW are negative.
[b]Volumes above MLLW are expressed as negative.

The largest area changes occurred in the Entrance subarea and were caused by jetty construction and shoaling (Fig.13). Measured changes for the entire estuary between 1868 and 1935 included the loss of 44.36km² from the 0.0 depth interval and the loss of nearly 66km² from the shallow depth intervals of 1.8 to 5.5m. Some of this area was transferred to supratidal and intertidal depths; some was transferred to intermediate depths (Fig.14). Areas of deepest water were somewhat reduced as the outer tidal delta was forced seaward. Most of the area lost was low intertidal shoal area in 1868 and was transferred to supratidal environments on Clatsop Spit and Peacock Spit by beach accretion around the newly constructed jetties. The 1868 survey of the Entrance subarea included 212.33km², the 1935 survey included 173.95km², and the 1958 survey covered 172.45km²; approximately 38km² was omitted from the 1935 survey period as a result of land growth. A rough estimate of the volume of sediment transferred to land in the Entrance subarea may be made by assuming that all of the omitted survey area grew from MLLW to mean higher-high water (MHHW). This suggests that 76 x 10^6m³ of sediment accreted between 1868 and 1935 and was omitted in the 1958 survey. Each additional meter of accumulation assumed increases that estimate by 38 x 10^6m³. Because dredging was insignificant in this subarea prior to 1939 and because essentially all dredging near the Entrance has resulted in in-water disposal, dredged material disposal has not played a direct role in the creation of new land here.

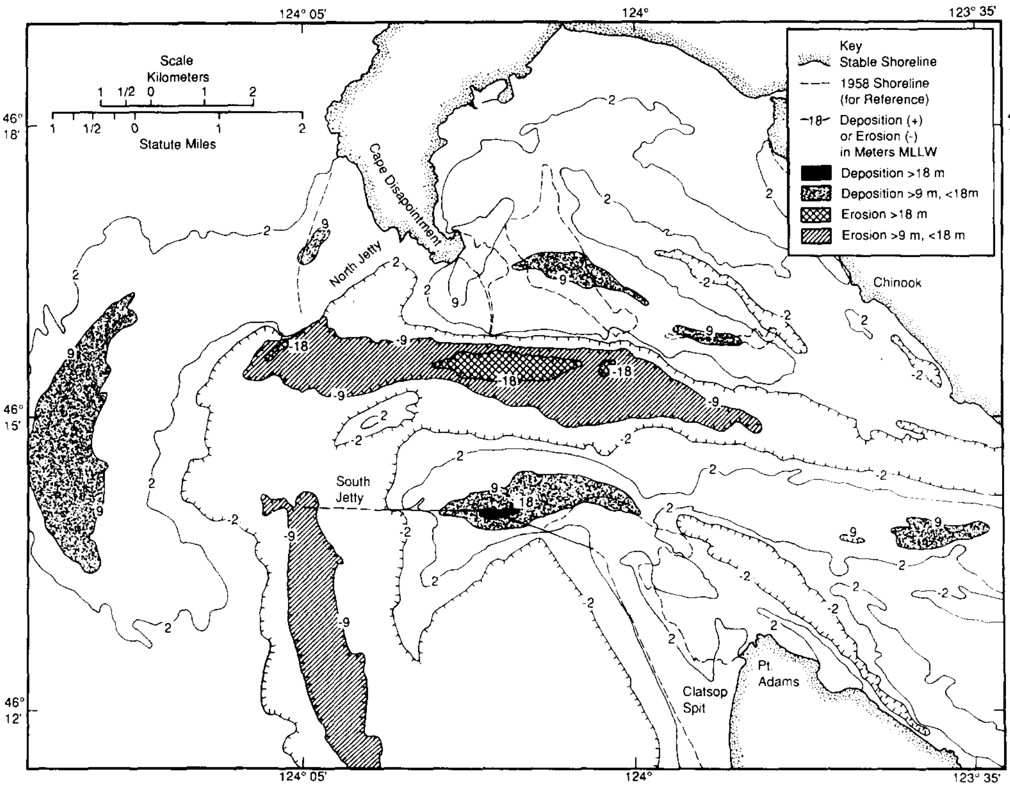

FIG.13. Shoaling and erosion in the Entrance region between 1868 and 1958 from the *Bathymetric Atlas* (COLUMBIA RIVER ESTUARY DATA DEVELOPMENT PROGRAM, 1983). The outer tidal delta has been forced seaward and scouring in excess of 18m has occurred between the jetties. Significant deposition has occurred adjacent to the jetties, and in Baker Bay.

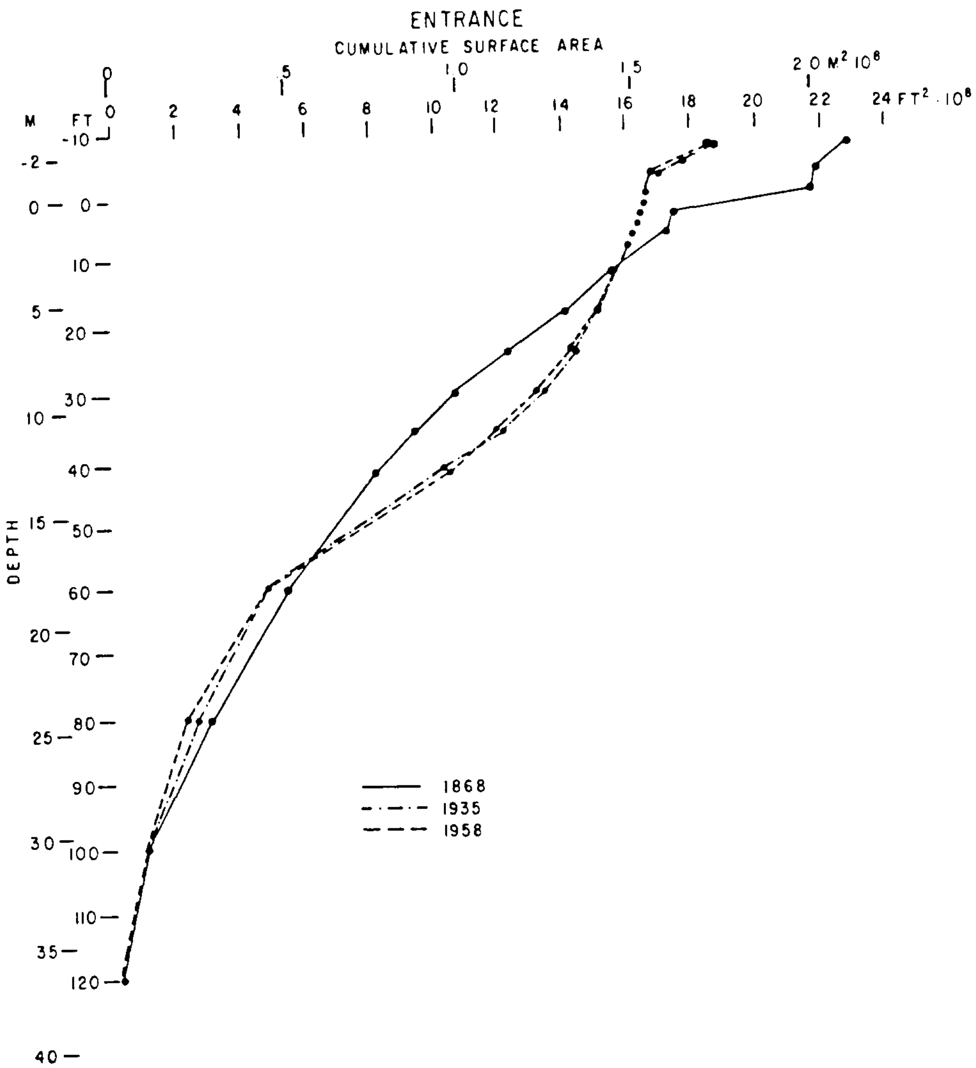

FIG. 14. Hypsometric curve relating cumulative surface area to depth below MLLW in the Entrance region for 1868, 1935, and 1958. Jetty construction and maintenance of the 19.5m (65ft) navigation channel has reduced the area within very shallow and very deep depth intervals.

The area changes in each depth regime of each subarea were calculated and are tabulated in SHERWOOD, CREAGER, ROY, GELFENBAUM and DEMPSEY, 1984. Changes in the Entrance subarea were much less dramatic in the period between 1935 and 1958, suggesting that an equilibrium had been reached. Area was lost in the 9.1m and 11.0m intervals and gained in the 12.8m and 24.4m intervals, probably reflecting dredging of the 14.6m (48ft) entrance channel which began in 1956.

The changes in channel depth in the Entrance subarea are apparent in the hypsometric curve (Fig. 14), which shows the cumulative area as a function depth in the estuary. The area to the left of the curve provides a water volume estimate. The shape of the hypsometric curve and the amount of water stored in various water depths changed dramatically between 1868 and 1935 and to a much lesser degree between 1935 and 1958. Large water volumes were removed from the shallow intertidal and subtidal areas through diking and filling activities. Smaller water volume losses occurred in the deepest areas (greater than about 17m; 56ft). Large increases of water volumes in the mid-depth ranges due to dredging and scour associated with navigational structures nearly offset the volume losses in shallower and deeper water.

Major changes have also occurred in two other subareas. The Youngs Bay subarea has been greatly modified by the dredging in the Skipanon waterway and the filling and/or diking of the surrounding marsh. THOMAS (1983) estimates that 40% of the original estuarine area has been converted to developed floodplain by diking and filling which began prior to even the 1868 survey. Survey coverage of the Youngs Bay area is inconsistent as a result of the changes, and more area was included in the 1935 survey than either the earlier or later survey. There is also a minor difference (1.68km^2) in the area covered by the 1935 and 1958 surveys in the South Channel. This decrease in survey coverage was related to the dredging of Mott Basin for use as a seaplane base during World War II and the construction of Mott and Lois Islands with the dredged materials.

Finally, some exchange between upper intertidal elevations and "dry" land has occurred in the -2.1m interval in all subareas, and calculations of area in the -0.9m interval and below should be used as the most accurate estimate of estuary areas. Because we have no reliable estimate of the volume of sediment that has been shifted to upland by filling activity and natural dune creation, our estimates of sediment accumulation place lower bounds on total accumulation in the system.

