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Geographic Signatures of North American West Coast Estuaries

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ABSTRACT: West Coast estuaries are geologically young and composed of a variety of geomorphological types. These estuaries range from large fjords to shallow lagoons; from large to low freshwater flows. Natural hazards include El Niños, strong Pacific storms, and active tectonic activity. West Coast estuaries support a wide range of living resources: five salmon species, harvestable shellfish, waterfowl and marine birds, marine mammals, and a variety of algae and plants. Although populations of many of these living resources have declined (salmonids), others have increased (marine mammals). West Coast estuaries are also centers of commerce and increasingly large shipping traffic. The West Coast human population is rising faster than most other areas of the U.S. and Canada, and is distributed heavily in southern California, the San Francisco Bay area, around Puget Sound, and the Fraser River estuary. While water pollution is a problem in many of the urbanized estuaries, most estuaries do not suffer from poor water quality. Primary estuarine problems include habitat alterations, degradation, and loss; diverted freshwater flows; marine sediment contamination; and exotic species introductions. The growing West Coast economy and population are in part related to the quality of life, which is dependent on the use and enjoyment of abundant coastal natural resources.

Introduction

Most of the 90,147-km long coastline of western North America lies in Alaska (Table 1). While Alaska, British Columbia, and northern Washington have convoluted coastlines with many inlets, islands, and sounds, much of the western Washington, Oregon, and California coasts are relatively straight and only occasionally interrupted by headlands and estuaries. For the purpose of this paper, we will consider only the conterminous West Coast of the United States and British Columbia, Canada. Alaska's estuarine systems are extensive, relatively unstudied, and merit a review of their own. In this paper we describe major aspects of estuarine systems along the West Coast of North America including geology, climate, oceanography, biological resources and processes, economics, and environmental stressors.

West Coast estuaries have historically played and are presently playing vital roles in the economy and life of western residents. Western estuaries provide gateways for shipping and commerce, flat land for agriculture, and areas for recreation, aquaculture, urban development, and resource harvesting. The U.S. West Coast presently has one estuary designated as a Land Margin Ecosystem Study Area (Columbia River) by the National Science Foundation, six estuaries are included in the Environmental Protection Agency National Estuary Program (Puget Sound, Columbia River, Tillamook Bay, San Francisco Bay, Santa Monica Bay, and Morro Bay), and four designated as National Estuarine Research Reserves (Padilla Bay, South Slough, Elkhorn Slough, and Tijuana River) (Fig. 1). The U.S. West Coast also has five coastal marine

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TABLE 1. Shore-line length of western North America not including Mexico (Primedia Reference, Inc. 1999).

State/Province	Shoreline (km)
Alaska (Pacific Ocean)	50,495
British Columbia, Canada	27,000
Washington	4,869
Oregon	2,269
California	5,514
Total	90,147

sanctuaries (Olympic Coast, Cordell Bank, Gulf of the Farallones, which includes Bolinas Lagoon, Monterey Bay, and Channel Islands).

On the Canadian west coast there are six federal Migratory Bird Sanctuaries (Christie Islet, Esquimalt Lagoon, Riefel Refuge, Shaol Harbour, and Victoria Harbour) and two federal National Wildlife Areas (NWA) (Alaksen, and Qualicum) located on British Columbia estuaries. The Alaksen NWA, located in the Fraser River estuary, is a Ramsar site of international significance for migratory waterfowl. Ramsar stands for the international treaty on "Convention on Wetlands of International Importance Especially as Waterfowl Habitat," signed in Ramsar, Iran in 1971. Under the Province of British Columbia's Ecological Reserve Program, 14 coastal sites have reserve status (no mineral prospecting, timber cutting, livestock grazing, camp building, road or trail construction, hunting or trapping, motorized vehicles, or flora or fauna collecting), many of which are islands on the outer coast supporting important seabird colonies. There are three estuarine ecological reserves, all on the west coast of Vancouver Island (Nitinat Lake, Tashsish River estuary, and Klaskish River estuary).

Under Canada's Pacific Estuary Conservation Program (a partnership of Federal, Provincial, and non-government organizations) major portions of marshes in a number of British Columbia estuaries have been secured by land purchase (Nanaimo River, Marble River, Millard Creek, Salmon River, Asseek River, Bella Coola River, Kumdis Bay, South Arm marshes of the Fraser River estuary, Englishman River, and Cowichan River) (Pacific Estuary Conservation Program 1995).

Many U.S. West Coast estuaries contain National Wildlife Refuges (NWR). These include Don Edwards San Francisco Bay, San Pablo Bay, Humboldt Bay, and Tijuana Slough in California; Bandon Marsh, Nestucca Bay, and Siletz Bay in Oregon; and Lewis and Clark, Julia Butler Hansen, Nisqually, Grays Harbor, and Willapa Bay in Washington. Adjacent coastal headlands and rocky islands, which are important breeding and rearing habitats for marine birds and mammals, are also designated as refuges. These include Farallons Islands, San Juan Islands, Oregon Islands, Cape Meares, and Washington Islands.

Compared to much of the eastern U.S. and Canada, the West Coast has only recently undergone industrial, agricultural, and urban development. Yet, development is putting increasing environmental demands and stresses within river basins and estuarine systems. While effective natural resource management necessitates an ecosystem perspective, this is seldom done. Presently most management actions are usually piece-meal or site specific.

The purpose of this paper is to provide the reader with a broad ecosystem-wide perspective of West Coast estuaries and their natural resources. As such, this paper highlights the diversity of West Coast estuaries and their resources, and presents specific regional problems and concerns.

Geographical and Geological Setting

The West Coast of North America (British Columbia to California) ranges from 32.5°N to 54.4°N and has diverse geography, geology, and estuarine types. Estuaries range from large deep fjords in Washington and British Columbia to small shallow lagoons in California.

This region has been strongly structured by tectonic and volcanic forces. Geologically young, much of the West Coast's geomorphology is a product of the North American Plate moving north-northwest against the Pacific Plate and other tectonic plates (Fig. 2). Off Oregon and Washington, the North American Plate is pushing against the Juan De Fuca Plate, producing an adjacent subduction zone. In California, numerous geologic faults, such as the San Andreas, occur in the coastal region. As a result of these tectonic collisions, the West Coast has a very rugged topography, which includes the Olympic, Coast Range, Klamath, and the volcanically active Cascade Mountains (Fig. 3).

Much of the northwest and coastal California surface bedform consists of ancient marine sediments that were the bottom of a shallow sea uplifted during the Miocene (c. 24 million years ago) (McKee 1972). Puget Sound and British Columbia were further transformed by glaciation, and until 15,000 years ago, were covered by a glacial ice sheet. Presently, rebounding and estuarine sedimentation rates (about 3 mm yr^{-1}) are keeping up with a concomitant sea level rise. If the rate of sea level rise increases, northwest salt marsh accretion rates may not keep pace (Thom 1992). Approximately every 300–500 years, a large subduction earthquake occurs off the northwest, often dropping much of the coast relative to sea level (Atwater 1987). The most recent large subduction

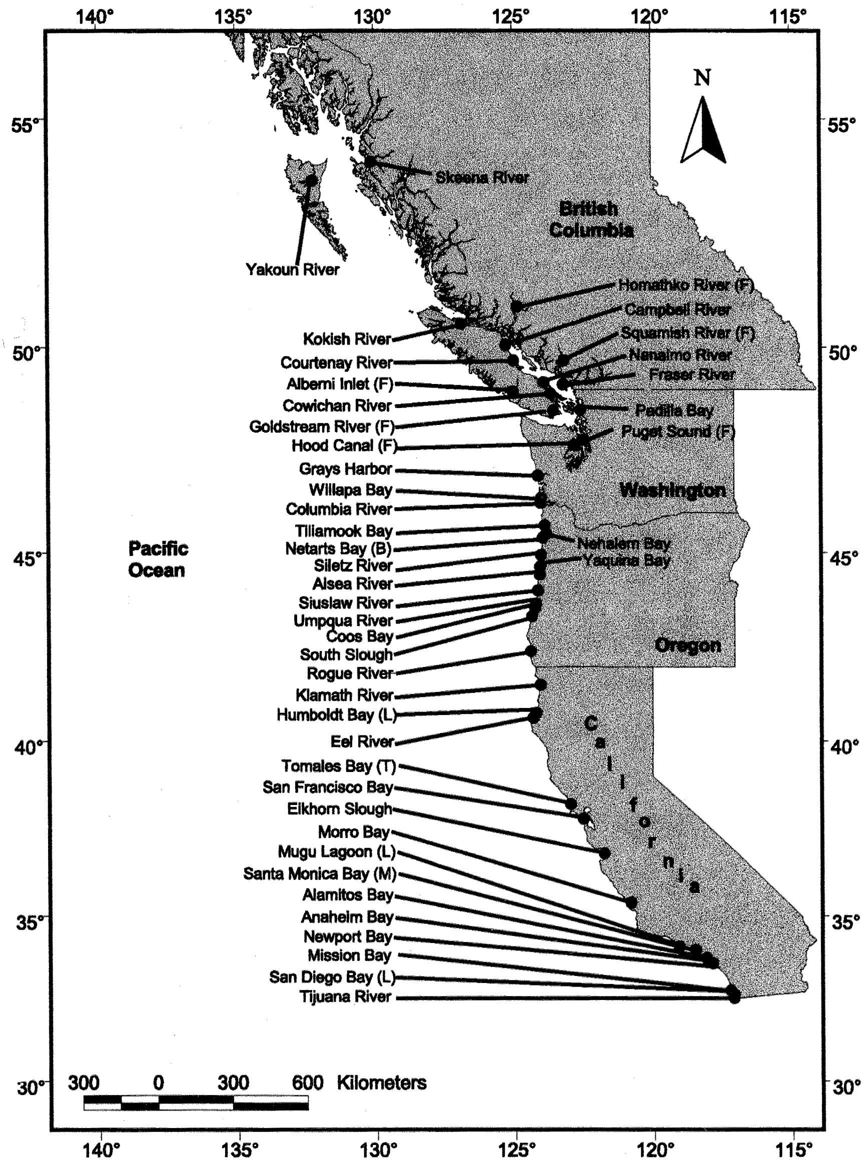

Fig. 1. Geographic location of important West Coast estuaries. All estuaries are drowned river valleys unless their name is followed by a letter; F = fjord systems, L = lagoon systems, T = tectonic systems, B = bar-built systems, and M = marine inlet.

earthquake was approximately 300 years ago (Yamaguchi et al. 1997).

The origin of estuaries along the coastal margin of California is also complex, due in part to the tectonics of the area. San Francisco Bay, California's largest estuary, was created by both lateral and vertical crust movements along a series of faults (Atwater et al. 1977). While geologic forces were the primary forces creating the basin's topography, the Holocene sea-level rise (ca. 10,000 years ago) drowned the basin and created present San Francisco Bay (Atwater 1979).

As a result of the West Coast's geomorphology (coastal mountain ranges with higher interior mountain ranges), the western U.S. and much of British Columbia are drained by relatively few large rivers. The Fraser River drains much of British Columbia; the Columbia River drains most of southeast British Columbia, eastern Washington, Oregon, Montana, Idaho, and parts of Canada; and the Sacramento and San Joaquin Rivers drain most of California (Fig. 3).

Size and Types of Estuaries

Most West Coast estuaries are relatively small (< 100 km^2 surface area) with the exceptions being the Fraser River estuary, Puget Sound, Hood Canal, Columbia River estuary, and San Francisco

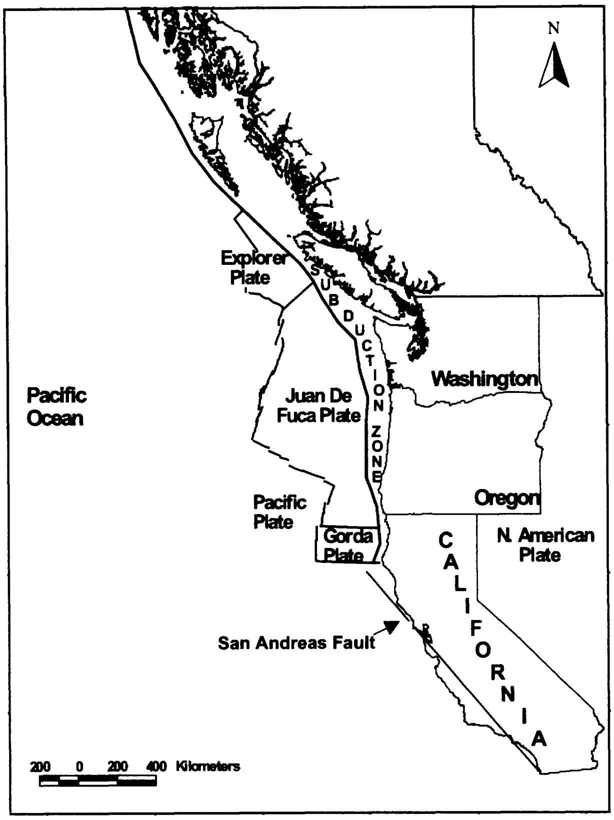

Fig. 2. Location of major geological faults and plates on the west coast of North America.

