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Downstream Effects of Water Withdrawal in a Small, High-Gradient Basin: Erosion and Deposition on the Skokomish River Delta

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ABSTRACT: This paper analyzes downstream effects of freshwater flow diversion from a small, active-continental-margin river basin. The Skokomish River delta, a tributary estuary to Hood Canal in Washington state, receives drainage from the southeastern side of the Olympic Mountains. Its drainage basin is steep, and rainfall is high. Since completion of two dams in 1930, approximately 40% of the annual average runoff of the entire system has been diverted from the North Fork Skokomish River for power production; this water does not pass through the lower river or over the delta. Extensive logging has occurred in the remainder of the basin. Comparison of prediversion (1885) and postdiversion (1941 and 1972) bathymetric surveys suggest that deposition (about 0.013 m yr^{-1} to 0.022 m yr^{-1}) has occurred on most of the inner delta and erosion (up to 0.011 m yr^{-1} to 0.033 m yr^{-1}) on much of the outer delta. More rapid postconstruction deposition occurred within the river mouth itself, where the 1926 to 1941 deposition rate was 0.04–0.11 m yr^{-1}. Nine of 12 historical bathymetric change cross-sections show steepening of the delta surface, two are neutral, and one shows aggradation. This steepening has apparently been caused by a loss of sediment transport capacity in the lower river and estuary combined with steady or increased (due to logging) sediment supply. Although the total area of unvegetated tidal flats has decreased by only about 2%, there has been a 15–19% loss of highly productive low intertidal surface area and an estimated 17% loss of eelgrass (*Zostera marina*) habitat. A reduction in the size of mesohaline mixing zone has also occurred. These habitat losses are similar to those observed elsewhere in the world in larger river basins that have suffered water withdrawals of the same magnitude, but their impacts either cannot be evaluated or understood casually through consideration of simple measures like changes in total estuarine deltaic area. Evaluation of estuarine effects of anthropogenic modification must, therefore, include consideration of both changes in habitat function and in the physical processes. These must be evaluated within the totality of the river basin-estuary system that cause these changes. In this case, sediment transport constitutes the critical link between fluvial alterations and the remote downstream, estuarine consequences thereof.

Introduction and Regional Setting

Freshwater flow diversion and regulation for purposes of flood control have caused serious damage to estuaries worldwide (Clark and Benson 1981; Rozengurt and Haydock 1981; Rozengurt and Hedgepeth 1989; Simenstad et al. 1992). Most studies of this problem have focused on large drainage basins in arid regions where the most extreme diversions have occurred. The intent of this paper is to examine changes caused by diversion of 40% of annual average flow from a small system situated in a region with a wet climate, the Skokomish River and estuary in Washington state (Fig. 1). It is argued herein that a loss of sediment transport capacity has caused erosion on the outer Skokomish delta combined with shoaling on the inner delta and in the lower part of the mainstem river tributary to the delta. Steepening of the delta has caused a substantial loss of low intertidal habitat and eelgrass (*Zostera marina*). A loss of primary productivity and compression of the mesohaline mixing zone have also likely occurred. These impacts are comparable with and similar to those in larger basins with similar percentages of water withdrawal. Alterations to the sediment transport regime arising from flow regulation and diversion

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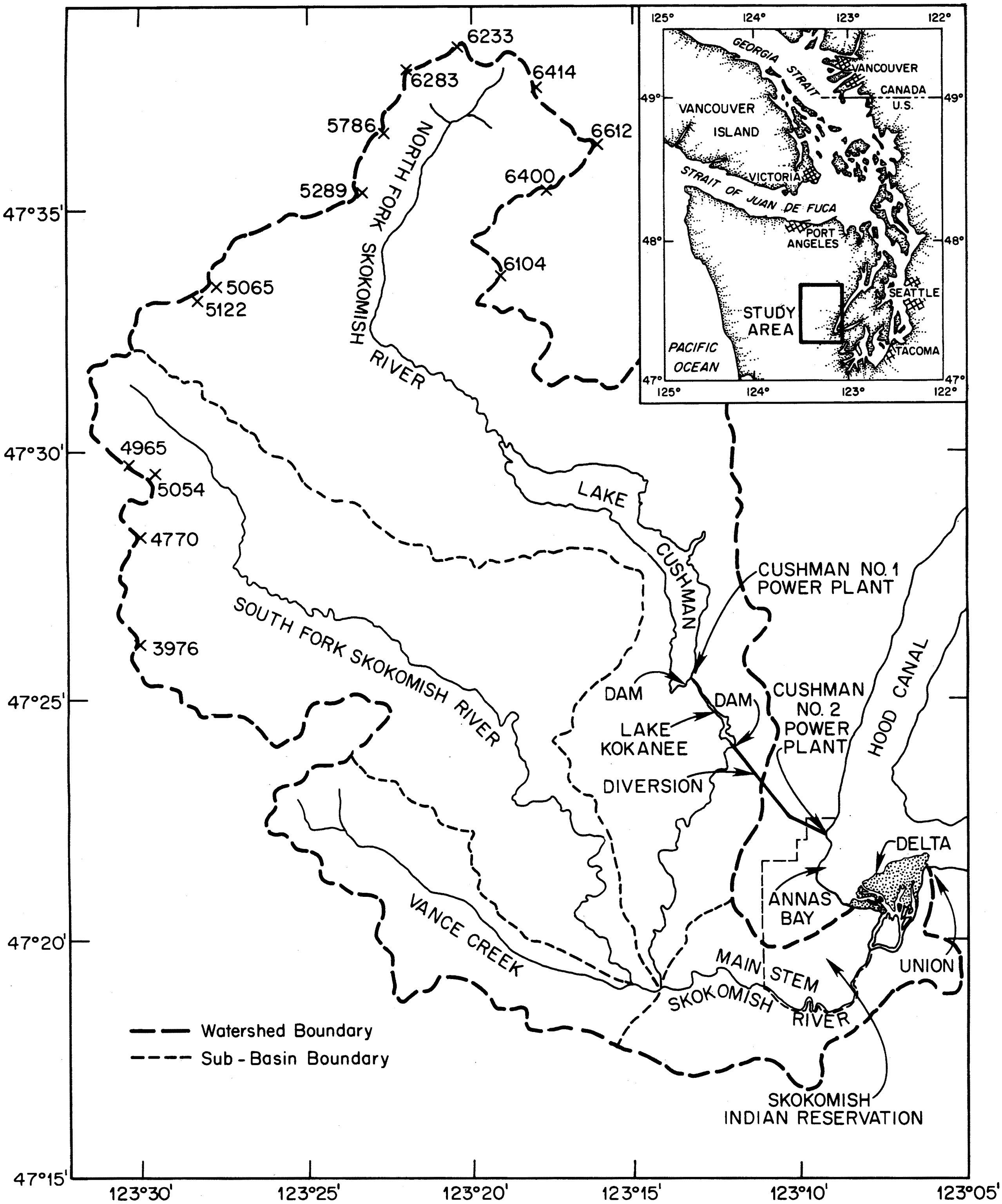

Fig. 1. Area location map for the Skokomish River drainage basin and delta in Washington state.

are, as in the larger basins, a major physical factor linking changes in the river basin and impacts on the estuary.

The Skokomish River river-delta is fed by a high-gradient stream typical of active-continental-margin, Pacific coastal basins in the United States. It is situated at the southwest corner of Hood Canal, a fjord tributary to Admiralty Inlet and the Strait of Juan De Fuca (Fig. 1), and is part of the greater Puget Sound complex of estuaries. The river originates in a small (640 km^2), steep drainage on the southeast side of the Olympic Mountains with a maximum elevation ca. 2,000 m. The last glaciation of the Puget Sound area ended about 11,000 to 13,000 YBP, and modern deltaic features date from the relative stabilization of regional sea level about 5,000 to 7,000 YBP. About 23 km^2 of low-gradient river valley has filled with sediment since the last glaciation. The area of unvegetated tidal flats is a $\sim$4 km^2; vegetated wetlands covered an additional 2.1 km^2 before diking for agriculture in the late Nineteenth Century (Bortleson et al. 1980). Diking and flood protection efforts in the mainstem have caused blockage or reduction in flow capacity of some subsidiary channels, including a major distributary leading to the west side of the delta.

Tidal influence in the Skokomish mainstem extends almost to the confluence of the South Fork and North Fork (Canning et al. 1988). The mean and diurnal tidal ranges at Union (at the outer edge of the delta) are 2.4 m and 3.6 m, respectively. The tidal range is reduced at stations further landward by shallow depths and, during the rainy season, by friction associated with strong river flow. Because of its location at the southwest corner of Hood Canal, the Skokomish delta is relatively protected from wave action during major winter subtropical storms that come predominantly from the south and west (Lilly 1983). The largest waves probably occur during less frequent winter storms from the northwest and as a result of summer winds from the same quarter during periods of high pressure.