A large overall loss in the area of the estuary excluding the Entrance is indicated by the changes in survey coverage since 1868. Nearly 40km^2 of area below -0.9m (3ft above MLLW) have been lost, representing a decrease of 9% relative to the 1868 area of 424.47km^2 (Table 4). Most of the loss (64%) was from the shallow subtidal depths in the intervals from 0.9 to 3.7m; and occurred between 1868 and 1935, but significant losses from the deeper intervals (5.5 to 11.0m, 26%; and 12.8m and deeper, 14%) also occurred. In the period 1935-1958 there was a slight increase in the area of the shallow depth intervals; but the losses in the intervals between 5.5 and 11.0m were twice as large. A slight gain in the area deeper than 12.8m also occurred during the more recent period, probably reflecting increased depths in the navigation channel.

It is difficult to estimate the changes in the upper intertidal area from the data presented in Tables 4 and 5 because of survey limitations and inconsistencies. THOMAS (1983) estimated that 121.6km^2 (30,050 acres) has been lost in the tidal marshes and swamps. This amounts to approximately 20% of the original estuary area. The loss of some of this area has been important in decreasing the tidal prism of the estuary; however, the diked and filled areas were originally at high elevations and many were upriver, where the tidal range and thus tidal prism were small.

The shift in area from the shallow subtidal depths to deeper depths is readily apparent in the hypsometric curves for the estuary for 1868 and 1958 (Fig.15). Much of the shift can be attributed to changes in the Entrance subarea, but a similar trend occurred in the South Channel and Upper River Channel subareas. In contrast, the subareas of Baker Bay and Cathlamet Bay have filled more uniformly, with no marked shift to relatively deeper water. The net effect of these changes has been to reduce the total surface area of the estuary, while shifting a larger percentage of the surface area and water volume into deeper water. Both the total volume and the tidal prism of the estuary have decreased substantially. A 12% loss of deep water area, coupled with greater losses of intertidal areas (THOMAS, 1983), has caused a 12 to 20% reduction of the tidal prism of the estuary. We have assumed the actual value is about 15%.

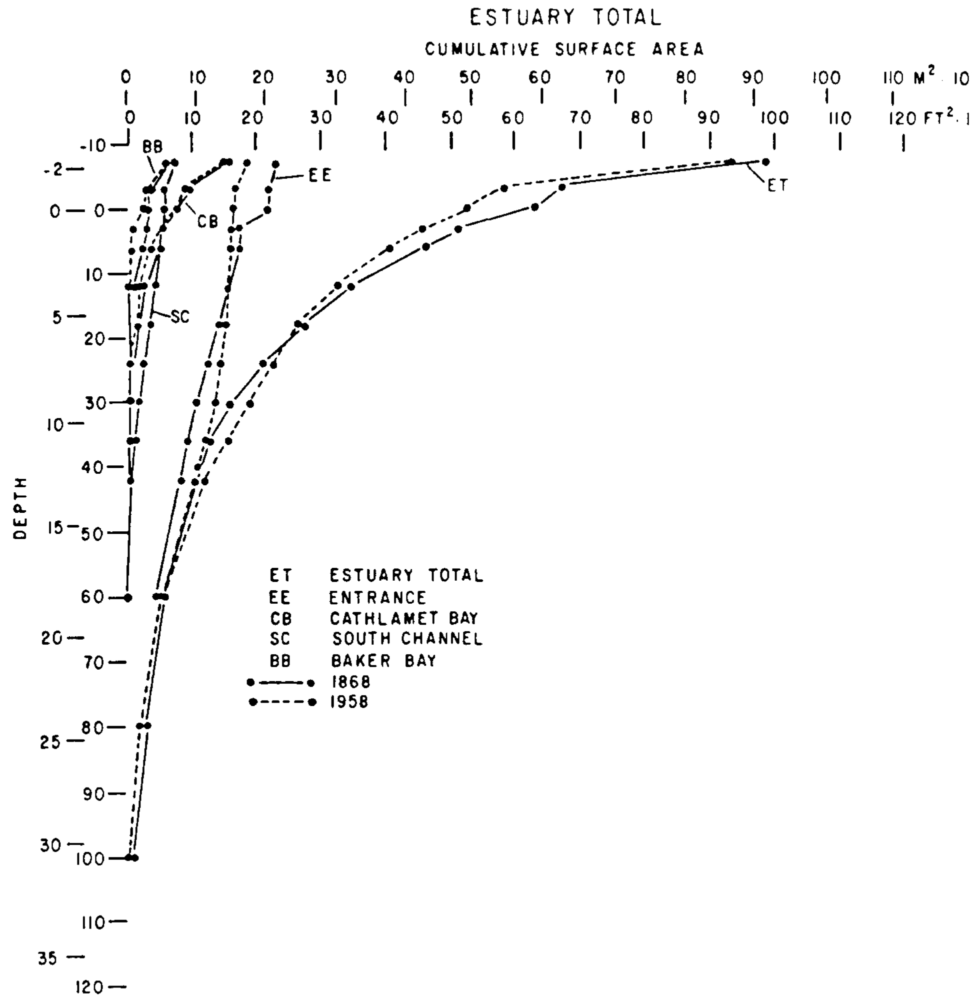

FIG.15. Hypsometric curve relating cumulative surface area to depth for the entire estuary and for several subareas. The changes associated with navigation development in the Entrance region (Fig.14) are also apparent for the estuary as a whole. Note also the reduction in area with shallow subtidal depths in Baker and Cathlamet Bays. Because more than 60% of the estuary is less than 2m deep on very low tides, wind-wave sediment resuspension is a potentially important process.

4.3 Volume changes and sedimentation estimates

The digitized bathymetric data were used to directly calculate the sediment volume changes in each of the subareas between the surveys. These calculations are not biased by incorrect estimates of the interval-mean depth or by inconsistent survey coverage, as are the area and water calculations, because only overlapping prisms from consecutive surveys were used. Thus, although sediment volume differences could not be computed for all areas of the estuary between each pair of surveys, those values that were calculated contain only survey and datum errors. The subareas which do not overlap exactly between surveys are the Entrance, the South Channel, and Youngs Bay (indicated by minus (-) on Fig.12). In these areas, the estimates of sedimentation are again minimum estimates, and even in areas with perfect overlap between surveys, the lumping of all elevations greater than 2.1m (7ft) above MLLW yields underestimates of shoaling. Sediment volume changes are tabulated and compared with water volume changes in Table 6. Considering the survey coverage inconsistencies and the bias in the water volume estimates, there is reasonable agreement between the two methods of estimating shoaling in the estuary.

The largest sediment volume changes occurred in the Entrance subarea between 1868 and 1935, following jetty construction (Table 6). During this period, nearly 213 x 10^6m^3 of sediment was lost from the areas with overlapping survey coverage. Another 34 x 10^6m^3 was lost in the subsequent period (1935-1958). As discussed earlier, a considerable portion of this total of 237 x 10^6m^3 was probably deposited on Clatsop Spit, Peacock Spit, and newly created land areas omitted in the later surveys. The nearby subareas of Trestle Bay (9 x 10^6m^3) and Baker Bay (91 x 10^6m^3) showed large gains during the early period. In the rest of the lower estuary, Desdemona Sands (46 x 10^6m^3) and Youngs Bay (31 x 10^6m^3) showed deposition, while the North and South Channels showed erosion of 3 and 10 x 10^6m^3 respectively. Overall, sediment losses in the Entrance and the lower estuary exceeded gains by nearly 50 x 10^6m^3. However, gains in the upper estuary, notably Grays Bay (23 x 10^6m^3) and Cathlamet Bay (49 x 10^6m^3), were more than sufficient to offset the loss in the lower estuary, and the system as a whole gained 43 x 10^6m^3. If the losses in the Entrance subarea are excluded, over 256 x 10^6m^3 of sediment accumulated in the estuary between 1868 and 1935.

The changes in the subsequent period (1935 to 1958) were less dramatic but still significant. Again, large losses of sediment occurred in the Entrance subarea (34 x 10^6m^3). Slight losses occurred in previously depositional Baker Bay and erosion continued in the North Channel. Trestle Bay (4 x 10^6m^3), Desdemona Sands (13 x 10^6m^3), and Cathlamet Bay (27 x 10^6m^3) remained depositional. The South Channel became depositional, gaining nearly 18 x 10^6m^3. The system as a whole gained 25 x 10^6m^3. Excluding the large losses from the Entrance subarea, the estuary gained 59 x 10^6m^3.

Over the total 90-year period (1868 to 1958), net deposition in the entire system amounted to 68 x 10^6m^3, including erosion in the Entrance subarea of 247 x 10^6m^3; therefore, the accumulation in the estuary excluding the Entrance subarea totalled 315 x 10^6m^3. An additional 50 to 70 x 10^6m^3 of dredged material has been placed on land and the 38km^2 of area omitted from the surveyed area between 1868 and 1958 may account for another 76 to 100 x 10^6m^3, producing a total accumulation estimate of 441 to 485 x 10^6m^3 of sediment for the estuary, excluding the Entrance.

The sediment volume changes and 1958 areas of the subareas were used to calculate the average rate of sediment deposition or erosion (Table 7; Fig.16). Shoaling rates vary from a maximum of 3.33cm y^{-1} (Trestle Bay between 1935 and 1958) to -1.84cm y^{-1} (erosion in the Entrance subarea between 1868 and 1935). The highest rate of net accumulation over the 90-year period also occurred in Trestle Bay (2.43cm y^{-1}) and the highest net erosion rate occurred in the Entrance subarea (-1.59cm y^{-1}). The 90 year area-weighted mean shoaling rate for the entire estuary is 0.09cm y^{-1}; when the Entrance subarea is excluded, the weighted mean shoaling rate for the remainder of the estuary is 0.5cm y^{-1}, roughly five times the average rate of sea level decrease. Because on-land disposal of dredged material and creation of land have been neglected here, this nominal rate may underestimate true shoaling rates by perhaps 15 to 50%.

TABLE 6. Volumes and volume changes by subarea.