Bay, which are larger than 350 km² (National Oceanic and Atmospheric Administration 1990). Puget Sound and Hood Canal are classified as large fjords. However, fjords such as Puget Sound also have many in-flowing rivers, creating smaller, drowned-river valley subestuaries. With the exception of the fjord estuaries in Washington and British Columbia and the lagoon estuaries in California, most West Coast estuaries are drowned river valleys (Fig. 1). California also has one estuary, Tomales Bay (and to some extent part of San Francisco Bay), which was created by the San Andreas Fault. California also has some semi-enclosed marine bays, these include Santa Monica and Monterey Bays.

Fjord

Fjords along the West Coast, created as a result of glaciation, include Homathko River, Goldstream River, Alberni Inlet, Squamish River, Puget Sound, and Hood Canal. The British Columbia systems are further classified into low-flow or high-flow systems by Canadian oceanographers (Pickard and Stranton 1980). The large, deep Puget Sound fjord estuarine system encompasses many smaller estuaries, such as Padilla Bay and Skagit River estuary. A similar situation is found in the large British Columbia fjords, which usually have one large river at their head and numerous small creeks draining the mountainous terrain along the sides of the fjord (Levings and Riddell 1992).

Drowned-River Valley

Drowned-river valley estuarine systems, created as a result of river valleys flooding when sea levels rose after the last ice age, are the dominant type along the West Coast. Because of topography and climate, they are more abundant and larger in the north (British Columbia, Washington, and Oregon) than in California. While most coastal river systems drain relatively small watersheds from adjacent coastal mountains (e.g., Willapa Bay, Tillamook Bay, Yaquina Bay), a few estuaries drain large watersheds. These include basins such as the Fraser River, Columbia River, Umpqua River, and Sacramento and San Joaquin Rivers, which drain large interior areas where snow melt at high elevations adds significantly to freshwater flows during spring. Besides the estuaries listed in Fig. 1, many small rivers enter the ocean directly from the Coast Ranges, creating relatively small but locally important estuaries (e.g., Campbell River in British Columbia, Necanicum River in northern Oregon, and the Sixes River and Elk River in southern Oregon).

Lagoons

Lagoon estuarine systems, resulting from relatively flat topographical features and low freshwater flows, are found primarily in California. Large lagoon systems include San Diego Bay and Humboldt Bay. In addition, California also has many very small lagoon estuaries (e.g., Mugu Lagoon and others not shown in Fig. 1) that provide very important habitats for a variety of species. Many of these small lagoon systems are closed to the sea during much of the year by wave-built sand spits, but during winter these spits are breached. For example, San Dieguito Lagoon, located in San Diego County, California is only open to the sea anywhere from 12% to 16% of the year depending on rainfall (Elwany et al. 1998).

Bar-Built

The final and rarest type of estuarine system on the West Coast is the bar-built estuaries. Netarts Bay in Oregon is a prime example of an estuary whose origin is related to a geologically structured bar, creating a semi-enclosed body of water. Other estuaries, such as Willapa Bay and Tillamook Bay, are primarily drowned-river valleys, but owe their current topography to the addition of ocean-built bars near their entrances. There are similar estuary-lagoons on the west coast of Vancouver Island

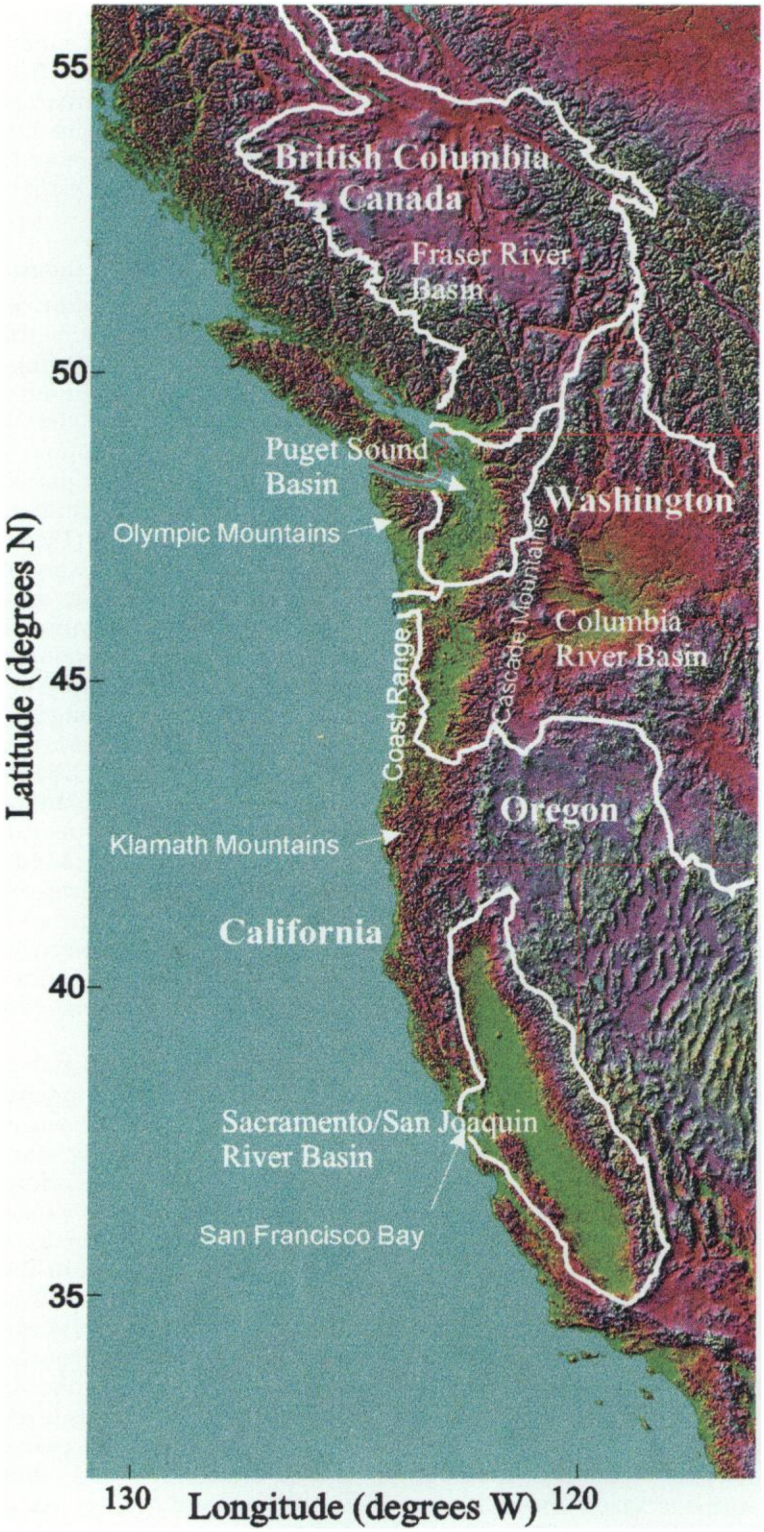

Fig. 3. False color elevation map of the west coast of North America showing major mountain ranges and watersheds. Base map courtesy of Ray Sterner, John Hopkins University, Baltimore, Maryland.

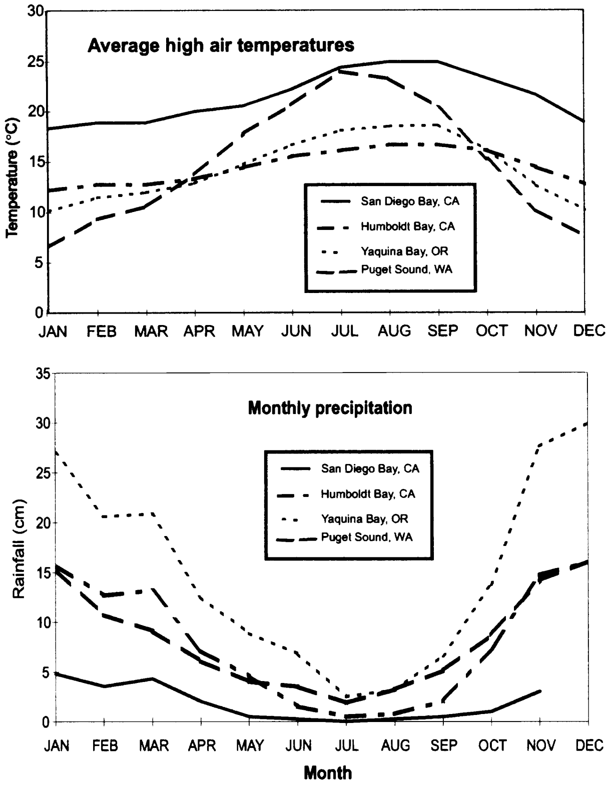

Fig. 4. Average monthly precipitation and high atmospheric temperatures at selected West Coast estuaries (data from Western Regional Climate Center, http://www.wrcc.dri.edu/index.html).

and the Queen Charlotte Islands (e.g., McIntyre Bay on Dixon Entrance).

Climate

The West Coast has a wide range of climatic conditions, from very wet and cool in the north, to hot and dry in the south. Air temperatures of the coastal region are generally Mediterranean over this wide latitudinal range, with relatively mild winters and rare freezes and snowfalls. Average high summer temperatures are about 25°C in the south and 15°C in the north. Near Humboldt Bay, California differences between summer and winter high air temperatures are only about 5°C (Fig. 4).

West Coast precipitation is much higher in the north than in the south. San Diego Bay, California, receives an average of only 5 cm rainfall in January, versus 25 cm for Yaquina Bay, Oregon (Fig. 4). Rainfall on the west coast of Vancouver Island is the highest in the region, averaging about 40 cm in December (Pickard and Stranton 1980). Most precipitation falls from October through May; whereas June through September are relatively dry (Fig. 4). As a result of this precipitation pattern, most West Coast estuaries receive their highest freshwater inflows during winter and very little during late spring and summer. Melting mountain snow and glacier melt from interior mountain ranges cause many estuaries in British Columbia and a few in the U.S. to have their highest flows during May and June (e.g., Columbia River, Fraser River, Squamish River estuary, and Homathko River estuary).

Oceanography

One of the dominant oceanographic features along the West Coast is the California Current. This relatively slow moving southerly current is part of the western boundary current system of the North Pacific Ocean. The California Current is most prominent in summer when northwest winds are the typical weather pattern. During winter, prevailing southwesterly winds cause an inshore counter-current to develop (Davidson Current) (Fig. 5).

West Coast estuaries are strongly influenced by seasonal coastal ocean/atmospheric conditions. During spring and summer when high atmospheric pressure systems develop, northwest winds commence and consequently ocean upwelling occurs (Huyer 1983). Upwelling carries cool, deep, nutrient-rich water nearshore and to the surface (Fig. 6), which, with the addition of sunlight, stimulates rapid growth in phytoplankton (primarily diatoms) populations. These productive coastal waters, along with their associated flora and fauna, are transported into estuaries by tidal exchanges and often account for much of the spring/summer plankton blooms (Cloern 1979). Coastal chlorophyll *a* (chl *a*) concentrations along the West Coast during upwelling events can be as high as 25 $\mu g\ l^{-1}$.

These distinct seasonal cycles (with northerly and onshore surface currents during winter, southerly, upwelling, and offshore currents during summer), may explain why many West Coast fish and shellfish spawn in the winter, a practice that ensures the retention of pelagic eggs and larvae in nearshore habitats. Furthermore, many salmonid stocks spawn in rivers in the fall and winter, and their juveniles migrate to sea in spring/summer just before or during the productive upwelling period, ensuring rapid growth and release from predation. Dungeness crab (*Cancer magister*), which uses estuaries during its juvenile stages, also spawns in winter, enabling its planktonic larvae to be retained nearshore and allowing early instars to move into estuaries to rear (McConnaughey et al. 1994).