The Skokomish River basin is drier than the Pacific coastal side of the Olympic Range, but annual rainfall is still high, varying from about 1.9 m to 5.3 m with an average of 3.4 m (Canning et al. 1988). Maximum river flow occurs as brief winter freshets during and after subtropical storms (Lilly 1983). There are three main tributary subbasins, the South Fork (269 km^2), the North Fork (305 km^2), and Vance Creek (64 km^2). Because of the high rainfall and steepness of the Skokomish basin, the river exerts a strong influence on its delta. The ratio of tidal prism to mean half-tidal-cycle runoff (H_R) was $\sim$7 before diversion and is 11.6 now. Six steep-gradient Pacific coastal estuaries studied by Peterson et al. (1984) exhibited H_R ranging from 4 to 86. Of these six systems, the four smallest (with estuarine surface areas less than 10 km^2) were similar to the Skokomish in that they had $H_R < 15$.

While its steep landscape is similar to that of nearby coastal systems, glaciation was absent in the coastal basins, and the Skokomish has a different history of postglacial, earthquake-related vertical displacement (Atwater et al. 1991; Atwater and Moore 1992). Moreover, tidal exchange is not a major source of beach sand as it is in coastal estuaries. Because of the steep gradient of and recent glaciation in the basin, poorly sorted gravels and cobbles predominate on the bed in the lower North and South Forks. Extensive gravel bars suggest that this was also the case before logging of the South Fork and diversion of flow from the North Fork. Many gravel bars in the North Fork are now relict because of the reduced stream flow. Mainstem sediments are largely sand and gravel; deltaic sediments are discussed below. Several months of salinity time-series observations during low-flow and high-flow periods show that shallow bottom depth limits salinity intrusion to the delta and the lower 0.5–2 km of the mainstem. Profile observations suggest that this intrusion normally occurs as a thin salt wedge. Salinity intrusion into the mainstem is absent during freshet periods. Surface salinities inside the river mouth are, therefore, usually low.

Studies of changes on the Skokomish delta are motivated by the importance of estuarine resources to the Skokomish Tribe and of shallow river deltas to the Hood Canal-Puget Sound ecosystem. Puget Sound and Hood Canal are typical fjords. Together they have a mean depth of 65 m, and aside from tributary river deltas, isolated shallow sills and a narrow, steep shore, the benthos is isolated from the surface and from light. An important part of the primary production in the entire system takes place on, and the food web is extensively influenced by, deltas, which provide a majority of the organic matter supporting detritally based secondary production (Simenstad and Wissmar 1985). These estuarine deltas are also the location of important shellfisheries and serve as a critical nursery habitat for juvenile shellfish and finfish (Simenstad et al. 1982, 1988). No major Puget Sound delta can be described as pristine, and some in urban areas have been so thoroughly altered that their productivity has been drastically reduced. The systems of interest are those like the Skokomish, that have been damaged but might be restored to fuller function.

About 40% of the annual average freshwater inflow of 60 m^3s^{-1} to the Skokomish delta has been diverted from the North Fork since about 1930 as a result of construction of the Cushman Hydroelectric Project, two dams that supply power to the city of Tacoma, Washington (Canning et al. 1988). This water flows down a pipe from Lake Cushman to a point on Hood Canal about 5 km north of the river mouth. It does not pass through the lower mainstem or over the delta (Fig. 1). This diversion has left only 3 m^3s^{-1} annual average flow in the North Fork, where the mean flow prior to diversion was about 27 m^3s^{-1} (Canning et al. 1988). Amongst the impacts of this flow diversion has been a reduction in bankfull capacity of the mainstem from 370–540 m^3s^{-1} during the 1940s (Dunn 1941; D. R. Dawdy personal communication) to its present value of ~150–195 m^3s^{-1} (Canning et al. 1988). This has been accomplished through a rise in the river bed of ~1 m in most locations. We show here that this deposition has been continuous to the river mouth and onto the inner delta.

The post-dam annual sediment input to the mainstem Skokomish is estimated to be 144,000 mt yr^{-1} (Downing 1983); no measurements of pre-dam sediment transport in the Skokomish River are available. It is, moreover, vital in analyzing changes in sediment transport to distinguish between actual sediment transport and sediment transport capacity. The former depends on a supply of material and thus on land use throughout a drainage basin and cannot generally be forecast or hindcast without a model of upstream erosional processes. The latter is a deterministic function of local flow and bed parameters. An estimate of loss of sediment transport capacity since 1930 in the mainstem and over the delta as a result of operation of the Cushman Project can be made using the assumption that transport capacity in the mainstem varies with the square of the discharge. If annual average sediment transport scales with the square of the annual average flow, then the observed 40% reduction in mean flow has caused a 64% reduction in transport capacity. Alternatively, one may assume that only freshets are relevant to sediment transport, and that flow in the North Fork is so small that it no longer contributes meaningfully to maximum flows. This would suggest a 70% reduction in transport capacity. Because ample quantities of sand and gravel are now and probably always have been available in the basin, the reduction in transport capacity has likely caused a similar reduction in sand and gravel transport in the mainstem.

It is probable, however, that along with the above 64% to 70% loss of sediment transport capacity in the Skokomish mainstem, an increase in fine sediment supply (clay, silt, and very fine sand) from the South Fork has also occurred because of extensive timber harvest. Approximately 80% of the South Fork subbasin has been clear-cut since 1947 (Canning et al. 1988). The soils of the drainage basin are highly erodible, and an average of 2.8 km km^{-2} of logging roads have been constructed in that part of the South Fork subject to timber cutting. It is unclear, however, whether timber harvest has increased transport of sands and gravels to the mainstem and estuary, as there likely has always been ample supplies of material to transport. Other unpublished studies cited by Canning et al. (1988) suggest that bank erosion in the mainstem associated with aggradation of the bed may also be an important source of sediment. Because of sediment trapping in the original, pre-dam Lake Cushman, it is likely that the South Fork has always been the dominant source of fine sediment in the mainstem.

In summary, the Skokomish River and its delta comprise a compact, easily studied system. Two minor alterations—diking of a small area of peripheral marshes and blockage or partial blockage of some peripheral channels—and two relatively large changes—removal of 40% of the freshwater inflow and logging of a large fraction of one subbasin—have occurred which have implications for the sediment budget of the system. We are able to focus almost exclusively on impacts of flow diversion by examining historical changes in deltaic bathymetry and habitat. The perturbing effects of logging can be largely neglected in this analysis for several reasons. First, there is now, and late 1930s aerial photos show that there has always been, an ample supply of bedload material (coarse sand and gravel) in the South Fork. Movement of these materials is transport capacity limited in mainstem and delta environments under almost all conditions, and changes in transport capacity are the primary factor governing historical changes in delivery of these coarser sediments to the delta. Therefore, logging can be expected to have altered primarily the supply of silt, clay, and fine sand to the delta. A large fraction of this material is washload, even on the delta. Fine sand and aggregates formed from silts and clays play an important role in deltaic sedimentation, and their supply may have been increased by logging. Nonetheless, results presented below show that loss of transport capacity, not the actual change in sediment supply, has been the decisive factor in these historical changes. These circumstances render the Skokomish a good natural laboratory in which to study downstream effects of water withdrawal on estuaries.

Methods

The United States Coast and Geodetic Survey and United States Army Corps of Engineers survey sheets were used to compare prediversion and postdiversion conditions on the Skokomish delta. Systematic bathymetric comparison provides, given careful attention to a variety of errors and nonanthropogenic processes, an estimate of net shoaling and erosion and the role of anthropogenic changes therein. The present analysis follows methods used during earlier analyses of historical changes in the Columbia River estuary (Sherwood et al. 1990) and San Francisco Bay (Krone 1979). There are two surveys available from the United States Coast and Geodectic Survey for the Skokomish delta. The first, 1885 survey H-1695, predates most human alteration of the area. It was plotted at a scale of 1:20,000 (Fig. 2a, b). Depths are in feet to 18 ft and in fathoms in deeper water. The second, 1972 survey H-9345, occurred some 40 yr after construction of the Cushman Project and was plotted at 1:10,000 (Fig. 2c). Soundings are in fathoms and tenths in shallow water, and in fathoms in deep water. Less extensive, postconstruction depth data (Fig. 2d) were also collected by the United States Army Corps of Engineers in 1941 (Dunn 1941). This survey supplements the 1972 United States Coast and Geodectic Service data with postdam construction coverage of the river mouth.