		Volumes[a] ($10^6 m^3$)			Volume Changes ($10^6 m^3$)					
		1868	1935	1958	1868-1935		1935-1958		1868-1958	
Estuary Subarea					(b)	(c)	(b)	(c)	(b)	(c)
1	Entrance	2279.23	2410.03	2378.64	130.80*	-212.86	-31.39*	-33.87	99.41	-246.73
2	Baker Bay	103.14	23.34	27.05	-79.80	90.89	3.71	-4.76	-76.09	86.13
3	Trestle Bay	9.76	3.23	1.61	-6.53	9.03	-1.62	3.96	-8.15	12.99
4	North Channel	226.25	228.56	238.40	2.31	-3.42	9.84	-5.63	12.15	-9.05
5	South Channel	379.44	391.28	413.50	11.84*	-9.96	22.22	17.64	34.06*	7.68
6	Youngs Bay	35.44	25.15	16.22	-10.29*	31.43	-8.93*	3.88	-19.22*	35.31
7	Desdemona Sands	159.57	115.31	100.82	-44.26	45.93	-14.49	12.92	-58.75	58.85
8	Mid Estuary Shoals	87.68	86.84	86.88	-0.84	1.26	0.04	-0.29	-0.80	0.97
9	Grays Bay	92.50	71.70	74.33	-20.80	23.13	2.63	-4.00	-18.17	19.13
10	Brix Bay	8.40	6.40	6.67	-2.00	6.18	0.27	-0.58	-1.73	5.60
11	Cathlamet Bay	249.33	207.87	191.31	-41.46	49.34	-16.56	26.86	-58.02	76.20
12	Lower River Channel	101.34	108.40	107.24	7.06	-7.11	-1.16	0.88	5.90	-6.23
13	Upper River Channel	311.73	303.18	291.41	-8.55	19.32	-11.77	8.24	-20.32	27.56
Estuary w/o Entrance		1764.58	1571.26	1555.44	-193.32	256.02	-15.82	59.12	-209.14	315.14
Estuary Total		4043.81	3981.29	3934.08	-62.52	43.16	-47.21	25.25	-109.73	68.41

[a]Based on water volume estimates.
[b]Based on water volume differences; positive numbers indicate erosion, negative numbers indicate shoaling.
[c]Based on bathymetric differencing (sediment volumes); negative numbers indicate erosion, positive numbers indicate shoaling.
*Numbers biased by unequal survey coverage (see text).

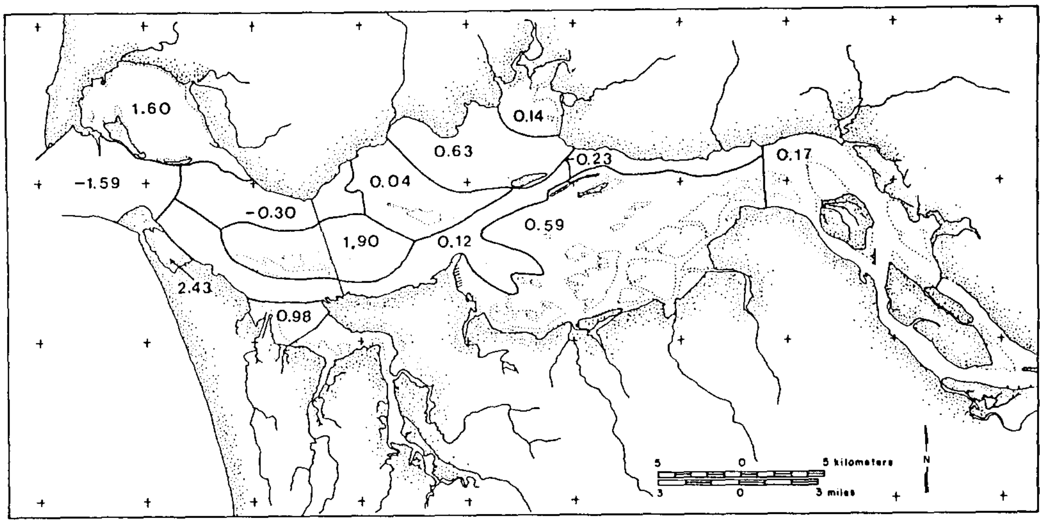

FIG.16. Net shoaling rates in cm y^{-1} for 13 subareas between 1868 and 1935, based on the 1958 areas. Shoaling rates are highest in the peripheral bays; significant loss of sediment has occurred in the Entrance region. Averaging shoaling rate for the estuary, excluding the entrance, for the entire period, is 0.50cm y^{-1}.

TABLE 7. Shoaling rates by subarea

	Estuary Subarea	1958 Area ($10^6 m^2$)	Shoaling (cm y^{-1}) 1868-1935	1935-1958	1868-1958
1	Entrance	172.45	-1.84	-0.98	-1.59
2	Baker Bay	59.60	2.27	-0.40	1.60
3	Trestle Bay	5.94	2.27	3.33	2.43
4	North Channel	33.19	-0.15	-0.85	-0.30
5	South Channel	69.07	-0.22	1.28	0.12
6	Youngs Bay	40.07	1.17	0.48	0.98
7	Desdemona Sands	34.35	2.00	1.88	1.90
8	Mid Estuary Shoals	27.17	0.07	-0.05	0.04
9	Grays Bay	33.49	1.03	-0.60	0.63
10	Brix Bay	44.07	0.21	-0.07	0.14
11	Cathlamet Bay	143.00	0.51	0.94	0.59
12	Lower River Channel	29.71	-0.36	0.15	-0.23
13	Upper River Channel	175.59	0.16	0.23	0.17
		Area Totals	Average Shoaling Rates cm y^{-1}		
	Estuary Total	867.79	0.07	0.17	0.09
	Estuary w/o Entrance	695.34	0.55	0.45	0.50

5. ANALYSIS OF HISTORICAL CIRCULATION PATTERNS

5.1 Modelling procedure

To qualitatively evaluate the effects of human intervention on flushing time, salinity intrusion length, and stratification, the multi-channel, laterally averaged, time-dependent circulation model described in HAMILTON (1984, 1990) was used to simulate the circulation and salinity structure of the estuary prior to human modification. The 1868-1877 USCGS bathymetric surveys described in Section 4 were used to define the channels shown in Fig.17a; the 1868 channels are considerably different from the modern channels shown in Fig.17b. Vertical grid spacing was the same in both cases, and horizontal grid spacing was similar.

All available historical tidal height data (summarized in Appendix C of JAY, 1984) were used to define historical tidal conditions. In most instances, harmonic analyses were not available and the data were tabulated as mean and diurnal range and Greenwich intervals (times of high and low water). There was considerable variability within the historical observations because of the short and variable record lengths and because reference stations as distant as San Francisco Bay were used in reducing the raw observations. However, minimal differences between present and historical tidal data were found. Therefore, modern Jetty A tidal data were used to drive the model for the historical runs. The model predicted tides in the upriver area for the historical runs that were nearly identical to those predicted for the comparable modern runs. River flows used were 2,000, 4,000 and 12,000m^3s^{-1} (71, 141, and 424 x $10^3ft^3s^{-1}$), comparable to flows used with the modern bathymetry.

5.2 Changes in transport patterns

One of the most striking historical changes that is portrayed by the model is the difference in the distribution of water transport. Dredging, dredged-material disposal, and pile dikes have concentrated flow in the navigation channel, diverting flow from other parts of the estuary and changing the balance between flood and ebb flows in the North and South Channels (compare Figs 18a,b,c and 19a,b,c). Ebb flows are now stronger in the South Channel (Fig.18b) than they were in 1868 (Fig.19b) because ebb flow has been diverted away from the North Channel and peripheral channels. The distribution of flood tide flows has been much less affected. Flow in the South Channel is now far more ebb-oriented than in 1868, and that in the North Channel is less so (Figs.18c and 19c). In 1868 (Fig.19b), strong ebb flows also occurred in deep channels which existed in northern Cathlamet Bay. Flow has since been diverted from all of these channels. The original shipping channel through Cathlamet Bay (called Cordell Channel) was totally blocked by the construction of Snag Island Jetty in 1893, and construction of Rice Island and the pile dikes at Harrington Point diverted flow away from Grays Bay. Much more flow also crossed the shoals off Astoria in 1868 because these shoals were generally deeper at that time.

It was argued (Section 4) that the tidal prism of the estuary has decreased by about 15% between 1868 and 1958. Modern tidal transports (Figs.18a,b) are, accordingly, smaller than historical transports (Figs.19a,b), but this is difficult to discern because of the change in distribution of the transports. The change in the distribution of depths (the hypsometric curve; Fig.15) has also influenced the circulation; the channels of the lower estuary are now deeper and greater in cross-section than were the corresponding channels in 1868. Previously submerged flats are now shallower and, in some cases, have been filled. The model assumes that the flow is conveyed in the channels and that the flats are only storage areas. Based on the hypothesis that