The tidal regime in this region is characterized by a mixed semi-diurnal period. The smallest total tidal fluctuations are in Southern California (1.75 m) and the largest in Puget Sound (3.46 m) (Table

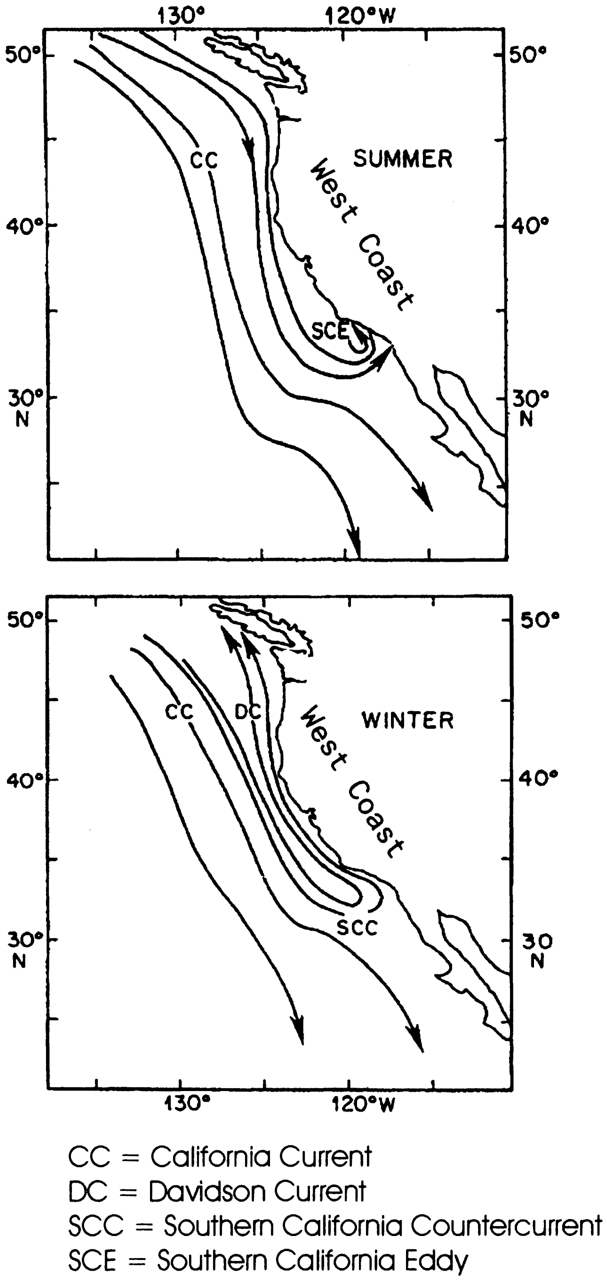

Fig. 5. General depiction of Pacific Ocean coastal currents off the West Coast during summer and winter.

2). However short-term and long-term atmospheric (e.g., storms) and oceanographic (e.g., El Niño) conditions strongly affect these tidal ranges.

Most West Coast estuaries have relatively small freshwater inflows because of their small watersheds. However, the Columbia River has the second highest flow in the U.S., averaging over 5,000 m^3 s^{-1} and accounting for 80% of the freshwater entering the ocean between San Francisco Bay and Strait of Juan De Fuca (Hickey 1989). Other estuaries with high freshwater inflows include the Fraser River and Puget Sound (Fig. 7). San Francisco Bay's mean freshwater inflow presently averages only 1,000 m^3 s^{-1} because over 80% of its freshwater flows are diverted or withdrawn for agriculture and urban use (Monroe and Kelly 1992). Most southern California estuaries have mean annual flows of < 3 m^3 s^{-1} because of their small watersheds and low rainfall (Fig. 7).

Biological Characteristics

Primary Production

Studies of primary production in West Coast estuaries show a wide range of values (Table 3). While few estimates have been made for annual phytoplankton primary production, phytoplankton population abundance appears to be closely linked with nutrient concentrations related to ocean upwelling and riverine inputs. In south San Francisco Bay for example, phytoplankton blooms are affected by river flow, but in a non-linear relationship, with other factors (turbidity and stratification) also important (Koseff et al. 1993; Cloern and Jassby 1995). Dominant West Coast diatom species include *Chaetoceros* spp., *Nitzchia* spp., *Rhizosolenia* spp., and *Skeletonema costatum* (Cloern 1979; Simenstad 1983).

In the Fraser River, chl *a* concentrations during a spring bloom (consisting mainly of diatoms) can range up to 10–20 μg l^{-1}. The influence of turbidity from Fraser River outflow, wind mixing, and nitrogen input from the open ocean are some of the factors controlling primary production (Harrison et al. 1994; Harrison and Kedong 1998). Nitrogen input from watersheds, including sewage from the city of Vancouver, British Columbia, was not thought to significantly influence primary production in the Strait of Georgia. However, nutrient input may be an important factor in embayments with poor circulation (Harrison et al. 1994).

West Coast marsh primary production has been relatively well studied. A wide range of production values has been calculated, with values related to marsh type and location, ranging from a low of 17 g C m^{-2} yr^{-1} in the Nanaimo River estuary to a high of 1,264 g C m^{-2} yr^{-1} in San Francisco Bay (Table 3). Although eelgrass meadows (primarily *Zostera marina* but also *Zostera japonica*) are generally not highly abundant in many West Coast estuaries, where they do exist, they are often significant carbon sources. In Puget Sound, eelgrass was calculated to produce 136–365 g C m^{-2} yr^{-1} (Thom et al. 1984; Thom 1990) and cover 9% of the bottom area below mean lower low water (Phillips 1984). Other U.S. West Coast estuaries with large areas of eelgrass include Padilla Bay, Grays Harbor,

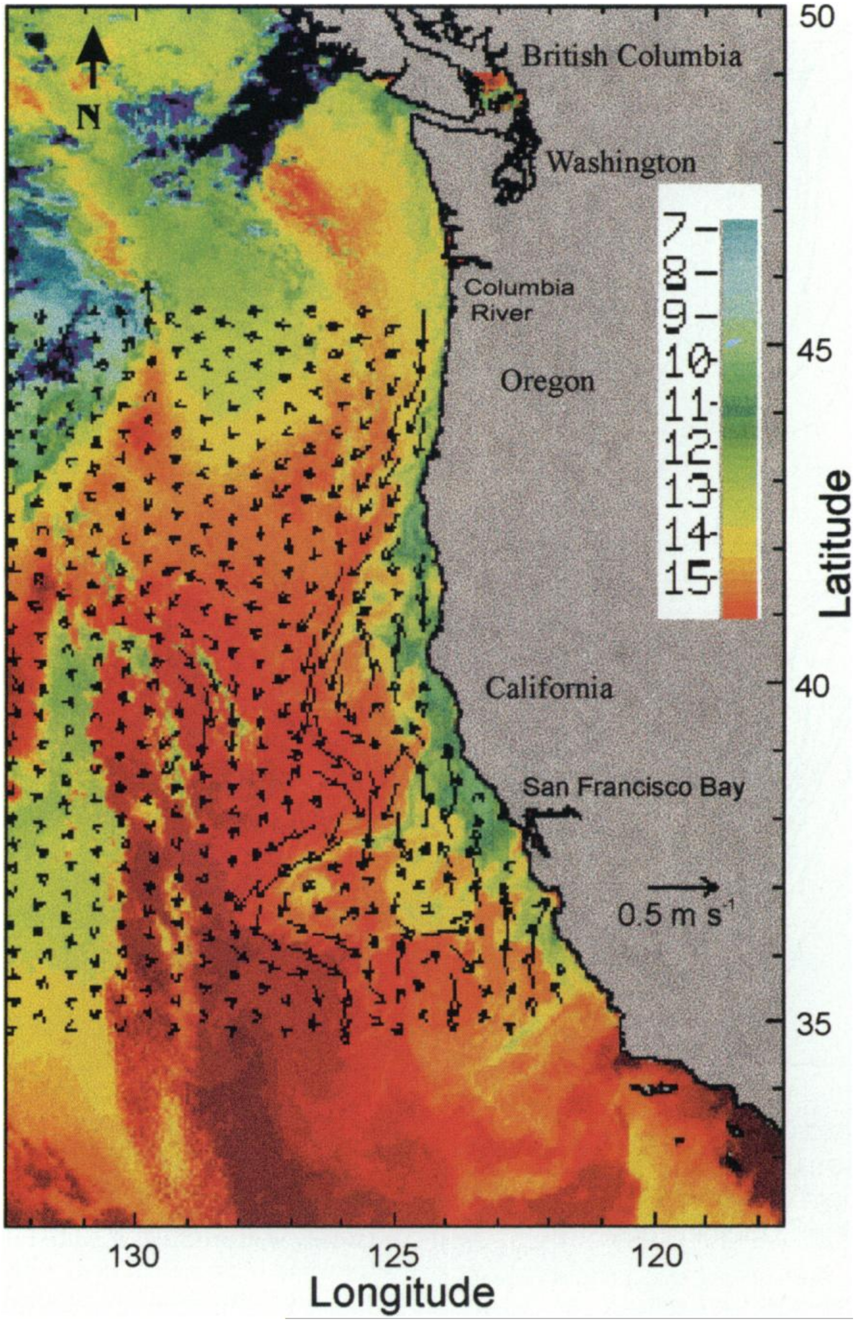

Fig. 6. West Coast sea surface temperatures and surface wind direction and strength (arrows) during a July 1988 upwelling period as determined from satellite Advanced Very High Resolution Radiometer (AVHRR) data (courtesy of P. T. Strub, Oregon State University, Corvallis, Oregon).

Willapa Bay, and Humboldt Bay (Phillips 1984). Padilla Bay has one of the largest contiguous eelgrass areas of all U.S. West Coast estuaries, with 3,200 ha (7,900 acres) (Bulthuis 1995). Boundary Bay in British Columbia, near the U.S. border, has approximately 4,142 ha of eelgrass, and there are other substantial beds in the Strait of Georgia (Dunn and Harrison in press).

Relative to their overall size, West Coast estuaries have extensive areas of mud flats because of high sedimentation rates and tidal fluctuations. While primary production in mud flat habitats has not

TABLE 2. Tidal changes at six West Coast estuaries. Mean High High Water (MHHW) shown is the average highest sea level as measured above Mean Sea Level (MSL), while Mean Lower Low Water (MLLW) is the average lowest sea level below MSL (Fraser River data from Canadian Hydrographic Service, other data from National Oceanic and Atmospheric Administration, National Ocean Service, http://www.co-ops.nos.noaa.gov/data_res.html).

Location	Average MHHW (m above MSL)	Average MLLW (m below MSL)
Fraser River, Vancouver, British Columbia	1.45	1.85
Puget Sound, Seattle, Washington	1.44	2.02
Columbia River, Astoria, Oregon	1.23	1.34
Willapa Bay, Washington	1.25	1.43
Humboldt Bay, California	0.97	1.14
San Diego Bay, California	0.85	0.90

been measured for many estuaries, it can be a significant source of organic carbon. Puget Sound has been shown to have tidal flat annual net primary production up to 1,286 g C m^{-2} yr^{-1} (Table 3). The annual benthic gross primary production for intertidal areas in the Columbia River (excluding emergent macrophytes) was calculated to be 2.175 $\times$ 10^6 kg C yr^{-1} (McIntire and Amspoker 1984). However, this represents only a relatively small source of carbon relative to extensive riverine inputs (Simenstad et al. 1990; Prahl et al. 1997). Presently much of the organic material in the Columbia River estuary turbidity maximum is derived from riverine phytoplankton (Prahl et al. 1997). This is probably a much different carbon source than pre-dam development, when high flushing rates would have precluded extensive riverine phytoplankton productivity, similar to the present situation in the lower Fraser River (Northcote et al. 1975).