Soundings and contours for all surveys were digitized and plotted at a common scale; surface areas were determined by planimeter and verified digitally. The 1885 sounding log likely contained more soundings than were plotted, and the 1972 analog echo sounder tracing allowed precise location of contours. We have therefore, made every effort to use information provided by these contours and have not transformed the data to metric units, though equivalent metric depths are given. Accounts of navigational usage during the 1865–1925 period were used to verify the interpretation of bathymetry for the 1885 survey. Aerial photos from the late 1930s and 1972 were used to validate the 1941 and 1972 interpretations.

Horizontal Control

There are two primary horizontal control problems to consider in comparing surveys: historical changes in projections and baselines, and migration of shorelines. Older surveys usually have been corrected to include the North American Datum of 1927, and this should be identical to the grid on the 1972 survey. Experience with surveys for the Columbia River estuary indicates, however, that discrepancies usually remain even after adjustment to the 1927 datum has been made. The best way to correct these is to compare stable features along the shoreline [the mean high water (MHW) line] scribed on the surveys. In the present case, a very good alignment of the entire east and west shorelines of Annas Bay (Fig. 1) is obtained by allowing a 1.5 mm (or 15 m on the ground) offset to the south of the 1885 survey. Horizontal differences in the match of the survey, such as might be associated with differences in projection, are undetectable over the ~5 km^2 area of interest Late 1930s aerial photos and monuments shown on the survey were used to align the 1941 and 1972 surveys.

Vertical Control

The primary vertical control issue is determination of the datum used in the 1885 survey. All modern west-coast surveys (e.g., H-9345) are referred to mean lower low water (MLLW). But Puget Sound differs from other ports in the lower 48 states by its large negative tides, and several datum levels below MLLW were used before 1920 (Shalowitz 1964). Internal evidence shows that the datum used was the Indian tide plane (2 ft or 0.61 m below MLLW); National Ocean Survey personnel concur (J. Hubbard personal communication 1991). It is also necessary to consider changes between 1885 and 1972 in MLLW caused by localized emergence and the submergence of the coast and by global sea-level rise. Holdahl et al. (1989) and Shipman (1989) indicate that the Skokomish delta is close to the neutral line where tectonic movement is zero. As a safe upper limit, it may be assumed that the coast at Union has subsided by 0.5 mm yr^{-1}. To this must be added 1 mm yr^{-1} sea-level rise. MLLW has then risen relative to the land by 0.087–0.13 m (0.29–0.43 ft) over the 1885–1972 period. To render the soundings on the 1885 survey comparable to those on the 1972 survey, about 0.70–0.74 m (2.3–2.4 ft) should be subtracted from the 1972 soundings or added to the 1885 soundings. Similar corrections must be made in comparing the 1941 and 1972 surveys.

Bathymetric Comparison Methodology

Bathymetric differences between surveys were calculated using the fact that the density of soundings generally increased over time, though aerial coverage decreased. Comparison was concentrated in those areas with water less than ~4 m where 1885 soundings were collected by current pole (Shalowitz 1964), a highly accurate sounding method. To compare the United States Coast and Geodectic Survey 1885 and 1972 surveys, each digitized sounding on the 1885 survey was considered in succession. Comparison soundings on the 1972 survey were sought within a search radius of 30 m. If one or more were found, then these were averaged and an 1972 to 1885 difference calculated using appropriate sea level and datum changes. If no comparison soundings were found, the search

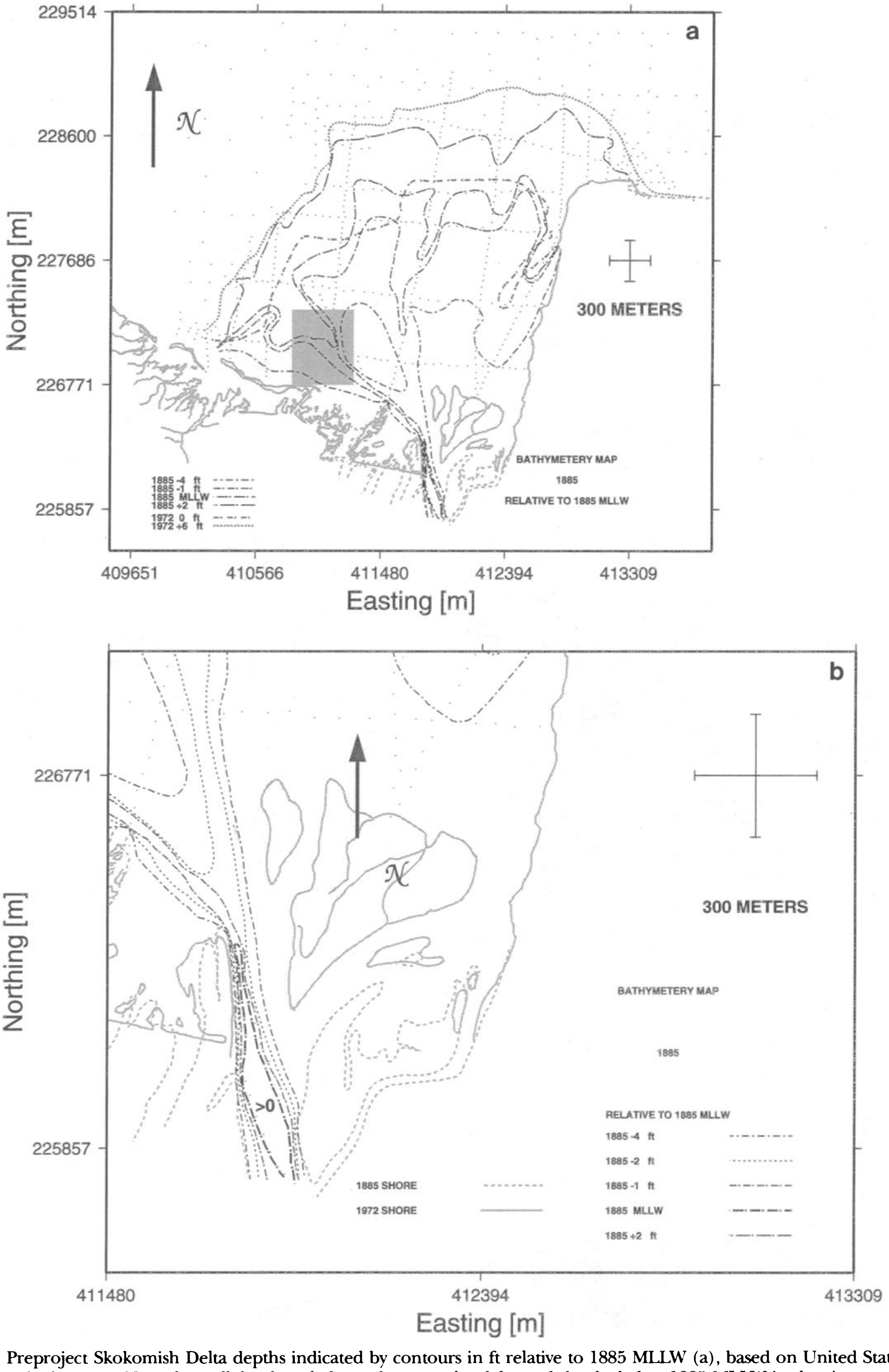

Fig. 2a, b. Preproject Skokomish Delta depths indicated by contours in ft relative to 1885 MLLW (a), based on United States Coast and Geodetic Survey bathymetry. Note the well-developed channels across the delta and depths below 1885 MLLW in the river mouth, which is shown at a larger scale in (b). Depths below MLLW are positive, those above are negative. 1972 MLLW and 6 ft contours are shown for reference. The shaded area is excluded from some area comparisons because of a lack of post construction soundings.