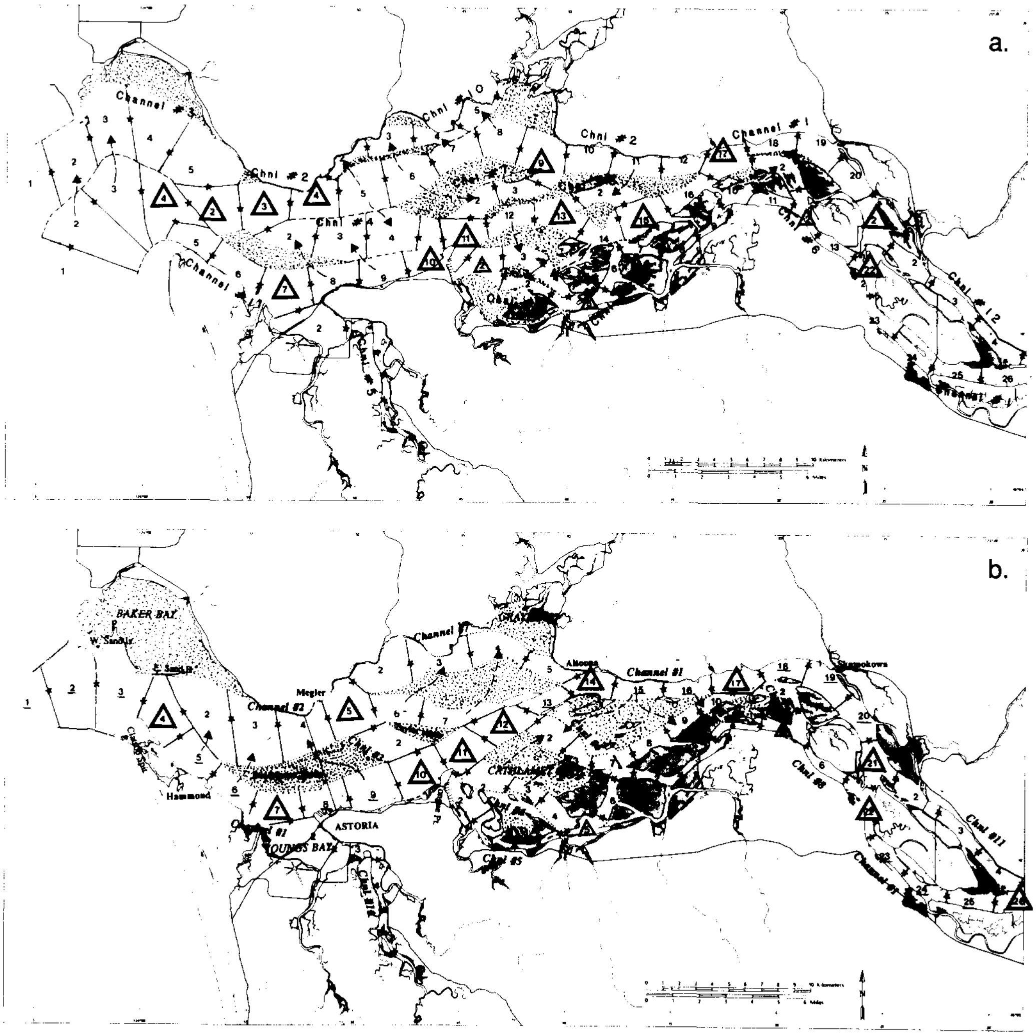

FIG. 17a. Model schematization of the 1868 estuary. Grid cell numbers denote the position of elevation points and stars denote transport points. Triangles denote channel junction grid points; dashed arrows denote across-barrier interchannel connection.

FIG. 17b. Model schematization of the modern (1980) estuary. Symbols are as on Fig. 17a.

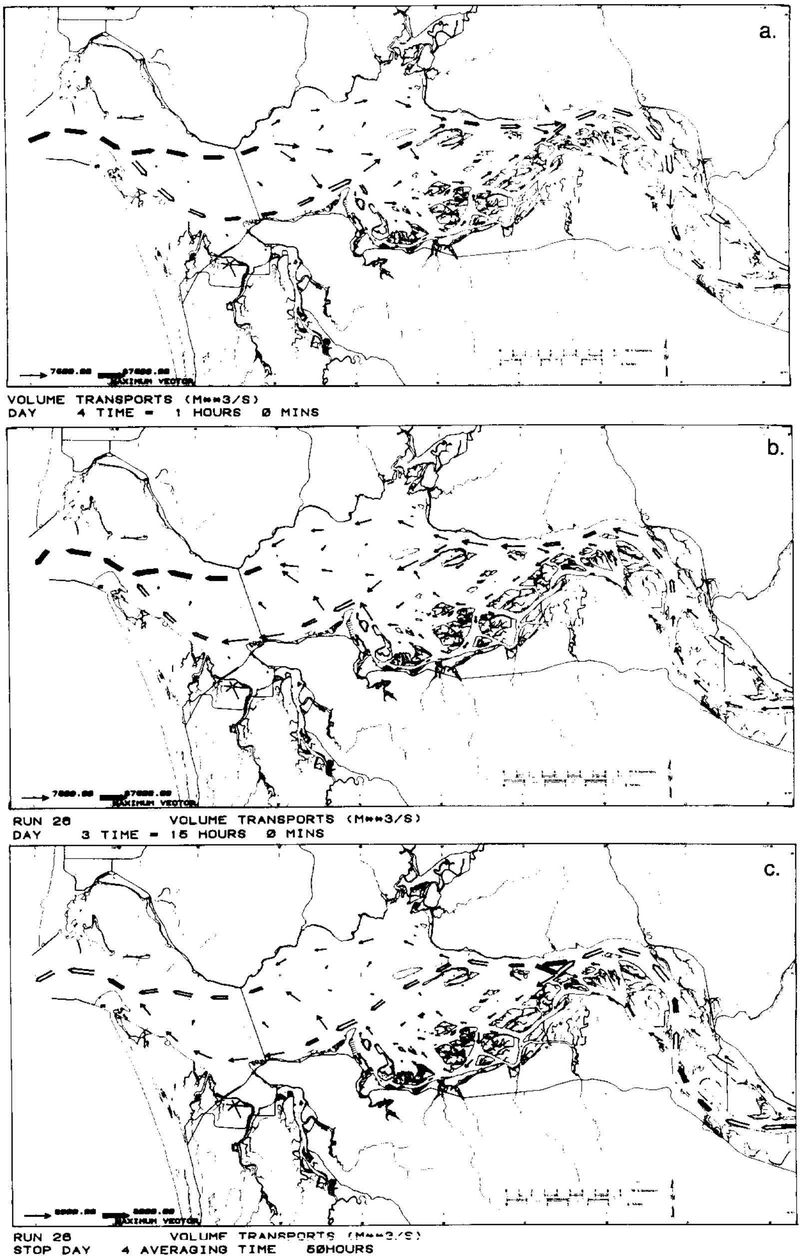

FIG.18a Model results: modern estuary, flood transport, riverflow = 4,000m^3s^{-1}, neap tide.

FIG.18b. Model results: modern estuary, ebb transport, riverflow = 4,000m^3s^{-1}, neap tide.

FIG.18c. Model results: modern estuary, mean transport, riverflow = 4,000m^3s^{-1}, neap tide.

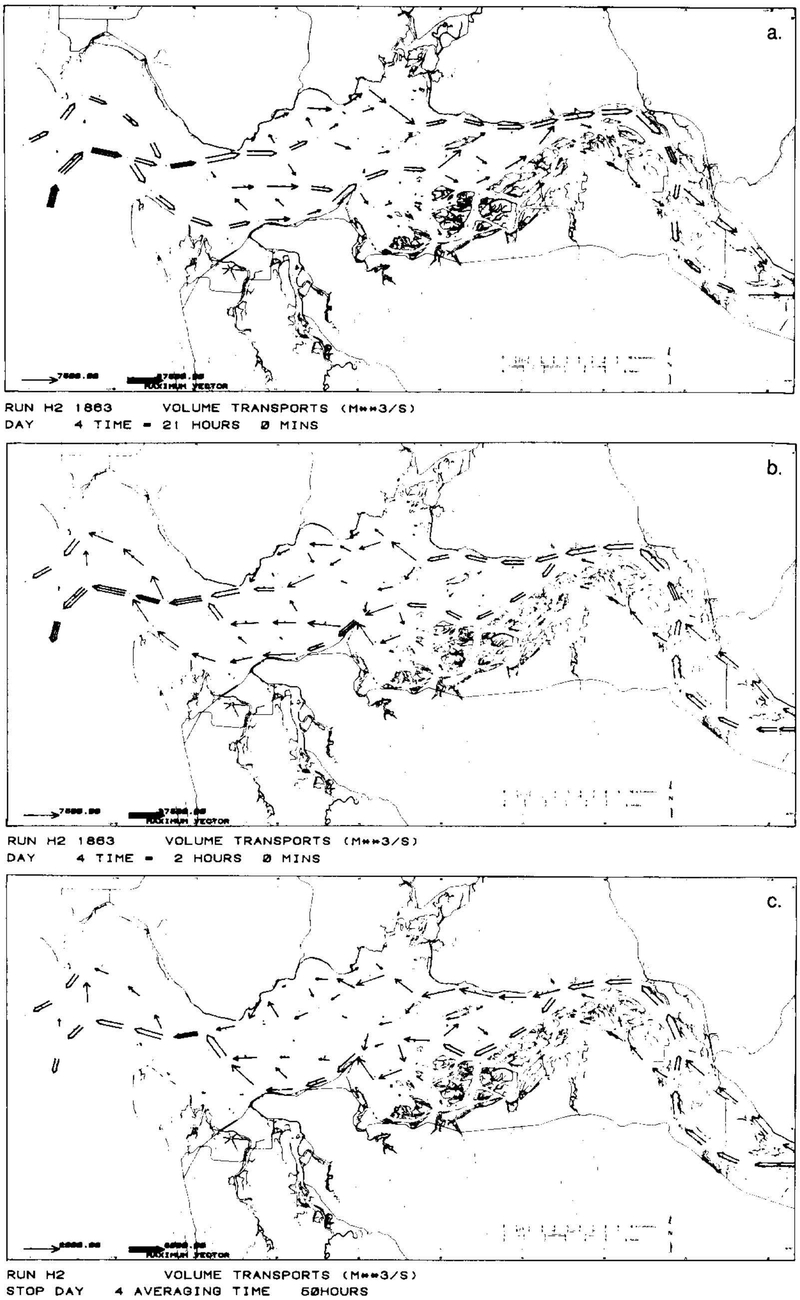

FIG. 19a. Model results: 1868 estuary, flood transport, riverflow = 4,000m^{3}s^{-1}, neap tide. Although total transport over the tidal cycle is larger in the 1868 estuary, it is diffused among many, relatively smaller channels compared with the modern estuary.

FIG. 19b. Model results: 1868 estuary, ebb transport, riverflow = 4,000m^{3}s^{-1}, neap tide.

FIG. 19c. Model results: 1868 estuary, mean transport, riverflow = 4,000m^{3}s^{-1}, neap tide.

the larger, historical transports were indeed confined to the channels, the model predicts that tidal current velocities for comparable tidal ranges were greater in 1868.

The validity of the assumption that most of the flow was (and is) conveyed in the channels defined in the model is clearly critical. It is nearly correct for the present bathymetry because the distribution of tidal transports calculated by the laterally averaged model (Figs.18a,b,c) is very similar to that calculated for the same flow conditions by a vertically integrated model (Hamilton, 1984), even though the latter did not confine flow to the channels (Figs.20a,b). However, the hypothesis that most of the flow was conveyed in the channels in the 1868 estuary cannot be directly tested. The 1868 estuary was less channelized than the present system, and more of the flow is likely to have been conveyed across shoals and flats which, in the model, are considered storage areas. This remains as one of the uncertainties in modelling circulation in the 1868 estuary.

