DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

Prepared in cooperation with the
U.S. DEPARTMENT OF JUSTICE AND THE BUREAU OF INDIAN AFFAIRS

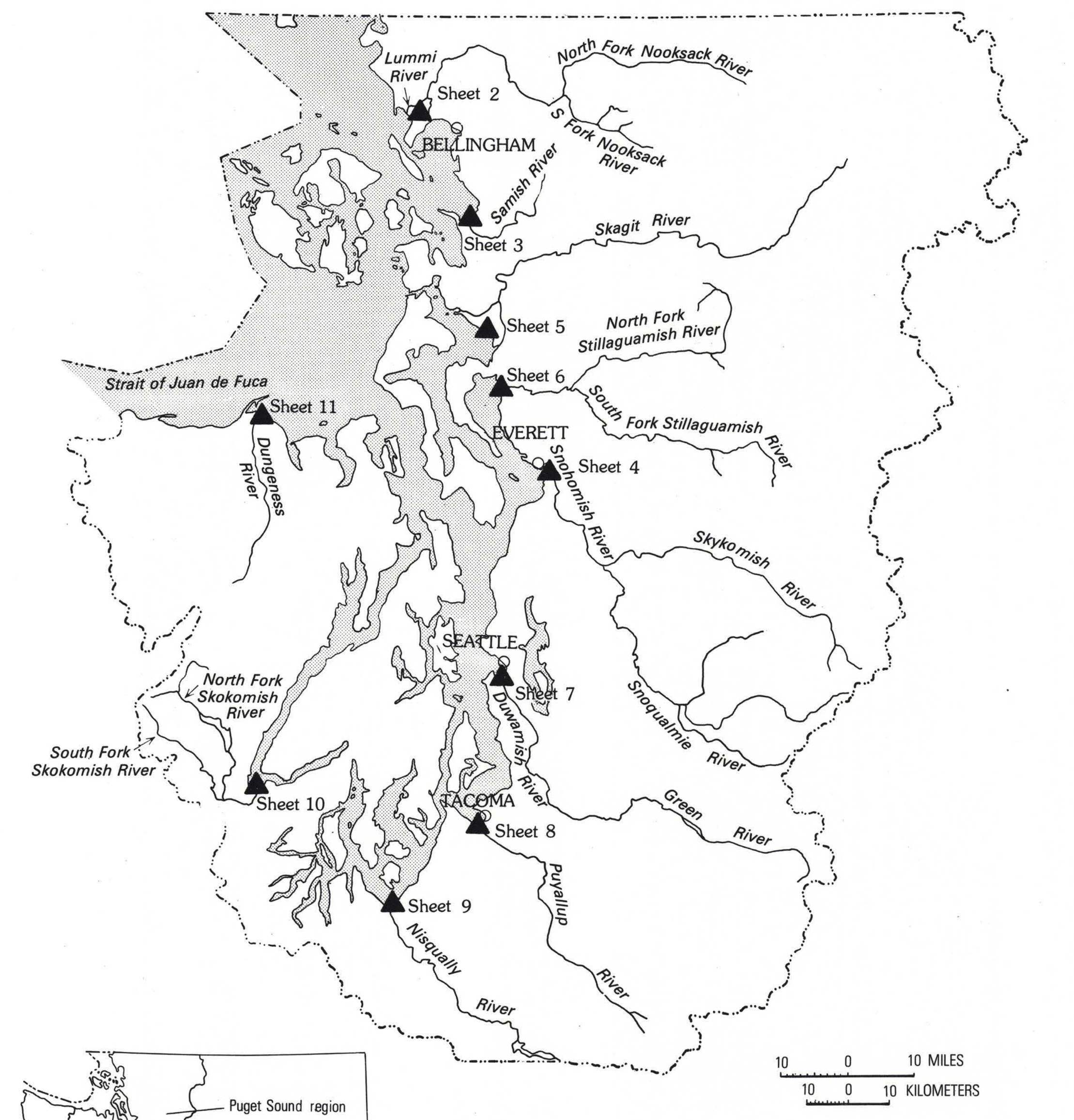
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

HISTORICAL CHANGES OF SHORELINE AND WETLAND AT ELEVEN MAJOR DELTAS IN THE PUGET SOUND REGION, WASHINGTON

By G. C. Bortleson, M. J. Chrzastowski, and A. K. Helgerson

Prepared in cooperation with the
U.S. DEPARTMENT OF JUSTICE
and the
BUREAU OF INDIAN AFFAIRS

HYDROLOGIC INVESTIGATIONS ATLAS
Published by the U.S. Geological Survey, 1980
W



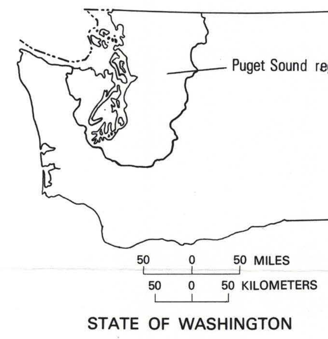


FIGURE 1—MAP OF PUGET SOUND REGION SHOWING LOCATION OF SELECTED MAJOR RIVER-MOUTH DELTAS (BLACK TRIANGLES)