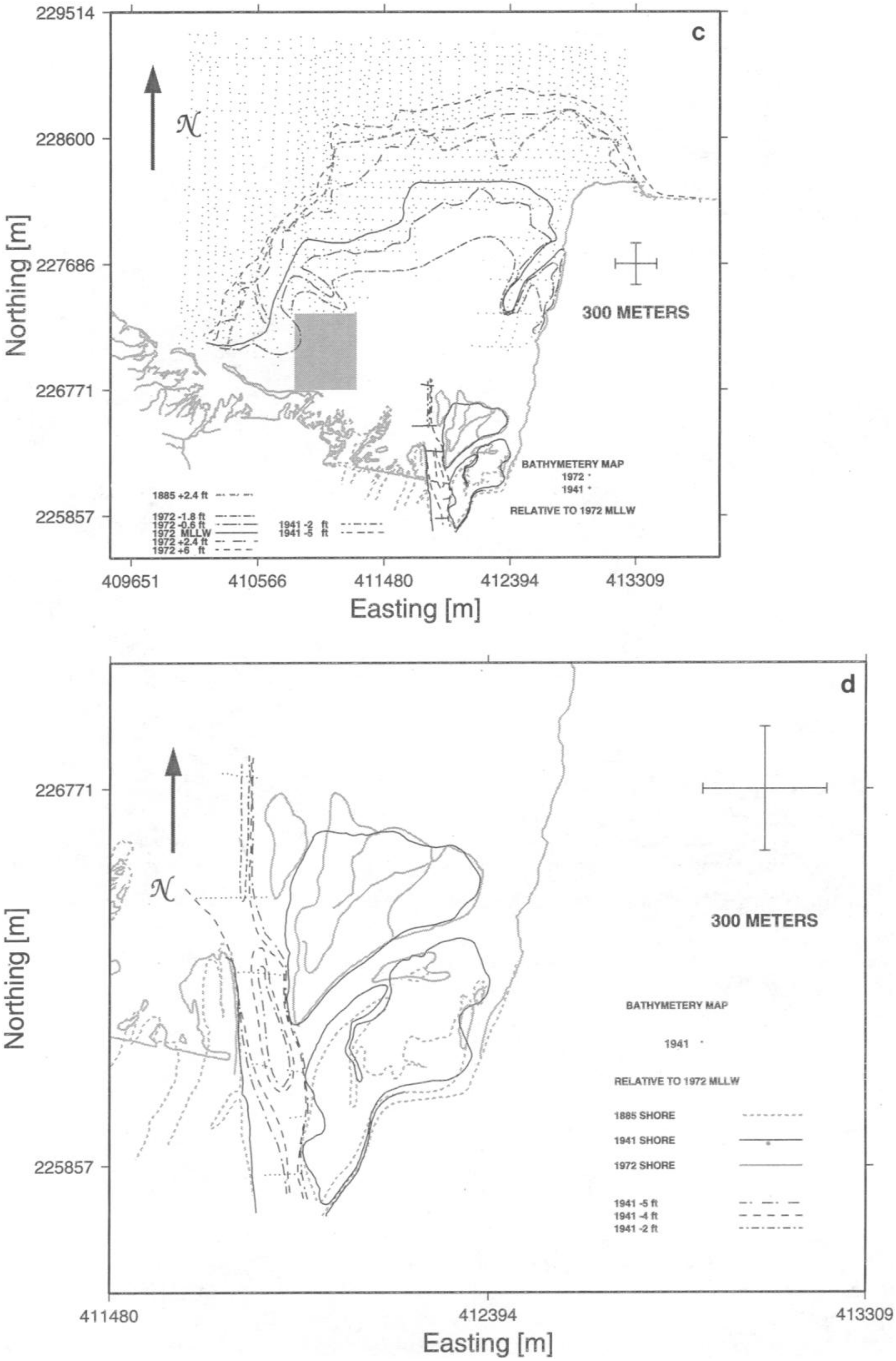

Fig. 2c, d. Postproject Skokomish delta depths indicated by contours in ft relative to 1972 MLLW (c), based on United States Coast and Geodetic Survey bathymetric (1972) and United States Army Corps of Engineers depth (1941) data. Note the absence of a well-developed north-south channel across the delta and the shoaling that has occurred in the river mouth, where depths below 2 ft above 1972 MLLW are absent, as shown at a larger scale in (d). Depths below MLLW are positive, those above are negative. The 1885 zero contour (2.4 ft below 1972 MLLW) is shown for reference. The shaded area is excluded from some area comparisons because of a lack of post-construction soundings.

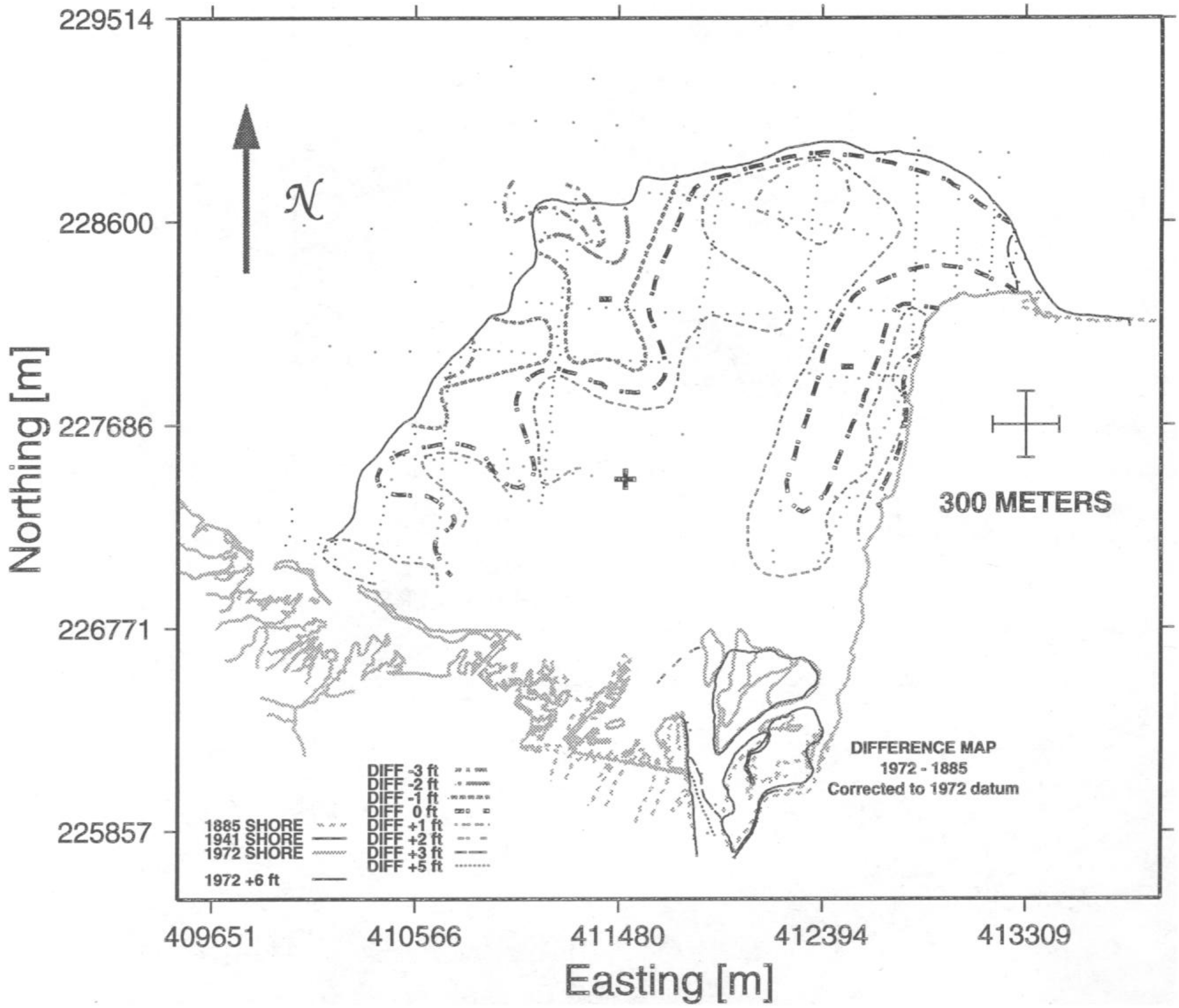

Fig. 3. Bathymetric difference contour map showing shoaling and erosion on the Skokomish delta between 1885 and 1972 (outer delta) and 1885 and 1941 (river mouth). Positive values indicate deposition and negative values indicate erosion. Up to >3 ft (0.9 m) of erosion has occurred along the outer margin of the delta and is strongest at the northwest edge of the delta. Channel meandering has occurred on the eastern side of the delta as indicated by alternating bands of NNW to SSW trending of erosion and deposition. Deposition has occurred on those parts of the inner delta where comparison is possible, and extends almost to the delta margin in mid-delta. The most extensive shoaling, 2 to 4 ft or more, has occurred in the river mouth.

radius was expanded in increments out to a maximum that was a function of depth. A maximum radius of 88 m was used on the low-slope portions of the upper delta; lesser values were used near the delta edge, where bed slopes are steeper. Calculated differences were plotted on maps (contoured manually) and as cross-delta elevation-change sections. No quantitative estimates of errors in calculated changes in depth and area are available, but if the datum difference is correctly resolved, there are no known systematic biases in the analysis. A more detailed discussion of possible errors is found in Sherwood et al. (1990).

