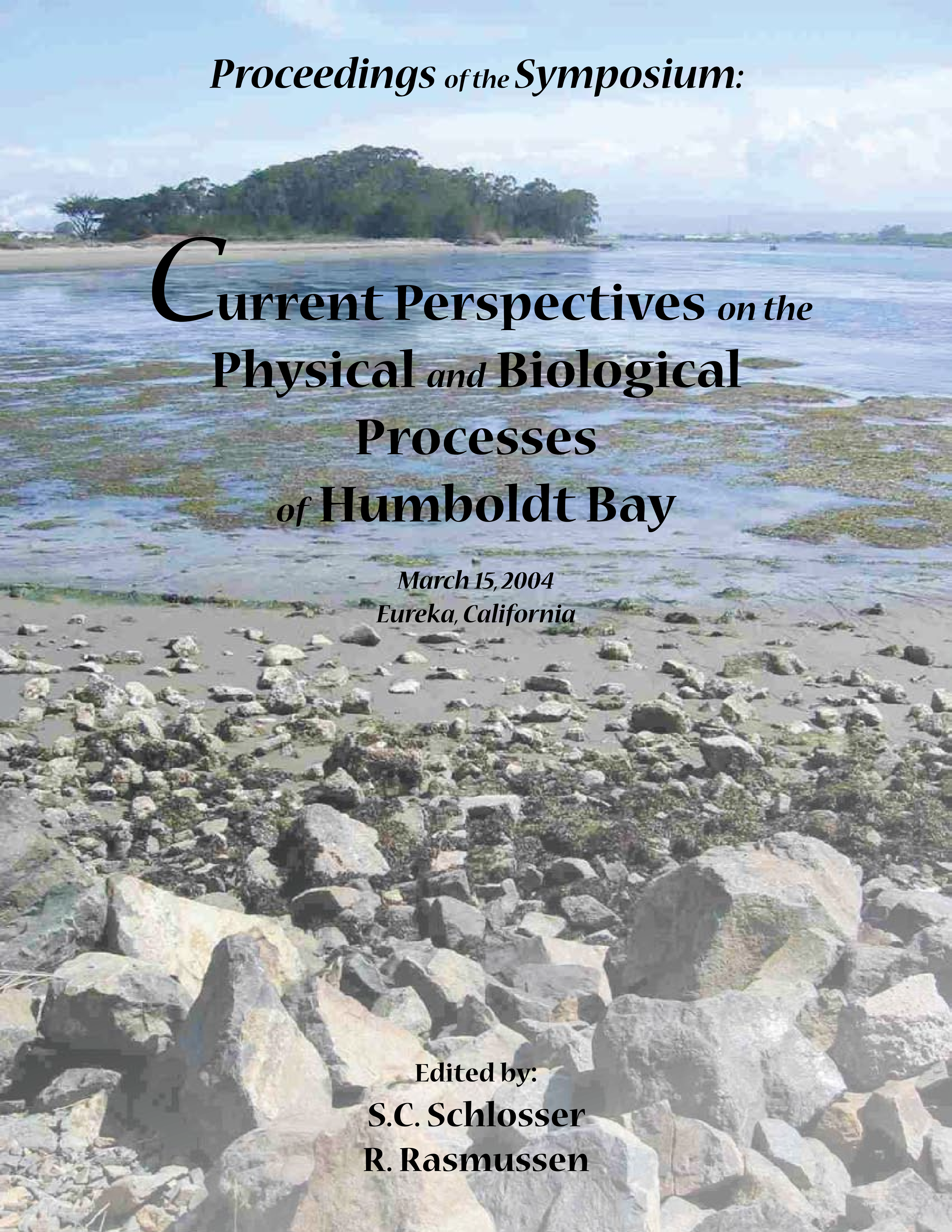

Proceedings of the Symposium:

Current Perspectives *on the* Physical *and* Biological Processes *of* Humboldt Bay

March 15, 2004
Eureka, California

Edited by:
S.C. Schlosser
R. Rasmussen

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(Cover) Rebecca Studebaker; (p. 1) Susan Schlosser;
(p. 5) Pacific Earthquake Engineering Research, UC Berkeley.

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Meeting Overview

The Humboldt Bay Stewards hosted a one-day public symposium titled, “Current Perspectives on the Physical and Biological Processes of Humboldt Bay,” on March 15, 2004. The meeting was held in the Wharfinger Building on the Eureka waterfront.

The purpose of the symposium was to examine biological and physical processes to gain a better understanding of Humboldt Bay. The need for the symposium was clear, as there were many plans, projects and studies ongoing at the time.

The symposium included 19 presentations and a panel discussion. Ten of the presentations are included here as papers or in the appendices as a report or plan. A major topic addressed in several papers was sediment sources and transport. Sediment was addressed historically (Tuttle), oceanographically (Crawford and Claasen), in the watershed (Barrett), relative to eelgrass (Shaughnessy et al.), fouling communities (Boyle et al.), and management (Davenport). Though Davenport did not submit a paper on the California Sediment Management Plan, Appendix A includes a copy of this important and innovative plan that was completed in 2006.

Other management topics included an overview of the Humboldt Bay Management Plan. Since the symposium, this plan has also been completed and can be found at http://www.humboldtbay.org/.

From the biological perspective, papers are included on marine invasive species, eelgrass, fish and fouling communities. Worldwide, increasing attention is directed towards aquatic invasive species and their impacts on biodiversity and ecosystems.

The presentation on invasive species at this symposium showed their occurrence around Humboldt Bay. The purpose of the study was to provide reliable baseline information for further studies and monitoring. The “Non-indigenous Marine Species of Humboldt Bay, California” is included in Appendix II. This study was part of a program funded by the California Department of Fish and Game that included most of the bays and estuaries in California. The full report and list of all species found during the statewide study is at http://www.dfg.ca.gov/ospr/about/science/misp.html. The innovative fish habitat paper, (Gleason et al.) uses a novel GIS approach to the study of Humboldt Bay fishes. Eelgrass provides a major habitat in Humboldt Bay. Summarizing what we know, don’t know and need to know about Humboldt Bay eelgrass provides a fruitful source of many possible studies. Fouling communities have not been previously studied in Humboldt Bay. The study presented here is the beginning of a long-term project that we can expect to hear more about at future symposia.

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—continued from p. 1

We would like to thank the presenters, authors and participants who made this symposium a success. The Humboldt Bay Stewards worked hard with their collaborators to provide this informative Humboldt Bay Symposium. We hope there will be many more Humboldt Bay Symposia in the future and look forward to seeing all of you there!

—Susan C. Schlosser and Robert Rasmussen

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Symposium Agenda

Current Perspectives on the Physical and Biological Processes of Humboldt Bay

"What we know, don't know, and should know for future planning."

March 15, 2004
Wharfinger Building, Eureka, California
Moderator: Sharon Kramer, Ph.D., Stillwater Sciences

HISTORY of HUMAN INFLUENCES

8:00 Traditional Cultural Uses of Wigi by the Wiyot People
Marnie Atkins, Wiyot Tribe
Mike Wilson, Humboldt Water Resources

8:20 History of Major Developments on Humboldt Bay
Donald C. Tuttle, Consultant

8:40 Brief History of Corps Activity and Summary of a Shoreline Monitoring Program in Humboldt Bay
Craig Conner and Stephan Chesser, U.S. Army Corps of Engineers

CIRCULATION MODELING USING LIDAR DATA

9:00 Numerical Simulation of Tidal Circulation in Humboldt Bay Based on a Recent LIDAR Survey
Nicholas Kraus, Ph.D., U.S. Army Corps of Engineers
Adele Militello, Ph.D., Coastal Analysis

PHYSICAL PROCESSES and FUNCTIONS

9:20 Overview of Circulation, Transport, and Mixing Processes in Humboldt Bay
Steven L. Costa, Ph.D., CH2MHILL

9:40 Waves and Tides Near the Entrance to Humboldt Bay
Greg Crawford, Ph.D., and Nathan Claasen, Humboldt State University

10:00 BREAK

10:10 Earthquake and Tsunami Hazards in the Humboldt Bay Area
Mark Hemphill-Haley, Ph.D., Humboldt State University

10:30 Freshwater Sediment Inputs to Humboldt Bay
Jeff Barrett, Ph.D., Pacific Lumber Company

10:50 Surface Sedimentation in Humboldt Bay: Processes and Patterns
Jeffry Borgeld, Ph.D., Humboldt State University

HABITAT RELATIONSHIPS to PHYSICAL FUNCTIONS

11:10 Understanding the Eelgrass Beds of Humboldt Bay: Positive Steps, and Embracing Bottom-up and Top-down Perspectives of Community Regulation
Frank Shaughnessy, Ph.D., Humboldt State University

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HABITAT RELATIONSHIPS to PHYSICAL FUNCTIONS—

11:30 Fish Distribution in Humboldt Bay: A GIS Perspective by Habitat Type
Erin Gleason, Tim Mulligan, Ph.D., and Rebecca Studebaker, Humboldt State University

11:50 The Importance of Birds to Humboldt Bay: Conservation and Management Implications
Mark Colwell, Ph.D., and Jeff Black, Ph.D., Humboldt State University

12:10 How They Came, Why They Will Stay: Introduced Species in Humboldt Bay
Milton Boyd, Ph.D., Humboldt State University

12:30 Fouling Community Structure: Influences of Periodic Winter Storms
Sean Craig, Ph.D., Humboldt State University

LUNCH 12:50

FUTURE PLANNING CONSIDERATIONS

1:20 Applying the Public Trust Doctrine to Humboldt Bay
Aldaron Laird, Trinity Associates

1:40 Coordinated Planning
Ruth Blyther, Redwood Community Action Agency

2:00 The Humboldt Bay Management Plan
David Hull and Jeff Robinson, Humboldt Bay Harbor Recreation and Conservation District

2:20 California Coastal Sediment Management Master Plan
Clifton W. Davenport, Coastal Sediment Management Workgroup

2:40 KRIS for the Bay
Patrick Higgins, Institute for Fisheries Resources

3:00 BREAK

3:15–4:30 **PANEL DISCUSSION**

A diverse group of scientists, businesses, environmental groups, and agency representatives will provide fresh perspectives on bay management and protection, as well as identify information gaps.
** NOTES from Discussion are included in PROCEEDINGS **

U.S. Army Corps of Engineers Perspective	Nicholas Kraus, Ph.D.
Resource Agency Perspective	Vicki Frey
Harbor District Perspective	David Hull
Physical Science Perspective	Steve Costa, Ph.D.
Physical Science Perspective	Adele Militello, Ph.D.
Biological Perspective	Milton Boyd, Ph.D.
Environmental Perspective	Tim McKay
Commercial Fisheries Perspective	Aaron Newman/Troy Nicolini
Aquaculture Perspective	Greg Dale
Coastal Commission Perspective	Lesley Ewing

Presentations

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History of Major Developments on Humboldt Bay

Donald C. Tuttle
Special Projects Manager
Humboldt County Department of Public Works

Image Credits
(Above) Early map of Humboldt Bay entrance, circa 1858: courtesy Don Tuttle;
(p. 8) Navigating Humboldt Bay: NOAA historical photo gallery;
(pp. 10, 11) Merle Shuster, Humboldt State University Library Special Collections.

Introduction

Major developments to Humboldt Bay over the last 125 years have resulted in a change in erosion rates of various shorelines, deepening of the bay's main channels, decrease of the tidal prism, and variations in the velocity and direction of tidal currents.

Diking Off Salt Marshes

The first diking in Humboldt Bay began in early 1892 when Thomas Bair started reclamation work on 320 acres located 2 miles west of Arcata. The Harpst and Spring Dike was built in 1892 from Butcher Slough (lower Jolly Giant Creek) to Jacoby Creek and upstream to the extent of the highest tides. In the fall of that year, J. Harpst, O.H. Spring, M.P. Roberts, Flanigan, Brosnan & Company, M.B. Morton, and E. Mason petitioned the Humboldt County Board of Supervisors to organize a reclamation district.

The Arcata Land Improvement Company was incorporated in 1893 and began ditching and dredging the marshland from the Arcata railroad westward to McDaniel Slough. The diking activities continued for two years and in 1895, the Arcata Land Improvement Company sold the dredger to Dr. Gross who used it to reclaim land on Freshwater Creek.

In 1904, E.G. Jackson, R.W. Bull, L. Pacheco, J.C. Bull, A.C. Noe, M.P. Hansen, L. Peterson, and P.J. Peterson, owners of reclaimed land on the Arcata Bottom, petitioned the Board of Supervisors to create a reclamation district for the purpose of operating and maintaining the dike. That reclamation district continues today as District 768. The dike extended mostly along the northern edge of Humboldt Bay. Before the dike was constructed, Humboldt Bay extended up to the corner of Fourth and D Streets in Arcata.

Mad River Canal

The history of the Mad River Canal and associated booms are important because of the significant impacts they had on Humboldt Bay.

The first efforts at connecting the waters of the Mad River with Humboldt Bay were initiated by the incorporation of the Humboldt Bay and Mad River Canal Company. The intent was to divert the Mad River through the Mad River Slough to transport logs into Humboldt Bay. In 1854 a small canal, one-half mile long, was dug from the Mad River to the upper end of Mad River Slough; and, in May 1858, the canal was used for the first time to float logs to the head of Humboldt Bay. The timber was most likely spruce logs from the Arcata Bottoms headed for Humboldt Bay mills.

The canal was 8-feet wide by 10-feet deep. Due to its small size, the canal was not very effective for floating logs from Mad River to Humboldt Bay as they could only be floated during high winter flows. The small dimensions of the canal required a catching point and holding area so that a few logs at a time could be moved through the canal. In November 1872, a boom on Mad River holding 100,000 board feet of logs broke during high-water flows. In 1873 the canal was enlarged and in 1874 another boom 600-feet long was constructed to catch and hold 1–2 million board feet of logs at low water; the plan was to float logs through the canal to the head of the bay during high flows. This boom broke and was carried away within a month of its construction.

The Mad River Boom Bill was introduced in the state legislature in 1876; and, despite strong arguments against the booms on Mad River, the "boom to end all booms" was built in the fall of 1877.

Within a few years, Arcata Bottoms farmers were complaining to the Harbor Commissioners about the damage to their lands from sediment and debris deposited from the canal. During a flood event in December 1881, the boom broke, ending efforts to drive logs on the Mad River. In 1886, the *Arcata Union* declared the canal a "nuisance" and wrote that as a "commercial enterprise it has been a failure." The Harbor Commission ordered the canal closed in 1888, but the Mad River continued to break through during winter high water; and it was not until 1890 that efforts were successful in shutting off the river's flow into Humboldt Bay.

The impacts of this canal on Humboldt Bay are demonstrated somewhat in the history of the Arcata Wharf, completed at a length of 11,000 feet into the bay in 1855. With the construction of Jolly Giant Mill in 1875, the owners reached an agreement with the Union Wharf Company to extend the wharf another 600 feet, as 20 years of running the Mad River into the bay had silted up deep water. In 1881, when a gale toppled the old warehouse on the wharf into the bay, the editor of the *Arcata Leader* observed, "where the old depot stood admonished us how rapidly the channels in the bay are filling up." He recalled seeing steamers discharging freight at that old depot, but now "the channel is so filled as to be useless for all boating purposes."

By 1883, logging and milling were booming on the Mad River at Blue Lake and North Fork. The Arcata Wharf was handling the export of these products, now moved by rail; and with increase in business, the wharf was extended another 600 feet to "enhance shipping." Lumber continued to be shipped from the wharf into the 1920s; but rail connections to San Francisco, completed in 1914, and sediment accretion in the channel significantly reduced the wharf's commerce. In time, the channels were too shallow to accommodate ocean-going vessels and the wharf was abandoned.

Early Dredging

Humboldt Bay has been maintained for commercial shipping since 1881. One of the earliest dredging projects by the U.S. Army Corps of Engineers (USACE) was along the Eureka waterfront where the water was only 8–9-feet deep at low tide. During the period September 1881 through May 1882, 80,000 cubic yards were dredged to create a channel 10-feet deep, 4,100-feet long and 240-feet wide. In the following years, the channel leading to the south end of the Arcata wharf was initially dredged to a depth of 10 feet, then to a depth of 13 feet and a width of 150 feet. Dredging of the channel to the Arcata Wharf by the USACE ended in the 1930s.

In the USACE dredging plans for 1930 and 1938, the spit at King Salmon was designated as a dumping ground for dredge spoils. Other dredging plans designated the south end of Indian Island as a spoils dumping ground. These relatively small dredging projects may have had a minor effect on bank sloughing at the edge of the newly created channels.

Humboldt Bay jetties in 1954.

Jetties at the Entrance to Humboldt Bay

Prior to the construction of the jetties, the depth over the bar at the entrance to Humboldt Bay changed drastically from year to year. On September 25, 1850, measurements showed the entrance to be one-half-mile wide with a depth of only 18 feet at low tide. In 1851 the depth was only 20 feet. In 1853–1854 it was only 16 feet at high tide, and in 1857 it was only 13 feet at high tide. This caused great delays in exporting products and importing supplies. Therefore, after several years of studies by the USACE, it was concluded that several jetties 7,000–8,000 feet in length should be built roughly one-half mile apart in a northwesterly direction.

Construction began in May 1889 and was completed in 1899. By 1904, the jetties were in dire need of repair and were rebuilt from 1911 to 1917, again from 1925 to 1927, and repairs made in the 1930s, 1963, 1972 and 1985.

Following construction of the jetties, impacts on the bay just inside its entrance were fairly dramatic. Because of erosion, currents associated with the jetties removed what was known as breaker flats just west of the north end of the South Spit, which had absorbed much of the wave energy. Once these breaker flats disappeared and the harbor entrance deepened, wave energy came into the bay and eroded what was known as the Middle Ground, which had protected the shoreline from King Salmon-Buhne Point north to Elk River.

The Buhne Point Ranch lost 188 acres in 101 years. The shoreline retreated one-quarter mile. From 1891 to 1929 the beach along the Northwestern-Pacific Railroad eroded landward 600 feet, requiring the company to install 3,000 linear feet of rock revetment in 1930.

In 1952 Pacific Gas & Electric (PG&E) bought the Buhne Point Ranch and immediately lost 50 acres, thereby requiring them to install 3,000 linear feet of revetment. From 1952 to 1954 the railroad, just north of PG&E property, had to place 4,500 linear feet of revetment. These revetments reflect waves that travel northwesterly across the bay and erode the eastern shoreline of the southerly end of the North Spit.

Additionally as Buhne Point eroded, it created a sizable sand deposit south of Buhne

Point and a new spit at the mouth of Elk River. The Elk River spit grew in length by 6,000 feet from 1897 to 1954 and in width by 700–800 feet from 1931 to 1954.

The spit deposited at King Salmon attracted the eye of developers; and in 1947 it was acquired, canals were dredged, and 25-foot lots were sold for recreational fishing. Over time, houses were built on those lots. Because of continuing wave action entering through the entrance to Humboldt Bay and the removal of the source of sand following placement of the revetment, the sand spit protecting the community slowly disappeared and by 1982 was completely gone.

Groins were installed by the USACE after 600,000 cubic yards of sand and silt were dredged from the entrance of Humboldt Bay and pumped over to King Salmon to replace the sand spit that had been lost due to erosion. The results of the reflected wave generated by these new groins, along with the revetment placed along PG&E's property and the railroad, accelerated erosion along the east side of the North Spit. The eroded areas immediately north of the Samoa Boat ramp and the Coast Guard groins are good examples, and this erosion continues to this day.

The jetties were rehabilitated in 1972 with the placement of dolosse on their westerly heads. Following the construction of the jetties in 1899, the width of the south end of the North Spit grew in a westerly direction 3,400 feet. The width of the north end of the South Spit grew 2,600 feet.

Construction of the Samoa Bridge 1970–1972

The bridge approach required some filling that narrowed the width of two of the bay's three main channels. The west channel width at high tide was reduced from 3,000 to 2,000 feet. The middle channel was narrowed from 1,450 to 900 feet; however, the width of the east channel remained unchanged. The velocity of water in the west channel was increased significantly, especially at extreme high tides, because 3,000 linear feet of fill was required for the road across Indian Island and the bridge approach.

1999 Harbor Deepening Project

In 1999 the Humboldt Bay Harbor District undertook a $15-million dredging project to deepen the bay's main navigation channels by 8 or 10 feet. Since that time, local commercial fishermen have noted erosion of various parts of the bay's shoreline or signs of lowering. Continuous monitoring will need to be done to check on the severity of this effect. In 1997 the USACE began to monitor sand erosion and accretion on the west (ocean) side of the North and South Spits.

The beach south of Elk River spit along the rock revetment that protects the railroad has dropped significantly in the last few years. Appropriate maintenance will be required to retain the integrity of the railroad bed.

Impacts of Developments in the Watersheds Around Humboldt Bay

This paper concentrated mostly on effects of developments that have occurred on and in Humboldt Bay. Tributaries to Humboldt Bay were the site of the region's first logging activities. The initial removal of old-growth forests in the watershed included using the tributaries to move logs to Humboldt Bay for milling and export. Historic human impacts on Humboldt Bay watersheds can be found in the Humboldt Bay Watershed Salmon and Steelhead Conservation Plan prepared by the Redwood Community Action Agency and the Humboldt Bay Watershed Advisory Committee.

Sources of Information

While working for the Humboldt County Department of Public Works for 31 years, the author collected many manuscripts, reports and documents from several state and federal agency archives. He placed them in special files in the Natural Resources Division of the Department of Public Works called the environmental data bank. The author also used many books covering the history of the county contained in his personal library. Information presented in this paper comes from these sources. Additional information was provided through peer review comments.

Modeling Wave-Current Interaction at the Entrance to Humboldt Bay, California

G.B. Crawford and
N.J. Claasen
Humboldt State University

Photo Credit
U.S. Army Corps of Engineers—Research & Development Center

Abstract

Numerical models of surface waves and tidal circulation have been adapted to the Humboldt Bay region of Northern California for future sediment transport studies. A general set of guidelines for coupled model applications is presented based on this study. For modest waves and tidal currents (significant wave height, H_s, < 1.8 m; dominant period, T_p, < 9 s; tidal currents, U < 1.0 m/s) and a dominant wave direction roughly aligned with the jetties, the one-way coupled runs reproduced the two-way coupled runs satisfactorily. For large waves (H_s > 2.4 m, T_p, > 11 s), large tidal flows (U > 1.5 m/s), or more oblique wave directions (> 20° from the jetty orientation), two-way coupling is required.

Introduction

Coastal inlets are by nature dynamic, continually shaped and reshaped by hydrodynamic forces. Waves and tidal currents may cause erosion, picking up sediment for deposition elsewhere. Channels may fill and sandbars may develop, increasing local wave steepness and refocusing wave energy that, in turn, increases risk to ships using the inlet. Expensive engineering projects, such as jetty construction or dredging, are often undertaken to maintain or increase both the safety and the accessibility of an inlet. A detailed understanding of the physical processes provides the basis for design and construction of stable navigation channels, which increases the usefulness of the adjacent harbors.

Waves and currents at coastal inlets interact. Inlets concentrate tidal currents, resulting in strong currents and strong interactions with waves. In the presence of a current, waves can refract, steepen, or even break (e.g., Thompson 1949; Wright et al. 1999) and if the current is strong enough, it may even lead to wave blocking. A detailed review of the subject is provided by Jonsson (1990). Currents are also modified by the presence of waves. Waves can generate mean horizontal stress, referred to as radiation stress; gradients of the radiation stress generate mean currents and modify background flows (Longuet-Higgins and Stewart 1964).

Much of our understanding of these processes is based on straightforward, idealized models, but the relative importance and consequences in real-world environments are not always obvious. In practice, most efforts to understand the dynamics of a particular coastal inlet revolve around numerical models of waves and tides. Such models, in principle, adequately describe the specific geography and bathymetry of a region, as well as forces and dynamics.

Historically, model applications have been limited by computational speed, which in turn limited spatial and temporal resolution and required parameterization of the dynamical terms. In the last decade, advances in computing power and model formulation have allowed numerical simulation of complex wave-current interactions on the scale of coastal inlets (Zhang and Wu 1999; Li and Davies 1996). Such models are still computationally expensive and, in many practical engineering applications, wave and current models are run either independently or with limited interaction (Kraus 2000).

The present study is based on the application of specific wave and tide models (STWAVE and ADCIRC) at Humboldt Bay, California. The energetics are relatively strong in this region: tidal currents through the inlet average 2.1 m/s for peak ebb near the entrance (Costa and Glatzel 2002); monthly-averaged significant wave heights, H_s, vary between 1.7 and 3.1 m throughout the year (Harris 1999), and large wave events with $H_s > 7$ m are observed during most years. In such a location, wave and current interactions might be expected to be substantial. The goal of the present study is two-fold: using these models to examine predicted wave and current patterns in and around the bay entrance; determining how well the simpler model coupling options (uncoupled and one-way coupled) reproduce the full two-way coupled model runs under various conditions. We define one-way coupling to refer specifically to the case of wave radiation stress fields applied to the circulation model.

The two-way coupled models were considered to represent "reality," since they have the most complete modeled physics; uncoupled and one-way coupled models represent simplified (less complete) models. All three modeling approaches were tested under a variety of climatological wave- and tidal-forcing conditions; key fields of interest were currents and significant wave height. Results from the uncoupled and one-way coupled runs were contrasted against the two-way coupled runs to determine how well these simpler models performed.

Study Area

Humboldt Bay is the only naturally enclosed, deep-draft harbor between Coos Bay, Oregon, and San Francisco, California. The section of coastline that contains the bay runs in a relatively straight northeast/southwest line from Cape Mendocino in the south to Trinidad Head in the north (Figure 1). Key geological features around the bay entrance are identified in Figure 2.

Extensive and rapid shoaling occurs at the Humboldt Bay Bar, Entrance Bay, and Arcata and South Bay Channels as a consequence of natural sediment transport processes. Shoaling is an ongoing problem, restricting safe navigation of deep-draft commercial vessels. To mitigate these influences, the United States Army Corps of Engineers (USACE) has conducted annual (and occasionally semi-annual) maintenance dredging of the bar and entrance and several navigational channels within Humboldt Bay. In June 2000, the USACE completed a project in Humboldt Bay to deepen the navigational channels from an initial 12 to 15 m to improve deep-draft navigation safety and to maximize the efficient use of the bay and harbor by commercial deep-draft vessels.

The bay watershed encompasses about 570 km^2, with no major rivers in the area emptying directly into the bay. The annual freshwater input to the bay is estimated to be on the order of the tidal prism, 7.4 x 10^7 m^3 (Costa 1982). Humboldt Bay is made up of three subbays, Arcata Bay (or North Bay), Entrance Bay, and South Bay. Both Arcata Bay and South Bay consist of a series of channels and large areas of intertidal flats. The long thalweg between Arcata Bay and Entrance Bay contributes additional complexity to tidal circulation near the entrance. At mean lower low tide, the total area of the bay is 21 km^2 while at mean high tide, the bay area averages 67 km^2 (Costa and Glatzel 2002).

Circulation in Humboldt Bay is tidally dominated, which makes for generally well-mixed marine water within the bay. Tides are mixed semi-diurnal, with a mean range of 1.51 m and a diurnal range of 2.11 m at the entrance. About 50% of the tidal prism volume flows to North Bay and 30% to South Bay (Costa and Glatzel 2002). Peak currents at the Humboldt Bay entrance exceed 2.1 m/s, with average peak velocity on ebb tide of 1.0 m/s and 0.82 m/s on flood.

The wave climate at Humboldt Bay is extreme in comparison to most U.S. inlets, with waves from the northwest being commonest and waves out of the southwest having the greatest energy (Costa 1982). Significant wave heights up to 7 m can occur annually and swell wavelengths as long as 1,000 m have been observed. The highest energy waves acting in the inlet are thought to significantly influence currents in the bay itself. The convex nature of the bar, the incident wave direction, and the alignment of the jetties tend to focus wave energy into Entrance Bay, causing erosion and influencing sedimentation, mixing, flushing and circulation within Entrance Bay (Costa and Glatzel 2002).

Sources of sediment to the entrance are the Eel River, 14 km to the south, and the Mad River, about 24 km to the north. Sediment coming from the Eel during winter months is thought to travel northward, providing material for the ebb shoal as well as depositing in the bay (Costa 1982). In summer, longshore transport may rework some coastal sediments, but the bay sediments remain.

Maintenance of the navigational channels continues to be an expensive and time-consuming process. As a preliminary step towards assessment of sedimentation processes at the entrance and within the bay, and to examine alternative approaches to channel maintenance, we have applied wave and tidal circulation models to the Humboldt Bay region. Ultimately these models will be coupled with a sediment transport model to examine erosion and deposition at the bay.

Methods

STWAVE is a steady-state, finite-difference, spectral wave transformation model developed by the USACE (Resio 1988a,b; Smith et al. 2001). This model is used to quantify changes in wave parameters as waves propagate from deep or intermediate water to the nearshore. STWAVE simulates depth-induced wave refraction and shoaling, depth- and steepness-induced wave breaking, simplified diffraction, wind-wave growth, and wave-wave interactions and whitecapping that redistribute and dissipate energy in a growing wave field. Influences of depth-averaged currents are also incorporated.

The STWAVE model is driven with a two-dimensional wave spectrum at the offshore boundary of the model grid. For the studies described here, offshore wave conditions are based on climatological observations of significant wave height, H_s, dominant period, T_p, and an assumed dominant wave direction. These quantities were used to generate two-dimensional wave spectra for the outer boundary using the TMA one-dimensional shallow-water spectral shape, a spectral "peakedness" coefficient, a directional distribution function, and a directional spreading coefficient (Smith 2001; Smith et al. 2001). Choices for coefficients were based on the recommendations of Thompson et al. (1996); details are provided in Claasen (2003).

The tidal circulation model used, ADCIRC (Luettich et al. 1992), is a finite element, depth-integrated, ocean circulation model. The model included Coriolis force, advection, mixing, and wetting and drying parameterizations; wind forcing is also an option but was not included in the work discussed below. Quadratic bottom stress was used, with a default friction coefficient of 0.025. Forcing data were provided at the outer edge of the model domain using tidal constituents (K1, O1, M2, N2, S2, K2, P1 and Q1) derived from a global tidal model (LeProvost et al. 1994). Bathymetric information represented a blend of data from the STRATAFORM project (Nittrouer and Kravitz 1996), a local high-resolution survey done by R. Flood[1] (pers. comm.) and supplementary data from the GEOphysical DAta System (GEODAS) compiled by the National Geophysical Data Center, National Oceanic and Atmospheric Administration (NOAA). Development of bathymetric grids for ADCIRC and STWAVE was undertaken using the Surface Modeling System, SMS (Zundel et al. 2002). For ADCIRC, the domain ranges from Baja California to the Alaskan border and extends as far as 400 km offshore. The grid comprises 30,165 elements, 16,174 nodes, with resolution in the surf-zone and the entrance channel on the order of 35 m. The STWAVE domain extended from just south of Trinidad Head to the Eel River mouth and out to roughly 4 km offshore, at water depths of approximately 40 m. The grid for the wave model comprises 218 x 806 points, with a horizontal resolution of 40 m (Claasen 2003).

The models were run and most of the postprocessing and data visualization were conducted using SMS (Surface Modeling System, developed by Environmental Modeling Systems, Inc.); additional analyses were developed using Matlab (The Mathworks, Inc.). Recent advances to the SMS software allow the

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[1] R. Flood, Marine Sciences Research Center, State University of New York, 2000.

user to control the extent of coupling between the wave and circulation models (Zundel et al. 2002). Water level variations were included in some coupling options by changing the bathymetry of the STWAVE grid according to calculated tidal heights from ADCIRC. The ADCIRC time step was 1.5 s, while the STWAVE model was updated every hour.

The ADCIRC tidal model was validated against tidal height observations made at the NOAA tide gauge located on the north spit of Humboldt Bay (40° 46.0′ N, 126° 13.0′ W) during August 2001. Wave conditions were generally low, with mean H_s = 1.5 m (maximum 3.5 m) and mean T_p = 9 s (maximum 20 s). Performance was very good, with all model values within 6% of observations and a majority of the model values within 4% of observed water level. Mean difference between modeled values and measurements at the tide station for the month was 0.04 m with a standard deviation of 0.017 m. A 36-hour segment of this comparison is shown in Figure 3.

As mentioned previously, we considered three types of model coupling: uncoupled, in which STWAVE and ADCIRC were run independently of each other; one-way coupling, in which STWAVE radiation stress gradients were input into ADCIRC; and two-way (or full) coupling, in which ADCIRC currents were input to STWAVE and radiation stresses from STWAVE were input to ADCIRC.

We have conducted wave and tide model runs corresponding to 36 combinations of offshore wave forcing and model-coupling conditions. Tidal conditions for all of these cases corresponded to the spring tides sequence from January 1 to 3, 2002, which allowed us to look at a wide range of tidal currents. Results are discussed extensively in Claasen (2003). Here we present a few examples to illustrate some of the circulation and wave-field patterns predicted by the models, as well as some of the differences in results based on the choice of model coupling. In particular, we will focus on some results for "large" and "small" offshore waves, defined by climatological conditions for January (H_s = 3.1 m, T_p = 13.2 s; hereafter referred to as large wave conditions) and August (H_s = 1.7 m, T_p = 8.9 s; hereafter referred to as small wave conditions, although we note that such waves may be considered moderate or large in some areas of the world). We consider two dominant offshore wave directions: 308° (waves roughly from the northwest, and approximately parallel with the jetties and entrance to the bay; hereafter referred to as down-jetty waves) and 253° (waves roughly from the west-southwest, at an angle of about 55° to the jetty orientation; hereafter referred to as cross-jetty waves). We also focus primarily on conditions during peak ebb. Claasen (2003) discusses a variety of other model runs, spanning different climatological conditions, wave directions and coupling conditions.

For each model run, forcing in the ADCIRC model was ramped over a two-day time interval (Zundel et al. 2002). Both tidal and wave forcing were scaled from zero to full strength using a hyperbolic tangent function over the first model run day, with the second day included to allow for any additional model adjustment. Results for the third day were archived at half-hour intervals for subsequent analysis. The ramping period was necessary for the ADCIRC model as sudden, strong forcing can shock the system, producing instability in the solutions (Zundel et al. 2002). A few additional model runs were extended to a fourth day to confirm model behavior. The third and fourth model days were generally nearly identical (except for the phase shift in times of high and low tides due to the lunar day), which helped to validate the use of model calculations from the third day. In other words, differences among model runs on day 3 were not merely due to model spin-up.

Because the ADCIRC output was archived at half-hour intervals, estimates of the timing for maximum ebb and maximum flood were considered to be ± 15 minutes. We note, however, that both wave-generated currents and the particular choice for coupling mode could modify the circulation patterns. Thus a "true" definition of higher high water (HHW) and peak current times depended on the particular model run and coupling conditions. Given these issues, it was considered most useful to compare different model results at the same time step and to base the definition of maximum ebb and maximum flood on the uncoupled ADCIRC model run.

Results

1. Circulation Patterns at Peak Ebb

Figure 4a, b and c displays the circulation pattern near the bay entrance for small waves oriented down-jetty at peak ebb for the uncoupled, one-way coupled, and two-way coupled model runs, respectively. (We note that Figure 4a corresponds to the predicted flow at peak ebb for all uncoupled model runs.) Without coupling, the ebb jet at Humboldt Bay fills much of the space between the jetties, narrowing as it approaches the jetty tips (Figure 4a). Offshore, the model predicts the ebb jet to remain relatively narrow and to sweep from south to north over the course of the ebb cycle. A large, low-velocity circulation cell appears in the middle of the ebb cycle and spins off to the northwest as slack tide approaches. Current velocities reach 1.8 m/s over most of the width of the entrance. Peak velocities of 2.3 m/s were obtained.

For the small, down-jetty wave conditions, the current fields are deformed significantly near peak ebb in both the one-way and two-way coupling cases (Fig. 4b and c). Both of these coupled cases show a slight, southward deflection of the ebb jet over the Humboldt Bar, a narrowing of the current stream in the entrance channel, and a net current into the channel along the north jetty. The one-way coupled case (Figure 4b) produces a maximum current speed of 2.2 m/s in the entrance channel with mean current rate over the navigation channel 1.5 m/s. The two-way coupled case (Figure 4c) shows a maximum current rate of 2.1 m/s in the entrance with a 1.5 m/s mean current speed in the navigation channel. Although the one-way and two-way coupled cases are similar, the one-way case deflects the current stream southward just offshore of the entrance as compared to the two-way coupled case. In addition, the one-way coupled case generates stronger currents (by as much as 0.3 m/s) than the two-way coupled case along the north jetty and over the channel shoal.

For the larger, longer waves typical of winter conditions, the effect of coupling on the current field becomes much more evident. For the one-way coupled, large wave, down-jetty model run (Figure 5a), the basic shape of the current fields remains the same as for the similar small wave case (Figure 4b), but the maximum currents in the navigation channel exceeds 4.1 m/s. Mean speed in the navigation channel are 2.1 m/s and currents into the bay along the north jetty are as high as 2.4 m/s. Compared with the uncoupled model output (Figure 4a), offshore currents in this case reach higher speeds, and are confined to a 300-m-wide channel along the south jetty; the ebb jet is also deflected southwards relative to the uncoupled case. In the two-way coupled, large wave, down-jetty case (Figure 5b), currents differ significantly from the one-way model output over the entire entrance area. In the navigation channel the two-way coupled model predicts peak currents of 2.2 m/s, with a spatially averaged current of 1.6 m/s and the main portion of the ebb jet is diverted north 170 m compared to the one-way case. In the one-way coupled case, extremely high currents are predicted at the inside tip of the south jetty, whereas in the two-way case these currents are not apparent. From the difference in current magnitude between two-way and one-way models (Figure 5c), the one-way solution predicts up to 50 cm/s lower currents within the navigational channel than the two-way coupled solution does, and up to 50 cm/s higher currents to the north of the channel. Both of these models predict a flow into the entrance towards the north jetty during this strongly ebbing flow, presumably driven by radiation stresses.

Figure 6a and b shows the current fields at peak ebb for the "cross-jetty" (253°) case of large waves (H_s = 3.1 m, T_p = 13 s) arriving at an angle to the jetties, corresponding to the one-way and two-way coupled runs respectively. For the one-way coupled case (Figure 6a), ebbing currents are concentrated in the navigation channel and peak there at 2.1 m/s. Mean ebb current in the navigation channel is 1.8 m/s in this case. Along the inside of the north jetty, currents are directed into the entrance and reach 1.9 m/s. Offshore the ebb jet is deflected northward by the radiation stress gradients over the Humboldt Bar (compare to Figure 4a). For the two-way coupled case (Figure 6b), current patterns are much the same within the entrance, although slightly higher in the navigation channel (2.3 m/s peak and 1.9 m/s mean). Onshore currents along the inside of the north jetty in the two-way coupled case are typically 0.1 m/s less than in the one-way case. Currents over the channel shoal in the two-way case are also less than in the one-way case. The largest differences between the one-way and two-way cases are seen outside the entrance, over the Humboldt Bar (Figure 6c). In the two-way coupled case, the ebb jet is turned sharply northward at the western edge of the bar, while in the one-way coupled case, the deflection is much less significant. In addition, just south of the south jetty, a very well-defined clockwise eddy with currents on the order of 1 m/s is present in the one-way solution. In the two-way solution, the flow is more erratic and generally slower, although a distinct eddy can be seen in roughly the same location.

2. Wave-Height Patterns at Peak Ebb

Figure 7 displays the significant wave-height fields for small, down-jetty waves at peak ebb for both one-way and two-way coupled runs (by our definition of one-way coupling, the wave fields for uncoupled and one-way coupled runs are the same). Within the navigational channel, the mean difference between the two runs was 0.5 m. Over the channel shoal, the two-way coupled case predicts waves up to 1.1 m higher than the one-way coupled case. Over the whole Entrance Bay, the two-way coupled solutions are at least 0.25 m larger than the one-way coupled solutions. Over the Humboldt Bar, the two-way case is up to 0.9 m times higher than the one-way case.

For the large wave, down-jetty runs, the difference in wave-height fields near peak ebb tide is even more dramatic. Figure 8 shows differences of up to 2.8 m in significant wave height between two-way and one-way coupling cases. On average, over the navigation channel the two-way coupled case predicts waves that averaged 2.1 m higher than the one-way coupled case. The two-way case also shows increased wave heights over the Humboldt Bar relative to the uncoupled case. Waves in the Entrance Bay average 1.0 m higher in the two-way solution over the one-way solution.

Wave-height fields for large, cross-jetty waves near ebb tide (Figure 9) show similar results as those from large, down-jetty waves. The two-way coupled model predicts significantly higher waves in the navigation channel, over the channel shoal, and in the Entrance Bay than did the one-way model. The peak difference in wave height in the navigation channel is 1.7 m; and over the channel shoal, the peak difference in wave height is 1.9 m.

3. Circulation and Wave-Height Patterns at Peak Flood

Here we consider a few cases of circulation and wave heights at peak flood for comparison. Figure 10a, b and c shows the current patterns at peak flood for large, down-jetty waves (uncoupled, one-way coupled and two-way coupled, respectively). For the uncoupled case, currents average 1.1 to 1.3 m/s across the width of the entrance. For the one-way coupled run, currents are spread over 80% of the width of the entrance and averaged 2.2 m/s. Large circulating current fields both to the north and to the south of the entrance are predicted in both one- and two-way coupled model runs but not in the uncoupled case, indicating these flows are all wave-driven. In the two-way case, higher currents funnel into the navigation channel near the channel shoal (Figure 10c). Overall, the average current speed within the entrance is 2.1 m/s, about 0.1 m/s less than in the one-way case. The uncoupled case shows higher currents over the shallower north side of the entrance channel than the one-way case, while the one-way case showed higher currents in the navigation channel. In general, the two-way case shows higher currents in the navigation channel than the one-way case, particularly near the channel shoal and into the turning basin, while the one-way case predicts higher currents along the shallower north side of the entrance and over the channel shoal (Figure 10d). Differences in current magnitude between one-way and two-way coupled cases in the navigation channel at this time average 0.54 m/s and are as large as 0.78 m/s.

Associated wave heights at peak flood are shown in Figure 11. The wave heights for these one-way and two-way cases are similar up to the channel shoal, at which point the two-way coupled solution predicts significantly larger waves than the one-way coupled case for the whole Entrance Bay. These larger waves presumably break, because within the bay we see larger waves in the one-way case. The mean difference in wave height for the Entrance Bay is 0.54 m.

4. Time Series Along Transects

Given the potential complexity associated with the nonlinear interaction between waves and tides, we compare time series from one- and two-way interactions at fixed locations. In particular, time series data are examined at specific nodes along three distinct cross-channel transects (Figure 12). Wave height and current velocities are extracted at these points for each of the cases presented above. One and two-way coupled model solutions and differences are plotted as time series for the five nodes nearest the navigation channel for each transect.

Under the highest energy wave spectra, differences in wave heights and currents are observed at transect nodes for all tide stages. Further differences are brought to light with the time series plots. Figure 13 shows time series of vector velocities along Transect 2 for one-way and two-way coupled models under large, down-jetty wave conditions (additional information on Transect 1 and 3 can be found in Claasen 2003). Current differences are greater between coupling cases for the first 12 hours of observation and lesser beyond that time. In addition, there is a substantial phase difference in the first part of the day that disappears in the second half. To determine whether or not these results are a consequence of the coupled models still approaching a stable solution, these model runs are extended out an additional day. The same results are observed: larger model differences earlier in the day and smaller differences later in the day. At this transect location, the peak difference is 2.11 m/s and the mean rms* difference is 0.63 m/s. Over the second half of the observation day, the peak difference between velocities along transect 2 is reduced to 0.24 m/s. Mean rms* differences for the last twelve hours are also reduced to 0.09 m/s and 0.11 m/s for Transect 1 and Transect 2, respectively. Further back in the entrance, at Transect 3 (Figure 13), the peak velocity difference is 0.09 m/s with the mean rms* difference of 0.04 m/s. Phase shifts among the two model runs are much less obvious. Our interpretation is that the flow patterns within the entrance can be very complex in space and time under strong wave and tidal flow conditions, but the effects are much less as one moves further into the bay.

Summary

The entrance to Humboldt Bay is, as expected, a place where waves and flows can interact with each other to a significant extent. Examination of the above climatological cases showed that differences in current fields between model coupling cases increased as the wave energy increased. For the lowest wave conditions, one-way and two-way coupled current magnitude fields shared the same basic features. For the 1.7-m waves, the maximum difference in current velocity for all cases was 0.31 m/s. Mean differences in current speeds were 0.08 m/s near slack tide, with the greatest disparities concentrated around bathymetric features such as the channel shoal. For both of the larger input wave cases the basic shape of the current field changed between coupling modes.

The wave-height fields were most affected by bathymetry, current velocity (for the two-way coupled model), and offshore wave direction. Both wave height and current fields showed significant differences in solutions between model coupling modes near bathymetric features, such as the entrance to the navigation channel and the channel shoal for the larger input wave energies.

Applying the above information to the Humboldt inlet, it was clear that the two-way coupled model was required for greater accuracy under most wave conditions. The largest wave climatology cases discussed in this paper were less than one-quarter as energetic as some of the waves observed regularly near the Humboldt Bay entrance (although some of this energy may dissipate due to wave breaking before the waves reach the entrance). The large tidal prism and narrow entrance at Humboldt Bay combine to produce high-velocity currents in and out of the bay's mouth.

Based on the results of this study and the more detailed analysis of Claasen (2002), we recommend that the two-way coupled model be used at Humboldt Bay when the wave conditions are comparable to spring or winter climatology (H_s > 2.4 m; T_p > 11 s), or when moderately large waves (H_s~ 1.8 m) arrive at significant angles to the entrance (> 20° away from channel alignment), or in the presence of moderate tidal currents (> 1.5 m/s).

Acknowledgments

We would like to thank Nick Kraus, Mitchell Brown, and Mary Cialone of CIRP/USACE and Adele Militello of Coastal Analysis for their support and input on this project. Funding was provided through a contract with the USACE (BAA-01-3321).

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*root mean square

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Figures

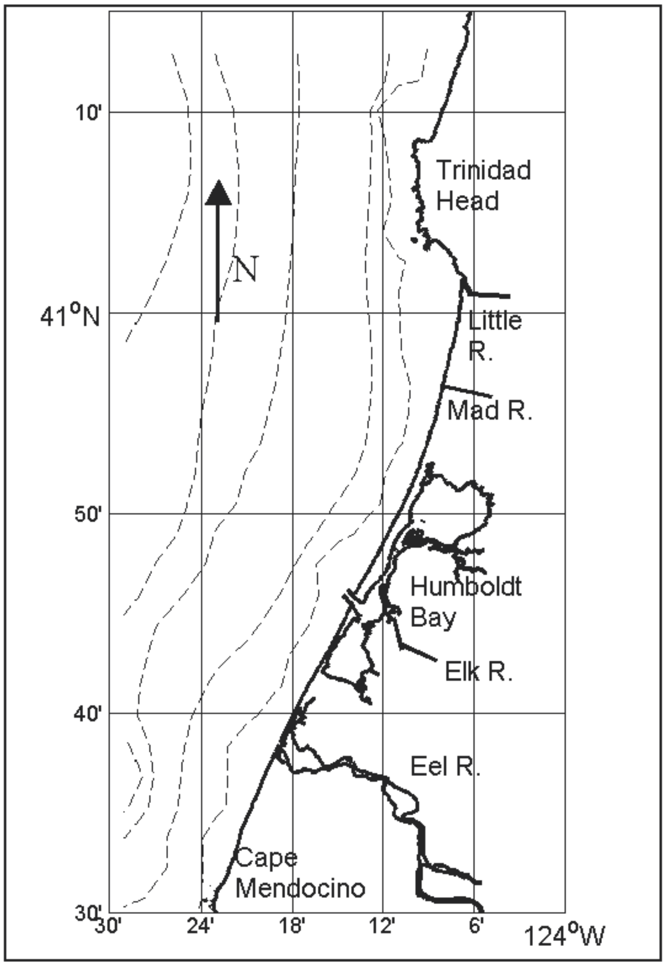

Figure 1. Northern California coastline, including Humboldt Bay. Dashed lines represent isobaths at 20, 50, 100, 200, and 500 m (derived from a subset of the GTOPO30 [Smith and Sandwell 1997] topographic data set).

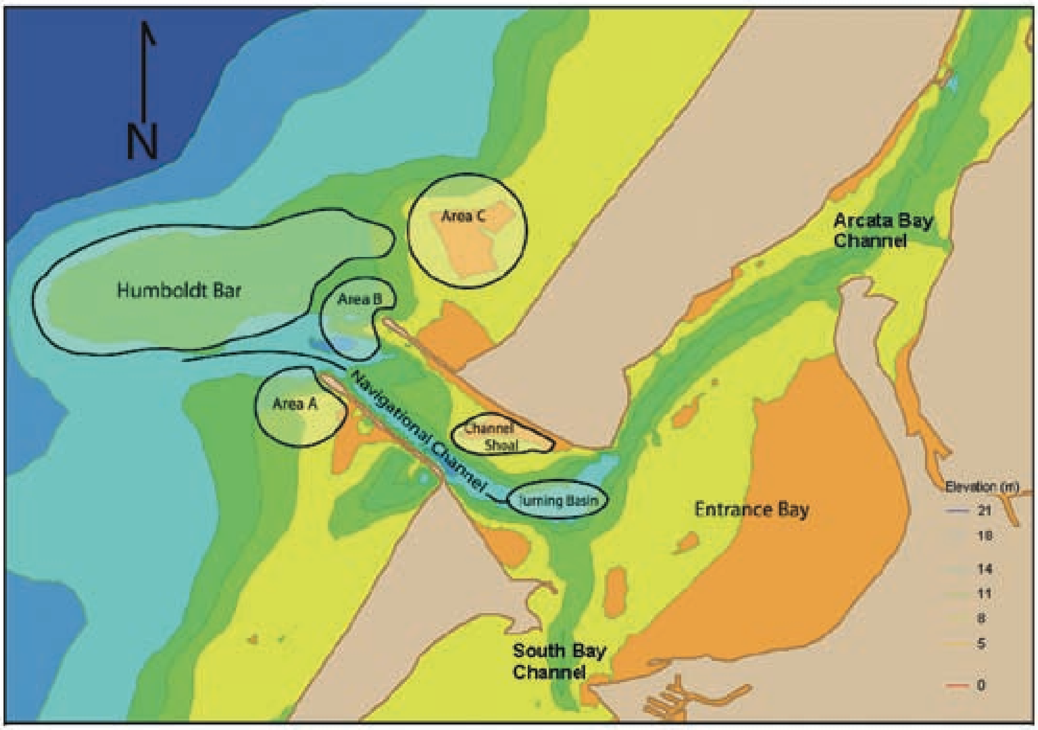

Figure 2. Bathymetry and coastline within the vicinity of the Humboldt Entrance Bay. Several key features are identified.

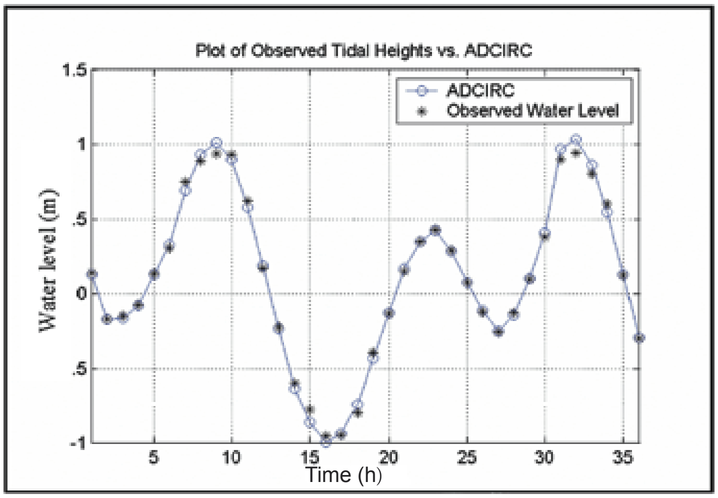

Figure 3. Typical ADCIRC model output compared to observations at the NOAA tide gauge 9418767 (40° 46.0′ N, 126° 13.0′ W) on the north spit of Humboldt Bay.

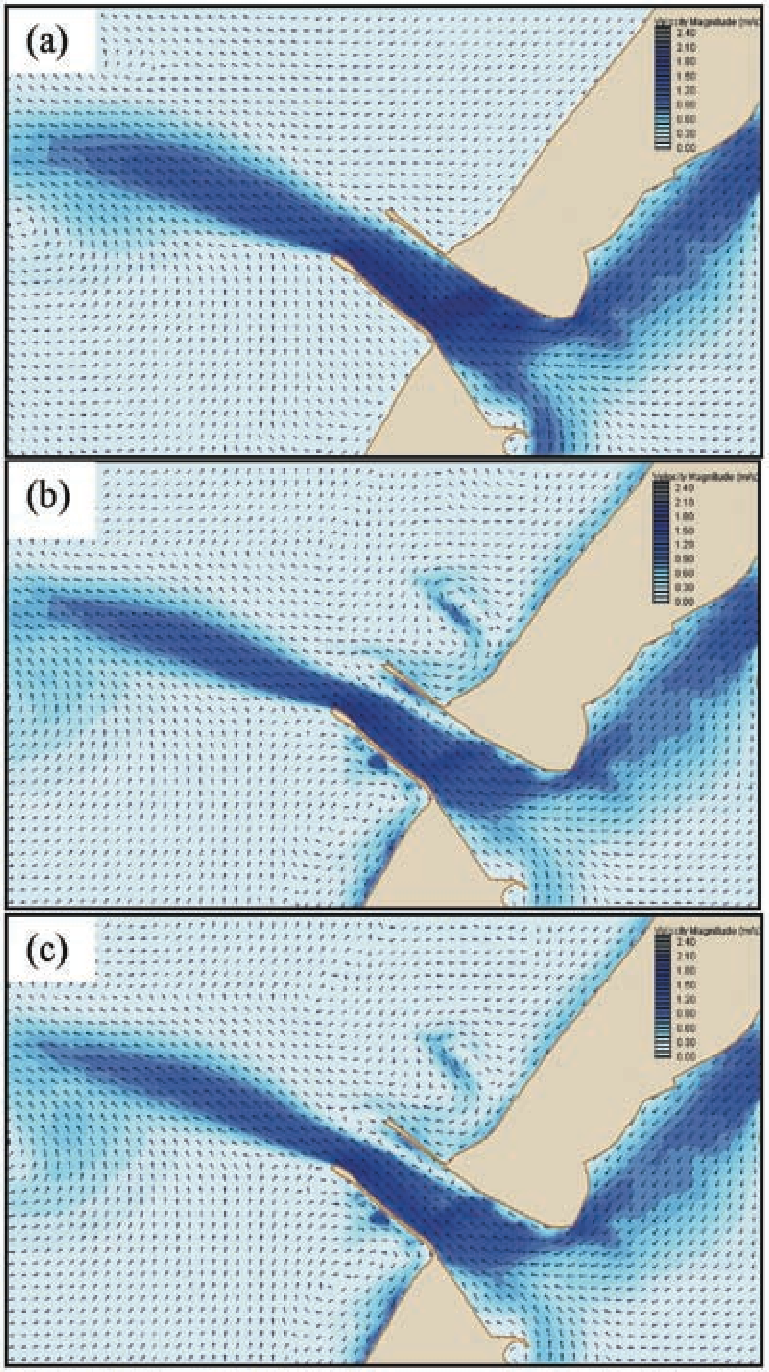

Figure 4. Velocity field at peak ebb tide for: (a) all uncoupled model runs; (b) small waves, down-jetty, one-way; (c) small waves, down-jetty, two-way. Color scale describes current magnitude; arrows identify current direction.

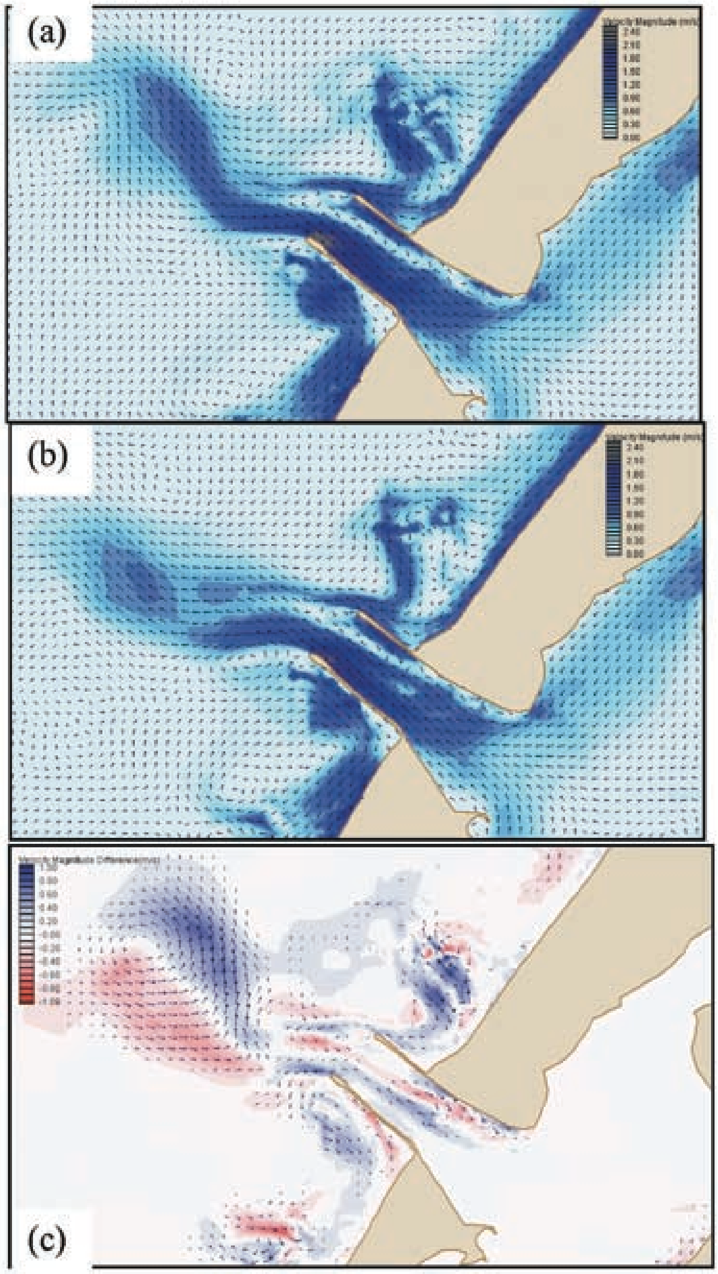

Figure 5. Velocity field at peak ebb tide for large waves, down-jetty: (a) one-way coupled; (b) two-way coupled; (c) difference in current magnitude (two-way minus one-way; blue and red indicate higher speeds in the two-way and one-way models, respectively).

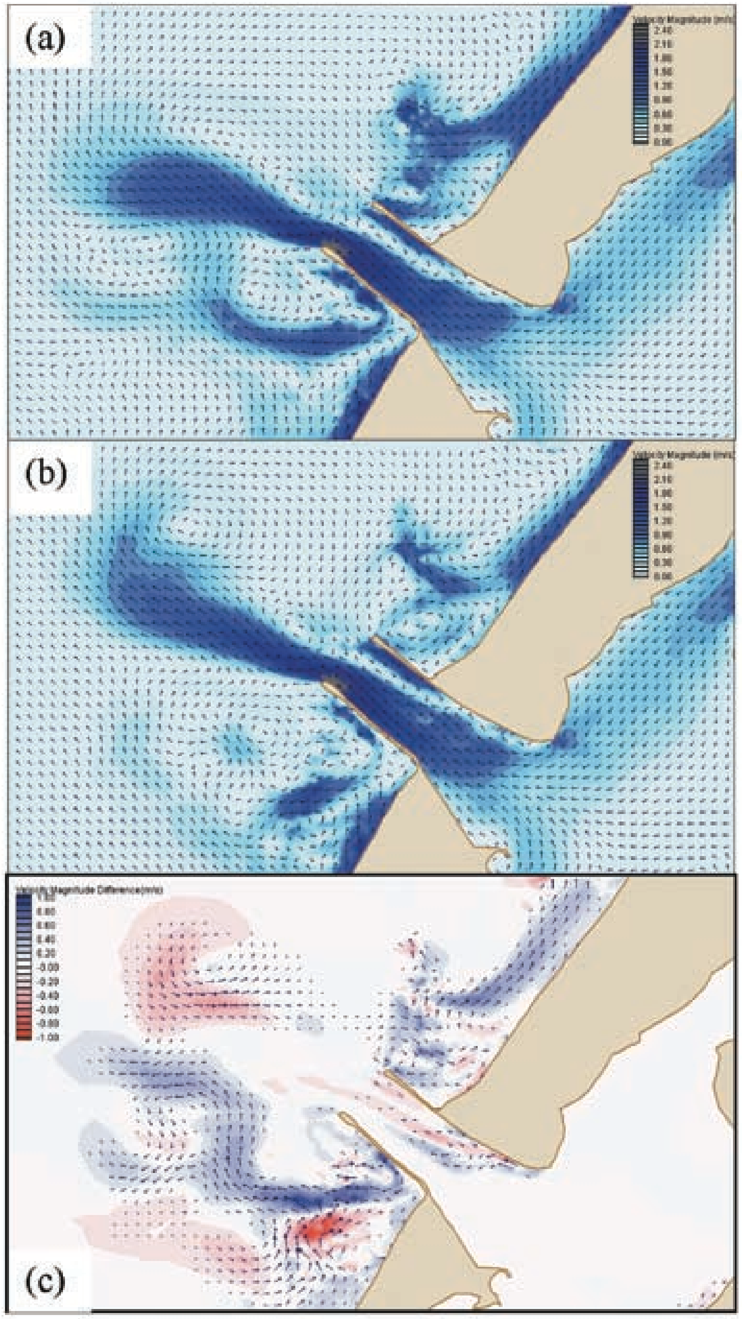

Figure 6. Velocity field at peak ebb tide (large waves, cross-jetty): (a) one-way; (b) two-way; (c) difference in current magnitude (two-way minus one-way; blue indicates higher speeds in the two-way model; red indicates higher speeds in the one-way model).

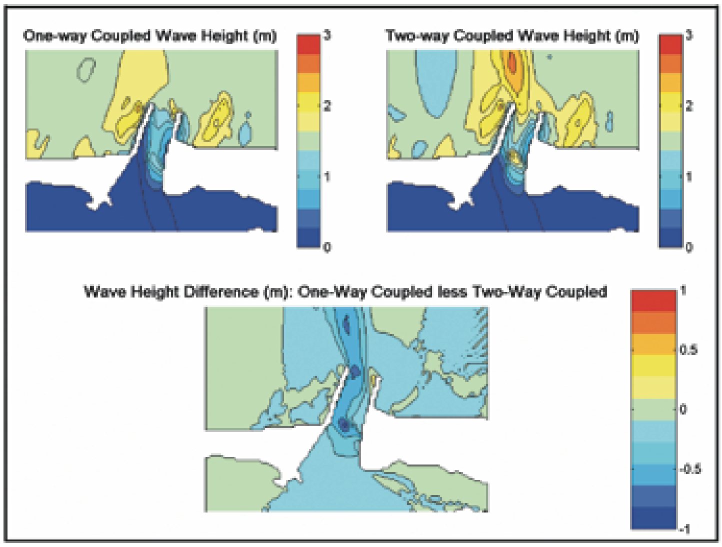

Figure 7. Comparison of wave-height fields for small, down-jetty waves at peak ebb. Two-way coupled solutions were more than 1.1 m higher over the channel shoal and more than 0.9 m higher in the navigation channel than one-way coupled solutions.

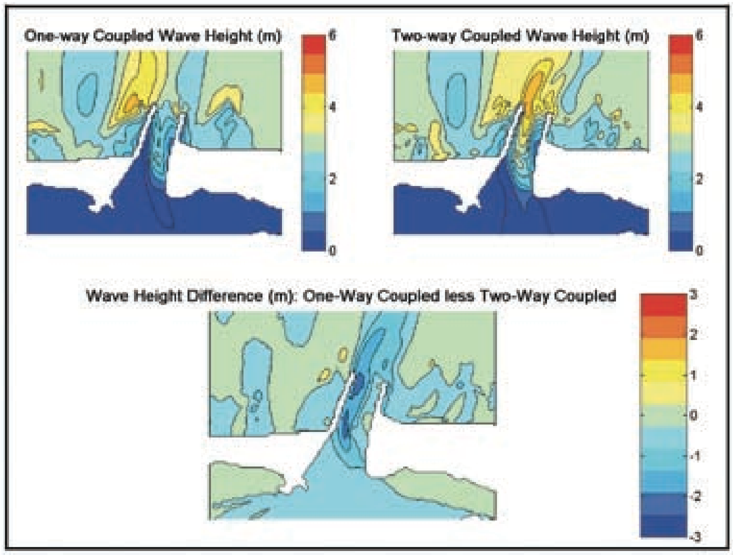

Figure 8. Comparison of wave-height fields for large, down-jetty waves at peak ebb. Two-way coupled solutions were more than 1.9 m higher over the channel shoal and more than 1.7 m higher in the navigation channel than one-way coupled solutions.

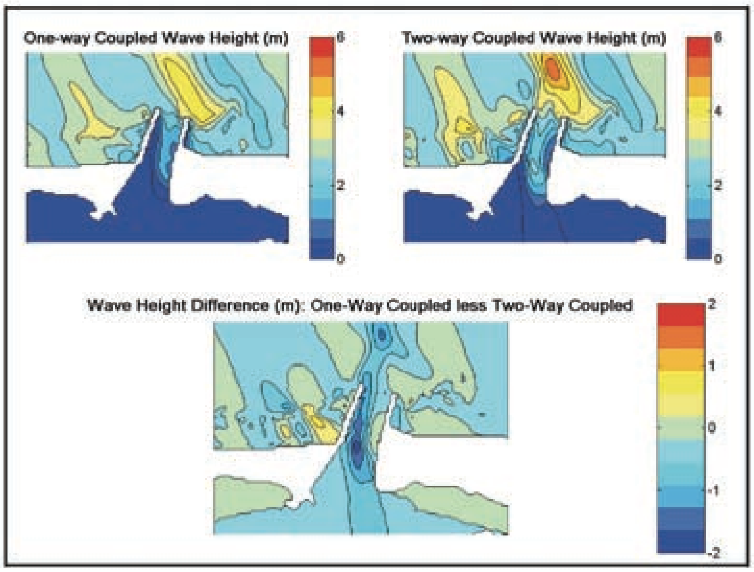

Figure 9. Comparison of wave-height fields for large, cross-jetty waves at peak ebb. Two-way coupled solutions were more than 1.9 m higher over the channel shoal and more than 1.7 m higher in the navigation channel than one-way coupled solutions.

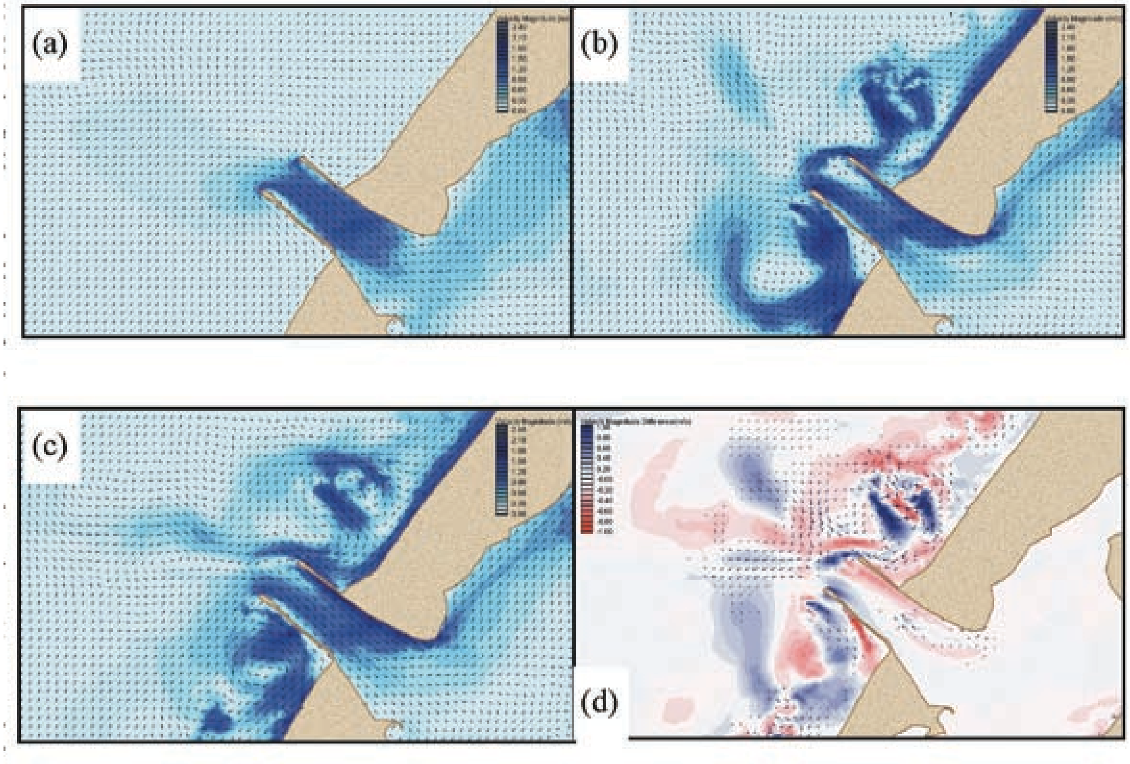

Figure 10. Velocity field at peak ebb tide for large waves, down-jetty: (a) uncoupled; (b) one-way; (c) two-way; (d) difference in current magnitude (two-way minus one-way; blue indicates higher speeds in the two-way model; red indicates higher speeds in the one-way model).

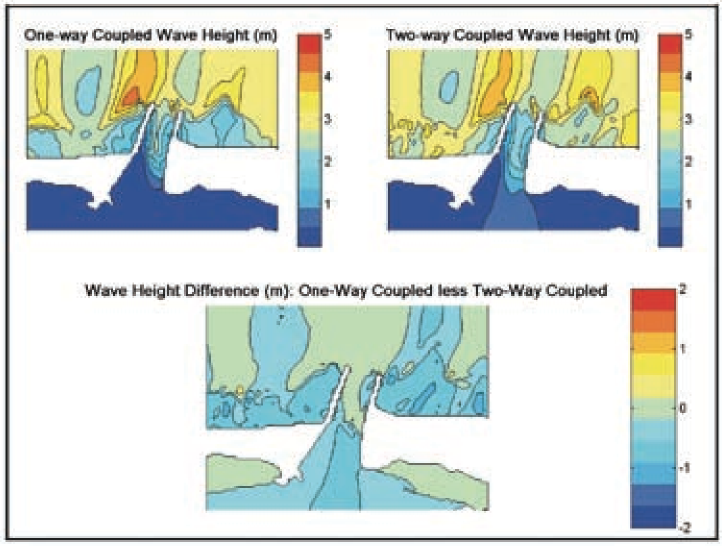

Figure 11. Comparison of wave-height fields for large, down-jetty waves at peak flood. Two-way coupled solutions average 0.61 m higher than one-way solutions over the Entrance Bay.

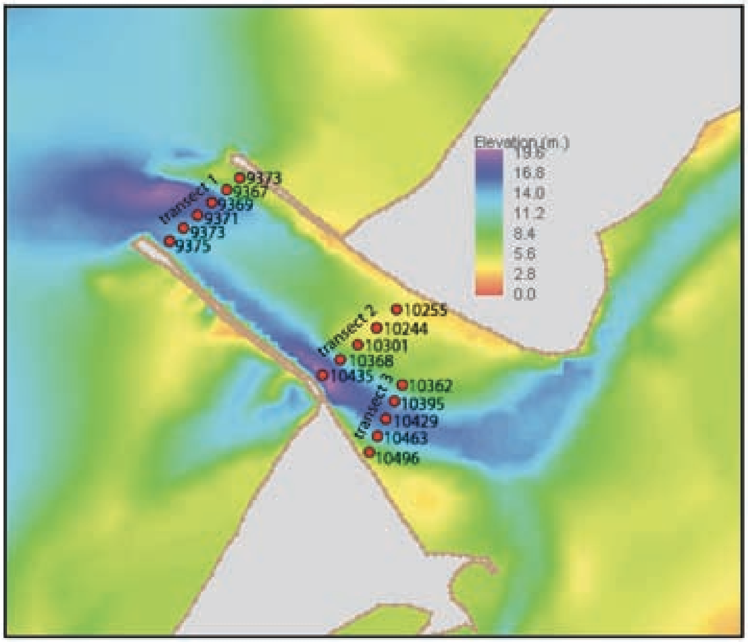

Figure 12. Transect nodes along with associated ADCIRC node numbers.