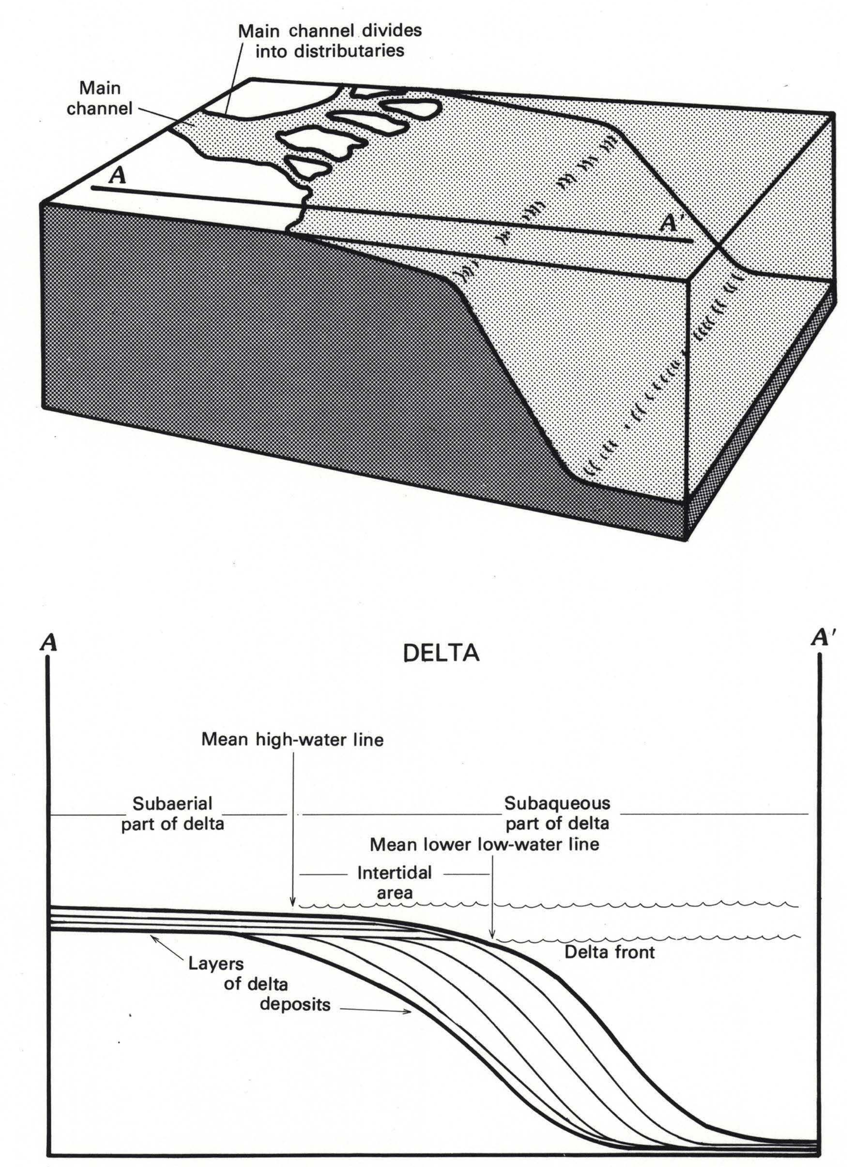


FIGURE 2—SCHEMATIC THREE-DIMENSIONAL AND CROSS-SECTIONAL VIEWS OF A TYPICAL RIVER-MOUTH DELTA

TABLE 1.—*Source maps for compilations of historical shorelines.*

Field sheet	Name	Year surveyed	Agency	Topographer	Original scale
T-539	New Dungeness—Strait of Juan de Fuca	1855	Coast Survey	J. L. Lawson	1:10,000
T-1453	Commencement Bay—Puget Sound	1877	Coast Survey	Eugene Ellicott	1:10,000
T-1560b	Hood Canal—Annas Bay	1884	C&GS[1]	J. J. Gilbert	1:10,000
T-1672	Puget Sound from Nisqually River to Tottan Inlet	1878	Coast Survey	Eugene Ellicott	1:20,000
T-1681	Snohomish River	1884-85	C&GS	J. F. Pratt	1:20,000
T-1755	Port Susan and Stillaguamish River	1886	C&GS	J. F. Pratt	1:20,000
T-1794	Rosario Strait—Guemes, Samish, Vendo Islands	1887	C&GS	J. J. Gilbert	1:10,000
T-1795	Rosario—Samish Bay	1887	C&GS	J. J. Gilbert	1:10,000
T-1798	Rosario Strait—North Port of Bellingham Bay	1887	C&GS	J. J. Gilbert	1:10,000
T-1799	Rosario Strait—Nooksack River	1887	C&GS	J. J. Gilbert	1:10,000
T-1871	Gulf of Georgia—Village Point to base of Sandy Point	1888	C&GS	J. J. Gilbert	1:10,000
T-2156	Skagit Bay, Delta and River-Washington	1889	C&GS	J. F. Pratt	1:20,000
T-2421	Seattle Bay and City-Washington	1899	C&GS	J. J. Gilbert	1:10,000
T-2422	Seattle Bay and City-Washington	1899	C&GS	J. J. Gilbert	1:10,000
H-432	Preliminary Survey of Duwamish Bay	1854	Coast Survey	James Alden	1:10,000
H-1728	"Mouth of Snohomish River, copied in part from original hydrographic sheet, H-1728"	1886	C&GS	C. T. Forse	1:20,000
	Seattle quadrangle	1908	USGS[2]	R. H. McKee	1:62,500
25-26	Duwamish-Puyallup Surveys	1907	USCE[3]		1:4800
	Plan of Seattle	1855-56		Thomas Phelps	1:2300

[1]U.S. Coast and Geodetic Survey
[2]U.S. Geological Survey
[3]U.S. Army Corp of Engineers