Important West Coast estuarine algal species include *Ulva* spp., *Porphyra* spp., *Enteromorpha* spp., *Rhizoclonium riparium, Sargassum muticum, Laminaria* spp., *Alaria* spp., and *Fucus* spp. (Simenstad 1983; Zedler et al. 1992). Besides the estuarine diatoms mentioned earlier, the marine species *Cylindroptyrix* sp., *Thalassiosira* spp., *Amphiprora paludosa,*

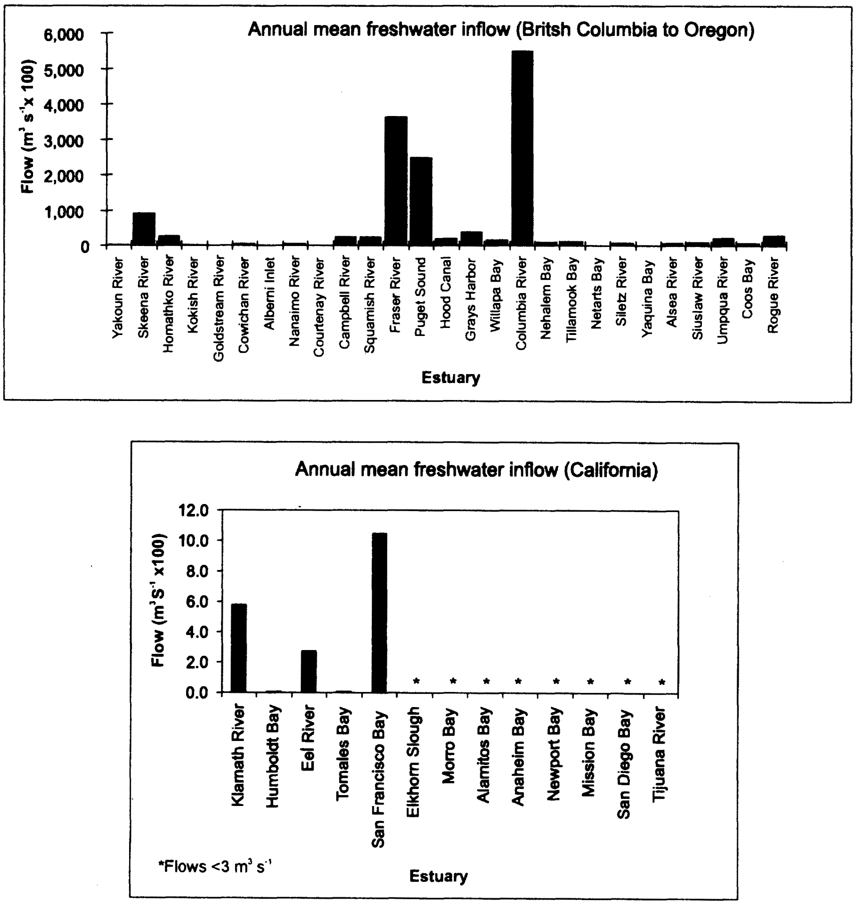

Fig. 7. Annual mean freshwater flow into West Coast estuaries. Note the different scales between California estuaries and northern estuaries (data from U.S. Geological Survey, http://waterdata.usgs.gov/nwis-w/US/).

TABLE 3. Estimates of net primary production (gC m^{-2} yr^{-1}) from West Coast estuaries from five different habitat types. Conversion, 1 g dry wt = 0.4 gC.

Estuary	Annual Plankton Primary Production	Aerial Annual Tidal Marsh npp	Aerial Annual Eelgrass npp	Annual seaweed npp	Annual Tideflat npp	Reference
Cowichan River		492				Kennedy 1982
Qualicum River		607–698				Dawe and White 1982; Kennedy 1982 in Hutchinson 1986
Nanaimo River		17–203				Kennedy 1982
Salmon River, British Columbia		474				Kennedy 1982
Campbell River, British Columbia		489				Kistritz and Yesaki 1979
Fraser River		275–718				Yamanaka 1975
Nisqually River		363–556				Burg et al. 1975
Nooksack River		680				Disraeli and Fonda 1979
Padilla Bay			351	296	148	Thom 1990, 1989
Strait of Georgia	300					Harrison et al. 1994; Harrison and Kedong 1998
Puget Sound	500		84–480			in Philips 1984
Puget Sound			1,355	4,185	1,285	Thom et al. 1984
Skagit River		112–521				in Hutchinson 1986
Squamish River		24–213			100	in Hutchinson 1986
Grays Harbor	9–110	196–280	322	8–503	26–234	in Thom 1981
Columbia River		432–1,501				Macdonald 1984
Nehalem River		350–702				Eilers 1975
Netarts Bay			737	1,120	12	McIntire et al. 1983
Selitz River		480–800				Gallagher and Kibby 1981
Yaquina Bay					3	McIntire et al. 1983
Coos Bay		123–480				Taylor and Frenkel 1979; Hoffnagle 1980
Oregon Estuaries		180–740				Kibby et al. 1980
Humboldt Bay			266			in Philips 1984
San Francisco Bay		110–1,264				in Josselyn 1983
Mugu Lagoon		80				Zedler 1982
Upper Newport Bay		240				Zedler 1982
San Diego Bay		240				Zedler 1982
Sweetwater River		440				Zedler 1982
Tijuana River		164–340		34–253		Zedler et al. 1992

Surinella ovata, and the freshwater species *Asterionella formosa, Melosira islandica, Melosira distans,* and *Stephanodiscus hantzschii* are often dominant taxa (Simenstad 1983).

Wetlands

As a result of its steep topography, the West Coast has the least amount of coastal wetlands per area of any coastal region (Field et al. 1991). West Coast estuarine wetlands consist of non-vegetated flats, fresh and brackish marshes, and scrub-shrub/forested wetlands. While there are now an estimated 4,641 km^2 of estuarine wetlands between Washington and California (National Oceanic and Atmospheric Administration 1990), California has lost over 90% of its historic wetlands to agriculture, housing, urban development, and other factors since modern settlement. Total tidal estuarine wetland loss in the Strait of Georgia and Puget Sound has also been substantial (Levings and Thom 1994), but changes in Oregon have not been quantified (Table 4). During the early settlement of the West Coast, many acres of estuarine tidal wetlands were diked for agriculture and development because of the limited amount of available flat lands (Seliskar and Gallagher 1983). Approximately 70% of all tidal wetlands have been lost in Puget Sound since the late 1800s. Since 1870, almost 24% of the Columbia River estuary's wetlands have been converted to diked floodplain, uplands, and non-estuarine wetlands (Thomas 1983). Willapa Bay lost

TABLE 4. Amounts of and changes in the area of estuarine wetlands along the Pacific coast (Levings and Thom 1994).

Region/Estuary	Existing Area (km^2)	% Lost Since Settlement
Strait of Georgia, British Columbia		
Fraser River	20	50%
Other British Columbia estuaries	7.5	60%
Puget Sound	1,002	70%
Oregon	not documented	unknown
Columbia River estuary	409	unknown
California		
San Francisco Bay	354	95%
% of all wetlands lost		90%

1,117 ha between 1905 and 1974, while Grays Harbor lost 558 ha between 1916 and 1981 (Boulé et al. 1983).

MARSHES

As the rate of sea level rise decreased 8,000–10,000 years ago, salt marsh sediments were able to accumulate along the banks and shoals of shallow-water embayments (Atwater et al. 1979). Similar to the loss described for wetlands overall, tidal marsh losses have been extensive in most estuaries on the West Coast. The greatest losses have been in San Francisco Bay and Puget Sound (Table 4). Prior to the California Gold Rush, over 800 km^2 of salt marsh habitat surrounded San Francisco Bay proper, and an additional 1,400 km^2 of salt marshes were identified in the San Francisco Bay Delta (Gilbert 1917).

In San Francisco Bay, 95% of the tidal estuarine marshes have been modified to the extent that many, while still wetlands, are no longer recognizable as marsh habitat (Atwater et al. 1979; Josselyn 1983). In the Fraser River estuary, at least 50% of the riparian vegetation (bogs, wetland forests, etc.) has been lost, as have 81% of its salt marshes (Levings and Thom 1994).

North of San Francisco Bay, marsh communities that have been altered include brackish tidal marshes largely dominated by the sedge (*Carex lyngbyei*) and salt marshes dominated by pickleweed (*Salicornia virginica*) and tufted hair grass (*Deschampsia caespitosa*). In addition, extensive freshwater swamp forests that once existed at the base of steep watersheds (such as in Tillamook Bay, Oregon) have been lost to diking. Efforts underway to restore tidal marshes have had good success when dikes have been breached (Frenkel and Morlan 1991), but other types of restoration have not always been successful (Zedler et al. 1992).

Important West Coast marsh species in high salinity habitats include *Spartina foliosa* (from Bodega Bay south), *Spartina densiflora, Salicornia virginica, Scirpus* spp., *Distichlis* spp., and *Jaumea* spp. In low salinity habitats *Carex lyngbyei, Scirpus californicus, Juncus balticus, Potentilla pacifica,* and *Typha* spp. are often dominant species (Seliskar and Gallagher 1983; Barnhart et al. 1992).

INVERTEBRATES

Zooplankton

West Coast estuarine zooplankton fauna is usually dominated by relatively few species, and these are usually copepods (Miller 1983). Important species include *Acartia clausi, A. longiremis, Pseudocalanus mimus, Calanus marshallae, Centropages abdominalis, Eurytemora americana,* and *Oithona similis* during summer and *Clausocalanus* spp., *Corycaeus anglicus, Ctenocalanus vanus,* and *Paracalanus parvus* during winter (Frolander et al. 1973; Miller 1983). In the Columbia River estuary and other West Coast river-dominated estuaries, important zooplankton species include the estuarine copepods *Eurytemora affinis* and *Coullana canadensis,* and the freshwater species *Acanthocyclops vernalis,* and the cladoceran *Bosmina longirostris,* and *Daphnia* spp. (Jones et al. 1990). Important West Coast estuarine large epibenthic zooplankton species include at least three species of *Crangon* shrimp and the mysid *Neomysis mercedis* (Orsi and Knutson 1979; Siegfried et al. 1979; Wahle 1985; Jones et al. 1990).

Estuarine zooplankton species maintain high populations in the Columbia River and other estuaries, particularly in the estuary turbidity maximum zone, using different behavioral techniques. The harpacticoid copepod *Coullana canadensis* maintains its estuarine populations by remaining passive in near-bottom circulation, whereas *E. affinis* migrates vertically per tidal cycle (Morgan et al. 1997). These and other copepod species support the food web of many species of pelagic and demersal estuarine fishes (e.g., Pacific herring, *Clupea pallasi*; Pacific sandlance, *Ammodytes hexapterus*; etc.) and large crustaceans (mysids and shrimp).

Benthic Invertebrates

Estuarine benthic communities of the West Coast of North America are structured primarily by physical and chemical factors that reflect the underlying morphology and hydrology of the estuary. Two commonly cited factors are substrate type and salinity. Communities of rocky shores have been described in terms of worldwide zonation patterns (Levings et al. 1983). The communities of soft sediments have been designated on the basis of hydrological features (Simenstad 1983; Nichols and Pamatmat 1988), sediment characteristics or water depth (Nichols 1970; Lie 1974; Levings et al. 1983; Llansó 1999), and the occurrence of vegetation (Levings et al. 1983; Phillips 1984).

A striking characteristic distinguishing soft-bottom benthic communities along the West Coast is the high proportion of introduced species in some estuaries in California as compared to estuaries in the Northwest (Nichols 1979, 1985). The inner portions of San Francisco Bay, for example, are characterized by about 40 species, most of which have been introduced, while the main basin of Puget Sound exhibits a large assemblage (> 120) of native species (Nichols 1985). Introduced species in San Francisco Bay represent the majority of benthic invertebrate organisms and over 95% of the biomass (Nichols 1979). A few of the introductions have radically changed benthic communities. For example, the Asian bivalve *Potamocorbula amurensis* became very abundant in San Francisco Bay shortly after its introduction in the mid 1980s, altering benthic communities by excluding species that previously dominated the upper estuary (Carlton et al. 1990; Nichols et al. 1990).

The occurrence of a large number of non-native species in Californian estuaries is thought to reflect the high frequency of cargo vessels traveling to southern harbors from Asian ports (Carlton et al. 1990). These vessels release ballast water with high densities of larvae at destination ports, providing a mechanism for the introduction of exotic species. Species introductions also are on the rise in Northwest estuaries. A recent survey conducted in Puget Sound reports 11 previously unrecorded non-native species (Cohen et al. 1998). In all, the survey collected and identified 39 non-native invertebrate, algae, and vascular plant species.