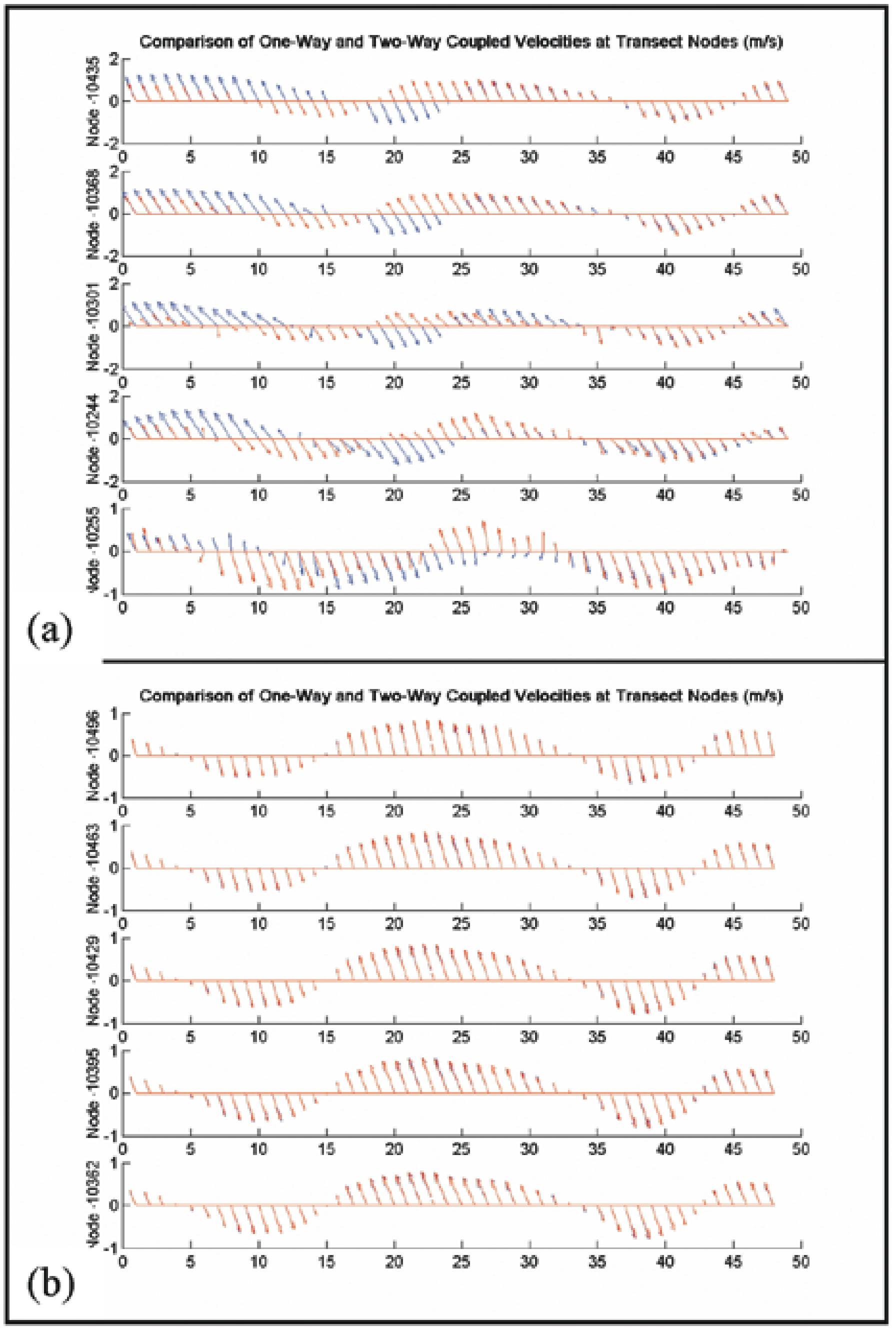

Figure 13. Comparison of half-hourly vector velocities along transect nodes for one-way (blue) and two-way (red) coupled model runs for large, down-jetty waves: (a) Transect 2; (b) Transect 3. Numbers along the x-axis denote semi-hourly time steps. The y-axis scale is in m/s.

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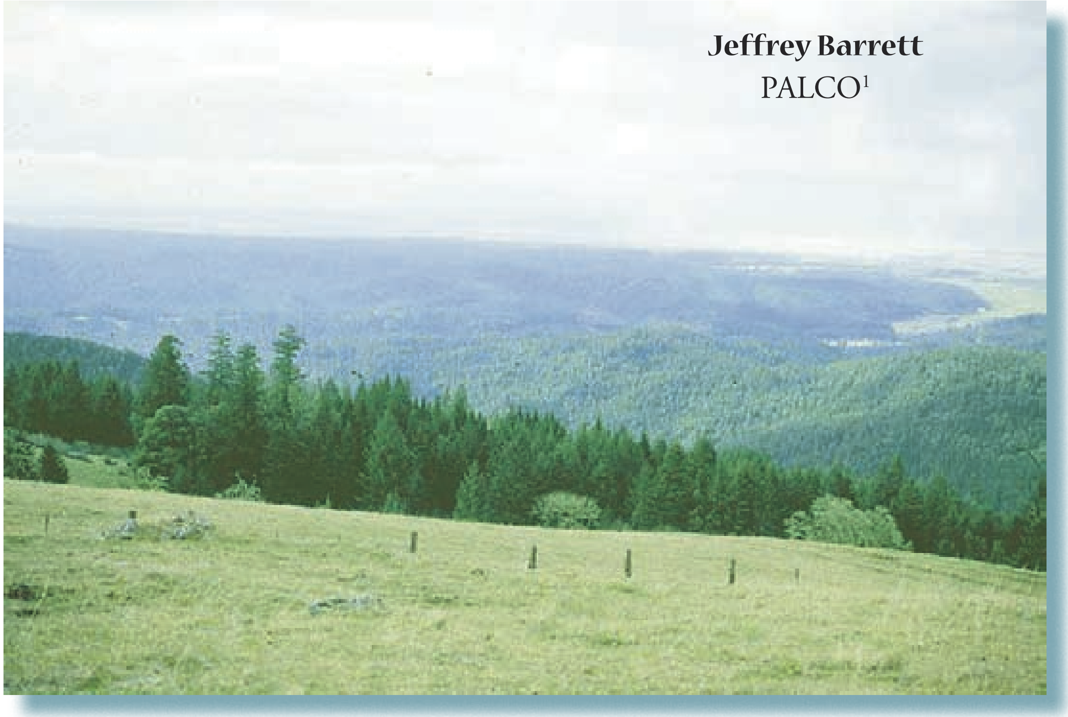
Sediment Inputs to Humboldt Bay



Jeffrey Barrett
PALCO[1]

Photo Credits

(Above) Freshwater drainage looking west to Humboldt Bay from Kneeland Ridge. Courtesy Salmon Forever; (p. 37) © Andy Huber /GROWISER); (p. 44) California Geologic Survey.

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Abstract

Sediment budget estimates for the two largest watersheds draining into Humboldt Bay, Freshwater Creek and Elk River, are reviewed to derive sediment inputs to the bay from upslope areas. These data sets indicate that geologic formation is a strong determinant both of total sediment loading rates, and of the grain-size distribution of those sediments. Wildcat formation sediments, which dominate the Elk River, are highly erodible siltstones and mudstones that yield sediments composed almost entirely of silts and clays with relatively high transport rates. By contrast, Franciscan and Yager formation sediments, although containing silts and clays, and which are common in Freshwater Creek, also produce gravel and cobble-sized materials with much slower transport rates.

Estimates of sediment yield for Elk and Freshwater are on the order of 140–350 metric tons/km^2/year (400–1,000 tons/mi^2/yr), with higher rates in the Wildcat-dominated Elk River system than in Freshwater Creek. Several sources suggest that current sediment yield from these watersheds is at least double natural levels. Extrapolation of an average sediment yield of 193 metric tons/km^2/yr (550 tons/mi^2/yr) and to the entire drainage area of Humboldt Bay (approximately 324 km^2 or 125 mi^2) yields an estimate of total sediment delivery to Humboldt Bay of 62,532 metric tons/yr (68,750 tons/yr). Of this, approximately 75% consists of silt, much of which is likely transported through the bay into the ocean. Data from the United States Army Corps of Engineers (USACE 2006*) can be used to derive an estimate of annual dredging in Humboldt Bay of 1.2–2.4 million metric tons (1.3–2.6 million tons). Given these data, it is apparent that much of the sediment being removed from Humboldt Bay has origins from areas other than the upslope lands draining directly to the bay.

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*Paper was reviewed and updated since presentation to include relevant citations.

Introduction

The Humboldt Bay Symposium was organized, in part, to develop a better understanding of how the bay is being managed, and to identify potential new directions for that management. A key issue in the bay's management is the annual dredging conducted by the United States Army Corps of Engineers (USACE) to maintain the system of navigational channels. Several companion studies within this symposium examined the effects of in-bay currents on sediment movement and accumulation, the potential effects of the Eel and Mad Rivers, located south and north of Humboldt Bay respectively, on sediment delivery to the bay, and evaluations of the biological effects of sediment accumulation and dredging. This study reviews information collected during watershed analysis studies of the Freshwater Creek and Elk River basins to derive some understanding of the quantity and types of sediment being delivered to Humboldt Bay from upland areas.

Specific questions examined in this study include:

(1) What natural and anthropogenic factors are most important in determining sediment delivery rates to Humboldt Bay?

(2) What are the total rates of sediment delivery from these basins to Humboldt Bay?

(3) What size sediment is being delivered to the bay, and what is the relative mobility of those sediment fractions?

(4) How does yield in Freshwater and Elk compare to other watersheds on the North Coast of California?

(5) If the sediment yield from Freshwater and Elk is extrapolated to the entire watershed area of Humboldt Bay, what is the total estimate of sediment delivery from upland areas and how does this compare to sediment amounts being removed from the bay by annual dredging?

Study Area

Pseudotsuga menziesii

The Pacific Lumber Company (PALCO) owns approximately 91,000 hectares (225,000 acres) of coastal redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii)* forests in northwestern California approximately 160 km (100 mi) south of the Oregon border (Figure 1). Company lands are zoned for commercial timber production as their sole use. Although water quality research and monitoring are being conducted across the ownership, this paper focuses on efforts in the two largest basins that drain directly to Humboldt Bay, Freshwater Creek and the Elk River, which represent roughly 25% and 42% of the 324 km^2 (125 mi^2) drainage area of the bay, respectively.

The Freshwater Creek watershed is a 81 km^2 (31 mi^2) drainage basin located approximately 5 miles east of Eureka, California, in Humboldt County. Major tributaries of Freshwater Creek include Cloney Gulch, South Fork Freshwater Creek, Little Freshwater Creek, McCready Gulch and Graham Gulch. Approximately 77% of the watershed is owned and managed for timber by PALCO. Private residences and several ranches comprise most of the remainder of the land ownership in the basin.

The Elk River watershed is a 137 km^2 (53 mi^2) watershed located approximately 7 miles southeast of Eureka in Humboldt County. Elk River drains into Humboldt Bay at the southern end of Eureka. Major tributaries include the North Fork, South Fork, Bridge Creek, and North Branch North Fork. The Elk River is managed for timber largely by PALCO, which owns approximately 66% of the watershed. Remaining portions of the watershed are parklands owned by the Bureau of Land Management, commercial timberlands owned by Green Diamond Timber Company, and a number of small residences and large cattle and dairy operations.

Methods

The Elk River and Freshwater Creek watershed analyses were prepared in conjunction with PALCO's Habitat Conservation Plan (HCP). Under the terms of the HCP, a team of state, federal, and company scientists evaluated watershed conditions in Freshwater and Elk from 1999 to 2003 and 2003 to 2004, respectively, following methods in PALCO's HCP (2000). These, in turn, follow the general approaches contained in the Washington Department of Natural Resources Methodology (WDNR 1997), but with modifications more appropriate for locations within the redwood zone.

With respect to sediment budgets, these watershed analyses included landslide inventories, modeling of surface erosion from roads using SEDMODL (WDNR 1997), modeling of surface erosion from hill slopes using the Water Erosion Prediction Project (Elliot et al. 2000), and in Freshwater, estimates of bed load and suspended sediment transport rates. The results of these watershed studies have been published and distributed to the public (PALCO 2003, 2004b).

Estimates of sediment production used here are from the period 1987 to 1998 (Freshwater) and 1987 to 2000 (Elk). These dates correspond to aerial photographic surveys, and are generally coincident with the use of contemporary state forest practice rules, although the periods almost entirely precede implementation of more protective practices associated with PALCO's HCP.

Each sediment budget allocated sediment sources to natural or management-related sources, thereby allowing some estimate of the degree to which management has increased sediment inputs in these basins. Similarly, soil surveys for Humboldt County (McLaughlin and Harradine 1965), and site investigations in the Elk and Freshwater analyses were used to estimate the grain sizes of sediments being delivered from the watersheds. Sediment transport studies were conducted as part of the Freshwater analysis, extrapolated to Elk River, and used in both basins to make estimates of the mobility of sediments entering watercourses and, qualitatively, of sediment mobility within Humboldt Bay.

Sediment yield in Freshwater and Elk River were subject to two comparisons to other data sets. First, sediment yields for these basins were compared to sediment yields for other watersheds on the North Coast using work from the California Geological Survey (CGS; CGS 2002) that, in turn, contains summary data from the U.S. Environmental Protection Agency (EPA) prepared as part of its Total

Maximum Daily Load (TMDL) studies in the region.

Second, yields from Elk and Freshwater were averaged, and this average yield rate was then applied to the total area draining to Humboldt Bay. Due to changes in the dominant geologic formations, this likely results in an overestimate of sediment yield rates for areas in the northern portion of the drainage basin of the bay (e.g., Jacoby Creek) and an underestimate for lands located in the south portion (e.g., Salmon Creek). Thus, the analyses of sediment yield presented for the entire bay are illustrative, but should be viewed with an appropriate level of caution. The resulting estimate of total sediment yield was then compared to the total amount of sediment being dredged from the bay each year, and the amounts being removed from just the interior channels of the bay. These dredging figures were derived using data presented at the symposium by the USACE on the volume of sediment that has been dredged annually from Humboldt Bay (Connor 2004). After deleting the outlying years of 1999 and 2003, figures for the period were used to estimate an approximate range of total sediment removal for the period 1993–2003. Due to high variance among years, a range was selected. For interior channels the average volume dredged was estimated for the period 1991–2003. All volumetric estimates were converted into estimates of mass using a conversion of 2,600 kilograms/cubic meter (4,382 pounds/yard^3).

Results

Natural Factors Affecting Sediment Yield

The watershed analyses found large differences in sediment yield, sediment transport rates, and sediment grain sizes associated with the major geologies in the upslope area.

In particular, the Wildcat formation, which is composed predominantly of poorly consolidated mudstones and siltstones, had high surface erosion rates, numerous mass wasting-related sediment sources, and delivered primarily silts and clays to streams. Wildcat-derived soils can be thought of as consisting almost entirely of silts and clays with relatively low amounts of sand and almost no gravel or cobble (Figure 2). Wildcat-derived streams are generally low gradient and have bottoms composed of sands, silts and clays. Because the majority of the sediment yield to streams is composed of very small particles, it is likely that most sediment is transported predominantly as suspended sediment or “wash load” during high flows from the watersheds and into Humboldt Bay.

By contrast, the Franciscan sandstone and Yager formations in Elk and Freshwater had lower rates of surface erosion. Franciscan- and Yager-derived soils also contain a high proportion of silt and clay, but have much higher levels of sand, gravel, and cobble-sized material (Figure 2). Accordingly, stream reaches underlaid by these formations often contain gravels, cobbles and boulders, and have higher gradients. Although a majority of the sediment from these formations is fine grained, and therefore has high transport rates, the larger clast sizes (i.e., gravel and larger) have much lower sediment transport rates and may require decades to be transported to Humboldt Bay.

Freshwater Creek aptly demonstrates the effects of geology on sediment yield. The Freshwater fault approximately bisects the basin, with Wildcat formation geologies and soils to the west of the fault, and Franciscan and Yager geologies and soils to the east of the fault (Figure 3). Given its more poorly consolidated and fine-grained nature, areas underlaid by Wildcat geology were estimated to have much higher rates of potential surface erosion than areas underlaid by Franciscan and Yager formation (Figure 4). By contrast, hill slope landslide rates were often similar (e.g., 5.19 landslides/km2 in Freshwater) on both Wildcat and Franciscan sediments. However, areas underlaid by Wildcat formation generally consist of low relief, rolling terrain, while the Franciscan and Yager formations are associated with much steeper and higher elevation typography with stream channels frequently having higher gradients and "v-notch" shaped drainages. Therefore, based on typography, one would expect higher hill slope landslide incidences in areas underlaid by Franciscan and Yager formation geologies. Thus, the relative parity of landslide rates among the geologic formations demonstrates the relative susceptibility of Wildcat formation geologies to mass wasting processes.

Anthropogenic Influences

The Freshwater Creek and Elk River watershed analyses both found that the anthropogenic activities associated with timber harvesting had increased sediment yields over naturally occurring levels. Anthropogenic sources of sediment represented approximately 70% of total sediment yield in Freshwater, and approximately 55% of sediment yield in Elk River. Thus, in both basins management activities have approximately doubled to tripled total sediment delivery to Humboldt Bay.

The particular sources of sediment differ by basin, however. In Freshwater Creek road-surface erosion was, by far, the most important source of management-related sediment (Figure 5). The second most important management source was landslides associated with roads. Together, roads represented more than 88% of all management-related sediment delivery in Freshwater. All other management-related sediment sources, including hill slope landslides and erosion from harvested areas, were relatively unimportant.

In Elk River, by contrast, landslides were the most important source of management-related sediment (Figure 6). Landslides from harvested areas and from roads and management features alongside streamside areas were all approximately of equal importance as management-sediment sources in Elk. Road surface erosion, however, was a relatively unimportant sediment source. As in Freshwater, surface erosion in harvested areas and other sediment sources were relatively unimportant.

In evaluating anthropogenic influences then, it is clear that roads are a significant sediment source, even if the particular mechanism of sediment generation and delivery differs by area. Given that timber harvesting has occurred in the Elk and Freshwater basins for over 100 years and that, consequently, many of the roads were constructed with little or no environmental consideration, this finding is not surprising. Somewhat differently, landslides from hill slope and streamside areas do not appear to be important within Freshwater Creek, nor from certain portions of the Elk River basin dominated by more stable geologic types. Thus, although the sediment yield from hill slope and streamside landslides is important in Elk River, and by extension is likely to be important within other upland areas of Humboldt Bay, the watershed analyses indicate that its importance may be relatively localized to particular geologic or topographic conditions.

Estimates of Sediment Yield

Estimates of total sediment yield (i.e., natural and anthropogenic sources combined) for Freshwater Creek and Elk River are available from a variety of sources including suspended-sediment studies from Salmon Forever and

PALCO, and from the sediment budgets in the Elk River and Freshwater watershed analyses. In common with many estimates of sediment yield, these values differ significantly from year to year, and from one another (Table 1). In part this is to be expected given differences in storm frequency and intensity from year to year, and due to differences in the natural and anthropogenic conditions already discussed. Still, the majority of estimates of sediment yield are in the range of 131–295 metric tons/km^2/yr (375–843 tons/mi^2/yr) (Table 1). A simple averaging of all the estimates produces a value for sediment yield of about 192 metric tons/km^2/yr (550 tons/mi^2/yr) for the Elk and Freshwater basins.

The entire upland area draining to Humboldt Bay is approximately 324 km^2. The product of this area and the average sediment yield given above provides an estimate of total sediment delivery from upslope areas draining to the bay of 62,532 metric tons/yr (68,750 tons/yr).

Comparison to Other Sediment Yields

The EPA has estimated natural sediment yields of 40–137 metric tons/km^2/yr (115–390 tons/mi^2/yr) for a variety of North Coast watersheds as part of its ongoing program of developing TMDLs. The CGS reanalyzed these data (CGS 2003) and concluded that the estimated natural sediment yield for the watersheds covered by EPA was more likely to be within the range of 105–1,051 metric tons/km^2/yr (300–3,000 tons/mi^2/yr).

The Freshwater and Elk estimates of total sediment yield exceed most of the EPA's estimates of natural sediment yield, which could be expected, given that the comparison is of total yields versus only natural yields. By contrast, the higher values of natural sediment yield calculated by CGS exceed all estimates of total yield for Elk and Freshwater.

A different estimate of sediment yield comes from records of the annual amount of sediment dredged out of Humboldt Bay by the USACE. Because this dredging is designed to restore the depths of navigation channels to fixed levels, this dredging is a *de facto* estimate of the amount of sediment entering Humboldt Bay on a yearly basis. When volumes are converted to mass, these records (Connor 2004) indicate that annual dredging in Humboldt Bay ranges from 1.2 to 2.4 million metric tons (1.3– 2.6 million tons). Some caution must be accorded the higher values, as they are affected by efforts in the past few years to increase the depth of several navigation channels. However, only twice in the past 13 years has dredging removed less than 1.2 million metric tons.

The USACE records separately list the subset of sediments removed from interior channels of Humboldt Bay (USACE 2006*). These estimates are affected to a far lesser degree by efforts to increase the depth of navigation channels because the majority of this effort was focused on the bar and entrance to Humboldt Bay. For the period of 1991–2003 dredging of interior channels has removed as little as 60,000 metric tons (66,100 tons) and as much as 695,800 metric tons (767,000 tons). An approximate average over the period is 348,053 metric tons (383,664 tons).

Discussion

The Humboldt Bay Symposium included a variety of speakers addressing sediment management within the bay, and the effects of sedimentation and sediment management on various biologic and ecological components of the bay. These presentations made it clear that there is a great deal of interest in sediment inputs to

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*Paper was reviewed and updated since presentation to include relevant citations.

Humboldt Bay, and how those sediment inputs might be better managed to support the various natural resource and commercial qualities of the bay.

The work presented here documents several general patterns of sediment input from the Freshwater and Elk watersheds, many of which are likely applicable to most or all of the upland areas draining to Humboldt Bay. First, "geology is destiny;" sediment yields and the relative importance of specific sediment-generating processes are affected by the types of soils and geology that are present. The relative proportions of the dominant geologic types varies by location, with more northern areas such as Jacoby Creek underlaid primarily by Franciscan and Yager formation sediments, and more southern areas such as Salmon Creek dominated by Wildcat formation. Thus, a corollary is that one should expect heterogeneity in total sediment yield, grain sizes of delivered sediment, and sediment transport rates to and through Humboldt Bay from the different watershed areas.

The second general pattern is that management activities have increased sediment yields. This is an intuitively obvious result, but the work here does offer the advantage of estimating the magnitude of this increase; management activities have roughly doubled to tripled sediment delivery rates over natural levels.

The third general pattern, like the first, relates to watershed heterogeneity, in this case to the relative importance of different management effects on sediment yield. In Freshwater, road surface erosion was by far the most important management-related sediment source. Yet in Elk, which lies immediately adjacent to Freshwater, road-surface erosion was unimportant as a sediment source. Instead, three types of mass failure, only one of which had any importance in Freshwater, dominated management-related sediment yields. This pattern, in turn, has broad implications on the adequacy of any regulatory or management approach that assumes uniformity across the landscape. It also supports the value of watershed specific studies.

A final thought relative to watershed patterns of sediment yield can be posed as a rhetorical question: "Is this a lot of sediment?" Certainly on a more global perspective the answer would be yes, as the North Coast of California is widely recognized as having some of the highest natural rates of erosion in North America. When anthropogenic sediment is added to these naturally high rates, the resulting values would be large compared to most landscapes.

However, relative to the North Coast, the estimated yields do not seem especially high. A yield rate of 193 metric tons/km^2/yr (550 tons/ml^2/yr) falls well within the range of natural sediment yield for North Coast watersheds calculated by CGS, and is only 40% greater than the upper estimate of natural sediment yields from the EPA. And other watershed studies conducted by PALCO but not discussed here (PALCO 2002, 2004a) have estimated sediment yields many times larger than those for Elk and Freshwater. Thus, although the watershed analysis studies in Elk and Freshwater both suggest that total sediment yield has been doubled or tripled by management activities, those total yields are still relatively low compared to the yields of some of the other watersheds on the North Coast.

Moving on to Humboldt Bay, the focus of the symposium in which this paper was presented, at least two major conclusions can be made. The first, stated above, is that sediment delivery to the bay has been increased over historic levels, with all of its attendant potential effects. The second, which counters the first, is that this increase may have few physical effects on the bay. Two lines of evidence support this.

One is the size of sediments being delivered from upslope areas; all of the major geologic types draining to Humboldt Bay produce soils that are dominated by silt and clay-sized particles. In addition, many management-related sediment inputs, for example road surface erosion, consist almost entirely of silt and clay-sized particles. Silts and clays being small and light are generally carried as so-called "wash load" during high-flow events, and have a strong tendency to remain in suspension upon entry into Humboldt Bay. In other words, a very large proportion of the material entering Humboldt Bay from upslope sources is probably transported by floodwaters as suspended sediment out of the watershed and into the bay. And, recalling that Humboldt Bay has one of the highest tidal volumes of any estuary on the West Coast, nearly 40% per tidal cycle (Costa presentation, this symposium), silts and clays transported into the bay are likely to be rapidly flushed to offshore areas during normal tidal exchange. Indeed, the talk by Don Tuttle at the symposium contained an aerial photograph demonstrating such flushing—in that case a turbidity plume extending from the mouth of the Elk River and out of the bay.

The second line of evidence comes through comparison of total upslope sediment inputs to the quantity of sediment that must be dredged annually from the bay to maintain navigation channels. Total sediment yield from upslope areas to Humboldt Bay is estimated in this paper as 62, 532 metric tons/yr (68,750 tons/yr). The analysis of dredging records by the USACE demonstrates that a total of 1.2–2.4 million metric tons (1.3–2.6 million tons) are removed from Humboldt Bay by dredging each year. Within interior channels of Humboldt Bay, dredging has averaged 348,053 metric tons (383,664 tons) annually over the past 13 years. Thus, even if all sediment from upslope areas to the bay was retained within the bay, it would constitute only 2.6–5.2% of the total sediment removed by dredging, and an average of only 18% of the sediment dredged from interior channels. Thus, it is clear that sediments entering from the oceanic environment overwhelmingly dominate sediment inputs to Humboldt Bay. By extension, increases or decreases in sediment inputs from upslope areas are likely to make little difference in the physical conditions or morphology of the bay.

None of this is meant to support the conclusion that management-related sediment sources should not be controlled in upland areas. One reason is that, even if upland sediments are unlikely to have physical effects on Humboldt Bay, they may have important biological effects, both by reducing light transmission within the bay, and through effects on the production and export of biota from upland areas to the bay (e.g., salmon smolts). Indeed, for PALCO's lands the entire motivation for conducting the watershed analyses covered by this paper was to determine significant management-related sediment sources, and to then develop specific prescriptions to reduce those sediment sources. Subsequent studies by PALCO indicate that management-related sediment yields are declining as these measures are implemented (K Sullivan, PALCO, pers. comm.). It appears that it is feasible to reduce management-related sediment inputs from upslope areas, which will benefit not just Humboldt Bay but also the stream ecosystems within these watersheds. Similarly, other upland landowners, including Green Diamond Timber Company, the City of Arcata, the Bureau of Land Management, and the Jacoby Land Trust, are conducting their own efforts to reduce management-related sediment delivery into Humboldt Bay. Collectively, there is reason to believe these efforts will yield a more natural sediment delivery rate to Humboldt Bay over the years and decades to come.

Acknowledgements

Particular thanks go to Dr. Matt O'Connor and Kathy Dube, whose data and figures I have liberally borrowed for this manuscript. Similarly, I would like to acknowledge the Watershed Professionals Network and Hart Crowser, Inc. who, respectively, oversaw the preparation of the Freshwater Creek and Elk River Watershed Analyses. I would also like to acknowledge my agency counterparts at the National Marine Fisheries Service, U.S. Fish and Wildlife Service, California Department of Fish and Game, California Department of Forestry and Fire Protection, and the California Geological Survey whose efforts were instrumental in the watershed analyses. Finally, I would like to acknowledge the financial support provided by PALCO, both for the watershed studies and the preparation of this manuscript.

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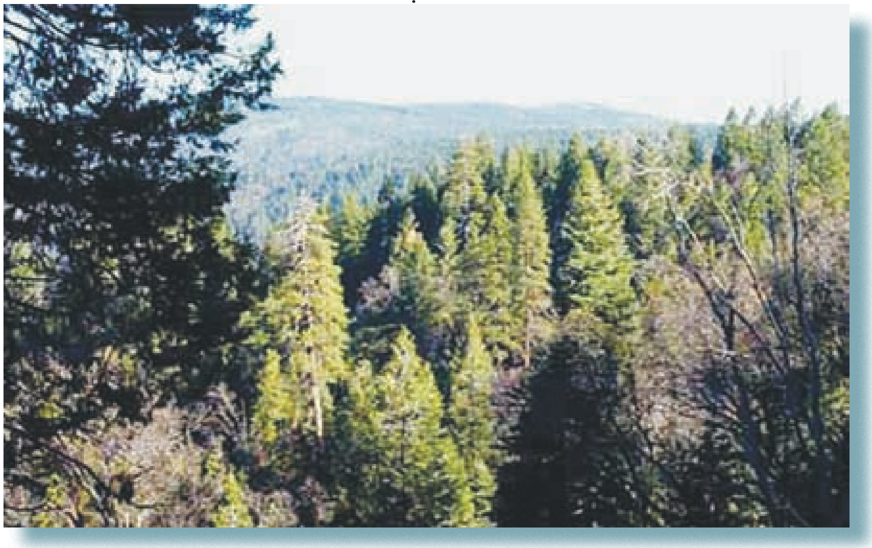

Figures and Table

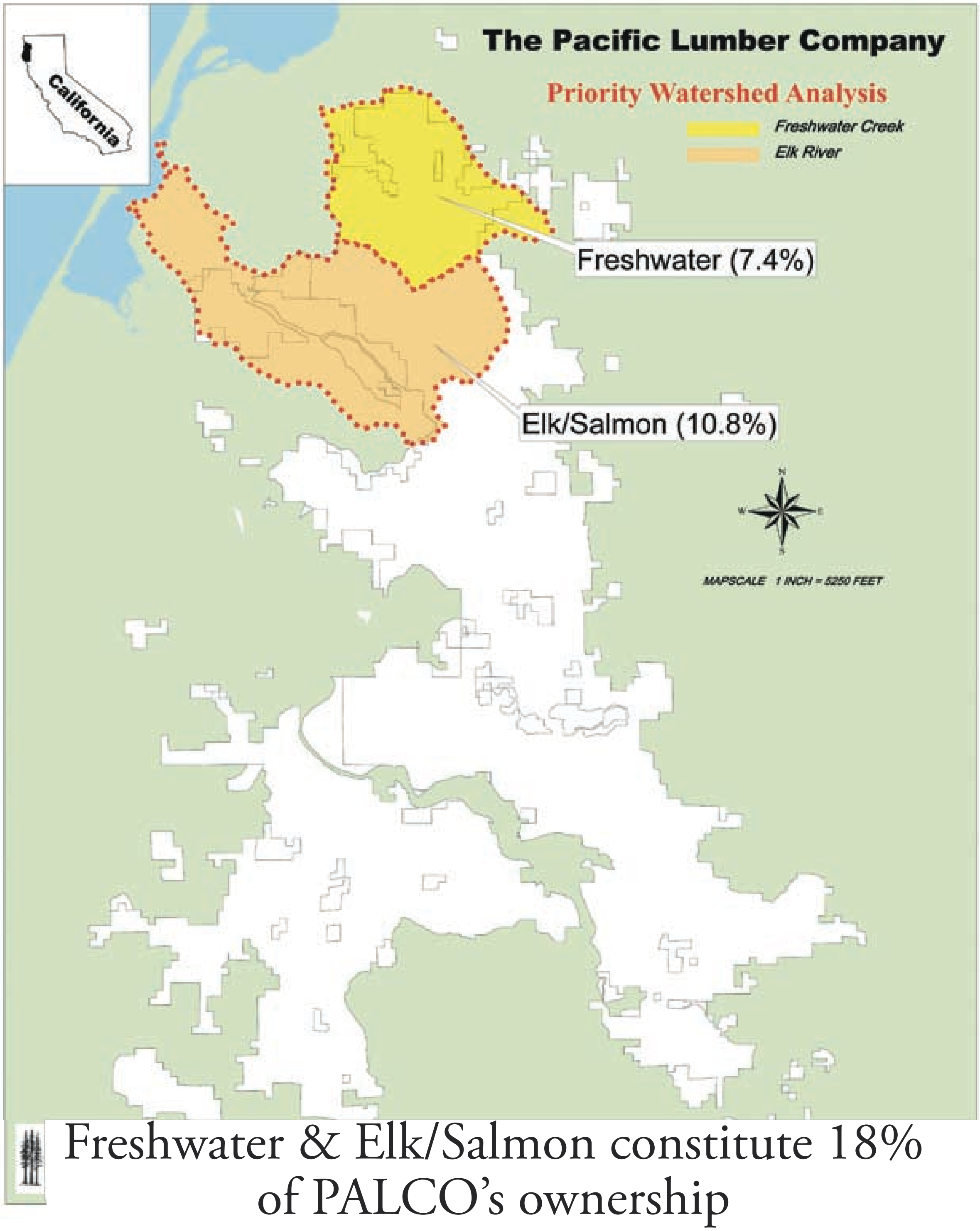

Figure 1. Map of PALCO's ownership.

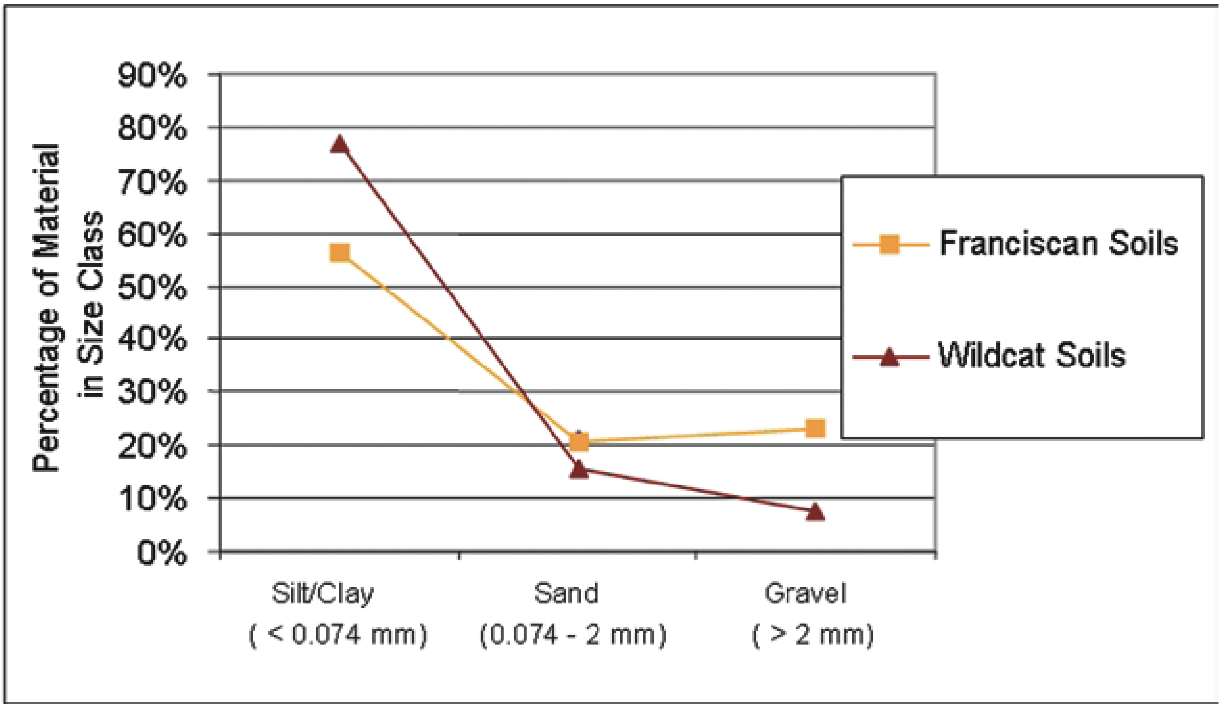

Figure 2. Grain sizes of Franciscan- and Wildcat-derived soils.

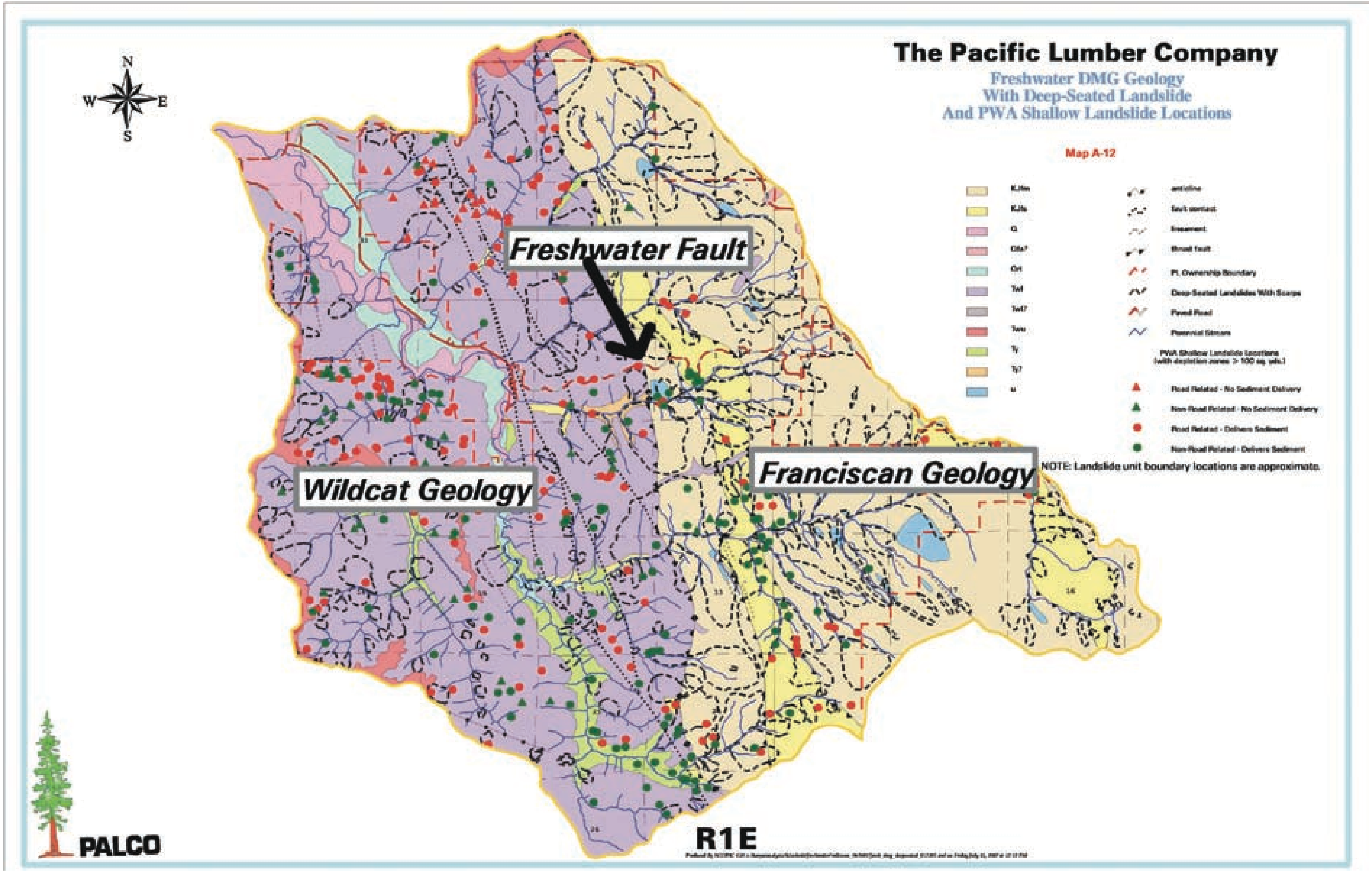

Figure 3. Wildcat, Franciscan and Yager geologies in Freshwater Creek.

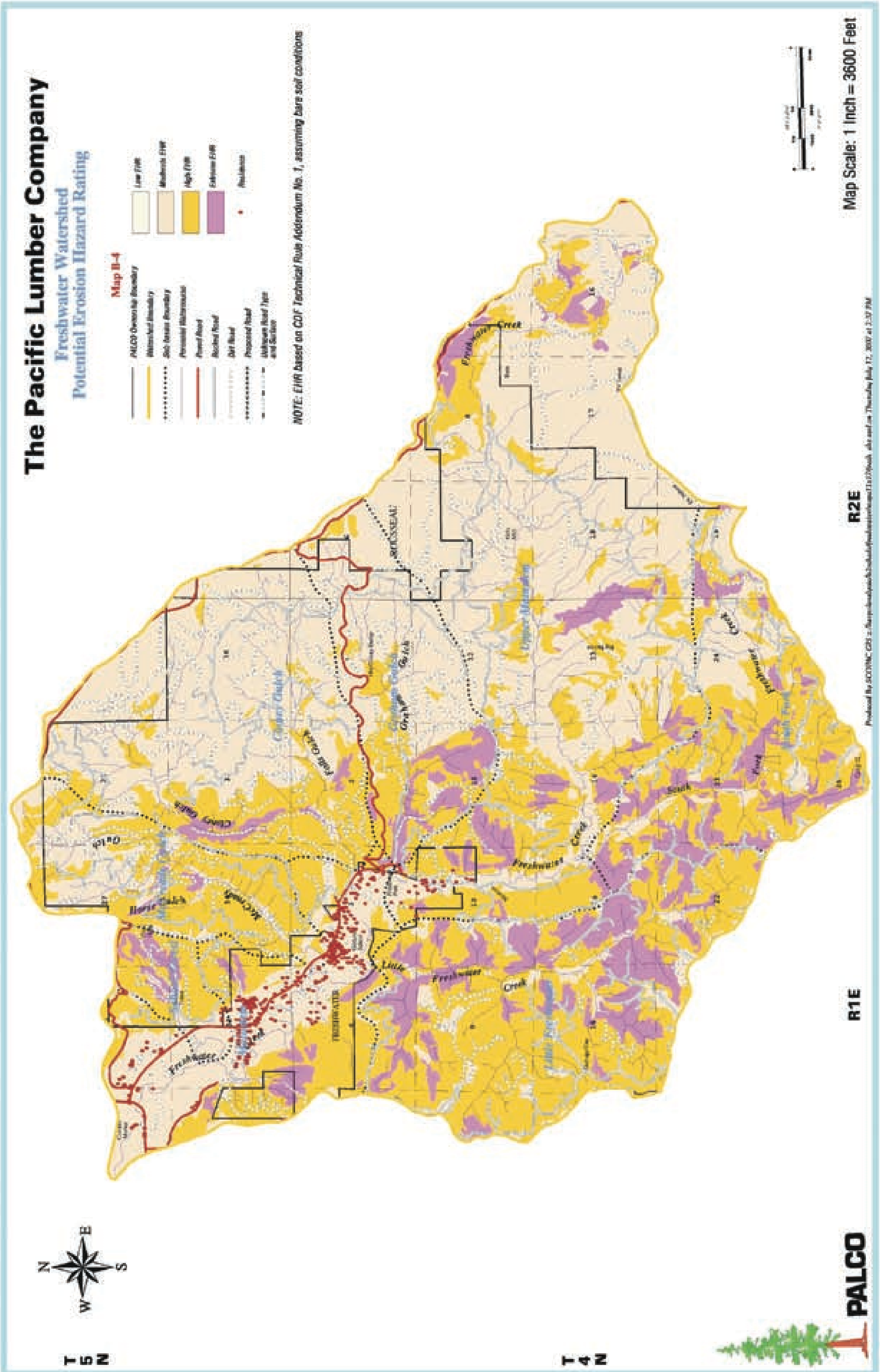

Figure 4. Potential surface erosion depicted in Freshwater Creek.

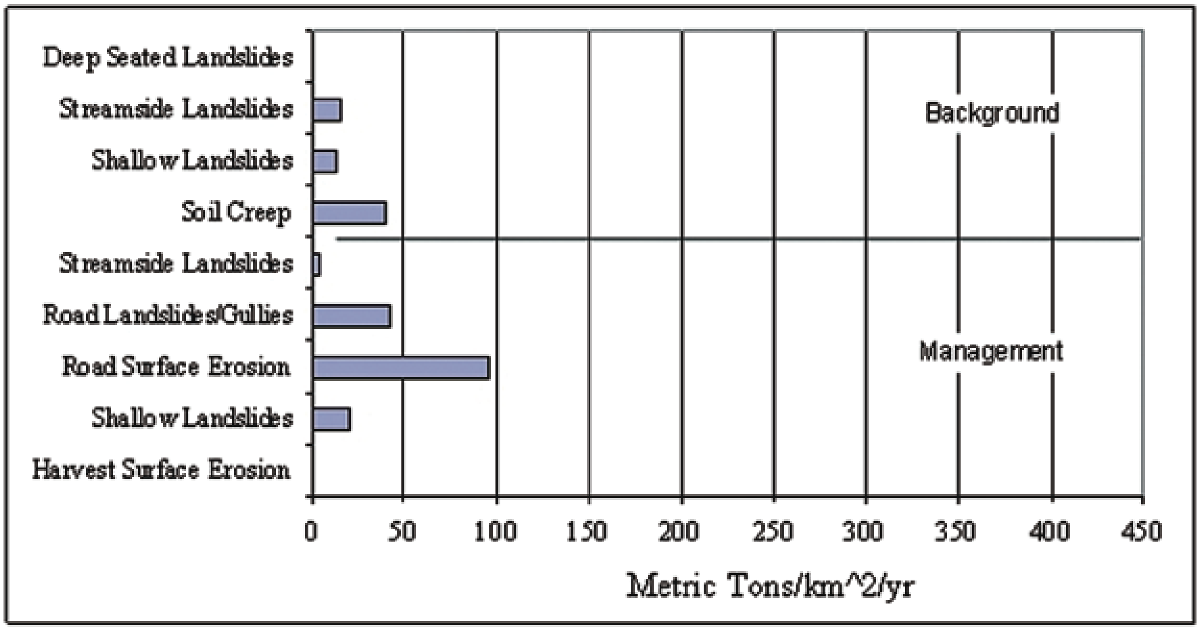

Figure 5. Freshwater Creek Sediment Budget.

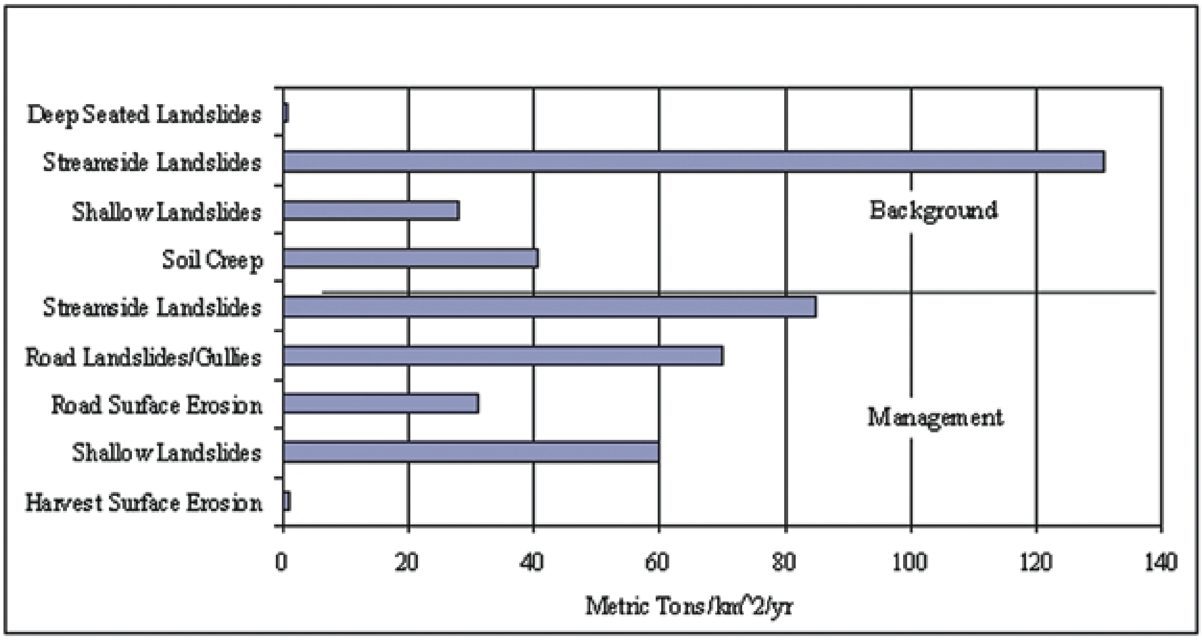

Figure 6. Elk River Sediment Budget.

Table 1. Sediment Delivery Rates to Humboldt Bay.

Data Type	Location/Period	Sediment Yield (metric tons/km^2/yr)	Sediment Yield (t/sq. mi/yr)
Suspended Sediment Measurements	Freshwater 1999[1]	165	~470
	Freshwater 2000[1]	131	375
	Freshwater 2001[1]	14	41
	Elk 2002[2]	425	1,213
Sediment Budgets	Freshwater 1988–1997[3]	144	410
	Elk 1988–2000[4]	295	843
Overall Average		193	~550

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[1] Source: Salmon Forever
[2] Source: PALCO unpublished data
[3] Source: Freshwater Watershed Analysis
[4] Source: Elk River Watershed Analysis

Humboldt Bay, California:

Surface Sediments 2000–2001

Jeffry C. Borgeld[1] **and**
Andrew W. Stevens[2]

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Abstract

The surface sediments in Humboldt Bay are generally distributed with mean grain sizes decreasing with increasing elevation and distance landward from the ocean inlet. Comparison of grain-size data collected during this study with those of a similar survey conducted about 30 years ago (Thompson 1971) suggests that the main tidal channels in 2000–2001 have larger average grain sizes and contain less clay-sized material than in 1970. These changes in sediment size likely reflect an increased propagation of silt- and sand-sized particles away from the ocean inlet into the bay. The suggestion is that the sand-dominated marine sediments, characteristic of the channels in the lower reaches of the bay, have propagated both northward and southward in the main tidal channels and away from the inlet. The major process that drives the transport and sorting of sediments in most regions of the bay is tidal currents. Waves entering the inlet from offshore are also important near the bay entrance.

Introduction

This paper summarizes the results of a re-examination of the surface sediments of Humboldt Bay, California at the start of the twenty-first century. Humboldt Bay is a well-mixed estuarine system located on the North Coast of California (40° 45′ N, 124° 13′ W) approximately 360 km north of San Francisco (Figure 1). The bay morphology developed primarily in response to the active tectonism in the area. The bay is generally described consisting of three sub-basins: North Bay (a.k.a. Arcata Bay), Entrance Bay, and South Bay that are connected by a long, narrow thalweg. About 70% of the bay consists of intertidal flats that are exposed at lowest tides (Costa 1982); only the Entrance Bay section remains submerged at low tide. Due to a large tidal prism and extensive tidal mixing, a vertically homogenous water column develops during most of the year (Gast and Skeesick 1964). Tidal oscillations in Humboldt Bay are mixed.

The bay is of vital importance to the economy of the region and is the largest commercially important harbor between San Francisco to the south and Coos Bay, Oregon, to the north. To facilitate safe navigation of large commercial vessels, the bay has been subject to several modifications over the years, including the construction of jetties, maintenance dredging, and the deepening and widening of portions of the tidal channels through engineering practices conducted by the U.S. Army Corps of Engineers.

The surface sediment distribution in the bay was previously studied by Thompson (1971). He noted that the general pattern for sediments in Humboldt Bay was for grain size to decrease with increasing elevation and distance landward from the ocean inlet. Dredged channel sediments were found to contain greater percentages of gravels and muds than their undredged counterparts. The focus of this paper is to compare and contrast the sediment size distribution seen in 2000–2001 with the sediments sampled by Thompson (1971) 30 years earlier.

Sample Collection and Analysis

A total of 315 surface sediment samples were collected from Humboldt Bay during 2000 and 2001. Two hundred, twenty-three samples were collected during June and July 2001 using a Peterson grab sampler from aboard either a small skiff or pontoon boat. These samples were supplemented by 92 samples that had been collected from the deeper sections of the bay's main channels during the prior fall. The supplemented samples were collected using a Smith-McIntyre grab sampler aboard the R/V *Coral Sea* and M/V *Ironic* as a part of a survey identifying nonindigenous species in Humboldt Bay (Boyd et al. 2002).

The locations of all 315 samples are shown in Figure 2. Samples were collected on transects orthogonal to the primary tidal channels and were nominally spaced at 0.5 nautical mile intervals. Generally, each transect consisted of five samples. Samples were collected from the main tidal channel, the intertidal flats on both channel flanks, and the high tidal flats on either side. A hand-held acoustic depth sounder was used to locate the center and the flanks of the channel on each transect, at the time of collection. Salt marsh environments were not sampled during this study.

From each sediment sample collected, the upper 5 cm was analyzed in bulk for sediment grain size using standard sieve and pipette techniques (Ingram 1971; Galehouse 1971). The analytical techniques were chosen to match the techniques that were used by Thompson (1971) in a previous examination of the sediments in the bay, in order to allow a direct comparison of the sediment grain-size distributions. Samples were disaggregated and the organic material was oxidized using 30% hydrogen peroxide. Particles of coarse silt size and larger were separated from the fine silts and clays by passing samples through a 5.25 (0.25 μm) wet sieve. The portion that did not pass through the wet sieve was dried and shaken for 30 minutes through nested sieves at intervals of 0.25 ϕ (Ingram 1971). The grain-size distribution of the portion that passed through the wet sieve was determined using a settling column and Stoke's Law (Galehouse 1971). Sodium hexametaphosphate was added to inhibit flocculation of the particles in the settling column. The fine silts were separated at intervals of 0.50 ϕ while the clays were separated at intervals of 1.00 ϕ. The graphical technique of Inman (1952) was used to determine sediment-size statistics.

Results

The mean grain-sizes of the surface sediments (upper 5 cm of sediment) in Humboldt Bay are shown in Figure 3. In general, the mean grain size decreased with increasing elevation and distance landward from the ocean inlet, as Thompson (1971) noted previously. The sample with the largest mean diameter was obtained from the bay inlet, between the two entrance jetties.

The trend of decreasing sediment size with distance from the inlet was not followed in areas where:

1) the main channel constricted and coarser-grained sediments were encountered, or
2) dredging had widened the channel and finer-grained sediments were sampled.

The break in trend can be easily seen in a graph of mean sediment size of channel sediments versus the distance to the bay inlet (Figure 4). Other statistical parameters such as median, dispersion and, to a lesser degree, kurtosis show similar trends with variations occurring in the up-channel direction and laterally from the center of the channel up onto the tidal flats.

Discussion

Primary Sediment Distribution

In estuaries similar to Humboldt Bay, the sediment distribution has been described as being controlled primarily by tidally driven circulation (Nichols 1979; Dyer 1994). During both the ebbing and flooding tides, current speeds in Humboldt Bay should be highest within the inlet and in the channel thalweg that connects the North Bay with the harbor entrance. Greater speeds should occur in the North Bay thalweg, as compared to the South Bay thalweg, due primarily to the larger tidal prism in the northern section of the bay. The highest speeds should occur in areas of channel constriction. These estimates are in good agreement with measurements of current velocities made in the field using various Lagrangian drifters in different parts of the bay (e.g., Gast and Skeesick 1964; Casebier and Toimil 1973).

The locations of highest expected current speeds provide a qualitative match to the locations of largest mean sediment diameter (Figure 3). In the shallow areas near the bay entrance, waves are also important. One result is that the surface sediments near the harbor entrance are better sorted than elsewhere in the bay.

The less vigorous circulation in South Bay, as compared to North Bay, provides an explanation for the differences in sediments encountered. At a similar distance from the inlet, South Bay sediments are finer grained than North Bay sediments (Figure 4). In addition, very coarse sand-sized and larger particles were encountered in a number of locations in North Bay, where almost none were found in South Bay.

Have Bay Sediments Changed? 1970 vs. 2000–2001

The influence of harbor modification and maintenance on sedimentary processes has been the subject of some prior research in Humboldt

Bay (Thompson 1971; Costa 1982; U.S. Army Corps of Engineers 1994). Thompson (1971) compared sediments from dredged and undredged portions of the tidal channels in Humboldt Bay and found that the dredged portions contained greater percentages of gravel and silt- and clay-sized particles than the undredged portions of the bay. The increased gravel content was thought to represent lag deposits that were exposed by dredging. The increased percentage of silt and clay was attributed to decreased current speeds where dredging had deepened the channel below its equilibrium level and had allowed for the deposition of fine-grained material. In a study of the Upper James Estuary in Virginia and the Thames River in England, Nichols (1979) suggested two main reasons for the increase in sedimentation that was observed following channel deepening: 1) decreased tidal currents caused by an increase in the channel's cross-sectional area, and 2) increased stratification leading to trapping of sediment in the lower layer by density-driven currents and an increased chance for deposition.

In 1994, numerical modeling was used to predict changes that might occur as a result of dredging on the sedimentary processes operating in Humboldt Bay (U.S. Army Corps of Engineers 1994). In essence, the model predicted that any deepening or widening of the bay channel would cause decreased current speeds in the increased cross-sectional areas and increased sedimentation rates in the channels in the vicinity of the inlet.

To examine any variations in sediment size that may have occurred since 1970, the sediments in this study were analyzed using the same techniques used by Thompson (1971). Thompson employed sediment textural triangle diagrams (Shepard 1954) to display his results; the data from this study have been similarly displayed. Figure 5 shows the sediment sizes of samples collected from the high tidal flats in 1970 and in 2000–2001; Figure 6 shows the sediment sizes of samples collected from the main tidal channels in 1970 and in 2000–2001.

Comparison of the sediments collected from the high tidal flats (Figure 5) suggests that the sediment size did not significantly change between 1970 and in 2000–2001. The textural triangle diagrams are suggestive that the sediments collected from the high tidal flats in 2000–2001 may have had less clay-sized fraction than the samples collected in 1970. However, this suggestion may be misleading due to some differences in sample collection for the two studies. Thompson (1971) extensively sampled the high tidal flats as well as the fringes of salt marsh environments, where he encountered the highest clay-sized fractions of his collected samples. In this study, the salt marsh environments were not sampled extensively and the silty clays sampled by Thompson (1971) may have been missed. The data suggest that the processes controlling sedimentation in the environments where the finest-grained sediments accumulate in the bay may not have significantly changed.

However, comparison of the sediments collected from the main tidal channels (Figure 6) indicate that the 2000–2001 samples had larger average grain sizes and contained less clay-sized material than in 1970. This apparent difference in sediment type cannot be explained by a sampling bias; the main tidal channels were sampled similarly during both studies and the samples were analyzed using the same techniques. The data suggest that the processes controlling sedimentation in the main tidal channels have changed.

These results are seemingly contrary to what would have been predicted by earlier numerical modeling (U.S. Army Corps of Engineers 1994). In a similar result, Costa (1982) observed an apparent shift in the sediment type in the central portion of Humboldt Bay after dredging had widened the North Bay channel in 1977 and 1978. The channels that had contained significant portions of silt- and clay-sized particles prior to dredging became dominated by sand after the channel had been widened. Costa (1982) provided no explanation for these observations.

These data suggest that the processes controlling sedimentation in the bay may have changed. Either the currents in the main tidal channels have become more vigorous and can better inhibit the accumulation of clay-sized sediments, or the sediments supplied to the channels are different. Prior modeling suggests that an increase in tidal currents is unlikely following the channel deepening or widening that occurred between 1970 and 2000 (U.S. Army Corps of Engineers 1994). The implication is that the sand-dominated marine sediments, characteristic of the channels in the lower reaches of the bay, have propagated both northward and southward in the main tidal channels and away from the inlet.

Conclusions

In general, the distribution of surface sediments in Humboldt Bay is similar to that observed by previous investigators (Thompson 1971; Boyd et al. 1975; Burdick 1976; Moore 1977; Costa 1982). The major process that drives the transport and sorting of sediments in most regions of the bay is tidal currents. Waves entering the inlet from offshore are also an important process in Entrance Bay.

Comparison of grain-size data collected during this study with results of a similar survey conducted by Thompson (1971) suggests that the main tidal channels have larger mean sediment sizes today than they had previously. These changes in sediment size may reflect an increased propagation of silt- and sand-sized particles away from Entrance Bay and into the North and South Bay Channels.

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Figures

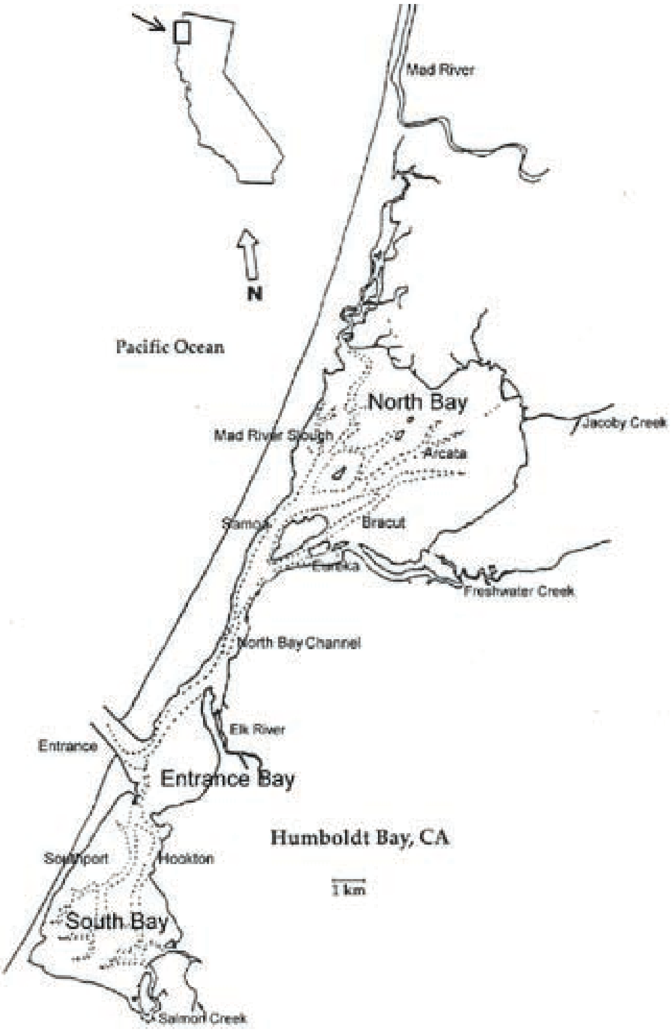

Figure 1. Humboldt Bay, California, study area showing North Bay, South Bay and Entrance Bay (after Costa 1982). The major tidal channels including Entrance, North Bay Channel, Samoa, Mad River Slough, Arcata, Bracut, Eureka, Hookton and Southport Channels are indicated by dashed lines. Major sources of freshwater to the bay, including Jacoby Creek, Freshwater Creek, Elk River and Salmon Creek, are shown.

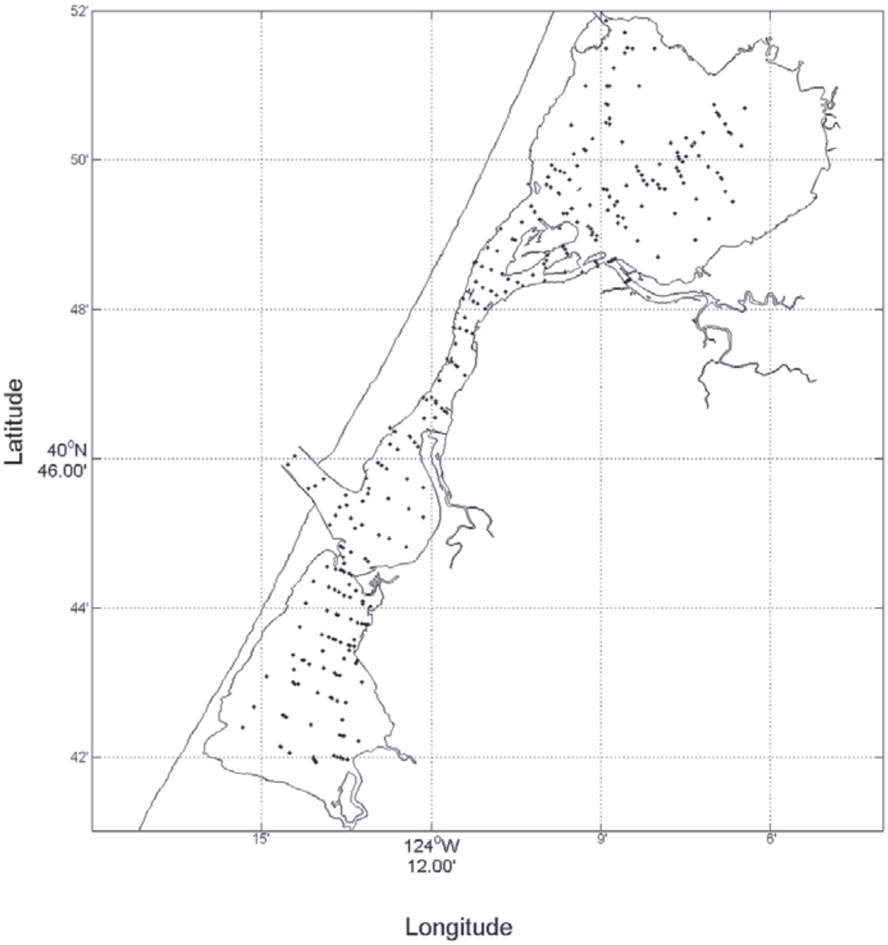

Figure 2. Locations of 315 surface sediment samples collected in 2000 and 2001. Two hundred, twenty-three samples were collected in June and July 2001 using a Peterson grab sampler from aboard either a small skiff or pontoon boat. Ninety-two samples were collected from the deeper sections of the main bay channels during fall 2000 using a Smith-McIntyre grab sampler aboard the R/V *Coral Sea* and M/V *Ironic* (the majority of the supplemented samples were collected as a part of a survey identifying nonindigenous species in Humboldt Bay, Boyd et al. 2002).

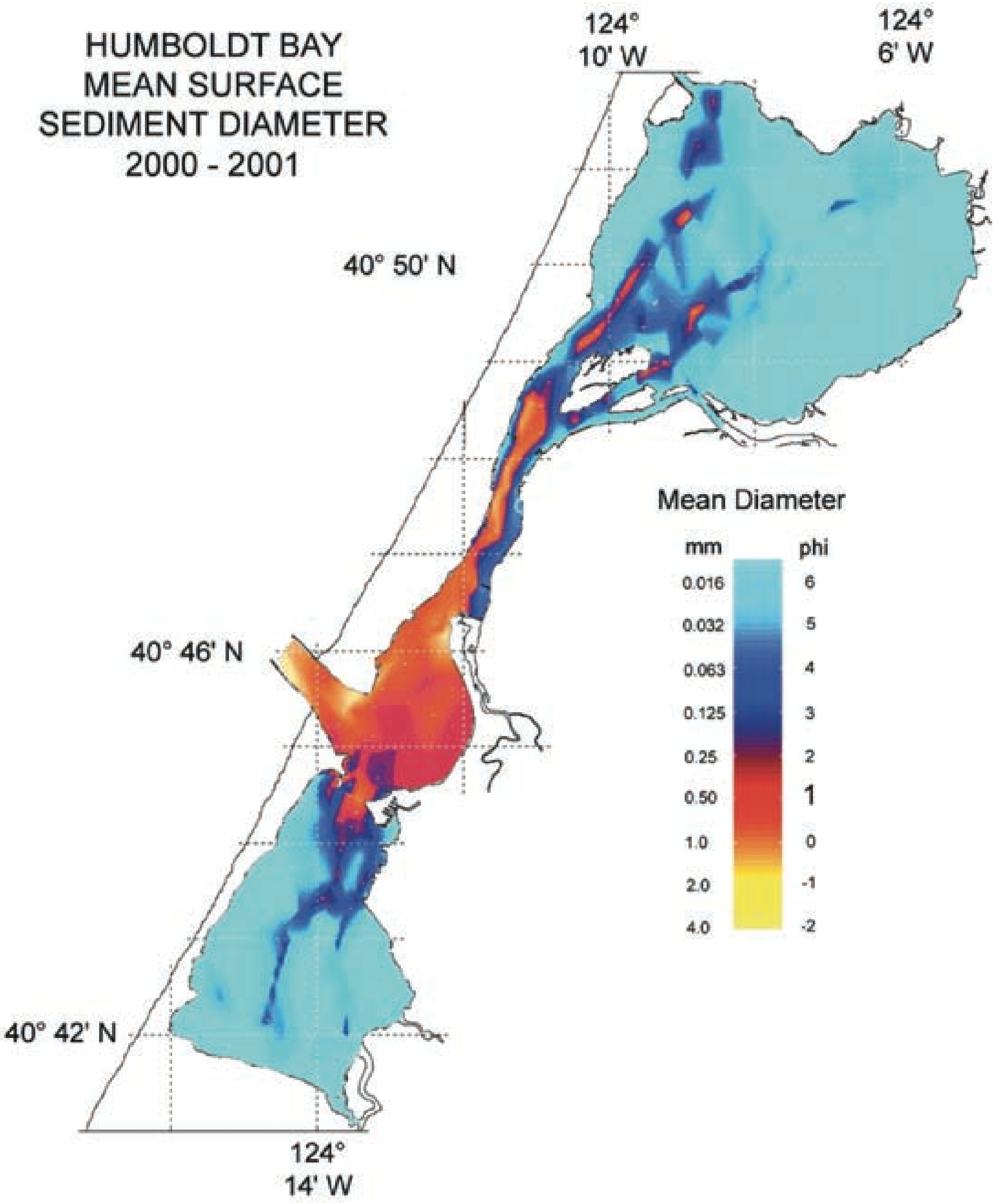

Figure 3. Mean sediment diameter of the upper 5 cm of the surface sediments in Humboldt Bay, 2000–2001. The upper 5 cm of each sediment sample was analyzed in bulk using standard sieve and pipette techniques (Ingram 1971; Galehouse 1971). Sediment size statistics were determined using the graphical technique of Inman (1952). The color-coded map was constructed using a simple contouring algorithm.

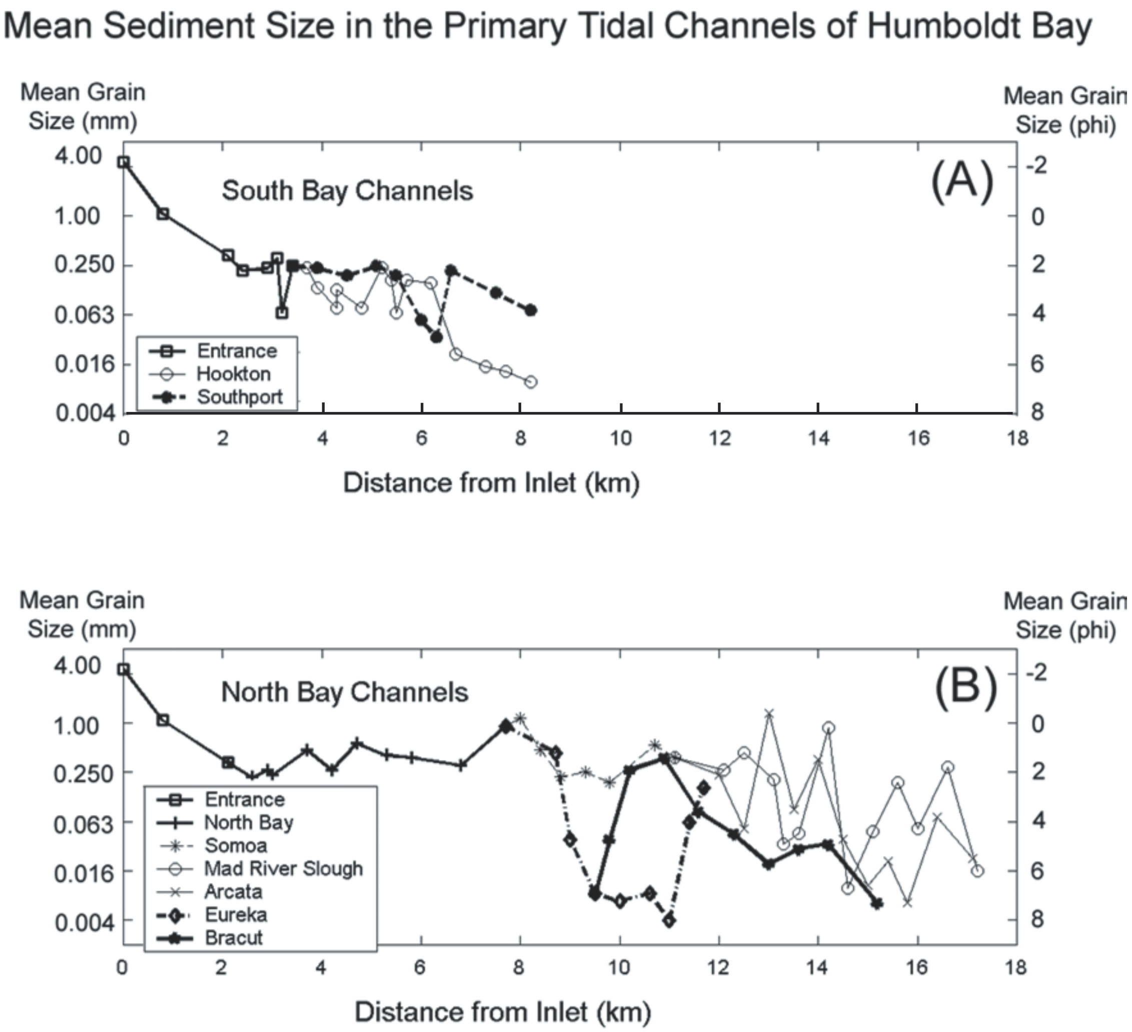

Figure 4. Graphs of the mean sediment diameter in the main tidal channels of Humboldt Bay versus the distance upstream from the ocean inlet. Two graphs are presented: (A) for the channels in South Bay and (B) for the channels in North Bay.