TABLE 2.—*Comparison of historical and present-day subaerial wetland areas.*

River delta	Estimated area of subaerial wetland (in square kilometers)			
	Historical	Present-day	Increase or (decrease)	Source
Nooksack	4.5	4.6	0.1	Topographic maps and aerial photographs
Lummi	5.8	.3	(5.5)	Topographic maps
Samish	1.9 (11)[a]	.4	(1.5)	Do.
Skagit	16 (29)[a]	12	(4)	Do.
Stillaguamish	3.0 (10)[a]	3.6	0.6	Do.
Snohomish	39	10	(29)	Topographic maps and aerial photographs
Duwamish	2.6	.03	(2.6)	Topographic maps
Puyallup	10	virtually none	(10)	Do.
Nisqually	5.7	4.1[b]	(1.6)	Do.
Skokomish	2.1	1.4	(0.7)	Topographic maps and aerial photographs
Dungeness	.5	.5	0	Do.
Totals for mapped areas	91	37	(55)	

[a]Number in parentheses is an estimate based on vegetation and landforms of wetland area present prior to its conversion and before the initial C&GS topographic survey under natural conditions.
[b]Includes about 1.6 sq km that were wet meadow and fresh-water marsh landward of present dikes prior to December 1975 dike break (Klotz and others, 1978), in addition to about 2.5 sq km of salt marsh.

TABLE 3.—*Comparison of historical and present-day intertidal wetland areas.*

River delta	Estimated area of intertidal wetland (in square kilometers)			
	Historical	Present-day[a]	Increase or (decrease)	Remarks
Nooksack	6.7	8.5[b]	1.8	Intertidal areas measured from lat 48°45′00″, near Fish Point, to long 122°32′30″.
Lummi	14	13	(1.0)	Intertidal areas measured from long 122°42′30″, near Sandy Point, to lat 48°45′00″, near Cagey Road.
Samish	not available	15	?	Present-day intertidal area measured from long 122°30′00″ near Fish Point, to lat 48°37′30″ near Pigeon Point.
Skagit	Do.	55	?	Present-day intertidal area measured from lat 48°16′12″, Browns Point, to lat 48°34′24″, near Deadman Island (off map).
Stillaguamish	Do.	20	?	Present-day intertidal area measured from long 122°27′35″, near Lona Beach, to lat 48°10′00″, near Warm Beach.
Snohomish	13[c]	8.8	(4.2)	Present-day intertidal area measured from lat 48°02′48″, near Mission Bay (off map), to lat 47°59′00″, near Port Gardner.
Duwamish	8.5	virtually none	(8.5)	Historical intertidal area measured from long 122°23′00″, Duwamish Head, counter-clockwise around Elliott Bay, to long 122°23′30″, near Smith Cove.
Puyallup	7.4	0.1	(7.3)	Historical intertidal area measured from lat 47°15′48″, near City Waterway, to lat 47°17′12″, near Hylebos Waterway.
Nisqually	7.4	5.8	(1.6)	Intertidal areas measured from long 122°45′00″, near DeWolf Bight, to long 122°40′00″, near Sequalitchew Creek.
Skokomish	5.0	4.5	(0.5)	Intertidal areas measured from lat 47°21′36″ to long 123°06′00″, near Union City.
Dungeness	5.9	6.0	0.1	Intertidal areas measured from lat 48°11′00″, near Dungeness Lighthouse, counter-clockwise around Dungeness Bay, to long 123°05′00″, near Jamestown.

[a]From U.S. Geological Survey topographic maps, except Nooksack River delta (see below).
[b]From NOAA hydrographic survey, H-8320, H-8321 (1:10,000 scale) dated 1956.
[c]Historical intertidal area calculated from 1886 hydrographic chart but mean lower low-water line is not entirely shown on sheet 5 because base map does not extend far enough in seaward direction.

HISTORICAL CHANGES OF SHORELINE AND WETLAND AT ELEVEN MAJOR DELTAS IN THE PUGET SOUND REGION, WASHINGTON

INTRODUCTION

River-mouth deltas and associated wetlands have a historical and continuing importance to human activities. Deltas in the Puget Sound region attracted early development because they were flat-lying, near water, and contained relatively large tracts of unforested land. These characteristics fostered the conversion to farmlands, port facilities, and centers of commerce and industry.

Delta areas in the Puget Sound region have undergone considerable change, both natural and man-related, since their first occupancy by non-Indian settlers. Until recent years, little thought was given to the environmental values of wetlands and the impacts of man's activities there. As the effects of these activities on the natural qualities of wetlands have become more widely known and better appreciated, information documenting past changes has been needed by planners, environmental groups, local agencies, and others concerned with the development and well-being of the delta areas. In response to this interest and need, comparisons of old and new maps delineating historical shoreline and wetland changes have been compiled for 11 major river deltas in the Puget Sound region, as shown on the accompanying maps. These maps document (1) shoreline changes, both natural and man-induced, since early non-Indian settlement, (2) loss of wetland habitat, and (3) patterns of land-use changes on delta lands. Also presented are discussions of some overall planning considerations related to shoreline and wetland changes. In addition, this report may serve as a basis for future studies of geologic and hydrologic conditions and processes in the delta areas.

The areas studied are shown in figure 1 and listed below:

- Sheet 2. Nooksack River and Bellingham Bay, and Lummi River and Lummi Bay
- Sheet 3. Samish River and Samish Bay
- Sheet 4. Snohomish River and Possession Sound
- Sheet 5. Skagit River and Skagit Bay
- Sheet 6. Stillaguamish River and Port Susan
- Sheet 7. Duwamish River and Elliott Bay
- Sheet 8. Puyallup River and Commencement Bay
- Sheet 9. Nisqually River and Nisqually Reach
- Sheet 10. Skokomish River and Annas Bay
- Sheet 11. Dungeness River and Dungeness Bay

The approach used, in general, was to locate and obtain the oldest authoritative maps of the areas and then to compare those historical maps with the most current topographic maps. The historical-map data were then carefully transferred, by optical projection and manual plotting, to film copies of modern maps of 1:24,000 scale. No attempt was made to show the progression of change in the delta areas and, therefore, intermediate-age maps are not shown in this series. However, for some map compilations, intermediate-age source materials were used to help verify or evaluate the overall changes.