Except for Central Bay, the benthos of San Francisco Bay is characterized by low diversity and is dominated numerically by a few species tolerant of large salinity fluctuations (Nichols and Pamatmat 1988). Most common mudflat invertebrates in San Francisco Bay are short-lived species with opportunistic life-history characteristics such as rapid growth and high reproductive potential (Nichols 1985; Nichols and Thompson 1985). Numerically dominant species (found on a 0.5-mm screen) at a polyhaline site in South Bay were the bivalve *Gemma gemma,* the polychaete *Streblospio benedicti,* and the amphipod *Ampelisca abdita* (Nichols and Thompson 1985). The bivalve *Macoma balthica* contributed most of the biomass. High-salinity regions in San Pablo Bay are inhabited predominately by the bivalve *Mya arenaria,* the amphipods *Corophium acherusicum* and *Ampelisca abdita,* and the polychaete *Streblospio benedicti* (Nichols et al. 1990).

High salinity bays in southern California are characterized by diverse benthic communities, with polychaete, mollusc, and arthropod species about equally represented (e.g., Dexter 1983). In Mission Bay, 180 species were collected over a period of eight years, and polychaetes and molluscs were dominant in terms of abundance and biomass (Dexter 1983). Bivalve molluscs are an important component of the benthos in U.S. West Coast estuaries. For example, bivalves (*Tresus capax, Clinocardium nuttallii, Macoma* spp., *Protothaca staminea*) occur in high densities in channels and tidal flats of Coos Bay, and in Netarts Bay, *Saxidomus giganteus* is restricted to the marine portion of the channel, while *C. nuttallii* is restricted to the mid and upper portions of the bay (Simenstad 1983).

The benthos of soft substrates of British Columbia, mainly the Strait of Georgia and associated fjords, has been reviewed by Levings et al. (1983) and Brinkhurst et al. (1994). The region is characterized by deep subtidal habitats (50–300 m), covering 71% of the surface area of the strait. Deep muddy habitats are dominated by burrowing macrofauna such as holothurians (*Molpadia intermedia* and *Chriridota* sp.), bivalves (e.g., *Macoma carlottensis*), and the sea urchin *Brisaster latifrons.* Shallow subtidal habitats (< 20 m) are characterized by burrowing polychaetes (*Abarenicola pacifica, Clymenella torquata*), decapods (*Neotrypea californiensis, Upogebia pugettensis*), bivalves (*Macoma balthica, Mya arenaria*), and the sand-dollar (*Dendraster excentricus*). In shallow subtidal rocky habitats of the Strait of Georgia and the San Juan Islands, the green sea urchin *Strongylocentrotus droebachiensis* can be extremely abundant, reaching average densities of 322 individuals m^{-2} (Levings et al. 1983). In sand flats, a variety of amphipods such as *Corophium salmonis, Euhastorius washingtonianus,* and *Eogammarus confervicolus* are common.

Oxygen depletion occurs commonly in some fjords. In Howe Sound, periods of low dissolved oxygen (< 1.0 mg l^{-1}) lasting on the order of months are followed by renewals of bottom water (Levings 1980). During periods of prolonged oxygen deficiency, the infaunal community behind the inner sill of the fjord experiences large mortalities (Levings 1980). However, catches of the sea urchin *Brisaster latifrons* increased in shallower water, suggesting migration from oxygen depleted areas. Epibenthic communities in deep basin habitats recovered quickly from oxygen deficiency through the invasion of mobile decapod crustaceans (*Munida quadrispina* and *Spirontocaris* sp.). In Saanich Inlet, a deep-water community highly tolerant of low-oxygen conditions was maintained (Tunnicliffe 1981). With few predators present, this epilithic community was dominated by ascidians and demosponges. Elsewhere, coelenterates, brachiopods, glass sponges, and the galatheid crab *Munidia* dominate the epilithic benthos of deep fjords (Levings et al. 1983). Brachiopods are common in all British Columbia fjords, where they are highly tolerant of low oxygen and turbidity stress (Tunnicliffe and Wilson 1988).

The complexity of benthic habitats along the West Coast, in combination with the age of the Pacific Basin, results in a great diversity of benthic invertebrate community types. In Puget Sound, a long-term monitoring program identified over 1,000 species of macrobenthic invertebrates (those found on a 1.0-mm screen) in subtidal sediments alone (Llansó 1999). Benthic communities in the Puget Sound region are mostly associated with sediment type and water depth (Lie 1968, 1974; Lie and Kelly 1970; Llansó 1999) (Table 5). In addition, assemblages are distinguished according to geographical location (Llansó 1999). Benthic as-

TABLE 5. Numerically dominant macrobenthos by sediment type from 0.1 m^{-2} grab samples (5 grabs per station per year) collected 1989–1993 at 76 stations (34 fixed stations sampled every year) throughout Puget Sound, Hood Canal, Strait of Georgia, and bays in the Strait of Juan de Fuca (Llansó 1999). Most stations were located in shallow water (7–33 m), and 11 stations in sand or mud were located in deep water (52–268 m). Sand = 62–100% sand and <13% clay, Mixed = 20–68% sand and up to 23% clay, Caly = <20% sand and 20–55% clay. B = Bivalvia, C = Cumacea, E = Echinodermata, O = Ostracoda, P = Polychaeta.

Sand	Mixed	Clay	Deep Clay
Euphilomedes carcharodonta (O)	*Axinopsida serricata* (B)	*Amphiodia urtica/periercta* (E)	*Macoma carlottensis* (B)
Prionospio jubata (P)	*Aphelochaeta* sp. (P)	*Eudorella pacifica* (C)	*Axinopsida serricata* (B)
Axinopsida serricata (B)	*Eudorella pacifica* (C)	*Sigambra tentaculata* (P)	*Pectinaria californensis* (P)
			Biomass Dominants:
			Molpadia intermedia (E)
			Briasaster latifrons (E)

semblages in the upper and middle reaches of inlets in South Puget Sound and in South Hood Canal appear to respond to low dissolved oxygen through reduced abundance and species numbers. Hood Canal is affected by seasonal episodes of low dissolved oxygen between April and October, and periods of low dissolved oxygen are also known, or hypothesized to occur, in South Puget Sound inlets (Llansó 1999).

Nichols (1985, 1988) compared benthic community dynamics at a 200 m station in Puget Sound with a shallow site in San Francisco Bay. At both sites, the numerical abundance of common species changed markedly with time. However, while the community of San Francisco Bay was characterized by large seasonal and annual fluctuations in abundance in response to natural disturbance, dominance shifts in Puget Sound occurred at irregular, multiyear intervals. An increase in overall macrofaunal abundance over 20 years at the deep Puget Sound site was explained by a hypothesized increase in water productivity resulting from human activities. Species composition in Puget Sound is relatively stable, but large multi-annual fluctuations in abundance are associated with the top dominant species (Lie and Evans 1973; Llansó 1999).

In general, and in contrast to coastal estuaries in Washington and Oregon, the major benthic communities in the Strait of Georgia and in Puget Sound have been described. However, very few investigations of productivity or benthic-pelagic coupling have been conducted (Brinkhurst et al. 1994). Notably, one study has examined the dynamics and energetics of three deposit-feeding benthic populations in Puget Sound (Nichols 1974, 1975). Sediment turnover by the polychaete *Pectinaria californiensis* at a 200-m station was estimated at 8.6 kg dry sediment m^{-2} yr^{-1}, and had important implications for the transfer of materials from the sediment to the water column. Also, *Pectinaria* used and then transferred to predators a significant fraction of the primary production that reached the benthos, despite the height of the water column. Presumably, *Pectinaria* is an important component in the diet of demersal fishes in Puget Sound. Two other species, the sea urchin *Brisaster latifrons* and the holothurian *Molpadia intermedia* contributed significantly to the energetic processes of the seabed.

Notwithstanding the importance of phytoplankton production on carbon cycling in Puget Sound, the detritus originating from vascular plants appears to be critical for many estuarine food webs (Simenstad 1983). Detritus provides food for abundant epibenthic crustaceans, which constitute an important prey resource for many fishes in estuarine shallow habitats of the northwest Pacific coast. The amphipod *Corophium salmonis* and various harpacticoid copepods, for example, are important prey for juvenile salmonids (Sibert et al. 1977; McCabe et al. 1983, 1986), and mysids are prey for shrimp (*Crangon franciscorum*), which are in turn food for starry flounder and harbor seals (*Phoca vitulina*) (Simenstad 1983). Abundant benthic and epibenthic invertebrate prey resources are also probably why estuaries are important nursery areas for Dungeness crab (*Cancer magister*) (Stevens and Armstrong 1984; Armstrong and Gunderson 1985; Emmett and Durkin 1985).

VERTEBRATES

Fishes

Although West Coast estuaries encompass a broad latitudinal range, relatively few fish communities exist. Using Principal Component Analysis on the presence and absence of 167 estuarine fish species, Monaco et al. (1990) identified six U.S. West Coast estuarine fish groups, ranging from a Fjord Group in northern Washington to a southern California Group composed of estuaries south of Alamitos Bay. Horn and Allen (1976) identified similar groups for southern California estuaries and identified a positive relationship between estuary size and the number of fish species.

Although detailed descriptions of fish community assemblages for many West Coast estuaries have been conducted (Fierstine et al. 1973; Allen and Horn 1975; Cailliet et al. 1977; Forsberg et al. 1977; Levy and Levings 1978; Allen 1982; Gordon and Levings 1984; Armor and Herrgesell 1985; Bottom and Jones 1990), most have been of limited duration. The Central Valley Bay-Delta Branch of the California Department of Fish and Game has one of the longest time series of estuarine fish resources on the West Coast, and has developed indices of fish, shrimp, and crab abundance in San Francisco Bay (http://www2.delta.dfg.ca.gov/baydelta/monitoring/baystudy.html). From these and other studies, it is clear that West Coast estuarine fish species assemblages are structured primarily by salinity and temperature tolerances, and the location of the turbidity maximum (Meng et al. 1994; Saiki 1997). Extensive fish food-web studies have been conducted only in a few estuaries. However, they indicate that West Coast estuaries have abundant invertebrate prey resources, particularly during spring and summer, which allows high diet overlaps but may not indicate competition (McCabe et al. 1983; Barry et al. 1996).

Important West Coast fish species include Pacific herring (*Clupea pallasi*), a valuable commercial and forage fish for many piscivorous birds, mammals, and fishes from British Columbia to San Francisco Bay. Adult female herring are harvested for roe, while juvenile catches supply the bait market, and eggs are also harvested as spawned-on-kelp. Adult harvest was low during 1997–1998 in San Francisco Bay at 1,800 MT (metric tons) (Watters personal communication). In Puget Sound there are 18 Pacific herring stocks, and these populations have been relatively stable, with recent harvests (primarily for bait) of 500 MT (Puget Sound Water Quality Action Team 1998). However, very recent declines in some stocks have precipitated inquires if they may need protection under the U.S. Endangered Species Act. British Columbia has six subpopulations, but their abundance, and thus harvest, has been much reduced in recent years. Only 32,000 MT of Pacific herring were harvested in British Columbia in 1997 (adults for roe) (Department of Fisheries and Oceans 1998).

In northern West Coast estuaries, other valuable fishes include surf smelt (*Hypomesus pretiosus*), with an annual commercial harvest of approximately 450,000 kg in Puget Sound, eulachon (*Thaleichthys pacificus*); longfin smelt (*Spirinchus thaleichthys*); and two species of sturgeon (*Acipenser transmontanus* and *A. medirostris*). While *A. transmontanus* populations are relatively healthy in the Columbia River estuary, abundance of both species appears to be declining in many other estuaries. Introduced to the West Coast in 1871, American shad (*Alosa sapidissima*) has some of its largest runs in North America, principally in the Columbia River, with annual run sizes > 2 million (Washington Department of Fish Wildlife and Oregon Department of Fish Wildlife 1996). However, American shad does not support a large commercial fishery on the West Coast because shad gillnets often have large incidental catches of salmon. There once was a large shad commercial fishery in San Francisco Bay, but the construction of Shasta Dam and water diversions contributed to the decline in this fishery (Herbold and Moyle 1989).