Results and Interpretation

Bathymetric Changes—Deltaic Steepening

Interpretation of historical bathymetric changes in terms of human manipulation of the system requires the assumption that unevaluated natural changes (those changes that would have occurred without human alteration of the Skokomish River system and that cannot be evaluated explicitly) are small relative to the human-induced changes and those natural changes (e.g., relative sea-level rise) that can be evaluated quantitatively. This assumption is met in the present case. Circulation in neighboring Hood Canal is unaltered aside from the effects of Skokomish River flow regulation on its density field. Nor have any other major perturbations (e.g., earthquakes or volcanic eruptions) occurred in the area. The primary human-induced changes that need to be considered are flow diversion, logging in the South Fork drainage basin, and diking of vegetated wetlands.

Examination of the shoreline (MHW) scribed on the surveys by the United States Coast and Geodectic Survey. (Fig. 2a, b, d) shows that it has moved only slightly, except at the head of the bay where diking and some migration of features have occurred. The steep slope of the delta face is bounded approximately by the 6 ft and 120 ft (1.8 m and 36.5 m) contours. Its shape has changed only slightly. The 0 ft contour occurs in an area of low slope near the outer edge of the delta, and (in 1885 only) in the river mouth. Apparent migration of the 0 ft contour results from a combination of bathymetric change and the different datums used in the surveys; further analysis is required to distinguish these influences. Larger changes have occurred on the inner delta. The interpretation in Figs. 2a, b showing continuous channels in 1885 from the delta edge into the river mouth is supported by an extensive compilation from contemporary sources describing navigational use of the river during the 1865–1925 period (personal communication, V. Martino, Skokomish Tribe). United States Army Corps of Engineers 1972 aerial photography shows that the north-south channel across the mid-delta in the 1885 survey had deteriorated and was shallower than that leading to the southwest delta margin. The incompleteness of the 1972 survey also reflects the loss of navigability of the river mouth. Prior to dam construction, contemporary accounts and existing pilings show that the lower river was used by tugs towing barges and log rafts. It is now accessible to gillnet boats only at high water, and requires portaging a kayak at low water.

Historical changes can be examined in detail by bathymetric comparison. Bathymetric difference contours (positive values indicating relative deposition) are shown in Fig. 3. The most prominent changes are disappearance of depths below MLLW in the river mouth (1885 versus 1941), and an increase of slope of the delta surface between 1885 and 1972. That is, there is a gradient from erosion on the outer edge of delta to substantial deposition of up to 0.6–1.6 m over those parts of the inner delta and river mouth for which comparison is possible. Erosion is strongest on the west and northwest sides of the delta. Deposition is greatest in the south-central part of the delta near the river mouth and extends almost to the delta edge in mid-delta. This pattern of deposition is consistent with analysis of records from a United States Geological Survey gauging station ~8 km upriver from the delta, which shows ~1 m of aggradation during the 1945–1990 period (personal communication, T. M. Watson, 1991). A similar conclusion has been reached for the entire lower 8 km of river by D. R. Dawdy (personal communication, 1995) through comparison of United States Corps of Engineers channel cross-sections of 1941 with 1994.

The effects of the bathymetric changes on the surface of the delta can be further examined using the twelve 1885 to 1972 deltaic elevation-change profiles. Of the 12 profiles located in Fig. 4 and shown in Fig. 5a, b, nine show erosion at the outer end and deposition at the inner end (i.e., steepening of the delta). The sections showing steepening are well distributed over the delta, but the steepening is most pronounced in sections B1, B3, B4, B5, and B7, all crossing the west and northwest part of the delta. This area is exposed to erosion by wind waves and currents during storms. Sections B2 and B11 are almost neutral, while profile B9 shows aggradation at all but one point. Section B2 is anomalous in that its inner end crosses a channel that has migrated, while its outer end is truncated by an absence of 1885 soundings. The outer end of section B11 also occurs at a relatively high elevation. Section B9 crosses the mid-delta, the one area where shoaling has extended to the delta edge and a decrease in delta slope has occurred. Deterioration of a prominent north-south channel has also occurred in this mid-delta area. Finally, section B10 is interesting for the alternating areas of deposition and erosion it shows. This reflects lateral channel migration that is also evident in alternating bands of erosion and deposition in Fig. 3.

Shoaling rates may also be estimated for the inner and outer parts of the delta from the calculated bathymetric differences (Fig. 3). Shoaling of the inner delta between 1926 and 1972 by $O(0.6–1\ \mathrm{m})$ corresponds to a sedimentation rate of $O(0.013–0.022\ \mathrm{m\ yr^{-1}})$. More rapid sedimentation occurred in the river mouth, with ~0.6 m to 1.6 m of deposition between 1926 and 1941, a rate of $O(0.04–0.11\ \mathrm{m\ yr^{-1}})$. About 0.5–1.5 m of erosion has occurred on the northwest corner of the delta; an erosion rate of 0.011–0.033 m $\mathrm{yr^{-1}}$. The areal coverage of the 1972 survey (H-9345) is insufficient to determine a net shoaling and erosion rate for the delta as a whole.

In summary, overall steepening has occurred because of widespread shoaling on the inner delta

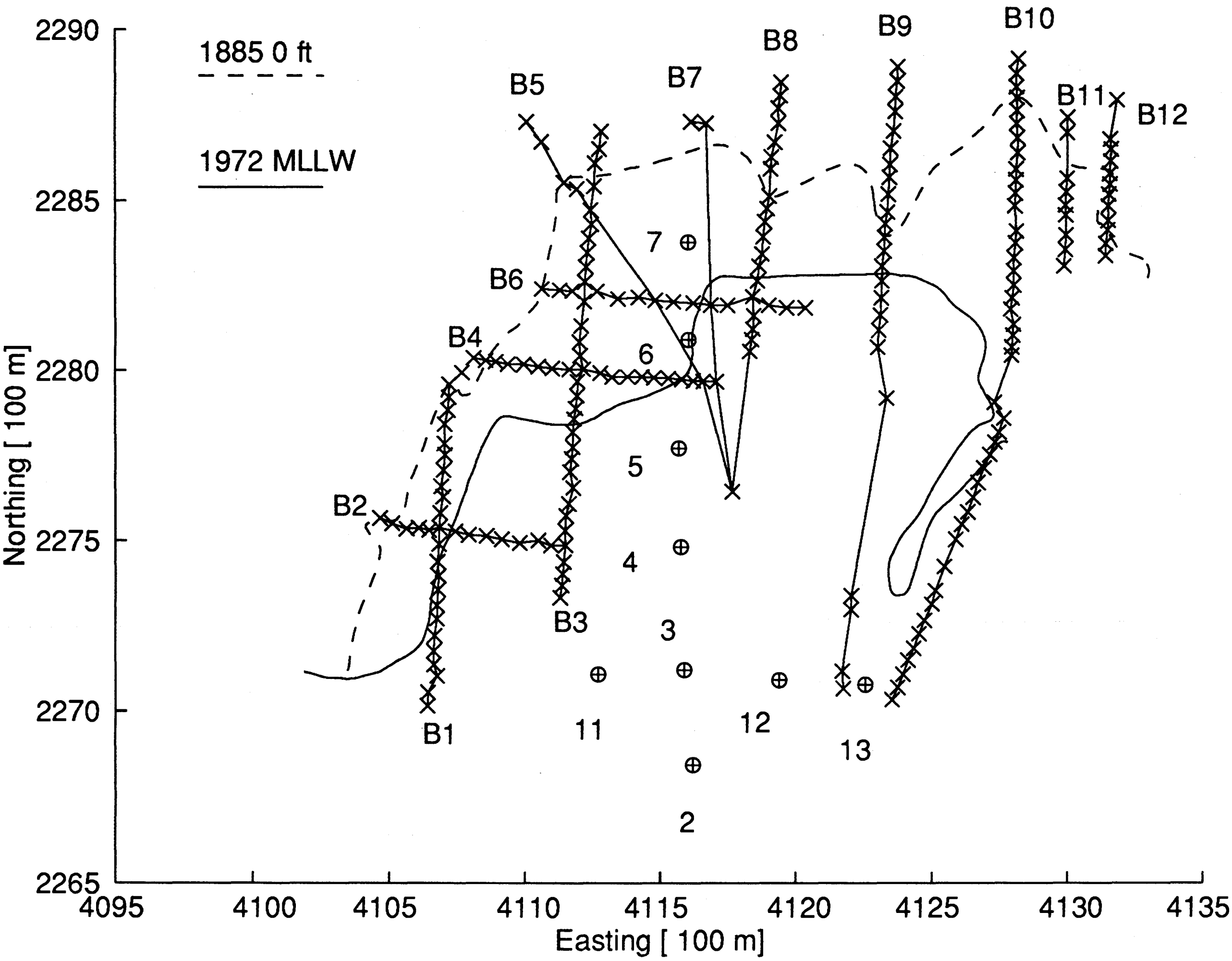

Fig. 4. Locations of deltaic elevation sections (B1 to B13) shown in Figure 5 and collection locations for cores (shown as ⊕) discussed in the text. Bathymetric comparison points are shown as x.

and erosion of the outer delta that is strongest at the northwest corner; these processes are illustrated in Fig. 6. Erosion of the delta foreslope is more local than the shoaling, which encompasses most of the inner delta and extends into the mainstem and lower river distributaries. There are, however, some areas of erosion on the inner delta. Tidal marsh is being eroded just seaward of the diked former wetlands. This may be occurring because of a loss of sediment supply associated with blockage of subsidiary channels by diking. Winter 1994 storms caused several dike breaches, which may result in further changes to the inner delta.