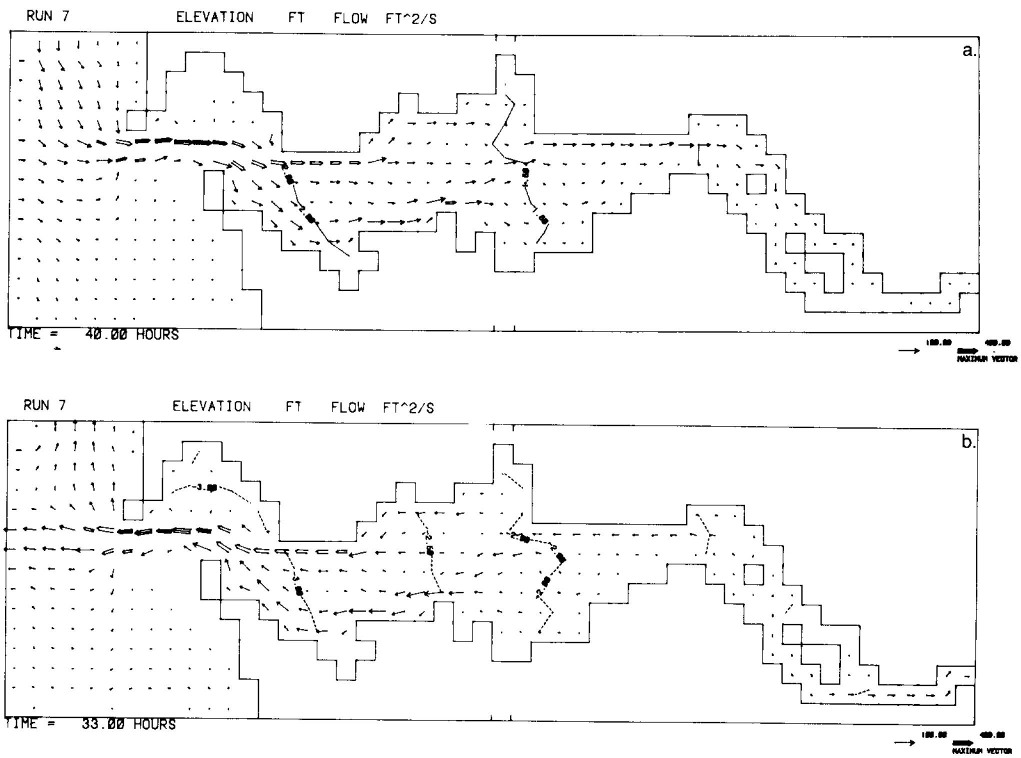

Fig. 20a. Flood transport (arrows) and surface elevation (contours) in the two- dimensional, vertically integrated model of the modern estuary (Hamilton, 1984).

Fig.20b. Ebb transport (arrows) and surface elevation (contours) in the two-dimensional, vertically averaged model of the modern estuary (Hamilton, 1984).

Perhaps the largest difference between the present and historical flows is one that is not directly illustrated by the model. The modern estuary is less variable because of the regulation and diversion of freshwater flow (described in Section 3). Modern river flows rarely exceed 17,000m^3s^{-1} (600 x $10^3ft^3s^{-1}$) or fall below 2,830m^3s^{-1} (100 x $10^3ft^3s^{-1}$), whereas such extreme conditions probably occurred in most years before flow regulation by the dams. The major freshets (e.g. 1894 and 1948) that would have really large impacts on the energy budget (JAY, GIESE and SHERWOOD, 1990) and sediment supply (Section 3) have been totally eliminated.

5.3 Changes in salinity distribution

One major difference between the modern and 1868 estuary suggested by the model is the greater salinity intrusion length in 1868 estuary for all riverflow conditions. The greater salinity intrusion was particularly prominent in the South Channel because ebb flows there were smaller with the 1868 bathymetry (Figs.21a,b). Furthermore, maximum salinity intrusion occurred during spring tides in 1868, but now occurs during neap tides, as will be discussed below. The excursion of salinity contours in both channels was also substantially larger in 1868 than at present. These differences occurred despite the shallower channel depths in 1868 and are a result of the greater tidal currents in that model configuration. Furthermore, seasonal maximum salinity intrusion was certainly greater in 1868, because minimum flows were much lower then (Section 2).

Figure 21a shows salinity of 1 intruded to about RM-28 (grid point 15) in 1868. Thus, given present-day autumn river flows and 1868 bathymetry, salinity intrusion of about 1 to 5 probably occurred throughout Cathlamet Bay. However, autumn river flows in 1868 were substantially lower than at present so larger salinity intrusions likely occurred on a sporadic basis. Furthermore, the model suggests that the difference in the salinity distribution between the present and historical bathymetry increased as flow was decreased. Thus, the model also predicts much greater maximum spring-tide salinity intrusion with 1868 bathymetry than with modern bathymetry for an extreme low flow (2,000m^3s^{-1} or 71 x $10^3ft^3s^{-1}$, a riverflow which no longer occurs because of regulation). Salinities of 10 to 15 are predicted in the interior of Cathlamet Bay during extreme low flow, and the salinity = 5 contour extended upriver to the downstream end of Puget Island.

The 1868 bathymetry also resulted in different neap-spring changes in salinity intrusion, compared with those for present bathymetry. The model produced slightly greater salinity intrusion on spring tide rather than neap tide, and no clear neap-spring change in stratification was found except in the 12,000m^3s^{-1} (424 x $10^3ft^3s^{-1}$) case, where the neap-spring difference in stratification was somewhat greater than at present. As discussed in JAY and SMITH (1990), it is to be expected that greatly decreasing the riverflow would eliminate the neap-spring transition at the point where the riverflow became insufficient to create strong stratification with even the weakest tides. The model indicated that the flow below which no neap-spring transition can occur was much higher with the 1868 bathymetry, probably because of the shallow depths and stronger tidal currents. It is therefore reasonable to infer that neap-spring transitions occurred at higher flows with the 1868 bathymetry.

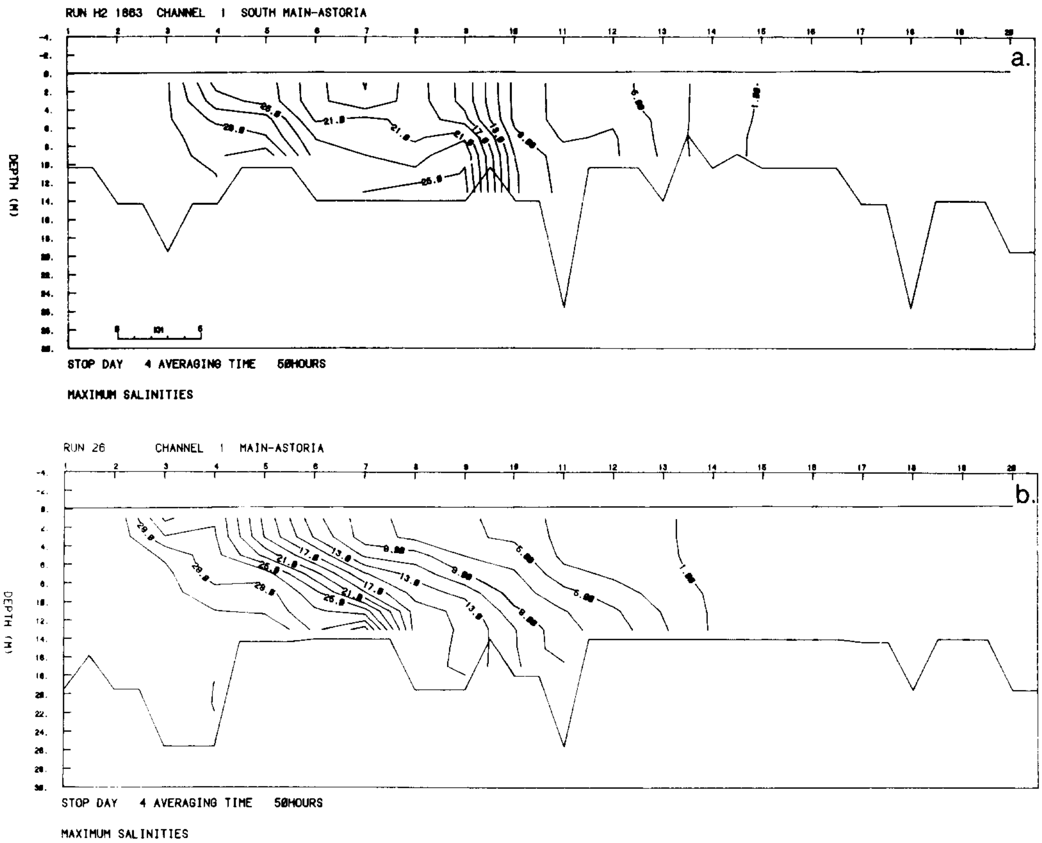

FIG.21a. Model results: 1868 estuary, maximum salinity intrusion, riverflow = 4,000m^3s^{-1}, neap tide. Salinity intrusion varied more, especially on seasonal time scales, prior to riverflow regulation.

FIG.21b. Model results: Modern estuary, maximum salinity intrusion, riverflow = 4,000m^3s^{-1}, neap tide. Salinity intrusion lengths has been reduced in the modern estuary because tidal transports are smaller. Stratification has increased because tidal mixing has been reduced and depths have been increased.

6. PHYSICAL EFFECTS OF CHANGES IN MORPHOLOGY AND CIRCULATION

6.1 Turbidity maximum processes

Mid-estuary accumulation of suspended material in a turbidity maximum (GELFENBAUM, 1983; SHERWOOD, CREAGER, ROY, GELFENBAUM and DEMPSEY, 1984) is of considerable importance as a sink for detritus and as a source of entrained food particles for primary consumers (SMALL, MCINTIRE, MACDONALD, LARA-LARA, FREY, AMSPOKER and WINFIELD, 1990). The turbidity maximum also represents one mechanism by which organisms remain in the estuary in the face of the strong outward mean flow. The effects of human alteration of estuarine flow patterns on the turbidity maximum probably have had large, ecosystem-level consequences.