These maps are one of a series of products being prepared by the Puget Sound Earth Sciences Applications Project to present basic information and interpretations of an environmental nature to assist land-use planning, resource development, and environmental protection in the Puget Sound region. The work was begun at the request of U.S. Fish and Wildlife Service and Justice Department, and received financial support by the Bureau of Indian Affairs.

The authors express their appreciation to: Dr. Howard Droker, historian, for contributing information on the early development of tidelands in the Puget Sound region; Richard Meyer, National Oceanic and Atmospheric Administration (NOAA), Seattle, for arranging use of microfilm files; Cmdr. Glen Schaefer, NOAA, Seattle, for technical advice, and Capt. Wesley Hull, NOAA, Rockville, Maryland, for investigating old-records files.

SOURCE MAPS

The sources of historical maps showing river deltas and estuarine wetlands include the following:

1. National Oceanic and Atmospheric Administration (NOAA) archives, Rockville, Maryland (early U.S. Coast and Geodetic Survey maps).
2. National Cartographic Information Center, Reston, Virginia (early U.S. Geological Survey maps).
3. U.S. Army Corp of Engineers, Records Section, Seattle.
4. National Archives (old aerial photographs).
5. University of Washington, Library Map Center.
6. University of Washington, Library Northwest Collections.
7. King County Courthouse, Records Section (old land plats).

The U.S. Coast and Geodetic Survey (C&GS) topographic maps were generally the best sources of historical data because of their early, area-wide coverage, suitable scale, detail of mapping which shows features that persist to the present, and the identification of land grids on the survey sheets. Photographic copies, mostly at the scale of 1:20,000, of the original C&GS topographic sheets from 1854 to 1899 were obtained from the Rockville, Md., archives.

The name, date, original scale of the topographic and hydrographic surveys, and other information on each source map are listed in table 1.

DATA-TRANSFER PROCEDURES

Every effort possible was made to accurately transfer data from the historical maps to provide the best fit on the modern maps. Clear photographic copies of the oldest available source maps were obtained and by optical projection were reduced to the base-map scale. The historical shorelines, low-water lines, wetland limits, and selected map-pattern data from the maps were projected to modern base maps by use of a Bausch and Lomb[1] model ZT4-H zoom transfer scope (ZTS). This instrument optically superimposes two separate images (source map and base maps), and allows the viewer to match the scales and adjust for some types of linear discrepancy (if any) between the source and base maps and to trace one image on the other. The data were transferred by manual tracing onto copies of 1:24,000 (in one case 1:62,500)-scale USGS topographic maps. The modern topographic maps range in date of compilation from 1952 to 1973.

FACTORS AFFECTING ACCURACY

The nature of the source maps, judgments of individual compilers, and problems of data transfer all limit the absolute accuracy of the historical data shown. These factors are described below and in the descriptions of procedures on the individual map sheets.

[1]The use of a brand name in this report is for identification purposes and does not imply endorsement by the U.S. Geological Survey

General Accuracy of the Early Surveys

The earliest maps of the region's coastlines on a scale large enough to have sufficient detail for quantitative study are those made by the C&GS (Shalowitz, 1964, p. 79). They represent the best evidence available of the condition of the coastline 80 to 125 years ago. However, the survey work, though outstanding for its period, was not as accurate as is possible with modern mapping practices. For example, the early surveys were done by planetable methods rather than the aerial photographic and photogrammetric methods available today. In planetable surveys, the surveyor plotted the map data in the field on drawing-board sheets and measured directions and distances to selected features of the terrain using a telescopic alidade and stadia rod. The shoreline between the surveyed sites was sketched free-hand by the topographer. From these early survey sheets, there is no way to determine which points along the shoreline represent actual surveyed sites. Different topographers also used their discretion about details to be omitted or included on the maps.

In summary, as stated by Shalowitz (1964, p. 81), the degree of accuracy of the early surveys depends on many factors, among which are the purpose of the survey, the scale and date of the survey, the standards for survey work then in use, the importance of the area surveyed, and the ability and care of the topographer.

Land Grid

The modern USGS topographic maps and most of the early topographic surveys used a polyconic projection for the transferral of the meridians and parallels of the curved earth's surface to a flat map (Shalowitz, 1964, p. 136 and 141). However, the horizontal data, which determine the geographic positioning of meridians and parallels on the surface of the earth to a common reference point, have changed since the early topographic surveys were completed. Practically all recent surveys in the United States are based on the North American 1927 Datum. The majority of C&GS maps used as source materials show different historical land grids including that of the North American 1927 Datum, which was added to the maps by the C&GS after 1927.

Analytical and Interpretive Limitations

In using the early maps, it was important to determine the specifications and objectives of topographers in mapping of shorelines, marshes, and intertidal areas as well as characteristics of features represented by symbols or patterns used on the early maps. The most authoritative source for this information is Shalowitz (1964). Some analytical and interpretive limitations to the use of the early maps are discussed below.