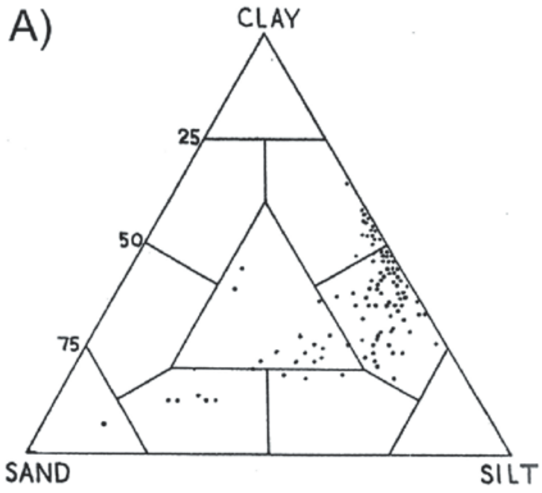

Figure 5. Textural triangle diagrams of sediment samples collected from the high tidal flats of Humboldt Bay based on sand, silt and clay weight percentages. The plots are (A) from 1970, after Thompson (1971), and (B) from 2000 to 2001.

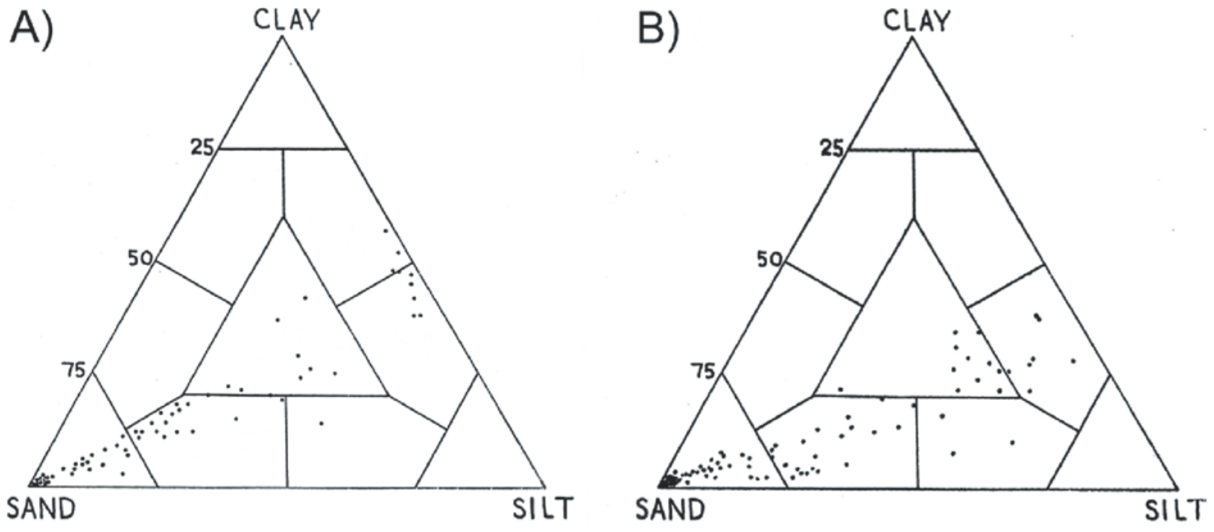

Figure 6. Textural triangle diagrams of sediment samples collected from the main tidal channels of Humboldt Bay based on sand, silt and clay weight percentages. The plots are (A) from 1970, after Thompson (1971), and (B) from 2000 to 2001.

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Known and Unknown Aspects of Bottom-Up and Top-Down Regulation of Eelgrass in Humboldt Bay, California

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Photo Credits
(Above) Humboldt Bay eelgrass beds and (p. 71)
Phyllaplysia taylori, Frank Shaughnessy*;* (p. 72) Whelan Gilkerson.

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Abstract

Maintaining functions of seagrass systems requires adopting a perspective that encompasses the wide variety of mechanisms affecting these communities. Objectives of this study were therefore to use a combination of novel and existing data in the context of an environmental stress model of community regulation in order to understand the roles of seedling recruitment, physical factors and biotic interactions in regulating eelgrass in Humboldt Bay. Since the data necessary for the environmental stress model are incomplete, the final objective was to suggest studies necessary to complete the large perspective of this model. Water-quality and climate data were obtained from the Center for Integrated Oceanic Observation, Research and Education (CICORE), the National Weather Service (NWS) and California Sea Grant to examine possible "bottom-up" stressors of eelgrass. Aquaria were used to test for "top-down" effects of the eelgrass epiphyte grazer, *Phyllaplysia taylori,* on epiphyte loads.

Seedling recruitment has never been examined in Humboldt Bay, although the perennial nature of most eelgrass beds suggests that the majority of shoots grow from existing rhizomes. Low light resulting from suspended sediments should be one of the largest stressors of eelgrass in Humboldt Bay and ebbing tidal currents, watersheds and probably wind are sources of turbidity. Nitrate levels appear limiting to eelgrass growth but plants may not be nitrogen limited if sediment ammonium levels, which have not been measured in the bay, are able to saturate growth. Eelgrass-grazing Black Brant (*Branta bernicla nigricans*) are numerous in the bay and *P. taylori* grazing significantly reduces diatom epiphytes. Further information about light attenuation, nutrients and grazers is necessary to complete an environmental stress model of eelgrass regulation, but this analysis already indicates that habitat requirements for eelgrass in Humboldt Bay should include top-down as well as bottom-up variables.

Introduction

Seagrass communities, such as the eelgrass beds in Humboldt Bay, California, have multiple functions within bays and estuaries including trophic support, nursery and refuge functions and the improvement of water clarity (Fonseca et al. 1982; Williams and Heck 2001). Many of the animals that rely on seagrasses are commercially important and the habitat has high recreational value. These communities and their functions are vulnerable because many beds are comprised of only one seagrass species and so, if natural or anthropogenic stresses reach a lethal threshold for that species, the entire system can collapse. Resource managers charged with preserving these seagrass functions not only need to know the spatial and temporal distribution and abundance of the seagrasses and their animal occupants, but also understand the ecological forces that cause members of the seagrass community to fluctuate in distribution and abundance.

There is a reasonable understanding of the location and abundance of eelgrass in Humboldt Bay due to a variety of studies. Most of these have focused on the geographical and temporal variation of eelgrass abundance (Waddell 1964; Harding 1973; Harding and Butler 1979; Shapiro and Associates Inc. 1980; Moore 2002; Moore et al. 2004; Keiser 2004; Rumrill and Poulton 2004; Schlosser, unpub. data). Others have described vertical and/or geographical eelgrass distributions (Keller 1963; Keller and Harris 1966; Western Ecological Services Company 1990; Miner 1993) and there has been one study of eelgrass primary productivity (Bixler 1982). However, as is the case for many other regions, there is less of an understanding of the mechanisms causing variation in the abundance of eelgrass community members. Research groups and agencies often focus on a subset of mechanisms, in particular the effects of light and nutrients on eelgrass abundance and the oceanographic and land-use practices that affect the light and nutrient environment. This perspective is essential and has improved our understanding of the mechanisms affecting seagrass communities (Hemminga and Duarte 2000), but this focus is also incomplete (Valentine and Heck 1999; Heck et al. 2000). Seagrass productivity, habitat complexity and consequently habitat function could respond positively or negatively to grazing as is the case for terrestrial systems (McNaughton 1985; Belsky 1986; McNaughton et al. 1989, 1991) and seagrass systems also benefit from epiphyte grazers (Jernakoff et al. 1996). Many of the people living around Humboldt Bay are engaged in trying to ensure that eelgrass bed functions are maintained. In order to achieve this goal, it will be necessary to keep both perspectives in mind and thus, the overall goal of this study is to bring together in one conceptual model what is known about how these different groups of mechanisms affect eelgrass in Humboldt Bay and to identify what types of information are still lacking.

There are a variety of simple to more complex conceptual models of how the abundance of terrestrial or aquatic community members is regulated. When applied to Humboldt Bay, these models provide a less myopic framework for helping us link mechanisms affecting eelgrass distribution and abundance and the same models could be applied to mudflat or high marsh communities. The purpose of these models is to predict the relative number of trophic levels and biomass within each of those levels, as well as the relative importance of mechanisms (i.e., physical processes, biotic interactions) regulating the community. Collectively, they are known as "top-down, bottom-up" models (Power 1992) and have undergone a series of changes (e.g., Hairston et al. 1960; Oksanen et al. 1981) in order to make them more general. Menge and Sutherland's (1987) environmental stress model (ESM), which is another version of these models, has been useful in understanding community regulation in marine systems and is what we apply to the eelgrass in Humboldt Bay in the present analysis.

In the ESM the x-axis is environmental stress instead of productivity, as is the case for earlier bottom-up and top-down models (e.g., Hairston et al. 1960; Oksanen et al. 1981). The y-axis is the relative importance of physical factors and biotic interactions in regulating the community and the z-axis is recruitment (Menge and Sutherland 1987). Stress in the ESM model refers to those physical factors that weaken organisms (Menge and Branch 2001). At their highest levels, these physical factors (e.g., wind-induced breakage of eelgrass shoots, dredging, desiccation) will be the most important in regulating the trophic structure of the community because they cause the rapid loss of biomass or disturbance. At slightly lower levels some of these same physical factors and others (e.g., light, nutrients) result in a bottom-up physiological limitation of productivity. In the absence of disturbance and bottom-up limitation, stress is very low and top-down biotic interactions (e.g., competition, predation) become relatively more important. Neither physical factors nor top-down interactions are important if recruitment of new individuals is very low. Recruitment is considered by this model to be a process independent of the factors that affect environmental stress (Menge and Branch 2001), although this assumption is more valid for animals with well-developed dispersal phases than it is for seagrass seeds. Seagrass communities are generally considered to be on the low end of the environmental stress continuum relative to other terrestrial and aquatic systems, but they still experience physical factors that can be intense enough to result in high stress. Recruitment of seagrasses and especially the animals in these communities can be highly variable (Orth et al. 2000; Williams and Heck 2001).

The objectives of this review are: (1) to assess what is known about eelgrass recruitment in the bay, (2) to use a combination of existing and new data presented herein to assess the importance of light, nutrients and other physical factors in affecting the amount of stress experienced by eelgrass in the bay and (3), to emphasize the potential importance of eelgrass grazing by Black Brant (*Branta bernicla nigricans*) and eelgrass epiphyte grazing by the opisthobranch *Phyllaplysia taylori.* Since even with the new data presented herein there are still large gaps in our understanding of eelgrass regulation in Humboldt Bay, our last objective is to (4) suggest studies that would make it possible to make the ESM model more complete and thus useful for developing management policies.

Materials and Methods

Site description

Humboldt Bay is located in Northern California (40° 45′ N, 124° 13′ W) approximately 482 km miles north of San Francisco and 161 km south of the Oregon border. It is subdivided into North Bay (also called Arcata Bay) that has eelgrass beds, mudflats and oyster leases; the central part of the bay (Entrance Channel, Entrance Bay, North Bay Channel, Samoa Channel, channels to the west and east of Woodley Island) that include some narrow eelgrass beds, the Eureka waterfront, as well as the primary shipping lanes (Figure 1); and South Bay, which is dominated by eelgrass beds and mudflats (Figure 2). Geological activity is causing both North Bay and South Bay to subduct. Humboldt Bay is considered more of an embayment than an estuary because of the lack of a major river draining directly into it and because salinities only drop during the winter when the creeks and relatively small rivers discharge the precipitation landing in the watersheds

(Barnhart et al. 1992). The tidal flushing rate of Humboldt Bay is fast relative to other bays and the flushing rate is faster in South Bay than North Bay (Barnhart et al. 1992). The bay is dominated by soft substratum; hard substratum occurs on docks, pilings, bridge abutments, oyster shells and the gear from mariculture companies and vessels.

Activities in and around Humboldt Bay potentially impact its marine communities. About 70,000 people live in the Humboldt Bay watershed with the two biggest concentrations in the City of Arcata (~ 16,600) and the City of Eureka (~26,000). Watersheds draining into North Bay contain logging, commercial greenhouses, dairy farms, sewage effluent from Arcata (that receives secondary treatment followed by a passage through marshes before release), a pulp mill and a sawmill by the Mad River Slough, where fungicides have historically been used. The central part of Humboldt Bay receives wastewater treated to secondary standards and then is dechlorinated and discharged to the bay on ebb tides. Eureka storm drains also empty directly into the bay. The upper reaches of the Elk River, which drain into the same part of the bay, are logged. Watersheds draining into South Bay are from dairy farms and logging operations; and the bay itself is a popular site for sport fisheries and waterfowl hunting. The Eel River discharges into the ocean 16.0 km south of the Humboldt Bay Entrance Channel; and activities in this watershed also potentially impact the bay since its water and sediment are presumably carried into the bay on flood tides (Barnhart et al. 1992). Some degree of dredging, whether in the entrance channel or inner shipping lanes, occurs almost every year. At least one oil spill (MV *Kure*, 11/1997, ~5,000 gallons) has occurred within the bay.

Water Quality and Climate Description

At this time only turbidity data are available for understanding the aquatic light environment to which the eelgrass in Humboldt Bay is exposed; these data are from the Humboldt State University (HSU) group within CICORE. The particular data logger—or sonde—in use is made by Yellow Springs Instruments (YSI; mo. 6600 with automatic wiping of optical probes) and contains probes for a variety of parameters. This is the same sonde used by the National Estuarine Research Reserve System (NERR). The YSI turbidity probe (mo. 6136, range 0–1000 Nephelometric Turbidity Units; NTU) is standardized with YSI styrenedivinylbenzene copolymer at 0.0 NTU and 123.0 NTU.

The sonde is located just south of the Eureka waterfront (Figure 1), where it hangs within an ABS plastic pipe that is attached to a piling underneath Dock B; this piling is about 2.0 m back from the front edge of the dock. Following the design developed by the NERR in Coos Bay, Oregon, the bottom of the ABS pipe is slotted to allow water to circulate around the turbidity and other probes. All probes remain ~ 1.5 m above the bottom and they are always underwater. Although the sonde can be deployed for three months, the chain it is hanging from inside the pipe was pulled up every three to four weeks. The data were uploaded and the sonde and probes were brought back to an HSU laboratory for cleaning and calibration and then redeployed. All of the probes on the HSU CICORE sonde took a reading every 15 minutes. The sonde was first deployed during June 2003, and data into June 2004 were included in this study. Values from the YSI turbidity probe greater than 500 NTU were removed because they were sporadic, and the NERR in Coos Bay also uses this cutoff value.

Other water-quality and climate variables were used in order to understand why turbidity values measured in this study varied with time. Salinity and tidal changes in water depth were measured by the HSU CICORE sonde. Hourly precipitation readings were taken by S. Schlosser's Davis Vantage Pro weather recorder coastally located ~ 15 km north of the sonde. The Eureka Buoy operated by NOAA (#46022), which is located 31 km west-southwest of Eureka (40° 43′ 12″ N, 124° 31′ 12″ W), was used as a source of data for hourly wind direction and speed. Buoy data used in this study had not received a final editing by NOAA, and so data were graphically inspected for anomalies.

Comparisons of wind direction and speed against turbidity were made by assigning wind directions to one of four possible unequal compass degree groups. These groups were constructed on the assumption that if wind is generating turbidity events, then mudflats around the north, east and southeast edges of North Bay are more likely to be sources of turbidity recorded by the Dock B sonde than sediments arising from the mudflats on the west side of the bay. Winds approximately out of the northeast (1°–60°) should be relatively rare but would generate waves that would break on the southeast mudflats, and these winds would be moving in the same direction as the ebb tide. Winds out of the east and south (61°–220°) should suspend sediments on the western mudflats and the northern mudflats on the western half of North Bay. Westerly and southwesterly winds (221°–280°) will have a long fetch within the bay and impact north and northeastern mudflats, whereas winds mostly out of the northwest (281°–360°) will also have a long fetch but potentially generate turbidity over the eastern and southeastern mudflats, which are closest to the Dock B sonde.

Turbidity events less than 200.0 NTU range are the most common at Dock B and therefore should be the most relevant for understanding what affects water clarity in this part of Humboldt Bay. Values greater than 500.0 NTU had already been removed by CICORE because their appearance for only one reading amid a series of very low readings (i.e., < 30.0 NTU) suggests that these high values were not representative. We found that values between 300.0 NTU–500.0 NTU had a similar pattern of appearance but were retained so that this analysis can be compared against future turbidity events that might persist in this range, such as during El Niño events.

Only short-term measures of the aquatic nutrient environment at multiple stations have been made in Humboldt Bay for the purpose of characterizing upwelling and nonupwelling periods in and just outside the bay (Pequegnat and Butler 1981; Barnhart et al. 1992; Althaus et al. 1997). Water temperatures from 1995 to 2004 were therefore inspected to determine if the bay experiences ENSO temperature changes, which could also mean changes in the concentration of oceanic nitrate. Water temperatures came from several sources. The NOAA Eureka Buoy hourly water temperatures were used to represent coastal waters just outside of the bay, whereas bi-hourly readings from the Sea Grant Extension office in Eureka (Figure 1) and 15-minute readings from the HSU CICORE sonde were used to represent water temperatures in the bay.

NOAA water temperature data from the North Spit in Humboldt Bay were not used because of the high number of anomalous readings. Since, in order to detect ENSO temperature changes, it is necessary to ensure that the temperatures used in this analysis were those of the flooding oceanic water, only the minimum daily temperatures occurring during the summer months were used. Data were smoothed by obtaining the minimum temperature for each day within a month and then the mean of these minimum values was used to represent the month. Means of minima were also used on the offshore buoy data, but fall and winter months were not omitted because of the assumption that this buoy is usually monitoring oceanic water. Chlorophyll fluorescence levels measured by the HSU CICORE sonde (YSI Fluorescence Chlorophyll Probe, Mo. 6025, range 0–200 ug/L) were also assessed to determine if seasonally upwelled nutrients, as reflected in phytoplankton blooms, are potentially entering the bay.

The eelgrass mesograzer, *Phyllaplysia taylori.*

Grazer Experiment

One hundred eelgrass shoots were haphazardly collected during March 2004 from the bed by the western end of the Samoa Bridge (40° 49′ 31″ N, 124° 10′ 20″ W) in Humboldt Bay. Shoots were immediately brought to HSU's Telonicher Marine Laboratory, where they were placed in running seawater. All individuals of the opisthobranch grazer, *Phyllaplysia taylori,* were carefully removed and put back into seawater. In order to keep leaf age relatively constant, the third leaf (starting from inside the leaf bundle) was removed from each shoot. Sixty of these were randomly sampled by cutting them from where they emerged from the sheath, and then once again 30.0 cm above the first cut. If the leaf was shorter than 30.0 cm, it was abandoned and a new leaf was sampled from the larger pool. The 60 leaves were equally divided into ten one-gallon glass aquariums. One Plexiglass clamp (each with two pieces, each piece 24.0 cm * 4.0 cm * 0.4 cm, bolted together) holding six sandwiched leaves was placed in each aquarium, and the clamp itself was in a stand so that the leaves could be held in an upright, natural position.

The ten aquaria, which were set up outside for ambient light, received circulated seawater. They were placed on a seawater table in two rows of five aquaria with a south aspect. The most southern row was raised enough so that the tank would not be shaded by the front edge of the table and the second row was raised even more so that it would not be shaded by the first row of aquaria. Water flowed into the top of the aquaria via tubing and exited through a J-shaped piece of ½″ PVC pipe. The intake of the pipe was covered with a 0.2-cm mesh and was located about 5.0 cm below the top of each aquarium. This arrangement prevented *P. taylori* from getting into the pipe and from crawling or floating out of the aquarium. *Phyllaplysia taylori* individuals were added to the five odd-numbered aquaria so that aquaria with and without *P. taylori* alternated in their position on the water table. One animal was attached to each leaf within a tank, and so each tank contained six individuals, which when moving underwater ranged from 1.0 to 2.0 cm in length. Each experiment, after commencing within 12 hours of the shoots and animals being collected, proceeded for seven days. The first experiment began on March 3, 2004 using a flow rate of 3.0 L /min. A second experiment using only

1.0 L / min. was initiated on March 27, 2004 because the first experiment showed that the higher flow seemed to cause mortality when animals were shaken loose and could not reattach or they moved down to the clamp.

At the termination of the each experiment all the leaves were removed and the *P. taylori* individuals were added to the eelgrass educational display tank in the Telonicher Marine Laboratory. The response variable, diatom epiphyte abundance, was enumerated by scraping both sides of each leaf with a razor blade as has been done in similar studies (Drake et al. 2003). Within an aquarium, diatoms from different leaves were combined. Diatoms were placed in 23.0-ml vials and preserved in 10% formaldehyde in seawater. Sub-sampling of frustules occurred at two levels. Frustules within a vial were first homogenized by shaking and a 1.0 ml of sample was quickly removed and deposited into a gridded Sedgwick Rafter counting cell, where each grid is 1.0 mm^3. Secondly, all of the frustules in five randomly picked 1.0 mm^3 grids were counted and then frustule numbers were extrapolated to represent all of the diatoms scraped from the leaves within an aquarium. Diatom epiphyte abundance was expressed as frustule density by dividing the total number of diatoms by the leaf area (leaf length * leaf width) of all the leaves in an aquarium. A two-sample t-test assuming unequal variances was used to determine if diatom densities were significantly different between treatments.

Results

Water Clarity: Turbidity Versus Tides, Precipitation and Wind

Turbidity values greater than 50 NTU occurred throughout the year but were more common during the fall and winter months (Figure 3A). Changes in turbidity less than 50 NTU correspond to the rise and fall of the tide, with peak values (usually from 10.0 to 20.0 NTU) occurring at the lowest point of the ebb tide (Figure 3b). Each day, the lower of the two low tides is when the greatest turbidity value occurred. Turbidity values from 50.0 to 200.0 NTU occurred at multiple times throughout the tidal curve (Figure 3c).

Salinities dropped to almost 15 ppt during the late fall and winter when precipitation, mostly in the form of rain, occurred (Figure 4). Salinities always decreased on the ebb tide and increased on the flood tide (Figure 5a). From 24 to 48 hrs following a precipitation event, such as those that occurred on February 6, 16, 18 and 24, 2004, there was a larger drop in salinity than occurred during times of no precipitation (Figure 5a). Turbidity events from 50.0 NTU to 200.0 NTU occurred during or just after precipitation events. Following periods of precipitation, it took more days for turbidity values to diminish to less than 50.0 NTUs when total precipitation was greater (e.g., February 17, 2004–February 21, 2004) than when total precipitation was lower (e.g., late February 24, 2004–early February 27, 2004; Figure 4a,b). Specific turbidity spikes during these same periods of precipitation occurred during ebb tidal stages (Figure 5a,b). Peaks of monthly precipitation during 2004 when this comparison to turbidity was made were about half of those recorded for 1997 and 2003 and about 2.5 times greater than 2001 values (Figure 6).

Wind velocities recorded by the offshore Eureka NOAA Buoy did not show a relationship with turbidity events in the bay, especially those events greater than 50.0 NTU. The largest cluster of high turbidity values occurred during September and October 1993, which was one of the calmest periods for wind speeds (Figure 7). Wind velocities during representative summer and early fall periods were lower than during the winter, and wind directions during the summer were primarily out of the northwest. During the fall, winds were from all directions except the west and southwest and the winter was dominated by east and southeasterly winds (Figure 8 a–c). Increases in turbidity values during these same three periods, especially those greater than 50 NTU or 200 NTU, occurred across the full range of wind speeds and directions. Turbidity values greater than 200 NTU during the early fall corresponded to low-wind velocities (i.e., 2.0–3.0 mph) out of the southeast and east; and although high-wind velocities (i.e., 15.0–20.0 mph) during mid-February 2004 are followed by increases in turbidity, prolonged high-wind velocities out of the same direction at the beginning and end of the same month do not show this relationship (Figure 8 b–c).

Water Temperature and Chlorophyll as Indicators of Nutrient Availability

Water temperatures and tidal curves from the summer and winter were compared in order to determine if the mean of the daily minimum temperatures during a month could be used as the measure of the temperature of the oceanic water entering Humboldt Bay. During the summer, the minimum water temperatures for the day always corresponded to flood tide peaks (Figure 9a), whereas flood tide peaks during the winter were associated with either the warmest or coolest water temperatures for the day (Figure 9b). Only minimum daily summer (June through September) water temperatures were therefore used to indicate the temperature of the oceanic water flooding into Humboldt

Bay (Figure 9c). Waters outside Humboldt Bay, as indicated by the Eureka Buoy, showed the highest temperatures (mean of all temperature values) during the summer of 1997, with smaller peaks during 1995 and 2003. The mean of the daily minimum temperature for a month within Humboldt Bay, as indicated by the Eureka Sea Grant logger, followed the same interannual temperature pattern as the outer coast water, except that the mean of the daily minimum water temperatures for a month was always about a degree warmer in the bay; preliminary data from the CICORE logger appears similar to the Sea Grant logger, which is in the same part of Humboldt Bay (Figure 1, Figure 9c). The 1998 and 2003 water temperatures in the bay were about 1° C warmer than the 2000 and 2001 temperatures.

Although chlorophyll fluorescence less than 30.0 µg/L briefly spiked during winter months, fluorescence values were generally higher during September and October as well as April and May; summer data were absent (Figure 10a). Fluorescence peaks lasting several days occurred during spring or neap tides and maximum chlorophyll values within a tidal cycle always occurred at the peak of each flood tide (Figure 10 b,c).

Grazer Exclusion Experiment

Eelgrass leaves in aquaria with the grazing opisthobranch *Phyllaplysia taylori* always had significantly fewer diatom frustules per cm^2 of leaf surface than leaves in aquaria without *P. taylori* (Figure 11). There were greater numbers of diatoms in each treatment during the first experiment in early March 2004 when each tank received 3.0 L of seawater / minute, but there was some mortality of *P. taylori* individuals that could not stay attached to the leaves. Therefore, the experiment was repeated in late March 2004 at the reduced flow rate of 1.0 L / minute. In this case there was less *P. taylori* mortality (Figure 11).

Discussion

The ESM model uses environmental stress and recruitment to determine whether or not physical factors or biotic interactions are relatively more important in regulating biomass and trophic structure of marine communities (Menge and Sutherland 1987, Menge and Branch 2001). This study has analyzed some novel data and combined it with existing information in order to determine how physical factors could be changing levels of stress (*sensu* Menge and Branch 2001) experienced by eelgrass within Humboldt Bay and how, under conditions of low stress, grazers could be affecting eelgrass primary productivity. This effort also highlights how much is unknown or needs to be more rigorously tested and so our final objective is to suggest studies that would make the ESM model in Humboldt Bay more complete and thus useful to managers.

Physical factors and biotic interactions are both relatively unimportant to community regulation according to the ESM if recruitment is minimal. Although rhizome-shoot fragments are capable of establishing new patches (Ewanchuk and Williams 1996), they are positively buoyant and not considered as important as the negatively buoyant seeds in establishing new patches (Orth et al. 2000; Bintz and Nixon 2001). There are no studies of flowering, seed bank or seedling dynamics of eelgrass in Humboldt Bay, so it is not possible to evaluate the importance of recruitment to the spatial and temporal variation in eelgrass abundance that have been described. Flowering for Pacific Northwest eelgrass is from March through July. Seeds are released from late July to October; the seed bank can last up to 12 months and most seedlings appear in the spring (Phillips 1984; Orth et al. 2000). Except for some patches in North Bay, it is currently assumed that eelgrass occupies most of its potential niche in Humboldt Bay, which suggests that the vast majority of new shoots are likely to be asexually produced and not recruits.

Since the repeated sampling of eelgrass in Humboldt Bay (Schlosser, unpub. data) indicates that most beds are perennial, an assessment of the relative importance of physical factors and biotic interactions is the most relevant for understanding the variation of eelgrass distribution and abundance in the bay. The seagrass literature indicates that, of the physical factors that increase levels of environmental stress (*sensu* Menge and Branch 2001) for eelgrass, light limitation is preeminent followed by nutrients and other physical factors. Despite the large number of adaptations to an aquatic existence, eelgrass and seagrasses in general are particularly vulnerable to light limitation. The minimum light requirement for seagrasses is high (i.e., 10%–22% of surface light; Gallegos 2001; Duarte 1991) relative to microalgae (i.e., 1% of surface light) because seagrasses are comprised of so many nonphotosynthetic cells that can only respire. Capturing the light necessary is also problematic because their aquatic environments are dominated by green light and they don't have the accessory pigments to capture these wavelengths; and, while they can photoacclimate to low light by increasing levels of chlorophyll pigments, there is an upper limit to this response because these pigments eventually shade each other within the chloroplast (i.e., the packaging effect; Cummings and Zimmerman 2003). Even if seagrasses are not light limited, that is, when the amount of light for saturating photosynthesis (E_k = 100 µE m^{-2} s^{-1}) occurs for a minimum of six hours during a day (H_{sat}; Dennison and Alberte 1985; Dennison 1987), seagrasses are restricted to even shallower depths by low amounts of dissolved CO_2 and inefficient carbon uptake (Beer and Rehnberg 1997; Zimmerman et al. 1997). The form of inorganic carbon required by photosynthesis, CO_2, is 150 times less available in seawater than bicarbonate (HCO_3^-); and the plant's enzyme (carbonic anhydrase) for converting bicarbonate to CO_2 is not abundant. Thus if the level of CO_2 in the water is experimentally increased, then seagrasses can potentially grow in deeper water, since, being able to fix carbon at a faster rate by direct uptake of CO_2, it will take them a shorter period of time to surpass the amount of carbon used during 24 hours of respiration (Zimmerman et al. 1997).

This light and carbon physiological Achilles heel of seagrasses is why management strategies are generally so focused on preventing degradation of the aquatic light environment. If seagrasses die, the entire community will collapse since there are no other similarly productive, large, soft-bottom macrophytes to replace them. How could stress from light limitation be affecting eelgrass distribution and abundance in Humboldt Bay? Typical fall-winter declines in light availability are not a proximate driver of biomass declines at this time of year since eelgrass has already adapted to the seasonal availability of this resource. However, large interannual and spatial differences in the aquatic light environment, especially when they occur during the spring and early summer when net primary productivity is highest, will affect the abundance of seagrasses (Bulthius 1987; Dennison 1987; Thom and Albright 1990; Duarte 1991; Vermaat and Verhagen 1996; Moore et al. 1997; Hemminga and Duarte 2000; Hauxwell et al. 2006*). There is no spatially complete sampling of water quality or the aquatic light environment in Humboldt Bay so, for now, inferences must be made from CICORE's time series turbidity data from Dock B.

The turbidity readings from Dock B provide a description of water clarity and hence an

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*Paper was reviewed and updated since presentation to include relevant citations.

indirect measure of the relative availability of light for eelgrass growth. Turbidometers optically measure the relative amounts of suspended solids in the water by recording the amount of incident light that is scattered when encountering suspended solids such as silt, clay, detritus, algal cells and large molecules such as tannins (Sadar 2002). Direct measurements of the downward attenuation coefficient (K_d) for photosynthetically active radiation (PAR) are preferred for describing the light environment of aquatic photoautotrophs (Kirk 1994). Since the relationship between K_d and turbidity in Humboldt Bay has not been established, this part of our study can: (1) indicate the times when turbidity is attenuating light and potentially limiting eelgrass growth; and, (2) compare turbidity patterns to mechanisms that cause it to vary in order to understand how turbidity could temporally and spatially vary in the bay.

Patterns of turbidity increase at Dock B fall within three groups: those that remain below 50.0 NTU with most peaks in the 10.0 NTU–20.0 NTU range, those from 50.0 NTU to 200.0 NTU and an anomalous group with dry season values greater than 50.0 NTU and wet season values greater than 200.0 NTU. The first group of values is produced by ebbing tidal currents; and the greater the tidal amplitude, the more turbidity is generated. The ebbing tide had the same effect on aquatic PAR at eelgrass and oyster mariculture sites in North Bay (Rumrill and Poulton 2004). The second group is produced by increases in watershed discharge during and following winter rain events. As the tide ebbs during a winter storm, the freshwater from the Freshwater watershed coming out through the Eureka Slough causes salinities to drop and turbidity levels to increase by the Dock B sonde. This is interpreted to mean that in this part of the bay, the primary source of the turbidity is from the Freshwater watershed and not from flooding waters that could be carrying Eel River or Elk River sediments. Since monthly precipitation is so different for Humboldt County watersheds during El Niño and La Niña years, the frequency and intensity of rain induced turbidity events presented in this study are likely to be intermediate between the extremes of the ENSO cycle.

The third group of turbidity values at Dock B cannot presently be attributed to any mechanism(s) of sediment suspension. Despite the common observation that summer afternoon wind waves over the mudflats in North Bay result in visibly turbid water, this study found no consistent relationship between wind and turbidity as has been documented in other bays (Nichols and Thompson 1985; Banas et al. 2005). This was even the case for winds out of the northwest that produce relatively long fetch waves that break on mudflats adjacent to Eureka Slough, and water from this slough is mixed into the water that moves by the Dock B sonde on the ebb tide (Figure 1). However, during lower tides, the majority of wind-generated turbid water may be blocked from entering Eureka Slough and the channel along the Eureka waterfront because the mudflats on the northern edge of the slough, while still intertidal, are high enough to be a partial dam to northwest wind waves (Figure 12). The aquatic light environment for North Bay eelgrass during summer afternoon high tides probably is being degraded by wind, but only a turbidometer located in North Bay itself or between Indian Island and Woodley Island would detect this type of event.

Based on the relationship of turbidity at Dock B to tidal currents and precipitation; and, assuming that wind generated turbidity is occurring, then what other sections of Humboldt Bay should have similar levels of high turbidity that could be stressing eelgrass? Most of North

Bay should also have high levels of turbidity because it receives water from the Freshwater watershed (15,014 ha), the Jacoby watershed (5,268 ha), the Elk River watershed (15,176 ha) on flood tides and some from the Mad River Slough, especially when the Mad River connects to this slough during episodic flood events. In contrast, most of South Bay should have relatively less turbid water since it receives water from the smallest watershed, Salmon Creek (6,637 ha). Even though the Eel River watershed (954,152 ha) does not empty directly into Humboldt Bay, bottom transport of sand into the bay from this river may be occurring during the winter (Thompson 1971; Gera 1973; Costa 1982a; Komar et al. 2000). However, origins of the finer suspended sediments that would degrade the light environment in South Bay are unknown. The only data currently available for developing a hypothesis on the spatial distribution of water turbidity in the bay come from Dock B and the positions of watersheds, despite some existing Secchi disk and downward irradiance (Ed) data (Pequegnat and Butler 1981; Barnhart et al.1992; Rumrill and Poulton 2004). North Bay and the central part of the bay should be more turbid than South Bay, particularly during high rainfall events; and environmental stress to eelgrass due to light limitation should also be acute in North Bay because eelgrass beds in this bay occur at lower elevations than those in South Bay.

Temporally, turbidity conditions that occur during the spring and early summer should have the greatest effect on eelgrass carbon balance (Bulthius 1987; Dennison 1987). Watersheds release their most turbid water during the winter when the physiological impact on eelgrass should be minimal because the plant survives the winter by photoacclimating and using carbon stored the previous summer (Zimmerman et al. 1991, 1995; Olesen and Sand-Jensen 1993; Burke et al. 1996). However, the same watershed sediments could decrease eelgrass growth and carbon storage during the spring and summer if they are resuspended by summer afternoon winds. Thus we hypothesize that the spring and summer winds and tidal-induced turbidity differences between the two bays, along with the deeper depth of North Bay, should be the best predictor of eelgrass biomass and distribution.

How do these hypotheses of the spatial and temporal distribution of turbidity in the bay compare to the abundance and compensation depths (i.e., the depth where H_{sat} occurs) of eelgrass in Humboldt Bay? Eelgrass shoot densities and above-ground biomass from North Bay are in fact significantly lower than for South Bay (Schlosser, unpub. data). Data on eelgrass compensation depths in Humboldt Bay are rare but consistent with patterns of abundance between the two bays. Eelgrass compensation depths at the northern end of the Samoa Channel (just south of the southwest corner of North Bay; Figure 1) were ~ 1.5 m below MLLW (Miner 1993), whereas an uninterrupted lower bed margin at sites at the northern end of South Bay occurred at ~ 3.0 m below MLLW (Western Ecological Services Company 1990). The latter study also reported discontinuous eelgrass below 3.0 m MLLW at the northern end of South Bay with some of it occurring as "clumps" as deep as 10.3 m below MLLW. However, this study did not follow up the sonar mapping with SCUBA as in the case of Miner (1993), and the deeper eelgrass may have arrived there from shallower bed fragmentation and been in the process of dying. This first examination of available turbidity and eelgrass data suggests that eelgrass abundance and distribution differences between the two bays are due to the greater light stress in North Bay.

Studies of nitrogen and eelgrass indicate that while it can be a source of physiological stress according to the ESM model because it can be toxic at high levels or limiting to growth at low levels (Williams and Ruckelshaus 1993; van Lent et al. 1995; van Katwijk et al. 1997), light is more frequently an important bottom-up factor to eelgrass growth (Dennison et al. 1987; Zimmerman et al. 1987; Murray et al. 1992). This is despite the fact that eelgrass demand for nitrogen would appear to be high because so much growth is occurring during the spring and early summer; and, even though upwelling is occurring at this time, nitrate availability might be curtailed by competition from planktonic and epiphytic algae that have more efficient uptake kinetics (Pedersen and Borum 1993; Williams and Ruckelshaus 1993). Leaves and the roots/rhizomes of eelgrass can take up almost equal amounts of nitrogen; but ammonium is preferred over nitrate and, in the case of the root/rhizome, ammonium uptake is light dependent (Zimmerman et al. 1987; Hemminga et al. 1994). Nitrate dominates in the water column whereas ammonium is the dominant form of nitrogen in the sediment, where it also leaches out into the water (Short 1983).

There are a number of reasons why nitrogen may not limit eelgrass biomass very often. Eelgrass requires approximately four times less nitrogen and phosphorous per atom of carbon than algae (Hemminga and Duarte 2000); and models have demonstrated that water column ammonium and nitrate levels that should be required to saturate growth, as well as sediment ammonium levels for saturating growth, should be less than ambient levels reported for temperate estuaries. In addition, since nitrogen uptake rates saturate at higher levels than for growth rates, it is possible to store nitrogen for times when ambient levels actually do fall below growth requirements (Zimmerman et al. 1987). Furthermore, eelgrass is capable of internally recycling nitrogen by moving it from older senescing parts of the plant to meristematic areas (Borum et al. 1989; Pedersen and Borum 1992, 1993); and lack of available water-column nitrogen can be partially offset by the large amount of nitrogen that is released from decomposing plant matter in the sediment (Kenworthy and Thayer 1984; Harrison 1989; Risgaard-Petersen et al. 1998). Nitrogen fixation, which occurs in the rhizosphere microenvironment and is enhanced by eelgrass photosynthesis (McGlathery et al. 1998), also supplements the nitrogen budget for eelgrass, but only to a small degree (Risgaard-Petersen et al. 1998).

In addition to the effects of light stress, could the lower eelgrass shoot densities and biomass in North Bay versus South Bay (Keller 1963; Harding 1973; Schlosser, unpub. data,) be due to ammonium toxicity or nitrogen limitation? There are no studies of sediment ammonium in Humboldt Bay even though oyster culture in North Bay, agricultural runoff into Mad River Slough and then North Bay, and sewage effluent from Arcata and Eureka could all increase sediment ammonium. However, eelgrass beds occur in sediment ammonium conditions over 500 µM (Zimmerman et al. 1987), so sediment ammonium must reach a high level for it to be toxic. Measures of water-column ammonium made throughout the bay and in Freshwater and Jacoby Creeks (0.0–4.22 µM NH_4^+; Barnhart et al. 1992; Althaus et al. 1997) are well below ammonium levels that are toxic in the water column (~ 25 µM NH_4^+; van Katwijk et al. 1997), but all of these measurements were made between May and August after the watersheds would have flushed ammonium into the bay. Present data are therefore inadequate for determining if water column or sediment ammonium is toxic to eelgrass anywhere in Humboldt Bay.

Is eelgrass in Humboldt Bay being stressed by a lack of nitrogen rather than nitrogen toxicity? Although some of the ammonium uptake in an eelgrass plant occurs via the leaves, most of it occurs via the rhizomes and roots (Thursby and Harlin 1982); and, since no sediment ammonium data are available for the bay, this analysis will continue by focusing on ambient patterns of water-column nitrate. Patterns of nitrate availability in Humboldt Bay can be inferred from changes in water-column chlorophyll, and some direct measures of nitrate have been made at a variety of sites. Chlorophyll concentrations for the two bays are similar and increase from April to June and again during the early fall. During the spring bloom, both of these bays have approximately half the chlorophyll found in offshore water (Pequegnat and Butler 1982); chlorophyll fluorescence in the central part of the bay also increased during the spring and early fall of the present study. These chlorophyll patterns suggest that similar but reduced amounts of upwelled nitrate are spread throughout Humboldt Bay on the flood tide and that some of this nitrate is being intercepted by the phytoplankton. However, in order for nitrate limitation to be part of the reason for the lower shoot densities in North Bay, both nitrate and ammonium would have to be limiting in North Bay and not in South Bay.

Direct measures of nitrate indicate that this form of nitrogen is either limiting or close to limiting in both bays, except in South Bay during upwelling events. During upwelling events, nitrate is three to ten times more concentrated just outside or inside Entrance Channel relative to North Bay or South Bay; and nitrate concentrations are in fact greater in South Bay than North Bay (Table 1). This is also the case during nonupwelling conditions (Table 1), perhaps because the phytoplankton in North Bay has more time to deplete nitrate. When these varying levels of ambient nitrate are compared to the nitrate levels at which eelgrass growth and leaf uptake rates should saturate (Table 2), they are all similar to or less than saturation levels, which means that eelgrass growth should be nitrate limited in both bays except for some sites in South Bay during upwelling. During May through August 1997, which was the beginning of an El Niño episode, Althaus et al. (1997) also assessed nitrate concentrations within Humboldt Bay and corroborated the above pattern (Table 1) by finding that sites at the southern end of North Bay or in this bay also had values that were generally too low to saturate eelgrass growth (0.0– ~ 4.2 μM NO_3^-). Existing data for nitrate indicates that it occurs at less than saturation values across much of Humboldt Bay and is therefore unlikely to explain the lower shoot densities in North Bay. In addition, nitrogen may not be limiting anywhere even if there is a differential availability of nitrate within the bay because the total nitrogen budget can be compensated by saturating amounts of ammonium in the sediment (Zimmerman et al. 1987).

Decreases in light and nutrient availability during El Niño may combine to produce stressful conditions that produce interannual patterns of eelgrass abundance. Eelgrass shoot density and flowering usually increased in the beds of Willapa Bay, Washington and Coos Bay, Oregon, following the strong 1997–1998 El Niño event (Thom et al. 2003); but subtidal eelgrass close to Friday Harbor, Washington, increased in biomass and productivity during the 1992 El Niño event, probably because H_{sat} actually increased and nitrate levels were well above what is required to saturate growth (Nelson 1997a). Multi-year data for eelgrass abundance are not yet available for Humboldt Bay; and, although the present study demonstrates climatic effects on the bay, it is not clear if they would cause significant stress to eelgrass. Precipitation is much greater around the bay during El Niño events (Figure 6), and there is a positive relationship between winter precipitation and turbidity (Figure 5). Nitrate levels, which should already be low because Humboldt Bay is distant from the more actively upwelling headlands of Cape Mendocino, California and Cape Blanco, Oregon (Strub et al. 1991), should drop by 5.0–7.0 µM NO_3^- during an El Niño event because oceanic water entering Humboldt Bay is at least a degree warmer during the El Niño versus the La Niña portion of the ENSO cycle (Figure 9c). Nitrate decreases during El Niño events because, below 15° C, nitrate decreases by ~5.0 µM NO_3^- for each degree of water temperature rise in the northeast Pacific Ocean (Dayton et al. 1999; Nielson 2003). However, the higher levels of suspended sediments produced by El Niño precipitation would only stress eelgrass if the same sediments were resuspended by summer winds and tides and sediment ammonium levels could be sufficient for eelgrass growth.

Although the literature indicates that, from the bottom-up perspective, light followed by nutrients should be given the most attention when trying to understand the factors affecting eelgrass distribution and biomass in Humboldt Bay, other physical factors can result in high environmental stress (Koch 2001; Thom et al. 2003; Greve and Krause-Jensen 2005[1]). Large hydrodynamic forces resulting from tidal currents or wind waves can directly reduce the biomass, shoot density and shoot length of *Zostera noltii* as well as the ability of leaf epifauna to graze off algal epiphytes (Schanz and Asmus 2002, 2003); and, although the seasonality of wind direction within the bay has been described (Costa 1982b), no empirical studies of wind waves within North Bay and South Bay have been made. Tidal velocities within the bays are also poorly known. Similarly, desiccation and photodamage due to high irradiance, which are environmental stresses that set upper intertidal limits to eelgrass (Hemminga and Duarte 2000; Boese et al. 2003, 2005*), have not been described in the bay; and upper limits of eelgrass distribution are only known from one location (Keller and Harris 1966). Salinity regimes ultimately set the inland distribution of seagrasses; and eelgrass, like other seagrasses, is euyhaline, tolerating salinities from 5.0 ppt to 42 ppt, although salinity requirements for eelgrass seed germination (down to 4.5 ppt) and seedling survival (~ 32 ppt) are more specific. In some estuaries, what appears as physiological plasticity may instead be ecotypic differentiation to low- and high-salinity regimes (Giesen et al. 1990; Kamermans et al. 1999; Hemminga and Duarte 2000). Ranges of short-term summer measures of salinity in North Bay and South Bay were 33.2 ppt –34.4 ppt and 33.5 ppt–33.8 ppt, respectively (Pequegnat and Butler 1981; Barnhart et al. 1992); and continuous readings from the central part of the bay in the present study ranged from winter lows of almost 15 ppt to summer highs of 34 ppt. All of these values are within the range of eelgrass toleration.

Physical factors resulting in environmental stress for eelgrass have been particularly acute for eelgrass in Humboldt Bay since the mid 1800s. Anthropogenic activities in the watershed and bay have either directly displaced eelgrass or stressed it by affecting the delivery and dispersal of suspended sediments into the bay. European development of the Humboldt Bay watershed began in earnest during the 1850s when lowland forests were cleared for residences and agriculture, most of which was dairy farming (Glatzel 1982). Enough logging was occurring during this time for the Mad River Slough Canal connecting the Mad River to Humboldt Bay to be built and rebuilt several

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*Paper was reviewed and updated since presentation to include relevant citations.

times between 1854 and 1881 in order to move logs into the bay, but the canal could not be maintained because it kept filling up with silt that also came into North Bay (Haynes 1986). Timber harvesting in the Jacoby and Elk River watersheds was also occurring by 1870 and 1880, respectively (Humboldt Bay Watershed Advisory Committee and Redwood Community Action Agency 2005*). Thus, the first substantial degradation to the aquatic light environment in the bay since the 1850s may have occurred when logging first peaked in the Humboldt Bay watershed between 1880 and 1910. After this time, logging activities declined for awhile but other activities affecting sediment dispersal and eelgrass habitat—like dock building, diking, shoreline armoring and dredging—did not abate (Costa and Glatzel 2002; Humboldt Bay Watershed Advisory Committee and Redwood Community Action Agency 2005*). Eelgrass beds in North Bay were further disturbed starting in the 1890s by several attempts at farming native and nonnative oysters, but farming activity became more established in the 1930s when nonnative oyster farming became successful (Waddell 1964; Shaw 1997; Dale, pers. comm.). The light environment in the entire bay may have been degraded again when, during the 1950s, bay headwaters and second growth lower basins were cut and extensive forest road building occurred. In addition to this light stress, some of the eelgrass beds in North Bay would have been physically disturbed by oyster dredges that were used from 1956 to 2000 (Dale, pers. comm.). Although oyster farming must reduce eelgrass abundance, present day long-line and hand-picking practices in North Bay can be less damaging to the beds (Rumrill and Poulton 2004). The majority of armoring in Humboldt Bay, especially in Entrance Channel, was completed by the early 1970s; but the third and most recent peak in watershed logging started in 1990 and dredging also continues today (Costa and Glatzel 2002; Humboldt Bay Watershed Advisory Committee and Redwood Community Action Agency 2005*). It is not possible to determine if present day dredging activities are affecting eelgrass distribution and productivity because eelgrass surveys have only been made prior to but not after dredging events (e.g., Western Ecological Services Company 1990; Miner 1993). Eelgrass habitat in Humboldt Bay has therefore been subject to a variety of anthropogenic disturbances since the mid-1800s, and many of these are still occurring in Humboldt Bay and the surrounding watersheds.

The ESM model predicts that when all the physical factors and disturbances described above for Humboldt Bay are minimal, then environmental stress will be low and biotic interactions (i.e., competition, predation) will be relatively more important in regulating biomass and the number of trophic levels in the eelgrass community. This is the top-down perspective, and its importance to understanding seagrass systems around the world has been neglected (Valentine and Heck 1999; Valentine et al. 2000; Williams and Heck 2001). The dominant paradigm as applied to Humboldt Bay is that all the carbon fixed by eelgrass is passed on to other trophic levels by a detritus-based pathway. Adopting this paradigm means that management decisions about eelgrass could be very bottom-up centric and not consider the top-down effects of grazing by Black Brant (*Branta bernicla nigricans)* and Widgeon on eelgrass in the bay (Moore et al. 2004) or the lethal effects of the eelgrass grazing limpet, *Tectura depicta*, which may be migrating north from Monterey Bay, California, as sea temperatures rise (Zim-

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*Paper was reviewed and updated since presentation to include relevant citations.

merman et al. 1996). Another shortcoming of the detritus paradigm is that it is accompanied by the misperception that most of the carbon in an eelgrass community is fixed by the eelgrass and not other photoautotrophs. In fact, about 50% of the net primary production in an eelgrass community can be fixed by the algae epiphytic on eelgrass leaves; and these algae can make substantial contributions in other seagrass systems as well (Nelson and Waaland 1997; Hemminga and Duarte 2000; Kaldy et al. 2002; Valentine et al. 2002). The inertia behind the seagrass-to-detritus paradigm of carbon flow affects decisions about what variables to include in monitoring and restoration plans for submerged aquatic vegetation (SAV). Plans dominated by variables causing physiological stress to eelgrass are appropriate for many estuaries, but the same plan may be less effective in another estuary where seagrass and epiphyte grazers have a larger role in affecting the productivity of the system.

What effects could grazers of eelgrass and epiphyte mesograzers have on the productivity and biomass of eelgrass in Humboldt Bay? Black Brant geese and some other migratory waterfowl graze on eelgrass beds in each of the bays between Baja California, Mexico, and Alaska (Wilson and Atkinson 1995; Reed et al. 1998; Ganter 2000; Moore et al. 2004; Ward et al. 2005*). Black Brant arrive in Humboldt Bay on their northward migration around December of each year. They are presently peaking in abundance at about 17,000 individuals by mid-March and most birds have flown north by May (Lee et al. 2007*). Terrestrial systems demonstrate a strong positive relationship between moderate levels of grazing and primary productivity (McNaughton 1985; Jeffries 1988; McNaughton et al. 1989, 1991; Rowcliffe et al. 1995; Bakker and Loonen 1998), and some of the warm-water seagrass grazers have also had positive effects on seagrass growth (Ziemen et al. 1984; Cebrian and Duarte 1998; Valentine and Heck 1999). The capacity of grazed plants to be more productive than nongrazed individuals of the same species is termed overcompensation or compensatory growth (Belsky 1986; Belsky et al. 1993). Overcompensation in seagrasses can occur either by increasing leaf growth rates or the rate of shoot production (Clausen 1994; Valentine et al. 1997). Black Brant often eat the youngest eelgrass leaves with the highest nitrogen content and avoid the shoot apical meristem, leading to the hypothesis that they "garden," or enhance the proportion of leaves with a high nitrogen content by regrazing and adding fecal matter to the same eelgrass patches (Moore and Black 2006). Southern Humboldt Bay, with its greater eelgrass shoot densities and biomass than North Bay, is also the bay where the majority of Black Brant feed and roost (Moore et al. 2004); and, since even the youngest eelgrass leaves are poor fodder relative to terrestrial grasses, the geese have to optimize their foraging time (Moore and Black 2006). Far fewer birds graze on North Bay eelgrass, which could be because of the greater amount of human activity on and around this bay, the lower shoot densities do not attract them, or the eelgrass may not be as accessible to the birds since the eelgrass in North Bay is deeper than South Bay and Black Brant only feed while floating over the eelgrass (Moore et al. 2004).

Seagrass mesograzers are capable of regulating epiphyte biomass (Williams and Ruckelshaus 1993; Jernakoff et al. 1996) and thus potentially also increasing seagrass productivity by removing epiphytes that intercept PAR, particularly in the blue and red wavelengths (van Montfrans et al. 1984; Drake et al. 2003). Caprellid and gammarid amphipods, the isopod *Idotea resecata*, the gastropod *Lacuna variegata* and the opisthobranch *Phyllaplysia*

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*Paper was reviewed and updated since presentation to include relevant citations.

taylori all occur in Humboldt Bay; and eelgrass epiphytes make up part or all of their diets (Beeman 1968, 1969, 1970; Zimmerman et al. 1979; Williams and Ruckelshaus 1993; Nelson 1997b; Nelson and Waaland 1997; DeLorenzo 1999). *Phyllaplysia taylori* is cryptically colored and spends its entire life on eelgrass leaves (Bridges 1975); and, while its reproductive biology has received some attention (Beeman 1970; Dykhouse 1976; Jaeckle 1984), its ecological function as an eelgrass mesograzer is just beginning to be appreciated. The number of adult *P. taylori* in North Bay shows an inverse relationship with eelgrass epiphyte loads (Keiser 2004). The present study therefore used aquaria to test the hypothesis that *P. taylori* can reduce epiphyte loads, and this hypothesis was supported each time the experiment was run. We also noticed that more *P. taylori* became permanently detached from the eelgrass leaves at the higher flow rate of 3.0 L/min, similar to the way snails are removed from shoots of *Zostera noltii* that occur at sites in the North Sea with more water movement. The loss of these snails results in epiphyte release (Schanz and Asmus 2002). The consequences of grazers to plant productivity in other systems, the dependence of Black Brant on eelgrass and the correlative and experimental data for *P. taylori* all indicate that Black Brant grazing could be increasing leaf growth rates or shoot densities in Humboldt Bay and that leaf cleaning by *P. taylori* and possibly other mesograzers allows eelgrass to be more productive. Eelgrass productivity and biomass in Humboldt Bay may not only be the result of fluctuations in physical factors.

The ESM conceptual model of community regulation that we applied to eelgrass in Humboldt Bay does not include parasitism as one of its biotic interactions although the pathogen *Labyrinthula zosterae* (Protista, Heterokontophyta), which has severely reduced eelgrass biomass in the northwestern Atlantic (Muehlstein 1989; Muehlstein et al 1991), could have a major effect on the eelgrass habitat in the bay. Although there has never been a large-scale die-off of eelgrass in Humboldt Bay, the characteristic black leaf lesions of the wasting disease and *L. zosterae* itself are present on eelgrass in the bay (Leander, pers. comm.). The conditions that trigger an outbreak of *L. zosterae* are unclear.

The advantage of this model is that it has a broad perspective, and its application to the eelgrass in the Humboldt Bay environment in this analysis leads us to hypothesize that low light due to suspended sediments will be one of the largest stressors to eelgrass. Mechanisms of importance that could also impact eelgrass at a bay-wide scale are nitrate levels that, if not compensated by sediment ammonium, could limit eelgrass growth and the intensity of epiphyte grazing by *Phyllaplysia taylori*. Other factors regulating eelgrass abundance and trophic relationships—in particular wind waves, desiccation, Black Brant grazing and anthropogenic activities like dredging and mariculture operations—will have more localized effects. In total, South Bay should be less stressed and more regulated by top-down trophic interactions than North Bay, and future information should show relatively finer-scale differences in stress within the bays.

Management Tools and Supporting Research

One approach to the conservation of the eelgrass ecosystem in Humboldt Bay is to use the environmental stress model of Menge and Sutherland (1987), or a similar model, in order to derive a set of eelgrass habitat requirements. While several endeavors of this kind are underway around the world, requirements developed for submerged aquatic vegetation (SAV) in the Chesapeake Bay are a particularly strong example (Kenworthy et al. 2006). Because of the susceptibility of SAV to low light and the multiple anthropogenic activities that degrade aquatic light, the Chesapeake Bay Program has focused on light attenuation either just through the water (based on Secchi depth or direct measures of light attenuation) or the more accurate but data-intensive approach of accounting for light attenuation by epiphytes as well as the water column (based on water column and epiphyte extinction coefficients, epiphyte biomass, total suspended solids, nutrients; Dennison et al. 1993; Batiuk et al. 2000). In both approaches, there is an attempt to manage the light environment to meet SAV requirements, which are stratified according to salinity regime. Batiuk et al. (2000) also recognize that other physical factors (e.g., tidal range, tidal velocities, wind waves, sediment grain sizes, porewater sulfide) have to be incorporated into habitat requirements in the future. This approach could be adapted for Humboldt Bay; but we suggest that, in addition to these physical factors, since eelgrass growth and the health of this critical fish habitat may be positively affected by Black Brant grazing and mesograzers like *Phyllaplysia taylori*, these organisms need to be part of the habitat requirements for eelgrass in Humboldt Bay.

Even when the original data presented in this analysis is combined with existing studies, it is clear that several types of studies are necessary for both a more complete perspective of eelgrass regulation in Humboldt Bay as well as the development of relevant and accurate habitat requirements for eelgrass in the bay. The first group of studies needs to expand upon what is known about the spatial and temporal patterns of eelgrass in Humboldt Bay. More complete maps of eelgrass and green algal distribution, with the upper and subtidal lower elevations of the eelgrass beds clearly demarcated, are necessary in conjunction with long-term monitoring of eelgrass metrics at select locations to identify watershed and climate effects.

The second group of studies needs to more completely enumerate the spatial and temporal variability of water-column and eventually epiphyte attenuation of light (e.g., Batiuk et al. 2000). Water column K_d values and corresponding compensation depths from San Francisco Bay should be similar to those in Humboldt Bay and therefore give a range of K_d values to expect and a possible target for management. These are K_d = 1.5, 1.6 (–2.0 m MLLW), K_d = 1.9 (–1.5 m MLLW), K_d = 2.2 (–1.0 m MLLW) and K_d = 3.1 (–0.5 m MLLW) (Zimmerman et al. 1991; Wyllie-Echeverria and Fonseca 2003). The present study indicates that water-column attenuation of light due to suspended sediments needs to be better understood in Humboldt Bay, and it will not be possible to manage for K_d if the origins of sediments in the bay remain relatively unknown. The efficacy of managing the light environment could be evaluated by both remote sensing (Batiuk et al. 2000) as well as Zimmerman's (2003) biooptical model for predicting eelgrass productivity in which K_d is one of the parameters.

A third group of studies needs to further describe the spatial and temporal pattern of nitrate, ammonium and phosphate in the water column and sediments of the bay and determine if any of these nutrients are contributing to light attenuation by promoting phytoplankton or epiphyte growth or if they are having directly toxic effects. As is the case for sediments, management of nutrients will only be possible if nutrient origins are known; and, since nitrate is primarily oceanic in origin, ammonium and phosphate need specific attention. A fourth set of studies should examine many of the less understood physical factors that affect eelgrass distribution and productivity, particularly the role of wind-wave disturbance and sediment grain size in setting upper limits for eelgrass in Humboldt Bay.

A final group of studies needs to examine the importance of top-down interactions from Black Brant and mesograzers on eelgrass productivity. Black Brant are known to occur in large numbers in Humboldt Bay and consume the eelgrass (Moore et al. 2004; Moore and Black 2006); but their effects on eelgrass productivity, potentially positive or negative depending upon feeding behavior and population size, are unknown. Since grazing changes the vegetation structure of the eelgrass bed, it is also possible that Black Brant affect the type, number and size of crabs, fish and shrimp using the bed. A more complete temporal and spatial description of the eelgrass mesograzer guild in the bay is also necessary, particularly for *Phyllaplysia taylori*. In addition, sources of mortality of *P. taylori*, likely suspended sediments and eutrophication (Clark 1995), need to be identified.

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Tables and Figures

Table 1. A comparison of the minimum and maximum ambient water column nitrate and ammonium levels (µM) in North Bay and South Bay during periods of upwelling and nonupwelling. Data are from Pequegnat and Butler (1981) and Barnhart et al. (1992). Data in these publications appear as ug atoms/L and are presented here as µM, and water-column ammonia (NH_3) values from these publications are presented as ammonium (NH_4^+). Samples from Pequegnat and Butler (1981) and Barnhart et al. (1992) were taken during high-salinity months (June and September 1980; July 1986) and, in order to represent the nitrogen environment for eelgrass in the two bays, the data presented are the minimum and maximum values from only those sites occurring well within the two bays.

Location	NO_3^- upwelling	NO_3^- nonupwelling	NH_4^+ upwelling	NH_4^+ nonupwelling
Just outside or inside Entrance Channel	9.9–16.9	0.23–4.03	1.90–2.41	0.0–2.98
North Bay	0.40–2.70	0.34–1.22	1.80–3.80	1.27–2.71
South Bay	0.79–5.23	0.00–2.40	1.96–2.98	0.46–2.98

Table 2. Concentrations (µM) reported to have saturated eelgrass growth and uptake rates.

Parameter		µM	Source
Growth Rate			
	NO_3^- water	4.0	Zimmerman et al. (1987)
		8.0	Thom and Albright (1990)
	NH_4^+ sediment	10.0–30.0	Zimmerman et al. (1987)
		100.0	Dennison et al. (1987)
		100.0	Williams and Ruckelshaus (1993)
Uptake Rate			
	NO_3^- leaves	> 23.0	Iizumi and Hattori (1982)
	NH_4^+ leaves	20.5	Thursby and Harlin (1982)
	NH_4^+ roots	211.0	Thursby and Harlin (1982)

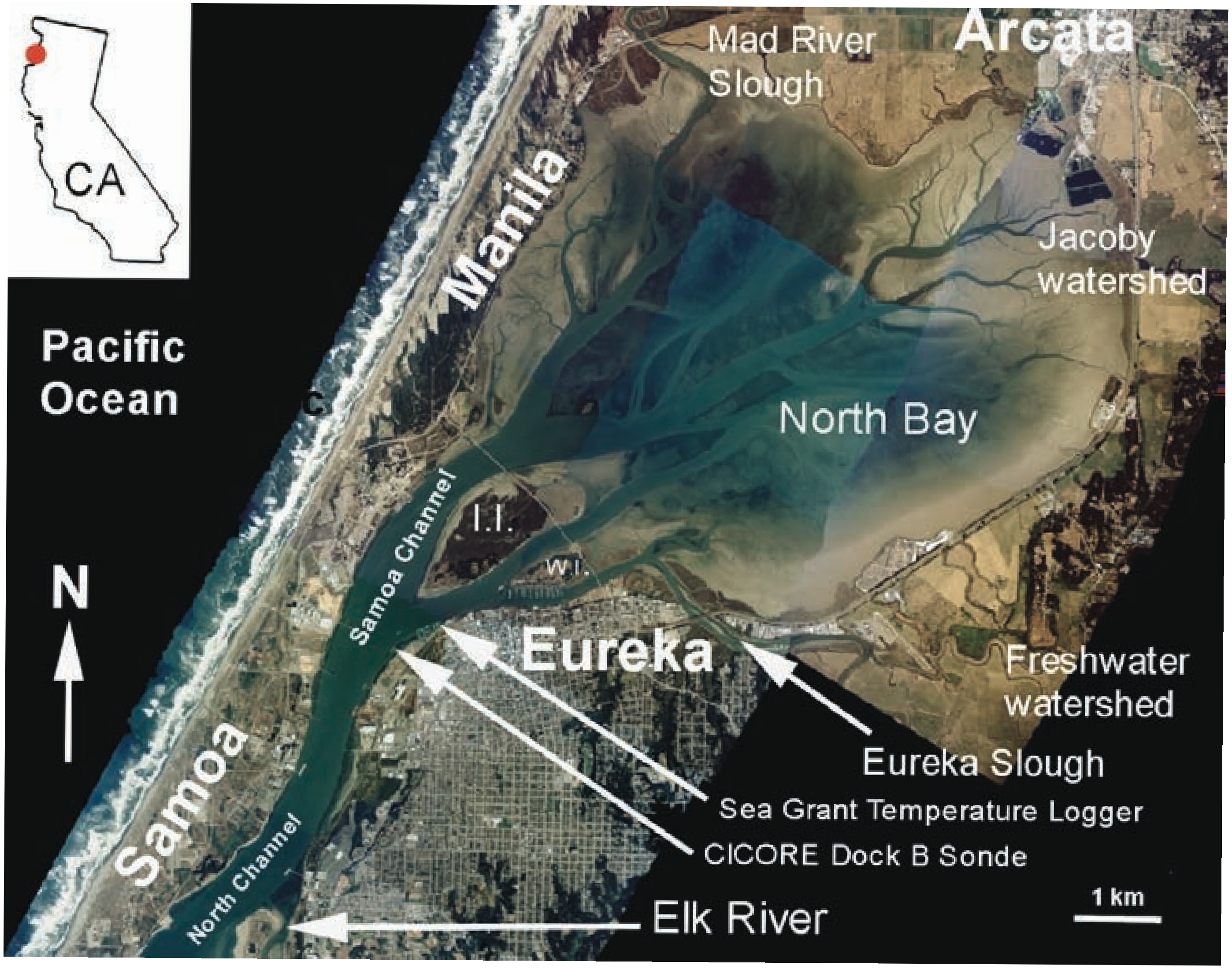


Figure 1. The North Bay (Arcata Bay) end of Humboldt Bay and part of central Humboldt Bay. Modified from the color aerial photograph (originally 1.6-m resolution) taken by The Humboldt Bay Harbor, Recreation and Conservation District during January 2000 (I.I. = Indian Island, W.I. = Woodley Island).

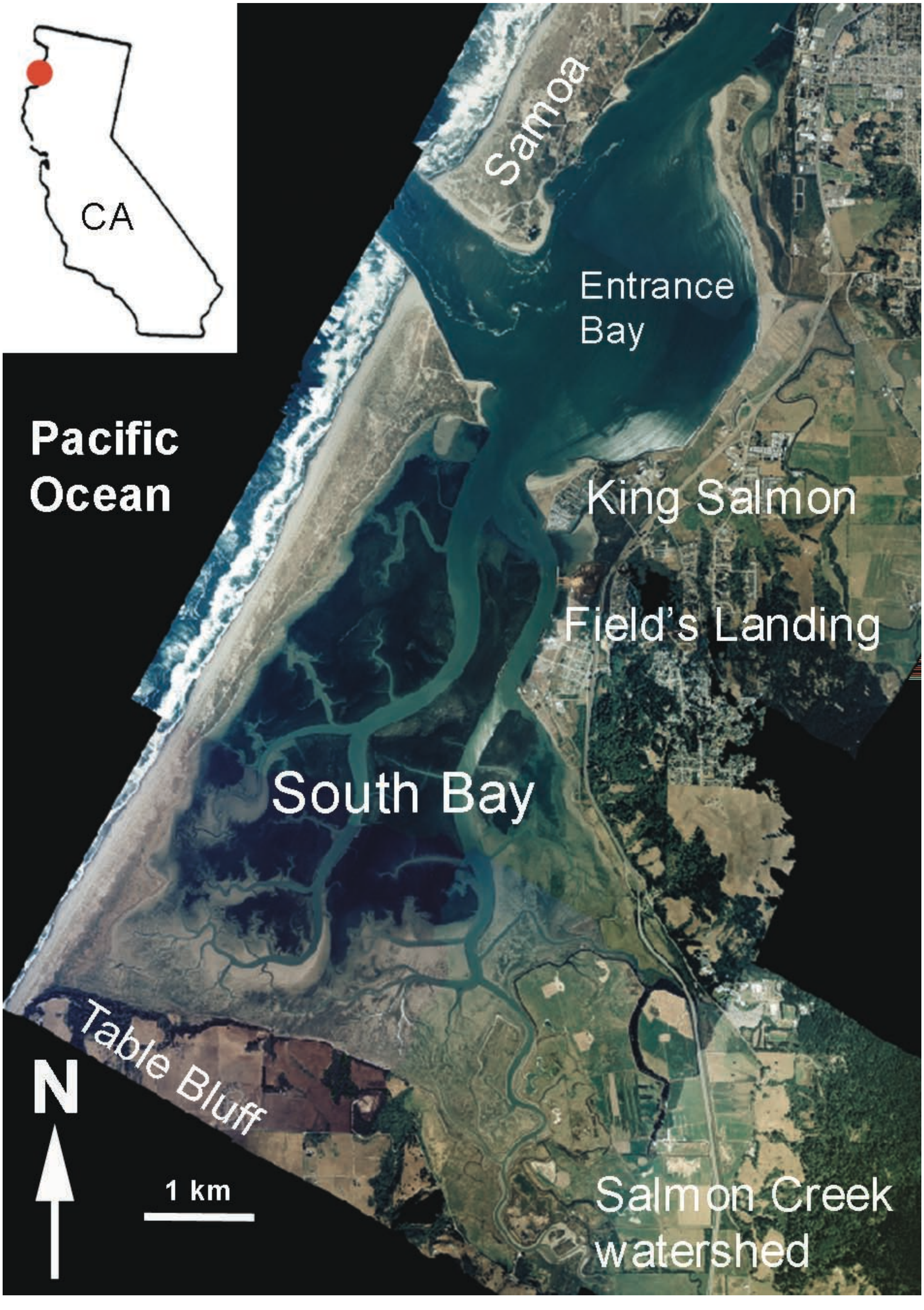


Figure 2. The South Bay end of Humboldt Bay and part of central Humboldt Bay. Modified from the color aerial photograph (originally 1.6-m resolution) taken by The Humboldt Bay Harbor, Recreation and Conservation District during January 2000.