Corroborative Evidence from Sediment Cores

Descriptions of 11 cores collected in 1990 from nine locations on the delta by Robinson (1990; Fig. 4) show that fining of surface sediments has occurred over much of the delta. The uppermost layers of sediment consist of very fine sand with local intermixing of silt and clay. Coarser material (medium sands to gravel) is found in most cores immediately below this upper unit. This pattern occurs over the entire delta, except at its eroding outer edge and in one core close to the marsh line. Consistent with erosion of the outer edge of the delta, what may be a lag deposit of slightly coarser sand and gravel was found at the surface. The absence of coarse sand and gravel in the upper layers in most cores is consistent with a reduction of sediment transport capacity in the river after 1930. A reduction of the supply of armoring material (coarse sand and gravel) to the delta may thus have been an important factor in the erosion of its outer margin over the last 60 yrs. It is unclear whether the lag deposit on the outer delta provides enough armoring to prevent further erosion. In contrast,

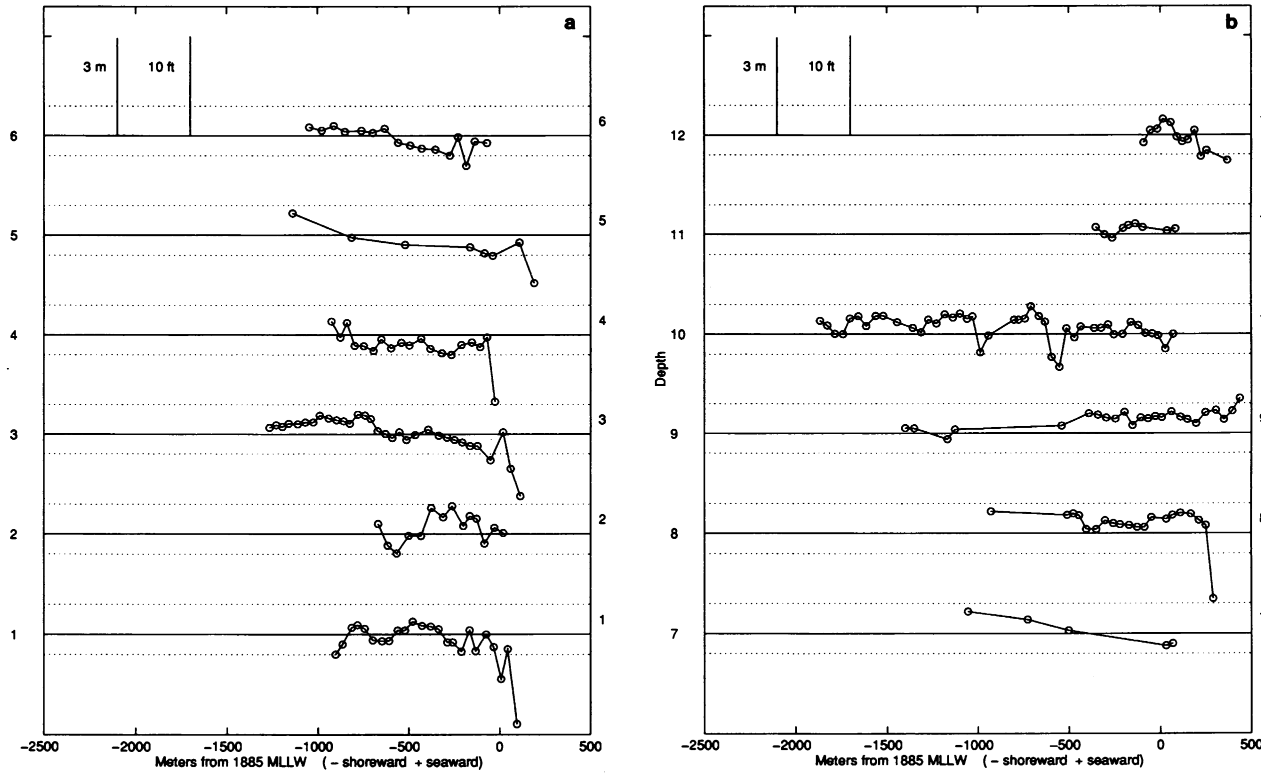

Fig. 5. Cross-delta bathymetric change sections showing erosion (negative) and deposition (positive) along 12 sections. Nine of 12 sections show steepening of the low-intertidal, outer delta, only one section shows a decrease in slope, while two are essentially neutral.

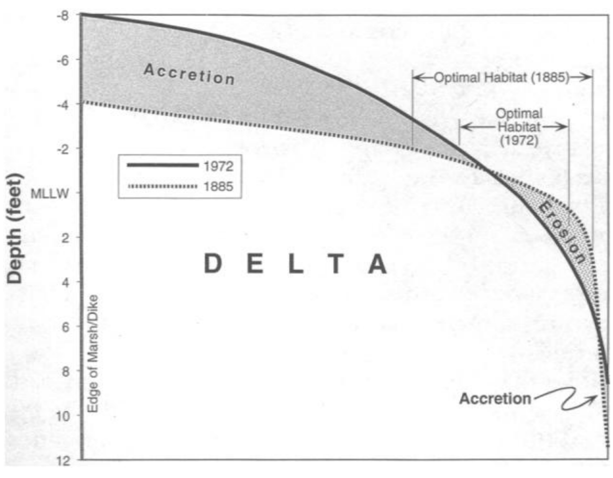

Fig. 6. A conceptual sketch of the effects of historical changes due to flow diversion on Skokomish River delta habitats. Accretion on the inner delta and erosion at the outer deltaic margin has steepened the delta and reduced the surface area of optimal low intertidal habitat.

the modern, finer material is stable at most other locations on the delta, as evidenced by measured accumulation, probably because currents are weaker and wind waves smaller than at the margin.

Causes of Deltaic Steepening

Loss of transport capacity in the mainstem due to water withdrawal is the only reasonable explanation for the particular combination of bathymetric and sedimentary changes observed here: shoaling and fining of surface sediments on the inner delta and erosion of the outer delta. The apparent mechanism for these changes is as follows. Most sediment transport in the Skokomish occurs during the few days per year having the highest river flow, that is during freshets. Flow diversion brings about a disproportionate decrease in sediment load, because of the nonlinear relationship between river flow and sediment transport (Andrews 1986). Transport of coarse sediment (coarse sand and gravels) is more strongly affected than that of fine sands, because these sands and gravels have a higher critical shear stress for erosion, and because their movement is likely to be transport-capacity limited in the lower sections of a steep basin. Thus, the decrease in sediment transport capacity caused by the Cushman project has caused a smaller percentage of the sediment brought into the mainstem and onto the inner delta to be transported to the outer delta. The sediment that is transported to the outer delta is on the average finer than before and more subject to subsequent erosion by winter storms and high tides. The result is a net accumulation of material on the inner delta and a net loss on the outer delta; that is, the delta has steepened. This is consistent with lag deposits seen in cores 6 and 7.

Thus, it is very likely that a reduction has occurred in the supply of sands and gravels to the delta. This may or may not have been accompanied by an increase in the supply of fines. There are two reasons we do not need to resolve this latter point to understand observed deltaic changes. First, the supply of armoring material, coarse sands and gravels, is of primary importance. Second, no alteration in the quantity of sediment supplied could simultaneously cause erosion of the outer delta and deposition near the river mouth and in the mainstem unless the transport capacity in the mainstem, and thus the character of sediment supplied, were also changed. Absent such a change in sediment transport capacity, loss of sediment supply would have starved the entire delta. Any increase in sediment supply from the South Fork caused by logging, if it were larger than the loss of supply from the North Fork, would have accelerated shoaling on the delta as a whole without a dramatic change in delta slope.