Delineation of Shoreline and Wetland

The shoreline (line dividing land from water) shown on modern topographic maps represents the approximate line of mean high-water. Likewise, according to Shalowitz (1964, p. 174), beginning with the earliest surveys, it was the intention of topographers to delineate, as nearly as possible but without recourse to leveling, the line of mean high-water as the shoreline. In the field, the mean high-water line was interpreted by the surveyor from the appearance of the beach or by reference to predicted tides (Shalowitz, 1964, p. 189). Thus, a map compilation showing historical and modern shorelines should provide a common reference for the shoreline from which to evaluate changes in shoreline or wetland margins. Although the above premise is generally correct, it does not represent complete consistency, because the exact location of the high-water line in tidal-influenced marsh is often difficult to identify (Shalowitz, 1964, p. 177). For such areas the shoreline shown on the map may not always be the mean high-water line.

The upper, landward edge of marsh is often more difficult to determine than the seaward edge. Shalowitz (1964, p. 181), in discussing early surveys, indicated that, in general, the landward edge of marsh areas has always been interpreted as the dividing line between the marsh and upland, and not as representing any particular tidal elevation; generally it may be considered to be the limit of penetration of the highest tides. The early maps do not necessarily show the full landward extent of wetland of those times because the mapping may have stopped short of some inland portions.

Low-Water Line

The maps for eight of the eleven major deltas show a low-water line delineating the seaward edge of the intertidal wetland. The low-water line, in the context of planetable surveys, is the topographer's estimate of the line representing a vertical datum defined by a phase of the tide, and is used as a reference plane for depths in the sea. The mean lower low-water line is the zero depth or datum from which water depths are measured and represents the low-water line of the early topographic surveys in the Puget Sound region (Shalowitz, 1964, p. 185).

Map Symbols

In the early period of topographic surveys, complete consistency in the use of symbols to represent various shore and land features reportedly was never attained due to the lack of standard symbols, and differing preferences of topographers. In order to facilitate comparison with modern conditions, the authors interpreted the original map symbols representing various features (for example, wetland, grassland, forested upland, shoreline, and dikes) to make them consistent for all the present map compilations. Also, the forested-uplands symbol on these compilations has been limited to a narrow band, rather than showing the entire landward extent as portrayed on the source maps. Otherwise, the limits of historical patterns as they are shown here represent the limits of mapping during the original surveys. The individual map explanations indicate symbols used to represent the historical map data and the corresponding modern symbols shown on the base map. Because there is no pattern for forested areas included on the base maps, the present-day extent of the forested upland is not shown and no distinction can be made between marsh and forested wetland.

Judgment of Compilers

Among the more important judgments made by the author-compilers was the selection of common points on the source and base maps for scale matching and map registration. Fortunately, a significant number of well-defined manmade features shown on the old maps, such as dikes, railroad lines, and intersections of roads, have persisted to the present; these were the preferred references for comparison and map control. The survival of these historical features was verified by use of intermediate-age maps, color aerial photographs, and spot-checking in the field on such evidence as present condition of the feature and vegetative growth. In addition, distinct topographic features (bluffs, ravines, and rock outcrops) were used as supplementary control points. These features were especially important where cultural landmarks were few or absent. Combinations of these control points were also used to adjust for shifts or skewness of data resulting from geodetic inaccuracies in the early surveys and for distortions in the photographic processing or printing of maps. In some cases, arbitrary decisions based on interpretations of local landforms were the basis for adjustment of the data. Details of the methods used for individual compilations are described on each sheet.

Accuracy of Data Transfer

Inaccuracies can result at several stages in the transfer of data between different maps or photocopies. Among these inaccuracies are distortions that may occur as the result of storage conditions, photographic processing, mosaicking of map parts, or optical projection. During this compilation, care was taken to minimize these errors, as discussed below.

Map Stability

Distortions in paper maps occur as the result of shrinking or swelling due to aging and storage conditions. It is not known how much the original planetable map sheets may have been distorted before being photocopied; therefore, no attempt could be made to correct for the distortions prior to transfer of the data, except to reconcile discrepancies between old and modern maps by adjusting to common control points. The historical information was drafted onto scale-stable film as it was taken from the old sources to ensure stability of the final compilation.

Optical Transfer

Inaccuracies resulting from the optical projection of images using the ZTS are believed to be slight. To avoid effects of any possible optical distortion from the lens system, only the center portion of the image, in as large a field of view as possible, was used during the transfer of data. When the source and base maps are nearly the same scale, the field of view is relatively large, and this enhances the accuracy of the data transfer because more features on the two maps can be matched at one time. For this purpose, all C&GS maps that were at an original scale of 1:10,000 were photographically reduced to 1:20,000 prior to image projection. The initial reduction was done as part of the requested photocopying of the original surveys at the NOAA archives at Rockville, Md. It is possible that some distortion, particularly of the margins of the original map sheets, may have occurred during the photocopying process.

Tracing

Errors in the actual hand tracing of data from historical maps are estimated to be about one-half millimeter (.02 in) plus or minus (±), or about ±12 meters (39 ft) at a scale of 1:24,000. This inaccuracy represents mechanical error and does not include, of course, any lateral adjustments or shifts in the tracing that were needed to match the original surveys to the modern maps.

GLOSSARY

Delta. The low, nearly flat, alluvial tract of land deposited at or near the mouth of a river, commonly enclosed or crossed by many distributaries of the main river. Most deltas are partly subaerial and partly subaqueous (below water). For this compilation, the subaerial part of the delta includes all the areas landward of the general salt-water shoreline; the subaqueous part includes intertidal land and the delta front. Schematic three-dimensional and cross-sectional diagrams of a river-mouth delta are shown in figure 2.