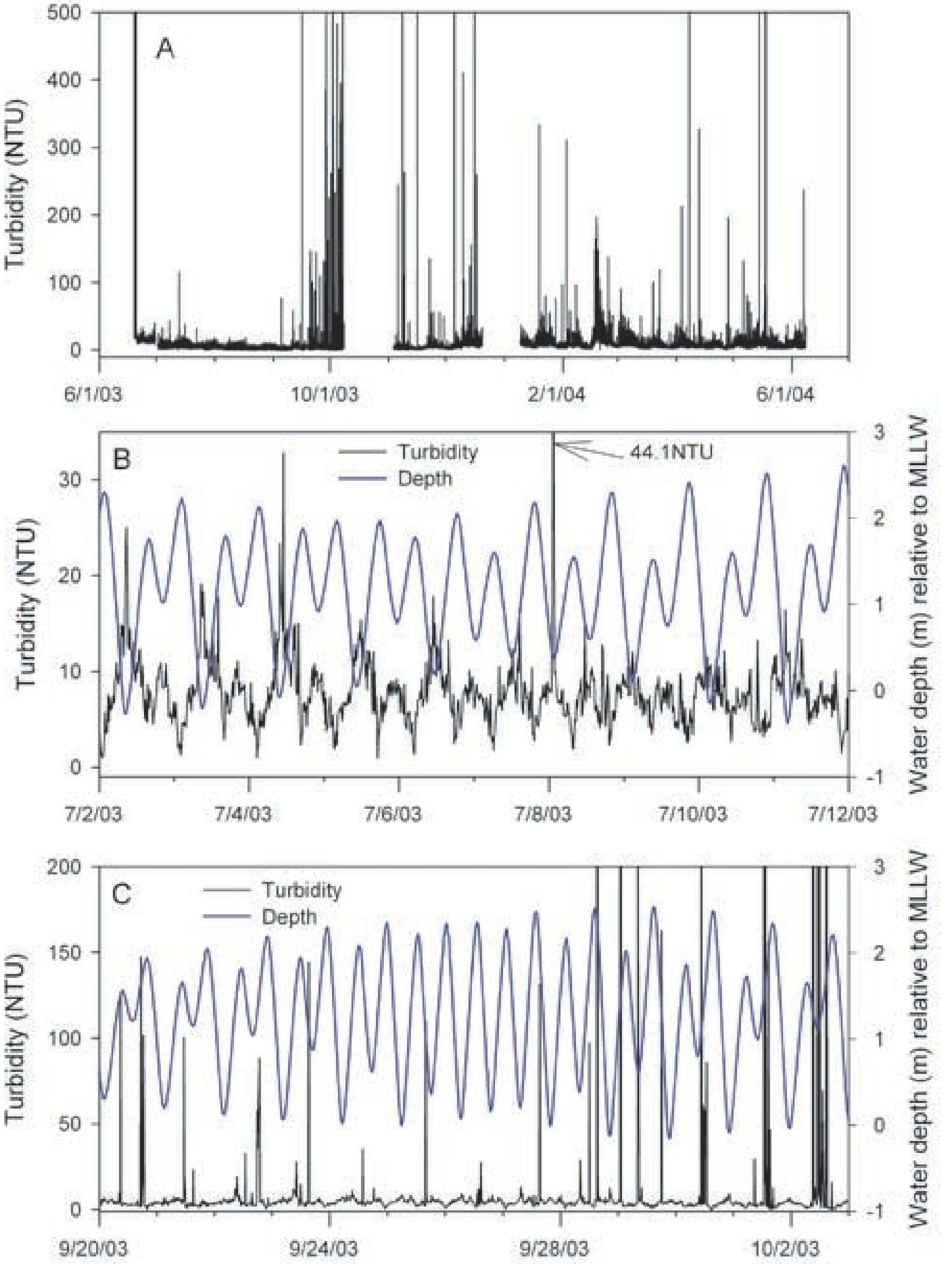


Figure 3. Turbidity values during 2003 and 2004: (A) during representative tidal cycles from July 2003, (B) an example of high-turbidity values during the fall of 2003 and (C) turbidity and water-depth data from the CICORE Dock B Sonde (Figure 1). Gaps in the turbidity curve (A) are due to missing data, and all values greater than 500 NTU were removed.

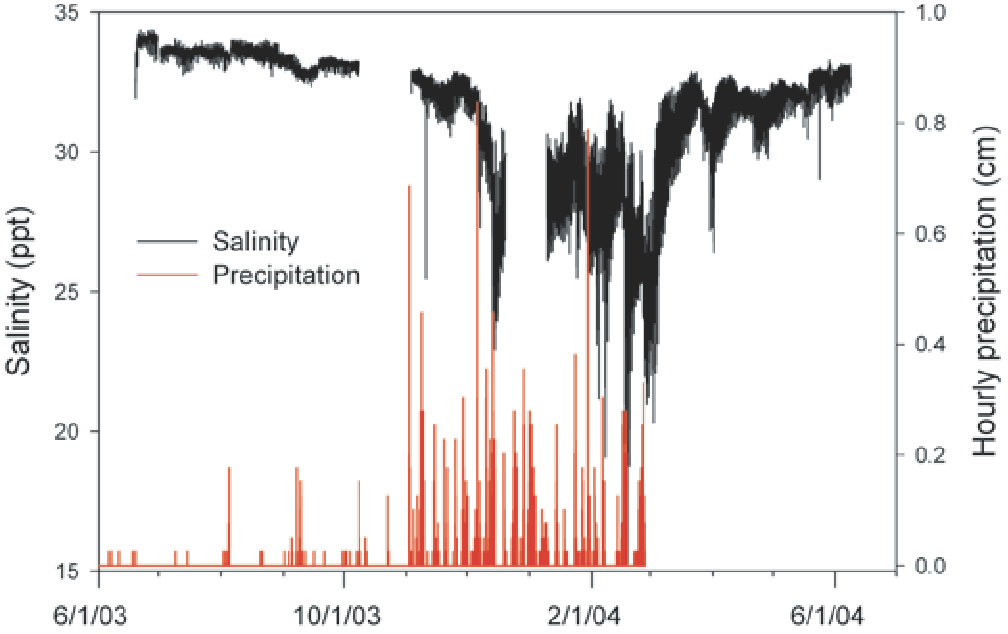


Figure 4. The relationship between salinity as measured by the CICORE Dock B Sonde and precipitation as recorded by Schlosser's Davis Pro weather station. Salinity gaps are missing data.

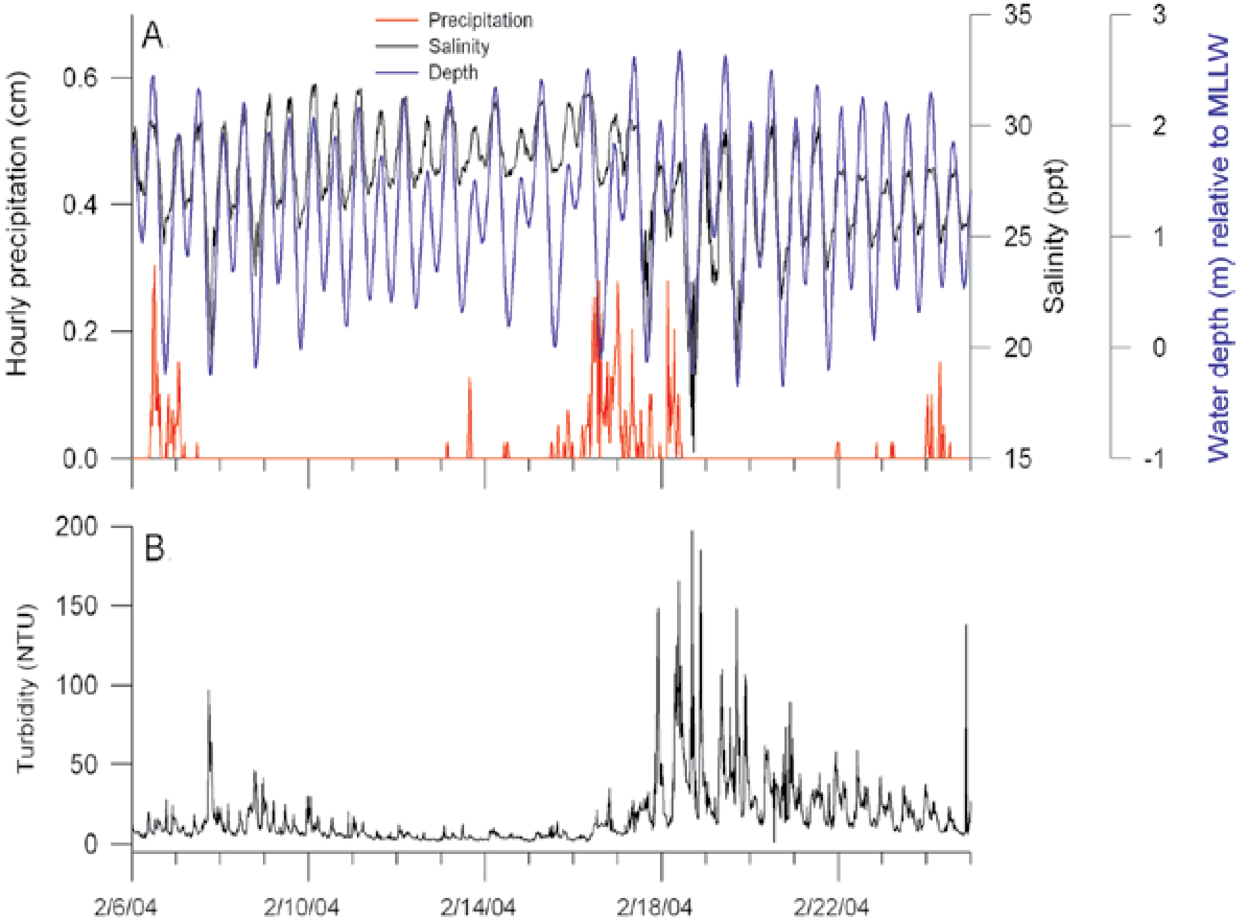


Figure 5. The relationship between precipitation, salinity, the water depth (A) and turbidity (B). Turbidity values greater than 500 NTU were removed. Precipitation data are from Schlosser's Davis Pro weather station; all other variables are from the CICORE Dock B Sonde.

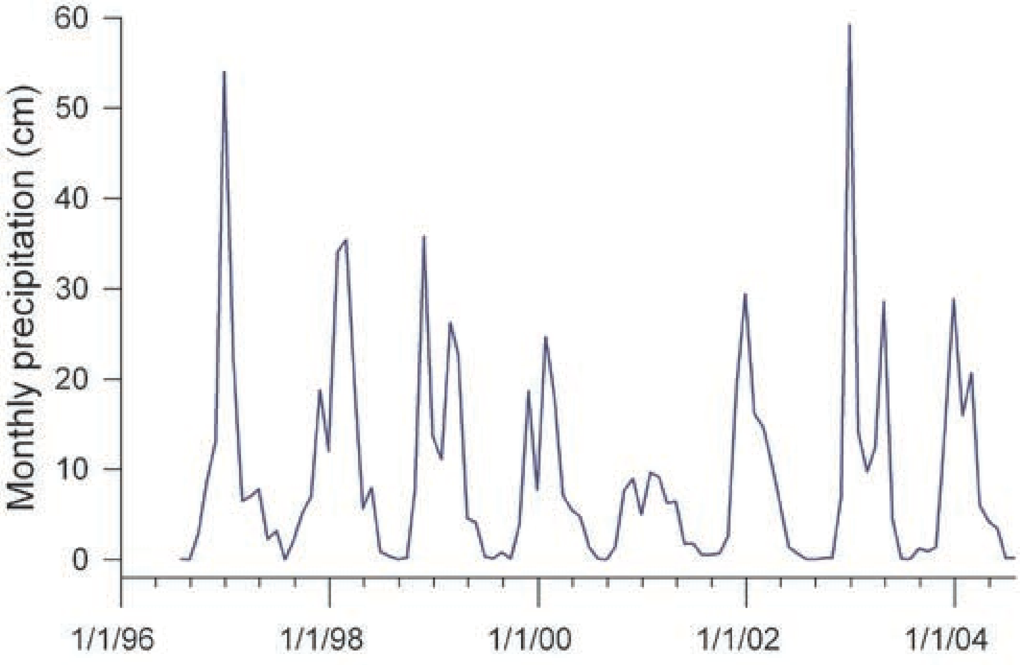


Figure 6. Total monthly precipitation at the NWS NOAA station on Woodley Island in Humboldt Bay, California.

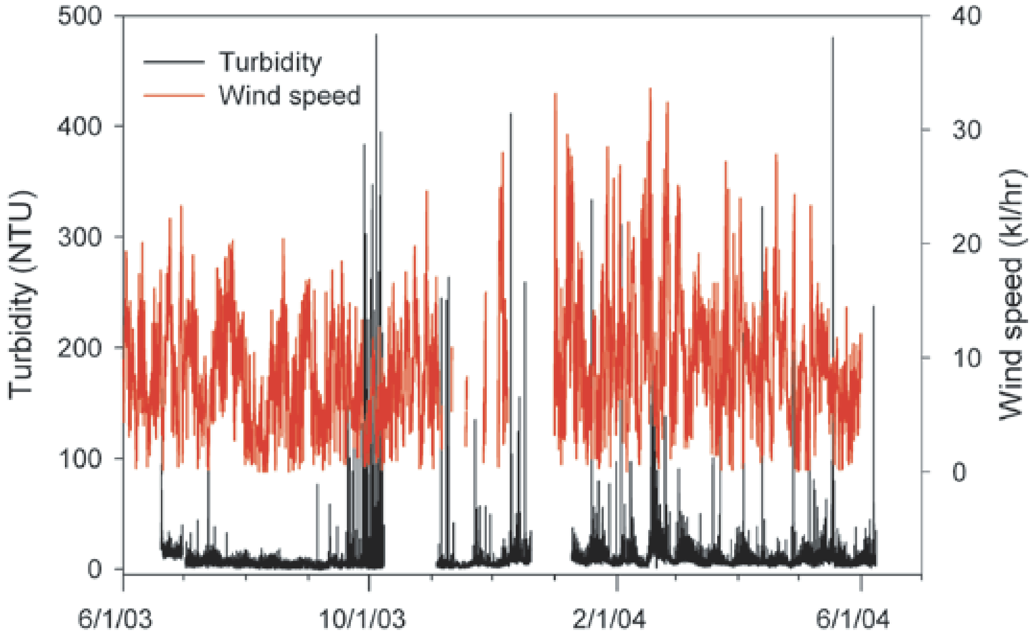


Figure 7. Turbidity (CICORE Sonde Dock B) compared to the wind speed readings from the NOAA Eureka Buoy (#46022), which is located 31 km west-southwest of Eureka (40° 43′ 12″ N, 124° 31′ 12″ W). Gaps in both curves are missing data.

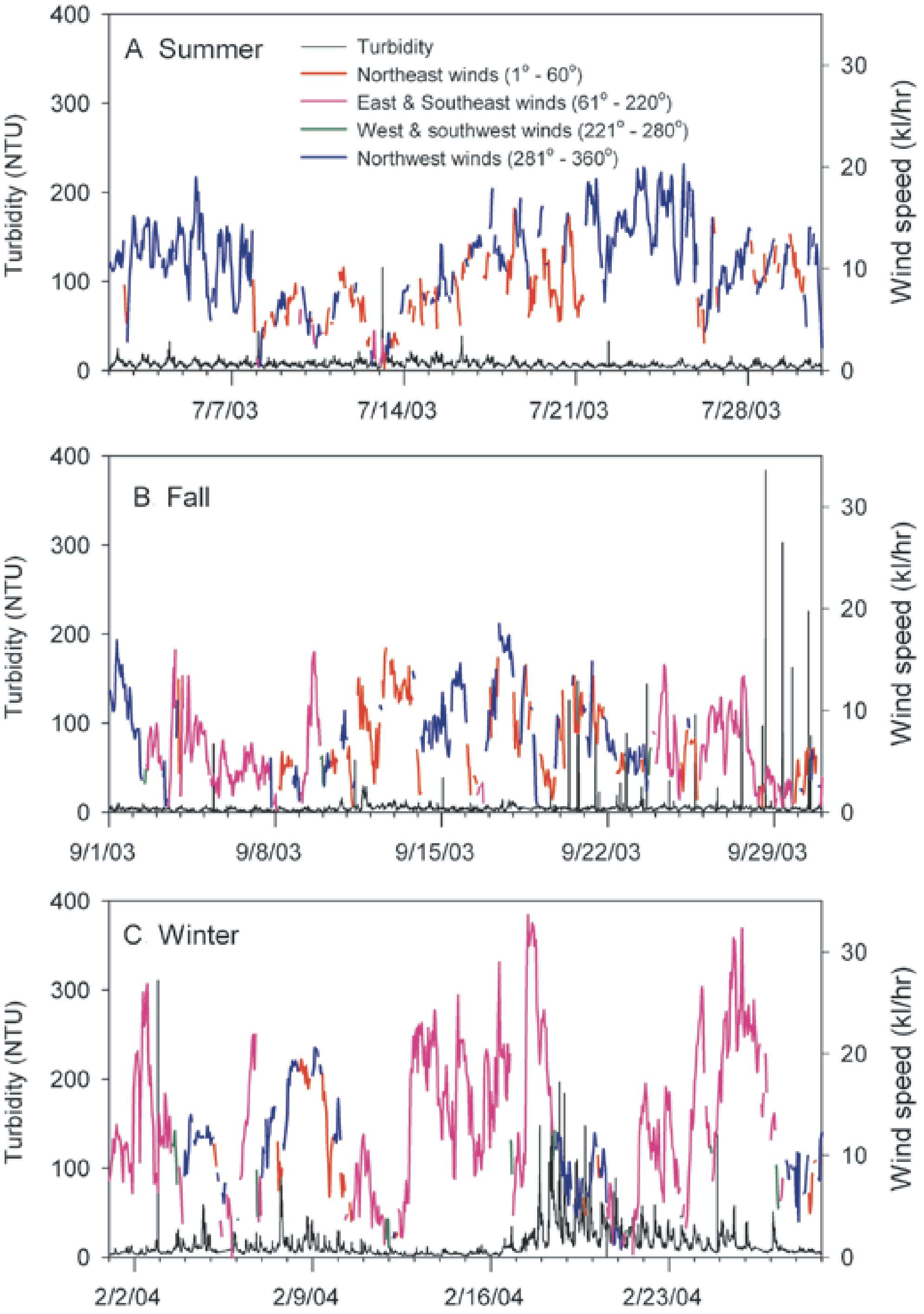


Figure 8. Comparisons of turbidity (CICORE Sonde Dock B) and wind speeds from specific directions during representative summer (A), fall (B) and winter (C) periods. Hourly wind speeds and directions are from the NOAA Eureka Buoy (#46022). Gaps in wind-direction curves are not missing data; the software would not draw a curve if there was only one wind-speed point for a given direction and time, nor would the software connect curves from different directions.

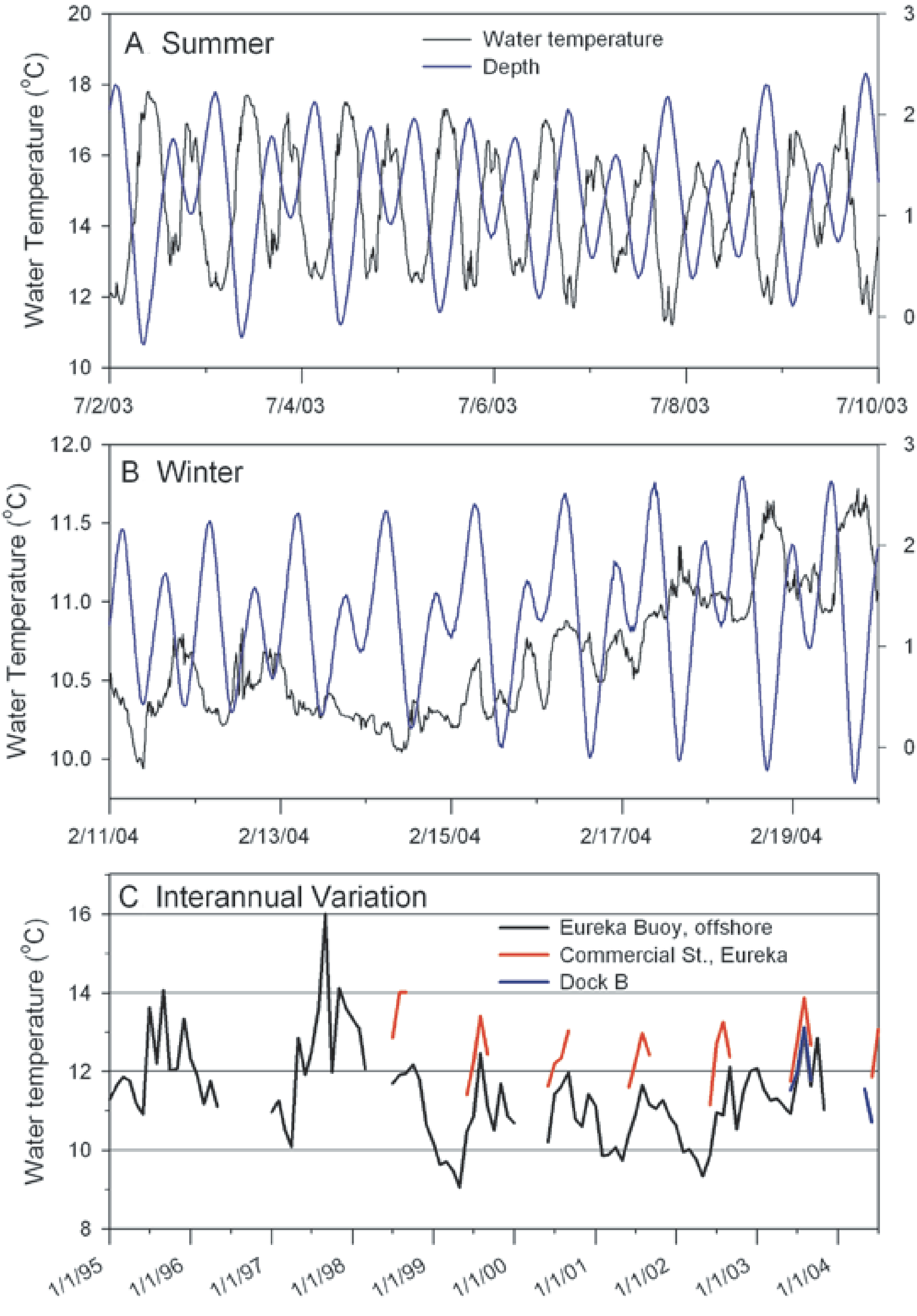


Figure 9. The relationship between water temperatures and tidal cycles in Humboldt Bay as recorded by the CICORE Sonde Dock B Sonde during representative summer (A) and winter (B) periods, as well as the interannual variation of seawater temperatures occurring outside and inside of Humboldt Bay (C). The latter temperatures are the mean of all the daily minimums that occur during a month. Offshore data are from the NOAA Eureka Buoy (#46022), whereas the Humboldt Bay temperatures are from the Eureka Sea Grant Temperature Logger (Figure 1) and the CICORE Dock B Sonde. Gaps in the offshore curve are due to missing data but gaps in the Humboldt Bay curves are due to the decision to use only summer temperatures (see RESULTS).

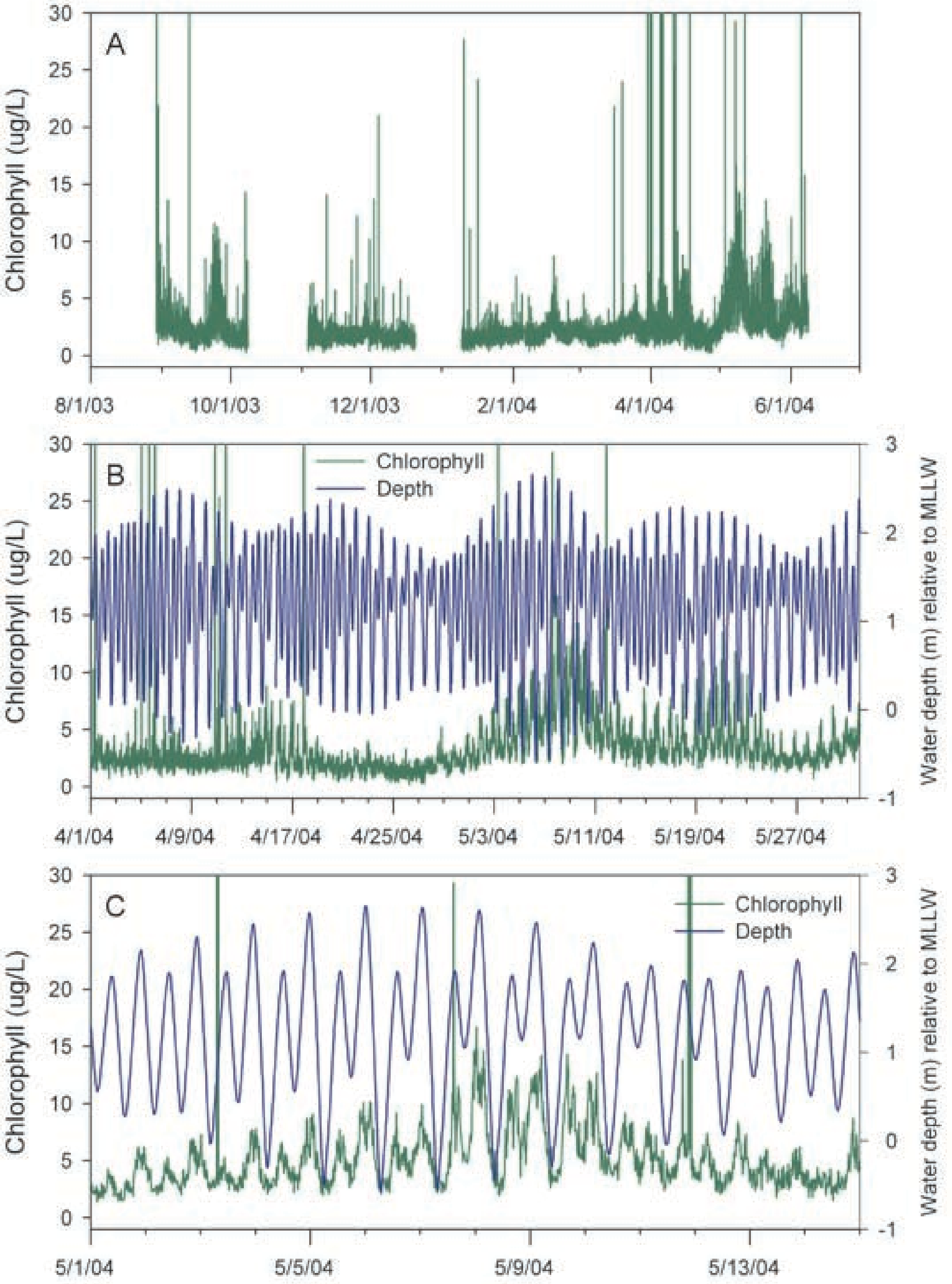


Figure 10. Variation in chlorophyll fluorescence during 2003 and 2004 (A), as compared to spring and neap tidal sequences during spring 2004 (B) and chlorophyll variation within tidal cycles (C). Data are from the CICORE Dock B Sonde, and gaps in the chlorophyll curve (A) are missing data.

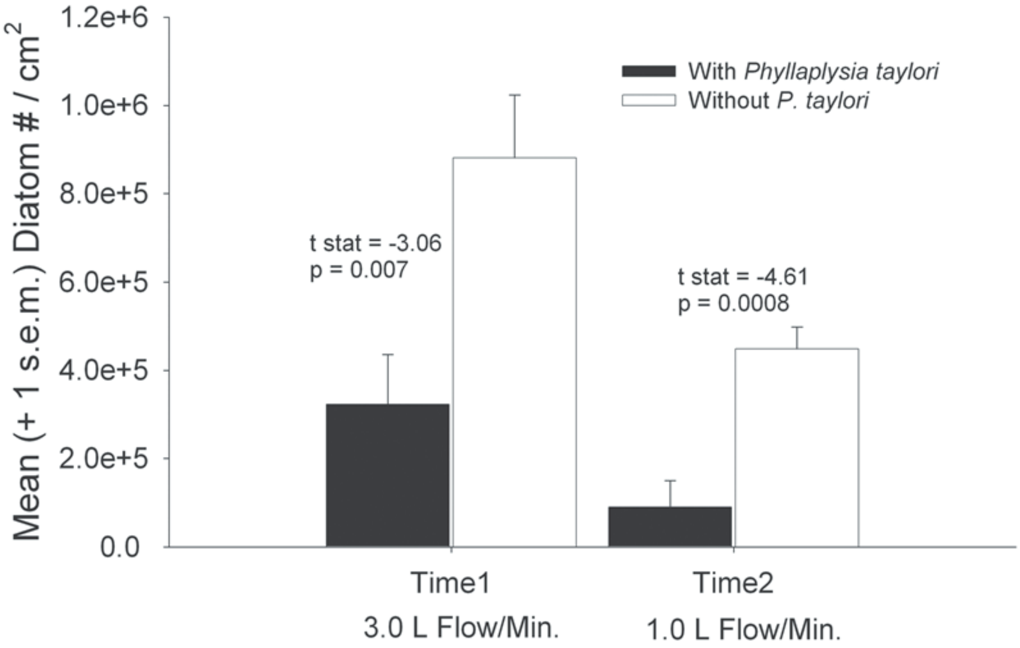
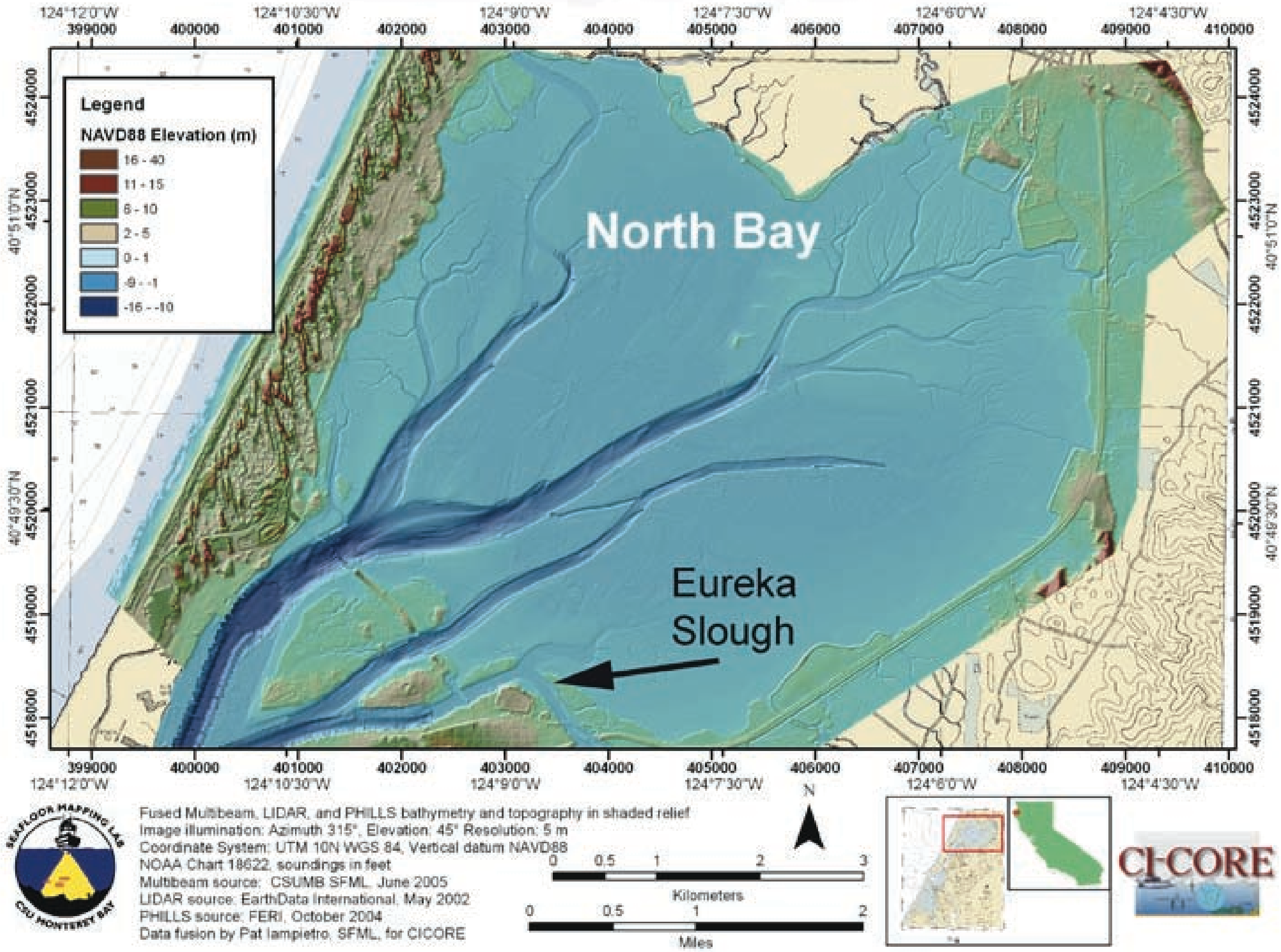


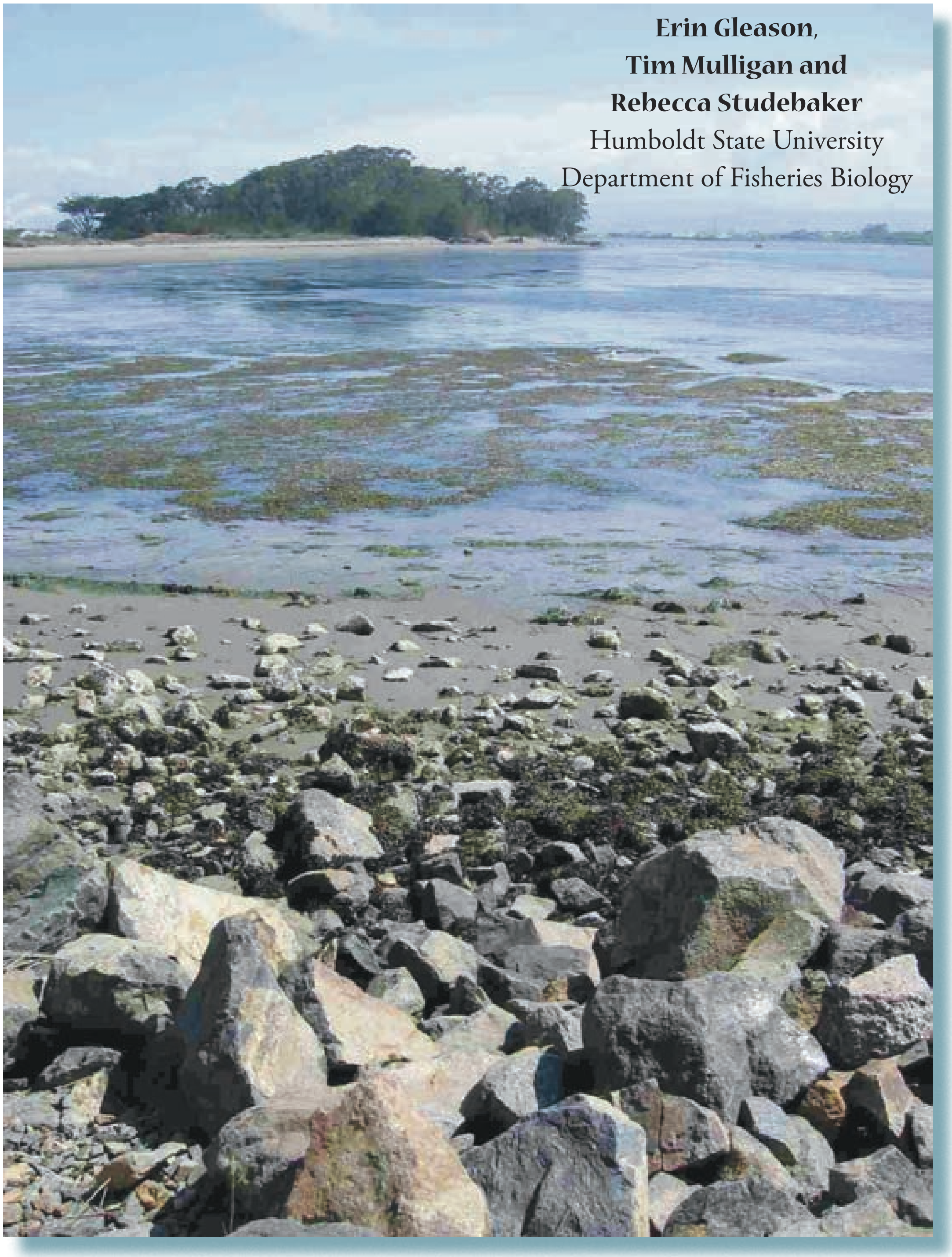
Figure 11. The effects of *Phyllaplysia taylori* presence or absence on mean (error bars are ± 1 s.e.m.) epiphytic diatom abundance during a high-flow experiment in early March 2004 and a low-flow experiment in late March 2004.



Fused Multibeam, LIDAR, and PHILLS bathymetry and topography in shaded relief
Image illumination: Azimuth 315°, Elevation: 45° Resolution: 5 m
Coordinate System: UTM 10N WGS 84, Vertical datum NAVD88
NOAA Chart 18622, soundings in feet
Multibeam source: CSUMB SFML, June 2005
LIDAR source: EarthData International, May 2002
PHILLS source: FERI, October 2004
Data fusion by Pat Iampietro, SFML, for CICORE

Figure 12. Bathymetry for part of North Bay (Arcata Bay) and Eureka Slough. Note the higher mudflat bars on the north side of the slough that may be preventing wind-generated turbidity from ebbing past the Eureka waterfront and the CICORE Sonde at Dock B.

Fish Distribution in Humboldt Bay, California:
A GIS Perspective by Habitat Type



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Abstract

In recent years, analysis using geographic information systems (GIS) technology has become very important to the natural and physical sciences. Fisheries biologists have been employing GIS in many aspects of fish management. Analyses in estuarine systems that contain commercially and recreationally important fish species are increasing in scope and value.

Fish abundance and diversity in Humboldt Bay, Humboldt County, California, were examined from September 15, 2000 to November 30, 2001. Sixty-seven fish species from 25 families were documented. Water quality parameters were also collected throughout the bay. These data were used to create several GIS coverages that can be used to analyze fish distribution with respect to habitat type within Humboldt Bay.

Introduction

Humboldt Bay is the second largest coastal estuary in California. In terms of its diversity and abundance of estuarine fauna, it is second only to San Francisco Bay (U.S. Department of the Army 1977). Its importance as a spawning, nursery and feeding ground for both estuarine and oceanic fishes has been established (Barnhart et al. 1992). It supports both commercial and sport fisheries for Pacific herring, Northern anchovy, and California halibut, as well as shark and surfperch (Warner 1982). Because of its ecological importance, studies of fish, bird and plant species inhabiting the bay are numerous.

Most fish studies involving Humboldt Bay have concentrated on commercially or recreationally important species. For example, Misitano (1970, 1976) studied the early life history stages of English sole, *Parophrys vetulus.* Misitano found that English sole enter Humboldt Bay at approximately the same time that they begin settling to the bottom. Anderson and Bryan (1970) described growth of surfperches in Humboldt Bay. They detailed length-weight relationships between males and females by studying scales from three species of surfperch collected in the bay. Rabin and Barnhart (1977, 1986) studied the fecundity and population characteristics of Pacific herring, *Clupea pallasi*, in Humboldt Bay. Through their research, eelgrass beds near freshwater creeks were determined to be the primary spawning areas. In 1978 Collins described feeding behavior of both English sole and speckled sanddab, *Citharichthys stigmaeus*. Collins discussed and modeled feeding strategies and food selection of the two species. Toole (1980) expanded on earlier English sole studies by describing the relationship between life stage and feeding behavior as it pertained to specific locations within Humboldt Bay. Bloeser (2000) described the biology of adult California halibut, *Paralichthys californicus*, in Humboldt Bay. Hers was the first study to research this species' use of Humboldt Bay and the effect of an El Niño event on the population's presence in the bay.

Much of the current knowledge of fish species known to use Humboldt Bay comes from Master's theses conducted at Humboldt State University. Eldridge (1970) found that the abundance of larval fishes increased with increasing distance from the mouth of Humboldt Bay. His study found a total of 37 species of larval fish. DeGeorges (1972) also collected a number of fish species in Humboldt Bay that had not yet been documented during his study of artificial reefs in South Bay. Samuelson (1973) and Sopher (1974) each conducted trawl surveys in South and North Bay, respectively, to determine species composition. These two studies are commonly cited in other publications describing the fish composition in Humboldt Bay. Waldvogel (1977) studied the distribution and age structure of Northern anchovy, *Engraulis mordax*, in Humboldt Bay. In the process, he documented 16 incidentally collected species. Other studies that provide information regarding species composition can be found in Prince and Gotshall (1976), Hill and Hendrickson (1991) and Chamberlain and Barnhart (1993), among others. Each of these has documented the presence of specific fish and added to the current information of species composition in Humboldt Bay.

Further information on the fish species inhabiting Humboldt Bay is often based on summary reports, both published and unpublished (Gotshall 1966; Monroe 1973; Shapiro and Associates 1980; Gotshall et al. 1980; Barnhart et al. 1992; Fritzsche and Cavanagh 1995). These papers reference the research of Humboldt State University, Master's theses, historical records and personal communications. Because of this, determination of dates and locations of fish species collected in Humboldt Bay are often difficult to ascertain. A majority of the data presented in these papers was collected in the 1970s.

These studies are also limited in application because only certain habitats within Humboldt Bay were sampled. Examination of many habitats would allow for a new understanding of fish distribution as it relates to habitat type, and provide detailed information for GIS analyses regarding ecological relationships within Humboldt Bay. It would also produce a database of current information regarding fish species and their distribution in Humboldt Bay.

Geographic information systems technology allows for complex spatial analyses to be conducted. Its capabilities allow scientists to examine ecological relationships to improve fisheries management decisions. For example, established characteristics for suitable salmon spawning habitat were entered into GIS in order to determine possible locations that met these criteria (Dauble et al. 1999). The health of fish habitat can also be determined using GIS. Hawks et al. (2000) used GIS as an aid in the development of watershed interactions, and determined appropriate acquisition areas based on human impacts, percentage of public land, species richness and habitat characteristics.

Geographic information systems can also be very useful for predictive analyses. Keleher and Rahel (1996) were able to model potential fish habitat loss based on gradual increases in temperature over time. Many variables affect the distribution of fish and habitat utilization. Geographic information systems allow a number of environmental factors to be analyzed. Zheng et al. (2002) found that statistical analyses used to describe spatial patterns of whiting, *Merlangius merlangus*, were limited and potentially incorrect. Subsequently, in order to accurately model the relationship between environmental conditions and abundance of whiting, GIS was used.

The ability of GIS to query spatial data and produce maps of species distribution makes it highly practical for analyzing fish habitat data. Fortunati et al. (2002) recognized the importance of analyzing and depicting trawl data using GIS, and therefore described the Trawl Survey Data Viewer (TSDV), a new GIS tool. This tool allows researchers to apply the graphic capabilities of GIS to the large amounts of data collected during trawl surveys. Singh et al. (2000) used maps created in GIS to support a proposal to include Musquash Estuary in New Brunswick, Canada, as a Marine Protected Area (MPA). The capabilities of GIS allowed clear representation of fish habitat and distribution.

Several physical and biological features of Humboldt Bay are currently being mapped using GIS. Many of these are available from the Humboldt Bay Harbor, Recreation and Conservation District at http://www.humboldtbay.org. Several of the maps describe the infrastructure surrounding the bay, including property lines and roads. There are also maps depicting bird habitat, oyster culture beds, and historic and current eelgrass bed locations. The capabilities of GIS are useful to the Humboldt Bay Harbor, Recreation and Conservation District because it is responsible for the management of the Port of Humboldt Bay. Consequently, it maintains the many GIS coverages of the bay. However, there is no coverage available that describes the location of finfish in Humboldt Bay.

This study is important because fish distribution data have never been collected over such a large scope of locations within Humboldt Bay. Physical-chemical parameters have also been recorded at many sampling locations. These data can easily be combined with habitat type data in GIS, allowing specific queries of the data. For this study, GIS will be used to determine habitat utilization by fishes of Humboldt Bay, and primarily for its ability to graphically depict fish distribution within the bay.

Site Description

Humboldt Bay is located 372 kilometers north of San Francisco Bay at latitude 40° 46′ N and longitude 124° 14′ W (Figure 1). The bay is composed of three subbays: North Bay, Entrance Bay and South Bay. Collectively, the bay measures 22.5 km in length, with an area of 62.4 km^2 at mean high water (MHW), and 28.0 km^2 at mean low water (MLW) (Proctor et al. 1980). Humboldt Bay is primarily exposed at low tide, with 65–70% of the entire bay made up of mudflats, the dominant habitat in both North and South Bays (Barnhart et al. 1992).

The bay is considered an atypical estuary because true estuarine conditions rarely occur due to limited freshwater input. There is also little mixing in the bay. At low tide, water that was covering the mudflats and present in the channels at high tide moves into the deeper channels and nearshore waters, respectively (Pequegnat and Butler 1982). A descriptive classification of Humboldt Bay was given by Costa (1982) when he described it as a tide-driven, multibasin coastal lagoon.

North Bay, also called Arcata Bay, is the largest of the three subbays, with a surface area of 8,000 acres (Monroe 1973). Jacoby Creek in the northeast, and Freshwater Creek and Elk River in the southeast provide freshwater to North Bay. Seventy-seven percent of the MHW area of North Bay is made up of intertidal mudflats, which are segmented by channels (Figure 2). North Bay Channel, Samoa Channel, and Eureka Channel are deepwater channels that extend from Entrance Channel, at the entrance of the bay, into North Bay. Mad River Slough Channel and Arcata Channel are shallower tidal channels that branch from deeper channels and segment into several tidal gullies.

South Bay is approximately 4,600 acres in area (Monroe 1973). Mudflats are the major habitat type, making up 81% of the MHW area in this subbasin. Freshwater input comes from Salmon Creek, which flows into the southeastern portion of South Bay. Two channels, Hookton Channel and Southport Channel, extend from Entrance Channel into South Bay. Because the tidal prism, MHW to MLW, of South Bay is 68% (higher than the 44% tidal prism of North Bay), the water in this bay is much closer in character to nearshore water (Pequegnat and Butler 1982).

Eelgrass, *Zostera marina*, is commonly found on the low mud flats near tidal gullies of both North and South Bays. Harding and Butler (1979) estimated the combined area of eelgrass cover in both North and South Bays to be 1,221 hectares, with a higher biomass in South Bay. Current mapping of eelgrass beds in Humboldt Bay is being carried out (McBride 2003, pers. comm.). Based on digital images taken in October 2000 by the California Department of Fish and Game, the area of eelgrass in all of Humboldt Bay was determined to be 1,951 hectares, with North Bay possessing a larger area of eelgrass than South Bay (McBride 2003, pers. comm.).

Entrance Bay connects North and South Bays and is essentially a deep channel that includes the mouth of Humboldt Bay. The area covered by water remains relatively constant throughout the tidal cycle, with only 10% of its area considered tidal flat (Barnhart et al. 1992). Two jetties, approximately 2 km in length, were constructed at the entrance of the bay from 1889 to 1899. The entrance to Humboldt Bay increased in depth from 12 to 27 feet due to this construction (Tuttle 1982). The addition of the jetties caused an increase in wave energy entering the bay (Costa 1982), and led to the complete rebuilding of the jetties from 1911 to 1925 (Tuttle 1982). Much of the shore of Entrance Bay is lined with rip-rap due to this increased wave action (Figure 3).

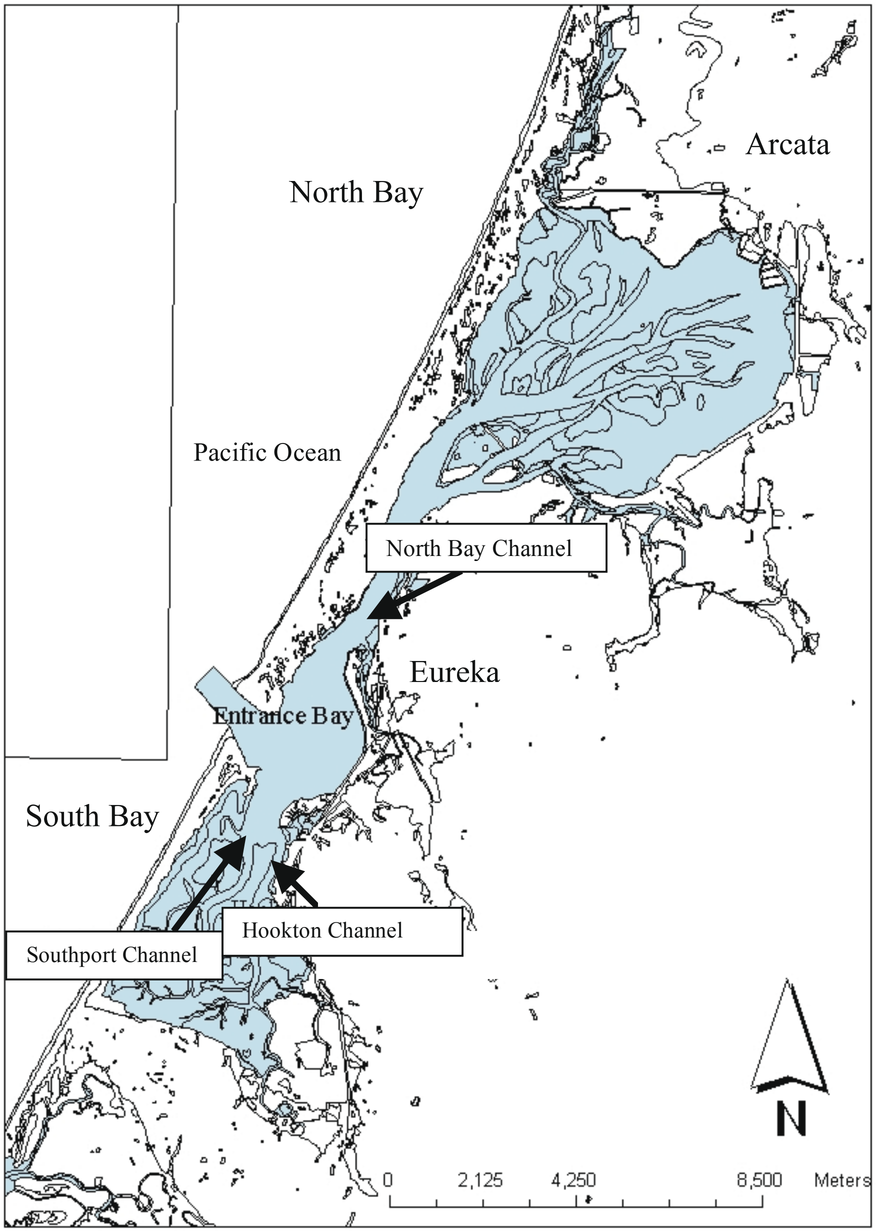


Figure 1. Humboldt Bay, Humboldt County, California. Map modified from National Wetlands Inventory (NWI) Data, U.S. Fish and Wildlife Service, 1987.

Figure 2. Intertidal mudflats in North Bay of Humboldt Bay, Humboldt County, California. These flats, located near the Arcata Marsh of northern North Bay, are segmented by tidal gullies.

Figure 3. The shore of Entrance Bay of Humboldt Bay, Humboldt County, California, is lined with rip-rap due to increased wave action. This photo was taken near the town of King Salmon, along the eastern shore of Entrance Bay.

In order to maintain channel depths, the U.S. Army Corps of Engineers (USACE) is required to dredge Humboldt Bay channels annually. Entrance Channel, North Bay Channel, Samoa Channel, Eureka Channel and Hookton Channel are dredged to depths of 7.9–10.7 meters (Barnhart et al. 1992). Major modifications of channels require sponsorship from the local Humboldt Bay Harbor District, which sponsored USACE projects to deepen Entrance Channel, North Bay Channel and Samoa Channel in April 2000 to improve navigation (Humboldt Bay Harbor District; http://www.humboldtbay.org). In addition to dredging, other modifications such as diking, draining and filling have changed the morphology of Humboldt Bay remarkably (Glatzel 1982).

The National Wetlands Inventory (NWI) of the U.S. Fish and Wildlife Service (USFWS) is responsible, under the 1986 Emergency Wetlands Resource Act, for characterizing and sizing the country's wetlands and deepwater habitats. The agency has mapped approximately 90% of the wetlands in the continental United States, 44% of the maps are available in digital format (http://wetlands.fws.gov). They have distributed over one million digital wetland files; all are available for use by the private sector.

The NWI uses Cowardin et al. (1979) for classification of wetlands and deepwater habitats (Appendix A). This scheme is widely used, and serves as a consistent system for describing wetland habitat. The hierarchical system begins with five major categories: Estuarine (E), Lacustrine (L), Marine (M), Palustrine (M), and Riverine (R). The digital map of Humboldt Bay, available through the NWI, is used as the base habitat map in this GIS study.

Materials and Methods

Field sampling of fishes in Humboldt Bay began on September 15, 2000, with surveys continuing until November 30, 2001. A major objective of the field sampling was to increase effort in areas that had not been typically investigated in past studies. Many locations along the periphery of the bay, as well as sloughs, channels, beach and rubble areas, mud flats and eelgrass beds were selected by reviewing a National Oceanic and Atmospheric Administration (NOAA) navigational chart. Some sampled areas not evident on the chart were detected through examination in the field.

Coordinates

Geographic coordinates were collected at each site in order to accurately record the location. Points for many intertidal and subtidal locations were collected on the shore adjacent to the wetted area sampled. Locations were recorded as geographic coordinates in degrees, minutes and seconds, using a Trimble GeoExplorer II hand held Global Positioning System (GPS) unit. The GPS points were collected instantaneously, and not averaged or corrected. A total of 280 points were collected using this GPS unit. Forty-nine trawling locations, sampled using the R/V *The Coral Sea*, were collected via a Furuno GPS 80 unit. Because the base layer map of Humboldt Bay was projected in Universal Transverse Mercator (UTM), these coordinates were then converted using Corpscon for Windows Version 5.11.08.

Fishes

The focus of fish sampling was in areas that had not been thoroughly sampled in the past, including small channels, sloughs, rip-rap areas in the vicinity of the jetties and flocculent mud flats. Sampling techniques varied with habitat type. Much of the sampling was completed from the shore using pole seines, which varied in size from 8–50 feet long by 4–6 feet deep with a mesh size of 0.25 inch. Two to four crewmembers pulled the pole seine either parallel to shore or at a slight angle towards the shore. Beach seines were also used, and ranged in size from

120 to 150 feet long by 6 to 8 feet deep with a mesh size of 0.25 inch. One end of a beach seine was stacked on the shore while the free end was attached to a small aluminum skiff. The skiff was then used to deploy the seine in order to make a half circle from the shore. Once the skiff had completed the set, crewmembers would pull the net onto the shore.

Sampling of the major channels in the bay was conducted from the R/V *Coral Sea* using a 32-foot epibenthic otter trawl with a 2-inch stretch mesh in the body and 1-inch stretch mesh in the cod end. Seventeen trawls were completed using this trawl net. Trawling over eelgrass beds was done using a 16-foot epibenthic otter trawl with a 1-inch stretch mesh in the body and 0.25-inch stretch mesh in the cod end. Sixteen trawls were done with this net from Humboldt State University's 27–foot aluminum pontoon boat. The tow speed and length of each trawl was dependent upon location, and was recorded to the nearest minute. On most occasions, geographical coordinates were taken once the trawl entered the water and again when the net was pulled out of the water.

The pontoon boat was also used to deploy a 6-foot modified beam trawl with 3-mm mesh to collect juvenile fishes a total of eight times. Standard minnow traps were also used in areas where nets could not be easily deployed. For example, minnow traps were attached to rip-rap at the entrance to the bay, which is a deep channel with very steep sides. A total of 30 traps were set in Humboldt Bay. The type of gear used reflected the habitat type being sampled, and there was no attempt to complete repetitive sampling. Due to this, the resulting data do not allow for any advanced statistical analyses.

All fishes were identified, enumerated, measured to the nearest millimeter (total length, TL), and released at the site of capture. Fish that could not be identified in the field were fixed in either 5–10% formalin, depending on life history stage. These specimens were brought back to the laboratory where they were subsequently transferred to 40% isopropyl alcohol and identified. An approved protocol was obtained under the Institutional Animal Care and Use Protocol #00/01.F.104.A. Fishes were primarily identified using Miller and Lea (1972). Other keys used were Tarp (1952), Hitz (1965), and Materese et al. (1989).

Water Quality

Temperature, salinity and dissolved oxygen were measured concurrently with fish sampling with either a Yellow Springs Instrument (YSI) model 85 or model 33. Location and number of readings were contingent upon the nature of the sample site. For example, a slough would require readings to be taken at the mouth where salinities might be higher, and also at the terminus, where salinities might be lower. In order to accurately represent changes in water quality over area, readings were taken as frequently as possible.

GIS Analysis

A digital habitat map of Humboldt Bay was obtained from the NWI Web site (http://www.nwi.fws.gov). Seven separate ARC/INFO export files corresponding with the U.S. Geological Survey (USGS) 7.5-minute topographic quadrangles, were downloaded to obtain a complete coverage of Humboldt Bay (Environmental Systems Research Institute 1999a). These were joined into one contiguous coverage and then the dissolve command was used to combine the attribute tables into one database table.

The polygons of the resulting coverage included habitat types as well as their area. The habitat types included estuarine, marine, palustrine and riverine. For each of these high-level categories, many subsystems were defined. A new column was added into the attribute table to condense the habitat code for all but the estuarine type into one code for each. For example, instead of including all three marine habitats: M1UBL, M2US2N and M2US2P, polygons were merged to include all subcategories under the single heading "Marine." This coverage was used as the base layer for fish and water-quality data.

Two separate tables were created in Microsoft® Excel to include spatial information for each sample location. Most sites were represented by points. Most trawl sites were represented by a pair of points representing the start and end of the trawl. Each point in both tables was given a unique number based on sampling order. These tables were saved as dBASE IV files, and imported as shapefiles using ArcView® 3.2 (Environmental Systems Research Institute 1999b). These shapefiles were then converted to coverages.

The point shapefile depicting trawl locations was edited in ArcMap to create lines (Environmental Systems Research Institute 2000). For trawls with a start and end point, lines were digitized connecting the two. Trawl lines that crossed an upland polygon when a straight line was digitized were given a central vertex outside of the upland polygon. For trawls with only a start point, trawl length was determined using the equation: $d = vt$, where d = distance, v = velocity and t = time, as both the speed of the boat as well as the length of time for each trawl were known. Once the distance was obtained, lines were digitized to the specific length. The appropriate azimuth was retained for all lines. These trawls were saved as a line shapefile. A column was added to the attribute table to give each line a new, unique identification number.

With the creation of the line shapefile, a completely new set of unique identifying numbers was created for the point shapefile. This was necessary, as the original point shapefile included all sampling events in one series of numbers. Because there were two separate shapefiles, new numbers were needed. The attribute table reflects the addition of new numbers with the original number identified as "Sample_#," and the new number identified as "ID." The sample number was retained in the attribute table to allow easy cross-referencing with originally collected tabular data.

Two tables were created in Excel to include fish data collected at each site: one for point locations and one for line locations. The tables included, for each feature, the common name of the fish species collected, the maximum, minimum and average length and abundance for each species. The table also included the respective identification number (ID) for each sampling site. Similarly, two water-quality data tables were created. These tables were saved as dBASE IV files.

Upon viewing the point shapefile with the habitat map shapefile in ArcMap, it was apparent that many points did not fall within the correct known habitat polygon. This was primarily due to established, inherent error in both the GPS units and the map data, but also the nature of GPS point collection. Therefore, many points appeared to fall on land. Other inaccuracies were noticeable when points fell just outside the respective channel sampled (Figure 4).

Point-in-polygon and line-in-polygon intersections were performed between the sample location files to allow easy examination of what habitat type contained points and transects by searching only the attribute table. A considerable number of locations that were, in actuality, sampled in estuarine habitat appeared to fall within upland or palustrine habitat polygons. These points were selected from the attribute table. An export file was created that contained only these points.

In order to move these points into the correct habitat polygons, the editing function in ArcMap was used. The original point shapefile was used as the editing layer. Each point

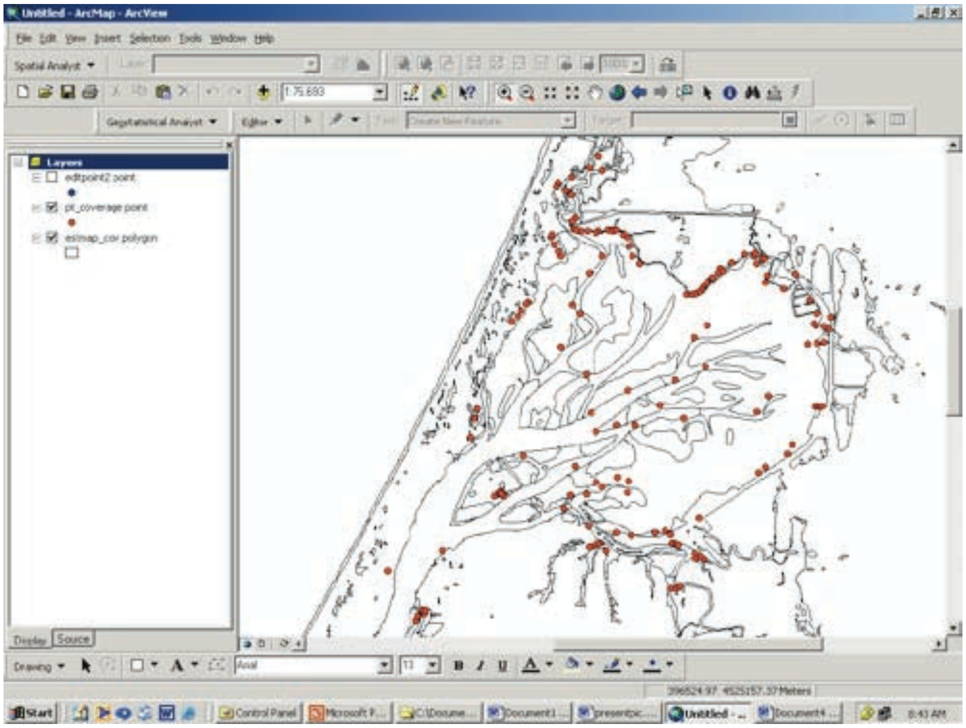


Figure 4. The habitat coverage of Humboldt Bay, Humboldt County, California, with associated sample points coverage. The red point layer entitled "pt_coverage" represents the sampling locations from September 2000 to November 2001 before editing occurred. Notice that many of the points fall just outside narrow channels, and also on land.

from the export file was examined individually while reviewing raw data sheets for accuracy of location. Points that fell outside the actual areas sampled were mapped to an appropriate nearby location. These included points in both estuarine and palustrine habitat polygons. Points that fell in the sloughs and channels that were not evident on the map were not edited. The newly edited points were saved as a separate shapefile (Figure 5).

The edited point coverage was intersected in ARC/INFO. After this intersection, the only points that fell within upland polygons were the unedited points from sloughs and channels not detectable on the map. The original intersected line shapefile was free of discrepancies. Any further editing of points was made directly to the new intersected coverage.

The fish and water-quality data tables were related to the intersected point and line coverages on the common ID field in the attribute tables in ArcMap. Because dBASE IV files created in Excel do not maintain cell formatting, columns containing text were not recognized in ArcMap. A new text column was added to the fish data tables in ArcMap, and the field calculator was used to copy the original species column, "Fish_Sp," to the new column, "Species."

After the finished tables were related to the spatial data, specific data were queried for all habitat analyses. Specific habitat types were selected from the intersected coverages. Because the fish data tables were related, statistics for all species collected in a selected habitat were easily queried. For example, searches for specific fish species were easily conducted to determine locations within the bay where these species were captured. (Figure 6). Likewise, the average length for a particular species was obtained

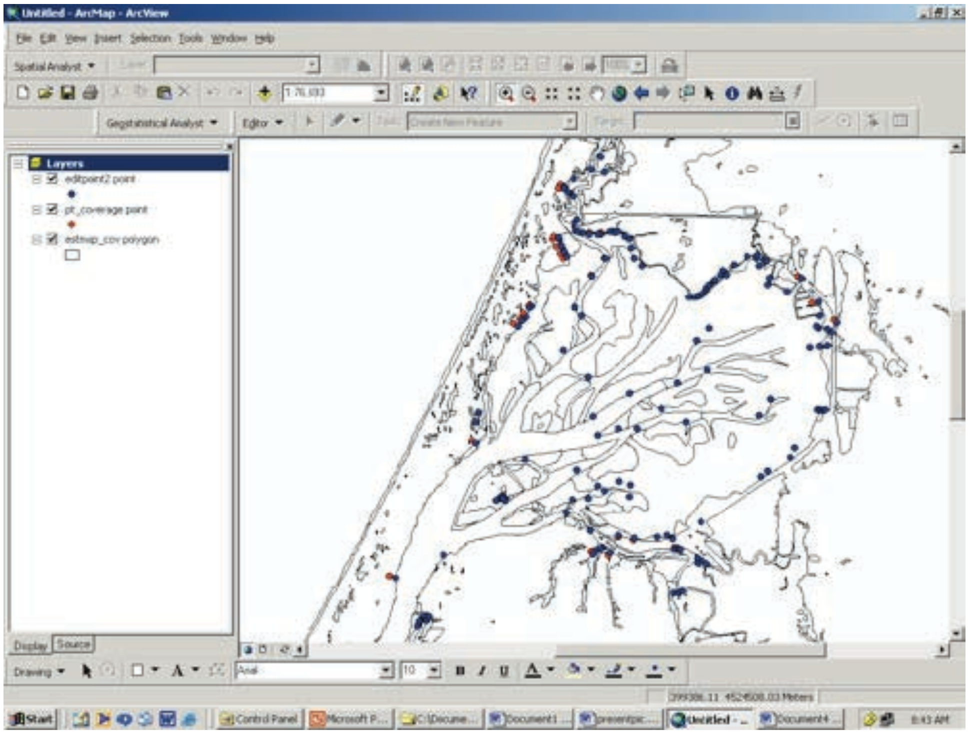
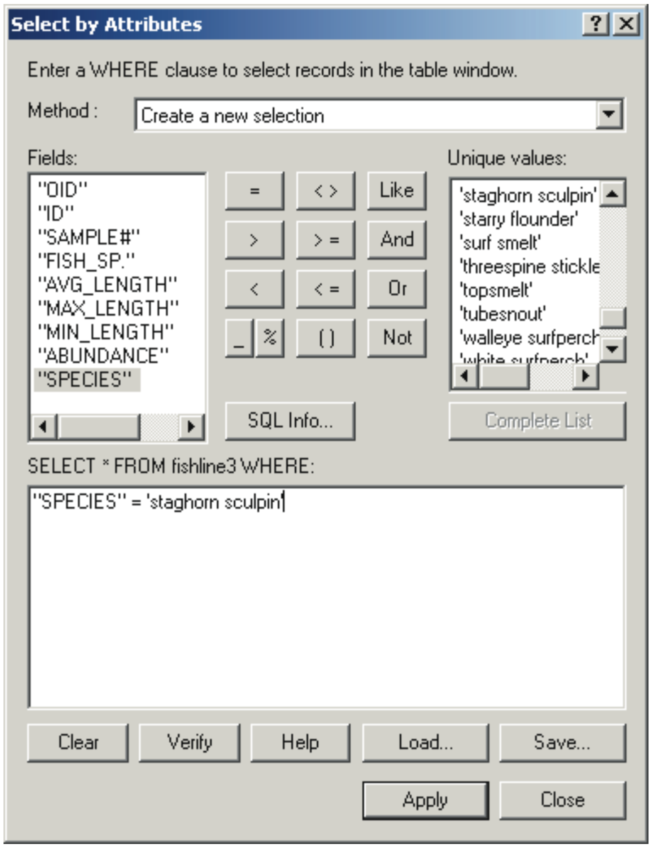


Figure 5. The habitat coverage of Humboldt Bay, Humboldt County, California, with associated sample points coverage. The red point layer entitled "pt_coverage" represents the sampling locations from September 2000 to November 2001 before editing occurred. The blue point layer entitled "editpoint2" reflects the revised points.


Select by Attributes

Enter a WHERE clause to select records in the table window.

Method : Create a new selection

Fields:
"OID"
"ID"
"SAMPLE#"
"FISH_SP."
"AVG_LENGTH"
"MAX_LENGTH"
"MIN_LENGTH"
"ABUNDANCE"
"SPECIES"

Unique values:
'staghorn sculpin'
'starry flounder'
'surf smelt'
'threespine stickle
'topsmelt'
'tubesnout'
'walleye surfperch
'white surfperch'

SELECT * FROM fishline3 WHERE:

```
"SPECIES" = 'staghorn sculpin'
```

Figure 6. Locating particular species collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001 using ArcView® ArcGIS 8.3 was done by performing a query in ArcMap. Certain attributes were selected to fit the search criteria.

by averaging the average length column; overall maximum lengths were obtained from the maximum-length column. In the same way, species were also queried by subbay.

Results

Point and line coverages were created to depict sampling locations in Humboldt Bay (Figure 7). Before the marine, palustrine and riverine habitat types were condensed into one, the Humboldt Bay coverage contained a total of 89 habitat types, under the five major headings: estuarine, marine, palustrine, riverine and uplands (Table 1). For a complete description of habitat types, see Gleason, Appendix A. For a specific example, the first habitat type in Figure 7, E1AB3L, describes a habitat type where E = Estuarine, 1= Subtidal, AB = Aquatic Bed, 3 = Rooted Vascular, L = Subtidal. Upland habitat made up most of the area of the coverage, followed by the three marine habitat types. There were 1,022 palustrine habitat polygons making up 60 different habitat types. The entire coverage was made up of 19 estuarine habitat types. Within the coverage, Humboldt Bay and immediately surrounding wetted areas contained 16 estuarine habitat types (Table 2). Of these estuarine habitats, 12 were sampled during the study.

A total of 67 identified fish species from 25 families were collected in Humboldt Bay using all methods between September 15, 2000 and November 30, 2001 (Table 3). The ten most abundant species accounted for 94.75% of the total catch; the three most abundant made up over 55%. The threespine stickleback, *Gasterosteus aculeatus*, was the most abundant species collected, with 15,655 individuals captured at 108 separate sites. Shiner surfperch, *Cymatogaster aggregata*, and topsmelt, *Atherinops affinis*, were the second and third most abundant, respectively.

The seventh most abundant species, the Pacific staghorn sculpin, *Leptocottus armatus*, was collected at 60.44% of the sites, the most of all species. Similarly, the fifth most abundant species, surf smelt, *Hypomesus pretiosus,* was collected at 38.32% of all sites. Topsmelt, the third most abundant species, was also the third most commonly collected species, closely following surf smelt with 38.01%. Juveniles of the family Osmeridae were not identified to species. In the results, these are counted as a separate species. One green sturgeon was collected in Samoa Channel outside these survey dates.

Eight of the survey points fell within the upland polygons, and 12 fell in palustrine. All but two of these points were actually in a narrow drainage ditch that runs alongside a diked area of North Bay. Based on personal observation, the habitat type of this channel is most likely E2US3N, as it is: estuarine (E), intertidal (2), with an unconsolidated shore (US), made up of predominately muddy sediment (3), and is regularly flooded (N). Therefore, the 18 sample points within this channel were assigned habitat type E2US3N. The other two points were assigned to habitat type E2EM1N, where E = estuarine, 2 = intertidal, EM = emergent, 1 = persistent, meaning emergent vegetation that remains, rather than falls to the surface at the end of the growing season, and N = regularly flooded.

All trawls were focused within the deeper portions of the bay. Therefore, the majority of lines fall within the habitat E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, and L = subtidal. However, two trawls entered more than one habitat type while sampling. It is impractical to separate the catch of these trawls by habitat type because the particular habitat where the species were collected is unknown. These two trawls and resulting fish collected are listed at the end of this section. The following results are listed separately by habitat type in order of area, largest to smallest. A short description of species collected by subbay, specifically North Bay, Entrance Bay, and South Bay, is also presented.