Nor is there any mechanism whereby diking of 0.7 km^2 of peripheral, vegetated wetlands (Bortleson et al. 1980) between 1884 and 1937 could have brought about the observed steepening. The fine material, mostly silt and clay, found in these formerly marsh areas could not have been a major source of the sands and gravels formerly found on the outer part of the delta. Because of the limited amount of diked land, diking cannot account for the observed changes. Thus, neither increased export of fine material after diking, unlikely because of the low intensity of agricultural use, nor failure of diked areas to trap sediment carried by the river could have caused the observed shoaling of the inner delta. Diking may have contributed, however, to the rapid localized shoaling within the river mouth through a reduction of tidal prism and thus maximum bedstresses in this area. The fact that deltaic steepening and fining of surficial sediments have occurred despite the continued availability of coarse sands and gravels higher in the basin shows that flow diversion and consequent loss of sediment transport capacity is the dominant factor controlling this situation. It is the only feature that could have caused the observed steepening of the delta.

Habitat Changes

Calculations indicate that total deltaic surface area above the 1885 zero level (2.4 ft or 0.73 m below 1972 MLLW) has decreased by about 2.2% or 0.1 km^2. While no definite error limits can be given, this loss is probably significant. It is of the same sign as an earlier loss estimate of 0.5 km^2 or 10% based on comparison of topographic survey sheets (Bortleson et al. 1980). Steepening of the delta (Fig. 5) shows, moreover, that the effects of habitat change may be considerably larger than suggested by net loss of deltaic area. In Puget Sound, the most critical habitat is the low intertidal zone between about 0.6 m and −0.91 m (+2 ft and −3 ft) on MLLW, because maximum primary productivity and important food web interactions occur here (Simenstad et al. 1982, 1988; Thom 1984, 1987, 1990; Thom et al. 1988). Nine of the 12 profiles in Fig. 5 show a reduction in habitat between these levels, as summarized schematically in Fig. 6.

Computation of areal changes in habitat in this depth range is complicated by the different spatial coverage of the United States Coast and Geodectic Survey 1885 and 1972 surveys, datum changes, sea-level rise, and the differences in depth intervals presented on the two surveys. The best estimate of historical change that can be made uses the depth range of 2 ft (0.6 m) below MLLW to 2 ft (0.6 m) above MLLW. The vertical distance between the 2.4 ft (0.4 fathom or 0.73 m below MLLW) and the −1.8 ft (0.3 m or 0.55 m fathom above MLLW) contours on the 1972 survey is 4.2 ft (1.28 m). These depth limits covers a very similar (though slightly larger) range of depths as the 1885 zero to −4 ft (−1.22 m) contours (2 ft or 0.61 m below to 2 ft or 0.61 m above 1885 MLLW), taking into account the 2 ft (0.61 m) datum difference between the two surveys and the 0.3–0.4 ft (0.09–0.13 m) relative sea-level change that occurred.

This leaves the different areal coverage to consider. The United States Coast and Geodectic Survey 1885 survey covered the entire delta and the river mouth. Deterioration of the inner delta and lower river channel had effectively eliminated navigation and depths below MLLW by 1941. Reference to 1972 aerial photography, furthermore, shows that the reason why the United States Coast and Geodectic Survey 1972 soundings did not extend directly south into the river mouth from mid-delta—there was at this time no well-developed north-south channel across this part of the delta. Thus, the United States Coast and Geodectic Survey 1972 survey covered all of the low intertidal areas of interest here, with one possible exception.

The area within the shaded box shown in Figs. 2a and 2c defines an area where 1972 aerial photography suggests that a small amount of bottom in the relevant depth range (2.4 ft or 0.73 m below to 1.8 ft or 0.55 m above MLLW) might have been found, had a more complete survey been done. The 1941 United States Army Corps of Engineers survey supports this idea. It indicates that a channel leading west from the river mouth had deteriorated by 1941, and that lower intertidal habitat was almost entirely absent from the river mouth; further shoaling likely occurred there by 1972. Therefore, the 1.8 ft (0.55 m) contour probably closed in 1972 without including very much of the boxed area.

Use of the essentially linear distribution of total surface area with depth in the low intertidal (verified for both surveys) then yields an estimate of loss of surface area over a 4-ft (1.22-m) lower intertidal depth range of 0.5 km^2 (from 2.76 km^2 to 2.25 km^2) or about 18.6% of the total surface area. This is reduced to 15.3% if the boxed area is excluded from the comparison. Given the linear, lower intertidal distribution of surface area with depth on both the 1885 and 1972 surveys, this conclusion applies equally to the low intertidal as a whole. Moreover, the difference in coverage of the two surveys is itself a significant fact, reflecting loss of navigational utility of the system.

The low intertidal zone that has been lost due to deltaic steepening contains a variety of habitats. Eelgrass is certainly amongst the most important of these. Eelgrass (*Zostera marina*) is a major source of primary production and a primary habitat for many species of juvenile fishes and crab in the Pacific Northwest (Phillips 1984). In addition to the diverse species assemblages that reside in eelgrass habitats through most of their life cycle, many economically important fish species depend upon eelgrass habitat during critical periods of their life history, especially for foraging on prey organisms that live therein (Simenstad et al. 1979, 1988). In these cases, there is a direct dependence upon the areal extent of habitat because fish production (e.g., growth and survival) is related directly to the extent of that habitat.

An estimated loss of highly productive eelgrass beds is derived by assuming that eelgrass grew in 1926 to the edge of the delta as it does today. Area lost from the edge of the delta then represents loss of eelgrass. The present area of eelgrass can be judged from the 1991 survey with a high-frequency echo sounder. In a 1.43 km^2 area with thick eelgrass, this particular acoustic echo sounder was unable to accurately detect the bottom. The area where eelgrass obscured the seabed was mostly but not entirely between about 2 ft below MLLW and 0.5 ft above MLLW, as determined by 1972 depth data. This is not the total 1991 area covered by eelgrass but simply that part of the delta where the thickest eelgrass was found. As a conservative estimate of loss of eelgrass, we take the change in surface area over a 3-ft depth 1972 range of 2.4 ft below MLLW and 0.6 ft above. This corresponds to an 1885 depth range of zero to 3 ft (0.9 m) relative to 1885 datum (2 ft or 0.61 m below to 1 ft or 0.3 m above 1885 MLLW). The surface area in this depth range has decreased by 0.35 km^2, from 2.08 km^2 to 1.73 km^2, a loss of ~16.7%. This loss estimate is conservative. A higher upper limit of eelgrass coverage (e.g., 1.8 ft on 1972 MLLW) would be consistent with known eelgrass coverage in the few Northwest estuaries where it has been systematically surveyed and would have resulted in a somewhat greater estimate of eelgrass loss.

The estimated low intertidal surface area losses of 15% to 19% (17% to 19% for eelgrass area) are insensitive to the largest uncertainty in our calculations, the 1885 to 1972 change in sea level, because they arise from a change in slope not in absolute elevation. These losses are much larger than any conceivable source of error. Examination of aerial photos taken in the late 1930s, 1957, 1972, 1985, 1991, and 1992 show that the delta margin is relatively stable and not subject to large short-term fluctuations. It would, moreover, require 10–20 yrs of the entire present estimated sediment supply to the mainstem to account for the observed shoaling on the inner delta, and not all the material supplied to the mainstem is available to the delta. Most sands and gravels are retained in the mainstem where shoaling has also occurred, and another (washload) fraction is exported to deep water because it cannot settle out in the 10 km-long mainstem or onto the delta (only ~2 km wide).

Steepening of the delta and reduction of freshwater flow has also affected salinity intrusion over the delta and into the Skokomish River. This is an important consideration, because shallow water areas of intermediate salinity (between freshwater and values typical for Hood Canal surface waters) are of great importance to anadromous fish such as Pacific salmon that often require a brackish salinity zone for physiological adaptation (Simenstad et al. 1982). While there were no salinity measurements made before construction of the Cushman Project, fluid-mechanical scaling arguments allow definite inferences to be made. First, the volume of a buoyant plume produced by an outflow over a fixed time (e.g., half a tidal cycle) increases linearly with freshwater discharge volume Q, while plume area scales with $Q^{1/2}$ (Luketina and Imberger 1987). The rate at which this volume is mixed into ambient waters is dependent on a variety of local conditions, but this mixing is inhibited by the stability of the plume, again positively correlated with discharge. Therefore, the volume of low-salinity water associated with the presence of a river outflow over a delta scales with a positive power of Q. Decreases in the extent of intermediate salinity habitat as a result of flow diversion have actually been observed in the Sea of Azov, the Dnieper and Dniester rivers, the Caspian Sea, and San Francisco Bay (Rozengurt and Haydock 1981; Nichols et al. 1986; Rozengurt et al. 1987; Rozengurt and Hedgepeth 1989; Kimmerer 1991).