Delta plain. The level or nearly level surface comprising the landward parts of a delta, characterized by multiple distributary channels and interdistributary flood basins.

Dike. An artificial wall, embankment, levee, or mound, usually of earth, stones, or riprap, built around a relatively flat, low-lying area to protect it from flooding by holding back the water and stopping or deflecting the water currents of an adjacent sea, lake, or stream.

Distributary. A stream branch flowing away from a main stream and not rejoining it.

High-water line. The intersection of a tidal plane of high water with the shore; it does not connote a specific phase of high water, such as higher high water or lower high water.

Higher high water. The higher of the two high waters of any tidal day.

Intertidal wetland (tideland, tideflat). The wetland that is covered and uncovered by daily rise and fall of the tide. More specifically, the zone between the mean high-water line and the mean lower low-water line along the coast.

Levee. See dike.

Lower low water. The lower of the two low waters of any tidal day.

Marsh. A water-saturated, poorly drained area, intermittently or permanently water-covered, having aquatic and grasslike vegetation.

Mean lower low-water line. The mean of the intersections of the tidal plane of the lower of two low waters in a tidal day with the shore.

Mean high water. The average height of the high waters recorded over a 19-year period.

Mean high-water line. The mean of the intersections of the tidal plane of diurnal high waters with the shore. In the context of the planetable surveys of C&GS, the topographer's estimate, without recourse of leveling, of the mean high-water line.

Progradation. A seaward advance of the shoreline resulting from the near-shore deposition of sediments.

Regression. A landward retreat of the shoreline resulting from processes such as erosion or subaqueous slumping.

Shoreline. A line representing the contact between the land and a body of water. On C&GS nautical charts and survey maps and USGS topographic maps the shoreline approximates the mean high-water line.

Subaerial. Formed, existing, or taking place on the land surface; contrasted to subaqueous (beneath the water).

Subaerial wetland. For this compilation, the wetlands that are landward of the general salt-water shoreline. Includes all the forested and nonforested wetlands on the subaerial part of the delta; excludes the intertidal wetland.

Topographic survey (C&GS). A field survey, on a given date, of the natural topographic and the cultural features of a portion of the land surface.

Wetland. Intertidal land and land that is waterlogged or inundated to shallow depths with either fresh, brackish, or salt water for a significant part of most years; includes forested wetland (seasonally flooded forested bottomland, wooded swamp, and shrub swamp), marshes (fresh-, brackish-, and salt-water marsh), fresh-water meadows, and open bogs (see Anderson and others, 1976, p. 17-18).

SUMMARY AND INTERPRETATIONS

A comparison of the earliest maps of 11 major deltas in the Puget Sound region with modern topographic maps can improve the understanding of dynamic processes of the river-mouth deltas and the impacts of man's activities upon the delta areas. Such a comparison provides documentation of (1) shoreline modifications, both natural and man-induced, since non-Indian settlement, (2) loss or gain of wetlands, and (3) patterns of land-use changes on delta lands.

Dredging, sinking of pilings, and manmade structures along the shoreline constitute changes; however, the influences of these changes are not specifically discussed in the report, and are not always discernable from the maps.

Shoreline Changes

The processes that result in delta-shoreline changes are several and complex and, for the deltas in the Puget Sound region, have not yet been adequately studied. The marine side of the delta environment is especially complex and dynamic, involving wave action, seasonal changes in shoreline erosion and deposition, major tidal fluctuations and currents, and, in some cases, significant transport of sediments by longshore currents. Even if those conditions and processes were well understood with respect to this region, detailed discussion of them here would be inappropriate. However, some understanding of the relationships between the fresh-water and salt-water sides of the deltas—of the general principles and processes involved—is necessary for an evaluation of the changes that take place at delta shorelines and, especially, the possible relationships of man's activities to the shoreline changes. Accordingly, the following brief discussions of delta progradation and recession include mention, in very generalized terms, of some of these basic principles and processes.

Progradation

Delta building, or progradation of the delta front, is a natural consequence of sediment-laden stream water discharging into a quieter body of water, such as a marine bay. Progradation takes place where, and so long as, the sediment load exceeds subsidence or the ability of currents and waves within the receiving waters to carry the sediment away from the delta front. Rivers are not the only source of sediment for local delta building; some sediment can be derived from natural erosion of sea cliffs and other segments of the shoreline and moved by estuarine, wind, and tide-generated currents.

Because of man's complex intervention with nature, it if often difficult to distinguish between natural and man-caused sediment loads that may influence the occurrence and amount of progradation of a particular delta. However, man's activities commonly affect sediment supply or the path of distributary streams and marine currents in ways that may be reflected in progradation of the deltas. These include:

(1) Activities that increase sediment load, such as erosion-producing activities in the drainage basin and along adjacent shorelines, sea cliffs, and other nearby streams that feed the delta. Examples include land clearing and cultivation, logging, mining, and in-stream construction.

(2) Activities that tend to reduce sediment load, at least for the short term. These include reducing erosion of land or streambanks through revegetation, bank stabilization, and construction of on-stream reservoirs. Sediment-reducing activities tend to retard delta progradation.

(3) Activities such as stream channelization, channel dredging, mining of beach materials, and construction of groins, jettys, and breakwaters that affect current flow and sediment erosion-deposition patterns. For example, manmade structures, such as groins and breakwaters, interrupt the movement of sediment, resulting in deposition on the updrift side of the structures and erosion on the downdrift side.

With information about the position of the shoreline at only two specific times—when the early and the modern mapping took place—only the overall change in shoreline can be discerned, and little can be said with confidence about the role that man's activities may have played in a change. Evaluation of artificial influences on shoreline change would require additional data such as shoreline positions at intermediate times, records of average sediment loads over time, and the nature and timing of different types of man's activities.