In southern California, dominant estuarine fishes include slough and deepbody anchovy (*Anchoa delicatissima* and *A. compressa*), topsmelt (*Atherinops affinis*), jacksmelt (*Atherinopsis californiensis*), white croaker (*Genyonemus lineatus*), arrow goby (*Clevelandia ios*), and diamond turbot (*Hypsopsetta guttulata*) (Horn and Allen 1976; Monaco et al. 1990).

Unlike fishes of the East Coast, where many species reside in estuaries during most of their life history, many West Coast fishes, especially anadromous species, use estuaries only during a short period of their life cycle. Nevertheless, populations of West Coast fish species whose entire life history is estuarine dependent, such as the delta smelt (*Hypomesus transpacificus*) and longfin smelt (*Spirinchus thaleichthys*), have declined precipitously in recent years and are either listed or proposed for listing under the Endangered Species Act of 1973 (ESA).

Salmonids

Estuaries play an important role in the life histories of many salmonid stocks. Each salmonid species uses estuarine environments differently depending on species, run, age, and watershed (Simenstad et al. 1982). While salmonids inhabit riverine, estuarine, and ocean environments during their life-cycle, estuaries provide a critical habitat where all anadromous fishes make the physiological transition between fresh and salt water, and some may rear extensively (Levings 1994; Simenstad 1997). Nevertheless, the relative importance of estuaries to salmonid recruitment variation is presently undetermined (Bradford 1997), but is likely to be highest for ocean-type chinook salmon (*Oncorhynchus tshawyscha*) (Levings and Bouillon 1997).

Nehlsen et al. (1991) identified 101 West Coast salmonid stocks at high risk of extinction, 58 at moderate risk, 54 of special concern and one as threatened under the ESA. There are presently 26 West Coast salmonid stocks (or Evolutionary Significant Units, ESUs) either threatened or endangered under ESA, but an additional 7 ESUs are either candidates or proposed for listing (Table 6).

TABLE 6. List of West Coast salmon species Evolutionary Significant Units (ESUs) that are either listed or candidates for listed under the U.S. Endangered Species Act (information from National Oceanic and Atmospheric Administration, National Marine Fisheries Service, http://www.nwr.noaa.gov/lsalmon/salmesa/index.htm).

Species	ESU	Status
Pink salmon (*Oncorhynchus gorbuscha*)	None	Non Presently Listed
Coho salmon (*O. kisutch*)	Central California	Threatened
	Southern Oregon; Northern California Coasts	Threatened
	Oregon Coast	Threatened
	Puget Sound/Strait of Georgia	Candidate
	Southwest Washington; Lower Columbia River	Candidate
Chinook salmon (*O. tshawytscha*)	Sacramento River Winter-run	Endangered
	Upper Columbia River Spring-run	Endangered
	Snake River Fall-run	Threatened
	Snake River Spring/Summer	Threatened
	Central Valley Spring-run	Threatened
	California Coastal	Threatened
	Puget Sound	Threatened
	Lower Columbia River	Threatened
	Upper Willamette River	Threatened
	Central Valley Fall Late Fall-run	Candidate
Chum salmon (*O. keta*)	Hood Canal Summer-run	Threatened
	Columbia River	Threatened
Sockeye salmon (*O. nerka*)	Snake River	Endangered
	Ozette Lake	Threatened
Steelhead (*O. mykiss*)	Southern California	Endangered
	South-central California coast	Threatened
	Central California coast	Threatened
	Upper Columbia River	Endangered
	Snake River Basin	Threatened
	Lower Columbia River	Threatened
	CA Central valley	Threatened
	Upper Willamette River	Threatened
	Mid-Columbia River	Threatened
	Northern California	Threatened
	Klamath Mountains Province	Candidate
	Oregon Coast	Candidate
Sea-run cutthroat (*O. clarkii*)	Southwest Washington; Columbia River	Proposed-Threatened
	Oregon Coast	Candidate

Many of the endangered stocks appear in California, southern Oregon, and in the Columbia River basin. As a result of these listings and continued low abundance, both sport and commercial catches for salmonids have been dramatically reduced. What little harvest is continuing is being supported primarily by hatchery production.

The reduction in Northwest salmonid run sizes appears to be at least partly related to poor marine (estuary + ocean) survival. While El Niño can cause strong annual fluctuations in salmonid stock sizes, the north Pacific Ocean evidently undergoes regime shifts whereby oceanographic conditions (currents, upwelling patterns, etc.) fluctuate at different levels (Mantua et al. 1997; Francis et al. 1998), which causes long-term changes to salmonid marine survival and thus recruitment patterns. The particular physical and biological mechanisms which influence marine survival are presently unknown. A recent decadal oceanographic shift occurred in 1977. Since that time, salmonid ocean survival and thus run sizes have been high in Alaska, while many runs have declined in the Northwest and California (Hare et al. 1999).

Mammals

Most marine mammal populations along the West Coast are healthy and growing, especially since the Marine Mammal Protection Act of 1972. Harbor seals and California sea lions (*Zalophus californianus*) frequently use estuaries for feeding, breeding, and resting. Present harbor seal populations are estimated to be approximately 35,000 in Washington, 10,000 in Oregon, and 33,000 in California (National Marine Fisheries Service 1997). The U.S. West Coast population of California sea lions was estimated to be between 161,066 and 181,355 in 1994 (Barlow et al. 1995). Because of their increasing abundance while salmonid runs are declining, some people believe that pinniped predation is responsible for salmonid declines, especially in specific locations (National Marine Fisheries Service 1997).

Studies have shown that while pinnipeds do feed on salmonids (usually within estuaries and rivers), they are not their usual primary prey. In some specific locations, a few individuals (usually California sea lions) will specialize on salmonid feeding (National Marine Fisheries Service 1997). For example, at Ballard Locks in Seattle, Washington, four sea lions became accustomed to feeding exclusively on salmonids, and in the Courtney River estuary, British Columbia, 35 harbor seals preferentially fed on salmonids (Olesiuk personal communication).

Other marine mammals that use West Coast estuaries are the harbor porpoise (*Phocoena phocoena*), occasionally the California gray whale (*Eschrichtius robustus*), and killer whale (*Orcinus orca*). The killer whale population in Puget Sound/ Straits of Georgia is composed of permanent residents (Hoelzel 1993), but most other estuaries receive only transients.

Wetland oriented mammals such as river otter (*Lutra canadensis*), nutria (*Myocastor coypus*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethica*), and mink (*Mustela vison*) have not been inventoried on most West Coast estuarine systems. However, mink and river otter populations in the Columbia River estuary are probably reduced because of past contaminant effects (PCBs and dioxins) on reproduction (Henny et al. 1996).

Birds

Besides supporting resident species, many West Coast estuaries and their associated wetlands are important habitats for migrating waterfowl and other birds using the Pacific flyway (Josselyn 1983). One estuary-dependent migratory species is the black brant (*Branta bernicla nigricans*), a small marine goose that feeds almost exclusively on eelgrass. The brant uses many West Coast estuaries while migrating between its summer residence in the Arctic and its wintering habitats in Mexico, with Humboldt Bay particularly important (Barnhart et al. 1992). The Fraser River estuary and parts of Puget Sound also provide important habitat for many species of waterfowl and are wintering grounds for Russian and Alaskan lesser snow geese (*Chen caerulescens hyperborea*) (Leach 1982). Many shorebirds, such as the dunlin (*Calidris alpina*) rely on invertebrates found on estuarine sand and mudflats during their annual migrations (Sewell 1997).

Since the Migratory Bird Treaty Act of 1918 and other habitat protections, some avain species populations have increased dramatically, sometimes resulting in controversy. For example, the largest Caspian tern (*Sterna caspia*) colony in the world (over 16,000 birds) is presently located on a manmade island created from dredged material in the Columbia River estuary. Unfortunately this colony

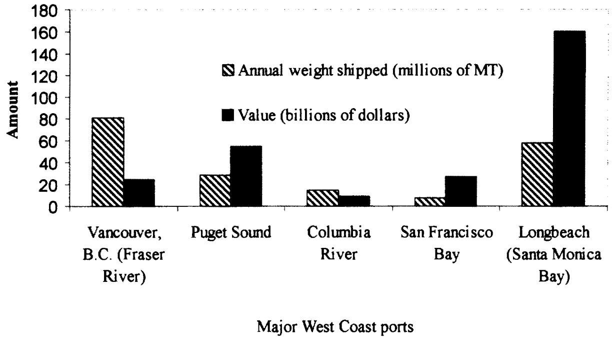

Fig. 8. Amount (weight) and value of goods moved from five major West Coast ports in 1997 (unpublished data from Washington Sea Grant, Seattle, Washington).

is estimated to eat 6–25 million salmonid smolts annually (Roby et al. 1998). Since the region is annually spending millions for salmonid recovery, the Army Corps of Engineers is initiating attempts to encourage the terns to nest elsewhere (U.S. Army Corps of Engineers Public Notice CENWP-EC-E-98-08, Portland, Oregon).

While populations of a few estuarine avian species appear to be growing or are relatively stable (cormorants, gulls, and Caspian terns) (Carter et al. 1995; Roby et al. 1998), many small avian populations are declining because they are dependent on a limited number of marshes or other estuarine habitats. In California, these include the salt marsh yellowthroat (*Geothlypis trichas sinuosa*) and California clapper rail (*Rallus longirostris obsoletus*), which are now threatened or endangered. While bald eagle (*Haliaeetus leucocephalus*) populations are increasing in Oregon and Washington and most of the West Coast, nesting success in the Columbia River estuary population remains low (< 50%). This low nesting success is not a result of contamination effects on egg shell thickness, but it is related to egg accumulation of DDE, PCBs, and poor habitat (Columbia Basin Fish and Wildlife Authority 1996; Tetra Tech 1996).

Economic Characteristics

Shipping and Commerce

West Coast estuaries play a vital part in the regional economy. Presently over 190 million tons of goods, worth 275 billion dollars, pass though West Coast ports annually (Fig. 8), much of which ships to or from Asia. To support this commerce, dredging of shipping channels and port facilities is often necessary. Dredging operations are particularly extensive in the Columbia River and Fraser River (Fig. 9). However, dredging has negative environmental effects, such as resuspension of contaminants, increases in turbidity, depletion of oxygen levels (LaSalle 1988), entrainment of aquatic spe-

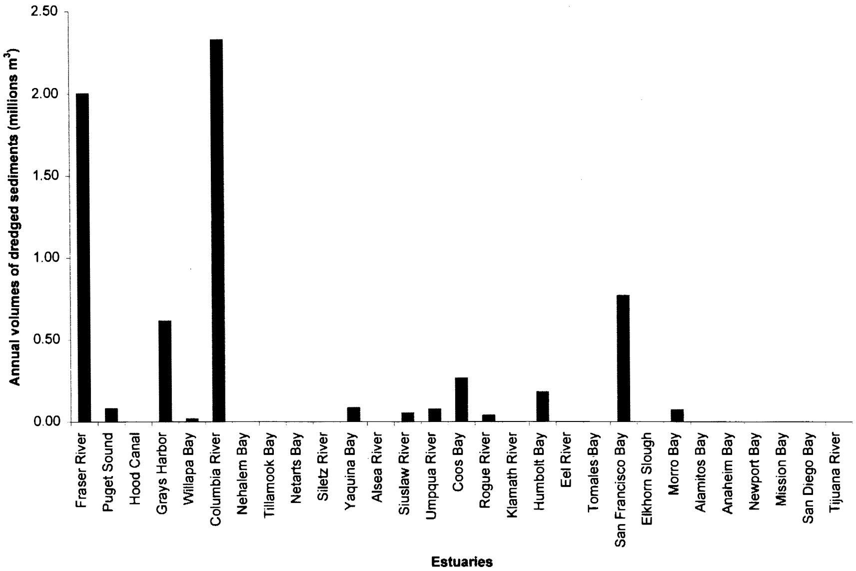

Fig. 9. Annual amounts of estuarine dredged material moved to maintain navigation channels in West Coast estuaries (excludes Alaska) (data primarily from U.S. Corps of Engineers, Portland, Oregon and Port of Vancouver, Vancouver, British Columbia, Canada).