Historical changes to the variability of estuary flushing time have affected the turbidity maximum. Flushing times in the modern Columbia River Estuary are very short (on the order of a few days; NEAL, 1972) relative to those of most other major estuaries. Flushing times vary both seasonally because of changes in riverflow and during the tidal month because of the variations in tidal currents and the density structure. The residence time of a particle or organism in the estuary may be longer than the flushing time of the system as a whole if the particle spends part of its time on the bottom, in areas of weak currents (e.g. the peripheral bays), or in those channel bottom areas where the residual flow is inward. Because particles tend to accumulate preferentially in such locations, a turbidity maximum forms. The annual mean flushing time of the 1868 estuary was, on the average, less than that of the modern estuary because (1) tidal exchange was greater, and (2) the average riverflow was slightly greater before diversion and regulation. More importantly, flushing times were seasonally much more variable, because the freshwater inflow was more variable. A decrease in temporal variability in flushing has, however, been accompanied by an increase in the spatial variability of flushing rates. Concentration of tidal and mean flow in the main channels has undoubtedly increased the flushing time of the subsidiary channels. Not only will parcels of water remain longer in smaller channels, but particles may spend more time on the bottom because of reduced shear stresses. Thus, lateral movement of suspended material into peripheral areas from the turbidity maximum in the channel is probably an important mechanism for deposition of fine material in the modern estuary (JAY and SMITH, 1990). Whether this was also true in 1868 is questionable. In this sense, the modern estuary is more favorable for the deposition of fine material in peripheral areas, exclusive of any changes that may have occurred in the supply of this material.

The flushing times of both the modern and the 1868 estuary are short relative to the tidal monthly periods (15 and 28 days) over which the tidal range and density structure vary. The residence time of inorganic suspended material in the modern estuary appears to be regulated by neap-spring changes in tides and stratification, at least during low-flow periods. Material is deposited during neap tides and eroded and transported seaward during spring tides because of the stronger tides and weaker stratification and shear, a pattern also seen in other shallow, strongly tidal systems (ALLEN, SOLOMON, DUPENHOAT and DE GRANDPRE, 1980). Finally, more suspended sediment is presently found in the South Channel than in the North Channel because the South Channel is more directly connected to the source of the material (the river) and because the greater tidal exchange results in a shorter residence time in the North Channel. It is probable that the difference between channels in suspended sediment concentrations was less in 1868 because the North Channel was connected more directly to the river at that time. This change in the distribution of the turbidity maximum may have caused smaller deposition rates in the northern peripheral bays and larger deposition rates in southern peripheral bays, relative to modern rates.

6.2 Long-term shoaling patterns and the sediment budget

Some evidence regarding the historical shoaling patterns in the estuary can be derived from further examination of the volume changes between 1868 and 1958 (Table 6). The volume calculations of Section 4 indicate that the net accumulation in the system has been at least 68 x $10^6 m^3$ since 1868. When adjusted for the loss of 247 x $10^6 m^3$ that occurred in the Entrance subarea and estimated losses to land, it is clear that 365 to 485 x $10^6 m^3$ of sediment accumulated inside the estuary during the 90-year period, a minimum annual rate of 4.1 to 5.4 x $10^6 m^3 y^{-1}$. However, several lines of evidence suggest that not all of this material was derived from the river. The history of change at the entrance, as related by HICKSON (1922, 1930), LOCKETT (1963, 1967), the

COLUMBIA RIVER ESTUARY DATA DEVELOPMENT PROGRAM (1983) bathymetric difference maps, and sedimentological evidence (BORGELD, CREAGER, WALTER and ROY, 1978; ROY, CREAGER, WALTER and BORGELD, 1979; WALTER, ROY, CREAGER and BORGELD, 1979; CREAGER, SIMS, SHERWOOD, ROY, STEWART, BARNETT and GELFENBAUM, 1980; ROY, CREAGER, GELFENBAUM, SHERWOOD and STEWART, 1982; SHERWOOD, CREAGER, ROY, GELFENBAUM and DEMPSEY, 1984) all suggest that much of the accumulation on Desdemona Sands, Baker Bay, and Trestle Bay is related to the displacement of sediments from the natural tidal delta as a result of the construction of the entrance jetties. Thus, scouring of the entrance channel by the constrained tidal currents has transported sediment both offshore and into the estuary. Whereas the inner and outer tidal deltas were relatively close to each other in 1868, they are now separated by several miles of deep channel and by the spits formed around the jetties. The inner tidal delta in 1868 was a distinct, if dynamic, feature consisting of intertidal islands and shoals (Sand Island and Middle Sands, Fig.1). The modern inner tidal delta has been forced further into the estuary and is no longer a distinct feature. The sandy sediment that made up the 1868 inner tidal delta is now found in Trestle Bay, Baker Bay, and Desdemona Sands (Fig.2).

Sandy sediments deposited in the lower estuary, including Trestle Bay, Baker Bay, Desdemona Sands, and the North and South Channels (totalling 157 x 10^6m^3), probably account for more than half of the sediment lost from the Entrance subarea. The remaining 90 x 10^6m^3 of the 247 x 10^6m^3 lost from the Entrance subarea has been either deposited on Clatsop or Peacock Spits or has been lost entirely from the system. An average of 2.3m of fill over the $38km^2$ of area omitted between surveys is required to account for all of this material; the average shoaling rate in the omitted region was probably less than that. The portion that was lost from the system and any additional sediment that has bypassed the estuary has been either pushed farther offshore or carried along the coast with the littoral drift. The patterns of erosion and deposition in the Entrance subarea, discussed in LOCKETT (1963) and evident in the *Bathymetric Atlas* (COLUMBIA RIVER ESTUARY DATA DEVELOPMENT PROGRAM, 1983) suggest that much of the displaced sediment has in fact moved seaward and north. This direction is consistent with studies of shelf sediment transport on the Oregon and Washington shelves and with the flux of winter wave energy. One possible implication is that the erosion of the outer tidal delta (since jetty construction was initiated in 1885) has provided unusually large quantities of sediment for the littoral drift system north of the Columbia River. In effect, a large pulse of sediment may have been introduced to the Washington beaches by jetty construction. The effects of the pulse, which may have been seen as jetty and beach accretion along Long Beach and sedimentation in Willapa Bay, may now be wearing off, and future littoral supply from the Columbia River will be much reduced because of the damping of the annual riverflow peaks.

Assuming that all of the sediment that accumulated in Trestle Bay, Baker Bay, Desdemona Sands, and the North and South Channels (157 x 10^6m^3) originated in the Entrance area, and assuming that all of the remaining sediment that accumulated in the estuary was of fluvial origin, 314 to 328 x 10^6m^3 of fluvial sediment is required to account for this accumulation, equivalent to a rate of 3.5 x 3.6 x $10^6m^3y^{-1}$ over the 90 years. The fluvial supply rates presented in Table 2 indicate that, over the 90-year period, an average of 5.9 x 10^6m^3 of sand was supplied annually to the estuary. The average total sediment supply was 12.5 x $10^6m^3y^{-1}$. Clearly, most of the total sediment supplied has escaped to the ocean, including almost half of the sand. This does not contradict the conclusion of SHERWOOD, CREAGER, ROY, GELFENBAUM and DEMPSEY (1984) that there is little net bedload transport out of the estuary because much of the sand-sized material travels in suspension. HUBBELL and GLENN (1973) estimated that approximately 30% of the fine sediment transported into the estuary is retained. The calculations presented above leave little room for accumulation of fine sediment, so HUBBELL and GLENN's estimate appears to be an upper limit and most of the fine sediment probably escapes from the estuary.

While sediment calculations suggest that most of the suspended fine sediment provided by the river has been lost to the ocean, the effects of major floods on bedload transport prior to regulation are harder to analyze. It is clear that large pulses of sand were brought into the estuary by the major freshets (HICKSON, 1930). Given the energy budget discussion (JAY, GIESE and SHERWOOD, 1990), it is improbable that even the largest freshets would have resulted in more transport of sand out of the mouth of the estuary than entered from the river. Thus, the larger freshets of the 1868-1958 period probably had a substantial impact on the total accumulation. The effects of basin development and significant flow regulation (post-1969) on bedload transport are too recent to be evaluated by our historical methodology, and it cannot be determined whether the estuarine shoaling rate has been altered by elimination of large freshets.

The sediment calculations may also be used to place perspective on the potential importance of infrequent catastrophic effects such as volcanic eruptions. Estimates of the volume of sediment in the mudflows from the 18 May 1980, eruption of Mt. St. Helens that reached the confluence of the Cowlitz and Toutle rivers approach 100 x $10^6 m^3$ (FAIRCHILD and WIGMOSTA, 1983). As much as 34 x $10^6 m^3$ of this sediment accumulated in the Columbia River adjacent to the mouth of the Cowlitz River (SCHUSTER, 1981). The COE has since removed more than 11.5 x $10^6 m^3$ of sediment from this reach, but the Cowlitz River continues to contribute sediment at an abnormally high rate (up to 5 x $10^6 m^3$ in the first year, SCHUSTER, 1981; DUNNE and LEOPOLD, 1981). The amount of this sediment that has reached, or will reach, the estuary, is unknown. Much less will arrive, because of the land disposal of dredged material, than would have reached the estuary from a similar eruption 100 years ago. However, the magnitude of sediment involved suggests that such eruptions may have a profound effect on the sediment budget of the estuary on a time scale of decades to a century or more.

7. HISTORIC CHANGES IN ECOSYSTEM STRUCTURE AND PROCESSES

Our ability to synthesize data on historical changes in physical characteristics and processes over the past century is far superior to our ability to assemble information on concurrent changes in the estuary's flora and fauna. There are neither pre-development data nor ecosystem simulation models with which to examine historical scenarios of alterations in biotic communities or ecosystem processes. Our studies, however, indicate that profound changes within the estuarine ecosystem originated from both within and without the system. Within the estuary, marked changes in habitat structure can be directly projected to measurable losses in primary production available for direct (herbivore) and indirect (detritivore) consumption. Changes external to the estuary resulting from flow regulation and impoundment throughout the Columbia River Basin have produced changes within the estuary which have undoubtedly accounted for additional shifts in community and trophic structure. The changes include (1) decreased fluvial energy and increased net sedimentation, (2) altered riverflow cycles and salinity patterns and (3) increased import of both phytoplankton and zooplankton from upriver populations.