However, some general observations can be made. For deltas that have prograded significantly—the Nooksack, Stillaguamish, and Dungeness deltas—the sediment load has been, on the average, greater than the ability of the marine currents and waves to move the sediments from the delta front. Those deltas are most likely, of all the deltas studied, to continue prograding at a relatively rapid rate. The Stillaguamish River, in particular, is susceptible to progradation because of its relatively quiescent receiving basin, unaffected by strong marine currents, and large intertidal fan serving as an "apron" for subaerial buildup of sediments. Similarly, the progradation of the Nooksack River into the relatively quiet waters of Bellingham Bay may be occurring at a faster rate than would have been the case if the river still flowed into the more exposed, active waters of Lummi Bay. Conversely, for the deltas whose shorelines have had no significant progradation such as the Skagit and Snohomish deltas, the ability of marine currents to move sediment from the delta front has, on balance, been equal to the average sediment load supplied to the delta.

For deltas where artificial filling has occurred far beyond the historical shoreline, such as the Duwamish and Puyallup deltas, little can be said about the natural tendency for, or rates of, progradation; at least unless or until the natural delta-building processes "catch-up" with man's artificial extensions of the delta lands. The future resumption of any progradation beyond these artificial fills may be delayed by periodic dredging of sediment from the channels.

Recession

Overall recession or retreat of a delta shoreline results from the sediment discharge of the delta distributaries being less than the transport of sediments from the delta front. Shoreline retreat may be the result of a natural shift of eroding marine processes or of a reduction in sediment supply by natural or manmade causes, or both. The natural systems tend to adjust to the reduction in available sediment by increasing erosion of unprotected delta land until a state of equilibrium is reached (see discussion of progradation). Therefore, any proposal to cut off sediment supply to a large segment of delta should be carefully considered because the predictable delta response would be a recession of the delta under unbalanced influence of marine processes.

As the flow and sediment load of the distributaries change with time, some parts of the delta shoreline may be eroded and retreat at the same time that other parts of the shoreline may be prograding. This apparently has taken place at the Skagit and Nisqually deltas. The slight erosion of the Lummi delta shoreline probably is related to the reduced discharge of sediment that resulted from the shift of the Nooksack River outlet to the present Nooksack delta. The shoreline of Lummi delta may be somewhat protected from erosion in the future by the dike for a large aquaculture pond completed in 1971.

Shifting of Stream Channels

Periodic shifting of distributary channels is a common characteristic of most deltas and is not necessarily caused by man. As the delta builds beds along one part of its perimeter, the stream also builds up its own bed, creating an unstable situation in which the stream eventually breaks out of its channel and takes a shorter, steeper route to another part of the delta front. Distributary patterns also change as a result of lateral migration of individual channels in easily erodible bank materials. Major channel shifts often occur during occasional large-scale flooding.

Major stream channel shifts have occurred for the Nooksack, Stillaguamish, and Dungeness Rivers. Since the early mapping these rivers have moved from one part of the delta to another. Lateral migration of individual stream channels is particularly noticeable for the Skagit and Nisqually deltas.

Man-caused Shoreline Modifications

Shorelines of river-mouth deltas in the undisturbed state represent an intricate set of processes at the land and water interface. Near the river mouth, shorelines include sand bars, islands, tidal creeks, and sloughs. In these areas fish and other estuarine and wetland inhabitants have available a variety of streambank, streambed, and vegetative environments that provide abundant food and shelter. Shoreline modifications, especially by diking and channelizing of streams, reduce the natural diversity of the shoreline and, along with the conversion of wetland to other land uses, reduce the habitat available for aquatic life.

Diking and filling near the distributary channels or the seaward shore of the delta has occurred at most of the deltas studied. In general, the fill for dikes or levees along the distributary channels has been placed closer to the edge of the water than the fill for dikes along the delta seashores. The most extensive modifications of shoreline have occurred on the Duwamish and Puyallup deltas by both dredge-and-fill and stream-channelization projects. In the Duwamish delta the meandering river has been reduced to about one half of its former length by channel straightening. Most of the present shoreline of the Duwamish and Puyallup deltas is landfill protected by bulkheads. The shorelines of the Snohomish delta have been altered by landfilling, but to a much lesser extent than the Duwamish and Puyallup deltas.

Development on Delta Deposits

In the Puget Sound region, river-mouth deltas are prized as residential, commercial, and industrial tracts because they provide large areas of flat-lying land close to water. The principal cities along Puget Sound are at the mouths of major rivers—Tacoma (Puyallup River), Seattle (Duwamish River), and Everett (Snohomish River). Natural deltaic sediments consist largely of sand, silt, and gravel. These geologic materials and manmade fill have differing physical characteristics that may directly affect land usage. Areas of poorly compacted manmade fill or saturated silt, clay, and organic mud may provide poor foundations for heavy structures. Land overlying part of a sanitary landfill of the Tacoma industrial area has reportedly settled, causing structural problems in buildings. Saturated silt and sand deposits and uncompacted manmade fill also may settle or become unstable during seismic shaking. For example, hydraulic fill that was used to create the industrial area along the Duwamish River subsided during the 1949 and 1965 earthquakes, apparently as a result of liquefaction (U.S. Geological Survey, 1975, p. 95, 99).

In wetland areas, pollution from landfills and other waste-disposal facilities are a potential problem because these areas are frequently subject to periodic flooding and a high water table. For example, the solid-waste disposal site at the mouth of the Snohomish River has an obvious impact on nearby water. The solid waste being deposited on the fill is in direct contact with, or just above, the surface water, making for easy access of leachate into the stream and adjacent estuarine waters.