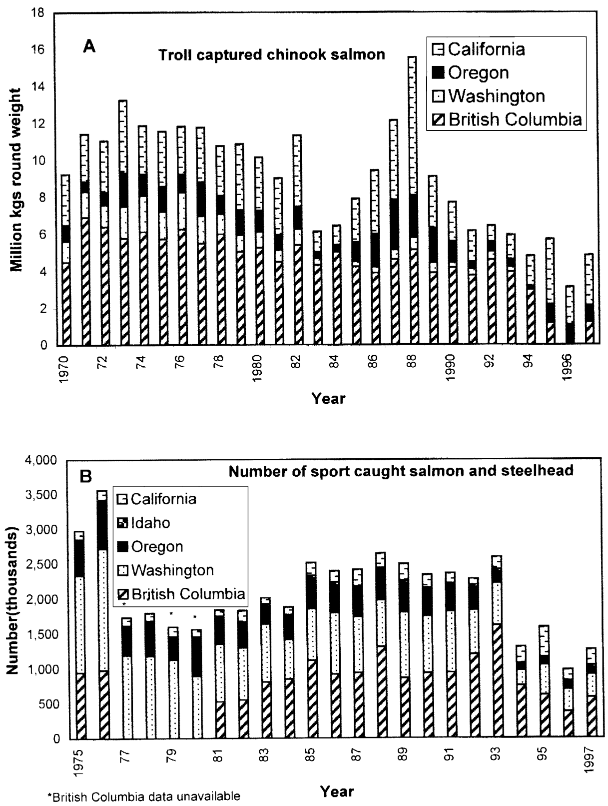

Fig. 10. Annual weight of commercial troll caught chinook salmon (*Oncorhynchus tshawytscha*) and numbers of recreationally caught salmon and steelhead (*Oncorhynchus mykiss*) (Pacific States Marine Fisheries Commission 1998).

cies (Larson and Moehl 1988; McGraw and Armstrong 1988), and burial of subtidal habitats, wetlands, and adjacent uplands.

Fishery Products

Subsistence, commercial, and recreational fishing for salmon has been a major activity of West Coast inhabitants. In the northwest, salmon fishing represents an important aspect of Native American culture and society's tie with and dependence upon nature. Nevertheless, because of a host of environmental factors (dams, pollution, lost and degraded habitat, ocean conditions, etc.) many salmon populations are presently at low levels, and this has reduced or eliminated most salmon fisheries. Although hatchery releases have helped maintain some harvests, recent commercial troll harvests for chinook salmon (*Oncorhynchus tshawytscha*) have declined in British Columbia from about 7 million kg in 1972 to 0 in 1997 and recreational salmon and steelhead catches have also plummeted (Fig. 10) (Pacific States Marine Fisheries Commission 1998). The once important commercial and recreational coho salmon (*Oncorhynchus kisutch*) fishery is now essentially closed from California to Washington.

Since appropriate estuarine habitats are available, both Washington and British Columbia estuaries have commercial salmonid pen-rearing facilities. In British Columbia's protected coastal waters, there were 16 companies with 79 grow-out sites (net-pen facilities) in 1995, producing 23.8 thousand MT of salmon product (British Columbia

TABLE 7. Amount and value of Pacific oyster (*Crassostrea gigas*) harvests from West Coast estuaries. Unless noted all data are from 1997 (data obtained from state and province agencies).

Estuary	Weight shucked meat (kg)	Value (US$)
British Columbia[1]	528,898	4,929,000
Puget Sound	539,600	2,397,866
Hood Canal	220,257	978,775
Grays Harbor	322,169	1,431,649
Willapa Bay	880,736	3,913,798
Tillamook Bay	38,301	337,767
Netarts Bay	11,038	97,318
Yaquina Bay	64,980	573,020
Umpqua River	21,754	191,837
Coos Bay	15,185	133,910
Humbolt Bay[1]	177,811	1,344,900
Tomales Bay[1]	325,736	2,528,600
Morro Bay[1]	8,664	114,600
Total	3,155,129	18,973,041

[1] Data are from 1996.

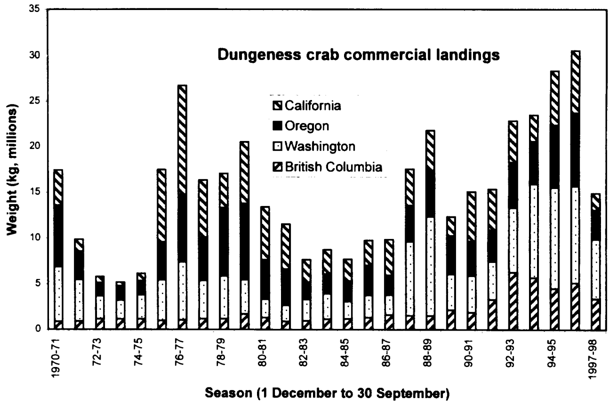

Fig. 11. West Coast commercial season landings of Dungeness crab (*Cancer magister*) from 1970–1971 to 1997–1998 (Pacific States Marine Fisheries Commission 1998).

Environmental Assessment Office 1998). In Puget Sound there are 2 companies with 8 net pen facilities producing 5,784 MT of salmon annually (Sturges personal communication).

Salmon aquaculture creates some environmental risks from organic enrichment, disease introductions, reduced water quality, lower benthic invertebrate numbers, possible genetic effects to wild salmon populations, and development of harmful bacteria resulting from the use of antibiotics (Weston 1986). Generally these effects are very localized, depending on local physical processes (flushing rates, depth, etc.) (Weston 1986; British Columbia Environmental Assessment Office 1998). However, the effects of possible accumulation of antibiotics liberated from these facilities on the local biota are poorly understood (British Columbia Environmental Assessment Office 1998).

Some West Coast estuaries produce large quantities of oysters and clams. These are harvested commercially, recreationally, and for subsistence, particularly in Washington and British Columbia, where much suitable clam habitat exists (Schink et al. 1983). Because native oysters (*Ostrea conchaphila*) were overharvested during the later part of the 19th century, they have been replaced by aquaculture production of Pacific oysters (*Crassostrea gigas*). California's primary clam and shellfish producing estuaries are Tomales and Humboldt Bays. Willapa Bay, Washington, is presently the largest single West Coast producer of Pacific oysters, but British Columbia produces more in terms of commercial value (Table 7). Because of oceanographic/hydraulic conditions (cool summer ocean temperatures), Pacific oysters rarely produce adequate natural spawn and set; thus commercial oyster spat hatcheries are necessary to maintain commercially viable populations.

Besides oysters, other commercially important West coast estuarine bivalves include Olympic oyster (*Ostrea conchaphila lurida*), softshell clam, (*Mya arenaria*), cockle (*Clinocardium nuttalli*), Manila clam (*Venerupis philipinarium*), native littleneck clam (*Protothaca staminea*), butter clam (*Saxidomus giganteus*), the horse clams (*Tresus nuttalli* and *T. capax*), geoduck (*Panope generosa*), blue mussel (*Mytilus trossulus*), spiny scallop (*Chlamys hastta*), and pink scallop (*C. rubida*) (Cheney and Mumford 1986; Bourne and Chew 1994). The softshell and Manila clam are introduced species. Washington's commercial geoduck fishery, which requires harvesting by SCUBA, is second only to oysters in value.

Dungeness crab constitutes one of the most important commercial fisheries on the West Coast. Although the commercial fishery captures Dungeness crab adults primarily in the nearshore coastal zone during winter, they are also captured in estuaries. Younger life stages of Dungeness crab use estuaries extensively. Commercial landings indicate that populations are cyclic, but the cause of this cycle is still unknown (Hankin 1985; Botsford et al. 1989). Recent landings (winter of 1995–1996) were the highest ever (over 30 million kg) (Fig. 11).

Regional Concerns

Human Population Increases

While it is not the purpose of this paper to highlight all the regional concerns, a few major problems are obvious. First and foremost has been the rapid rise in the human population within many West Coast estuarine watersheds. The larger population increases the demand for buildable land, roads, water, and pollution loads. Over half of Brit-

TABLE 8. Changes in human population by estuarine drainage area. Estuaries are listed by decreasing change in population densities. Data primarily from national Oceanic and Atmospheric Administration 1990 (http://spo.nos.noaa.gov/projects/cads/ftp_data_download.html).

Estuary	1980 Density (No. km^{-2})	1990 Density (No. km^{-2})	Percent Change
Morro Bay, California	43.4	122.7	183
Hood Canal, Washington	7.4	15.2	105
Tijuana River, California	102.0	157.8	55
Netarts Bay, Oregon	21.5	33.2	55
Newport Bay, California	968.0	1,366.0	41
Yaquina Bay, Oregon	10.5	14.5	37
Elkhorn Slough, California	184.4	245.3	33
Alsea Bay, Oregon	3.9	5.1	30
San Diego Bay, California	634.8	814.5	28
Puget Sound, Washington	134.4	169.1	26
San Francisco Bay, California	319.1	384.0	20
Umpqua River, Oregon	4.3	5.1	18
Coos Bay, Oregon	23.0	27.0	17
Rogue River, Oregon	4.7	5.5	17
Humboldt Bay, California	108.2	125.4	16
Tillamook Bay, Oregon	7.4	8.6	16
Eel River, California	5.1	5.9	15
Anaheim Bay, California	2,389.8	2,754.7	15
Nehalem River, Oregon	2.7	3.1	14
Mission Bay, California	1,218.8	1,368.0	12
Grays Harbor, Washington	16.4	18.0	10
Columbia River, Oregon	72.7	78.9	9
Alamitos Bay, California	2,382.8	2,481.3	4
Tomales Bay, California	12.9	13.3	3
Willapa Bay, Washington	5.5	5.5	0
Siuslaw River, Oregon	4.7	4.7	0
Klamath River, California	1.2	1.2	0
Siletz Bay, Oregon	7.4	3.9	−47

ish Columbia's population lives in the lower Fraser River valley and its estuary. A large percentage of Washington's and California's human population lives within estuarine drainage systems, but most of Oregon's population lives in the Portland metropolitan area (about 160 km away from the coast). While Portland, Oregon lies within the Columbia River estuary and its watershed, its distance from the estuarine mouth reduces its overall direct effects. Nevertheless, agricultural, urban, and industrial development in the Portland, Oregon, metropolitan area directly affects Columbia River water quality. Most other Oregon estuarine drainage areas have low population densities and some watersheds have had recent population declines (Table 8). These population declines (e.g., Siletz River) may be attributed to the decline in logging and fishing industries. On the other hand, estuarine drainage areas in California and Puget Sound have some of the highest population densities in the country and have shown some of the greatest population increases (Table 8). The challenge for estuarine resource managers is to continue to protect and enhance estuarine health and resources while increased urbanization continues to place demands on those resources.

Toxic Algae Blooms

Recent toxic algae blooms in Oregon and Washington by phytoplankton responsible for amnesic shellfish poisoning (*Pseudonitzschia australis*) and paralytic shellfish poisoning (*Alexandrium tamarense*) have closed oyster and clam beds to harvest, along with the nearshore Dungeness crab fishery. In California, *Gonyaulax polyhedra* and/or *Gymnodinium* spp. have been seasonally reported from eight estuaries (National Oceanic and Atmospheric Administration 1998). Other problem algae include *Gymnodinium sanguineum*, *Ceratium fusus*, and *Heterosigma* spp. Causes of the increased frequency of harmful algae blooms on the West Coast are uncertain (possibly increased nutrients and reduced flushing), but these blooms are affecting both harvestable and non-harvestable resources and pose human and estuarine animal health risks.

Fisheries

Dams and river diversions have negatively affected salmonid populations and altered West Coast estuarine systems (Simenstad et al. 1992). For example, the Columbia River basin alone has over 22 major and 353 minor dams. While modification of freshwater inflow into the Columbia River estuary has not had any obvious effects on salmonid resources (Weitkamp 1994), the withdrawal of freshwater flowing into San Francisco Bay has been one the major factors leading to the decline of many of its living marine resources. Jassby et al. (1995) found a significant relationship between the location of the 2‰ bottom salinities in the San Francisco Bay (i.e., Sacramento/San Joaquin Delta) with annual measures of many biological estuarine resources. Presently, a major source of freshwater and nutrient input into San Francisco Bay comes from sewage treatment plants (Conomos 1979; Nichols et al. 1986). The loss of estuarine and watershed habitat, changes in freshwater inflow, pollution, changes in ocean productivity, and introduced species, have all contributed to declines in West Coast estuarine fish and shellfish populations.