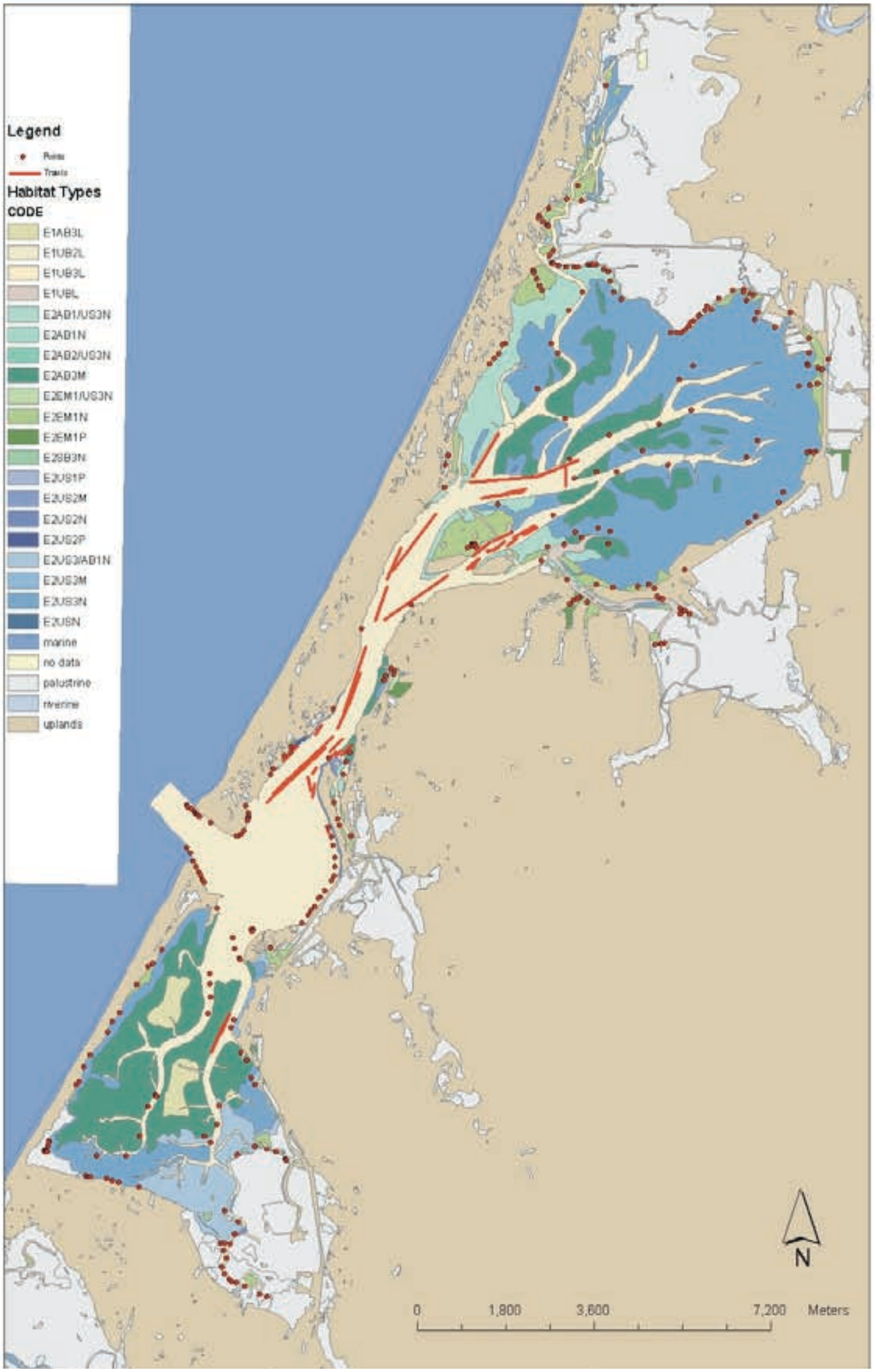


Figure 7. Sample locations within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Habitat map digitized by NWI.

Table 1. Habitat types in the coverage of Humboldt Bay, Humboldt County, California, before marine, palustrine and riverine habitats were condensed into one habitat type for each. For description of habitat types, see Gleason, Appendix A.

Habitat Type	No. of Polygons	Total Area (m^2)	Habitat Type	No. of Polygons	Total Area (m^2)	Habitat Type	No. of Polygons	Total Area (m^2)
E2US1P	1	15347	PEM/UBHH	1	6733	PSS/EM1C	23	230271
E2AB1N	2	23855	PUBFH	6	7418	PSS/EM1A	4	253513
E2SB3N	1	39234	PEMC	2	9768	PUBH	19	285531
E2EM1/US3N	1	52021	PEM1R	1	9951	PEM1A	15	331971
E2AB2/US3N	1	61538	PSS1A	3	10293	PUBHH	20	353460
E2US3M	3	101458	PSS1B	1	11533	PSS1/USA	6	606507
E2US2M	2	186062	PUSA	2	12315	PEM1CH	2	637004
E2EM1P	15	345227	PUBKHX	1	13594	PFO1C	53	644714
E1AB3L	3	1068204	PSS/EM1FH	1	17651	PEM1F	56	1146969
E2US2N	22	1150698	PEM1FX	2	19271	PEM1AD	3	1222171
E2US2P	17	1373438	PFO/SS1C	5	19689	PSS1C	235	1827335
E2US3/AB1N	10	2702989	PFO/SS1R	1	21956	PFO1A	20	1988493
E1UB3L	12	3830974	PAB3HH	1	22073	PEM1C	379	8540953
E2AB1/US3N	24	3996251	PFO4C	1	22392	PEM1CD	47	47022343
E2EM1N	86	4581905	PEM1/AB3HX	1	23470	R2UBH	1	33999
E1UBL	8	4868397	PFO/EM1F	1	23853	R1UBV	2	189113
E2AB3M	28	12019885	PUBF	8	28562	R3UBH	12	428275
E1UB2L	3	19082203	PUBFX	11	29615	R1USR	2	565004
E2US3N	35	23617745	PAB3H	1	30060	R3USA	4	595855
M2US2P	1	112015	PEM1/UBHX	1	34273	R3USC	11	1683454
M2US2N	4	3170451	PEM1HX	1	39717	UPLAND	27	565901526
M1UBL	1	305884320	PEM1/AB3F	1	43916	No data	1	62348
PUSCH	1	607	PUB/EM1F	1	47914			
PUBGX	1	1734	PEM1/UBHH	2	51869			
PEM1CF	1	1997	PEM1FH	4	67168			
PAB4HH	1	2051	PUBHX	24	67983			
PSS2C	1	2361	PAB4H	1	71004			
PEM1CX	1	2419	PSS1/USS	1	71441			
PEM1/UBFH	1	2972	PAB3F	3	91755			
PSS1/4A	1	3054	PEM/SS1C	7	107965			
PSS1CD	1	3204	PUSC	8	127571			
PUSCX	2	4131	PSS/EM1F	7	152161			
PEM1B	3	5136	PEM1/USA	3	156827			
PAB3HX	1	6308	PEM1/UBF	11	183020			

Table 2. Estuarine habitats of Humboldt Bay, Humboldt County, California, and the surrounding wetted areas. The codes are listed in order of area, which is given in meters squared. The number of habitat polygons of the coverage is given, as well as the number of sampling locations in the form of points and lines. Four estuarine habitat types in Humboldt Bay were not sampled.

Code	Area	Percent Area	No. of Polygons	No. of Points	No. of Lines
E2AB1N	23855	< 0.1	2	0	0
E2US2M	31773	< 0.1	1	0	0
E2US2P	36177	< 0.1	1	0	1
E2EM1/US3N	52021	< 0.1	1	2	0
E2US3M	101458	0.1	3	0	0
E2US2N	175368	0.2	6	4	0
E2EM1P	324165	0.5	14	5	0
E1UBL	966043	1.4	5	8	0
E1AB3L	1068204	1.5	3	0	0
E2US3/AB1N	2702989	3.8	10	6	0
E2EM1N	3547248	5.0	80	26	0
E1UB3L	3830974	5.4	12	17	0
E2AB1/US3N	3996251	5.6	24	22	0
E2AB3M	12019885	16.8	28	10	1
E1UB2L	19082203	26.7	3	89	47
E2US3N	23423963	32.8	26	70	0

Table 3. Sixty-seven identified species were collected in Humboldt Bay, Humboldt County, California, from September 15, 2000 to November 30, 2001. Species are ordered by number of sites where collection occurred. Rank of abundance is given for the 25 most abundant species.

Fish Sp.	No. of Sites	Abundance	Abundance Rank for top 25 species	% Abundance	% of Sites
boneyhead sculpin	1	2		<0.01	<1
brown smoothhound	1	1		<0.01	<1
calico surfperch	1	1		<0.01	<1
copper rockfish	1	1		<0.01	<1
curlfin turbot	1	1		<0.01	<1
cutthroat trout	1	2		<0.01	<1
gopher rockfish	1	1		<0.01	<1
lingcod	1	1		<0.01	<1
longjaw mudsucker	1	1		<0.01	<1
medusa fish	1	1		<0.01	<1
red Irish lord	1	2		<0.01	<1
ringtail snailfish	1	1		<0.01	<1
rock greenling	1	2		<0.01	<1
steelhead	1	1		<0.01	<1
fluffy sculpin	2	2		<0.01	<1
mosquito fish	2	10		<0.1	<1
petrale sole	2	2		<0.01	<1
showy snailfish	2	5		<0.1	<1
spiny dogfish	2	5		<0.1	<1
brown Irish lord	3	7		<0.1	<1
California halibut	3	3		<0.1	<1
whitebait smelt	3	5		<0.1	<1
buffalo sculpin	4	5		<0.1	1.2
coho salmon	4	5		<0.1	1.2
leopard shark	4	88	22	<1	1.2
longfin smelt	4	11		<0.1	1.2
Pacific tomcod	4	9		<0.1	1.2
sharpnose sculpin	4	4		<0.1	1.2
Pacific sanddab	5	15		<0.1	1.6
striped surfperch	5	10		<0.1	1.6
juvenile rockfish	6	14		<0.1	1.9
kelp greenling	6	15		<0.1	1.9
Pacific sardine	6	46	25	<0.1	1.9
penpoint gunnel	6	7		<0.1	1.9
pile surfperch	6	14		<0.1	1.9
spotfin surfperch	6	24		<0.1	1.9
silver surfperch	7	121	17	<1	2.2
juvenile flatfish	8	25		<0.1	2.5
night smelt	8	11		<0.1	2.5
plainfin midshipman	8	68	23	<1	2.5
tidewater goby	8	26		<0.1	2.5
bat ray	9	33		<0.1	2.8
butter sole	10	98	20	<1	3.1
sandsole	10	15		<0.1	3.1

—continued p. 122

Table 3. (continued) Sixty-seven identified species were collected in Humboldt Bay, Humboldt County, California, from September 15, 2000 to November 30, 2001. Species are ordered by number of sites where collection occurred. Rank of abundance is given for the 25 most abundant species.

Fish Sp.	No. of Sites	Abundance	Abundance Rank for top 25 species	% Abundance	% of Sites
Pacific sandlance	11	234	15	<1	3.4
bay goby	12	34		<0.1	3.7
white surfperch	12	35		<0.1	3.7
cabezon	13	23		<0.1	4
prickly sculpin	13	34		<0.1	4
redtail surfperch	13	101	19	<1	4
chinook salmon	14	89	21	<1	4.4
black rockfish	17	139	16	<1	5.3
walleye surfperch	17	62	24	<1	5.3
tubesnout	20	312	12	<1	6.2
jacksmelt	21	287	13	<1	6.5
saddleback gunnel	21	44		<0.1	6.5
Pacific herring	24	444	10	<1	7.5
Northern anchovy	33	4499	6	8.2	10.3
speckled sanddab	39	270	14	<1	12.1
starry flounder	39	104	18	<1	12.1
English sole	61	1616	8	2.9	19
arrow goby	72	474	9	<1	22.4
bay pipefish	72	392	11	<1	22.4
Osmerid sp	86	5201	4	9.5	26.8
shiner surfperch	103	8152	2	14.9	32.1
threespine stickleback	108	15655	1	28.5	33.6
topsmelt	122	6805	3	12.4	38
surf smelt	123	5009	5	9.1	38.3
staghorn sculpin	194	4152	7	7.6	60.4
total no. of sites	321	54888			

Estuarine, Intertidal, Unconsolidated Shore, Mud, Regularly Flooded (E2US3N)

This habitat type has the largest area of estuarine habitat in Humboldt Bay at 32.81%. Twenty-five percent of the sampling points fell in this habitat type (Table 4). A total of 19,425 individuals from identified species including juveniles from the family Osmeridae were collected; nearly half of these were threespine stickleback (48.93%). Northern anchovy and Pacific staghorn sculpin followed in abundance. Forty plainfin midshipman, *Porichthys notatus*, averaging 36.60 mm in size were also collected at three points. Eighty-six leopard sharks, *Triakis semifasciata*, were also collected at two points in this habitat type. The largest was approximately 1,219 mm. Seven tidewater gobies, *Eucyclogobius newberyi*, and three unidentified juvenile rockfish were also collected in habitat type E2US3N.

Eighteen points that fell in both upland and palustrine habitat polygons on the map were assigned this habitat type for purpose of analysis. These fish were collected in a narrow channel that parallels the contour of the bay along both the northern and western border. The map depicts this slough as a line, and therefore has no associated habitat data. A total of 3,532 fish were collected (Table 5). Threespine stickleback were collected at 12 points, Pacific staghorn sculpin were collected at 11 of the points. However, threespine stickleback made up 86.66% of the total catch. Pacific staghorn sculpin and topsmelt each made up less than 5% of the total catch. The remaining 3.74% included 14 other species, including juveniles of the family Osmeridae.

Estuarine, Subtidal, Unconsolidated Bottom, Sand, Subtidal (E1UB2L)

This habitat type constituted 26.73% of all estuarine habitat within the bay. Thirty-two percent of all points fell in this habitat. The identified species, including juveniles of the family Osmeridae, were collected by methods other than trawl in habitat type E1UB2L (Table 6). The most abundant species was topsmelt, followed by surf smelt and Pacific staghorn sculpin, respectively. One medusa fish, *Icichthys lockingtoni*, was collected in this habitat type, as well as two coho salmon, *Oncorhynchus kisutch*. A single gopher rockfish, *Sebastes carnatus*, was also found in this habitat type in South Bay.

The identified species, including juveniles of the family Osmeridae, were collected during the 39 trawls that were concentrated within this habitat (Table 7). Juveniles of the family Osmeridae were the most abundant group collected by trawl. Shiner surfperch and English sole were the second and third most abundant. Plainfin midshipmen were represented in both the point and line coverages. In all, 17,080 individuals from 60 identified species, including juveniles of the family Osmeridae, were collected in habitat type E1UB2L.

Estuarine, Intertidal, Aquatic Bed, Rooted Vascular, Irregularly Exposed (E2AB3M)

Four percent of points fell within this habitat type, which makes up 16.84% of estuarine habitat in Humboldt Bay. The identified species, including juveniles of the family Osmeridae, were collected (Table 8). Of these, the most abundant was shiner surfperch at 46.66% of the entire catch. The second and third most abundant species were surf smelt and threespine stickleback making up 30.41%, combined. One leopard shark measuring 281 mm was collected in this habitat type near Daby Island, which is just northeast of Woodley Island in North Bay.

Estuarine, Intertidal, Aquatic Bed, Algal/Unconsolidated Shore, Mud, Regularly Flooded (E2AB1/US3N)

Two percent of all points fell in this habitat type, which makes up 5.60% of estuarine habitat in Humboldt Bay. Of the 20 identified spe-

Table 4. Fish species collected in habitat type E2US3N, where E = estuarine, 2 = intertidal, US = unconsolidated shore, 3 = mud, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
pile surfperch	1	1	324	324	324
sharpnose sculpin	1	1	57	57	57
redtail surfperch	1	2	92	92	91
speckled sanddab	1	2	55	65	45
white surfperch	1	2	76	79	72
bat ray	1	3	759	900	620
black rockfish	2	3	55	68	43
saddleback gunnel	4	7	84	141	71
tidewater goby	1	7	46	64	37
bay goby	2	9	51	96	25
prickly sculpin	6	10	70	103	44
starry flounder	8	13	105	246	33
tubesnout	1	20	138	149	124
jacksmelt	5	27	232	346	39
walleye surfperch	5	28	67	211	23
English sole	10	29	65	108	35
plainfin midshipman	3	40	37	60	28
butter sole	1	60	23	32	8
bay pipefish	14	71	172	265	40
leopard shark	2	86	683	1219	300
arrow goby	24	142	51	66	20
Pacific herring	5	173	62	92	25
surf smelt	38	912	76	167	47
shiner surfperch	23	994	75	155	40
Osmerid sp.	26	1274	50	67	12
Topsmelt	38	1455	89	262	20
staghorn sculpin	54	1507	53	130	12
Northern anchovy	7	3042	69	111	32
threespine stickleback	27	9505	53	86	11
total		19425			

Table 5. Fish species collected in the habitat type E2US3N, where E = estuarine, 2 = intertidal, US = unconsolidated shore, 3 = mud, N = regularly flooded, of the narrow channels of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
coho salmon	1	1	127	127	127
starry flounder	1	1	24	24	24
bay pipefish	2	2	174	211	136
cutthroat trout	1	2	276	370	182
surf smelt	2	2	58	62	54
shiner surfperch	1	3	123	137	101
jacksmelt	3	6	19	22	17
prickly sculpin	2	6	84	130	57
Pacific herring	3	7	33	38	27
tidewater goby	2	8	30	48	20
Northern anchovy	4	9	53	96	44
mosquito fish	2	10	27	41	13
Osmerid sp.	6	24	51	58	46
arrow goby	9	51	49	62	36
topsmelt	4	165	119	140	62
staghorn sculpin	11	174	66	150	24
threespine stickleback	12	3061	39	65	12
total		3532			

Table 6. Fish species collected by methods other than trawl in habitat type E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific sanddab	1	1	20	20	20
buffalo sculpin	1	1	151	151	151
calico surfperch	1	1	179	179	179
copper rockfish	1	1	36	36	36
gopher rockfish	1	1	76	76	76
medusa fish	1	1	79	79	79
steelhead	1	1	126	126	126
Pacific sandlance	2	2	88	99	76
coho salmon	1	2	102	105	98
fluffy sculpin	2	2	44	53	34
juvenile rockfish	1	2	32	34	30
petrale sole	2	2	35	36	34
pile surfperch	2	2	265	330	200
red Irish lord	1	2	62	64	60
rock greenling	1	2	76	84	67
sharpnose sculpin	2	2	51	61	40
white surfperch	2	2	144	196	91
brown Irish lord	1	5	62	79	48
penpoint gunnel	4	5	129	162	105
walleye surfperch	4	5	70	78	61
plainfin midshipman	2	6	44	54	33
arrow goby	3	8	53	58	46
cabezon	5	8	126	214	80
sandsole	7	9	73	95	32
saddleback gunnel	6	10	98	147	70.5
striped surfperch	5	10	101	200	51
Northern anchovy	6	11	50	55	44
bay goby	5	13	59	94	17
butter sole	2	14	41	50	20
kelp greenling	5	14	108	183	79
spotfin surfperch	6	24	151	189	54
jacksmelt	5	30	251	372	143
Pacific sardine	2	38	102	132	95

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Table 6. (continued) Fish species collected by methods other than trawl in habitat type E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
starry flounder	13	44	116	212	36
speckled sanddab	11	55	63	104	35
chinook salmon	13	87	96	119	70
redtail surfperch	11	96	131	212	56
silver surfperch	7	121	61	82	52
black rockfish	11	132	57	74	44
bay pipefish	19	134	174	324	67
Pacific herring	9	198	46	81	28
English sole	20	221	68	117	32
tubesnout	10	254	127	219	93
shiner surfperch	18	423	76	141	37
threespine stickleback	22	492	53	84	15
Osmerid sp.	14	635	50	62	32
staghorn sculpin	35	1279	80	242	14
surf smelt	43	3106	77	428	25
topsmelt	32	3592	103	337	24
total		11106			

Table 7. Fish species collected by trawl in habitat type E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific herring	1	1	213	213	213
brown Irish lord	1	1	125	125	125
brown smoothhound	1	1	600	600	600
curlfin turbot	1	1	101	101	101
plainfin midshipman	1	1	50	50	50
ringtail snailfish	1	1	42	42	42
sharpnose sculpin	1	1	54	54	54
Pacific sardine	2	2	132	148	116
California halibut	3	3	591	760	473
buffalo sculpin	2	3	79	117	65
redtail surfperch	1	3	241	281	180
butter sole	1	4	96	109	82
juvenile rockfish	3	4	83	105	67
starry flounder	3	4	229	372	112
Northern anchovy	2	5	113	142	97
saddleback gunnel	4	5	99	115	85
showy snailfish	2	5	98	165	70
spiny dogfish	2	5	419	462	395
whitebait smelt	3	5	109	143	90
sandsole	3	6	75	100	30
threespine stickleback	5	6	67	75	45
cabezon	5	7	120	282	41
surf smelt	2	8	40	125	65
Pacific tomcod	4	9	155	215	96
longfin smelt	4	11	126	131	120
night smelt	8	11	121	136	102
Pacific sanddab	4	14	81	114	42
tubesnout	6	18	125	165	103
walleye surfperch	3	19	128	191	101
white surfperch	5	19	145	160	133
bat ray	3	22	294	463	265
topsmelt	4	23	82	99	47
juvenile flatfish	7	24	29	39	12
bay pipefish	14	67	158	298	69
speckled sanddab	20	83	76	117	27
staghorn sculpin	17	195	104	207	21
Pacific sandlance	8	231	84	99	76
English sole	16	1182	92	230	18
shiner surfperch	16	1474	99	147	75
Osmerid sp.	15	2490	42	69	10
total		5974			

Table 8. Fish species collected in habitat type E2AB3M, where E = estuarine, 2 = intertidal, AB = aquatic bed, 3 = rooted vascular, M = irregularly exposed, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
arrow goby	1	1	62	62	62
bat ray	1	1	352	352	352
black rockfish	1	1	64	64	64
leopard shark	1	1	281	281	281
walleye surfperch	1	2	120	148	91
starry flounder	2	3	79	86	76
Northern anchovy	1	4	97	113	80
Osmerid sp.	1	12	53	65	47
bay pipefish	3	18	164	281	62
topsmelt	3	19	90	204	48
jacksmelt	1	39	265	322	178
staghorn sculpin	8	43	73	142	33
threespine stickleback	5	60	63	79	31
surf smelt	6	131	73	111	54
shiner surfperch	7	293	74	138	43
total		628			

cies collected, including juveniles of the family Osmeridae, the most abundant was threespine stickleback at 54.52% of the entire catch (Table 9). Shiner surfperch was the second most abundant species at 19.73%, followed by staghorn sculpin at 5.37%. Pacific sardine, *Sardinops sagax*, and one longjaw mudsucker, *Gillichthys mirabilis,* were also collected here.

(Left) The threespine stickleback, *Gasterosteus aculeatus.*

Estuarine, Subtidal, Unconsolidated Bottom, Mud, Subtidal (E1UB3L)

Habitat type E1UB3L makes up 5.37% of estuarine habitat in the bay; 6% of all points were in this habitat type. A total of 4,567 fish were collected, representing identified species, including juveniles of the Osmeridae family (Table 10). Shiner surfperch made up 56.8% of entire catch. Northern anchovy was the second most abundant species comprising just over a quarter of the remaining individuals. Topsmelt was the third most abundant species. Other species collected in this habitat type were tidewater goby and plainfin midshipmen. One juvenile flatfish was not identified to species.

Table 9. Fish species collected in habitat type E2AB1/US3N, where E = estuarine, 2 = intertidal, AB = aquatic bed, 1 = algal / US = unconsolidated shore, 3 = mud, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
bay goby	1	1	0	0	0
black rockfish	1	1	51	51	51
longjaw mudsucker	1	1	93	93	93
speckled sanddab	1	1	49	49	49
tidewater goby	1	1	43	43	43
chinook salmon	1	2	103	104	102
walleye surfperch	2	2	60	67	53
Pacific sardine	1	4	105	112	96
prickly sculpin	2	4	85	126	35
saddleback gunnel	2	16	90	133	49
jacksmelt	3	20	53	107	25
bay pipefish	6	29	139	265	40
surf smelt	4	62	70	88	51
Northern anchovy	4	156	75	116	41
arrow goby	15	184	51	69	21
Osmerid sp.	4	201	49	60	32
topsmelt	15	208	79	237	21
staghorn sculpin	19	235	63	166	16
shiner surfperch	12	864	56	150	36
threespine stickleback	15	2388	41	76	21
total		4380			

Table 10. Fish species collected in habitat type E1UB3L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 3 = mud, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
unidentified juvenile flatfish	1	1	40	40	40
pile surfperch	1	1	378	378	378
Pacific sardine	1	2	82	82	81
black rockfish	2	2	56	56	55
tidewater goby	1	2	21	23	18
Osmerid sp.	1	3	38	40	35
saddleback gunnel	3	3	67	81	45
bat ray	2	4	252	386	150
bay goby	3	5	72	84	51
white surfperch	3	5	75	91	61
walleye surfperch	2	6	150	213	82
threespine stickleback	3	9	34	50	21
Pacific herring	3	10	74	92	49
speckled sanddab	2	10	55	89	45
starry flounder	5	13	156	291	59
plainfin midshipman	2	21	37	101	31
bay pipefish	5	29	146	268	37
surf smelt	3	30	83	103	71
arrow goby	9	53	50	66	24
English sole	4	61	81	153	38
staghorn sculpin	11	117	81	162	28
jacksmelt	4	165	131	340	60
topsmelt	10	254	71	178	37
Northern anchovy	2	1167	102	127	81
shiner surfperch	14	2594	65	144	40
total		4567			

Estuarine, Intertidal, Emergent, Persistent (Emergent Vegetation that Remains into the Next Growing Season), Regularly Flooded (E2EM1N)

Nine percent of points fell within this habitat type, which is 4.97% of the bay. A total of 2,395 individuals from 15 species, including juveniles of the family Osmeridae, were collected (Table 11). The most abundant species was shiner surfperch at 35.99 %. Topsmelt comprised 23.13% of the catch; surf smelt comprised 12.61%. Two coho salmon were collected in habitat type E2EM1N in small channels segmenting the mudflats in the northeast corner of North Bay.

Table 11. Fish species collected in habitat type E2EM1N, where E = estuarine, 2 = intertidal, EM = emergent, 1 = persistent, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
coho salmon	2	2	96	99	93
starry flounder	1	2	66	67	65
butter sole	2	3	35	45	22
tidewater goby	1	6	31	43	21
arrow goby	5	9	51	59	42
speckled sanddab	1	10	35	50	22
bay pipefish	2	11	192	240	162
English sole	2	77	37	63	21
threespine stickleback	8	88	42	70	14
Osmerid sp.	10	91	55	65	44
Northern anchovy	5	99	50	69	42
staghorn sculpin	19	279	45	102	14
surf smelt	12	302	67	141	48
topsmelt	4	554	86	170	29
shiner surfperch	4	862	73	97	46
total		2395			

One point that fell in the uplands habitat type and another that fell in palustrine were assigned this habitat type for purposes of analysis. These points are located in western North Bay near the town of Manila. Only six individuals from two species were collected at these two points: shiner surfperch and topsmelt (Table 12). These two species are representative of the overall abundance for this habitat type. The combined total number of individuals for all sampling within this habitat type was 2,401 from 15 species.

Table 12. Fish species collected in western North Bay, habitat type E2EM1N, where E = estuarine, 2 = intertidal, EM = emergent, 1 = persistent, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
shiner surfperch	1	1	85	85	85
topsmelt	2	5	91	100	81
total		6			

Estuarine, Intertidal, Unconsolidated Shore, Mud/Aquatic Bed, Algal, Regularly Flooded (E2US3/AB1N)

This habitat type makes up 3.79% of all estuarine habitat in the bay. Two percent of sample points fell within this type. From these points, a total of 1,208 individuals from identified species, including juveniles of the family Osmeridae, were collected (Table 13). The three most abundant species made up nearly three quarters of the entire catch. These were juveniles of the Osmeridae family with 339 individuals, topsmelt with 323 individuals and surf smelt with 235 individuals. One 850 mm leopard shark was collected in this habitat type in Hookton Slough in South Bay. An unidentified juvenile rockfish was also collected in habitat type E2US3/AB1N.

Estuarine, Subtidal, Unconsolidated Bottom, Subtidal (E1UBL)

Three percent of points fell in this habitat type, which made up 1.35% of estuarine habitat within Humboldt Bay. From these points, 16 species, including juveniles of the family Osmeridae, were collected (Table 14). Of the 803 individuals collected, shiner surfperch was the most abundant making up just over half the entire catch at 57.91%. Topsmelt was the second most abundant species at 13.08%, followed by surfsmelt at 12.08%. One tidewater goby was also found in habitat type E1UBL.

Table 13. Fish species collected in habitat type E2US3/AB1N, where E = estuarine, 2 = intertidal, US = unconsolidated shore, 3 = mud / AB = aquatic bed, 1 = algal, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific herring	1	1	47	47	47
bat ray	1	1	335	335	335
juvenile rockfish	1	1	28	28	28
kelp greenling	1	1	64	64	64
leopard shark	1	1	850	850	850
saddleback gunnel	1	1	69	69	69
English sole	2	2	58	71	45
threespine stickleback	3	7	55	77	50
white surfperch	1	7	69	77	62
arrow goby	2	8	56	59	52
pile surfperch	1	9	83	88	60
starry flounder	3	10	109	227	36
bay pipefish	3	12	147	227	58
staghorn sculpin	5	90	64	107	23
shiner surfperch	4	160	58	122	41
surf smelt	3	235	69	120	52
topsmelt	6	323	59	161	17
Osmerid sp.	1	339	54	100	42
total		1208			

Table 14. Fish species collected in habitat type E1UBL, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
starry flounder	1	1	85	85	85
tidewater goby	1	1	30	30	30
English sole	2	2	113	131	95
bat ray	1	2	343	427	258
bay pipefish	1	2	102	116	88
saddleback gunnel	1	2	85	88	81
arrow goby	1	3	34	39	29
threespine stickleback	3	4	41	43	39
Northern anchovy	1	5	83	85	79
bay goby	1	6	74	86	58
butter sole	3	9	26	32	18
Osmerid sp.	4	37	57	82	48
staghorn sculpin	6	62	47	112	11
surf smelt	4	97	68	128	58
topsmelt	2	105	75	137	59
shiner surfperch	1	465	75	119	53
total		803			

Estuarine, Intertidal, Emergent, Persistent (Emergent Vegetation that Remains into the Next Growing Season), Irregularly Flooded (E2EM1P)

This habitat type makes up 0.45% of the entire estuarine habitat of the bay. Two percent of the sample points fell within this habitat type. Seventeen species, including juveniles of the family Osmeridae, representing a total of 287 individuals were collected (Table 15). Over half of the total catch was made up of Pacific staghorn sculpin, and speckled sanddab, each totaling approximately 30% of the entire catch. A total of 99 sculpins of four different species were collected in this habitat type, 86 of which were Pacific staghorn sculpin. Ten prickly sculpin, *Cottus asper*, two bonehead sculpin, *Artedius notospilotus*, and one buffalo sculpin, *Enophrys bison*, were also collected.

Estuarine, Intertidal, Unconsolidated Shore, Sand, Regularly Flooded (E2US2N)

A total of 19 species, including juveniles of the family Osmeridae, were collected in habitat type E2US2N (Table 16). Of the 461 individuals, the three most abundant each comprised approximately 20% of the total catch. Surf smelt were the most abundant at 22.99%, followed by topsmelt at 22.13% and juveniles from the Osmeridae family at 19.52%. One percent of all sample points were within this habitat, which makes up 0.25% of estuarine habitat in the bay. One tidewater goby was found in this habitat type in Hookton Slough in South Bay. Seven juvenile rockfish were not identified to species.

Table 15. Fish species collected in habitat type E2EM1P, where E = estuarine, 2 = intertidal, EM = emergent, 1 = persistent, P = irregularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Osmerid sp.	1	1	58	58	58
bay pipefish	1	1	192	192	192
buffalo sculpin	1	1	55	55	55
penpoint gunnel	1	1	105	105	105
pile surfperch	1	1	285	285	285
bonehead sculpin	1	2	82	88	75
tubesnout	1	2	130	145	114
cabezon	1	6	81	163	45
butter sole	1	8	34	47	27
threespine stickleback	1	9	42	66	21
prickly sculpin	2	10	65	89	47
starry flounder	1	10	129	156	112
arrow goby	2	12	35	54	30
surf smelt	2	18	80	142	61
English sole	3	34	63	128	44
speckled sanddab	1	85	66	110	22
staghorn sculpin	4	86	67	240	23
total		287			

Table 16. Fish species collected in habitat type E2US2N, where E = estuarine, 2 = intertidal, US = unconsolidated shore, 2 = sand, N = regularly flooded, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Northern anchovy	1	1	121	121	121
Pacific sandlance	1	1	131	131	131
cabezon	1	1	126	126	126
lingcod	1	1	78	78	78
penpoint gunnel	1	1	118	118	118
tidewater goby	1	1	49	49	49
arrow goby	1	3	45	55	38
bay pipefish	1	3	214	280	161
starry flounder	1	3	160	285	90
prickly sculpin	1	4	50	54	47
English sole	1	7	104	150	78
juvenile rockfish	1	7	79	86	67
threespine stickleback	2	15	61	137	28
speckled sanddab	1	16	87	105	50
shiner surfperch	2	19	57	142	39
staghorn sculpin	3	26	88	129	51
Pacific herring	2	54	55	66	45
Osmerid sp.	1	90	55	64	50
topsmelt	2	102	102	176	26
surf smelt	4	106	102	148	60
total		461			

Estuarine, Intertidal, Emergent, Persistent (Emergent Vegetation that Remains into the Next Growing Season)/Unconsolidated Shore, Mud, Regularly Flooded (E2EM1/US3N)

This habitat type makes up 0.07 % of the entire estuarine area of Humboldt Bay. Only two species, comprising 64 individuals, were collected from 1% of all points (Table 17). Pacific staghorn sculpins made up 92.19% of the entire catch, with the remaining percentage represented by threespine sticklebacks.

E1UB2L-Estuarine, Intertidal, Unconsolidated Shore, Sand, Irregularly Flooded (E2US2P)

A 36.80-meter section of one juvenile sampling trawl entered the habitat type E2US2P. The remainder of the trawl, 302.32 meters, fell in the E1UB2L habitat type. Habitat type E2US2P makes up 0.05% of estuarine habitat in Humboldt Bay. A total of 23 individuals from six species, including juveniles of the family Osmeridae, were collected (Table 18). The most abundant was the tubesnout, *Aulorhynchus flavidus*, followed by speckled sanddabs.

E1UB2L-E2AB3M

A 16-foot trawl was used to sample from two habitat types (E1UB2L and E2AB3M). Most of this trawl sampled habitat type E2AB3M, 249.68 meters of the 309.03 total meters. Twenty-nine individuals from 4 species, including juveniles of the family Osmeridae, were collected (Table 19). Bay pipefish, *Syngnathus leptorhynchus*, was the most abundant with 13 individuals, followed by tubesnout with nine individuals.

North Bay

Species composition by subbay was also analyzed. A total of 50 species were collected in North Bay using all sampling methods. Thirty-six species were collected at 141 points by methods other than trawl (Appendix C). Thirty-four species were collected during 21 trawls (Appendix D). The most abundant species collected in North Bay was threespine stickleback—11,623 individuals. No threespine stickleback were collected by trawl. Shiner surfperch, the second most abundant species, were collected more frequently than any other species. The majority of tidewater gobies collected during the entire survey was found in North Bay. Three coho salmon, two chinook salmon, and two cutthroat trout were also collected in North Bay.

Table 17. Fish species collected in habitat type E2EM1/US3N, where E = estuarine, 2 = intertidal, EM = emergent, 1 = persistent / US = unconsolidated shore, 3 = mud, N = regularly flooded of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
threespine stickleback	1	5	28	51	16
staghorn sculpin	2	59	34	65	15
total		64			

Table 18. Fish species collected by trawl entering habitat types E2US2P, where E = estuarine, 2 = intertidal, US = unconsolidated shore, 2 = sand, P = irregularly flooded, and E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
English sole	1	1	19	19	19
brown Irish lord	1	1	96	96	96
cabezon	1	1	51	51	51
Osmerid sp.	1	3	36	39	32
speckled sanddab	1	8	42	61	35
tubesnout	1	9	128	152	102
total		23			

Table 19. Fish species collected by trawl entering habitat types E2AB3M, where E = estuarine, 2 = intertidal, AB = aquatic bottom, 3 = rooted vascular, M = irregularly exposed, and E1UB2L, where E = estuarine, 1 = subtidal, UB = unconsolidated bottom, 2 = sand, L = subtidal, of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
Osmerid sp.	1	1	38	38	38
threespine stickleback	1	6	54	81	45
tubesnout	1	9	126	139	97
bay pipefish	1	13	155	210	83
total		29			

Entrance Bay

A total of 45 species were collected in Entrance Bay using all sampling methods. Thirty-six species were collected at 70 points using methods other than trawl (Appendix E). Eighteen trawls were conducted in Entrance Bay resulting in a total of 27 species (Appendix F). Topsmelt were the most abundant species making up nearly half of the entire catch taken by methods other than trawl. Four species from the family Osmeridae were collected in Entrance Bay. Two coho salmon and 86 chinook were also collected.

South Bay

A total of 47 species were collected in South Bay using all methods. Forty-five species were collected at 68 points using methods other than trawl (Appendix G). Eleven species were collected during 2 trawls (Appendix H). The most abundant species collected in South Bay was threespine stickleback, followed by surf smelt and staghorn sculpin. Eight tidewater gobies, one chinook salmon and one steelhead were also collected in South Bay.

Discussion

Of the 67 species collected during this study, all but five have been previously documented in Humboldt Bay. Locations of the 15 most abundant species can be viewed in Figures 8–22. The most abundant species collected over the course of this study was threespine stickleback (*Gasterosteus aculeatus*). This species was collected at 108 points, or approximately one-third of all sampling locations. It is regularly found in freshwater as well as coastal marine environments—bays, backwaters, river tributaries and other areas with low flows (Wootton 1976). Salinities where threespine sticklebacks were collected ranged from 16 parts per thousand to 36 parts per thousand (Appendix I). Gotshall et al. (1980) and Shapiro and Associates (1980) noted year-round presence of *G. aculeatus* in Humboldt Bay.

While threespine stickleback was the most abundant species, the Pacific staghorn sculpin was the most commonly captured species. Previous studies of Humboldt Bay support this extensive distribution of staghorn sculpin. Shapiro and Associates (1980) claimed staghorn sculpin was one of the most abundant and widely distributed fish in Humboldt Bay. Barnhart et al. (1992) listed staghorn sculpins as abundant, and strongly euryhaline, allowing the species to live in both fresh and saltwater habitats.

Staghorn sculpins were found at just over 60% of all locations and collected in all but one habitat type sampled in the bay. Water quality readings taken both during trawls and other sampling methods ranged from 0.6 parts per thousand to 37 parts per thousand (Appendix J). Lengths of staghorn sculpins ranged from 11 mm TL in habitat type E1UBL to 242 mm TL in habitat type E1UB2L.

Shiner surfperch was the most abundant species collected in both Samuelson's (1973) South Bay study and Sopher's (1974) study of North Bay. Because Sopher found no females carrying young after May and no individuals less than 85 mm TL between January and May, he determined that spawning in Humboldt Bay must occur between May and June. The highest numbers of smaller individuals occurred between the months of June and July. Similarly, Samuelson found that between the months of February and April, *C. aggregata* ranged in total length from 73 mm–225 mm. However, between the months of June and October, total lengths ranged from 50 mm–132 mm.

In this study of Humboldt Bay, shiner surfperch, collected from September 25, 2000 to November 30, 2001, was the second most abundant species. The highest numbers were collected during the summer months of June through September (Appendix K). Shiner surfperch were primarily collected by seine during these months. No trawl samples were collected. The smallest individual measured 36 mm TL, and was collected in July. Most of the smaller individuals were collected in July with the average TL being lowest between the months of June through August. The higher number of individuals collected in the month of September is a reflection of the over 1,000 shiner surfperch caught by trawl in Eureka Channel.

Collected at only 33 sites, Northern anchovy was the sixth most abundant species collected. Waldvogel (1977) found that Northern anchovy entered Humboldt Bay in April, and remained until the first week of November. Samuelson (1973) and Sopher (1974) found Northern anchovies in Humboldt Bay from April to October, and March to September, respectively. Eldridge and Bryan (1972) found *E. mordax* larvae in the months of March, August, September, and December.

These results are consistent with the present study, as anchovies were found in the bay from March to October. Anchovies were most abundant from June to August. Northern anchovy

—text continued p. 156

Figure 8. Locations within Humboldt Bay, Humboldt County, California, where **threespine stickleback** were collected from September 2000 to November 2001. Threespine stickleback ranged in length from 11 mm to 137 mm. The overall average length was 49.17 mm. Habitat map digitized by NWI.

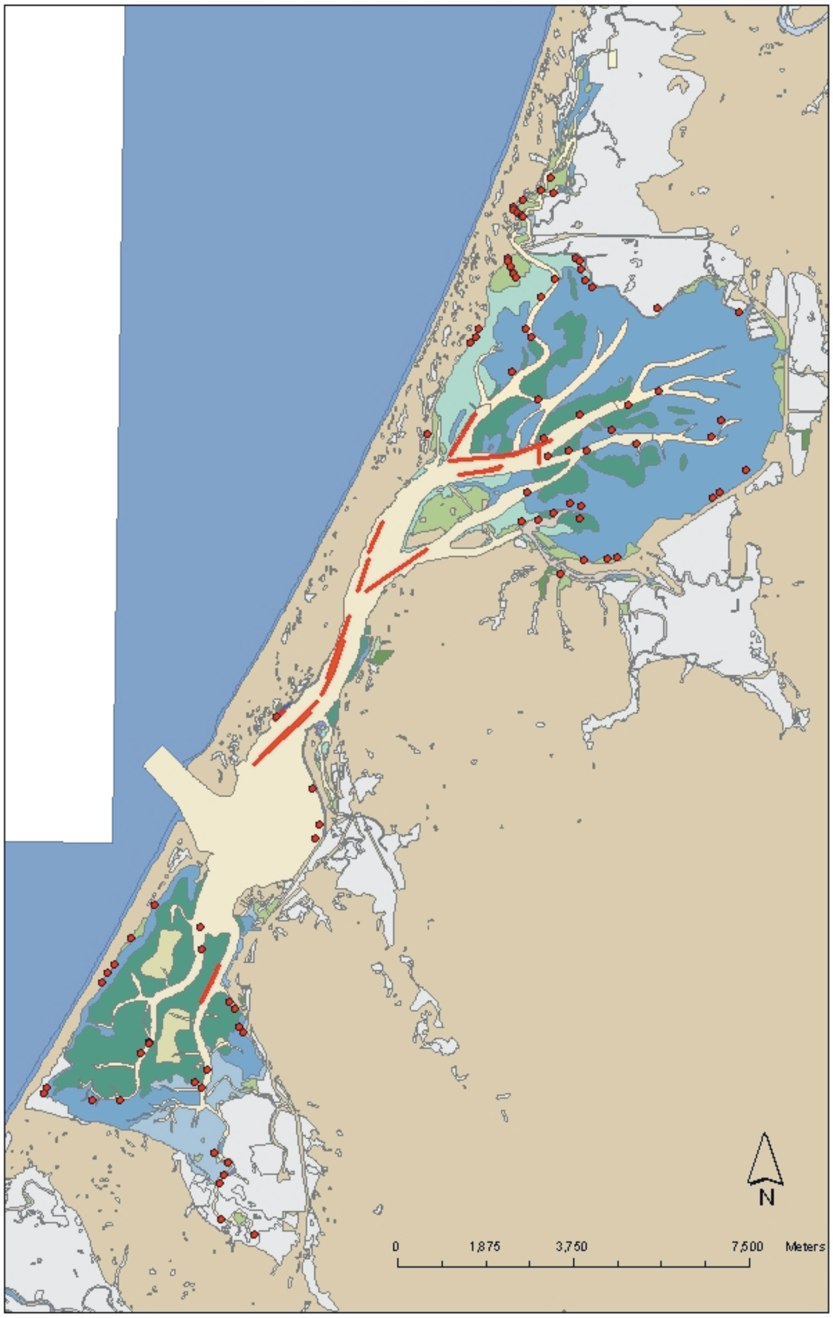

Figure 9. Locations within Humboldt Bay, Humboldt County, California, where **shiner surfperch** were collected from September 2000 to November 2001. Shiner surfperch ranged in length from 36 mm to 155 mm. The overall average length was 75 mm. Habitat map digitized by NWI.

Figure 10. Locations within Humboldt Bay, Humboldt County, California, where **topsmelt** were collected from September 2000 to November 2001. Topsmelt ranged in length from 17 mm to 337 mm. The overall average length was 89.43 mm. Habitat map digitized by NWI.

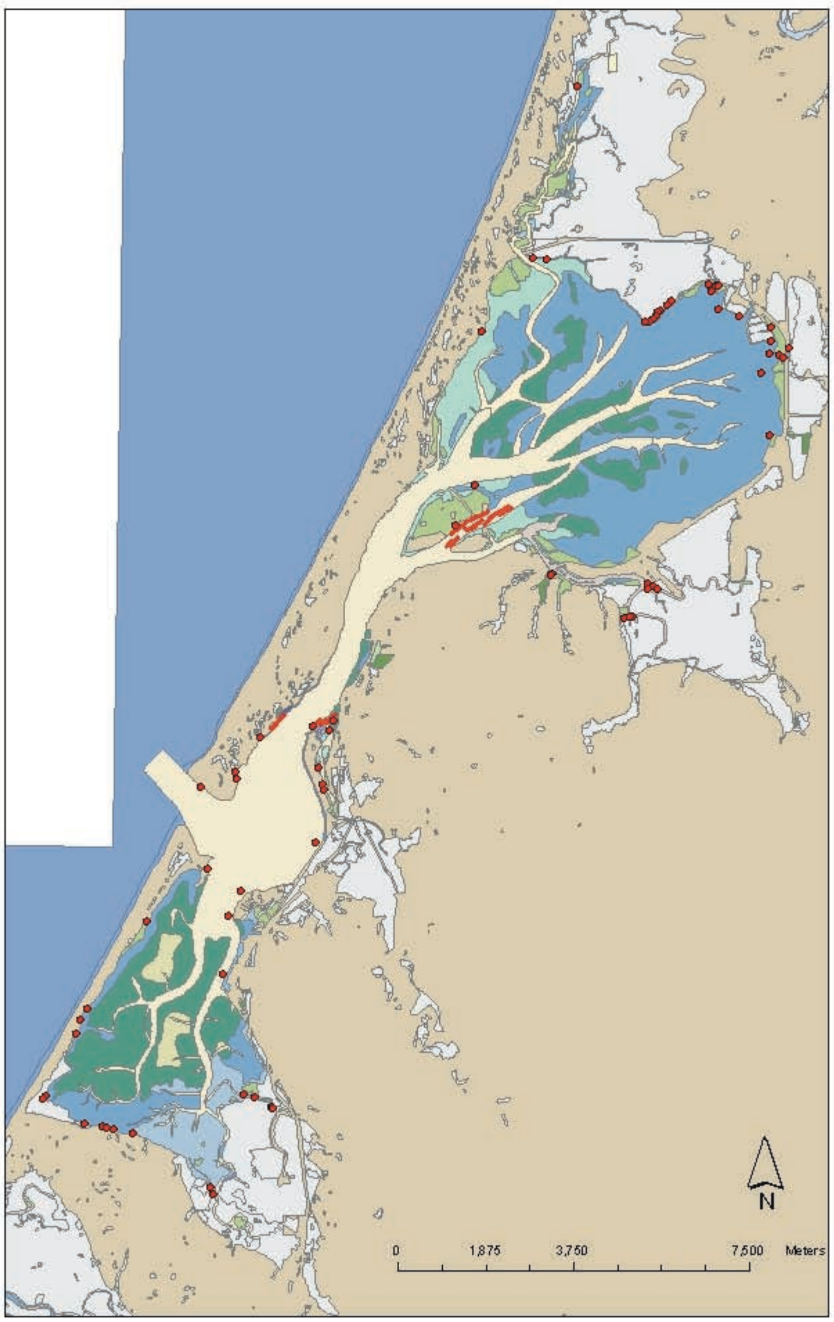

Figure 11. Locations within Humboldt Bay, Humboldt County, California, where juveniles of the family **Osmeridae** were collected from September 2000 to November 2001. Juveniles of the family Osmeridae ranged in length from 10 mm to 100 mm. The overall average length was 49.59 mm. Habitat map digitized by NWI.

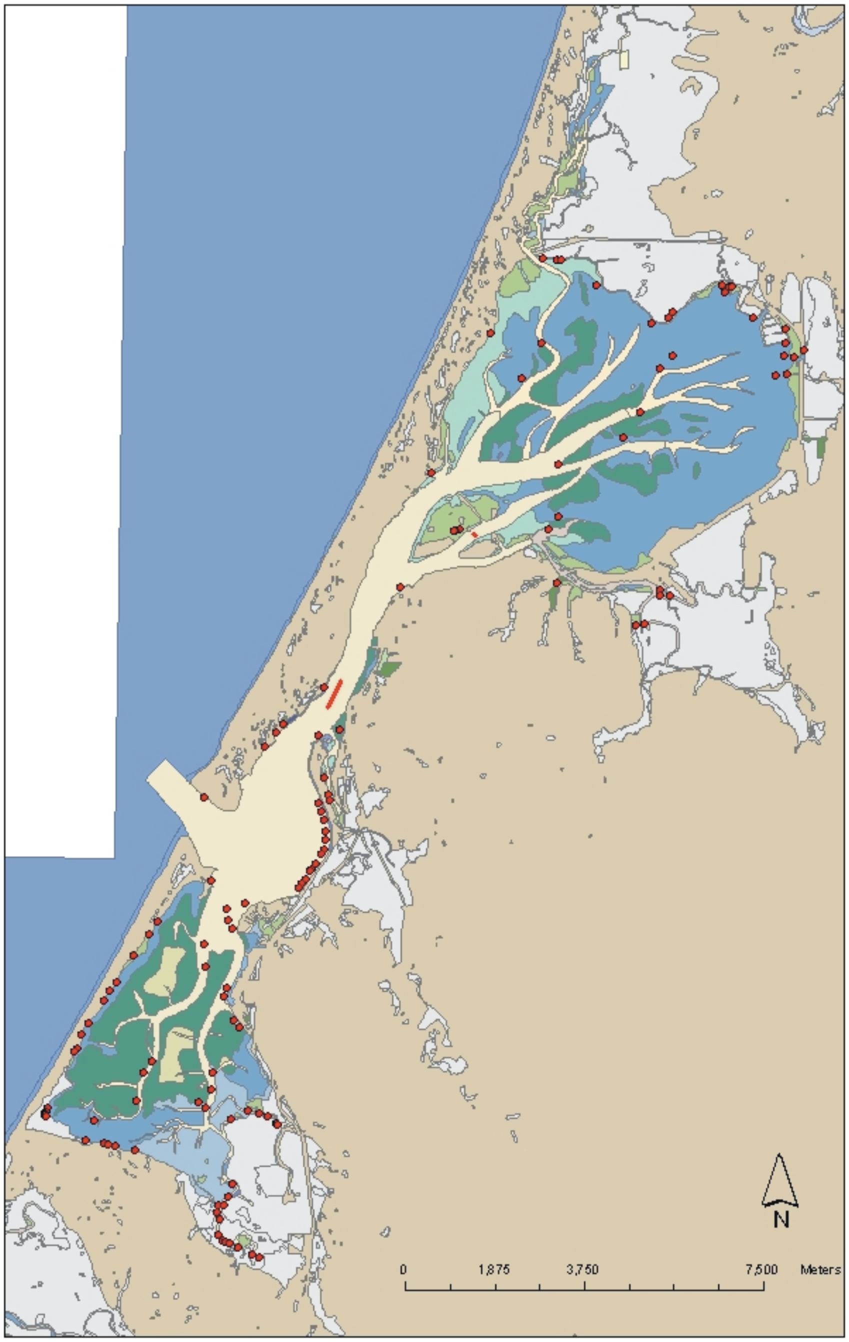

Figure 12. Locations within Humboldt Bay, Humboldt County, California, where **surfsmelt** were collected from September 2000 to November 2001. Surfsmelt ranged in length from 25 mm to 428 mm. The overall average length was 75.24 mm. Habitat map digitized by NWI.

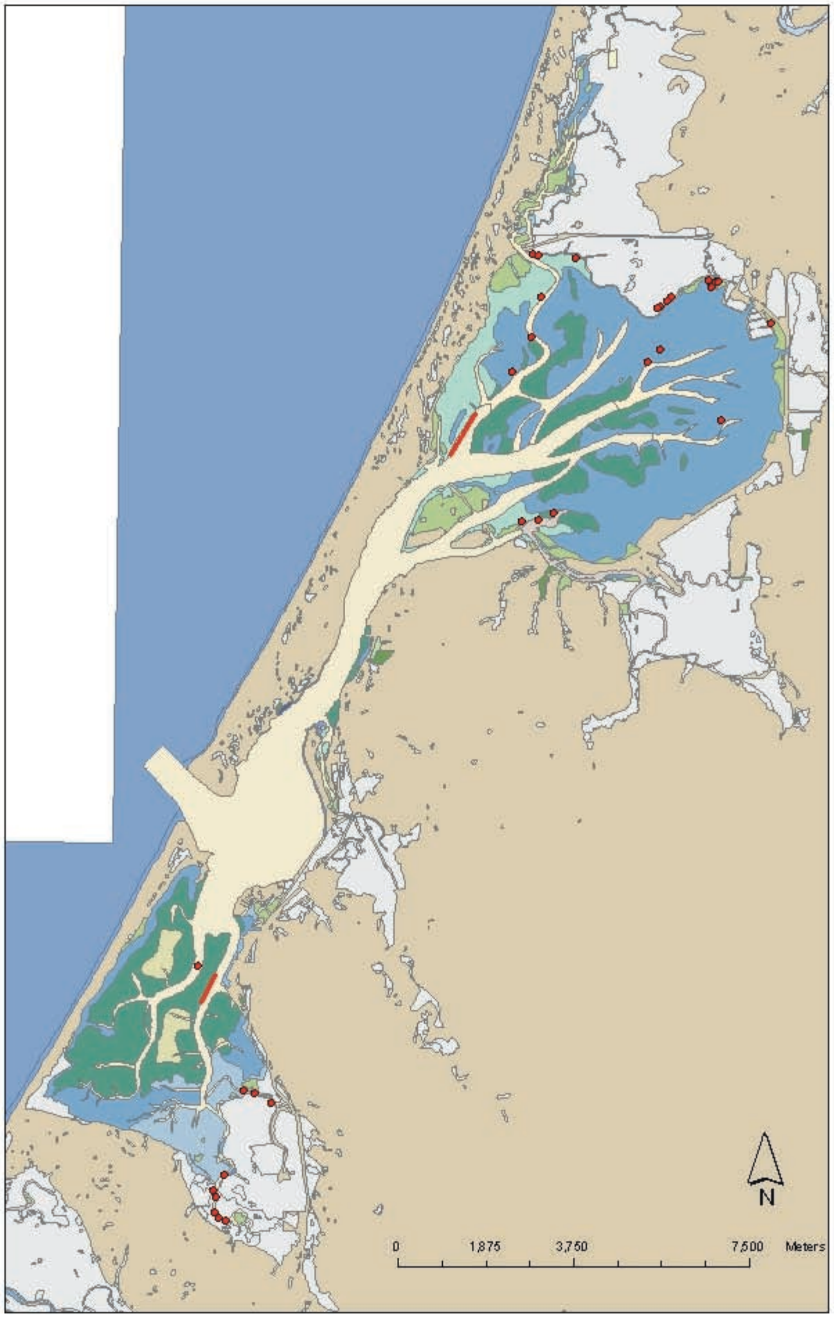

Figure 13. Locations within Humboldt Bay, Humboldt County, California, where **Northern anchovy** were collected from September 2000 to November 2001. Northern anchovy ranged in length from 31 mm to 142 mm. The overall average length was 69.51 mm. Habitat map digitized by NWI.

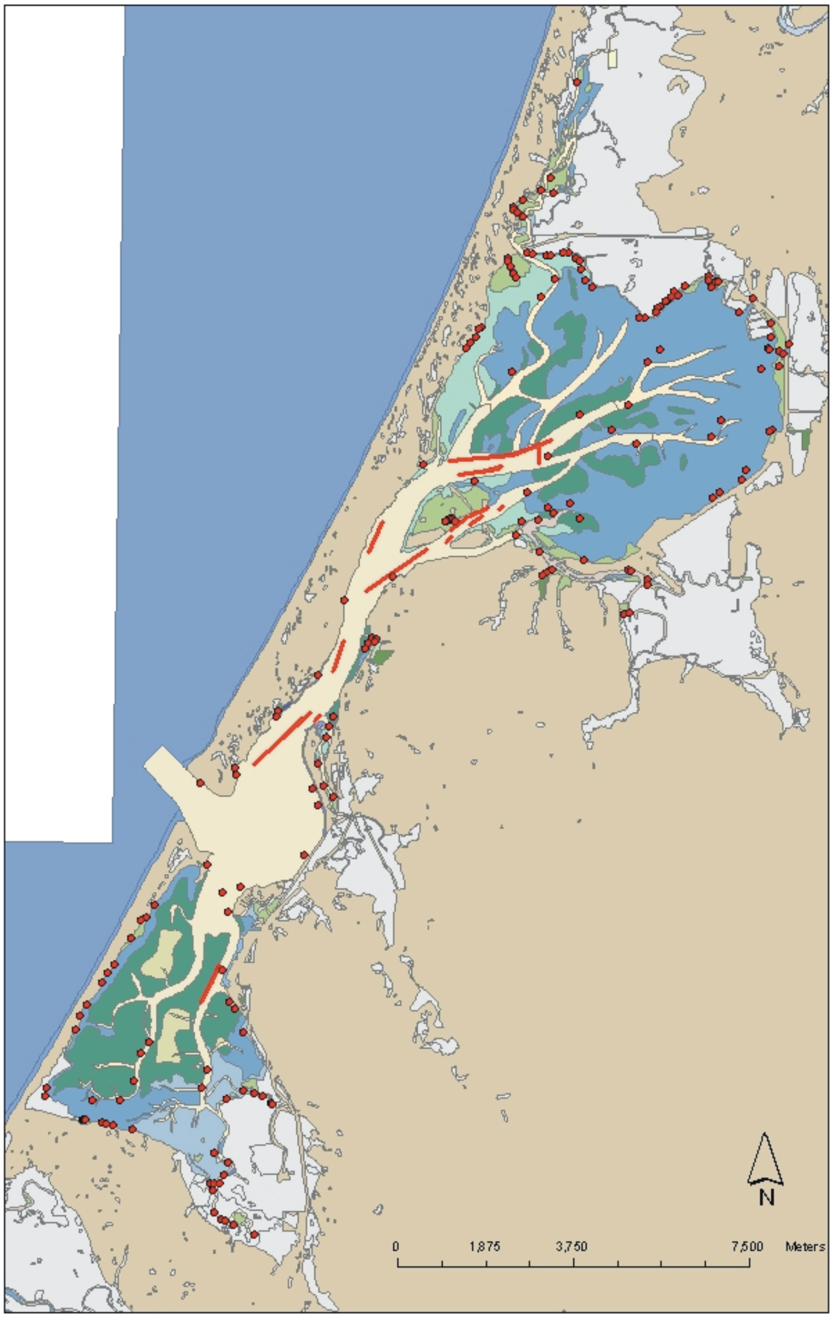

Figure 14. Locations within Humboldt Bay, Humboldt County, California, where **staghorn sculpin** were collected from September 2000 to November 2001. Staghorn sculpin ranged in length from 11 mm to 242 mm. The overall average length was 66.27 mm. Habitat map digitized by NWI.

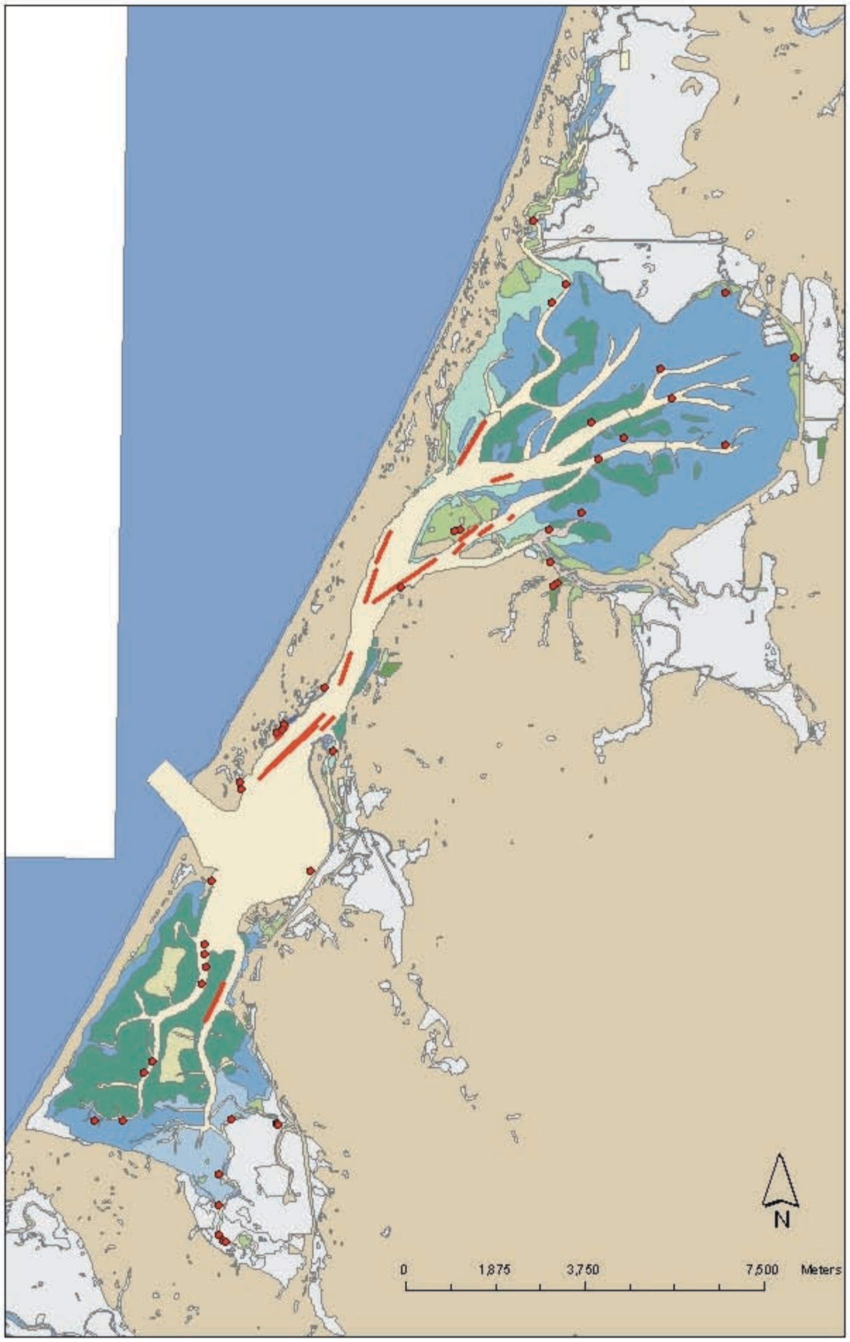

Figure 15. Locations within Humboldt Bay, Humboldt County, California, where **English sole** were collected from September 2000 to November 2001. English sole ranged in length from 18 mm to 230 mm. The overall average length was 74.34 mm. Habitat map digitized by NWI.

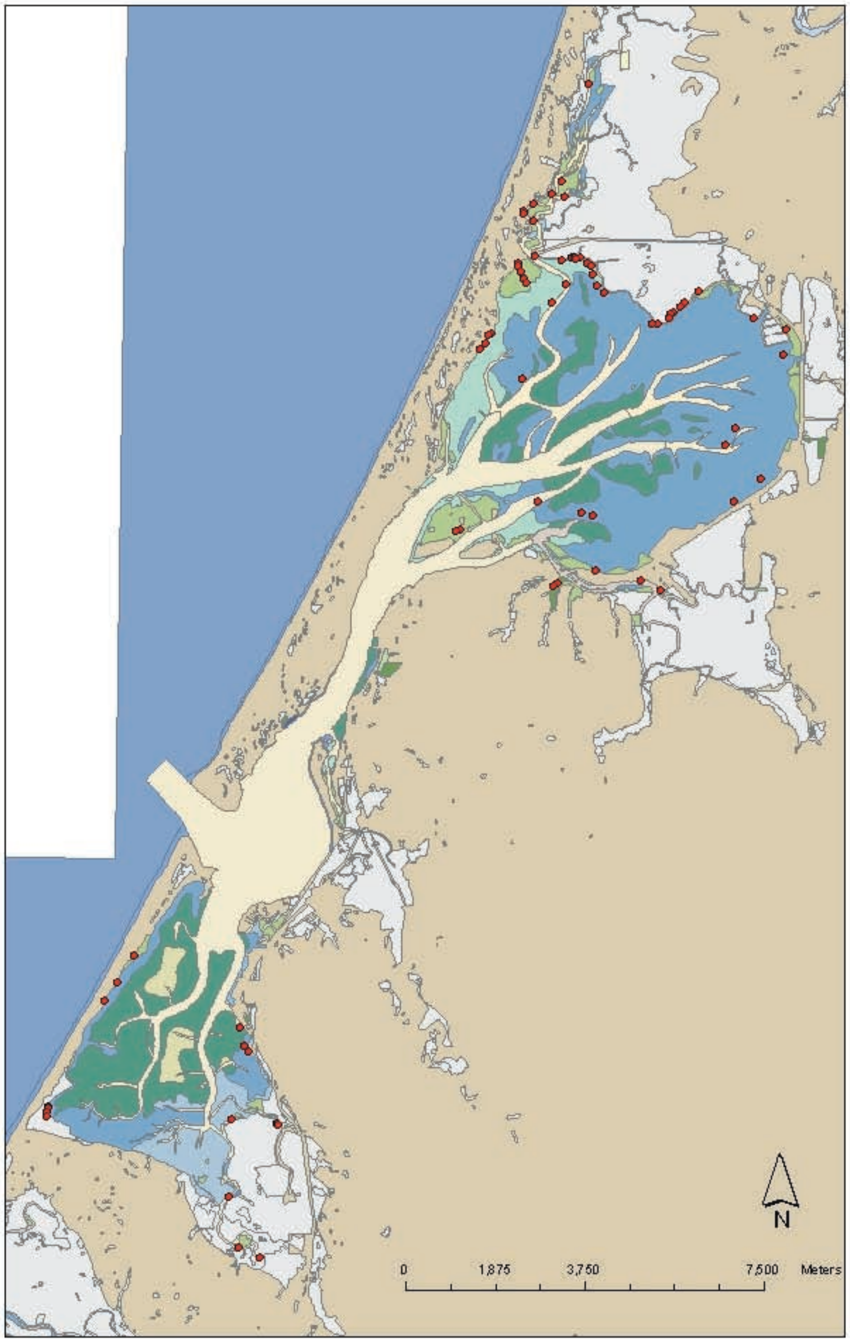

Figure 16. Locations within Humboldt Bay, Humboldt County, California, where **arrow goby** were collected from September 2000 to November 2001. Arrow goby ranged in length from 20 mm to 69 mm. The overall average length was 50.26 mm. Habitat map digitized by NWI.

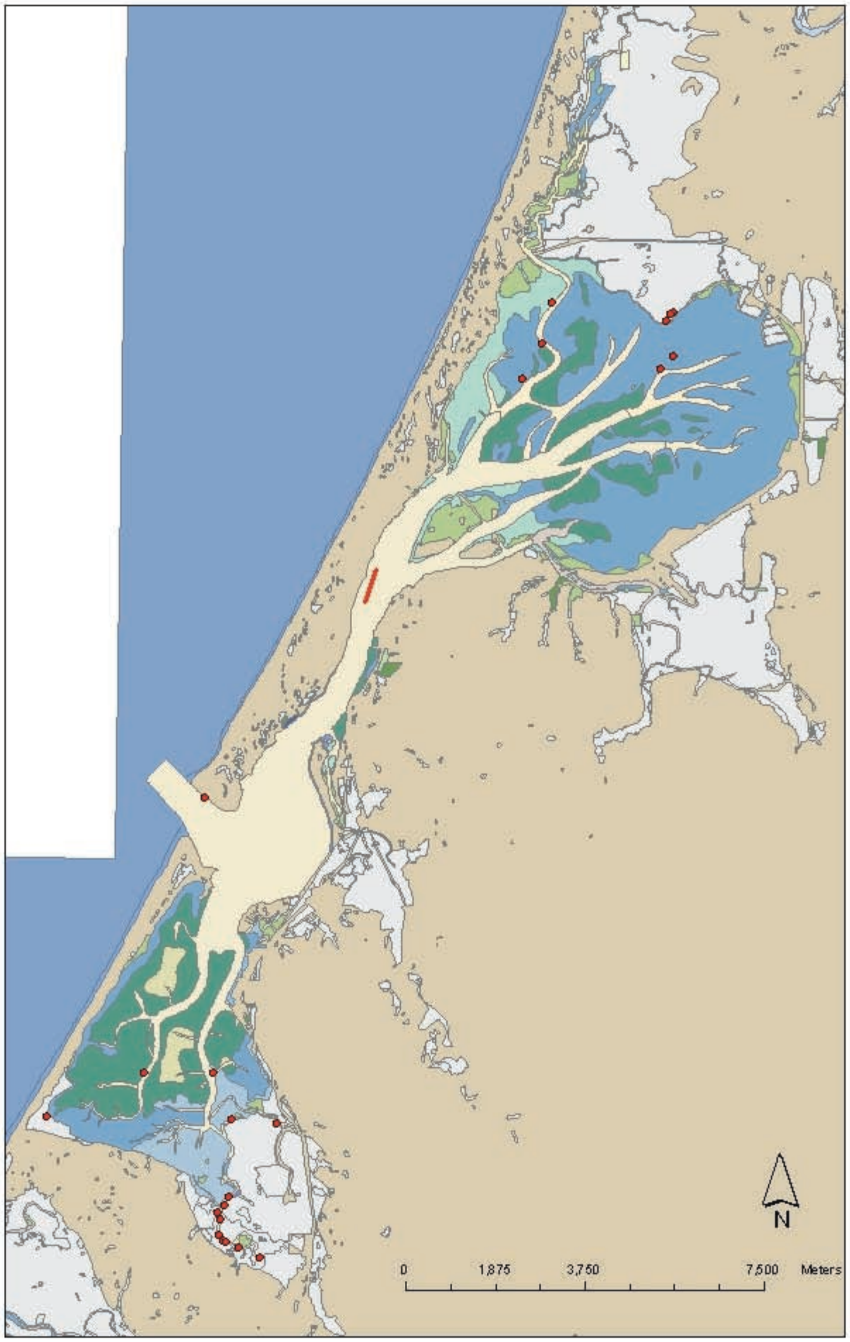

Figure 17. Locations within Humboldt Bay, Humboldt County, California, where **Pacific herring** were collected from September 2000 to November 2001. Pacific herring ranged in length from 25 mm to 213 mm. The overall average length was 58.91 mm. Habitat map digitized by NWI.

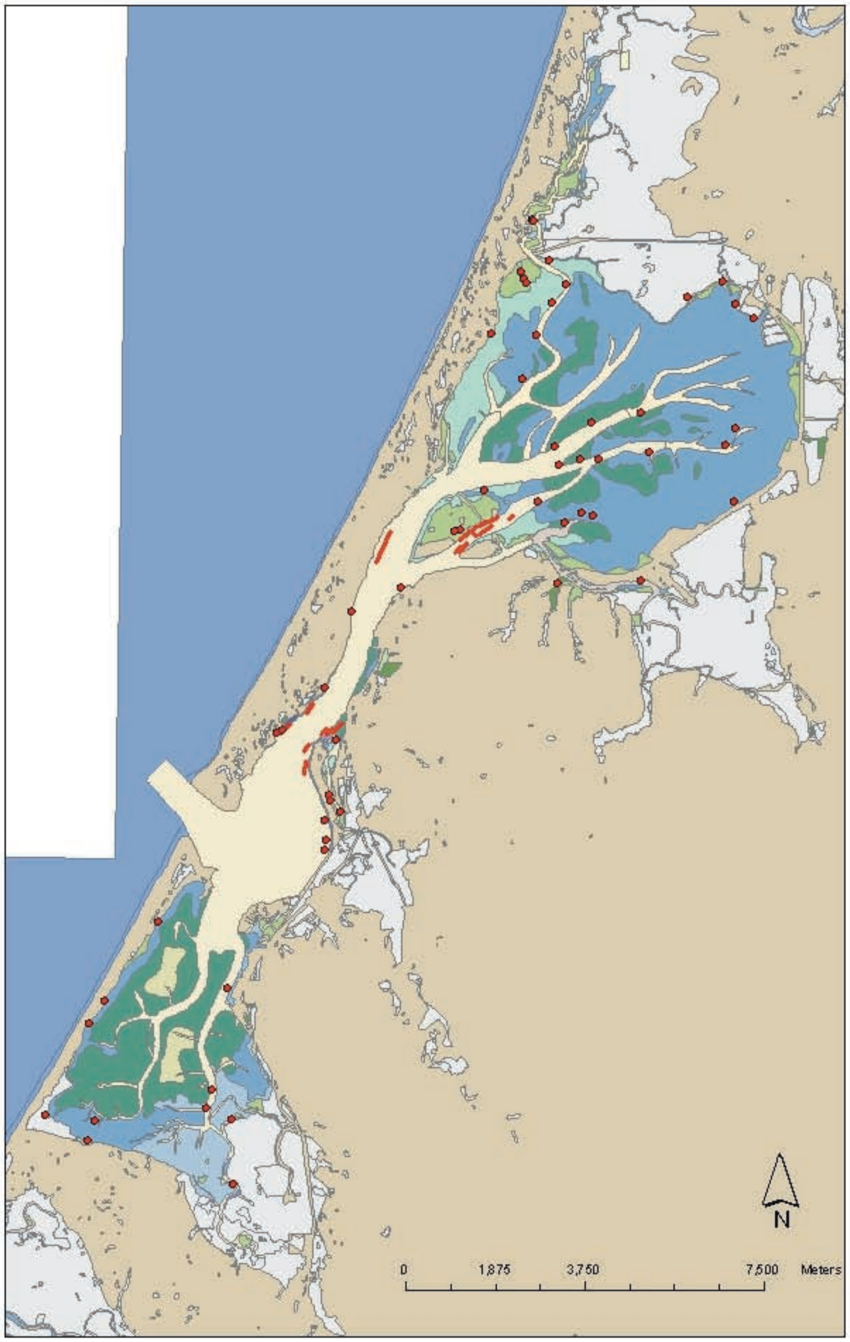

Figure 18. Locations within Humboldt Bay, Humboldt County, California, where **bay pipefish** were collected from September 2000 to November 2001. Bay pipefish ranged in length from 37mm to 324 mm. The overall average length was 164.08 mm. Habitat map digitized by NWI.