Loss of Wetland

Subaerial Wetland

Coastal wetlands, generally grading from salt-water to fresh-water marsh, are well-known as critically important habitat for fish and wildlife. Sloughs dissecting the marshes attract an abundance and diversity of life and are nursery areas for young fish. Wetland areas are essential for nesting, wintering, and feeding of waterfowl and shore birds. They also help stabilize shorelines, reduce erosion, and buffer the force of storms and floods.

A comparison of present-day and historical wetland area for each of the deltas is shown in table 2. Eight of the 11 deltas show a loss of subaerial wetland; three deltas show a significant wetland loss of 5 sq km (1.9 sq mi) or more. Diking was an early activity of settlers in the region and accounts for the greatest loss of former wetland. Dikes stopped the tidal flow of salt water into areas they enclosed permitting the gradual freshening of the soil water and introduction of plant species suitable for subsequent agriculture. The forested wetland of the Nooksack delta has not been diked at the lower reaches and has about the same amount of wetland as in 1887-88 (table 2). The Lummi and Samish deltas are fed by small river systems and generally have only a narrow fringe of marsh seaward of the dikes near the delta shore. The Skagit delta also has a fringe of marsh seaward of the dikes in the northern part of the delta but a much larger area of wetland (including some forested wetland) along the South Fork distributaries. The Stillaguamish delta, because of its prograding nature, has gained some subaerial wetland since the early mapping in 1886. The Snohomish delta has residual "pockets" of wetlands, mostly in its northern part; it originally had the largest wetland area of the deltas studied (table 2). The Duwamish and Puyallup deltas have been most extensively developed and have little or no remaining wetland. The Nisqually and Skokomish deltas have been partly diked and have much remaining undisturbed wetland. For the Dungeness delta, although natural changes have occurred, the net loss or gain of wetland from former conditions does not appear to be significant. Of the 11 river-mouth deltas studied, about 55 sq km (21 sq mi) of subaerial wetland have been converted to other land uses from the original 91 sq km (35 sq mi) mapped during the historical surveys.

Intertidal Wetland

Tideflats and submerged grass beds also are critical habitat for aquatic life. The plant production from these areas becomes available as organic detritus which provides the chief food for the coastal fish and shellfish populations of commercial importance. Natural, unspoiled mud flats teem with animal life that includes snails, mussels, and oysters, as well as a variety of crabs, shrimps, and small fishes.

A comparison of present-day and historical intertidal areas for eight of the eleven deltas is shown in table 3. The intertidal area of the Lummi, Skokomish, and Dungeness deltas has remained about the same since the early mapping. Extensive dredge-and-fill projects carried out on the Duwamish and Puyallup deltas have eliminated about 16 sq km (6 sq mi) of intertidal habitat. In the Snohomish delta, dredge-and-fill operations have eliminated about 2.6 sq km (1.0 sq mi) of intertidal area from an estimated overall loss of 4.2 sq km (1.6 sq mi) of intertidal wetland based on comparison of historical and present-day maps (table 3).

REFERENCES CITED

Anderson, J. R., Hardy, E. E., Roach, J. T., and Witmer, R. E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Hynding, Alan, 1973, The public life of Eugene Semple: Seattle, University of Washington Press, 195 p.

Klotz, S. A., Madsen, S. J., Miller, P. A., and Smith, D. F., 1978, A survey of terrestial organisms on the Nisqually River delta, Washington: final report, Olympia, Washington, The Evergreen State College, 166 p.

Phelps, Thomas, (undated), Plan of Seattle 1855-56: Seattle, University of Washington Northwest Collections, scale 1:2300, 1 sheet.

Shalowitz, A. L., 1964, Shore and sea boundaries with special reference to the interpretation and use of Coast and Geodetic Survey data: v. 2, U.S. Department of Commerce, Publication 10-1, 749 p.

U.S. Army Corps of Engineers, 1907, Duwamish-Puyallup Surveys: U.S. Army Corps of Engineers Survey Sheet 25-26, map, scale 1:4800, 2 sheets.

U.S. Army Corps of Engineers, 1973, Report on flood control, Nooksack River basin, Washington: Seattle District, 59 p.

U.S. Army Corps of Engineers, 1975, Water resources development by the U.S. Army Corps of Engineers in Washington: Portland, North Pacific Division, 120 p.

U.S. Geological Survey, 1975, A study of earthquake losses in the Puget Sound, Washington, area: U.S. Geological Survey Open-File Report 75-375, 298 p.

Washington State, (undated), Historic preservation legislation, state and national summary: Olympia, Washington Office of Archaeology and Historic Preservation, Parks and Recreation Commission, unpublished report, 10 p.

Williams, R. W., Laramie, R. M., and Ames, J. J., 1975, Volume 1, Puget Sound region, *in* A catalog of Washington streams and salmon utilization: Olympia, Washington, State of Washington Department of Fisheries, 780 p.

CONVERSION TABLE

The following factors are provided for conversion of metric units used in this report to inch-pound units.

Multiply	By	To obtain
Millimeters (mm)	0.03937	inches
Meters (m)	3.281	feet (ft)
Kilometers (km)	.6214	miles (mi)
Square kilometers (sq km)	247.1	acres
Square kilometers (sq km)	.3861	square miles (sq mi)
Hectares (ha)	2.471	acres

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA.—1980—L79387

For sale by Branch of Distribution, U.S. Geological Survey, Box 25286, Federal Center, Denver, CO 80225