Introduced Species

Introduced species pose a severe threat to West Coast estuarine ecosystems. San Francisco Bay, for example, is the most invaded aquatic ecosystem in North America (Cohen and Carlton 1998). It has 212 introduced species composed of 69% invertebrates, 15% fish and other vertebrates, 12% vascular plants, and 4% protists. Since 1850, San Francisco Bay has received one new species every 36 weeks (Cohen and Carlton 1995, 1998). The intro-

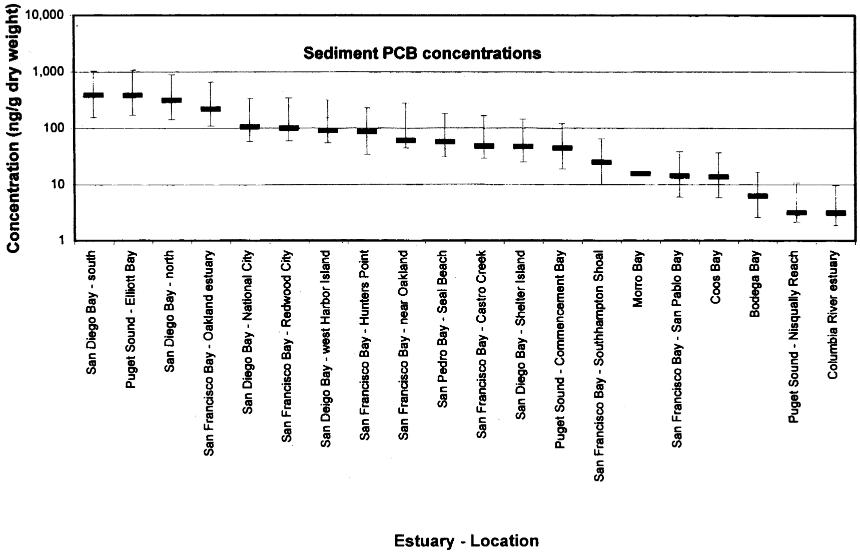

Fig. 12. Sediment concentrations of PCBs (geometric mean and ± SD) at selected West Coast estuaries (from Brown et al. 1998).

duced clam *Potamocorbula amurensis* was probably the cause of recent declines of zooplankton in San Francisco Bay (Kimmerer et al. 1994). Recent introductions into the Columbia River estuary include the Asian copepod *Pseudodiaptomus inopinus* (Cordell et al. 1992) and the Asian freshwater shrimp *Exopalamaeon modestus* (Emmett unpublished data). Of particular concern in the northwest is the recent spread of the green crab, *Carcinus maenas,* into Willapa Bay and Grays Harbor, Washington. Green crab is a voracious feeder which threatens native shellfish, oysters, and other crab populations. Other introduced species of concern include purple loosetrife (*Lythrum salicaria*), Japanese eelgrass (*Zostera japonica*), and the varnish clam (*Nuttallia obscurata*).

In Willapa Bay, Washington the spread of the eastern cordgrass (*Spartina alterniflora*) threatens to eliminate productive mudflats (Patten 1997). Over the past 15–20 years *Spartina* has rapidly expanded in Willapa Bay and it now covers mud flat areas formerly used by fishes and shorebirds for feeding, and oyster production areas. As a result, Washington State has initiated an aggressive eradication program using mowing and herbicide application. The full ecological impacts of the *Spartina* invasion and its control treatments are just beginning to be understood (Simenstad and Thom 1995).

Pollution

Contaminant inputs into West Coast bays and estuaries began as early as the late 1800s, as human settlement began to increase. In San Francisco Bay, the earliest anthropogenic influence of contamination occurred between 1850–1880, when enriched mercury sediments were deposited from debris associated with hydraulic gold-mining activities in the watershed (Hornberger et al. 1999). Localized pollution sources from military bases; ports, harbors, and industrial facilities; and urban development dramatically increased the amount of both organic and inorganic contaminants discharged into the San Francisco Bay between 1910–1950s (van Geen and Luoma 1999). Because San Francisco Bay drains up to 40% of California's surface area, agricultural practices in the Central Valley have a significant effect on water quality in the Bay, since herbicides, pesticides, and other soil amendments are widely used (Nichols et al. 1986). Since the 1970s, extensive advanced waste treatment efforts have reduced point source pollution in most West Coast watersheds. In San Francisco Bay, for example, the sum of all metal loadings was estimated to be 993 T yr^{-1} in 1960, but by 1986 it was 171 T yr^{-1} (Monroe and Kelly 1992).

Data from the U.S. National Benthic Surveillance Project reveal that contaminant concentrations in estuarine fishes and sediments at the most-polluted West Coast sites are highest in urban areas and are comparable to those found on the Atlantic coast (National Oceanic and Atmospheric Administration 1998). Estuaries and marine bays with elevated contaminants include San Francisco Bay, Santa Monica Bay, San Pedro Bay, San Diego Bay, and Elliott Bay (Puget Sound) (Brown et al. 1998). For example, PCBs were found to be highest in San Diego Bay and much lower in nondeveloped

TABLE 9. San Francisco Bay pollutant loadings from major sources (MT yr^{-1}) (Monroe and Kelly 1992). na = not available.

Pollutant	Municipal and Industrial Effluent	San Joaquin River	Urban Runoff	Total Nonurban Runoff	Concentrations Exceeding Median International Standards in Biota
Arsenic	1.5–5.5	12	1.9–9.0	10–120	Yes
Cadmium	1.8–4.0	na	0.3–3.0	0.52–6.0	Yes
Chromium	12–13	66	3.0–15	130–1,500	Yes
Copper	19–30	80	7.0–59	51–580	Yes
Lead	11–16	51–55	30–250	31–360	Yes
Mercury	0.2–0.7	na	0.026–0.15	0.15–1.7	Yes
Nickel	19–27	51	na	na	Yes
Selenium	2.1	4.2	na	na	Yes
Silver	2.7–7.2	na	na	na	No
Zinc	77–80	164–175	34–268	130–1,450	No
PCBs	na	na	0.006–0.400	na	Yes
PAHs	na	na	0.50–5.0	na	No
Total Hydrocarbons	na	na	1,000–1,100	na	

estuaries such as the Columbia River estuary (Fig. 12). While there do not appear to be temporal trends in PCB and DDT concentration levels, which are relatively stable, PAH contaminants show increasing levels in both urban and nonurban sites. Since most PAHs are non-point source contaminants, additional control remedies for these sources may be needed (Brown et al. 1998).

While treatment of point sources of pollution has reduced inputs into many West Coast estuaries, existing metal and other contaminant loads in estuarine biota, and thus food webs, continue to cause problems. For example, in San Francisco Bay concentrations of many metals and PCBs levels in estuarine biota exceed median international standards (Table 9) (Monroe and Kelly 1992). In the Columbia River estuary, contaminant levels may be impairing the health (affecting growth or reproduction) of bald eagles, river otter, and probably mink (Henny et al. 1996), but the synergistic affect of habitat loss and degradation can not be discounted (Columbia Basin Fish and Wildlife Authority 1996). While research has been conducted on the pathology of pollution effects on estuarine fish (Varanasi et al. 1986; McCain et al. 1988), the overall effects of pollution on fish and invertebrate recruitment and population abundance is unclear. However, for salmonids in particular, estuarine pollution can cause sublethal effects such as suppressed immune responses, reduced growth, and behavior changes which may influence marine survival (Casillas et al. 1997).

Current contaminant inputs into many West Coast estuaries and embayments are dependent upon ongoing and past land use activities within each watershed. Elkhorn Slough for example, is currently surrounded by agricultural fields primarily growing strawberry plants, but past uses included dairy farms. Present estuarine contaminants associated with agricultural use include high levels of insecticides (DDT, dieldrin, toxaphene, aldrin chlordane, and chlopyrifos) and herbicides (dacthal) (ABA Consultants 1989).

Besides chemical contaminants, high levels of coliform bacteria affect water quality in many West Coast estuaries, posing a human health risk and either temporarily or permanently closing productive clam and oyster beds. High coliform levels, attributed to non-point agricultural processes and other sources, occur regularly in Elkhorn Slough (ABA Consultants 1989), Tillamook Bay (Tillamook Bay National Estuary Project 1998), and localized areas in Puget Sound, Grays Harbor, and Willapa Bay (Newton et al. 1997).

Because of wide tidal fluctuations and freshwater inflows, most West Coast estuaries do not have low dissolved oxygen (DO) concentrations (hypoxia) or anoxic conditions resulting from organic pollution or high nutrient loadings. Anoxic conditions occur primarily in southern California estuaries and are related to water column stratification (National Oceanic and Atmospheric Administration 1998). Low DO events also occur behind sills in fjords (Levings 1980). Recent studies in Puget Sound reveal that at least six areas have regular hypoxic DO levels (Newton et al. 1997). However, trends in minimum DO levels are unknown for 24 out of 38 West Coast estuaries because neither regular monitoring nor research studies have been done (National Oceanic and Atmospheric Administration 1998).

While probably no West Coast estuary has been altered and modified as much as San Francisco Bay, nearly all show some evidence of anthropogenic perturbation. Tomales Bay, for example, a non-industrialized or urbanized estuary 45 km north of San Francisco, has a small, inactive mercury mine in its watershed which has contributed a small amount of mercury into the Bay (Hornberger et al. 1999). Willapa Bay, a non-urbanized, non-industrialized estuary in southwest Washington receives contaminants from waters originating in the Columbia River. During winter, the Columbia River plume flows north and along the coast, and some of this water is entrained in Willapa Bay during tidal exchange. Nevertheless a broad synoptic survey of estuarine pollution levels in all West Coast estuaries, including non-urbanized estuaries, has not been done.

Summary

West Coast estuaries range from 32.5°N to 54.4°N latitude, encompassing a wide range of environmental conditions. While most West Coast estuaries are relatively small, they provide valuable biological and economic resources. A few West Coast estuaries have large watersheds and drain much of the West Coast's interior. In southern California, estuaries are particularly small, have little freshwater inflow, and have been dramatically altered. Because they are now so limited, these estuaries and their associated wetlands are of extreme ecological value to the species that inhabit them, and many contain species that are threatened or endangered. While northern West Coast estuaries are morphologically larger, have higher freshwater inflows, and are more diverse (fjord and drowned-river valley), they also have lost many habitats due to diking and development because of the shortage of flat land for human habitation.

The biological resources of most West Coast estuaries are under stress. Many fish stocks (salmonids in particular) are at low numbers and listed as threatened or endangered, exotic species are altering estuarine habitats, harmful algae blooms are more frequent and affecting shellfish harvesting, and pollution (particularly non-point sources) continues to affect water quality. Nevertheless, it is impossible to undertake a comprehensive evaluation of the overall health of West Coast estuaries because measurements of pollution and habitat quality are severely lacking for many estuaries.

Some native fish and invertebrate species have declined to an extent that they are now listed as either threatened or endangered. However, marine mammal populations and a few species of marine birds have responded to protection and are reaching historic population levels. Except in a few cases, information on the population abundance of many estuarine wetland dependent mammals and birds has not been collected.

Compared to other regions, such as East Coast and Gulf of Mexico, we still have much to learn regarding the physical and biological functions and mechanisms of West Coast estuaries. This appears to be particularly true for estuarine food webs (Thom 1987). For example, we still cannot quantify the value of estuaries to salmonid life histories (Bradford 1997), but there is strong evidence these habitats provide important components of salmonid life cycles (Levings et al. 1989; Levings and Bouillon 1997). The threats to estuarine habitats on the West Coast continue to be primarily from upstream land use activities (logging, road building, and urban and industrial development), freshwater withdrawals and degradation, dams, dredging, exotic species invasions, and potentially from aquaculture. Nevertheless, estuarine restoration actions are showing encouraging results, with dike and jetty breaching and marsh and wetland creation being a major tool for restoring estuarine habitats (Josselyn et al. 1990). Although water quality (i.e., turbidity and low DO) may threaten submerged plants such as eelgrass, little is known about this impact.

West Coast estuaries and their watersheds are expected to have continued increases in human populations and thus demands on estuarine resources. The problem for estuarine resource managers is to allow utilization of estuarine habitats for economic resources (transportation, aquaculture, water use, resource harvesting, etc.) while enhancing, rebuilding, and protecting the natural estuarine resources (birds, marshes, fishes, water quality, etc.) that humans value and enjoy.

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