However, in the case of the Skokomish delta there is an additional factor that has not been discussed with regard to other systems. Salinity intrusion driven by estuarine circulation varies approximately with the cube of the mean water depth and inversely with river flow (Hansen and Rattray 1965; Jay and Smith 1991). Because of this sensitivity of salinity intrusion to water depth, steepening the delta must also have strongly affected salinity intrusion. On the outer delta, increased water depth and decreased freshwater outflow have together acted to increase salinity intrusion. In contrast, the 1885 survey and the distribution of pilings associated with log rafting operations in the mouth of the mainstem and largest distributary indicate that these channels, now navigable only in a small boat at high tide, were once accessible to tugboats with substantial draft. This critical change from subtidal to intertidal depths in the river mouth must have tended to decrease salinity intrusion while loss of freshwater flow has tended to increase it. Although some salinity intrusion still occurs in the most seaward 0.5–2 km of the Skokomish mainstem, the transition between fresh and salt (Hood Canal) water must occur over a smaller distance than previously, and the area of intermediate salinity habitat has clearly been reduced.

Remains of benthic infauna in sediment cores further corroborate our interpretations of deltaic change. Ten of 11 cores shown in Fig. 4 were examined for total proportion of bivalve shell remains and for faunal taxonomic composition by core strata to define infaunal community changes on the delta mud and sand flats. Except for core SK-7, bivalve remains increased in both taxa richness and density with increasing depth. Furthermore, a shift has occurred (except in cores SK-7 at the outer edge of the delta, SK-13 in mid-delta, and SK-2 at the inner edge) from a robust oyster (*Ostrea*) and surface clam assemblage (*Protothaca, Saxodomus*) typical of coarse substrates at the lower (earlier) intervals to a less rich assemblage composed of infaunal clams (*Macoma, Mya*) more typical of fine sediment habitats that exist on the delta today. An alternative explanation, that historic depositional processes were more prone to leave shell to be incorporated into the sediment, cannot be disproved, but there is no obvious mechanism for such an occurrence. The faunal composition of SK-2 on the inner flats indicates a shift from shallow subtidal benthic infauna and epifauna typical of a fine sediment habitat to more intertidal, coarser sediment fauna. The outer face of the delta (SK-7) appears to have undergone a shift to more subtidal fauna from an intertidal fauna. Conventional dating methods (e.g., ^{210}Pb) could not be used to date these cores because of the extensive bioturbation typical of such infaunal communities.

In summary, there was a loss of about 2% in total deltaic surface area between 1885 and 1972. Erosion of parts of the outer delta and accretion on the inner delta steepened the slope of the deltaic surface, decreased the size of the mesohaline mixing zone and caused large losses of low intertidal habitat between about 0.6 m and −0.6 m (+2 ft and −2 ft) on MLLW (15–19%) and eelgrass beds (≥17–19%). These results illustrate that changes in total surface area alone are not an adequate measure of the effects of human alteration of deltaic function; changes in processes and the distribution of habitats must also be considered.

Discussion: Changes in the Skokomish in Relation to Other Systems

Habitat losses in the Skokomish resemble those in other, larger systems where major withdrawals of water have occurred, despite a diversity of geographical circumstances and the presence of a variety of other human alterations in most systems where diversion has occurred. Large systems that are at least partially analogous to the Skokomish estuary in estuarine configuration, percentage of water withdrawal, and extent of impacts include North San Francisco Bay, the Sea of Azov in Ukraine and Russia (Nichols et al. 1986; Rozengurt et al. 1987), and the Black Sea deltas of the Dniester and Dnieper rivers in Ukraine (Rozengurt and Haycock 1981). In all these cases, an embayment or a delta in an estuarine embayment is present, and water withdrawal has averaged about 40% to 60%, with larger reductions in freshets. Losses of sediment input to both North San Francisco and the Sea of Azov have been estimated to be 60% to 75% (Rozengurt et al. 1987). Damage to anadromous fish populations has been extensive in each case.

There is also a direct connection between river inflow (or position of the 2 PSU salinity contour) and population and/or productivity of numerous species, particularly those associated with the estuarine turbidity maximum (Arthur and Ball 1979;

Cloern et al. 1983; Rozengurt et al. 1987; Kimmerer 1991; Jassby 1992). In the Sea of Azov, diversion of the Donets and Kuban rivers has caused loss of nutrient input, radical changes in biota, and reduced productivity of the planktonic and benthic communities (Rozengurt and Haydock 1981; Remisova 1984; Volovik 1986; Bronfman 1977; Rozengurt et al. 1987). Catches of anadromous fish have decreased by 90–95%, and 50–80% of fish spawning, breeding, and rearing habitat has disappeared. Compression of the intermediate salinity estuarine mixing zone has contributed markedly to these losses. Black Sea deltas including those of the Danube (20% withdrawal of freshwater), Dniester and Dnieper rivers (both 40% withdrawal) also exhibit compression of the mesohaline mixing zone and consequent losses of primary and secondary productivity, and fishery resources (Rozengurt and Haydock 1981).

Catch statistics to quantify changes in fish production in and utilization of the Skokomish delta are absent, but extensive adverse effects may be inferred from ethnographic sources (e.g., Castile 1985), and construction of a salmon hatchery on the North Fork of the Skokomish was undertaken largely to counteract these losses (Canning et al. 1988). Decreases in fish production are expected because of a) elimination of salmon and trout spawning habitat in the North Fork, b) decreased utilization of remaining North Fork habitat because of reduced flows, c) changes in the composition and abundance of fish prey taxa due to shifts in sediment texture, and d) reduced utilization of eelgrass beds by a wide variety of fish species (Simenstad et al. 1982, 1988). Losses associated with changes in estuarine habitat are likely to be proportional to area of habitat lost (~17% eelgrass beds and 15–19% lower intertidal area).

Summary and Conclusions

We have sought to evaluate changes caused by diversion of 40% of the freshwater inflow from the Skokomish River since circa 1930 and to place them in a global context of changes wrought in estuaries where major water withdrawal has occurred. Analysis of two United States Coast and Geodectic Survey hydrographic surveys from 1885 and 1972 and less extensive 1941 data collected by the United States Army Corps of Engineers has allowed construction of a map of erosion and deposition for the Skokomish delta and calculation of net gain and loss of deltaic surface area by habitat. Historic loss of total deltaic area above 2 ft below MLLW has been about 0.1 km^2 or 2%. A loss of sediment transport capacity associated with flow diversion in the North Fork has apparently caused steepening of the delta and a 15–19% loss of habitat between 0.6 m (2 ft) below MLLW and 0.6 m (2 ft) above. Included in this loss of habitat has been a decrease of ~17% in area of eelgrass beds. Several lines of argument also lead to the conclusion that there has been a decrease in the amount of the mesohaline mixing habitat. Thus, changes in total deltaic area do not alone provide an adequate measure of the consequences of human alteration. It is necessary in evaluating consequences of such changes to consider processes throughout the river basin and their effects on estuarine habitats. Sediment transport in particular plays a vital role in linking alterations of fluvial processes with downstream, estuarine consequences.

Changes to the Skokomish River delta parallel those in North San Francisco Bay, the Sea of Azov and Black Sea deltas of the Dniester and Dnieper rivers in percentage of water withdrawn and adverse consequences thereof. Despite differences in scale and geological setting—the Skokomish is much the smallest of the systems and the only one to have suffered recent glaciation—there are striking similarities amongst the systems in terms of disruption of the sediment budget, decreases in mesohaline mixing area and primary and secondary productivity, and loss of fishery resources. Percentage of water withdrawn appears then to be a fundamental measure of human impact on estuarine systems, and it might be useful to examine the above large deltas, to see if sedimentary processes in these systems have responded to water withdrawal in a manner similar to the Skokomish. Unlike many other systems where a major water withdrawal has occurred, the Skokomish has not suffered obvious changes of its nutrient dynamics; neither eutrophication nor its opposite, nutrient starvation, is evident. Thus, while disruptions of the sediment and nutrient budgets are both possible consequences of water withdrawal, they are independent processes with distinct but often overlapping consequences. Further studies in systems like the Skokomish where only a few, relatively severe alterations have occurred would be useful in separating the effects of flow regulation and withdrawal from those associated with other perturbations like eutrophication and loss of tidal prism.

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