7.1 Reduction in primary production related to habitat change

Production change estimates have been made by reconstructing pre-1870 habitat structure and applying modern relationships between habitat assemblage compositions, standing stocks, and production. One of the most significant changes in the estuary is the inferred decreased input of macrophyte-based detritus caused by dramatic reduction in area of emergent wetlands. THOMAS (1983) estimated the conversion of estuarine habitats and non-estuarine lands between 1870 and 1970. Diking and filling was primarily responsible for a 77% net loss (8,100ha) of the original tidal swamps, 62% (4,050ha) of the tidal marshes, and 7% (1,195ha) of the tidal flats and demersal slope habitats. In addition to absolute losses of estuarine habitat, a net conversion of 4,455ha of open water (i.e. channel bottom and water column habitats) to tidal flat and demersal slope habitat occurred through accretion and erosion, and 1,397ha of tidal flat and demersal slope habitat was converted to dry land through natural vegetative colonization. When the changes in habitat area are applied to the mean areal primary production rates estimated during the 1980-1981 CREDDP studies, we estimate losses of emergent plant primary production of approximately 37,230mt C in high marsh, and 14,165mt C in low marsh. Losses of 280mt C in tidal flat and low marsh benthic microalgae primary production are also calculated. Thus, assuming that pre-1870 macrophyte assemblages were associated with comparable estuarine habitats, the annual total emergent plant production has been reduced by approximately 82% and the benthic microalgae production on tidal flats has been reduced by approximately 15%. Unfortunately, we have no macrophyte production data for tidal swamp habitats, the habitats which have suffered the most significant reduction since 1870. Therefore, our estimate for total decrease in vascular plant production, and resulting detritus production within the estuary is considered a minimum estimate.

Disregarding other factors which limit production of wetland herbivores such as muskrat (*Ondatra zibenthica*), nutria (*Myocastor coypus*), and American beaver (*Castor canadensis*), the estimated original marsh production could have supported between 17 and 138 times the modern estimate of herbivore production for the estuary. However, SIMENSTAD, SMALL and MCINTIRE (1990) have indicated that wetland herbivore grazing consumes a minimal proportion of the above-ground emergent plant production in the estuary marshes, suggesting that other influences constrain herbivore production and that the populations which could actually have been sustained by the lost primary production would have been considerably smaller. In addition, we do not have consumption rate estimates for other wetland herbivores (e.g. dabbling ducks, voles, mice, and passerine birds) which might also have been supported by the historic marsh production.

7.2 Reduction in macrodetritus production

Detritus production from emergent marsh vegetation, which we term "macrodetritus", supports other estuarine consumers. Historical changes in the rate of marsh detritus production has probably affected these consumers, but our conclusions in this regard are even more speculative. Fauna which utilize this macrodetritus as an important food resource include benthic infauna such as bivalves (*Macoma balthica*), gammarid amphipods (*Corophium salmonis, C. spinicorne, Eohaustorius estuarius, Paraphoxus milleri*) and polychaete annelids (*Hobsonia florida, Neanthes limnicola*) which populate the tidal flats adjacent to peripheral bays (JONES, SIMENSTAD, HIGLEY and BOTTOM, 1990). SMALL, MCINTIRE, MACDONALD, LARA-LARA,, FREY, AMSPOKER and WINFIELD (1990) have indicated that approximately 53% of the above-ground emergent marsh plant production is either grazed or translocated into below-ground biomass by fall, leaving 47% (24,156mt C y^{-1}) potentially available to the estuary detritus pool by sloughing and decomposition of the above-ground vegetation at the end of the growing season. Litter-bag decomposition experiments indicated that approximately 68% (3,605mt C y^{-1}) of that material is actually exported from the marsh. Such initially large particulate organic matter would have to be broken down and decomposed into smaller particles before it could be utilized effectively by estuarine detritivores. Assuming that all of the lost detritus production was available in usable form, that the infaunal consumption rates of Simenstad, Small and McIntire (1990) were representative of pre-development fauna, and that their production was food limited, we estimated that more than 12 times the extant standing crop of infaunal detritivores could have been sustained by the marsh production before 1870. We will not speculate on related changes in trophic linkages between these primary consumers and their predators. It should be noted, however, that these macrodetritivores are commonly prominent prey of juvenile fishes (including juvenile salmon, *Oncorhynchus* spp.) and shorebirds utilizing intertidal and shallow subtidal habitats in the estuary, and it is not unrealistic to suggest that their population would have benefited from higher prey production.

7.3 Increased fluvial import of microdetritus

Although we have no direct evidence that the impoundment of the river has enhanced the import of phytoplankton and zooplankton into the estuary, a recent remote sensing (laser fluorosensor) survey of the Columbia and Snake Rivers (Bristow, Bundy, Edmonds, Ponto, Frey and Small, 1985) provided data arguing for increased phytoplankton productivity in impoundments. These data also indicated that the average chlorophyll *a* fluorescence (indicative of phytoplankton production) increased incrementally downriver from reservoir to reservoir. Both phenomena may be attributed to a number of factors affecting phytoplankton production, including (1) increased sinking and access to fresh nutrient sources, (2) increased water temperatures, (3) increased nutrient availability from agricultural and urban activities, and (4) decline in suspended sediments, allowing increased light penetration. Whatever the mechanism(s) of upriver phytoplankton enhancement, a rapid transition from high to low chlorophyll *a* concentrations and from a robust freshwater phytoplankton assemblage to a relatively sparse marine phytoplankton assemblage corresponded with a sharp decrease in fluorescence at the surface 2 to 5 salinity zone at the upriver boundary of the estuarine mixing zone. Frey, Lara-Lara and Small (1984) and Small, McIntire, Macdonald, Lara-Lara, Frey, Amspoker and Winfield (1990) attribute this distinct transition to osmotic disruption of freshwater phytoplankton cells and subsequent contribution to the non-fluorescent dissolved organic carbon (DOC) and detrital particles [cell wall particulate organic carbon (POC)] which are concentrated in this region. Whether this flux of living to non-living organic carbon (microdetritus) contributes to the detritus pool available to estuarine detritivores is debatable, but the production and consumption of prodigious quantities of estuarine omnivorous copepods such as *Eurytemora* and *Scottolana* (Simenstad, Small and McIntire, 1990) are difficult to explain without taking this contribution into account. The fallout of phytoplankton carbon occurs near the turbidity maximum, implying entrainment and recycling of the microdetritus within this "null zone" and lateral transport into adjacent peripheral bays. Both processes enhance consumption by epibenthic and benthic detritivores within the region.

There are no pre-impoundment data on phytoplankton or detritus concentrations in the Columbia River. Therefore, our best estimate of the possible historic change is suggested by the four-fold increase in chlorophyll *a* fluorescence which occurs between the free-running upper Snake River and the Bonneville Dam on the Columbia River, documented by Bristow, Bundy, Edmonds, Ponto, Frey and Small (1985). Small, McIntire, Macdonald, Lara-Lara, Frey, Amspoker and Winfield (1990) estimate that 36,205mt C y^{-1} of living phytoplankton is being converted to microdetritus in the upper reaches of the estuary. A reasonable estimate of the historic import rate of phytoplankton-derived detritus to the estuary is then 9,000mt C y^{-1}. If, as under present conditions, approximately 50% of this was converted to water-column detritus in the turbidity maximum, about 5,300mt C y^{-1} entered the detritus-based food web through this pathway prior to 1870. If a significant proportion of the non-living riverine detritus currently imported into the estuary is derived from upriver phytoplankton production, this detritus source was probably also lower before river basin development, perhaps half of the present value of 146,495mt C y^{-1}, or about 73,000mt C y^{-1}. Assuming comparable pre-1870 circulation, this would imply a reduction from 159,185 to 80,000mt C y^{-1} in water-column detritus exported to ocean. Therefore, the post-development carbon budget of the Columbia River Estuary may have involved approximately equivalent substitution of riverine phytoplankton-derived microdetritus for emergent vegetation-derived macrodetritus (Fig.22).

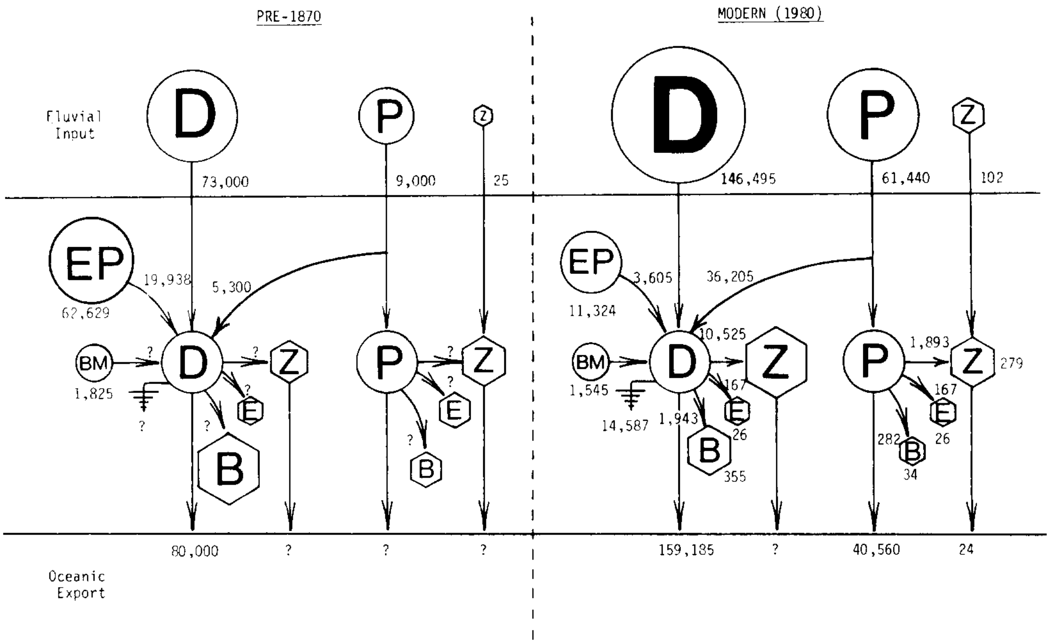

FIG.22. Postulated historical shifts in organic carbon sources (10^{6} metric tons Carbon y^{-1}) and pathways for detritus-based food web in Columbia River Estuary. The pre-1870 food web and carbon pathways (left) are compared with the modern (1980) condition (right); D = water column detritus, P = phytoplankton, Z = zooplankton, EP = emergent plants, BM = benthic macrolide, E = epibenthos, B = benthos. See SIMENSTAD, SMALL and MCINTIRE (1990) for discussion of estimation procedures and extant trophic structure.