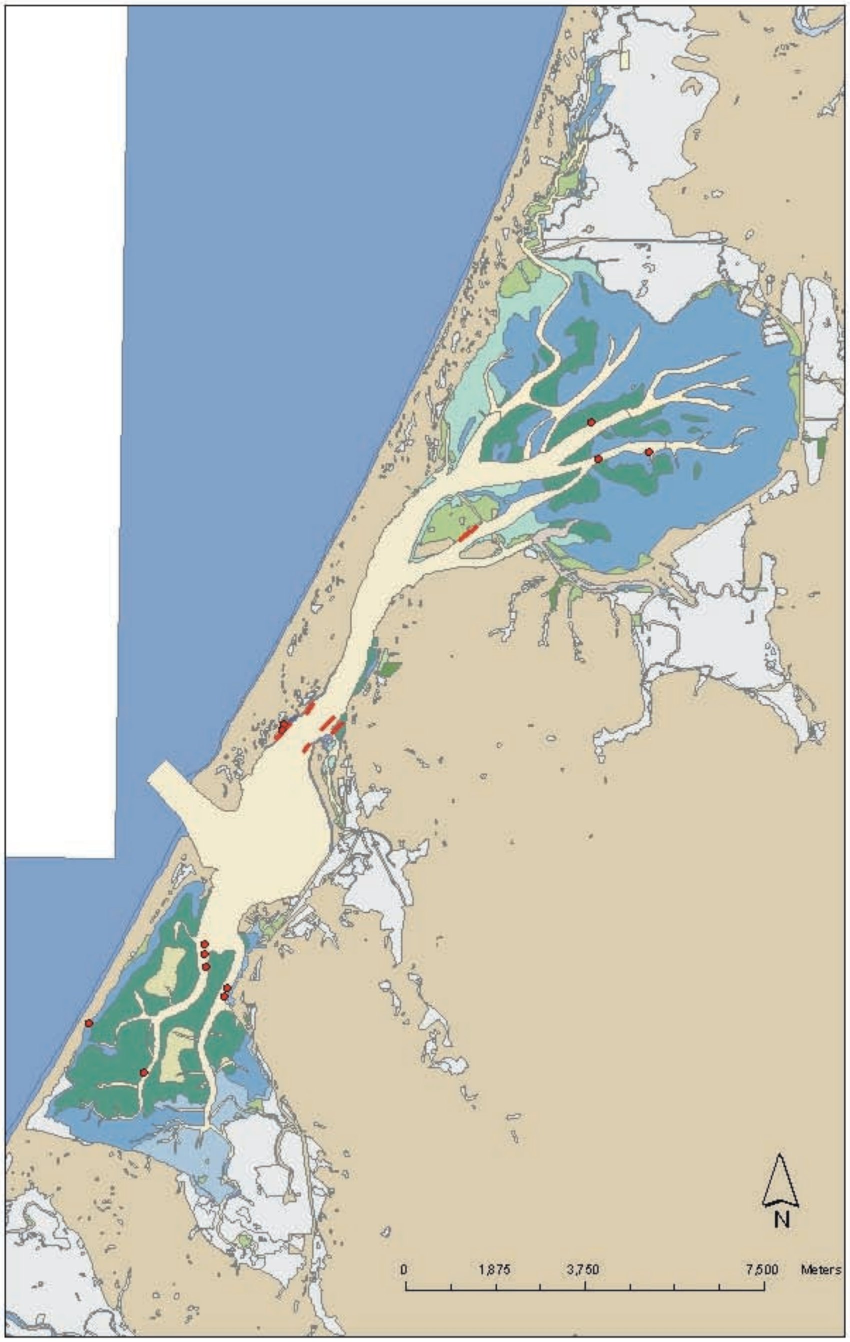

Figure 19. Locations within Humboldt Bay, Humboldt County, California, where **tubesnout** were collected from September 2000 to November 2001. Tubesnout ranged in length from 93 mm to 219 mm. The overall average length was 127.32 mm. Habitat map digitized by NWI.

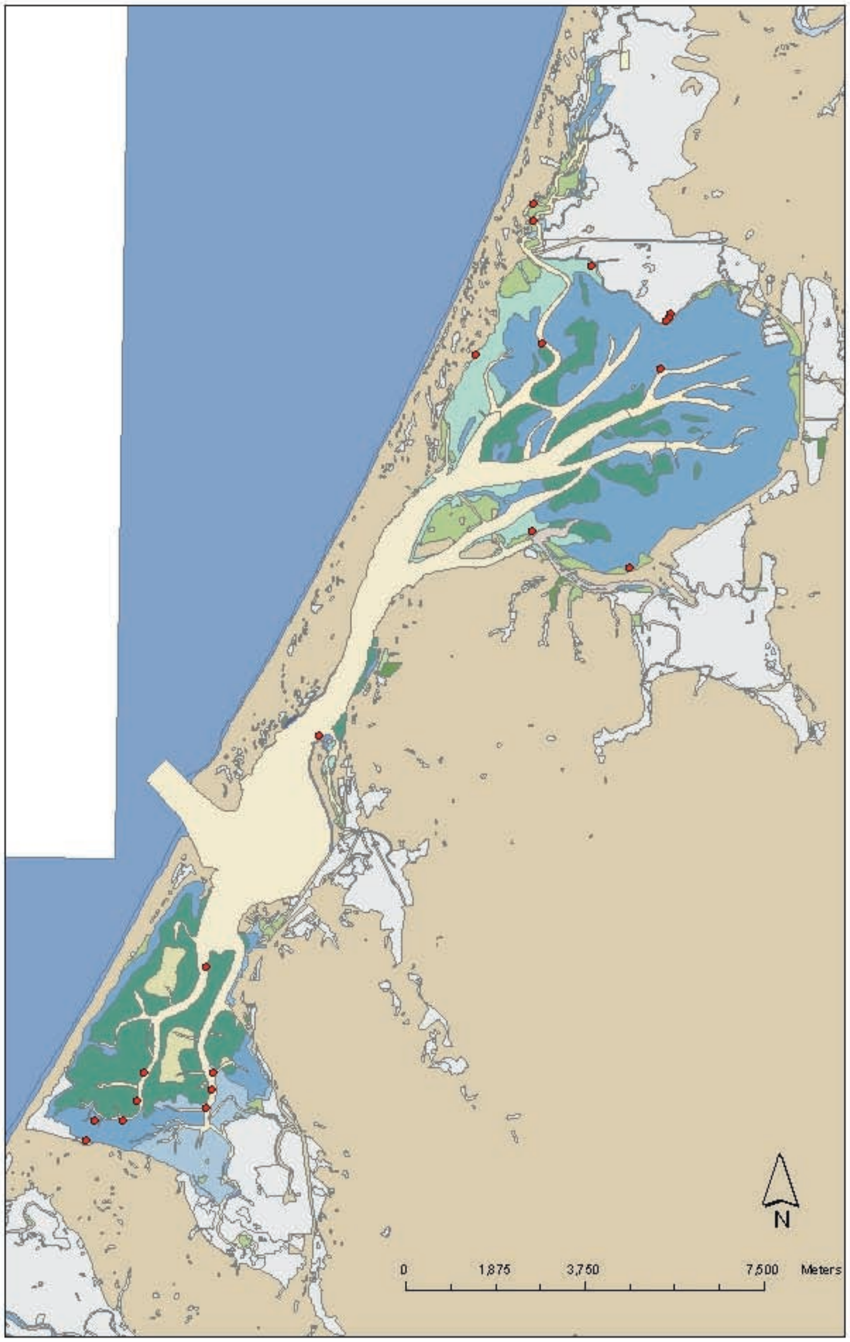

Figure 20. Locations within Humboldt Bay, Humboldt County, California, where **jacksmelt** were collected from September 2000 to November 2001. Jacksmelt ranged in length from 17 mm to 372 mm. The overall average length was 162.70 mm. Habitat map digitized by NWI.

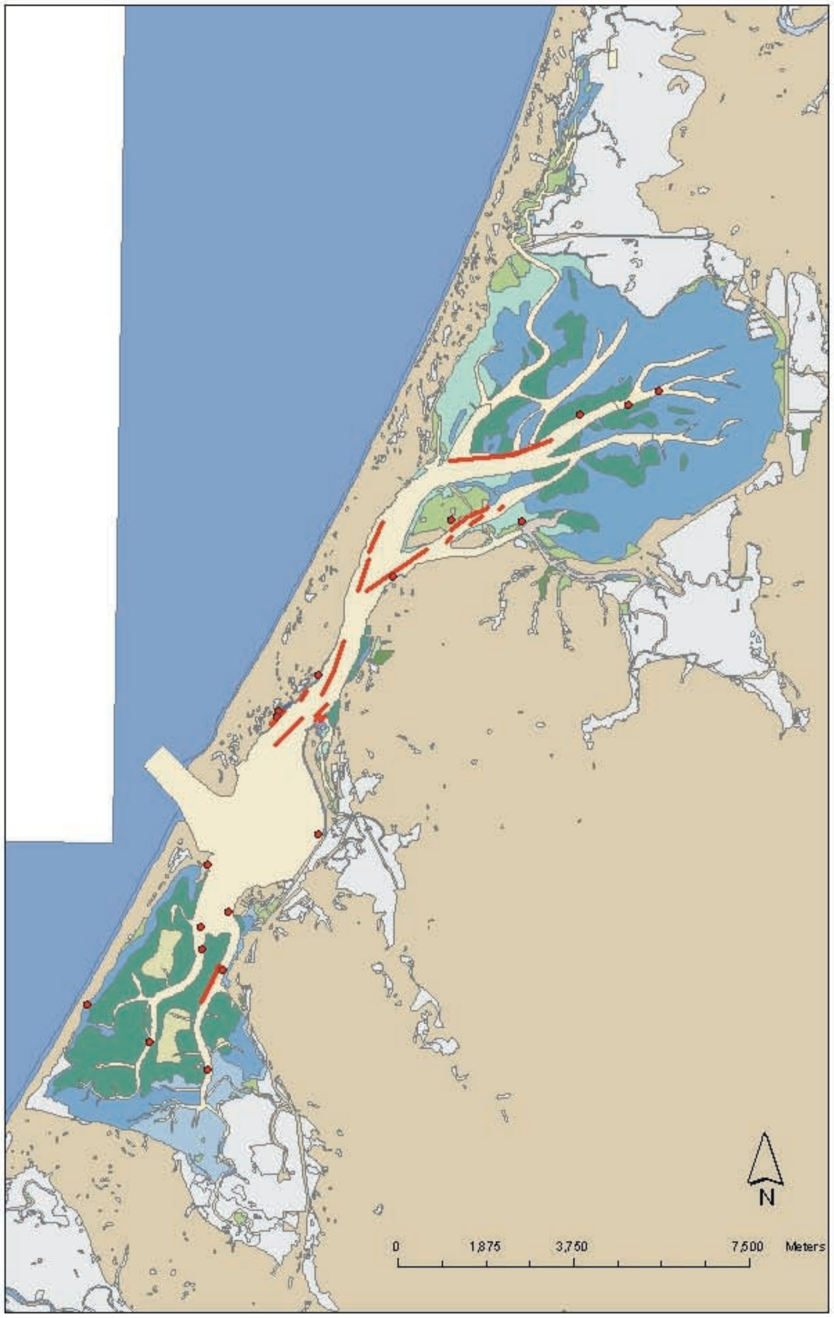

Figure 21. Locations within Humboldt Bay, Humboldt County, California, where **speckled sanddab** were collected from September 2000 to November 2001. Speckled sanddab ranged in length from 22 mm to 117 mm. The overall average length was 68.16 mm. Habitat map digitized by NWI.

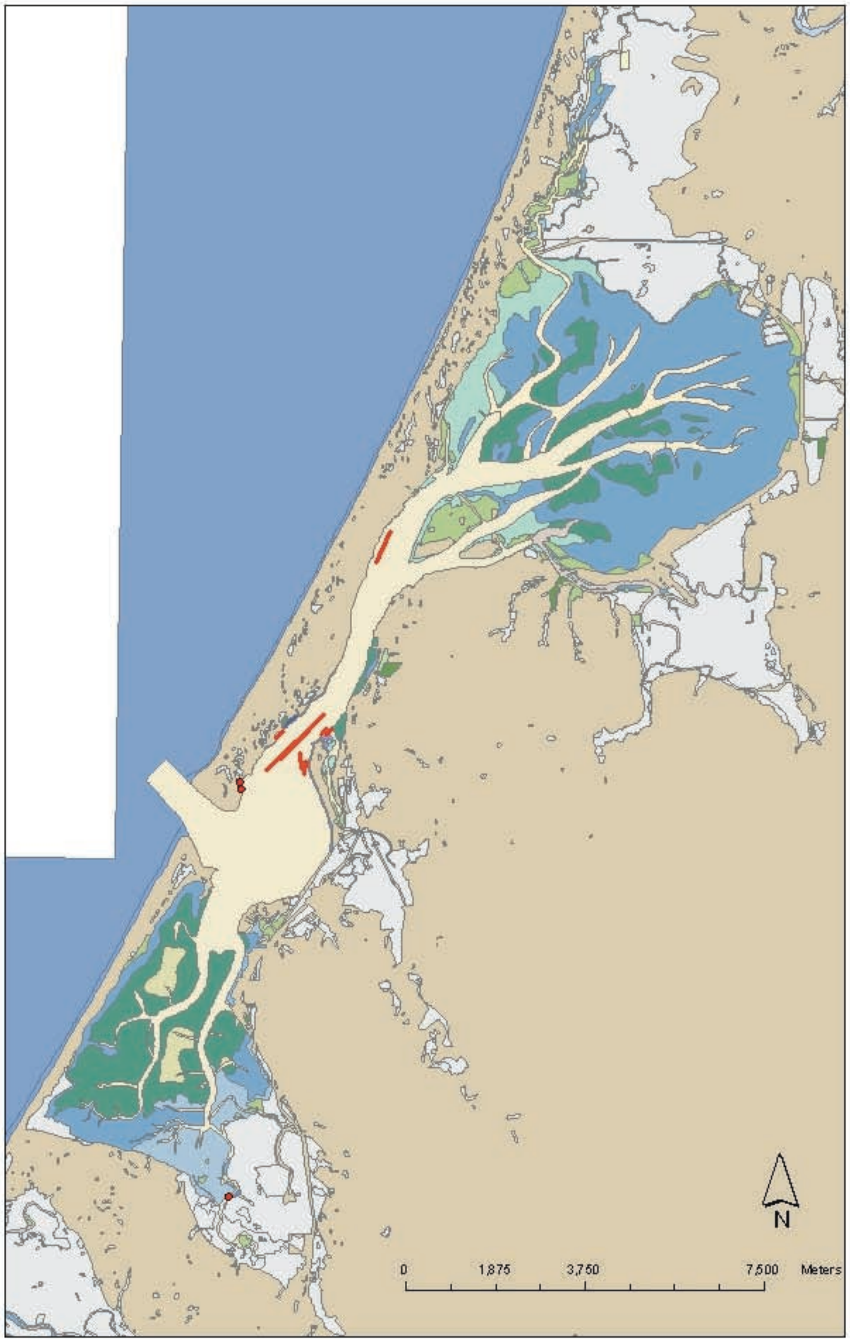

Figure 22. Locations within Humboldt Bay, Humboldt County, California, where **Pacific sandlance** were collected from September 2000 to November 2001. Pacific sandlance ranged in length from 76 mm to 131 mm. The overall average length was 88.73 mm. Habitat map digitized by NWI.

are abundant in other California coastal estuaries, and was the most abundant species in August and September. They were also the most abundant species overall in a study of Colorado Lagoon (Allen and Horn 1975). Northern anchovy are thought to bring coho salmon, *Oncorhynchus kisutch*. and chinook salmon, *O. tshawytscha*, into Humboldt Bay, as they are a major food source for both species.

English sole were the eighth most abundant species for this study. This is consistent with results from other published studies of Humboldt Bay (Samuelson 1973; Sopher 1974; Shapiro and Associates 1980; Chamberlain and Barnhart 1993), where English sole were among the most commonly collected species. Misitano (1970, 1976) found that English sole use Humboldt Bay as a nursery area, and that entry into the bay occurs when they are between 19 mm–26 mm TL. Young-of-the-year English sole were determined to be present in Humboldt Bay between the months of February and April, when they became abundant until the emigration of yearlings from the bay (Toole 1980).

The smallest examples of English sole collected in this study were found on March 13, 2001. For this one sampling date, mean lengths of each trawl ranged from 19 mm to 34 mm TL, with the smallest individual being 18 mm TL. These sole were collected in North Bay channel and the channel between Indian and Woodley Islands while sampling for juvenile fishes with the 16-foot modified beam trawl.

Over the entire study, the mean lengths of English sole ranged from 37.39 mm to 104.29 mm TL at each collection site. The largest specimen collected in this study was 230 mm TL. This individual was taken in North Bay Channel, northwest of the mouth of Elk River slough on November 30, 2001. Based on Ketchen (1956), this individual would be considered near sexual maturity, and was collected during the English sole spawning season between October and May (Matarese et al. 1989). Because no sexually mature English sole have been collected in Humboldt Bay, spawning is believed to occur in ocean waters.

The presence of leopard sharks in Humboldt Bay has been noted by several researchers (Samuelson 1973; Sopher 1974; Gotshall et al. 1980; Shapiro and Associates 1980; Fritzsche and Cavanagh 1995). A 1975 study of food habits of leopard sharks in San Francisco and Tomales Bays noted that *Callianassa* shrimp, crabs of the genus *Cancer*, and an echiuran worm, *Urechis caupo*, were the most frequent choices (Russo 1975). Each of these is a demersal invertebrate, which supports the claim that leopard sharks are benthic feeders on mud flats.

Although leopard sharks were found in North Bay and Hookton Slough, they were collected in abundance in the southwestern portion of South Bay on May 8, 2001 (Figure 23). On this day, a total of 86 individuals were collected on an incoming tide. The habitat at this location is E2US3N, and is best described as mudflat segmented by narrow channels. Miklos et al. (2003) studied leopard sharks in Tomales Bay and found that summer location is greatly affected by tidal stage, with movement into the littoral zones to feed occurring at high tide. The temperatures in the intertidal areas of Tomales Bay during the study often reached 25° C. Water temperatures recorded on May 8, 2001 in Humboldt Bay reached 21° C, with a salinity of 34 parts per thousand.

One medusafish, *Icichthys lockingtoni*, family Centrolophidae, was collected in eelgrass beds near Southport Channel in South Bay. Gotshall et al. (1980) stated that a medusafish had been collected in Humboldt Bay by trawl in September 1968. Fritzsche and Cavanagh (1995) reiterated that this was the only medusafish recorded from Humboldt Bay, and that they are rarely found in shallow water. The individual found in this study measured 79 mm TL. It was collected on July 12, 2001 on an outgoing tide.

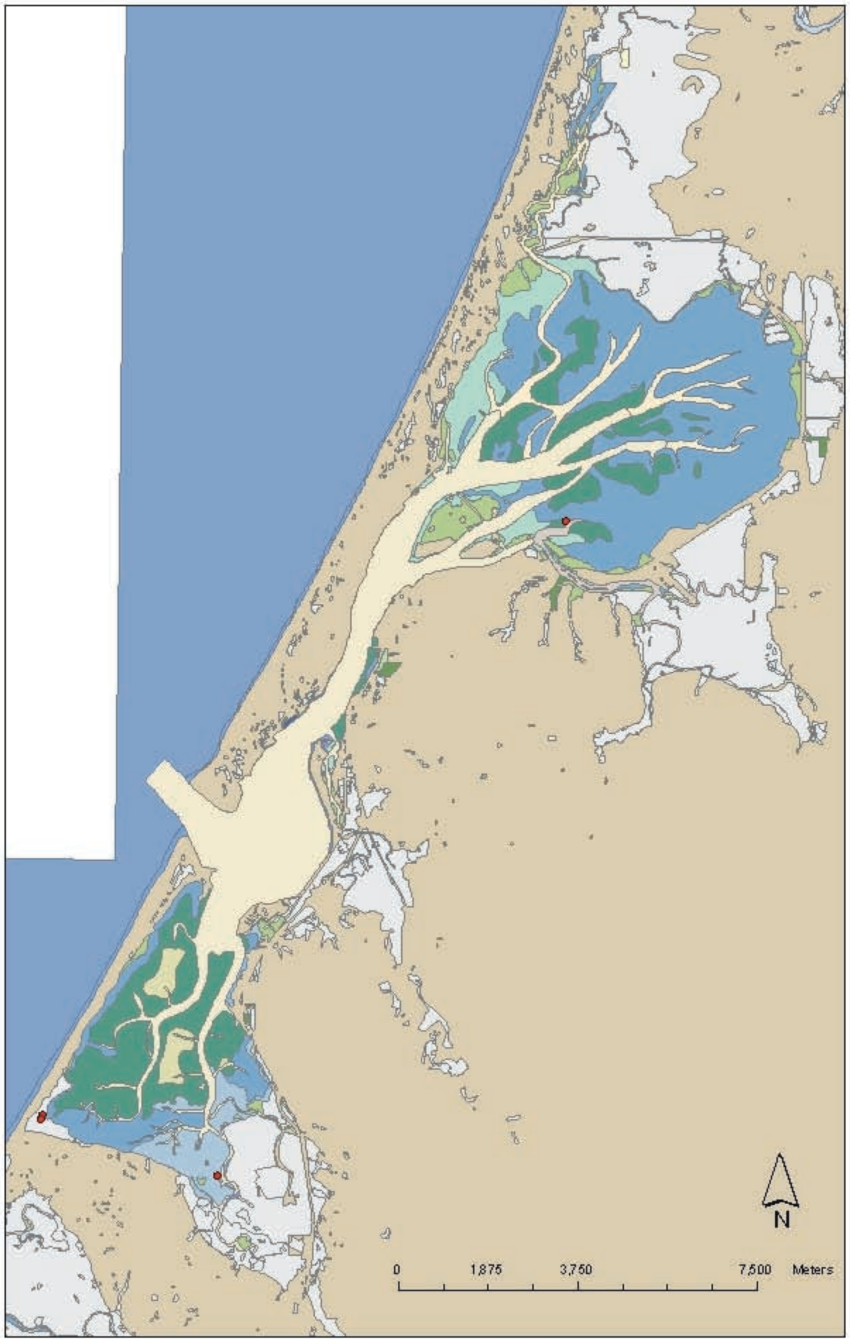

Figure 23. Locations within Humboldt Bay, Humboldt County, California where **leopard sharks** were collected from September 2000 to November 2001, ranging in length from 281 mm to 1,219 mm. The overall average length was 624.31 mm. Habitat map digitized by NWI.

Twenty-six tidewater gobies were collected in six habitat types in Humboldt Bay, including the assigned habitat type of E2US3N for the drainage ditch in North Bay (Figures 24 and 25). Gobies were collected on both sides of the tide gate between the drainage ditch (nine gobies) and Eureka Slough (one goby). Tidewater gobies were also collected near and in Mad River Slough in the northwest corner of North Bay, and Hookton and White Sloughs in the southeast corner of South Bay.

Figure 24. Tide gate separating Eureka Slough, Humboldt Bay, Humboldt County, California, and the drainage ditch that parallels California State Highway 101. The drainage ditch is in the foreground.

Figure 25. Tide gate separating Eureka Slough, Humboldt Bay, Humboldt County, California, and the drainage ditch that parallels California State Highway 101. Eureka Slough is in the background.

During the course of this study, five species not previously documented in Humboldt Bay were collected. These were gopher rockfish, *Sebastes carnatus*, Pacific sardine, *Sardinops sagax*, mosquitofish, *Gambusia affinis*, longjaw mudsucker, *Gillichthys mirabilis*, and petrale sole, *Eopsetta jordani*. These species are not uncommon to the northeast Pacific Ocean, however, no prior studies have noted their presence in Humboldt Bay.

Because of our sampling techniques, only juvenile rockfish were collected in this study. Most of the 155 individuals were black rockfish, a species known to reside in Humboldt Bay (Gotshall et al. 1980). Juvenile rockfish have been shown to reside in other California bays and estuaries (Moring 1972; Yoklavich et al. 1991, 1996). The single copper rockfish collected on August 14, 2001 at the mouth of Hookton Slough in South Bay is also considered to be resident in Humboldt Bay (Gotshall et al. 1980). One gopher rockfish was collected in the southern end of Southport Channel in South Bay on July 11, 2001. While copper rockfish are considered residents of Humboldt Bay (Gotshall et al. 1980), gopher rockfish have never been noted in Humboldt Bay. Their range is described as San Roque, Baja California to Eureka, California (Miller and Lea 1972). However, rockfish of the subgenus *Pteropodus*, the "copper complex," which include the gopher rockfish, were thought to be common near Monterey Bay (Yocklavich et al. 1996).

The geographic range of Pacific sardines is from Guaymas, Mexico, to Kamchatka, Russia (Miller and Lea 1972). While common within this range, this species has never previously been documented in Humboldt Bay. Pacific sardines may be identified by the striations on the operculum and black spots on their sides. These two characteristics differentiate them from other common Clupeioid fishes such as the Pacific herring. The Pacific sardine spawns from January to June, with northward migrations beginning in early summer (Hart 1973). In the present study, 46 sardines were collected at six separate sites on four different dates. Collection occurred between July 12 and November 30, 2001, with 37 individuals being collected on August 14, 2001. The smallest sardine collected was 81 mm TL; the largest 148 mm TL. Based on the age description of sardines off Central California given by Hart (1973), the individuals collected over the course of this study were approximately one year old.

Mosquitofish were collected in the drainage ditch near the Eureka airport. There is a tide gate located at this location on Eureka Slough, as noted on the USGS topoquad. This gate separates the slough from the drainage ditch that follows the outline of the bay (Figures 24 and 25). The mosquitofish were found on only one side of this disconnect, in the direction of the drainage ditch. Ten mosquitofish varying in size from 13 mm to 41 mm TL were collected. This species is considered a freshwater or brackish fish and is not native to Humboldt Bay.

The California Department of Fish and Game has no historical record of when mosquitofish may have been planted into Eureka Slough or the drainage ditch, however, a 2001 USFWS study of the ditch found mosquitofish and threespine stickleback (Goldsmith 2003, pers. comm.). Mosquitofish are found in other California bays and estuaries. In San Francisco Bay it is considered an introduced species, where it was found in less than 1% of both otter trawls and beach seines during a 20-year study of Suisun Marsh (Matern et al. 2002). However, mosquitofish were abundant in a study of a more southern estuary, Mugu Lagoon, the largest estuarine lagoon in southern California, located at Point Mugu, Ventura County (Saiki 1997).

One longjaw mudsucker, *Gillichthys mirabilis,* was collected in a small channel that dead-ends just west of the mouth of Mad River

Slough. Salinities on the day of capture ranged from 33 to 34 parts per thousand. This is consistent with what is considered typical habitat of the longjaw mudsucker: shallow backwater with soft, muddy substrate and moderate to high salinities (Barlow 1961). Its geographical range is Tomales Bay just north of Point Reyes to the Gulf of California (Miller and Lea 1972). Although Barlow (1961) gives the same northern limit, he notes that the northernmost "permanent" population may be in San Francisco Bay, due to the abundance of the species there.

Longjaw mudsuckers were present and found to be tolerant to the fluctuating conditions of tidal marshes in San Francisco Bay estuary (Josselyn 1983). A study in the Sweetwater Marsh National Wildlife Refuge in San Diego, California, found juvenile *Gillichthys mirabilis* to be abundant in spring and summer, with adults present in most samples throughout the study (West and Zedler 2000). In the study, juveniles were determined to be those individuals less than 100 mm. The individual collected in Humboldt Bay would, therefore, be considered a juvenile at 93 mm TL.

Two juvenile petrale sole were collected near the eastern shore in Entrance Bay. This area is characterized by high wave action, and sandy beaches. None of the identified specimens in the larval fish studies of Humboldt Bay by Eldridge (1970) or Eldridge and Bryan (1972) was petrale sole. There are no publications that have documented petrale sole in Humboldt Bay. Miller and Lea (1972) define the range of petrale sole from Islas Los Coronados, Baja California, to the northern Gulf of Alaska. Petrale sole are found in nearshore waters near Humboldt Bay.

Juvenile fishes use Humboldt Bay as a refuge from predators and as a nursery area. Mature fishes use its many habitats for both feeding and spawning. A study in the Kariega Estuary in South Africa (Paterson and Whitfield 2000) supports the supposition that juvenile fishes seek out the shallower habitats of estuaries to avoid predation. Similarly, many of the same species found in Humboldt Bay were also found during an ecological profile of San Francisco Bay (Josselyn 1983). These fishes were abundant in shallow tidal sloughs. Spatial analyses of fish distribution within Humboldt Bay using GIS have shown that fish utilize many habitats in the bay, and that juvenile fishes are abundant in shallow areas.

In the field of fisheries, GIS allows for comprehensive spatial analyses and generates descriptive graphical output. It is this output that provided an updated display of finfish distribution in Humboldt Bay for this study. However, by entering the fish data into GIS, additional advantages were provided. For example, simple analyses of fish species by habitat type were easy to perform and meaningful to obtain. Likewise, water-quality data were easily added to the spatial database.

Collected data like these may be used in many ways because they are displayed visually. Other studies have used GIS to present data for both conservation and management. Lunetta et al. (1997) used GIS to combine aspects of salmon-spawning habitat such as stream bank vegetation and gradient to identify particular areas in a stream. By using GIS and other remotely sensed data, suitable habitat locations were predicted before attempting to find them in the field. Fish abundance and habitat usage are not often described using GIS. This was the reason for the study of whitefish in a boreal lake in Ontario, Canada (Bégout Anras et al. 1999). Location of the whitefish was tracked over two spawning seasons. These data were combined with detailed habitat data to determine patterns of whitefish-spawning behavior.

The habitat-type data layer used here was digitized from USGS topographic maps, which were photorevised in the 1970s. Because not all of the small sloughs were apparent on the habitat map, sample points appeared to fall on land.

Similarly, points that landed in palustrine habitats were inaccurate as none of the sites sampled during this study were nontidal. Clearly there is a need for new cartographic media to describe wetland habitats of North America.

The Humboldt Bay Harbor, Recreation and Conservation District maintains a current Humboldt Bay atlas of GIS coverages. Of these, several map biological characters. These coverages can be intersected with our new fish distribution coverage to perform analyses similar to the fish by habitat analysis in this study. One of the available coverages of Humboldt Bay is a 1980 sediment layer. This layer was hand- digitized in 2000 from two paper maps (Shapiro and Associates 1980). The coverage gives a description of sediments from clay to sand and silt, as well as a coarseness category (Figure 26). When this coverage is intersected with our fish distribution layer, a list of the detected species can be queried by sediment type. For example, at least 18 species, including juveniles of the family Osmeridae, were collected by methods other than trawl over the sediment type described as marsh (Table 20). Topsmelt accounted for over one-half of the total number of fishes collected in marshy sediment type. A total of 42 species collected by methods other than trawls were associated with the sandy sediment type when the coverages were intersected (Table 21).

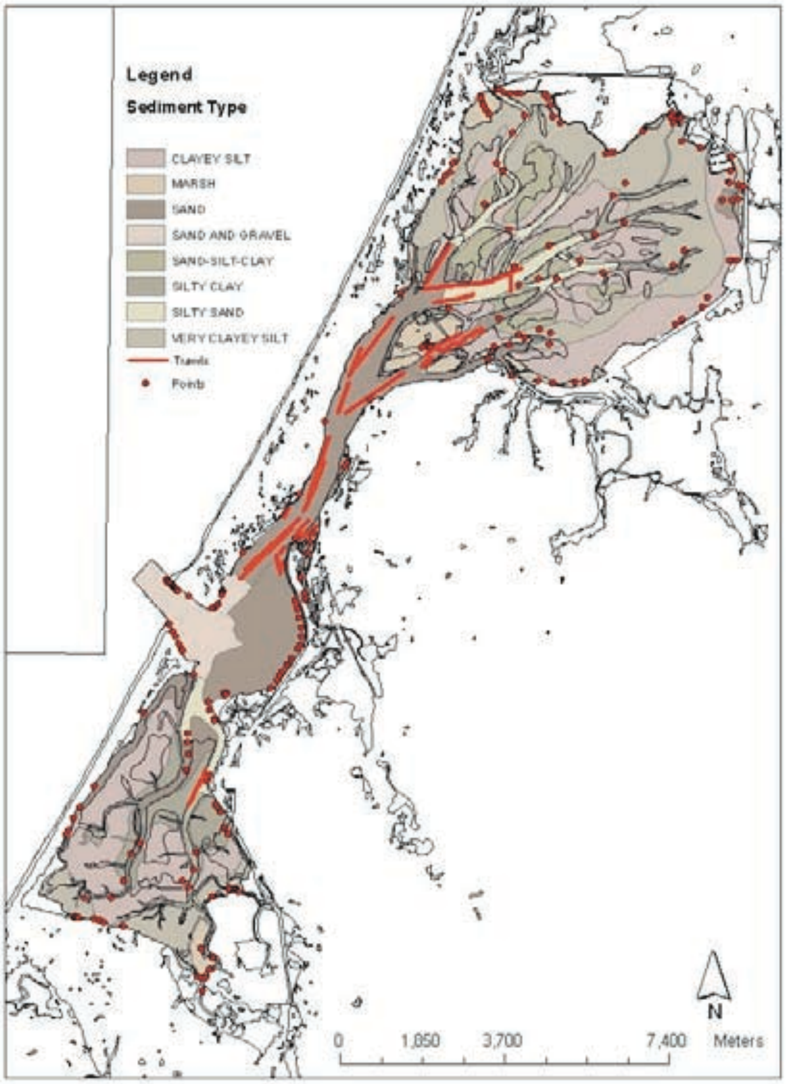

Figure 26. Sediment types of Humboldt Bay, Humboldt County, California, and the locations sampled from September 2000 to November 2001. Sediment coverage is available from the Humboldt Bay Harbor, Recreation and Conservation District at http://www.humboldtbay.org.

Table 20. Fish species collected by methods other than trawl over the marshy sediment of Humboldt Bay, California, from September 2000 to November 2001.

SPECIES	No. of Points	Abundance
Pacific herring	1	1
juvenile rockfish	1	1
kelp greenling	1	1
leopard shark	1	1
saddleback gunnel	1	1
English sole	2	2
bay pipefish	2	2
coho salmon	2	2
prickly sculpin	1	2
starry flounder	2	8
threespine stickleback	5	16
arrow goby	4	19
shiner surfperch	4	43
Osmerid sp.	5	58
staghorn sculpin	12	81
Northern anchovy	4	98
surf smelt	5	198
topsmelt	5	718
total		1252

Table 21. Fish species collected by methods other than trawl over sandy sediment in Humboldt Bay, California, from September 2000 to November 2001.

SPECIES	No. of Points	Abundance
Pacific sardine	1	1
buffalo sculpin	1	1
calico surfperch	1	1
gopher rockfish	1	1
medusa fish	1	1
sharpnose sculpin	1	1
white surfperch	1	1
Pacific herring	1	2
bat ray	1	2
cabezon	2	2
coho salmon	1	2
kelp greenling	2	2
petrale sole	2	2
red Irish lord	1	2
rock greenling	1	2
penpoint gunnel	3	4
walleye surfperch	4	5
Northern anchovy	2	6
bay goby	1	6
juvenile rockfish	1	7
saddleback gunnel	4	7
sandsole	6	8
arrow goby	4	9
striped surfperch	4	9
starry flounder	7	13
speckled sanddab	6	22
spotfin surfperch	6	24
jacksmelt	3	25
bay pipefish	13	28
English sole	11	33
butter sole	1	60
chinook salmon	13	87
redtail surfperch	11	96
black rockfish	7	107
silver surfperch	7	121
tubesnout	4	132
threespine stickleback	15	143
staghorn sculpin	29	612
Osmerid sp.	12	658
shiner surfperch	13	882
topsmelt	23	890
surf smelt	34	2563
total		6580

There is also a coverage depicting eelgrass beds in Humboldt Bay from 1997. Because eelgrass beds are known to be very productive areas in the bay, and provide habitat for shelter, feeding and spawning, the results from intersecting this coverage with the fish distribution layer are worthy of note (Figure 27). A total of 22 species were collected in eelgrass beds throughout the entire study (Table 22). Shiner surfperch was the most abundant species; two other surfperch species were also collected. Just as a substantial amount of editing was required for this study to assure that sampling locations fell within the correct habitat type, further editing would be required for this analysis. Bay pipefish, which are known to reside in eelgrass beds, are clearly underrepresented as the majority of the bay pipefish collected in this study were in fact collected over eelgrass beds. Most likely points from fish sampling areas either fell among the fringe of the defined eelgrass beds or the current eelgrass coverage needs further updating.

The Humboldt Bay Harbor, Recreation and Conservation District updates coverages as they are created. Both the sediment coverage and eelgrass coverage are several years old, as was the habitat map used for this study. Because of this, slight discrepancies, like changes in tidal sloughs, are apparent when the coverages are used as a base layer for current fish data.

This study of Humboldt Bay fishes has accomplished several goals. The need for current fish species data was apparent, as most of the published data are vague in terms of location and comes from the 1970s. A new GIS coverage for Humboldt Bay has been created that can be layered with other available GIS coverages. For this study, the creation of this fish species coverage has offered a new understanding of fish distribution by Humboldt Bay habitat type. The addition of this new coverage will also allow for future analyses to be performed as more GIS coverages of the natural resources of Humboldt Bay are created.

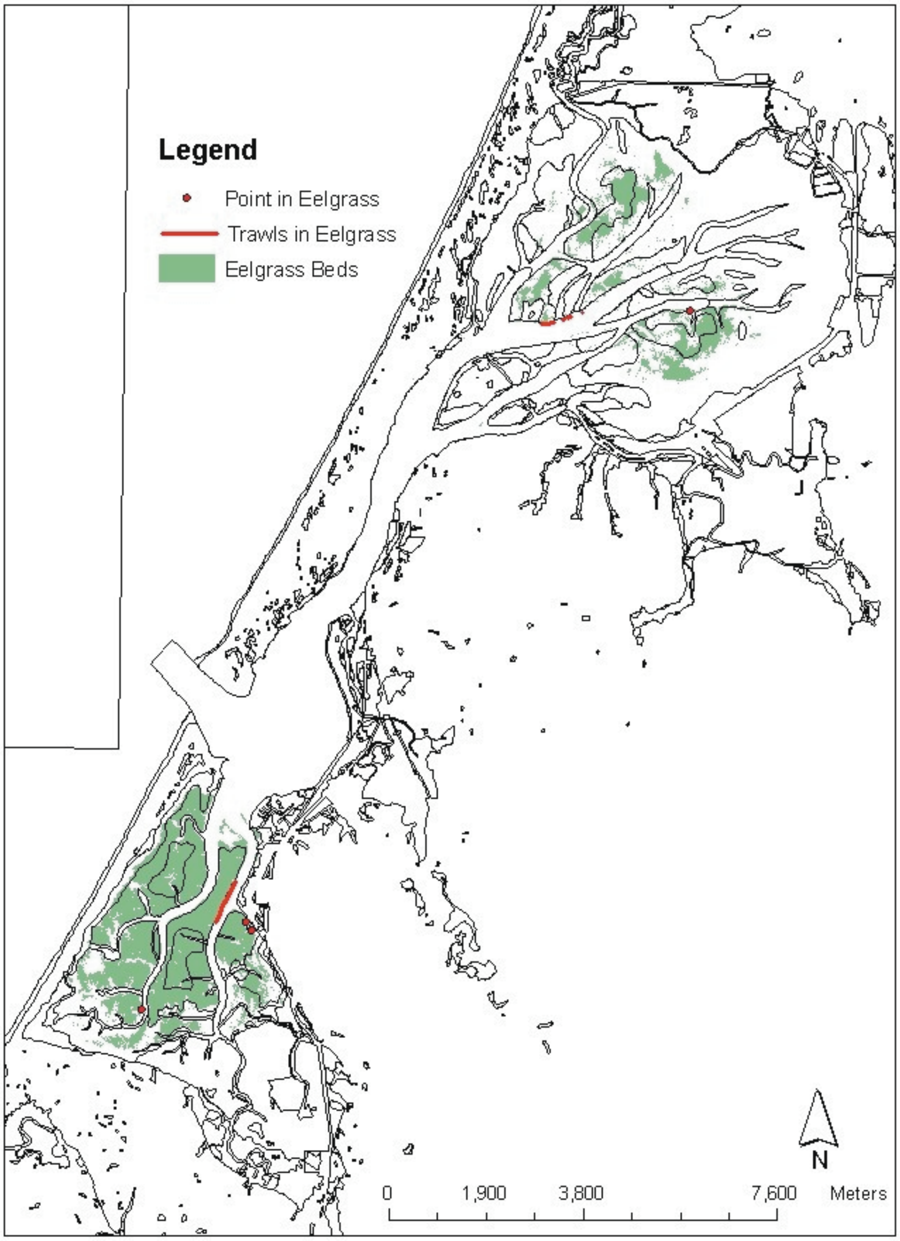

Figure 27. Eelgrass beds of Humboldt Bay, Humboldt County, California, and the locations sampled from September 2000 to November 2001. Eelgrass coverage is available from the Humboldt Bay Harbor, Recreation and Conservation District at http://www.humboldtbay.org.

Table 22. Fish species collected by all methods in eelgrass beds of Humboldt Bay, California, from September 2000 to November 2001.

SPECIES	No. of Points	Abundance
arrow goby	1	1
black rockfish	1	1
brown smoothhound	1	1
saddleback gunnel	1	1
tubesnout	1	1
Northern anchovy	1	2
juvenile rockfish	1	2
starry flounder	2	2
spiny dogfish	1	4
bat ray	2	5
night smelt	2	5
speckled sanddab	3	5
bay pipefish	1	6
white surfperch	2	6
walleye surfperch	3	19
staghorn sculpin	7	26
threespine stickleback	3	35
jacksmelt	1	39
English sole	2	40
topsmelt	2	41
surf smelt	3	109
shiner surfperch	6	143
total		494

Acknowledgments

Funding for this 15-month collection of fish species in Humboldt Bay was provided by the California Department of Fish and Game through the Non-indigenous Marine Species of Humboldt Bay, California project. This study covered more areas of Humboldt Bay than any other before, by and large due to a number of people who helped both in the field and with fish species identification.

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Appendices A–L

Appendix A. Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

U=Uplands

System	Subsystem	Class	Subclass
M=Marine	1=Subtidal	RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		AB=Aquatic Bottom	1=Algal
			3=Rooted Vascular
			5=Unknown Submergent
		RF=Reef	1=Coral
			3=Worm
		OW=Open Water	Unknown Bottom
	2=Intertidal	AB= Aquatic Bed	1=Algal
			3=Rooted Vascular
			5=Unknown Submergent
		RF=Reef	1=Coral
			3=Worm
		RS=Rocky Shore	1=Bedrock
			2=Rubble
		US=Unconsolidated Shore	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic

—continued p. 173

Appendix A. (continued) Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

System	Subsystem	Class	Subclass
E=Estuarine	1=Subtidal	RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		AB=Aquatic Bed	1=Algal
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		RF=Reef	2=Mollusc
			3=Worm
		OW=Open Water	Unknown Bottom
	2=Intertidal	AB=Aquatic Bed	1=Algal
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		RF=Reef	2=Mollusc
			3=Worm
		SB=Streambed	3=Cobble-Gravel
			4=Sand
			5=Mud
			6=Organic
		RS=Rocky Shore	1=Bedrock
			2=Rubble
		US=Unconsolidated Shore	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		EM=Emergent	1=Persistent
			2=Nonpersistent

—continued p. 174

Appendix A. (continued) Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

System	Subsystem	Class	Subclass
E=Estuarine	2=Intertidal	SS=Scrub, shrub	1=Broad Leaf Deciduous
			2=Needle Deciduous
			3=Broad Leaf Evergreen
			4=Needle Evergreen
			5=Dead
			6=Indeterminate Deciduous
			7=Indeterminate Evergreen
		FO=Forested	1=Broad Leaf Deciduous
			2=Needle Deciduous
			3=Broad Leaf Evergreen
			4=Needle Evergreen
			5=Dead
			6=Indeterminate Deciduous
			7=Indeterminate Evergreen

—continued p. 175

Appendix A. (continued) Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

System	Subsystem	Class	Subclass
R=Riverine	1=Tidal 2=Lower Perennial 3=Upper Perennial 4=Intermittent 5=Unknown Perennial	RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		SB=Streambed	1=Bedrock
			2=Rubble
			3=Cobble-Gravel
			4=Sand
			5=Mud
			6=Organic
			7=Vegetated
		AB=Aquatic Bed	1=Algal
			2=Aquatic Moss
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		RS=Rocky Shore	1=Bedrock
			2=Rubble
		US=Unconsolidated Shore	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
			5=Vegetated
		EM=Emergent	2=Nonpersistent

—continued p. 176

Appendix A. (continued) Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

System	Subsystem	Class	Subclass
L=Lacustrine	1=Limnetic	RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		AB=Aquatic Bed	1=Algal
			2=Aquatic Moss
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		OW=Open Water	Unknown Bottom
	2=Littoral	RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		AB=Aquatic Bed	1=Algal
			2=Aquatic Moss
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		RS=Rocky Shore	1=Bedrock
			2=Rubble
		US=Unconsolidated Shore	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
			5=Vegetated
		EM=Emergent	2=Nonpersistent
		OW=Open Water	Unknown Bottom

—continued p. 177

Appendix A. (continued) Habitat classification from the NWI Wetland and Deepwater Habitat mapping code. Estuarine habitats have a tidal flooding classification beyond subclass, where: L = Subtidal, M = Irregularly Exposed, N = Regularly Flooded and P = Irregularly Flooded. (Classification definitions derived from Cowardin et al. 1979).

System	Subsystem	Class	Subclass
P=Palustrine		RB=Rock Bottom	1=Bedrock
			2=Rubble
		UB=Unconsolidated Bottom	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
		AB=Aquatic Bed	1=Algal
			2=Aquatic Moss
			3=Rooted Vascular
			4=Floating Vascular
			5=Unknown Submergent
			6=Unknown Surface
		US=Unconsolidated Shore	1=Cobble-Gravel
			2=Sand
			3=Mud
			4=Organic
			5=Vegetated
		ML=Moss/Lichen	1=Moss
			2=Lichen
		EM=Emergent	1=Persistent
			2=Nonpersistent
		SS=Scrub/Shrub	1=Broad Leaf Deciduous
			2=Needle Deciduous
			3=Broad Leaf Evergreen
			4=Needle Evergreen
			5=Dead
			6=Indeterminate Deciduous
			7=Indeterminate Evergreen
		FO=Forested	1=Broad Leaf Deciduous
			2=Needle Deciduous
			3=Broad Leaf Evergreen
			4=Needle Evergreen
			5=Dead
			6=Indeterminate Deciduous
			7=Indeterminate Evergreen
		OW=Open Water	Unknown Bottom

—end Appendix A

Appendix B. Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
1	15-Sep-00	1345	40 52' 02.52" N	124 08' 48.65" W	403351.77055	4524454.94712	MR Pond
2	15-Sep-00	1345	40 51' 59.38" N	124 08' 51.94" W	403273.48365	4524359.13237	MR Pond
3	16-Sep-00	940	40 46' 29.42" N	124 12' 38.79" W	397822.36353	4514256.16947	Somoa BR
4	25-Sep-00	1345	40 48' 27.36" N	124 10' 16.86" W	401198.09959	4517847.70816	Eka Channel Trawl Out
5	25-Sep-00	1408	40 47' 57.54" N	124 11' 12.00" W	399893.68430	4516945.57340	Eka Channel Trawl In
6	25-Sep-00	1443	40 49' 07.92" N	124 10' 27.84" W	400957.58819	4519101.83521	Somoa Channel Trawl Out
7	25-Sep-00	1503	40 48' 30.12" N	124 11' 05.10" W	400068.95297	4517948.00380	Somoa Channel Trawl In
8	25-Sep-00	1524	40 47' 39.66" N	124 11' 27.36" W	399526.25506	4516399.11756	N Bay Channel Trawl Out
9	25-Sep-00	1542	40 46' 56.40" N	124 11' 46.02" W	399070.75640	4515071.13361	N Bay Channel Trawl In
10	25-Sep-00	1554	40 46' 40.26" N	124 11' 54.84" W	398857.21803	4514576.27436	Fairhaven Trawl Out
11	25-Sep-00	1612	40 46' 02.28" N	124 12' 46.44" W	397631.45939	4513421.77776	Fairhaven Trawl In
12	25-Sep-00	1622	40 45' 56.10" N	124 12' 52.14" W	397495.18539	4513233.06468	N Bay Trawl Out
13	25-Sep-00	1645	40 46' 32.76" N	124 12' 01.56" W	398696.52820	4514347.16398	N Bay Trawl In
14	1-Oct-00	820	40 43' 23.46" N	124 13' 28.98" W	396565.77740	4508538.39391	Hookton Channel Out
15	1-Oct-00	828	40 43' 36.18" N	124 13' 21.54" W	396745.78453	4508928.18330	Hookton Channel In
16	1-Oct-00	858	40 43' 10.98" N	124 13' 37.44" W	396361.92467	4508156.34353	Hookton Channel Out
17	1-Oct-00	908	40 43' 29.64" N	124 13' 25.98" W	396638.81480	4508727.97318	Hookton Channel In
18	1-Oct-00	1505	40 46' 10.14" N	124 12' 33.6" W	397935.83307	4513659.98710	Entrance Channel Out
19	1-Oct-00	1520	40 46' 28.32" N	124 12' 08.76" W	398525.86958	4514212.56714	Entrance Channel In
20	4-Oct-00	1140	40 48' 15.01" N	124 07' 14.84" W	405458.07933	4517411.13385	Johnson Ranch
21	11-Oct-00	1325	40 48' 09.27" N	124 08' 16.34" W	404014.72357	4517252.70291	Somoa Blvd Pasture
22	11-Oct-00	1105	40 53' 52.23" N	124 08' 05.34" W	404409.50164	4527824.72372	Seahorse Ranch
23	13-Oct-00	1440	40 51' 02.70" N	124 09' 31.46" W	402325.19654	4522623.55429	Manilla Park
24	12-Oct-00	1043	40 49' 46.90" N	124 10' 17.89" W	401206.75462	4520300.68228	Vance Ave
25	12-Oct-00	1043	40 49' 40.49" N	124 10' 19.92" W	401156.56191	4520103.66266	Vance Ave

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
26	19-Oct-00	1100	40 46' 59.40" N	124 11' 57.60" W	398800.59070	4515167.34629	Fairhaven
27	20-Oct-00	1200	40 51' 18.84" N	124 05' 52.62" W	407455.67224	4523055.22442	Arcata Marsh
28	23-Oct-00	1320	40 45' 34.20" N	124 11' 31.20" W	399383.69058	4512531.74798	Elk River Slough
29	23-Oct-00	1520	40 49' 21.66" N	124 09' 28.02" W	402364.57173	4519506.86808	North Bay Trawl Out
30	23-Oct-00	1530	40 49' 25.14" N	124 09' 10.32" W	402780.61232	4519608.70913	North Bay Trawl In
31	23-Oct-00	1538	40 49' 28.86" N	124 09' 58.56" W	401652.11568	4519738.36981	North Bay Trawl Out
32	23-Oct-00	1559	40 49' 44.40" N	124 08' 24.06" W	403871.97969	4520188.42302	North Bay Trawl In
33	23-Oct-00	1610	40 49' 39.60" N	124 08' 35.52" W	403601.61968	4520043.91011	North Bay Trawl Out
34	23-Oct-00	1621	40 49' 27.78" N	124 08' 35.52" W	403596.86473	4519679.43519	North Bay Trawl In
35	23-Oct-00	1635	40 49' 23.58" N	124 09' 12.54" W	402727.97561	4519561.29016	North Bay Trawl Out
36	23-Oct-00	1650	40 49' 18.90" N	124 09' 49.20" W	401867.29234	4519428.33382	North Bay Trawl In
37	23-Oct-00	1720	40 50' 01.56" N	124 09' 34.50" W	402229.05719	4520739.21073	North Bay Trawl Out
38	23-Oct-00	1743	40 49' 33.06" N	124 09' 56.94" W	401691.78663	4519867.37384	North Bay Trawl In
39	26-Oct-00	1425	40 46' 23.49" N	124 11' 43.36" W	399119.27585	4514055.49463	Elk River Slough
40	26-Oct-00	1400	40 46' 25.98" N	124 11' 58.37" W	398768.44898	4514137.07785	Elk River Slough
41	26-Oct-00	1410	40 46' 15.43" N	124 11' 45.47" W	399066.42314	4513807.63676	Elk River Slough
42	27-Oct-00	1350	40 51' 18.86" N	124 05' 52.59" W	407456.38239	4523055.83233	Arcata Marsh
43	27-Oct-00	1350	40 51' 14.15" N	124 05' 34.64" W	407874.84811	4522905.34007	Arcata Marsh
44	29-Oct-00	1500	40 49' 27.36" N	124 10' 23.11" W	401076.42073	4519699.79264	N. Somoa Bridge
45	30-Oct-00	1530	40 51' 24.64" N	124 05' 24.68" W	408112.08098	4523225.89798	Arcata Marsh
46	30-Oct-00	1530	40 51' 23.39" N	124 05' 50.44" W	407508.47240	4523194.88633	Arcata Marsh
47	3-Nov-00	1210	40 48' 25.85" N	124 08' 33.38" W	403622.09861	4517769.14586	Montgomery Wards
48	3-Nov-00	1210	40 48' 37.95" N	124 08' 55.55" W	403107.52723	4518149.04279	Montgomery Wards
49	3-Nov-00	1210	40 48' 56.99" N	124 08' 26.45" W	403796.96976	4518727.24437	Montgomery Wards
50	5-Nov-00	1330	40 49' 14.64" N	124 09' 34.03" W	402220.92136	4519292.26461	Indian Island

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
51	13-Nov-00	1600	40 47' 52.20" N	124 11' 37.80" W	399286.85461	4516789.12022	Tina Town
52	1-Dec-00	1330	40 46' 27.18" N	124 11' 52.75" W	398900.70165	4514172.27971	Eelgrass Beds 1&2
53	1-Dec-00	1400	40 46' 26.69" N	124 11' 57.05" W	398799.69248	4514158.54779	Eelgrass Beds #3
54	1-Dec-00	1410	40 46' 35.00" N	124 11' 38.77" W	399231.70984	4514408.94292	Eelgrass Beds #4
55	1-Dec-00	1434	40 46' 15.51" N	124 12' 12.73" W	398427.38401	4513818.84375	Eelgrass Beds #5
56	1-Dec-00	1447	40 45' 59.71" N	124 12' 12.37" W	398429.14046	4513331.53113	Eelgrass Beds #6
57	1-Dec-00	1458	40 45' 35.86" N	124 11' 57.70" W	398763.02784	4512591.40155	Eelgrass Beds #7
58	1-Dec-00	1509	40 46' 47.81" N	124 12' 05.45" W	398611.69613	4514812.48356	Eelgrass Beds #9
59	7-Dec-00	1310	40 48' 32.10" N	124 10' 00.15" W	401591.57169	4517988.64652	Woodley Island Trawl #1
60	7-Dec-00	1331	40 48' 38.84" N	124 09' 49.94" W	401833.55373	4518193.29692	Woodley Island Trawl #2
61	7-Dec-00	1345	40 48' 44.64" N	124 09' 38.37" W	402107.00187	4518368.54780	Woodley Island Trawl #3
62	7-Dec-00	1401	40 48' 47.68" N	124 09' 26.20" W	402393.37028	4518458.51729	Woodley Island Trawl #4
63	7-Dec-00	1421	40 48' 54.81" N	124 09' 11.76" W	402734.57330	4518673.91459	Woodley Island Trawl #5
64	7-Dec-00	1427	40 49' 00.70" N	124 09' 02.68" W	402949.68397	4518852.73910	Woodley Island Trawl #6
65	7-Dec-00	1449	40 48' 57.46" N	124 09' 08.79" W	402805.22885	4518754.71317	Woodley Island Trawl #7
66	7-Dec-00	1506	40 48' 56.84" N	124 09' 21.61" W	402504.63324	4518739.55050	Woodley Island Trawl #8
67	7-Dec-00	1530	40 48' 49.90" N	124 09' 40.12" W	402068.14980	4518531.28505	Woodley Island Trawl #9
68	17-Jan-01	955	40 46' 33.24" N	124 12' 31.08" W	398004.72639	4514371.46769	Fairhaven
69	17-Jan-01	955	40 46' 21.78" N	124 12' 14.76" W	398382.44726	4514012.83390	Fairhaven
70	23-Jan-01	1210	40 47' 22.59" N	124 11' 03.91" W	400068.70485	4515865.31464	Mudflats EKA garbage
71	23-Jan-01	1235	40 47' 25.44" N	124 11' 05.32" W	400036.84600	4515953.64172	Mudflats EKA garbage
72	23-Jan-01	1310	40 47' 25.22" N	124 11' 03.16" W	400087.37779	4515946.17413	Mudflats EKA garbage
73	23-Jan-01	1415	40 47' 17.85" N	124 11' 11.45" W	399890.01201	4515721.54416	Mudflats EKA garbage
74	23-Jan-01	1430	40 47' 20.97" N	124 11' 09.83" W	399929.28196	4515817.23672	Mudflats EKA garbage
75	28-Jan-01	1035	40 45' 54.99" N	124 13' 13.41" W	396996.02294	4513205.75757	Coast Guard Station

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
76	28-Jan-01	1253	40 45' 47.58" N	124 13' 15.89" W	396934.69771	4512978.07741	Coast Guard Station
77	30-Jan-01	1505	40 46' 30.02" N	124 11' 40.16" W	399197.03476	4514255.82696	Trendsale Ave (Eureka)
78	30-Jan-01	1252	40 48' 07.64" N	124 10' 47.79" W	400465.20371	4517249.35366	Wharfinger Building
79	1-Feb-01	1240	40 43' 32.62" N	124 13' 17.44" W	396840.44008	4508817.07179	Fields Landing
80	1-Feb-01	1322	40 43' 27.49" N	124 13' 19.72" W	396784.75061	4508659.63230	Fields Landing
81	2-Feb-01	937	40 46' 18.67" N	124 12' 47.19" W	397620.86437	4513927.41084	Somoa Beach
82	2-Feb-01	937	40 46' 15.93" N	124 12' 52.50" W	397495.21055	4513844.64471	Somoa Beach
83	10-Feb-01	1242	40 45' 43.10" N	124 13' 39.41" W	396381.30631	4512847.63088	North Spit
84	11-Feb-01	1040	40 44' 19.41" N	124 13' 17.56" W	396857.69958	4510259.88454	King Salmon
85	11-Feb-01	1100	40 44' 13.19" N	124 13' 13.51" W	396950.02576	4510066.76886	King Salmon
86	13-Feb-01	1230	40 44' 30.99" N	124 13' 02.64" W	397212.59994	4510612.09368	King Salmon
87	13-Feb-01	1347	40 44' 26.45" N	124 13' 19.02" W	396826.47721	4510477.44042	King Salmon
88	13-Feb-01	1347	40 44' 11.93" N	124 13' 12.90" W	396963.79360	4510027.71773	King Salmon
89	15-Feb-01	1340	40 43' 08.29" N	124 15' 22.24" W	393901.95432	4508108.16219	South Spit
90	15-Feb-01	1510	40 43' 00.04" N	124 15' 27.30" W	393779.59385	4507855.47201	South Spit
91	16-Feb-01	905	40 49' 51.83" N	124 05' 05.10" W	408535.07338	4520358.36767	Bracut
92	16-Feb-01	1000	40 49' 52.46" N	124 05' 02.78" W	408589.65354	4520377.12143	Bracut
93	20-Feb-01	1252	40 48' 20.94" N	124 07' 16.54" W	405420.58393	4517594.49653	Murray Field
94	20-Feb-01	1416	40 48' 33.06" N	124 06' 51.01" W	406023.53379	4517960.59335	Murray Field
95	20-Feb-01	1553	40 48' 14.37" N	124 07' 11.86" W	405527.65408	4517390.50688	Eka Slough Channel
96	20-Feb-01	1600	40 48' 13.61" N	124 07' 09.77" W	405576.32752	4517366.44660	Eka Slough Channel
97	22-Feb-01	1235	40 42' 51.53" N	124 15' 33.51" W	393630.12733	4507595.15353	South Spit
98	22-Feb-01	1313	40 42' 48.85" N	124 15' 35.69" W	393577.79117	4507513.24920	South Spit
99	22-Feb-01	1425	40 44' 10.33" N	124 14' 30.67" W	395138.94468	4510003.96250	South Spit
100	22-Feb-01	1450	40 44' 07.12" N	124 14' 33.53" W	395070.45973	4509905.93101	South Spit

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
101	27-Feb-01	1307	40 41' 39.81" N	124 14' 37.76" W	394906.90831	4505365.02742	Southport Landing
102	27-Feb-01	1408	40 41' 41.88" N	124 14' 56.68" W	394463.75241	4505435.15559	Southport Landing
103	27-Feb-01	1555	40 41' 43.67" N	124 15' 02.21" W	394334.74687	4505492.19650	Southport Landing
104	5-Mar-01	1430	40 44' 45.19" N	124 13' 38.30" W	396382.35843	4511061.59999	South Spit/Kill Beach
105	8-Mar-01	1210	40 48' 04.11" N	124 06' 45.82" W	406133.80514	4517066.36724	Fay Slough
106	8-Mar-01	1210	40 48' 05.76" N	124 06' 49.81" W	406040.95428	4517118.43268	Fay Slough
107	8-Mar-01	1210	40 48' 04.22" N	124 06' 53.92" W	405944.04185	4517072.17055	Fay Slough
108	8-Mar-01	1210	40 48' 07.95" N	124 06' 53.95" W	405944.80160	4517187.19505	Eureka Slough
109	9-Mar-01	845	40 47' 43.53" N	124 07' 15.14" W	405438.64003	4516440.52943	Freshwater Slough
110	9-Mar-01	905	40 47' 43.15" N	124 07' 11.35" W	405527.30870	4516427.67718	Freshwater Slough
111	9-Mar-01	920	40 47' 44.94" N	124 07' 07.52" W	405617.76879	4516481.72652	Freshwater Slough
112	13-Mar-01	810	40 46' 27.22" N	124 12' 33.77" W	397939.10840	4514186.70842	Bay Plankton Tow Out
113	13-Mar-01	816	40 46' 33.77" N	124 12' 25.55" W	398134.58492	4514386.02530	Bay Plankton Tow In
114	13-Mar-01	824	40 46' 32.13" N	124 12' 28.06" W	398075.04960	4514336.26538	Bay Plankton Tow Out
115	13-Mar-01	830	40 46' 23.63" N	124 12' 37.29" W	397855.06345	4514077.14790	Bay Plankton Tow In
116	13-Mar-01	836	40 46' 24.38" N	124 12' 38.08" W	397836.86277	4514100.52992	Bay Plankton Tow Out
117	13-Mar-01	842	40 46' 28.44" N	124 12' 31.84" W	397984.87081	4514223.70382	Bay Plankton Tow In
118	13-Mar-01	856	40 46' 39.01" N	124 11' 46.25" W	399058.05218	4514534.98147	Bay Plankton Tow Out
119	13-Mar-01	902	40 46' 30.44" N	124 11' 57.43" W	398792.36526	4514274.30183	Bay Plankton Tow In
120	13-Mar-01	915	40 46' 03.73" N	124 12' 14.26" W	398386.53022	4513456.09674	Bay Plankton Tow Out
121	13-Mar-01	920	40 46' 13.89" N	124 12' 16.77" W	398331.98584	4513770.19065	Bay Plankton Tow In
122	13-Mar-01	1037	40 48' 32.44" N	124 10' 00.30" W	401588.19670	4517999.17733	Bay Plankton Tow Out
123	13-Mar-01	1040	40 48' 38.29" N	124 09' 52.24" W	401779.44044	4518177.05317	Bay Plankton Tow In
124	13-Mar-01	1059	40 48' 45.89" N	124 09' 33.40" W	402223.95372	4518405.55107	Bay Plankton Tow Out
125	13-Mar-01	1104	40 48' 43.36" N	124 09' 42.70" W	402005.03117	4518330.42252	Bay Plankton Tow In

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited between the months of September 2000 and November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
126	13-Mar-01	1110	40 48' 44.07" N	124 09' 41.45" W	402034.60768	4518351.92751	Bay Plankton Tow Out
127	13-Mar-01	1118	40 48' 44.48" N	124 09' 43.60" W	401984.40285	4518365.23770	Bay Plankton Tow In
128	15-Mar-01	1211	40 45' 40.83" N	124 11' 49.13" W	398966.06337	4512741.90848	Elk River Estuary
129	15-Mar-01	1312	40 45' 45.59" N	124 11' 51.47" W	398913.20085	4512889.43271	Elk River Estuary
130	15-Mar-01	1312	40 45' 56.93" N	124 11' 52.75" W	398887.96383	4513239.51371	Elk River Estuary
131	19-Mar-01	1310	40 48' 12.23" N	124 08' 27.35" W	403757.92047	4517347.32843	Bay Street Slough
132	19-Mar-01	1350	40 48' 11.33" N	124 08' 32.06" W	403647.19355	4517321.01378	Bay Street Slough
133	20-Mar-01	1200	40 48' 14.04" N	124 08' 21.69" W	403891.27167	4517401.41553	Eureka Slough @ Bay St
134	20-Mar-01	1230	40 48' 13.24" N	124 08' 23.38" W	403851.35094	4517377.26204	Eureka Slough @ Bay St
135	20-Mar-01	1230	40 49' 51.80" N	124 04' 59.72" W	408661.07407	4520355.88364	Bracut
136	20-Mar-01	1230	40 49' 52.52" N	124 04' 58.06" W	408700.22949	4520377.60452	Bracut
137	20-Mar-01	930	40 41' 46.33" N	124 15' 22.26" W	393865.34189	4505580.93086	Southport Landing
138	20-Mar-01	1010	40 41' 45.05" N	124 15' 06.68" W	394230.44136	4505536.24285	Southport Landing
139	20-Mar-01	1010	40 41' 46.33" N	124 15' 21.44" W	393884.58725	4505580.65572	Southport Landing
140	20-Mar-01	1135	40 41' 46.58" N	124 15' 24.80" W	393805.83848	4505589.49221	Southport Landing
141	21-Mar-01	855	40 50' 46.23" N	124 04' 53.20" W	408834.50591	4522032.36871	Bracut
142	21-Mar-01	1205	40 50' 55.06" N	124 04' 51.41" W	408879.78246	4522304.12842	Bracut
143	27-Mar-01	1413	40 51' 06.15" N	124 05' 11.09" W	408423.19446	4522651.79542	South G Street Ramp
144	27-Mar-01	1505	40 50' 57.37" N	124 05' 04.59" W	408572.03974	4522379.17357	South G Street Ramp
145	29-Mar-01	1440	40 50' 47.91" N	124 04' 56.92" W	408748.03484	4522085.24828	Gannon Slough
146	29-Mar-01	1555	40 50' 48.93" N	124 05' 05.28" W	408552.65956	4522119.12232	Gannon Slough
147	29-Mar-01	1615	40 50' 49.77" N	124 05' 06.61" W	408521.83618	4522145.40988	Gannon Slough
148	4-Apr-01	755	40 51' 31.51" N	124 06' 00.32" W	407280.29344	4523448.17311	McDaniel Slough
149	4-Apr-01	915	40 51' 36.63" N	124 06' 02.80" W	407224.21477	4523606.78076	McDaniel Slough
150	4-Apr-01	1000	40 51' 35.49" N	124 05' 56.50" W	407371.26979	4523569.77561	McDaniel Slough

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited between the months of September 2000 and November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
151	4-Apr-01	1030	40 51' 35.29" N	124 05' 53.74" W	407435.81013	4523562.79781	McDaniel Slough
152	5-Apr-01	1155	40 48' 46.39" N	124 09' 51.58" W	401798.22173	4518426.61450	Indian Island
153	5-Apr-01	1215	40 48' 48.78" N	124 09' 53.36" W	401757.49781	4518500.86522	Indian Island
154	5-Apr-01	1255	40 48' 47.78" N	124 09' 55.43" W	401708.59065	4518470.67447	Indian Island
155	5-Apr-01	1255	40 48' 48.51" N	124 09' 56.05" W	401694.36420	4518493.37747	Indian Island
156	5-Apr-01	1330	40 48' 46.65" N	124 09' 58.25" W	401642.05816	4518436.70921	Indian Island
157	5-Apr-01	1350	40 48' 46.17" N	124 09' 59.77" W	401606.24939	4518422.38210	Indian Island
158	5-Apr-01	1425	40 48' 47.15" N	124 09' 54.34" W	401733.86969	4518450.90867	Indian Island
159	10-Apr-01	1305	40 42' 06.57" N	124 12' 49.10" W	397468.61747	4506154.50290	White Slough
160	10-Apr-01	1430	40 42' 09.34" N	124 12' 57.43" W	397274.31191	4506242.61893	White Slough
161	12-Apr-01	1235	40 41' 59.49" N	124 12' 31.71" W	397873.72064	4505930.56490	NWR-Gold Dredge
162	12-Apr-01	1245	40 42' 00.62" N	124 12' 32.38" W	397858.47618	4505965.62471	NWR-Gold Dredge
163	12-Apr-01	1505	40 42' 05.51" N	124 12' 39.51" W	397693.22428	4506118.71207	NWR-Gold Dredge
164	17-Apr-01	1325	40 40' 38.36" N	124 13' 17.42" W	396766.19454	4503443.77122	Hookton Slough
165	17-Apr-01	1325	40 40' 39.24" N	124 13' 21.27" W	396676.18732	4503472.16256	Hookton Slough
166	17-Apr-01	1500	40 40' 43.33" N	124 13' 26.00" W	396566.89988	4503599.82240	Hookton Slough
167	24-Apr-01	1210	40 41' 04.88" N	124 13' 30.30" W	396475.21581	4504265.71938	Hookton Slough
168	24-Apr-01	1220	40 41' 03.93" N	124 13' 27.31" W	396544.99485	4504235.44815	Hookton Slough
169	24-Apr-01	1330	40 40' 55.34" N	124 13' 26.43" W	396561.96284	4503970.28917	Hookton Slough
170	24-Apr-01	1345	40 41' 00.16" N	124 13' 27.99" W	396527.41279	4504119.42320	Hookton Slough
171	24-Apr-01	1145(2.5hr)	40 40' 49.01" N	124 13' 30.38" W	396466.51616	4503776.39676	Hookton Slough
172	24-Apr-01	1415	40 40' 35.31" N	124 13' 08.42" W	396976.17898	4503346.79161	Hookton Slough
173	24-Apr-01	1415	40 40' 38.80" N	124 13' 12.23" W	396888.22609	4503455.64615	Hookton Slough
174	26-Apr-01	1135	40 50' 37.11" N	124 04' 56.99" W	408742.28019	4521752.24570	North Bay (Red House)
175	26-Apr-01	1159	40 50' 36.29" N	124 05' 03.62" W	408586.70653	4521728.88091	North Bay (Red House)