7.4 Changes in community structure

The shift over the course of the last century to microdetritus in the estuarine food web may represent a change in detritus quality rather than quantity. Macodetritus from emergent plant sources is more refractory (e.g. less nutritious to consumers) than the highly labile microdetritus from lysed phytoplankton (TENORE, CAMMEN, FINDLAY and PHILIPS, 1982). The primary consumers which would utilize these two detritus sources are fundamentally different. Primary consumers which utilize microdetritus entrained in the turbidity maximum are suspensionfeeding calanoid (*Eurytemora affinis*) and harpacticoid (*Scottolana canadensis*) copepods. We found high densities of these suspension feeders in the vicinity of the turbidity maximum (SIMENSTAD, SMALL and McINTIRE, 1990). Higher level consumers which prey upon *Eurytemora* and *Scottolana* are principally pelagic fishes of the water column, channel bottom, and demersal slope habitats such as Pacific herring (*Clupea harengus pallasi*), American shad (*Alosa sapidissima*), and various smelts (*Osmeridae*), and motile macroinvertebrates such as the sand shrimp *Crangon franciscorum* and mysids *Neomysis mercedis*. The macroinvertebrates are important prey of higher-level consumers (fish and marine mammals; BOTTOM and JONES, 1990). These consumers comprise a basically different assemblage than that which feeds upon benthic detritivores such as *Corophium* and *Macoma*. The latter assemblage includes juvenile salmon, flatfish (starry flounder, *Platichthys stellatus*, and English sole, *Pleuronectes vetulus*), and sculpins (Pacific staghorn, *Leptocottus armatus*, and prickly, *Cottus asper*) of intertidal and shallow subtidal habitats. We postulate, therefore, that production has shifted from shallow-water benthic consumers to water-column pelagic and deep-water epibenthic consumers, but cannot quantitatively assess these changes.

These postulated changes in community structure occurred at a low consumer level in the estuarine food web. Several changes have also occurred at the secondary consumer level but the latter changes are only weakly attributable to historical alterations in estuarine circulation, morphology, or fluvial supply. Some of these changes are, however, notorious. Dramatic decline in some consumers such as Pacific salmon have occurred (FULTON, 1968, 1970; NETBOY, 1974; SALO and STOBER, 1977). The aboriginal harvest of all species migrating into the Columbia River prior to human alteration has been estimated to be about 8 x 10^6kg annually (BEININGEN, 1976). After the arrival of Europeans in the Pacific Northwest, fishing efficiency and intensity increased by several orders of magnitude. Between 1866 and 1940, almost 14 x 10^6kg of salmon were harvested; the harvest plummeted to approximately 4 x 10^6kg over the next 35 years (NETBOY, 1974).

Unfortunately, it is nearly impossible to separate the above-postulated effects of potential changes in the estuarine ecosystem from those of overexploitation, loss of spawning habitat, decline in water quality, blockages and hindrances to migration, and the many other external factors which have ultimately contributed to the decline of the Columbia River salmon stocks. For example, the 42.3 x 10^4km^2 of habitat once available for spawning in the watershed has been reduced to 18.9 x 10^4km^2 and juvenile salmon migrating downstream face a mortality rate of 15% at each dam (SALO and STOBER, 1977). There can be no doubt, however, that secondary consumption in the estuary by the millions of juvenile salmon which used to migrate downstream every year has declined dramatically. Although recent increases in hatchery production have reversed the decline for some species (e.g. coho, *Oncorhynchus kisutch* and chinook, *O. tshawytscha*), artificial propagation has not directly substituted for historical populations because hatchery releases are more punctuated and differ in species and size composition from natural migrations. In addition, hatchery production has not compensated for the losses of chum (*O. keta*) and sockeye (*O. nerka*) stocks, which have functionally disappeared from the Columbia River system despite restoration and management efforts (FULTON, 1970).

Other changes in the estuarine ecosystem include increases in some fish and macroinvertebrate populations. In some instances, this is due to the introduction of exotic species which are filling new or undeveloped niches in the modern estuarine ecosystem. American shad, an Atlantic species which was introduced into the Sacramento River, California in 1871 entered the Columbia River between 1876-1877 and were also planted there in 1885-1886 (WYDOSKI and WHITNEY, 1979). Shad now constitutes one of the most abundant species during its adult and juvenile migrations through the estuary (Bottom and Jones, 1990). As pelagic planktivores, shad exploit both the freshwater calanoid copepods and cladocerans imported into the estuary and the *Eurytemora, Neomysis* and *Corophium* populations concentrated in the estuarine mixing zone. The increase in shad populations coincides with the shift toward a microdetritus-based food web. An exotic freshwater clam (*Corbicula manilensis*) has also become well established in the upper tidal-fluvial region of the estuary. As a deposit feeder, the clam may have benefited from detritus transported laterally from the turbidity maximum to the peripheral bays.

In summary, we hypothesize that emergent plant and benthic macroalgae primary production was higher and microdetritus availability was lower in the pre-development estuary than it is today. The largest changes in productivity are the result of decreased intertidal and wetland habitat. This is hypothesized to have resulted in a related decrease in macrodetritus production availability. Anthropomorphic changes in the fluvial system have probably resulted in an increased influx of freshwater phytoplankton to the estuary, producing an increase in more labile microdetritus. The estuarine food web has apparently adjusted to the change in detritus composition, especially at lower trophic levels. More dramatic changes in higher trophic levels are certainly related to development of the river basin, overexploitation, and the introduction of exotic species, but may also reflect changes in the food web caused by physical changes within the estuary.

8. SUMMARY AND CONCLUSION

A combination of circulation modelling, analysis of riverflow records, and computerized cartographic analysis has been used to formulate a detailed analyses of historical change in the circulation and morphology of a moderately developed estuarine system on the active margin of North America. The methodology should be applicable in other estuarine systems where historical changes in form have been large and a good historical bathymetric database is available. Implications regarding changes in the ecosystem have been inferred from the measured physical changes.

8.1 Summary of historical trends

Human intervention in the Columbia River flow cycle began with irrigation in the late 1840s, followed shortly thereafter by logging of much of the coastal part of the drainage basin. The first major dam was completed in 1933. Analyses of USGS-calculated monthly mean riverflow (1928-82) at the mouth of the Columbia River and of observed flows at The Dalles (1878-1982) suggest, however, that large-scale regulation of the flow cycle began around 1969. Only since then has the variability of the monthly mean riverflow been greatly decreased and have major year-to-year transfers of flow been effected through manipulation of dam storage. The geological effects of these human-induced changes to the hydrological cycle are so recent that they cannot be evaluated by this analysis of historical bathymetric data. In addition to the effects of flow regulation and irrigation withdrawal, over the last century there have been natural fluctuations of up to about 20% in riverflow with periods of decades.

The analysis of historical bathymetric data indicates an historical shoaling rate in the estuary of 0.5cm y^{-1}. Judging from the ample sediment supply, the Columbia River Estuary appears to have reached a quasi-equilibrium state in prehistoric times. The relatively high shoaling rates measured in historic times (four times the rate at which sea level has fallen) are believed to be primarily the result of changes in circulation within the estuary as a result of development of the estuary and river. While average sediment supply to the estuary has apparently decreased in recent years because of the damping of peak riverflows, circulatory processes have changed to render the estuary a more efficient trap. As a result, less sand and fine material is being delivered to the Oregon and Washington coasts and continental shelves, and finer material is being trapped in the estuary. Most shoaling of the estuary, however, is still caused by accumulation of fine and medium sand because the permanent retention of silt and clay was, and is, small.

A useful comparison with the more extensively studied San Francisco Bay Estuary may be made. Sediment supply to that estuary was greatly increased by debris from hydraulic placer mining in the Sierra Nevada during the nineteenth century (GILBERT, 1917). More recently, sediment discharge has been sharply curtailed by diversion of a large fraction of the freshwater inflow (KRONE, 1979). The physiography of the Bay has been greatly altered by diking and filling of intertidal and shallow subtidal areas; marsh area has, for example, decreased by more than 90% (ATWATER, CONRAD, DOWDEN, HEDEL, MACDONALD and SAVAGE, 1979). The result has been a substantial reduction in flushing and an increased residence time for detritus and urban pollutants. As in the Columbia River Estuary, the effects of loss of intertidal and shallow subtidal wetlands has resulted in changes in sedimentation patterns that may be as important as changes in the sediment input. In both estuaries, shoaling and loss of habitat has slowed in recent decades.

The temporary retention of detritus in the turbidity maximum is extremely important to biological processes in the Columbia River Estuary. Numerical modelling of the circulation and salinity distribution suggests that the decrease in tidal prism and diversion of flow away from subsidiary channels has decreased salinities throughout the system, increased the stratification and residence time of suspended material, and perhaps caused increased shoaling in peripheral areas. Neap-to-spring changes in density structure and mean flow are now more pronounced during low flow periods; in the pre-development era, they probably were more pronounced during high flow periods. Diversion of river flow from the North Channel to the South Channel may also have reduced the supply of resuspended material to the north side of the estuary.

8.2 Implications for the future of the system

Although the Columbia River Estuary is dominated by tidal currents and strong riverflow and is a highly energetic system, the trends that have emerged from this analysis of the historical changes in the estuary are alarmingly similar to those in more-developed and less-energetic estuaries throughout the world. The river hydrograph has been damped and the mean flow reduced by the construction of numerous dams and irrigation withdrawal. The result is that major floods no longer occur and the residence time of water in the river has been increased. Overall, physical variability in the system has been reduced.

Unfavorable or potentially unfavorable results of estuarine development have included: a major loss of wetlands and shoreline habitat, decreased estuary surface area and tidal prism, reduced tidal mixing and increased flushing time, and increased sedimentation. Residence times in the estuary for detritus and nutrients have increased and vertical mixing has decreased. Although hydrodynamic changes have probably enhanced the pelagic primary productivity within the estuary, the cost of enhancing estuarine conditions for detritivorous epibenthic and pelagic copepods and conversion to a less-energetic microdetritus-based ecosystem with higher sedimentation rates have yet to be evaluated in terms of the effects on consumer populations. However, it is apparent that these changes, and other changes in the fluvial part of the system, have contributed to the dramatic decline in salmon populations.

The implications of major modifications such as have taken place in the Columbia River Estuary and watershed need to be incorporated into contemporary estuarine and shorelands management strategies. In particular, proposals for comprehensive hydroelectric and water withdrawal developments, shoreline modifications, and navigation projects should all be evaluated in terms of potential consequences to the estuarine ecosystem and resulting effects on other resources, including fisheries, which depend on a highly coevolved and biologically diverse estuarine environment.

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School of Oceanography, University of Washington, contribution 1867.

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