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	Date	Time	Latitude	Longitude	Easting	Northing	Location
176	26-Apr-01	1225	40 50' 35.51" N	124 05' 12.95" W	408367.91833	4521707.53707	North Bay (Red House)
177	26-Apr-01	1405	40 51' 53.30" N	124 08' 26.87" W	403857.92767	4524163.98161	North Bay near MRS
178	26-Apr-01	1425	40 51' 52.08" N	124 08' 30.12" W	403781.35298	4524127.35381	North Bay near MRS
179	26-Apr-01	1445	40 51' 53.31" N	124 08' 37.73" W	403603.69352	4524167.60677	North Bay near MRS
180	26-Apr-01	1510	40 51' 52.95" N	124 08' 43.74" W	403462.85110	4524158.34524	North Bay near MRS
181	27-Apr-01	850	40 44' 20.12" N	124 12' 46.71" W	397581.58784	4510271.74354	King Salmon Bridge
182	27-Apr-01	850	40 44' 32.47" N	124 13' 02.24" W	397222.61437	4510657.59956	King Salmon Rip-Rap
183	27-Apr-01	850	40 44' 32.29" N	124 13' 03.76" W	397186.88776	4510652.54372	King Salmon Rip-Rap
184	1-May-01	1200	40 51' 53.77" N	124 08' 16.15" W	404109.07666	4524175.20891	Liscom Slough
185	1-May-01	1200	40 51' 54.15" N	124 08' 18.30" W	404058.89652	4524187.58068	Liscom Slough
186	1-May-01	1330	40 51' 53.59" N	124 08' 13.97" W	404160.03938	4524168.99548	Liscom Slough
187	1-May-01	1330	40 51' 53.87" N	124 08' 11.10" W	404227.33951	4524176.75713	Liscom Slough
188	1-May-01	1455	40 51' 54.28" N	124 08' 50.40" W	403307.47422	4524201.39803	Liscom Slough
189	1-May-01	1540	40 51' 53.99" N	124 08' 48.32" W	403356.05078	4524191.81779	Liscom Slough
190	3-May-01	1225	40 51' 20.95" N	124 06' 41.56" W	406310.62466	4523134.74211	Liscom Slough
191	3-May-01	1245	40 51' 21.39" N	124 06' 40.82" W	406328.12293	4523148.08986	Liscom Slough
192	3-May-01	1307	40 51' 32.37" N	124 06' 23.90" W	406728.55945	4523481.64757	Liscom Slough
193	3-May-01	1338	40 51' 27.77" N	124 06' 34.43" W	406480.22840	4523342.92359	Liscom Slough
194	3-May-01	1356	40 51' 38.21" N	124 06' 11.79" W	407014.35385	4523658.14971	Liscom Slough
195	3-May-01	1356	40 51' 38.59" N	124 06' 02.14" W	407240.42636	4523667.02423	Liscom Slough
196	8-May-01	1230	40 42' 02.26" N	124 16' 02.00" W	392939.73090	4506085.52671	South Spit
197	8-May-01	1251	40 42' 03.20" N	124 16' 04.24" W	392887.57996	4506115.27012	South Spit
198	8-May-01	1314	40 42' 05.05" N	124 16' 01.89" W	392943.55340	4506171.51913	South Spit
199	8-May-01	1409	40 42' 02.91" N	124 16' 02.11" W	392937.43850	4506105.60670	South Spit
200	8-May-01	1409	40 42' 05.90" N	124 16' 01.10" W	392962.47124	4506197.46147	South Spit

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
201	8-May-01	1438	40 42' 07.52" N	124 15' 59.90" W	392991.35318	4506247.00807	South Spit
202	8-May-01	1452	40 42' 09.73" N	124 15' 59.83" W	392993.97850	4506315.12976	South Spit
203	8-May-01	1530	40 42' 11.57" N	124 16' 00.57" W	392977.43063	4506372.11660	South Spit
204	10-May-01	1352	40 51' 09.29" N	124 07' 05.00" W	405757.21878	4522782.18576	North Bay
205	10-May-01	1352	40 51' 09.47" N	124 06' 59.97" W	405875.06594	4522786.23358	North Bay
206	10-May-01	1445	40 51' 09.78" N	124 06' 56.22" W	405962.99309	4522794.67361	North Bay
207	10-May-01	1500	40 51' 11.30" N	124 06' 53.14" W	406035.70706	4522840.62534	North Bay
208	10-May-01	1517	40 51' 13.90" N	124 06' 50.20" W	406105.56568	4522919.92186	North Bay
209	10-May-01	1547	40 51' 16.17" N	124 06' 48.35" W	406149.77210	4522989.36771	North Bay
210	10-May-01	1600	40 51' 17.75" N	124 06' 45.69" W	406212.67264	4523037.29632	North Bay
211	10-May-01	1637	40 51' 21.08" N	124 06' 40.66" W	406331.74781	4523138.48330	North Bay
212	10-May-01	1637	40 51' 24.66" N	124 06' 36.12" W	406439.44492	4523247.52646	North Bay
213	10-May-01	1702	40 51' 26.26" N	124 06' 31.60" W	406545.89758	4523295.52270	North Bay
214	14-May-01	1030(4hr)	40 45' 39.20" N	124 13' 14.61" W	396961.11395	4512719.26051	North Jetty
215	14-May-01	1030(4hr)	40 45' 37.66" N	124 13' 15.20" W	396946.61937	4512671.96673	North Jetty
216	14-May-01	1030(4hr)	40 45' 35.15" N	124 13' 16.77" W	396908.72975	4512595.08262	North Jetty
217	14-May-01	1030(4hr)	40 45' 34.47" N	124 13' 17.65" W	396887.80397	4512574.40190	North Jetty
218	29-May-01	820	40 40' 30.59" N	124 12' 54.87" W	397292.27772	4503196.84628	Hookton Slough
219	29-May-01	945	40 40' 29.24" N	124 12' 46.70" W	397483.51266	4503152.56983	Hookton Slough
220	30-May-01	745	40 42' 03.45" N	124 13' 12.88" W	396909.21380	4506066.02882	South Bay-Gold Dredge
221	30-May-01	930	40 41' 04.15" N	124 13' 14.77" W	396839.45360	4504238.13678	S Bay-Hookton Slough
222	5-Jun-01	1043	40 50' 47.54" N	124 06' 45.58" W	406203.41407	4522105.72244	Arcata Ruins
223	5-Jun-01	1043	40 50' 38.85" N	124 06' 57.48" W	405921.33894	4521841.30696	Arcata Ruins
224	6-Jun-01	0740 (I cyc)	40 45' 46.55" N	124 13' 11.82" W	397029.68280	4512944.98964	Coast Guard
225	6-Jun-01	0740 (I cyc)	40 45' 46.06" N	124 13' 11.98" W	397025.72127	4512929.93253	Coast Guard

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
226	6-Jun-01	0740 (I cyc)	40 45' 45.62" N	124 13' 11.96" W	397026.00155	4512916.35851	Coast Guard
227	6-Jun-01	0740 (I cyc)	40 45' 45.39" N	124 13' 12.07" W	397023.32810	4512909.30227	Coast Guard
228	13-Jun-01	604	40 51' 01.58" N	124 09' 33.31" W	402281.42078	4522589.59166	North Manilla Muni Park
229	13-Jun-01	604	40 50' 56.75" N	124 09' 38.14" W	402166.34992	4522442.15355	North Manilla Muni Park
230	13-Jun-01	604	40 50' 52.73" N	124 09' 40.66" W	402105.69790	4522318.97663	North Manilla Muni Park
231	13-Jun-01	604	40 50' 49.17" N	124 09' 46.46" W	401968.42496	4522211.00390	North Manilla Muni Park
232	18-Jun-01	945	40 51' 30.72" N	124 07' 49.10" W	404733.15492	4523456.24632	North Bay
233	18-Jun-01	945	40 51' 35.52" N	124 07' 55.60" W	404582.88581	4523606.22302	North Bay
234	18-Jun-01	1105	40 51' 43.21" N	124 07' 58.60" W	404515.71704	4523844.25722	North Bay
235	18-Jun-01	1105	40 51' 48.87" N	124 08' 00.59" W	404471.38745	4524019.38975	North Bay
236	18-Jun-01	1230	40 51' 50.84" N	124 08' 04.24" W	404386.72460	4524081.24258	North Bay
237	19-Jun-01	1027	40 43' 23.85" N	124 15' 08.97" W	394220.13796	4508583.50895	South Spit
238	19-Jun-01	1046	40 43' 31.40" N	124 15' 05.24" W	394310.96343	4508815.06624	South Spit
239	19-Jun-01	1106	40 43' 37.14" N	124 14' 58.21" W	394478.40385	4508989.71097	South Spit
240	19-Jun-01	1106	40 43' 54.57" N	124 14' 41.74" W	394872.39664	4509521.67856	South Spit
241	19-Jun-01	1245	40 44' 19.56" N	124 14' 24.55" W	395286.51549	4510286.54154	South Spit
242	25-Jun-01	950	40 44' 54.12" N	124 12' 03.95" W	398598.86505	4511306.34643	Entrance Bay
243	25-Jun-01	950	40 44' 58.32" N	124 12' 00.12" W	398690.45533	4511434.62532	Entrance Bay
244	25-Jun-01	1130	40 45' 08.16" N	124 11' 52.32" W	398877.51570	4511735.54420	Entrance Bay
245	25-Jun-01	1100	40 45' 05.07" N	124 11' 54.42" W	398826.96914	4511640.93594	Entrance Bay
246	25-Jun-01	1210	40 45' 14.44" N	124 11' 51.10" W	398908.76742	4511928.79850	Entrance Bay
247	25-Jun-01	1250	40 45' 20.62" N	124 11' 51.16" W	398909.96098	4512119.37899	Entrance Bay
248	25-Jun-01	1305	40 45' 28.07" N	124 11' 53.28" W	398863.38579	4512349.77960	Entrance Bay
249	25-Jun-01	1330	40 45' 33.65" N	124 11' 54.83" W	398829.39126	4512522.33626	Entrance Bay
250	25-Jun-01	1410	40 45' 40.12" N	124 11' 57.74" W	398763.88549	4512722.77229	Entrance Bay

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
251	26-Jun-01	915	40 50' 31.25" N	124 09' 00.61" W	403034.82989	4521644.25438	North Bay
252	26-Jun-01	1051	40 51' 35.65" N	124 08' 23.07" W	403939.80361	4523618.57431	North Bay
253	26-Jun-01	1200	40 51' 23.46" N	124 08' 35.22" W	403650.43824	4523246.39608	North Bay
254	27-Jun-01	1204	40 41' 19.16" N	124 13' 11.01" W	396934.14017	4504699.74221	Wildlife Refuge
255	27-Jun-01	1100	40 41' 26.18" N	124 13' 23.45" W	396645.15480	4504920.26193	Wildlife Refuge
256	27-Jun-01	1350	40 41' 11.08" N	124 13' 14.10" W	396858.14924	4504451.60375	Wildlife Refuge
257	2-Jul-01	1020	40 51' 35.02" N	124 09' 01.44" W	403041.22061	4523610.89471	MRS side channels
258	2-Jul-01	1053	40 51' 38.14" N	124 09' 04.55" W	402969.67317	4523708.05879	MRS side channels
259	2-Jul-01	1200	40 51' 42.86" N	124 09' 07.75" W	402896.66976	4523854.58836	MRS side channels
260	2-Jul-01	1200	40 51' 47.96" N	124 09' 11.32" W	402815.16156	4524012.95035	MRS side channels
261	2-Jul-01	1200	40 51' 50.43" N	124 09' 10.50" W	402835.36147	4524088.86162	MRS side channels
262	3-Jul-01	1253	40 42' 50.04" N	124 12' 58.28" W	397271.74111	4507497.87756	Kramers Dock
263	3-Jul-01	1320	40 42' 54.11" N	124 13' 01.80" W	397190.88822	4507624.52013	Kramers Dock
264	3-Jul-01	1350	40 43' 05.72" N	124 13' 06.05" W	397096.13573	4507983.89715	Kramers Dock
265	3-Jul-01	1416	40 43' 11.14" N	124 13' 10.65" W	396990.53089	4508152.52102	Kramers Dock
266	11-Jul-01	1137	40 42' 42.57" N	124 14' 24.27" W	395250.84505	4507295.75430	Fields Landing Channel
267	11-Jul-01	1200	40 42' 41.22" N	124 14' 23.60" W	395265.97858	4507253.90509	Fields Landing Channel
268	11-Jul-01	1230	40 42' 34.47" N	124 14' 31.09" W	395087.28574	4507048.25193	Fields Landing Channel
269	12-Jul-01	1024	40 43' 36.13" N	124 13' 40.09" W	396310.59487	4508932.71402	Fields Landing
270	12-Jul-01	1105	40 43' 47.21" N	124 13' 37.70" W	396371.43749	4509273.58281	Fields Landing
271	12-Jul-01	1145	40 43' 56.08" N	124 13' 38.59" W	396354.38343	4509547.38188	Fields Landing
272	12-Jul-01	1222	40 44' 02.49" N	124 13' 39.13" W	396344.48019	4509745.21197	Fields Landing
273	13-Jul-01	1045	40 44' 36.73" N	124 12' 19.83" W	398219.08922	4510775.22953	Entrance Bay
274	13-Jul-01	1105	40 44' 42.14" N	124 12' 14.07" W	398356.46813	4510940.19335	Entrance Bay
275	13-Jul-01	1119	40 44' 45.31" N	124 12' 11.65" W	398414.56376	4511037.16241	Entrance Bay

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
276	13-Jul-01	1119	40 44' 47.85" N	124 12' 08.83" W	398481.77261	4511114.57726	Entrance Bay
277	13-Jul-01	1203	40 44' 53.19" N	124 12' 05.07" W	398572.20675	4511278.02926	Entrance Bay
278	16-Jul-01	850	40 52' 36.93" N	124 08' 37.04" W	403637.41677	4525512.44795	Mad River Slough
279	16-Jul-01	905	40 52' 34.68" N	124 08' 28.25" W	403846.67511	4525779.57543	Mad River Slough
280	16-Jul-01	945	40 52' 35.53" N	124 08' 24.55" W	403929.1985	4525465.465	Mad River Slough
281	16-Jul-01	1020	40 52' 30.35" N	124 08' 53.00" W	403261.1921	4525314.439	Mad River Slough
282	16-Jul-01	1050	40 52' 26.30" N	124 09' 05.14" W	402975.3898	4525193.286	Mad River Slough
283	16-Jul-01	1140	40 52' 24.03" N	124 09' 06.92" W	402932.8038	4525123.837	Mad River Slough
284	16-Jul-01	1140	40 52' 19.82" N	124 08' 54.13" W	403230.483	4524990.086	Mad River Slough
285	16-Jul-01	1200	40 52' 21.48" N	124 08' 57.66" W	403148.5251	4525042.357	Mad River Slough
286	16-Jul-01	1215	40 52' 18.72" N	124 08' 53.00" W	403256.4892	4524955.82	Mad River Slough
287	17-Jul-01	0858(4.5hr)	40 45' 53.81" N	124 14' 01.09" W	395877.62284	4513185.00630	North Jetty
288	17-Jul-01	0858(4.5hr)	40 45' 52.78" N	124 13' 59.77" W	395908.12481	4513152.81087	North Jetty
289	17-Jul-01	0858(4.5hr)	40 45' 51.38" N	124 13' 57.09" W	395970.35329	4513108.75850	North Jetty
290	17-Jul-01	0858(4.5hr)	40 45' 49.56" N	124 13' 54.85" W	396022.08436	4513051.90071	North Jetty
291	17-Jul-01	0858(4.5hr)	40 45' 48.61" N	124 13' 53.52" W	396052.85661	4513022.16943	North Jetty
292	17-Jul-01	0858(4.5hr)	40 45' 47.73" N	124 13' 52.43" W	396078.03226	4512994.67572	North Jetty
293	17-Jul-01	0858(4.5hr)	40 45' 47.02" N	124 13' 51.51" W	396099.29575	4512972.48001	North Jetty
294	17-Jul-01	0858(4.5hr)	40 45' 46.01" N	124 13' 50.03" W	396133.55966	4512940.84962	North Jetty
295	23-Jul-01	1445	40 48' 23.41" N	124 07' 22.10" W	405291.28165	4517672.32719	Brainard
296	23-Jul-01	1515	40 48' 21.94" N	124 07' 31.35" W	405073.96284	4517629.77847	Brainard
297	23-Jul-01	1515	40 48' 19.94" N	124 07' 52.93" W	404567.52235	4517574.61629	Brainard
298	23-Jul-01	1630	40 48' 21.45" N	124 08' 07.37" W	404229.77643	4517625.55198	Brainard
299	30-Jul-01		40 42' 01.37" N	124 15' 15.20" W	394037.66057	4506042.32143	Southport Channel
300	30-Jul-01		40 42' 01.76" N	124 14' 49.18" W	394648.48114	4506045.65392	Southport Channel

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Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
301	30-Jul-01		40 42' 14.83" N	124 14' 37.50" W	394928.29846	4506444.78107	Southport Channel
302	31-Jul-01	1050(5hr)	40 45' 24.79" N	124 14' 04.91" W	395775.46784	4512291.42708	South Jetty
303	31-Jul-01	1050(5hr)	40 45' 20.46" N	124 14' 01.72" W	395848.39158	4512156.85840	South Jetty
304	31-Jul-01	1050(5hr)	40 45' 15.50" N	124 13' 58.58" W	395919.87265	4512002.88080	South Jetty
305	31-Jul-01	1050(5hr)	40 45' 12.25" N	124 13' 56.13" W	395975.91672	4511901.85939	South Jetty
306	31-Jul-01	1050(5hr)	40 45' 08.40" N	124 13' 54.09" W	396022.08815	4511782.47225	South Jetty
307	31-Jul-01	1050(5hr)	40 45' 06.40" N	124 13' 52.75" W	396052.64613	4511720.36088	South Jetty
308	31-Jul-01	1050(5hr)	40 45' 03.41" N	124 13' 50.81" W	396096.84687	4511627.52545	South Jetty
309	31-Jul-01	1050(5hr)	40 45' 01.81" N	124 13' 49.65" W	396123.35794	4511577.80769	South Jetty
310	6-Aug-01	715	40 48' 49.67" N	124 07' 57.25" W	404478.14345	4518492.65798	North Bay Channels
311	6-Aug-01	720	40 48' 57.99" N	124 07' 56.33" W	404503.01198	4518748.92975	North Bay Channels
312	6-Aug-01	720	40 49' 00.15" N	124 08' 06.72" W	404260.46137	4518818.68288	North Bay Channels
313	6-Aug-01	1041	40 48' 53.73" N	124 08' 20.78" W	403928.49868	4518624.99342	North Bay Channels
314	6-Aug-01	1041	40 48' 48.55" N	124 08' 35.44" W	403582.95983	4518469.73782	North Bay Channels
315	6-Aug-01	1041	40 48' 47.41" N	124 08' 49.91" W	403243.48810	4518439.01482	North Bay Channels
316	7-Aug-01	845	40 49' 47.74" N	124 05' 58.58" W	407280.86409	4520247.86477	North Bay Channels
317	7-Aug-01	915	40 49' 58.79" N	124 05' 48.70" W	407516.54623	4520585.69540	North Bay Channels
318	7-Aug-01	1036	40 49' 07.92" N	124 08' 45.95" W	403344.53576	4519070.23503	North Bay Channels
319	14-Aug-01	1520	40 42' 15.19" N	124 13' 41.55" W	396241.44061	4506437.40743	Hookton Slough Mouth
320	14-Aug-01	1520	40 42' 23.54" N	124 13' 30.67" W	396500.35383	4506691.31378	Hookton Slough Mouth
321	14-Aug-01	1430	40 42' 11.19" N	124 13' 35.80" W	396374.65418	4506312.18221	Hookton Slough Mouth
322	14-Aug-01	1548	40 42' 35.59" N	124 13' 28.99" W	396544.95799	4507062.32533	Hookton Slough Mouth
323	16-Aug-01	1215	40 49' 05.08" N	124 05' 55.96" W	407325.73663	4518931.65834	Spit South of Bracut
324	16-Aug-01	1045	40 49' 24.95" N	124 05' 25.71" W	408042.02441	4519535.50509	Spit South of Bracut
325	16-Aug-01	1045	40 49' 18.31" N	124 05' 29.70" W	407946.00848	4519331.92204	Spit South of Bracut

—continued p. 191

Appendix B. (continued) Sampling locations in Humboldt Bay, Humboldt County, California, visited from September 2000 to November 2001 including geographic coordinates and converted UTMs with a brief location description. Times of seines and trawls are also given. Minnow traps were set for a period of time, given in hours or cycles (24 hours).

Sample #	*Date*	*Time*	*Latitude*	*Longitude*	*Easting*	*Northing*	*Location*
326	16-Aug-01	1215	40 49' 09.09" N	124 05' 49.81" W	407471.36009	4519053.50299	Spit South of Bracut
327	21-Aug-01	855	40 49' 42.20" N	124 07' 06.47" W	405688.51263	4520097.16343	North Bay Channels
328	21-Aug-01	855	40 49' 51.16" N	124 07' 28.87" W	405167.37673	4520380.16473	North Bay Channels
329	21-Aug-01	855	40 49' 37.10" N	124 07' 51.14" W	404640.16352	4519953.33237	North Bay Channels
330	21-Aug-01	855	40 49' 37.06" N	124 08' 08.44" W	404234.91536	4519957.33982	North Bay Channels
331	21-Aug-01	855	40 49' 32.71" N	124 08' 27.46" W	403787.64751	4519828.99323	North Bay Channels
332	22-Aug-01	810	40 50' 18.78" N	124 06' 46.73" W	406165.21717	4521219.23615	North Bay
333	22-Aug-01	842	40 50' 09.40" N	124 07' 14.33" W	405515.13285	4520938.23964	North Bay
334	22-Aug-01	842	40 50' 01.65" N	124 07' 58.05" W	404488.09181	4520712.43326	North Bay
335	22-Aug-01	1012	40 49' 45.51" N	124 08' 31.70" W	403693.47319	4520224.98081	North Bay
336	23-Aug-01	850	40 50' 55.24" N	124 08' 43.83" W	403437.46712	4522378.85004	MRS Channel
337	23-Aug-01	920	40 51' 00.84" N	124 08' 50.19" W	403290.80198	4522553.47846	MRS Channel
338	23-Aug-01	1000	40 50' 12.18" N	124 08' 36.69" W	403587.32575	4521048.88746	MRS Channel
339	30-Nov-01	1336	40 46' 45.24" N	124 11' 51.72" W	398932.45140	4514728.83504	Entrance Bay Trawl Out
340	30-Nov-01	1349	40 47' 03.30" N	124 11' 40.68" W	399198.82204	4515282.19122	Entrance Bay Trawl In
341	30-Nov-01	1402	40 47' 01.26" N	124 11' 41.40" W	399181.08901	4515219.51709	Entrance Bay Trawl Out
342	30-Nov-01	1414	40 47' 22.56" N	124 11' 32.52" W	399398.15854	4515873.47661	Entrance Bay Trawl In
343	30-Nov-01	1430	40 47' 57.30" N	124 11' 19.74" W	399712.20770	4516940.63005	Entrance Bay Trawl Out
344	30-Nov-01	1432	40 48' 19.80" N	124 11' 09.90" W	399952.18123	4517631.30324	Entrance Bay Trawl In
345	30-Nov-01	1520	40 48' 24.42" N	124 11' 09.60" W	399961.13802	4517773.66772	Entrance Bay Trawl Out
346	30-Nov-01	1530	40 48' 45.48" N	124 10' 58.74" W	400224.36265	4518419.62338	Entrance Bay Trawl In

—end Appendix B

Appendix C. Fish species collected by methods other than trawl in the North Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
juvenile flatfish	1	1	40.00	40	40
leopard shark	1	1	281.00	281	281
longjaw mudsucker	1	1	93.00	93	93
chinook salmon	1	2	103.00	104	102
cutthroat trout	1	2	276.00	370	182
juvenile rockfish	1	2	32.00	34	30
penpoint gunnel	2	2	108.50	112	105
pile surfperch	2	2	351.00	378	324
coho salmon	3	3	106.33	127	93
Pacific sardine	1	4	104.75	112	96
bat ray	3	6	282.39	427	150
black rockfish	6	6	53.17	64	43
white surfperch	4	7	75.00	91	61
mosquito fish	2	10	27.00	41	13
tidewater goby	6	18	30.94	48	18
butter sole	7	22	32.75	50	18
bay goby	9	23	63.72	96	0
tubesnout	3	23	109.00	139	93
starry flounder	14	27	99.33	291	24
walleye surfperch	7	27	83.82	213	23
prickly sculpin	10	28	76.28	130	35
speckled sanddab	6	28	48.50	89	22
Pacific herring	8	31	55.98	92	27
saddleback gunnel	12	31	66.97	147	0
plainfin midshipman	7	67	38.86	101	28
English sole	20	177	73.45	153	21
bay pipefish	36	184	157.05	281	37
jacksmelt	10	190	75.03	340	17
arrow goby	56	433	49.57	69	20
Osmerid sp.	37	542	51.78	82	12
surf smelt	41	711	67.71	151	0
staghorn sculpin	104	1589	61.26	166	11
topsmelt	65	2648	76.91	237	20
Northern anchovy	21	4476	69.92	127	32
shiner surfperch	55	5491	64.82	150	36
threespine stickleback	53	11623	38.78	76	0
total		28438			

Appendix D. Fish species collected by trawl in the North Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific herring	1	1	213.00	213	213
brown Irish lord	1	1	125.00	125	125
juvenile rockfish	1	1	0.00	0	0
plainfin midshipman	1	1	50.00	50	50
ringtail snailfish	1	1	42.00	42	42
threespine stickleback	1	1	45.00	45	45
tubesnout	1	1	0.00	0	0
whitebait smelt	1	1	90.00	90	90
California halibut	2	2	506.50	540	473
Pacific sandlance	1	2	84.50	86	83
buffalo sculpin	1	2	93.00	117	69
walleye surfperch	1	2	111.00	116	105
Northern anchovy	1	3	98.67	100	97
night smelt	3	3	81.67	132	0
sandsole	2	3	90.25	100	80
starry flounder	2	3	157.00	280	112
surf smelt	1	3	68.33	71	65
cabezon	2	4	96.00	125	46
longfin smelt	2	4	125.50	128	122
spiny dogfish	1	4	442.00	462	400
saddleback gunnel	4	5	99.00	115	85
showy snailfish	2	5	97.50	165	70
Pacific tomcod	2	7	137.25	164	96
Pacific sanddab	3	12	73.06	114	42
white surfperch	4	17	146.85	160	133
bat ray	3	22	294.37	463	265
topsmelt	4	23	81.66	99	47
juvenile flatfish	7	24	28.53	39	12
speckled sanddab	9	51	90.85	117	51
bay pipefish	8	56	163.07	298	69
staghorn sculpin	11	163	92.59	176	21
English sole	9	1078	93.42	144	34
shiner surfperch	8	1302	96.08	147	75
Osmerid sp.	11	2464	42.83	69	10
total		5272			

Appendix E. Fish species collected by methods other than trawl in the Entrance Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific herring	1	1	63.00	63	63
Pacific sanddab	1	1	20.00	20	20
jacksmelt	1	1	361.00	361	361
kelp greenling	1	1	183.00	183	183
Pacific sandlance	2	2	87.50	99	76
boneyhead sculpin	1	2	81.50	88	75
buffalo sculpin	2	2	103.00	151	55
coho salmon	1	2	101.50	105	98
petrale sole	2	2	35.00	36	34
pile surfperch	2	2	242.50	285	200
rock greenling	1	2	75.50	84	67
sharpnose sculpin	2	2	50.50	61	40
penpoint gunnel	3	3	128.33	162	105
tubesnout	2	5	143.42	197	114
walleye surfperch	4	5	69.63	78	61
bay goby	1	7	31.57	39	17
cabezon	2	7	103.25	163	45
striped surfperch	4	7	105.08	200	51
juvenile rockfish	2	9	55.29	86	30
sandsole	7	9	73.38	95	32
butter sole	1	12	31.58	44	20
shiner surfperch	4	13	112.58	141	85
threespine stickleback	6	19	47.82	68	16
spotfin surfperch	6	24	150.59	189	54
starry flounder	11	43	134.27	285	52
bay pipefish	11	58	175.70	324	127
English sole	9	73	77.97	150	35
chinook salmon	12	86	96.01	119	70
redtail surfperch	11	96	130.86	212	56
black rockfish	5	99	54.73	63	44
silver surfperch	7	121	60.75	82	52
speckled sanddab	6	134	70.52	110	22
staghorn sculpin	25	498	79.10	242	14
Osmerid sp.	14	728	50.21	65	32
surf smelt	28	1817	80.23	153	48
topsmelt	18	3206	94.93	231	37
total		7099			

Appendix F. Fish species collected by trawl in the Entrance Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
California halibut	1	1	760.00	760	760
brown Irish lord	1	1	96.00	96	96
buffalo sculpin	1	1	65.00	65	65
curlfin turbot	1	1	101.00	101	101
juvenile rockfish	1	1	67.00	67	67
sharpnose sculpin	1	1	54.00	54	54
spiny dogfish	1	1	395.00	395	395
Pacific sanddab	1	2	103.50	111	96
Pacific sardine	2	2	132.00	148	116
Pacific tomcod	2	2	172.00	215	129
night smelt	3	3	120.67	128	110
redtail surfperch	1	3	241.33	281	180
sandsole	1	3	45.00	65	30
butter sole	1	4	96.00	109	82
cabezon	4	4	114.75	282	41
whitebait smelt	2	4	117.84	143	109
surf smelt	1	5	11.80	125	93
longfin smelt	2	7	126.75	131	120
threespine stickleback	5	11	68.83	81	45
staghorn sculpin	4	18	115.84	207	36
bay pipefish	7	24	151.29	211	80
Osmerid sp.	6	30	31.67	60	0
tubesnout	7	35	125.47	165	97
speckled sanddab	10	37	56.07	116	27
English sole	6	65	76.33	230	18
shiner surfperch	6	122	100.10	135	75
Pacific sandlance	7	229	83.64	99	76
total		617			

Appendix G. Fish species collected by methods other than trawl in the South Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
Pacific sandlance	1	1	131.00	131	131
calico surfperch	1	1	179.00	179	179
chinook salmon	1	1	98.00	98	98
copper rockfish	1	1	36.00	36	36
gopher rockfish	1	1	76.00	76	76
juvenile rockfish	1	1	28.00	28	28
lingcod	1	1	78.00	78	78
medusa fish	1	1	79.00	79	79
sharpnose sculpin	1	1	57.00	57	57
steelhead	1	1	126.00	126	126
fluffy sculpin	2	2	43.50	53	34
penpoint gunnel	1	2	135.00	137	133
red Irish lord	1	2	62.00	64	60
redtail surfperch	1	2	91.50	92	91
striped surfperch	1	3	85.33	97	78
bay goby	2	4	41.00	44	39
bat ray	3	5	482.11	900	335
brown Irish lord	1	5	62.40	79	48
prickly sculpin	3	6	57.33	76	46
cabezon	5	8	125.70	214	80
saddleback gunnel	5	8	94.30	141	69
tidewater goby	2	8	47.50	64	37
white surfperch	3	9	118.71	196	62
pile surfperch	2	10	206.28	330	60
walleye surfperch	3	11	95.61	148	76
kelp greenling	5	14	84.56	115	64
speckled sanddab	6	17	63.36	81	35
Northern anchovy	10	18	53.03	121	0
starry flounder	12	32	109.92	278	36
black rockfish	6	34	62.45	74	49
Pacific sardine	3	40	94.95	132	81
arrow goby	16	41	52.68	63	38
butter sole	1	60	23.03	32	8
bay pipefish	11	71	186.72	295	58
leopard shark	3	87	738.74	1219	300
jacksmelt	9	95	251.82	372	79
English sole	16	185	60.41	117	32

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Appendix G. (continued) Fish species collected by methods other than trawl in the South Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Points	Abundance	Average AVG	Maximum MAX	Minimum MIN
tubesnout	7	248	132.44	219	96
Pacific herring	14	411	49.28	86	25
topsmelt	36	978	110.57	337	17
shiner surfperch	27	1173	74.25	155	37
Osmerid sp.	18	1437	51.98	100	30
staghorn sculpin	48	1870	57.48	154	20
surf smelt	53	2474	78.94	428	25
threespine stickleback	43	4001	58.82	137	17
total		13381			

Appendix H. Fish species collected by trawl in the South Bay of Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Average, maximum and minimum lengths were obtained using table queries in ArcMap and are given here under columns Average AVG, Maximum MAX and Minimum MIN. All measurements are total length in millimeters.

SPECIES	No. of Trawls	Abundance	Average AVG	Maximum MAX	Minimum MIN
brown smoothhound	1	1	600.00	600	600
starry flounder	1	1	372.00	372	372
Northern anchovy	1	2	127.00	142	112
juvenile rockfish	1	2	99.50	105	94
white surfperch	1	2	138.50	142	135
speckled sanddab	2	3	92.75	97	90
night smelt	2	5	119.50	136	102
staghorn sculpin	2	14	139.68	161	110
walleye surfperch	2	17	137.15	191	101
English sole	2	40	97.94	133	77
shiner surfperch	2	50	110.80	140	89
total		137			

Appendix I. Dates, locations, and water quality measurements for threespine sticklebacks collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to the location (see Gleason, Appendix B). Dissolved oxygen (DO readings are in milligrams per liter (mg/L), salinity readings are in parts per thousand (ppt), and temperature is in C°.

Date	Sample No.	DO	SALINITY	TEMPERATURE
15 Sept	1		28	22
15 Sept	2		28	25
4 Oct	20	11.50	16	18
11 Oct	21	7.80	34	16
13 Oct	23	10.04	35	17
19 Oct	26	9.01	35	13
26 Oct	40	9.45	35	13
27 Oct	43	8.23	34	15
29 Oct	44	6.22	29	15
13 Nov	51	7.78	34	10
1 Feb	79	8.82	31	11
15 Feb	89	8.92	31	10
16 Feb	91	8.02	25	10
20 Feb	94	8.23	24	11
9 March	109	7.89	21	15
27 March	143	7.40	27	16
10 April	160	9.53	31	17
12 April	162	7.10	26	15
17 April	166	8.46	24	15
24 April	167	7.08	31	16
24 April	169	7.08	30	17
26 April	177	7.04	31	18
1 May	184	7.07	32	13
1 May	185	8.04	32	12
1 May	186	9.45	21	18
1 May	187	10.92	22	20
1 May	189	10.30	21	18
3 May	192	10.94	21	20
8 May	197	7.32	31	17
8 May	198	6.85	35	19
8 May	201	7.11	36	22
29 May	218	6.38	35	25
29 May	219	6.26	31	15
13 June	228	5.57	34	16
19 June	237	7.97	33	18
19 June	239	6.65	34	17

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Appendix I. (continued) Dates, locations, and water quality measurements for threespine sticklebacks collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to the location (see Gleason, Appendix B). Dissolved oxygen (DO) readings are in milligrams per liter (mg/L), salinity readings are in parts per thousand (ppt), and temperature is in C°.

Date	Sample No.	DO	SALINITY	TEMPERATURE
19 June	240	6.60	34	17
27 June	254	6.70	32	182
27 June	256	6.45	32	18
2 July	257	7.12	33	20
2 July	261	6.13	34	23
3 July	262	6.13	34	23
3 July	265	13.36	33	24
11 July	267	5.96	33	15
11 July	268	12.43	33	16
12 July	270	3.19	33	15
12 July	271	7.21	33	15
16 July	284	6.69	34	20
23 July	297	9.66	36	27
30 July	299	9.11	33	19
30 July	301	8.67	33	17
14 August	320	6.36	34	21
22 August	333	5.21	34	19
30 Nov	342	6.00	33	19

Appendix J. Dates, locations, and water quality measurements for staghorn sculpin collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleaon, Appendix B). Dissolved oxygen (DO) readings are given in milligrams per Liter (mg/L), salinity readings are given in parts per thousand (ppt), and temperature readings are given in C°.

Date	Sample No.	DO	SALINITY	TEMPERATURE
25 Sept	13	7.00	35	16
1 Oct	15	6.00	34	15
11 Oct	22	8.02	34	16
13 Oct	23	10.04	35	17
19 Oct	26	9.01	35	13
23 Oct	28	17.92	34	19
23 Oct	36	9.00	32	15
26 Oct	39	9.5	35	13
27 Oct	43	8.23	34	15
29 Oct	44	6.22	29	15
3 Nov	49	8.43	33	14
5 Nov	50	9.45	34	14
13 Nov	51	7.78	34	10
17 Jan	68	10.24	31	11
23 Jan	73	8.75	31	11
28 Jan	76	8.39	33	10
30 Jan	77	9.11	32	12
30 Jan	78	8.87	31	10
1 Feb	79	8.82	31	11
10 Feb	83	8.84	32	11
11 Feb	85	8.34	32	11
13 Feb	86	8.36	32	12
15 Feb	89	8.92	31	10
16 Feb	91	8.02	25	10
22 Feb	97	8.89	27	11
27 Feb	101	8.54	29	11
27 Feb	103	9.49	28	15
5 March	104	9.55	31	13
8 March	107	8.79	21	12
9 March	109	7.89	21	15
15 March	128	9.00	8	12
15 March	130	9.58	9	13
19 March	131	7.58	15	17
20 March	133	6.97	26	14
20 March	137	5.40	32	16

—continued p. 201

Appendix J. (continued) Dates, locations, and water quality measurements for staghorn sculpin collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleason, Appendix B). Dissolved oxygen (DO) readings are given in milligrams per Liter (mg/L), salinity readings are given in parts per thousand (ppt), and temperature readings are given in C°.

Date	Sample No.	DO	SALINITY	TEMPERATURE
21 March	142	6.31	28	13
27 March	143	7.40	27	16
27 March	144	7.92	28	17
27 March	143	7.32	25	16
4 April	148	6.05	30	11
4 April	151	5.37	30	12
5 April	152	8.80	32	14
10 April	159	7.75	31	13
10 April	160	9.53	31	17
12 April	162	7.10	26	15
17 April	166	8.46	24	15
24 April	167	7.08	31	16
24 April	172	5.62	21	17
26 April	174	9.55	0.6	13
26 April	177	7.04	31	18
1 May	184	7.07	32	13
1 May	187	10.92	22	20
1 May	189	10.3	21	18
3 May	192	10.94	21	20
10 May	205	6.90	35	20
10 May	211	5.87	35	25
29 May	219	6.26	31	15
30 May	220	6.67	33	15
30 May	221	6.77	33	15
5 June	222	6.33	35	16
5 June	223	6.16	36	16
13 June	228	5.57	34	16
13 June	230	5.72	33	15
18 June	232	6.74	37	17
19 June	237	7.97	33	18
19 June	239	6.65	34	17
19 June	240	6.60	34	17
25 June	250	6.70	33	15
26 June	253	5.27	33	18
27 June	254	6.70	32	182

—continued p. 202

Appendix J. (continued) Dates, locations, and water quality measurements for staghorn sculpin collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleason, Appendix B). Dissolved oxygen (DO) readings are given in milligrams per Liter (mg/L), salinity readings are given in parts per thousand (ppt), and temperature readings are given in C°.

Date	Sample No.	DO	SALINITY	TEMPERATURE
27 June	256	6.45	32	18
2 July	257	7.12	33	20
2 July	261	6.13	34	23
3 July	262	6.13	34	23
3 July	265	13.36	33	24
11 July	268	12.43	33	16
16 July	278	7.42	33	15
16 July	280	5.86	34	20
23 July	297	9.66	36	27
30 July	299	9.11	33	19
30 July	301	8.67	33	17
6 August	310	3.89	35	19
6 August	313	5.48	34	21
6 August	315	5.06	34	22
7 August	317	4.13	34	20
14 August	320	6.36	34	21
16 August	326	6.51	34	17
21 August	328	6.13	34	17
22 August	333	5.21	34	19
22 August	334	6.79	33	19
30 Nov	342	6.00	33	19
30 Nov	346	8.00	28	12

—end Appendix J

Appendix K. Dates, locations, and lengths of shiner surfperch collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleason, Appendix B) Average lengths were obtained using table queries in ArcMap and are given here under column Average AVG. All measurements are total length in millimeters.

Date	Sample No.	Abundance	Average AVG	Abundance by Month
25 Sept	5	1025	105.44	
25 Sept	9	16	108.31	
25 Sept	11	11	91.45	
25 Sept	13	11	110.00	1063
1 Oct	15	25	111.64	
1 Oct	17	25	109.96	
11 Oct	21	1	80.00	
12 Oct	24	1	85.00	
23 Oct	30	8	91.25	
23 Oct	32	38	99.22	
23 Oct	34	8	98.88	
23 Oct	36	17	95.18	
23 Oct	38	48	96.32	
27 Oct	43	3	91.67	174
17 Jan	69	1	85.00	1
13 March	113	1	99.00	1
17 April	164	1	132.00	1
8 May	200	34	132.92	
8 May	202	3	103.33	
10 May	209	3	123.33	
29 May	219	6	40.67	
30 May	221	1	44.00	47
13 June	228	12	68.42	
14 June	229	4	51.50	
15 June	230	1	53.00	
18 June	232	80	62.12	
18 June	233	107	53.62	
18 June	234	72	51.28	
18 June	235	59	49.64	
18 June	236	45	50.68	
19 June	237	6	86.00	
19 June	238	1	122.00	
19 June	239	1	57.00	
19 June	240	821	56.20	
19 June	241	13	115.62	

—continued p. 204

Appendix K. (continued) Dates, locations, and lengths of shiner surfperch collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleason, Appendix B). Average lengths were obtained using table queries in ArcMap and are given here under column Average AVG. All measurements are total length in millimeters.

Date	Sample No.	Abundance	Average AVG	Abundance by Month
25 June	246	7	126.57	
25 June	250	1	122.00	
26 June	251	207	50.79	
26 June	252	780	59.12	
26 June	253	1188	70.16	
27 June	254	33	52.88	
27 June	255	3	74.00	
27 June	256	18	70.50	3463
2 July	257	156	52.85	
2 July	258	153	56.63	
2 July	259	172	54.12	
2 July	260	30	57.28	
2 July	261	16	54.00	
3 July	262	84	48.28	
3 July	263	11	48.73	
3 July	264	1	100.00	
3 July	265	6	84.00	
11 July	266	1	53.00	
11 July	267	49	54.92	
11 July	268	1	46.00	
12 July	270	1	45.00	
12 July	272	1	113.00	
16 July	278	63	57.93	
16 July	279	39	57.88	
16 July	280	73	67.92	
16 July	281	41	69.24	
16 July	282	111	64.52	
16 July	283	69	67.44	
16 July	284	40	58.68	
16 July	285	49	66.64	
16 July	286	143	53.85	
23 July	295	1	114.00	
23 July	296	1	97.00	
23 July	297	23	68.22	
30 July	299	35	64.42	

—continued p. 205

Appendix K. (continued) Dates, locations, and lengths of shiner surfperch collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001. Sample No. refers to location of collection (see Gleason, Appendix B). Average lengths were obtained using table queries in ArcMap and are given here under column Average AVG. All measurements are total length in millimeters.

Date	Sample No.	Abundance	Average AVG	Abundance by Month
30 July	300	4	52.50	1374
6 August	310	18	78.00	
6 August	311	22	54.05	
6 August	312	79	55.68	
6 August	313	218	73.20	
6 August	314	465	74.56	
6 August	315	144	75.52	
7 August	316	56	58.72	
7 August	317	211	63.36	
7 August	318	239	59.16	
14 August	319	5	61.00	
14 August	320	6	82.33	
14 August	321	27	64.44	
16 August	323	36	67.88	
16 August	324	25	76.36	
16 August	326	30	69.40	
21 August	327	48	55.94	
21 August	328	6	58.50	
21 August	329	15	60.73	
21 August	330	4	62.00	
21 August	331	41	61.84	
22 August	332	56	75.00	
22 August	333	11	71.91	
22 August	334	8	59.63	
22 August	335	7	59.29	
23 August	336	3	65.67	
23 August	337	1	56.00	
23 August	338	6	68.33	1787
30 Nov	340	29	96.76	
30 Nov	342	54	95.07	
30 Nov	344	48	92.78	
30 Nov	346	110	89.56	241

—end Appendix K

Appendix L. Family, specific and common names for all species collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001.

Family	Species	Common Name
Squalidae	*Squalus acanthias*	Spiny dogfish
Carcharhinidae	*Triakis semifasciata*	Leopard shark
	Mustelus henlei	Brown smoothound
Myliobatididae	*Myliobatis californica*	Bat Ray
Clupeidae	*Clupea harengus pallasi*	Pacific herring
	Sardinops sagax	Pacific sardine
Engraulidae	*Engraulis mordax*	Northern anchovy
Salmonidae	*Oncorhynchus clarkii*	Cutthroat trout
	Oncorhynchus mykiss	Steelhead
	Oncorhynchus tshawytscha	Chinook salmon
	Oncorhynchus kisutch	Coho salmon
Osmeridae	*Hypomesus pretiosus*	Surf smelt
	Allosmerus elongatus	Whitebait smelt
	Spirinchus starksi	Night smelt
	Spirinchus thaleichthys	Longfin smelt
		unidentified juveniles
Batrachoididae	*Porichthys notatus*	Plainfin midshipman
Gaddidae	*Microgadus proximus*	Pacific tomcod
Atherinidae	*Atherinopsis californiensis*	Jacksmelt
	Atherinops affinis	Topsmelt
Poeciliidae	*Gambusia affinis*	Mosquitofish

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Appendix L. (continued) Family, specific and common names for all species collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001.

Family	Species	Common Name
Gasterosteidae	*Aulorhynchus flavidus*	Tubesnout
	Gasterosteus aculeatus	Threespine stickleback
Syngnathidae	*Syngnathus leptorhynchus*	Bay pipefish
Scorpaenidae	*Sebastes caurinus*	Copper rockfish
	Sebastes melanops	Black rockfish
	Sebastes carnatus	Gopher rockfish
	Sebastes sp.	unidentified juveniles
Hexagrammidae	*Ophiodon elongatus*	Lingcod
	Hexagrammos decagrammus	Kelp greenling
	Hexagrammos superciliosus	Rock greenling
Cottidae	*Scorpaenichthys marmoratus*	Cabezon
	Hemilepidotus spinosus	Brown Irish lord
	Hemilepidotus hemilepidotus	Red Irish lord
	Leptocottus armatus	Pacific staghorn sculpin
	Enophrys bison	Buffalo sculpin
	Artedius notospilotus	Bonehead sculpin
	Oligocottus snyderi	Fluffy sculpin
	Clinocottus acuticeps	Sharpnose sculpin
	Cottus asper	Prickly sculpin
Liparididae	*Liparis pulchellus*	Showy snailfish
	Liparis rutteri	Ringtail snailfish
Embiotocidae	*Amphistichus koelzi*	Calico surfperch
	Amphistichus rhodoterus	Redtail surfperch
	Hyperprosopon anale	Spotfin surfperch
	Hyperprosopon argenteum	Walleye surfperch

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Appendix L. (continued) Family, specific and common names for all species collected within Humboldt Bay, Humboldt County, California, from September 2000 to November 2001.

Family	Species	Common Name
Embiotocidae	*Hyperprosopon ellipticum*	Silver surfperch
	Cymatogaster aggregata	Shiner surfperch
	Embiotoca lateralis	Striped surfperch
	Damalichthys vacca	Pile surfperch
	Phanerodon furcatus	White surfperch
Pholidae	*Apodichthys flavidus*	Penpoint gunnel
	Pholis ornata	Saddleback gunnel
Ammodytidae	*Ammodytes hexapterus*	Pacific sandlance
Gobiidae	*Eucyclogobius newberryi*	Tidewater goby
	Gillichthys mirabilis	Longjaw mudsucker
	Lepidogobius lepidus	Bay goby
	Clevelandia ios	Arrow goby
Centrolophidae	*Icichthys lockingtoni*	Medusafish
Bothidae	*Paralichthys californicus*	California halibut
	Citharichthys sordidus	Pacific sanddab
	Citharichthys stigmaeus	Speckled sanddab
Pleuronectidae	*Pleuronichthys decurrens*	Curlfin turbot
	Psettichthys melanostictus	Sand sole
	Parophrys vetulus	English sole
	Isopsetta isolepis	Butter sole
	Platichthys stellatus	Starry flounder
	Eopsetta jordani	Petrale sole
		unidentified juveniles

—end Appendix L

How They Came, Why They Will Stay: Introduced Species in Humboldt Bay

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Entrance to Humboldt Bay. ©2002 Kenneth and Gabrielle Adelman—http://www.californiacoastline.org/; (p. 211) ©2001 Joe DiTomaso.

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During this survey, we collected and identified 97 species that are possibly nonindigenous marine species (NIS) in Humboldt Bay. There were representatives from most major groups of organisms, ranging from vascular plants to fish. The largest number of species is found in various invertebrate groups, including polychaetes (24), amphipods (20), and bryozoa (8). Previous studies in Humboldt Bay (Barnhart et al. 1992) were not focused on identification and enumeration of introduced species, but many of the NIS found in this study have been reported in that earlier work.

A number of introduced species have been in Humboldt Bay for a long time, some cases going back to the first settlement of the region by Europeans in the mid-1800s. Almost immediately following initial settlement, maritime trade began, with shipping of lumber and lumber products to all parts of the world. Sometime in the 1860s, the most abundant plant of Humboldt Bay salt marshes, *Spartina densiflora*, was brought into the bay from South America, probably as shingle or dry ballast (Barnhart et al. 1992).

Spartina densiflora.

Intentional introductions have also accounted for a number of species that are numerous in the bay. Beginning in the 1890s, efforts to introduce and grow oysters were pursued all along the California coast (Bonnot 1935). Attempts to grow Eastern and European oysters failed, but Japanese oysters were successfully introduced into Humboldt Bay. A significant commercial aquaculture activity continues around the planting, growth and harvesting of Japanese oysters. The seed oysters for this species are produced in Puget Sound and shipped in bags to Humboldt Bay. We identified one species of algae, previously unreported from Humboldt Bay, which has probably arrived from Puget Sound in this manner.

Other examples of species that were introduced intentionally include the Eastern soft shell clam (*Mya arenaria*) and the Japanese cockle (*Venerupis phillippinarium*). However, unintentional introductions also occurred. Early methods of transporting marine organisms from one area to another might take several days and packing in wet algae was commonly used to retard dessication. Numerous small, inconspicuous juveniles of other species might be concealed among the algae or attached to its blades. In this manner, small polychaetes or crustaceans were inadvertently introduced when the algal material was tossed into the bay.

We included in this study species that are clearly the result of introductions and those that have been characterized as cryptogenic (Cohen and Carlton 1995; Carlton 1996a). Cryptogenic species are organisms that appear to be widespread in bays, ports, and estuaries of the world and cannot be identified as definitely native or exotic to a particular region. Carlton (1996b) has proposed that many of these species are the result of maritime trade and other human activity that go back hundreds of years. Some cryptogenic species occurrences are the result of intentional or unintentional introductions that are lost in time and history. Others are of uncertain relationship to species that have a wide range of occurrence but may be genetically distinct in parts of their range. In yet others, their present-day occurrence is merely an indication of their capacity to adapt to a wide range of environmental conditions. Of the 97 species that we identified as possible introductions to Humboldt Bay, 11 are probably cryptogenic, while an additional 13 species may fall into that category.

We compared the occurrence of introduced species in Humboldt Bay to their occurrence mentioned in previous studies done along the Pacific coast of North America (Cohen and Carlton 1995; Ruiz et al. 2000). In particular, we compared the reported occurrence of species in San Francisco Bay to the south and in Coos Bay, Oregon to the north. Of the 97 species in Humboldt Bay, 31 have been reported from all three bays, 23 species in San Francisco and Humboldt Bays, but no species that were found only in Coos and Humboldt Bays. Twenty-seven of the introduced species we report are found only in Humboldt Bay. These data on co-occurrence suggest that San Francisco Bay could be an important source area for introductions to Humboldt Bay, a finding consistent with ship and small boat traffic moving between these two locations. The 27 species that appear to be found only in Humboldt Bay suggests that there may be factors such as shipping or other human influences that are unique to the bay.

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The full report submitted to the California Department of Fish and Game may be found in Appendix II and online at http://www.dfg.ca.gov/ospr/about/science/misp.html

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Succession in a Humboldt Bay Marine Fouling Community: The Role of Exotic Species, Larval Settlement and Winter Storms

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Abstract

The initiation and pattern of succession in a marine "fouling" community was observed on a set of 20 black plastic panels suspended horizontally underneath the docks at Woodley Island Marina, Humboldt Bay, California, from August 2001 to May 2003. The role of recruitment in the development of this community was examined using a second set of 20 panels, which were scraped clean each month to allow new larvae to settle. Each month, both "undisturbed" and "settlement" panels were digitally photographed, and the percent cover of all species occupying at least 2% cover on each photo was recorded. Approximately 54 species of motile and sessile organisms were identified from these photos, of which roughly 35% were exotic species.

The "undisturbed" fouling community was characterized by seasonal pulses of fast-growing, short-lived species (e.g., colonial tunicates) combined with the persistent accumulation of longer-lived, slower-growing species (e.g., mussels, sponges and tubiculous amphipods). The initial phases of development were dominated by colonial and solitary ascidians, bryozoans and hydroids, almost all of which were introduced to Humboldt Bay. Rainstorms, which brought fresh water and heavy sediment loads into the bay each winter, appeared to lead to the sudden disappearance of many of these suspension feeders. Over time, mussels, sponges and tubiculous amphipods gradually increased in their abundance, perhaps due to their tolerance to heavy sediment loads.

In conclusion, the "fouling" community in Humboldt Bay is heavily influenced by non-native taxa, many of which disappear following repeated winter storms, leading to sudden increases in free space. Concurrent increases in sedimentation after winter storms appear to select for slow-growing, tolerant species (e.g., mussels) that may form a "climax" community over a longer temporal scale.

Myxicola infundibulum

Introduction

The intentional or accidental introduction of "exotic" species by humans is one of the leading causes of the biodiversity crisis (Wilcove et al. 1998). The release of larvae from the hulls and ballast tanks of ships from distant ports, the dumping of algal "packing material" (with associated species) when shipping live organisms for human consumption, and the deliberate introduction of non-native shellfish species for aquaculture have all contributed to an accelerated homogenization of species in coastal marine habitats. As a result, estuarine habitats such as San Francisco Bay (Carlton 1979) are among the most threatened ecosystems in the world (Carlton and Geller 1993). Further knowledge of the mechanisms used by exotic species to invade new locales, and whether particular types of communities repel or facilitate their arrival, is clearly needed.

The functional role that successful invaders have on future ecosystem function in marine habitats has been largely unexplored. Invasive species can potentially out-compete native populations and drive them to local extinction. This may in turn affect higher trophic levels (e.g., commercial or sport fisheries), as witnessed by the collapse of the anchovy fishery in the Black Sea from the introduction of an exotic comb jelly (Kideys 2002). Likewise, sessile marine invertebrates attached to ship hulls, docks and other man-made structures often feed on suspended plankton during both their larval and adult phases, and therefore their growth and/or survivorship may reflect changes in planktonic communities within a bay. Benthic-pelagic coupling of communities could have implications for commercial operations, such as the rearing of oysters for human consumption. A baseline study of marine "fouling" communities, for example, might establish important biological indicators of early changes in the "health" of a bay or estuary.

In this study we report on preliminary data from an ongoing effort to monitor the settlement, growth and subsequent establishment of "fouling" communities under the Woodley Island Marina in Humboldt Bay, California. Because of Humboldt Bay's location between San Francisco Bay and Coos Bay, Oregon, it receives substantial shipping traffic from fishing vessels traveling up and down the U.S. West Coast, as well as larger, ocean-going vessels traveling from ports as far away as Japan. A study by Boyd et al. (2002) has shown that a substantial number (97) of exotic species currently reside within Humboldt Bay. These exotics represent several major phyla ranging from vascular plants to fish. The largest numbers of invasive species, however, are from various invertebrate taxa including polychaetes (24 species), amphipods (20 species) and bryozoans (8 species). Some of the invasive species identified by Boyd et al. (2002) were likely to have been introduced long ago, from dry ballast or "shingle" on wooden ships in the mid-1800s. The most abundant salt marsh cordgrass, *Spartina densiflora*, was probably introduced in this way to Humboldt Bay from South America sometime in the 1860s. Since its introduction, *S. densiflora* has become the dominant cordgrass species within Humboldt Bay.

For the majority of introduced marine species living in Humboldt Bay, little is known about their natural role within the bay ecosystem. Our work represents one of the first attempts to record the presence of native and exotic species under docks in Humboldt Bay, and to investigate their relative ecological role within fouling communities on man-made structures within the bay.

Man-made structures are increasingly common elements along the shoreline of bays and estuaries and may even represent novel habitats for marine invertebrates (Connell 2000). Many of them, including pier pilings and floating docks, have a luxuriant growth of marine invertebrates on them. These systems are relatively easy to study because of their ease of access, and deployment of experiments and data-gathering methods do not require SCUBA gear. Field experiments can address the ongoing debate concerning factors governing time-dependent patterns of succession, such as whether succession leads to alternative stable states or "climax" communities (Sutherland 1974; Petraitis and Dudgeon 2004). More applied concerns, including whether exotic species affect local fisheries and other commercial activities, can be examined.

Specifically, the goals of this study are to: (1) describe the pattern of settlement and succession in invertebrate "fouling" communities within Humboldt Bay, (2) evaluate the relative importance of native and exotic species as space occupiers within this system, and (3) determine the variability in community structure through time.

Long-term goals include (1) identification of water-column factors that might influence community structure and perhaps reflect the "health" of the bay, (2) establish methods for the early detection of exotic species introductions, and (3) field test recently developed theory on the mechanisms of succession in epifaunal marine communities.

Methods

Site

Recruitment and community development of fouling invertebrates were observed on artificial plastic panels suspended below the south breakwater dock at Woodley Island Marina, Humboldt Bay, California. Because this marina receives heavy traffic from commercial fishing boats and pleasure craft, it is a likely site for exotic species to first appear within the bay. Woodley Island Marina is the largest marina within Humboldt Bay, comprising a series of nine (30–70 ft) floating docks oriented perpendicular to the shoreline. These large docks extend into North Bay channel, one of two channels connecting North Bay and Eureka Slough with the entrance channel into Humboldt Bay.

Site Characteristics

Precipitation patterns within Humboldt Bay are highly seasonal and rainfall amounts vary from year to year (Figure 1). Water temperature within the bay varies daily with tidal flow and cloud cover, and both seasonal and annual patterns are detectable with mean low values ~ 9.0 °C and mean highs ~ 18.0 °C. Intermittent salinity measurements taken at panel depth along the dock ranged from a low of 19 ‰ during periods of high rainfall, to a high of ~ 34 ‰ during high tides (data not shown). North Bay water surrounding Woodley Island was visibly turbid from sediment loading following periods of high rainfall, and often remained turbid for days at a time, despite tidal flushing.

Fouling panels

Two sets of artificial fouling panels were deployed on rectangular frames constructed of 1-in.-diameter polyvinyl chloride pipe (PVC). Each frame measured 150 x 50 cm, and held 20 (15 x 10 x 0.65 cm) ABS black plastic sheets (panels), individually engraved for identification and attached with stainless steel bolts and wing nuts. The panel replicates were evenly spaced on each frame and randomly reattached to the alternate frame after each sampling.
A vertical section of the frame was affixed to the dock side with galvanized pipe brackets and screws; panels were oriented horizontally, face-down, and submerged directly beneath the "shade" of the dock at a depth of 1 m. Position effects along the dock were avoided by alternating among designated frame-attachment locations.

Settlement

The first frame with 20 panels, deployed February 2001, was designed to record newly arrived recruits of various marine invertebrates. These "settlement" panels were monitored for monthly and seasonal larval settlement and used to detect species introductions as well as reproductive periods of sessile invertebrates in Humboldt Bay. All "settlement" panels were scraped clean and soaked in fresh water after each census to ensure free substrate was continuously available for settlement of marine larvae each month.

Community Development

The second set of 20 panels, deployed July 2001, was designed to follow the development of "undisturbed" sessile marine communities. Panels in this set were sampled in a non-destructive manner by taking photographs to record the settlement, growth and mortality of sessile species through time. Monthly census of this "undisturbed" set coincided with the settlement set. Sampling the two sets simultaneously allowed insights from seasonal time comparisons of recruitment and growth within the developing "undisturbed" community.

Panel Census Methods

Data were recorded at Telonicher Marine Laboratory (TML), Trinidad, California. At 4–6 week intervals, both panel sets were retrieved from the dock and suspended within plastic containers of fresh seawater. These containers were brought to TML where the panels were maintained face-up in circulating filtered seawater (FSW) tables. Care was taken during the retrieval and handling process to avoid long periods out of water or physical loss of sessile species. Each panel was digitally photographed using Nikon® Coolpix 990 or 995 cameras.

Corresponding panel and image numbers were recorded along with notes describing important trends. Photographs captured the whole panel so that species-specific coverage of occupied space could be accounted for in a systematic manner. In addition to whole panel images, "close-up" pictures were taken through an Olympus® SZ9 Microscope by a stem-mounted DP11 2.5 mega-pixel digital camera. This helped to identify adults and newly settled individuals and provided a closer look at species interactions during community development. Panels were typically returned to Humboldt Bay within 24 hours of their removal.

Analysis of Digital Photographs

Photographs of "undisturbed" panels were analyzed by computer. Each digital photo was overlaid with a 5x5 rectangular grid created in Adobe® Photoshop 6.0. Percent cover data was recorded for all species occupying at least 2% of observable space. Coverage estimates frequently exceeded 100% due to multi-level growth. Summary statistics and graphs of percent cover data were produced in SigmaPlot® 8.0. It should be noted that because some species were cryptically hidden underneath a thick canopy of hydroids, bryozoans and other fouling invertebrates, it is likely that some species were missed.

Results

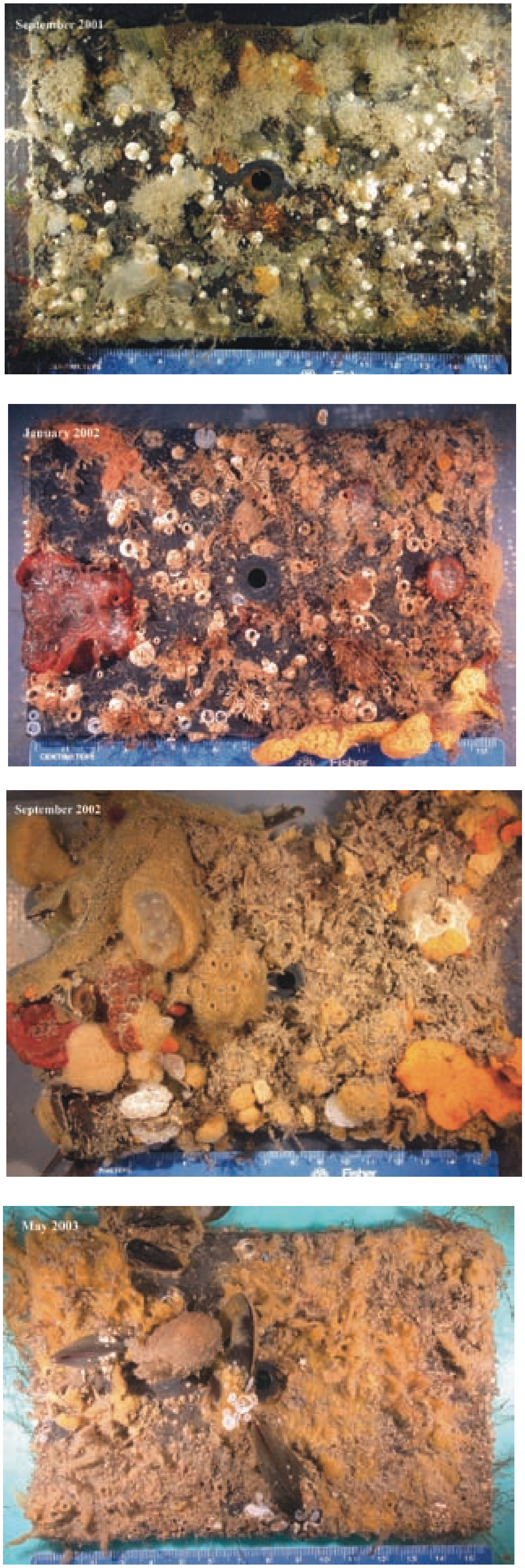
Organisms

More than 54 species of marine invertebrates from seven different phyla were identified from photographs taken during the sampling period. Exotic species accounted for ~ 34% of all species (both motile and sessile) identified from these photos (see Table 1 for a list of sessile species). Motile invertebrates were identified only if they were clearly visible in digital photos; caprellids, chitons and nudibranchs were regularly observed feeding on sessile organisms attached to the panels, but were often found hidden beneath a canopy of hydroids, bryozoans and feather duster worms. Because photographs only captured the overstory or canopy layer of fouling communities that developed on our panels, total species richness is underestimated. Destructive sampling of several fouling panels each month is needed to produce a more complete species list. This would require a much larger number of fouling panels in the "undisturbed" treatment.

Settlement

Several of the most conspicuous species displayed seasonal pulses of settlement varying dramatically within and between years (Figure 2a–c). Recruitment levels were higher during summer and fall; little or no settlement was observed during winter months.

The hydroid *Obelia dichotoma* and bryozoan *Celleporella hyalina*, both exotic species, were present most months of the study. *Obelia* peaked in abundance in May 2001 and again in March 2003. *Celleporella* settled in 2001 during the months of May, August and November, and peaked in abundance on settlement panels in October 2002. Colonial tunicates demonstrated



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Caption: (Left) Successive images of a single fouling panel, deployed under the Woodley Island Marina in Humboldt Bay, California, over a period of three years. (Top) In September 2001, this panel was covered by colonial bryozoans (primarily *Bugula californica*) and solitary barnacles (*Balanus crenatus*), with a few encrusting ascidians (*Botrylloides* sp. and *Botryllus tuberatus*) present. (Second) Following winter storms in January 2002, most of the "overstory" in this community (especially colonies of *Bugula*) disappeared and many of the barnacles died. However, two colonies of the bright red invasive bryozoan *Watersipora subtorquata* appear. (Third) Eight months later in September 2002, one of the two colonies of *Watersipora* was completely overgrown, while the second was surrounded by colonial ascidians (*Diplosoma macdonaldi* and *Distaplia occidentalis*). At this point, a large percentage of the panel was occupied by sponges and the fine, muddy tubes of *Corphium*. (Bottom) Another eight months later, in May 2003, these colonial ascidians have disappeared, leaving the panel primarily covered with sponges (through which some of the original barnacles can be seen) and a few large mussels.

comparatively strong settlement during summer and early fall months (Figure 2a–c). *Botrylloides* settled heaviest from June through August 2001 and again from July through September 2002. *Botryllus* settled in the early fall months of October 2001 and September 2002, although it did not comprise more than 10% cover on any occasion. In 2001, both *Distaplia occidentalis* (July) and *Diplosoma macdonaldi* (October) recruited heavily, dominating nearly half the space on settlement panels. Nevertheless, recruitment levels for these two species resulted in less than 20% cover during the same months in 2002. In contrast, settlement numbers were low for the solitary tunicate *Ciona intestinalis* during fall 2001 and 2002.

Two large pulses of recruitment from the barnacle *Balanus crenatus* occurred during October 2002 and May 2003 (Figure 2c). These peaks, representing close to 40% cover, are remarkable given that a newly metamorphosed barnacle comprises less than 0.5% cover. Prior to these peaks, settlement of *B. crenatus* was extremely low, even during the same months in 2001.

The barnacle, *Balanus crenatus.*

Community Development

The initial composition of the "undisturbed" panel set, deployed in July 2001, was characterized by a steady accumulation of competitive, fast growing colonial tunicates (Figure 3a,b). *Diplosoma macdonaldi* and *Botrylloides* sp. dominated most of the space after two months of development. *Diplosoma* peaked in abundance at 30% cover in September and then rapidly declined in October, failing to reach that level in any of the remaining months of the study. As *Diplosoma* growth subsided there was a rise in the abundance of *Botrylloides* (in October) that lasted until December. *Ciona intestinalis*, originally from the East Coast of the United States, followed on the heels of these two species, peaking at almost 25% cover in November. This peak in *Ciona* coverage resulted from dramatic growth of a few individuals, with some reaching 5 in. or more in length and covering a substantial portion of the fouling panels.

The encrusting bryozoan *Watersipora subtorquata*, a recently observed introduction to Humboldt Bay, settled and expanded on the panels from October through November 2001. *Watersipora* maintained up to 10% coverage through March 2002. We have observed this species forming large (6–8 in.-diameter) lettuce-like "heads" on the new Eureka municipal docks located across the channel from Woodley Island Marina. *Watersipora* declined rapidly in abundance after April 2002 at the study site.

Winter months were characterized by heavy rain, sedimentation and turbid waters with decreased settlement and growth of any new individuals in the fouling community. There was a noticeable increase in free space on the panels following large storm events (Figure 1), resulting from the disappearance of *Botrylloides*, *Ciona* and other tunicates. The hydroid *Obelia dichotoma* appeared soon after these storms and colonized any available space. *Obelia* maintained ~18% coverage from January through July 2002.

During spring months, *Balanus crenatus* recruitment to the undisturbed panels was low and never occupied more then 5% cover. Tube-dwelling amphipods, *Corophium* sp., formed clusters of tubes from fine sediment grains accumulating on panel surfaces after winter storms. These crustaceans increased on the panels from January to April 2002 and remained throughout the study. *Botrylloides* reappeared in the spring to occupy 35% of the undisturbed fouling panels. Their rapid peak in abundance was followed by a steady decline through spring 2003.

The sponge *Halichondria bowerbanki*, an exotic species, first appeared in April 2002 on the "undisturbed" panels. Its coverage increased through December 2002, dropped off in January, and recovered in spring of 2003.

There were strong pulses of recruitment and growth from *Ciona intestinalis*, *Watersipora subtorquata* and a new colonial tunicate, *Distaplia occidentalis*, during the fall of 2002.

Throughout the study, dominant organisms in the community were observed arriving in short pulses of recruitment that typically occurred within a single month. These species were very competitive and overgrew any previous occupants. Beneath these ephemeral species, several disturbance-resistant taxa, including the sponge *Halichondria bowerbanki*, the tube-forming amphipod *Corophium* sp. and the mussel *Mytilus trossulu*s (data not shown) gradually increased their substrate occupancy over time (Figure 3b). In contrast to repeated seasonal dominance by fast growing, short-lived species, these durable slow-growing forms were persistent. Recent observations of these same "undisturbed" panels (July, 2004) show continued dominance by the mussel *M. trossulus* and the sponge *H. bowerbanki* (Janiak, pers. obs.), demonstrating they are capable of persisting for at least several years on these panels.

Discussion

Roughly 35% of the species identified from this study were introduced from various areas of the worlds' oceans. These introduced species play a critical role in the development of the fouling communities in Humboldt Bay. The initial phases of community development on "undisturbed" panels, for example, were dominated by colonial and solitary ascidians, bryozoans and hydroids, almost all of which were introduced to Humboldt Bay. In addition, some of the late successional species, including *Watersipora subtorquata* and *Halichondria bowerbanki*, are also introduced. It is therefore impossible to know what the "native" communities within Humboldt Bay should look like.

It is notable that other fouling studies have shown very similar patterns of succession, often with the very same species, in other localities (e.g., Dean 1981; Mook 1981). Most of the hard-substrates available for settlement by sessile marine invertebrates and algae within Humboldt Bay are man-made structures, like those that stabilize the shores within the bay (e.g., rip-rap that lines the entrance channel and other areas within the bay) or those that have been introduced for aquaculture (e.g., the Japanese oyster *Crassostrea gigas*). Studies by Connell (2000, 2001) have shown that within Sydney Harbor, Australia, new urban structures may facilitate the invasion of new taxa. Our own observations on the newly constructed municipal floating docks in Humboldt Bay also suggest this may occur. We have seen greater abundances and much larger colonies of the newly discovered bryozoan *Watersipora subtorquata* at these docks relative to those seen at the Woodley Island Marina. This pattern may represent a temporal correlation between the deployment of these new floating docks and the arrival of *Watersipora*.

Introduced species contributed disproportionately to the development of the fouling community on docks at Woodley Island Marina. This community is characterized by seasonal pulses of fast-growing, short-lived species (e.g., colonial tunicates), combined with the persistent accumulation of longer-lived, slower growing species (e.g., mussels, sponges and tubiculous amphipods). Ephemeral species frequently grew over and on mussels and other longer-lived species, forming a "canopy" layer that showed dramatic changes in percent cover from month to month. Winter storms, which transported both fresh water and heavy sediment loads through the channel adjacent to the Woodley Island Marina, appeared to lead to the sudden disappearance of weedy suspension feeders, including colonial tunicates and bryozoans. Most of these species are exotic and can be found in bays and estuaries on both the Pacific and Atlantic Coasts of the United States, where they inhabit docks and pier pilings in a wide range of salinities. This tolerance of fluctuating salinity makes it more likely that the sudden declines in abundance, following winter storms, may be due to mortality from heavy sedimentation on the "undisturbed" panels. These conditions can effectively clog the suspension feeding organs of many sessile invertebrates (Maughan 2001).

Although both the "undisturbed" and "settlement" panels initially reflected a pulse in settlement by tunicates, later changes in the dominance of species on "undisturbed" panels did not necessarily reflect pulses in recruitment. Initial settlement by the colonial sea squirts *Diplosoma* and *Botrylloides* onto the "undisturbed panels" lead to brief dominance by these species in September and October, whereas fairly low (<5% cover) recruitment by the solitary tunicate *Ciona* was followed by rapid growth, and subsequent dominance by a small number of individuals (25% cover on panels) in November, 2001. A peak in recruitment of the barnacle *Balanus crenatus* seen on "settlement" panels in October 2002 did not result in an increase in percent cover of this species in subsequent months. Osman and Whitlatch (1995) found that the major affect that resident adults have on the recruitment of settling larvae in a developing benthic community is to prevent them from taking over space. In addition, increases in percent cover are not always driven by prior settlement. An increase in the establishment of *Botrylloides* on "undisturbed" panels in May 2002 did not appear to be caused by heavy settlement of this species. Thus, increases in percent cover can be due to apparently "sudden" increases in growth by colonies, which may be present yet hidden below an upper "canopy." In conclusion, dominance on "undisturbed" panels was not always driven by settlement processes, which changed in importance over the course of succession.

Similar studies of marine fouling communities have also shown the importance of settlement changes during the successional process. Field (1982) found that the species that initially settled on panels suspended in the Damariscotta River in Maine were different from those that settled in older, more mature communities. He concluded that species that settled first altered the community, facilitating the recruitment of later species which otherwise may not have invaded.

Chalmer (1982) also found that species selectively settled into different aged fouling communities on asbestos panels immersed near Garden Island, Western Australia. Most species in his study settled on young panels because they had little structure and considerable free space. In contrast, the mussel *Mytilus edulis* was able to settle freely on both young and old panels, and Chalmer (1982) suggested that the ability of *Mytilus* to settle in established communities was the reason for its ultimate dominance as a "climax species."

Dean (1981) found that mimicking the physical structure supplied by sessile organisms, such as colonial tunicates, hydroids and barnacles, facilitated the settlement of the mussel *Mytilus edulis*, which in turn pre-empted settlement by other species. Observations made in July 2004 of our "undisturbed" panels indicate that the mussel *Mytilus trossulus* is steadily increasing its percent cover over time, along with increases in the sponge *Halichondria bowerbanki* and tubiculous amphipods. Gradual increase in *M. trossulus* abundance, despite any sign of recruitment of this species onto "settlement" panels, may stem from preferential settlement into established communities with pre-existing structure. Alternatively, the relative absence of mussel predators, such as motile crabs and sea stars, may enable mussels to outcompete other species (Enderlein and Wahl 2004). Although mussels may not settle in high numbers, their persistence could be due to their ability to tolerate heavy sedimentation following winter storms, as well as their ability to settle in established communities. We hypothesize that mussels, sponges and tubiculous amphipods will form the eventual "climax community" on our panels if given enough time. These species appear to dominate the floating docks at Woodley Island Marina.

Seasonal declines in abundance, seen in some of the dominant occupiers of space (including *Botrylloides* sp., *Botryllus* sp., *Ciona intestinalis*, *Watersipora subtorquata*, and *Obelia dichotoma*), could be due to either natural history variation or variation in water conditions in the bay. Short life spans, for example, could lead to synchronized senescence amongst a "cohort" of individuals that recruited simultaneously. Such a phenomenon could lead to sudden apparent "mortality" at different times of the year. While we cannot rule out natural senescence as an explanation for the sudden decline in percent cover of *Botrylloides*, *Ciona* and *Halichondria* in January 2002 and 2003, these declines are correlated with high rainfall levels (Figures 1 and 3). It is unclear whether low salinity or increased sedimentation levels from rainstorms is responsible for these sudden disappearances. However, Dybern (1967) showed that *Ciona* is tolerant of a wide range of salinities, and many exotic species have a euryhaline distribution. Therefore, we suggest that deposition of fine sediments, along with reduced salinity from freshwater runoff, are the primary agents of disturbance responsible for the decline of many species in this fouling community. Repeated disturbances may ultimately influence the composition of fouling communities at Woodley Island Marina by favoring "disturbance tolerant" taxa.

In conclusion, this study shows that the diverse community of sessile marine invertebrates that "foul" docks within Humboldt Bay is a highly dynamic system that changes markedly from month to month. Pulses of recruitment, rapid growth and sudden mortality characterize this system. Nevertheless, this community may be gradually approaching a less diverse state dominated by a few species, including the mussel *Mytilus trossulus*, the sponge *Halichondria bowerbanki* and the tubiculous amphipod *Corophium* sp. Persistent cover by a few dominant taxa may provide secondary substrate for more opportunistic species to settle on during high-recruitment months, masking a stable set of species in the understory.

Because many of the species identified on our panels (~35%) are non-native, it is clear that Humboldt Bay is not immune to invasion by exotic species. In fact, it is likely that this process has been occurring since the mid-

1800s, although it is unclear if the number of exotic species has increased exponentially, as has been seen in San Francisco Bay (Carleton and Geller 1993). Clearly, further study over a longer time span is necessary to determine whether a "climax" community is attained, and whether this community can repel further invasion by exotic species. In addition, the role of sediment deposition in these communities appears to be an important source of disturbance that may drive this system.

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Figures and Table

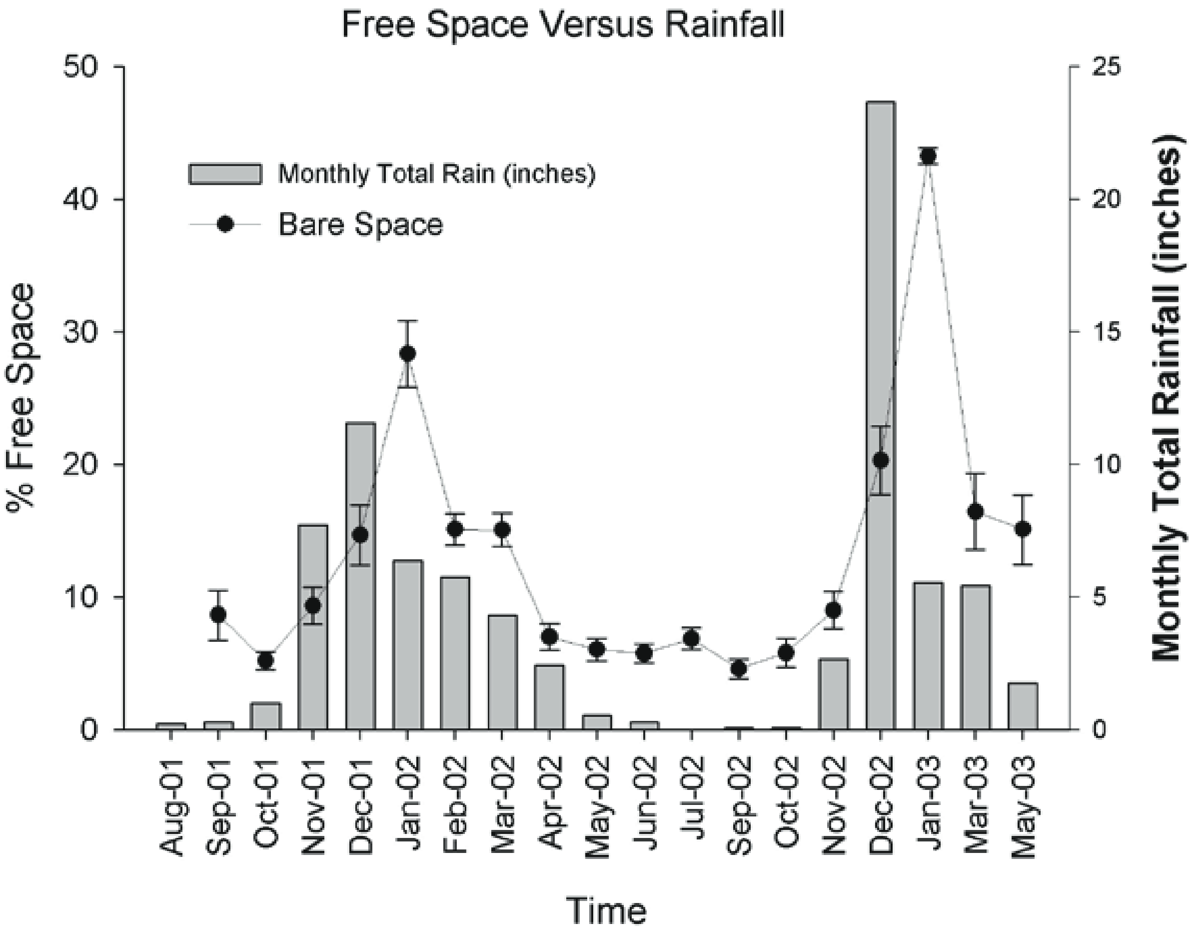
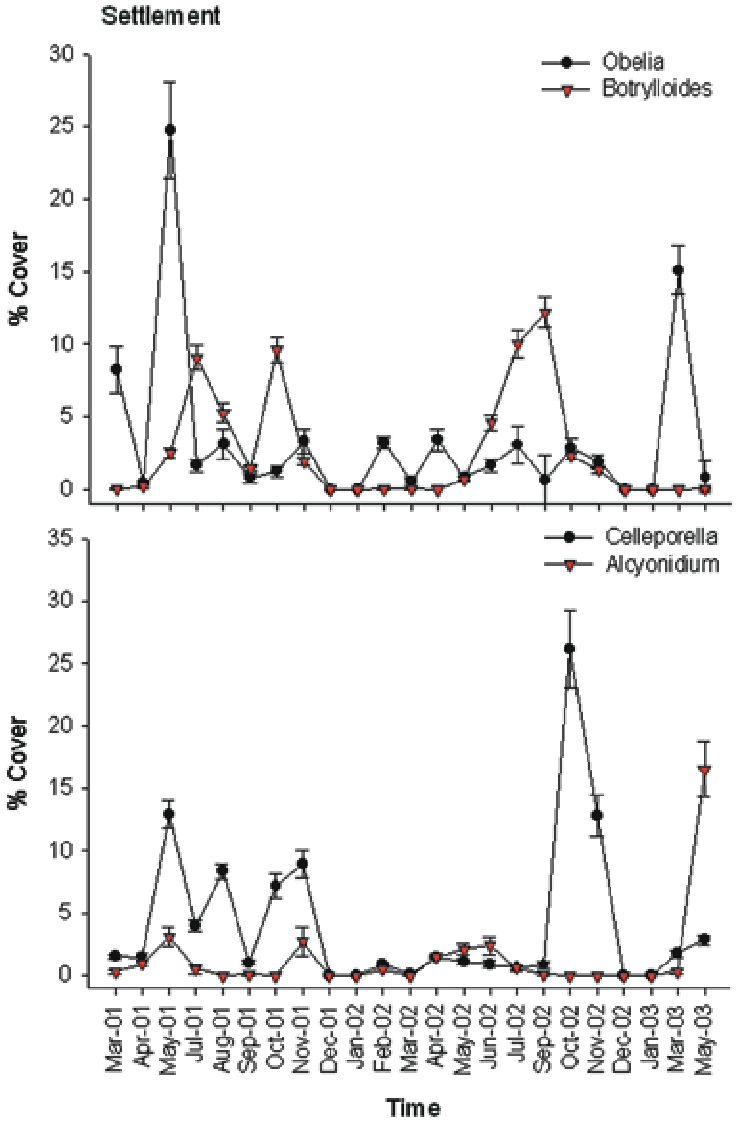


Figure 1. Plot of the average % free space (± 1 S.E.) on "undisturbed" fouling panels at Woodley Island Marina, Humboldt Bay, California. Rainfall data plotted represent the sum of monthly rainfall amounts (in inches) August 2001–May 2003, obtained from the National Weather Service.

a.



Settlement

Figure 2a. Mean percent cover (± 1 S.E.) of subtidal invertebrates on settlement panels over time at Woodley Island Marina, Humboldt Bay, California. Graphs present settlement data for frequently recorded species during the sampling period (March 2001–May 2003).

b.

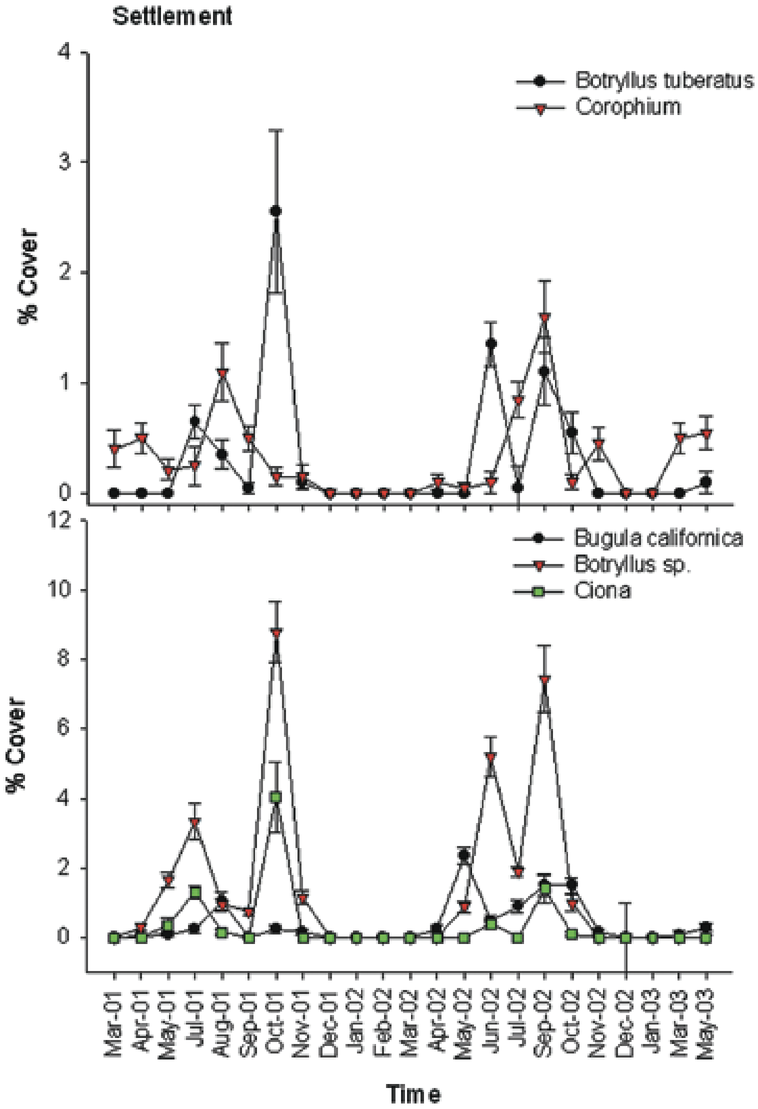


Figure 2b. Mean percent cover (± 1 S.E.) of subtidal invertebrates on settlement panels over time at Woodley Island Marina, Humboldt Bay, California. Graphs present settlement data for frequently recorded species during the sampling period (March 2001–May 2003).

c.

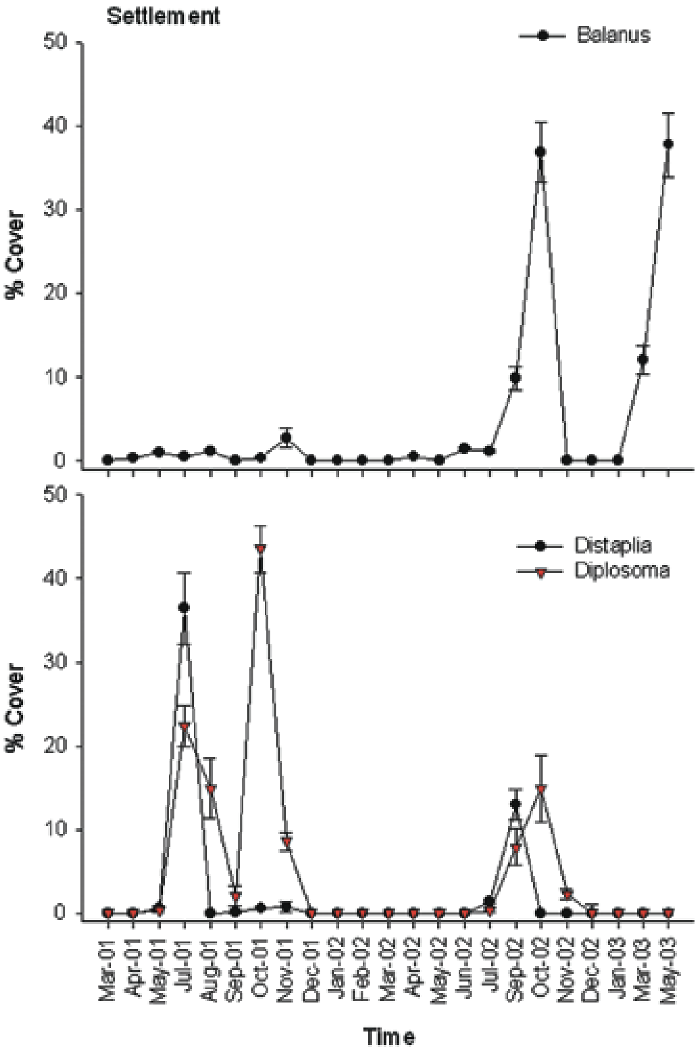


Figure 2c. Mean percent cover (± 1 S.E.) of subtidal invertebrates on settlement panels over time at Woodley Island Marina, Humboldt Bay, California. Graphs present settlement data for frequently recorded species during the sampling period (March 2001–May 2003).

a.

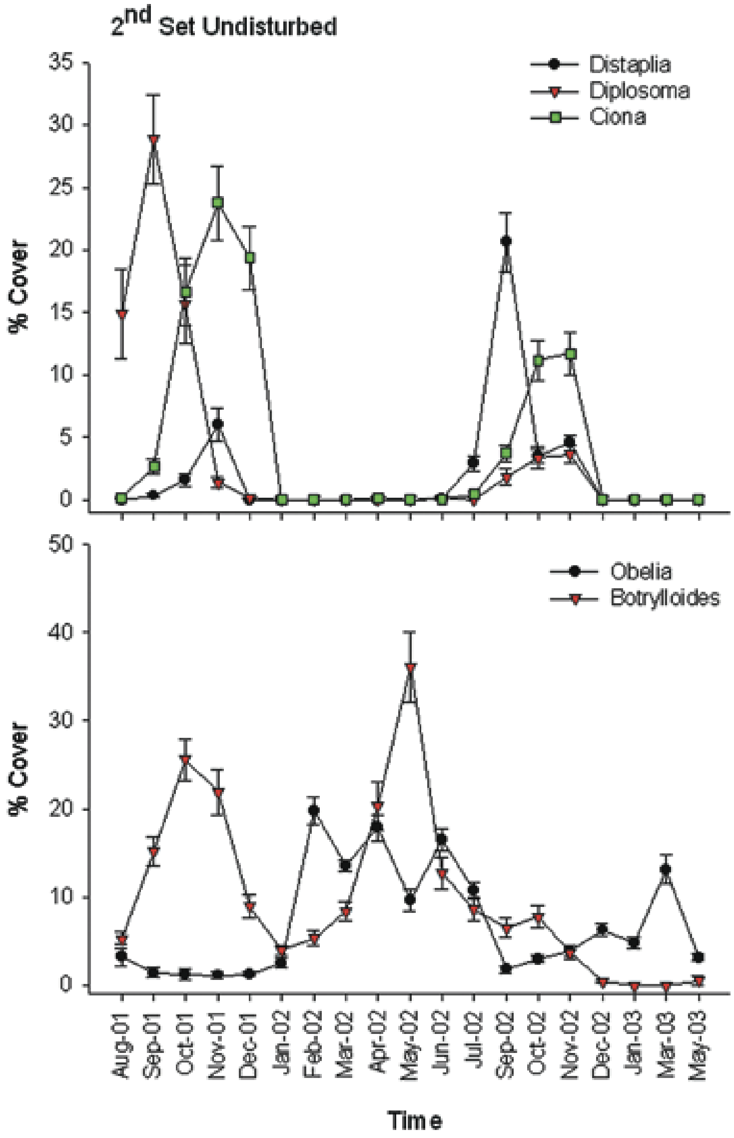


Figure 3a. Mean percent cover (± 1 S.E.) of subtidal invertebrates on undisturbed fouling panels over time at Woodley Island Marina, Humboldt Bay, California. Graphs present the more common species occupying space on panels during the sampling period (August 2001–May 2003).

b.

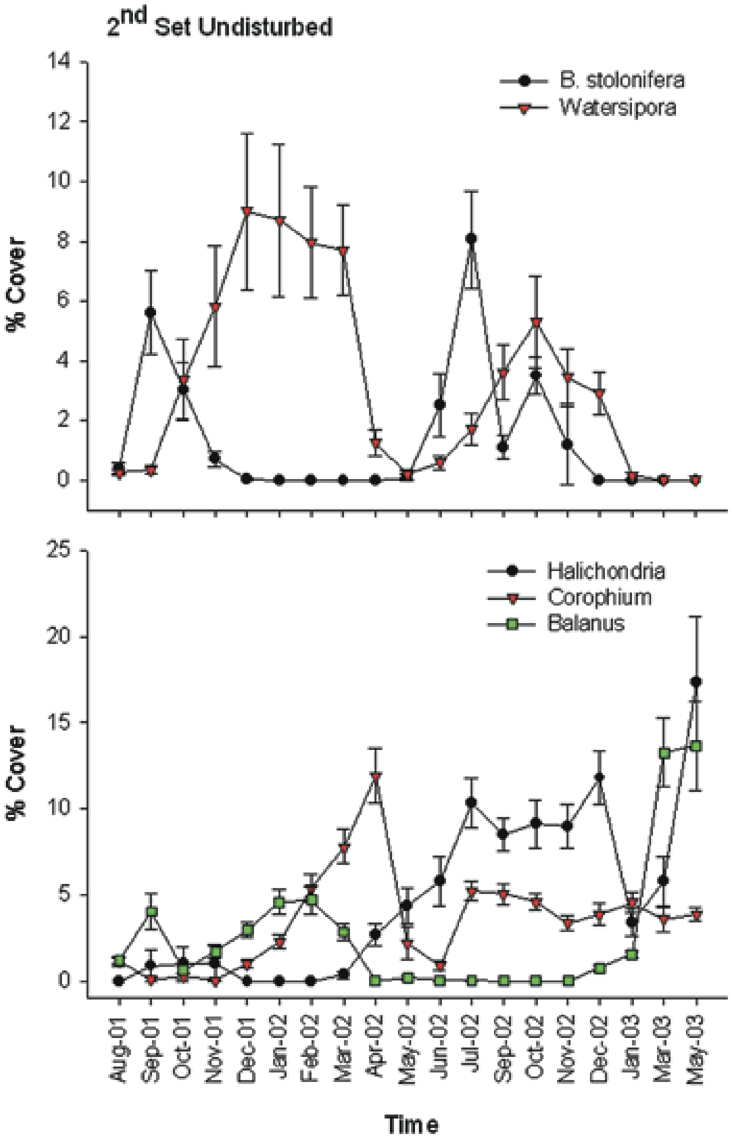


Figure 3b. Mean percent cover (± 1 S.E.) of subtidal invertebrates on undisturbed fouling panels over time at Woodley Island Marina, Humboldt Bay, California. Graphs present the more common species occupying space on panels during the sampling period (August 2001–May 2003).

Table 1. Sessile invertebrate fouling species identified from photographs of panels deployed under the Woodley Island Marina, Humboldt Bay, California. E = Exotic; N = Native. (Note: understory species were not sampled, so this list is not exhaustive)

Porifera	
Halichondria bowerbanki	E
Haliclona sp.	N
Cnidaria	
Obelia dichotoma	E
Tubularia crocea	N
Plumularia setacea	N
Diadumene leucolena	E
Metridium senile	N
Polychaeta	
Schizobranchia insignis	N
Eudistylia vancouveri	N
Myxicola infundibulum	E
Bivalvia	
Mytilus trossulus	N
Pododesmus cepio	N
Crustacea	
Balanus crenatus	N
Balanus nubilus	N
Bryozoa	
Alcyonidium polyoum	E
Celleporella hyalina	E
Bugula californica	N
Bugula stolonifera	N
Bugula neritina	E
Bowerbankia gracilis	E
Watersipora subtorquata	E
Schizoporella unicornis	E
Scrupocellaria diagenesis	N
Urochordata	
Botrylloides sp.	E
Botryllus sp.	E
Botryllus tuberatus	E
Ciona intestinalis	E
Mogula manhattensis	E
Styela clava	E
Diplosoma macdonaldi	N
Distaplia occidentalis	N
Pyura haustor	N

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Enhancing Seasonal Wetlands in the Coastal Zone: A Regulatory Constraint Analysis of the California Coastal Act[1]

Aldaron Laird[2]

Photo Credits

(Above) Pacific Earthquake Engineering Research, UC Berkeley;
(p. 239) Department of Biology, San Diego State University; (p. 240) Eric Secker;
(p. 245) U.S. Fish and Wildlife Service;
(p. 249) Natural Resources Conservation Service, USDA.

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1. Introduction

Some members of California's "restoration community" believe that the efforts and costs required to secure authorization from the California Coastal Commission (Commission) to enhance seasonal coastal wetlands are so onerous and the process so obscure that many people do not pursue grant funding to enhance seasonal coastal wetlands in the Coastal Zone.

The restoration community has identified four factors that contribute to this dilemma. (1) The California Coastal Act (Act) places priority on "recovering" tidelands that were diked, drained and filled more than a century ago (whenever feasible and when it is the least environmentally damaging option) rather than on improving existing freshwater wetlands on land created by dikes. (2) The Act places priority on re-establishing former wetlands rather than on improving the quality of existing wetlands. (3) The Commission requires compensatory mitigation for wetland-enhancement projects that are proposed solely to increase the quality and/or quantity of wetlands. Such projects are "self mitigating" and should not require compensatory mitigation. And, (4) the Commission narrowly interprets the state and federal "no-net-loss" of wetland areas policies, which severely limits opportunities to enhance the functions and values of existing wetlands. The requirement to reduce wetland habitat area by placing fill, when the sole purpose of the project is to enhance wetlands, should be balanced against improving habitat functions and values.

A primary goal of this paper is to help project proponents of seasonal freshwater wetland-enhancement projects understand the Act's regulatory and the Commission's administrative priorities and constraints that may affect approval of applications for Coastal Development Permits (CDP). Members of the Northern California Component of the Pacific Coast Joint Venture (PCJV 2004) hope that if project proponents have such knowledge when applying for wetland-enhancement projects, it will assist Commission staff in their evaluation of and recommendations for Commission approval of such projects.

2. Framing the Problem

California's Coastal Act of 1976 (Act) protects existing coastal wetlands (Public Resource Code [PRC] § 30000 et seq.; see Appendix 6.1). The PCJV, as does the Act, aspires to improve the overall quality of natural and artificial coastal wetlands (PRC § 30001.5), a goal that if achieved would benefit us all. Improving the quality of a wetland can be achieved by increasing its *functions* (what it does), the *processes* (physical, chemical, biological aspects of how it performs) or *values* (those characteristics resulting directly or indirectly from its function that are perceived by society as desirable and worthy of protection, or those characteristics that contribute to the habitat quality of the resident biota). The methods accepted in restoration ecology to improve wetland habitat are:

1. **restore:** re-establish historic functions and values of a former wetland;
2. **enhance:** increase the size and/or improve functions and values of an existing wetland;
3. **create:** establish a new, self-sustaining wetland in an upland area.

The Commission staff face an administrative "albatross" when evaluating wetland restoration or enhancement projects for compliance. The Act interprets any immediate construction action (e.g., diking, filling, excavating), regardless of its purpose, as "development" (PRC § 30106) that will require a CDP (PRC § 30600), even if that action is necessary to complete a wetland restoration or enhancement design. To secure a CDP, any action that might cause adverse environmental effects must, if feasible, be mitigated (PRC § 30233 [a]). The wetland-enhancement proponent/permit seeker is thus faced with the curious dilemma of having to mitigate for restoring or enhancing a wetland. Unfortunately, many enhancement projects cannot overcome the compensatory mitigation hurdle, or the paradox, and are abandoned.

Fortunately, the Act provides guidance to resolve this paradox and to achieve its basic goals, which are to "*protect, maintain, and, where feasible, enhance and restore the overall quality of the coastal zone environment and its natural and artificial resources*" (PRC § 30001.5 [a]). The Act also can resolve conflicting policies by seeking a balance that is the most protective of significant coastal resources (PRC § 30007.5). When assessing a project whose sole purpose is restoration or enhancement, Commission staff should weigh the net benefit derived from such activities and conclude that these activities, when balanced, are beneficial and therefore are "self-mitigating" and do not warrant compensatory mitigation.

In California, PCJV partners face significant challenges in complying with the Act when proposing to enhance coastal freshwater wetlands. For former tidelands that are diked, the Act favors restoring freshwater wetlands back to tidelands rather than allowing freshwater wetland enhancement. Freshwater coastal wetlands created on diked former tidelands shall, according to the Act, be restored to tidal influences where feasible (PRC § 30230), i.e., if there are no physical, economic or political impediments. However, these impediments do exist at many sites or on surrounding lands making restoration infeasible, or risking greater adverse environmental effects than enhancing existing seasonal freshwater wetlands. Consequently, such sites are better suited to enhancing existing freshwater wetlands.

Another significant challenge the PCJV faces in enhancing existing freshwater wetlands is the Commission's interpretation of California's Wetlands Conservation Policy (Executive Order W59-93), commonly referred to as the "no-net-loss" of wetlands policy. One goal of this policy is to "*Ensure no overall net loss and achieve a long-term net gain in the quantity, quality, and permanence of wetlands acreage and values in California …*" Although "overall" was meant to qualify "no net loss," this policy is generally applied as a strict prohibition against net loss of area for every wetland. Rather, "overall" implies some latitude or balancing is permissible in order to achieve a long-term net gain of wetland quality in California, which is the goal of enhancement. Likewise, the federal "no-net-loss" policy (Executive Order 11990; see Appendix 6.2) is often cited in support of an outright prohibition on any net loss of wetland acreage. But it also allows for balance by stating "*in order to avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands … wherever there is a practicable alternative … .*"

When the sole purpose of a project is enhancement of wetland functions and values, there is likely no practicable alternative to achieving the project's purpose. The federal policy goes on to encourage enhancing the natural and beneficial values of wetlands. Ironically, the federal policy states that it does not apply to issuance of federal agency permits or allocations to private parties for activities involving wetlands on nonfederal property (see Appendix 6.2), yet it is routinely applied to private parties who propose to enhance wetlands. Lastly, in support of a more balanced approach to apply these orders, neither the Act nor the federal Coastal Zone Management Act of 1972 (16 U.S.C. 1451 et seq.) has been amended to incorporate a "no-net-loss" policy.

Enhancement of an existing wetland can often result in some loss of wetland acreage, while restoration of a former wetland or creation of a new wetland generally does not. The Commission's application of the "no-net-loss" policy fails to value the benefits of enhancing function or value over a net loss in acreage. It is important to note that function may not be directly related to acreage (Commission 1995). Thus the opportunity to improve an existing, degraded wetland is often discouraged by the Commission's application of the "no-net-loss" policy. Therefore, the wisdom of strictly adhering to a narrow interpretation of this policy must be questioned. This is particularly important as current expectations of successfully improving wetland quality by increasing its functions and values may be greater, or realized sooner, when enhancing an existing wetland as opposed to either attempting to restore a historic wetland or creating an entirely new one.

In support of enhancement, the Commission's procedures (p. 1-8, Commission 1994) encourages staff to work with what exists, because wetlands are hard to restore and even harder to create, and recommends that compensatory mitigation not be required (p. 9-1, Commission 1995).

Determining which diked former tidelands are feasible for restoration to tidal functions would identify those freshwater wetlands that are best suited for enhancement. In most instances completely removing or breaching a dike is not feasible if adjacent lands, roads or infrastructure would become inundated with salt water; therefore, in those situations it is often necessary to relocate the dike or build a new one. Naturally, on those lands where it is not feasible to restore tidal functions, PRC § 30230 would not apply and enhancing existing freshwater wetlands would be the appropriate option.

3. Coastal Act Regulations that can Constrain Enhancement of Coastal Wetlands

The PCJV's promotion of coastal wetland-enhancement projects is primarily affected by the application of the following: PRC § 30106, 30519, 30121, 30230, 30231, 30233 (a)(c), 30600 (a)(e), and 30607.1. How the application of these sections may constrain enhancement of coastal wetlands is discussed below.

3.1. Coastal Development Permit Jurisdiction—PRC § 30106, 30519, and 30600 (a)(e)

For purposes of habitat enhancement or restoration projects, development can be defined simply as any proposed action that will involve physical disturbances or a change in the intensity of land or water use within the Coastal Zone (PRC § 30106).

Nearly all proposed enhancement or restoration projects in the Coastal Zone, with few exceptions, will need to secure a CDP (PRC § 30600 [a], [e]). A CDP is issued by one of two entities: the Commission who retains jurisdiction on all submerged lands, tidelands, and public trust lands such as diked former tidelands (PRC § 30519 [b]), or local land-use authorities such as a county or city who have jurisdiction pursuant to their certified Local Coastal Program on all other lands within the Coastal Zone (PRC § 30519 [a]). Those non-federal or nonstate projects residing on lands under local land-use authority will have to apply for a CDP to these authorities, and not the Commission.

Local authorities, in addition to issuing a CDP, also control use on all lands except those that are federal or state-owned. Most local land-use authorities have identified land uses that are permitted, i.e., do not need a use permit, uses that must be conditionally approved—usually via a planning commission—while all other uses not identified are prohibited.

Typically, habitat enhancement and restoration projects are required to secure a Conditional Use Permit (CUP), but before a permit can be issued, the local land-use authority must first comply with the California Environmental Quality Act (CEQA) (PRC §21000 et seq., and CEQA Guidelines California Code of Regulation [CCR] §15000 et seq.). Unless CEQA has been complied with by some other permitting agency, the local land-use authority becomes the lead agency for compliance.

Preparing appropriate environmental documents and processing a use-permit application can often take many months. During the process of securing a CUP and CDP from the lead agency, the CEQA document is circulated among other regulatory agencies for review and comment. Often, in the course of this circulation, the lead agency or project proponent will receive notices that additional permits or consultations are required. For projects located on lands where the Commission has not retained jurisdiction to issue a CDP, the project proponent can expect their permit efforts to increase in complexity, time and cost.

3.2. Coastal Wetland Definition, PRC § 30121

In California's coastal zone, wetlands are broadly defined as lands that may be covered periodically or permanently with shallow water. The Commission relies on consultation with the California Department of Fish and Game (CDFG) to delineate wetlands, but requires that only one of three criteria used by federal agencies (e.g., hydrology, hydric soils or hydrophytic vegetation) need be present to delineate a wetland (Environmental Services Division 1987, in CCC, 1994).

On the coast, diked former tidelands are often inundated during winter and spring months with fresh water from either overland flows or from a high groundwater table that form seasonal wetlands. Livestock grazing can often limit seasonal wetland functions and values by reducing or altering native plant cover and associated species diversity, in favor of exotic species with less habitat value. Enhancing grazed seasonal wetlands often requires some fill and/or grading to increase topographic diversity and the duration of more vegetation, thereby improving a seasonal wetland's functional capacity and values. But excavation and placing fill during restoration or enhancement in a seasonal wetland is considered a development, causing an adverse impact that requires compensatory mitigation.

Because of the Commission's broad definition of what constitutes a wetland on diked former tidelands, it is often difficult, if not impossible, to locate an area that is not a seasonal wetland in order to provide compensatory mitigation (i.e., replace the wetland area being filled).

> *Wetland shall be defined as land where the water table is at, near, or above the land surface long enough to promote the formation of hydric soils or to support the growth of hydrophytes, and shall also include those types of wetlands where vegetation is lacking and soil is poorly developed or absent as a result*

> *of frequent and drastic fluctuations of surface water levels, wave action, water flow, turbidity or high concentrations of salts or other substances in the substrate. Such wetlands can be recognized by the presence of surface water or saturated substrate at some time during each year and their location within, or adjacent to, vegetated wetlands or deep-water habitats.* (California Code of Regulations Title 14, Division 5.5 Chapter 8, § 13577)

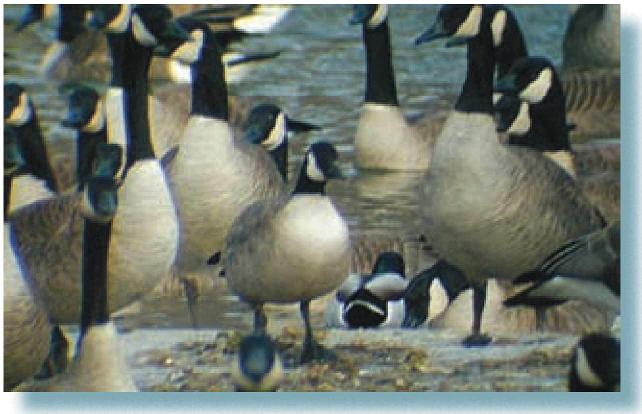
Yet, forgoing the enhancement of a grazed seasonal wetland would appear to be contrary to meeting a major goal of the Act, which is to enhance the overall quality of the coastal zone environment (PRC § 30001.5).

3.3. Marine Resources, PRC § 30230

Marine resources, such as submerged areas and tidelands, shall be maintained, enhanced and, where feasible, restored. Consequently, on diked former tidelands the Act prioritizes their restoration over enhancing existing freshwater wetlands. Whether it is feasible to restore a former tideland can be determined by the presence of physical, economic or political impediments to restoring tidal waters to these lands.

A commonly encountered constraint to restoring tidewater to former tidelands is an inability to prevent salt water from flooding adjacent agricultural or residential lands, inundating utility easements, public roads or rail corridors. Another policy of the Act, PRC § 30607.1, supports restoring marine resources such as former tidelands, while PRC § 30607.1 requires that a condition of approving fill in wetlands, if feasible, be mitigated at a minimum by opening up equivalent areas to tidal action. On former tidelands that are deemed infeasible to restore, then enhancement of seasonal freshwater wetlands would be the means to improve the quality of coastal wetlands.

Restoring former tidelands is not a simple activity and merely opening an area to tidal action is no assurance that historic tideland habitats will be restored. Many former tidelands were diked and drained over a century ago. Since then these tidelands have been cut off from tidal ebb-and-flow and may have subsided, so some areas are several feet lower than the submerged lands in adjacent tidal waters. Also during the intervening time, sea levels have risen—lately the increase in peak high-tide elevations has become particularly noticeable. In many situations simply restoring tidal flows to subsided diked former tidelands may create mudflat habitat rather than salt marsh because of the increased saltwater inundation on these lower surfaces. Therefore, the benefit of restoring tidal influences to former tidelands should be balanced against the loss of functions and values if these lands currently support seasonal freshwater wetlands, i.e., the cumulative loss of seasonal freshwater areas used by waterfowl such as Cackling Geese here on the North Coast.



3.4. Biological Productivity, PRC § 30231

PRC § 30231 of the Act requires that biological *productivity* (a function of both growth rate and biomass of an organism) and quality of coastal wetlands be maintained and, where feasible, restored. Where dike and fill development in wetlands is permitted, PRC § 30607.1 requires that the affected areas be mitigated by acquiring other areas of equal or greater biological productivity.

Depending on the expected gain in functions or values from enhancing a freshwater wetland versus restoring tidelands, this biological productivity policy may conflict with the apparent mandate to restore marine resources, where feasible, contained in PRC Sections 30230 and 30607.1. Further, this policy's emphasis on improving biological productivity and quality of coastal wetlands supports this paper's position that increasing function and value, i.e., quality, should be allowed even if there is a loss of wetland area as a consequence of enhancement activities.

3.5. Diking, Filling, or Dredging, PRC § 30233(a)

This section regulates the alteration of coastal wetlands from diking, filling, or dredging (excavating), and stipulates several criteria under which these developments are permitted:

- they shall be limited to certain allowable uses such as for "restoration" purposes, and
- where there is no feasible less environmentally damaging alternative, and
- where feasible mitigation measures have been provided to minimize adverse environmental effects.

Allowable Uses: The Act allows diking, filling, dredging or excavating a wetland when restoration is the main purpose of the project or similar resource-dependent activities such as enhancement. The Act does specifically address enhancement as one of the state's basic goals in the coastal zone (PRC § 30001.5 [a]), and the Commission has found in previous project approvals that a wetland-enhancement project, where the primary purpose of a project is to improve wetland habitat values, shall be considered for purposes of complying with this section "restoration," which is an allowable use (Commission—Fay Slough 2001).

The Commission, in previous projects, found that a project involving fill associated with dikes, which by itself is not an allowable use, was allowable because the project was designed to enhance the diversity of freshwater wetland types and enhance habitat values for water-associated wildlife (Commission—Fay Slough 2001). Similarly, restoring former tidelands around the bay that have been diked may require the relocation of a dike or construction of a new dike, often on a seasonal freshwater wetland, to contain tide waters from inundating adjacent land.

While placing fill in a wetland to re-locate or construct a dike is not an allowable use by itself, if restoration of an equivalent area of tidelands is integrated into the project, it may be allowed. However, not all property located on diked former tidelands borders a tidal channel or a dike, and without access to tidewaters it is not feasible to restore marine resources. In such instances enhancement of existing seasonal freshwater wetlands may be the only option available to increase the quality of coastal wetlands.

A key assumption in the Commission's approval of a wetland restoration or enhancement project is that it will be successful and provide a net gain in wetland acreage, functions and values and become a self-sustaining environment. The Commission's evaluation of proposed restoration or enhancement projects could require the preparation of a comprehensive environmental assessment describing baseline habitat functions and their desirable values.

Restoration versus enhancement projects may have an additional burden of providing an environmental assessment of a reference area to be used to ascertain the success of the restoration activities. Restoration and enhancement projects will also be required to provide a monitoring plan that should describe methods to measure improvements in habitat value and diversity at the site, including species and abundance, over the course of five years following project completion. A monitoring plan or, more appropriately, an adaptive management plan, should include provisions for remediation to ensure that the goals and objectives of the wetland-enhancement project are met.

Least Environmentally Damaging Feasible Alternative: An alternative analysis is required of all developments, even for restoration and enhancement projects. The proposed project is compared to other feasible alternatives that the applicant provides to determine which is the least environmentally damaging (including the proposed project). This alternative analysis assesses and compares only two impacts: loss of wetland acreage and loss of *functional capacity*, which means the level and number of species, level of biological productivity, and relative size and number of habitats. The alternative with least overall impact is the least environmentally damaging alternative. Alternatives to the proposed project could be:

1. "no project" or relocate project to have no impact to wetlands, and
2. modified project design (size, fill footprint, grading, hydrologic modifications, planting, etc.).

As the alternative analysis is applied, there are several difficult hurdles for any enhancement project to overcome. Foremost is that any alternative, including the project that would result in a net loss of wetland acreage, can be denied, because a "no project" alternative would maintain existing wetland acreage, i.e., "no net loss." Therefore, if any alternative may cause a net loss of wetland acreage, then proposing compensatory mitigation will be necessary to achieve "no net loss" of wetland acreage. Increasing wetland acreage can only occur on land that is not already a wetland.

In the case of diked former tidelands around the bay, almost all of those lands qualify as a seasonal wetland in the winter. To compensate for filling these seasonal wetlands, it may be necessary to go off-site and increase the size of an existing wetland or to create a new one. Given the unique nature of these seasonal wetlands and their proximity to tidal waters, compensatory mitigation may be achieved by opening up an equivalent area to tidal waters as it is being filled. Lastly, using the "no-net-loss" policy in this alternative analysis would conflict with the Commission's procedural guidance of not requiring compensatory mitigation, *habitat compensation*, for projects where the sole purpose of the project is restoration enhancement of a wetland, which is considered a beneficial activity (pp. 8-2, 9-1, Commission 1995).

If the proposed project or an alternative passes this first threshold, then the second criterion to evaluate is whether the functional capacity of an existing wetland is maintained or increased. An ecological assessment can assist in evaluating whether the proposed project will maintain or increase functional capacity by describing and quantifying baseline attributes of a specific function, which necessitates an understanding of the relationship between the attributes and the function.

When evaluating the functional capacity of alternatives such as enhancing a seasonal freshwater wetland, it is worth noting that just extending the seasonality or duration of inundation does not guarantee that existing functions or values will be increased. While the ephemeral nature of a seasonal wetland may reduce the time period of a function, the performance of that function and its overall value are not necessarily diminished relative to perennial wetlands or wetlands that are wet for longer durations. In fact, many of the same functions and values are present in both types of wetlands.

Additionally, seasonally wet wetlands can, during certain times of year, provide greater value for certain functions (e.g., ground water recharge, floodwater storage, habitat for endangered species or feeding and resting spots for migratory birds), relative to nearby perennially wet wetlands (Commission 1994). The alternative analysis, as administered, seems to place greater weight on achieving "no net loss" of area rather than balancing gains in functional capacity to determine the most beneficial project. The "no project" alternative in a degraded wetland should not be an acceptable alternative if enhancement could increase desirable wetland values.

Feasible Mitigation Measures: The Act, while allowing filling, diking and excavating of wetlands during restoration activities, requires feasible mitigation measures to *minimize* adverse environmental effects (PRC § 30230 [a]). Generally, environmental regulations do not treat all mitigation measures equally; there is a hierarchy of mitigation, which in descending order of preference is: avoid, minimize, rectify, reduce and compensate. The Commission's procedural guidance documents emphasize avoidance, where feasible, as opposed to minimization (Commission 1994, 1995). However, the Commission's administration of the Act has imposed an additional requirement that can affect enhancement projects—that of achieving "no net loss" of wetland acreage. The effect of applying this "no net loss" standard is requiring habitat compensation even for projects where the main purpose of the project is restoration or enhancement of wetlands, contrary to the Commission's own guidance document (p. 9-1 Commission 1995).

In coastal wetlands, adverse impacts to existing wetlands such as seasonal freshwater pastures, i.e., "farmed wetlands," often associated with filling, diking or excavating during restoration and enhancement projects include:

- covering (fill) or altering (excavating/grading) wetland topography;
- removing or damaging wetland vegetation;
- discharging stormwater runoff causing an increase in turbidity or sediment delivery to coastal waters;
- changing hydrological conditions that affect the duration or frequency of inundation resulting in the conversion of a seasonal wetland (or riparian region) to another type, such as open water or salt marsh with different functions or values.

Even projects whose main purpose is the beneficial improvement of a wetland via restoration or enhancement will, of necessity, involve one or more changes to existing conditions: topography, hydrology or vegetation. Any change to existing wetland conditions, certainly in the short term, may adversely affect wetland functions or values.

The Commission has found that allowing fill of a freshwater wetland from dike rehabilitation and construction as part of a restoration project would require compensatory mitigation to prevent "no net loss" of wetland acreage pursuant to their interpretation of Executive Order W-5993 (Commission—Fay Slough 2001).

Compensatory mitigation is either achieved by restoration, enhancement or creation and is the most common mitigation proposed by the Commission to replace lost or adversely impacted habitat by development projects (Commission 1994). There are two types of compensatory mitigation: *in-kind*, which involves the same type of habitat as that impacted by the development activity, or *out-of-kind*, which involves different types of habitat.

Common to all mitigation plans is the need for an environmental assessment of the existing wetland habitat and functions that will be adversely impacted by the proposed project. Assessing function is achieved by describing associated *biological* (which species and their distribution and abundance), *chemical* (such as water-quality conditions—salinity, temperature, and dissolved oxygen) and *physical* (habitat structure) attributes. Assessing values (the importance society places on that characteristic derived from each function) helps to prioritize the importance of the functions.

PRC § 30607.1 utilizes a compensatory mitigation ratio of 1:1 as a minimum for dike, fill or excavation actions permitted in wetlands in conformity with PRC § 30233, when the proposed mitigation is either acquisition of equivalent areas of equal or greater biological productivity, or opening up equivalent areas to tidal action. The Commission may also require compensatory mitigation ratios greater than 1:1; normally the ratio required is determined on a project-by-project basis to establish the mitigation area. The ratio required is often linked to whether in-kind or out-of-kind mitigation is being proposed. The determination of what is an appropriate ratio will depend on many factors such as:

- habitat function and values of the area to be affected by filling, diking or excavating;
- level of confidence in success of proposed mitigation plan;
- time lag between when impacts to existing habitat are sustained and when habitat values have been fully realized at mitigation sites.

Higher mitigation ratios may be required as a balance against the uncertainty of creating wetland habitat, and to offset adverse wetland impacts that result from a lengthy time lag between project impact and implementation of mitigation (Commission 1995). Any mitigation plan must have measurable goals, objectives and appropriate financial commitment for its successful implementation. A mitigation plan must also have a monitoring program to measure performance, determine compliance ("as-built" assessment) and evaluate whether desired habitat functions and values have been achieved. A mitigation-monitoring plan should include an adaptive management clause in case mitigation goals have not been achieved and further remedial measures are required.

3.6. Functional Capacity, PRC § 30233(c)

This section of the Act states that diking, fill or dredging (excavation) in existing wetlands shall maintain or enhance the functional capacity of the wetland. As mentioned earlier, function refers to what a wetland does and the processes it performs.

Evaluating a wetland's function is best achieved by describing and quantifying the physical, chemical and biological attributes that are at work in a particular wetland (Commission 1995). The section would appear to preclude changing what an existing wetland does and the processes it performs, as may be the case when enhancing a seasonal wetland or converting one to a brackish-water environment. Applying this section may also conflict with two other sections of the Act pertaining to restoring marine resources (PRC § 30230) or restoring tidal influences by filling, diking or excavating wetlands (PRC § 30607.1) when an existing freshwater wetland's function is altered by converting it to tidelands. This section does implement that portion of the state's "no net loss" of wetland policy concerned with protecting wetland quality and value (Executive Order W-59-93).

3.7. Minimum Mitigation Measures, PRC § 30607.1

When a project is involved with filling, diking or excavating a wetland, pursuant to PRC § 30233, its compensatory mitigation measures shall include at a minimum, either acquisition of equivalent areas of equal or greater biological productivity, or opening up equivalent areas to tidal action. This policy's emphasis on an equivalent area would reinforce a minimum compensatory mitigation ratio of 1:1 even if the loss of wetland area is a consequence of wetland-enhancement activities that may increase biological productivity. This section, in conjunction with PRC § 30230, also constrains enhancement of coastal wetlands by prioritizing restoration of tidal influences and marine resources. One benefit derived from this section is that it allows temporary or short-term filling or diking of a wetland, with requiring mitigation, if restoration is assured in the shortest feasible time.

4. Recommendations

Sometimes it is necessary to strive for a balance between conflicting policies in order to achieve the laudable goal of improving the quality of coastal wetlands. The following recommendations are offered for consideration to assist in the enhancement and restoration of coastal wetlands.

1. The effort and cost to secure authorization from the Commission for enhancement projects would be reduced if project proponents incorporate a regulatory compliance review in their project development efforts. Knowledge of regulatory constraints presented in this paper that may affect a proposed project should enable the proponent to redesign their project to avoid conflicts, or to develop suitable mitigation measures. For instance, describing the functions and values as well as the functional capacity of a seasonal wetland to be impacted, versus the wetland habitats being proposed, will greatly assist in development of the project and later when the Commission evaluates it. Presenting a project to the Commission that has successfully completed a regulatory compliance review will greatly improve and hasten the ability of staff to recommend that the project be approved.

2. There is extensive acreage of diked former tidelands that now support grazing of seasonal freshwater wetlands. The often-insurmountable problem encountered when enhancing seasonal wetlands is what to do with the material generated from grading or excavation. One means to overcome the conundrum of compensating for fill placement in a wetland, while implementing an enhancement project, is to focus on projects in areas where there is an opportunity to access tidal waters. The Act has prioritized: restoring former tidelands, a marine resource, wherever feasible (PRC § 30230), and when mitigating impacts to coastal wetlands by opening an equal area to tidewater inundation (PRC § 30607.1).

Combining the restoration of former tidelands with the enhancement of seasonal freshwater wetlands can increase the number of habitats, their ecological functions and societal values. Many of the century-old dikes are now severely eroded and their failure could threaten existing freshwater wetlands, agricultural uses, buildings, infrastructure, livestock and people, with breaches and perhaps catastrophic flooding.

In some situations, the most feasible way to restore diked former tidelands and to enhance freshwater wetlands is to relocate an existing dike. By moving a dike away from the shore, slough or tidelands, the area subject to tidal ebb-and-flow can be expanded. In many cases, building a dike to present-day standards will require increasing the former dike footprint and will reduce net wetland acreage. However, the loss of freshwater acreage to an increased dike footprint creates an opportunity to restore former tidelands. This strategy for restoring tidelands also creates an opportunity to enhance adjoining seasonal freshwater wetlands; when building a dike there is new upland area, and the relocated dike can be filled with any excavated material generated by enhancing the topographic and aquatic diversity of the wetland behind the dike. These types of projects can successfully integrate three interdependent needs: dike rehabilitation, salt marsh restoration and freshwater wetland enhancement.

3. There are several possible administrative remedies to streamline review and permitting of publicly funded projects where the main purpose of the project is restoration or enhancement of coastal wetlands. Publicly funded resource agency (e.g., CDFG, National Marine Fisheries Service, U.S. Fish and Wildlife Service, or Natural Resource Conservation Service) projects have already been developed and reviewed to assure protection of wetland resources. The Commission could utilize the Act's conflict-resolution policy contained in PRC § 30007.5 to weigh the net benefit derived from a project whose sole purpose is enhancement or restoration, and conclude on balance that these activities are beneficial and therefore "self-mitigating" and do not warrant compensatory mitigation measures. If the Commission did not treat these types of projects as a *development* pursuant to PRC § 30106, they could be exempted from needing a CDP. Again, if these projects were considered self-mitigating, they could also be exempted from needing a CDP pursuant to PRC § 30600(e). When assessing alternatives (PRC § 30233 [a]) to enhancement projects, determining the least environmentally damaging alternative should also achieve the proposed and preferred project's goals and objectives.

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6. Appendix

6.1. California Coastal Act of 1976, Public Resources Code 30000 et seq.

30001.5: *The Legislature further finds and declares that the basic goals of the state for the coastal zone are to: (a) Protect, maintain, and, where feasible, enhance and restore the overall quality of the coastal zone environment and its natural and artificial resources.*

30007.5: *The Legislature further finds and recognizes that conflicts may occur between one or more policies of the division. The Legislature therefore declares that in carrying out the provisions of this division such conflicts be resolved in a manner, which on balance is the most protective of significant coastal resources.*

30106: *"Development" means, on land, in or under water, the placement or erection of any solid material or structure; discharge or disposal of any dredged material or of any gaseous, liquid, solid, or thermal waste; grading, removing, dredging, mining, or extraction of any materials; change in the density or intensity of use of land, including, but not limited to, subdivision pursuant to the Subdivision Map Act (commencing with Section 66410 of the Government Code), and any other division of land, including lot splits, except where the land division is brought about in connection with the purchase of such land by a public agency for public recreational use; change in the intensity of use of water, or of access thereto; construction, reconstruction, demolition, or alteration of the size of any structure, including any facility of any private, public, or municipal utility; and the removal or harvesting of major vegetation other than for agricultural purposes, kelp harvesting, and timber operations which are in accordance with a timber harvesting plan submitted pursuant to the provisions of the Z'berg-Nejedly Forest Practice Act of 1973 (commencing with Section 4511).*

30230: *Marine resources shall be maintained, enhanced, and, where feasible, restored. Special protection shall be given to areas and species of special biological or economic significance. Uses of the marine environment shall be carried out in a manner that will sustain the biological productivity of coastal waters and that will maintain healthy populations of all species of marine organisms adequate for long-term commercial, recreational, scientific, and educational purposes.*

30231: *The biological productivity and the quality of coastal waters, streams, wetlands, estuaries, and lakes appropriate to maintain optimum populations of marine organisms and for the protection of human health shall be maintained and, where feasible, restored through, among other means, minimizing adverse effects of waste water discharges and entrainment, controlling runoff, preventing depletion of ground water supplies and substantial interference with surface water flow, encouraging waste water reclamation, maintaining natural vegetation buffer areas that protect riparian habitats, and minimizing alteration of natural streams.*

30233. (a): *The diking, filling, or dredging of open coastal waters, wetlands, estuaries, and lakes shall be permitted in accordance with other applicable provisions of this division, where there is no feasible less environmentally damaging alternative, and where feasible mitigation measures have been provided to minimize adverse environmental effects, and shall be limited to the following:*

(7) Restoration purposes

30233. (c): *In addition to the other provisions of this section, diking, filling, or dredging in existing estuaries and wetlands shall maintain or enhance the functional capacity of the wetland or estuary.*

30240. (a): *Environmentally sensitive habitat* *areas shall be protected against any significant disruption of habitat values, and only uses dependent on those resources shall be allowed within those areas.*

30519. (a): *Except for appeals to the commission, as provided in Section 30603, after a local coastal program, or any portion thereof, has been certified and all implementing actions within the area affected have become effective, the development review authority provided for in Chapter 7 (commencing with Section 30600) shall no longer be exercised by the commission over any new development proposed within the area to which the certified local coastal program, or any portion thereof, applies and shall at that time be delegated to the local government that is implementing the local coastal program or any portion thereof.*

(b) Subdivision (a) shall not apply to any development proposed or undertaken on any tidelands, submerged lands, or on public trust lands, whether filled or unfilled, lying within the coastal zone, nor shall it apply to any development proposed or undertaken within ports covered by Chapter 8 (commencing with Section 30700) or within any state university or college within the coastal zone; however, this section shall apply to any development proposed or undertaken by a port or harbor district or authority on lands or waters granted by the Legislature to a local government whose certified local coastal program includes the specific development plans for such district or authority.

30600. (a): *Except as provided in subdivision (e), and in addition to obtaining any other permit required by law from any local government or from any state, regional, or local agency, any person, as defined in Section 21066, wishing to perform or undertake any development in the coastal zone, other than a facility subject to Section 25500, shall obtain a coastal development permit.*
30600. (e): *This section does not apply to any of the following projects, except that notification by the agency or public utility performing any of the following projects shall be made to the Commission within 14 days from the date of the commencement of the project:*
…
30607.1: *Where any dike and fill development is permitted in wetlands in conformity with Section 30233 or other applicable policies set forth in this division, mitigation measures shall include, at a minimum, either acquisition of equivalent areas of equal or greater biological productivity or opening up equivalent areas to tidal action; provided, however, that if no appropriate restoration site is available, an in-lieu fee sufficient to provide an area of equivalent productive value or surface areas shall be dedicated to an appropriate public agency, or the replacement site shall be purchased before the dike or fill development may proceed. The mitigation measures shall not be required for temporary or short-term fill or diking if a bond or other evidence of financial responsibility is provided to assure that restoration will be accomplished in the shortest feasible time.…*

6.2 "No-Net-Loss" Wetland Policies

California

On August 23, 1993, Governor Pete Wilson signed Executive Order W-59-93, establishing a State Wetland Conservation Policy (SWCP), and providing comprehensive direction for the coordination of state-wide activities for the preservation and protection of wetland habitats. The SWCP was the first state-wide conservation policy of its type in the United States. The Resources Agency and the California Environmental Protection Agency (Cal EPA) are designated as co-leads to implement the goals of the SWCP. The SWCP has three central goals:

- Ensure no overall net loss and achieve a long-term net gain in the quantity, quality, and permanence of wetlands acreage and values in California in a manner that fosters creativity, stewardship and respect for private property;

- Reduce procedural complexity in the administration of State and Federal wetlands conservation programs; and
- Encourage partnerships to make landowner incentive programs and cooperative planning efforts the primary focus of wetlands conservation and restoration.

Federal Government

EXECUTIVE ORDER No. 11990 (1977): May 24, l977, 42 F.R. 26961

By virtue of the authority vested in me (Jimmy Carter) by the Constitution and statutes of the United States of America, and as President of the United States of America, in furtherance of the National Environmental Policy Act of 1969, as amended (42 U.S.C. 4321 et seq.), in order to avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands wherever there is a practicable alternative, it is hereby ordered as follows:

> Section 1. {a} Each agency shall provide leadership and shall take action to minimize the destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands in carrying out the agency's responsibilities for (1) acquiring, managing, and disposing of Federal lands and facilities; and (2) providing Federally undertaken, financed, or assisted construction and improvements; and (3) conducting Federal activities and programs affecting land use, including but not limited to water and related land resources planning, regulating, and licensing activities.

(b) This Order does not apply to the issuance by Federal agencies of permits, licenses, or allocations to private parties for activities involving wetlands on non-Federal property.

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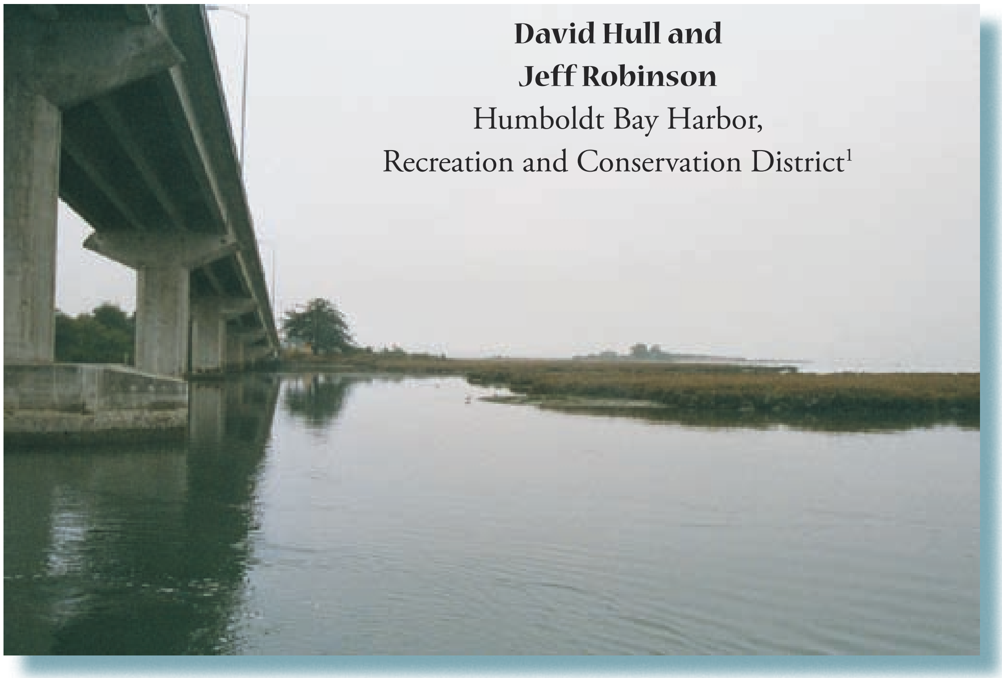
An Overview of the Humboldt Bay Management Plan

David Hull and
Jeff Robinson
Humboldt Bay Harbor,
Recreation and Conservation District[1]



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(p. 254) Humboldt Bay Harbor, Recreation and Conservation District
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http://www.humboldtbay.org

Abstract

Because of the need to balance port usage by commerce, industry and expanding recreational activities with environmental protections, a planning tool was deemed necessary by the Humboldt Bay Harbor, Recreation and Conservation District (Harbor District). This tool would need to envision population growth, include the best possible natural resource and physical information available and involve all agency land managers and bay stakeholders. The effort was entitled the Humboldt Bay Management Plan (Plan).

With oversight by a Harbor District Board of Commissioners Committee, staff and environmental consultants, Plan recommendations were reviewed by an 18-member Task Force comprised of agency land managers and bay stakeholder representatives. This Task Force conducted seven stakeholder meetings attended by over 120 interested citizens; these meetings netted more than 350 comments and ideas to be considered for inclusion in the Plan. As the Humboldt Bay Management Plan was not finalized as of the date of this writing,* this paper examines the process and development of the Plan to date.

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*The Humboldt Bay Management Plan was adopted by the Harbor District Board in August 2006.

Introduction

As California's second largest natural bay, Humboldt Bay is a valuable resource to both California and the nation because it offers natural resources, aesthetic appeal, commercial and recreational opportunities, as well as transportation links. Visitors and Humboldt County residents alike value Humboldt Bay for the various attributes that we, as human beings, cannot replicate or replace. The growing number of users and uses, as well as the intended and unintended impacts on the bay's ecosystem, potentially strains its ability to meet ever-changing needs.

Native dunegrass, *Leymus mollis.*

The Humboldt Bay Harbor, Recreation and Conservation District

In order to more efficiently balance the variety of uses in Humboldt Bay, the State of California established the Humboldt Bay Harbor, Recreation and Conservation District (Harbor District) in 1970. The enabling legislation may be found in the California Harbors and Navigation Code, Appendix II.

The statutory purpose of the Harbor District is to manage Humboldt Bay for the promotion of commerce, navigation, fisheries, recreation, protection of natural resources, and to acquire, construct, maintain, operate, develop and regulate harbor works. The important point to stress here is balance amongst all uses of Humboldt Bay, which the Harbor District continually strives to achieve and which the Plan is intended to facilitate.

Territory and Jurisdiction

The Harbor District is a county-wide public agency with a regulatory jurisdiction in Humboldt Bay shoreward to mean higher high water (MHHW) elevation.

Organizational Structure

The Harbor District is governed by five elected commissioners, representing the same jurisdictional boundaries as the Humboldt County Supervisors. The staff of 12 is comprised of management, maintenance and clerical personnel. The Harbor District is divided internally into three main functional divisions, namely the Port of Humboldt Bay, Woodley Island Marina, and Resource Conservation. Within these three divisions, a variety of projects and activities occur to fulfill the Harbor District's mission.

Examples of Projects and Activities

Harbor: The Harbor District oversees channel maintenance, channel improvement, dredging projects, port marketing and shipping facility improvements, oil spill response, navigation safety education and oceanographic research. In April 2000, the Harbor Deepening Project was completed; the harbor entrance was deepened to minus 48 feet (MLLW) and the North Bay and Samoa shipping channels to minus 38 feet (MLLW). This project was needed to improve navigation safety and to accommodate the needs of the current shipping fleet.

Other harbor-related projects of the Harbor District include participation in the Harbor Revitalization Plan effort, a commercial industrial siting study, cruise ship planning, qualifying and licensing of bar pilots, assisting in the research of navigation and safety improvements for Humboldt Bay, coordinating the Humboldt Bay Oil Spill Cooperative, operating a marina and a boat yard, supporting commercial fishing and mariculture and numerous other activities. Except for mariculture located in Arcata Bay, commercial and industrial harbor uses are limited to mid-Humboldt Bay (or Entrance Bay) in an area extending from the Samoa Bridge south to the southern end of the Fields Landing Channel.

Recreation: The Harbor District owns and operates Woodley Island Marina, serving commercial and recreational vessels since 1981, and Fields Landing Boat Yard, a self-service facility equipped with a 150-ton boat hoist. Woodley Island Marina with 237 berths is the largest recreational marina in Humboldt County.

Other recreational projects that the Harbor District is involved in include the Humboldt Bay water trail, the Shelter Cove boat-launching facility serving southern Humboldt, assistance and support for other agencies, design and improvement of boat launching facilities (e.g., Eureka Public Marina, Fields Landing, Hookton Slough), assistance in the promotion and funding of the bay-wide interpretive signing program, as well as supporting a variety of other activities in and around Humboldt Bay.

Conservation: Humboldt Bay Harbor, Recreation and Conservation District as the name implies, has ongoing involvement in a multitude of conservation activities around Humboldt Bay. These include: managing three wildlife areas (Gerald O. Hansen Wildlife Area, King Salmon and Park Street); educational outreach including an "Adopt-the-Bay" program; assisting in the planning and funding of biological research projects around the bay, including annual eelgrass *Zostera marina* surveys; and monitoring and removal of the nonindigenous species, *Z. japonica*.

In addition, the Harbor District was the first on the West Coast to develop and implement a ballast water exchange program in an attempt to limit the introduction of invasive species from other ports (now overseen by the State of California). It also organizes ongoing removal of nonindigenous species in wildlife areas, as well as supporting and participating in other agencies' conservation programs.

Lastly, the Harbor District has regulatory jurisdiction over all the tide and submerged lands of Humboldt Bay. Therefore, its Board of Commissioners exercises authority over every development project proposed in Humboldt Bay and in many cases is also the lead agency for compliance with the requirements of the California Environmental Quality Act (CEQA).

More information on the Humboldt Bay Harbor, Recreation and Conservation District's programs and activities may be found on the Harbor District's Web site: www.humboldtbay.org.

Humboldt Bay Management Plan

The concept of a Humboldt Bay Management Plan originated in 1997 with the need to update and develop a common database for use by bay landowners and agency land managers to guide planning and research around Humboldt Bay. The Harbor District had previously created an ad-hoc agency/citizens committee labeled the Interagency Coordination Committee (ICC). The ICC's original intent was to create a regular forum whereby agencies could report ongoing or forthcoming bay-related projects or issues.

Early in the history of the ICC, it became evident that there was a lack of common base maps, resource databases and coordinated bay management amongst agencies. In order to improve bay management in the future, the ICC recommended that an overall bay management plan be developed by the Harbor District in coordination with other agency land managers and with input from bay stakeholders representing a vast array of recreational, commercial and conservation uses. This coordinated effort was titled the Humboldt Bay Management Plan (Plan).

With the assistance of staff from Region 1 of the California Department of Fish and Game, the Harbor District was successful in obtaining a $17,000 grant from the U.S. Fish and Wildlife Service (FWS) to develop a bay-wide parcel and ownership map (Figure 1); and a $202,304 grant from the U.S. Environmental Protection Agency (EPA) to assist in developing 22 GIS maps, representing all of the existing biological and physical characteristics of Humboldt Bay. Although some of the data sets were several years old, they still represented the best existing information.

A conscious effort was made to focus on building this baseline database with the best existing information rather than embarking on new bay-wide data-collecting efforts. The premise was that this baseline database would expose the needs for updating certain data sets, which then would be recommended as implementation measures in the Plan.

The only data set deemed vital enough to deviate from this approach was spatial distribution of bay-wide eelgrass (*Zostera marina*). As eelgrass is an important species throughout Humboldt Bay, updated eelgrass distribution information was necessary. Therefore, a new set of aerial photographs of the entire bay was taken in September 2000 and subjected to a multispectral analysis. The entire baseline database was completed in 2002. The GIS information database is currently accessible on the Harbor District's Web site: www.humboldtbay.org.

The Plan process was formalized with the appointment of the Plan Task Force (Task Force) by the Harbor District. This Task Force was made up of agency land managers and representatives of various bay-user stakeholder groups, many of whom were regular participants in the ICC. These representatives are detailed in Figure 2. As the planning process began to take shape, the depth and importance of this effort became evident. Therefore, in order to assure proper stewardship over the planning process, the Harbor District appointed two of its own Board members, created the Conservation Specialist position and retained Dr. Chad Roberts, an environmental consultant, to assist with Plan preparation and oversee the Plan's compliance with the CEQA.

It also became evident that additional funding would be required to complete the Plan. A $100,000 grant was awarded to the Harbor District in 2000 from the California Coastal Conservancy to augment the planning effort and existing funding from the EPA and the FWS.

Planning Process

One of the Task Force's first tasks was to develop project boundaries and a mission statement to guide the production of the Humboldt Bay Management Plan.

Planning Boundary: This area of the Plan consists of two components, namely, the Plan Boundary and the Sphere of Interest (Figure 3).

The Plan Boundary is defined as all of the tide and submerged lands of Humboldt Bay shoreward to a tidal elevation of MHHW, covering approximately 27 square miles. The planning boundary was chosen because it represents that portion of Humboldt Bay under the regulatory jurisdiction of the Harbor District.

The Sphere of Interest (SOI) is defined as those lands surrounding Humboldt Bay from MHHW inland to the established California Coastal Commission Coastal Zone boundary. Although the Task Force realized that the Humboldt Bay Management Plan could not dictate land use within the SOI, it was thought that the Plan should take into consideration the existing and planned land uses adjacent to the bay. This was to avoid land-use conflicts and to provide the basis for commenting on adjacent land uses that actually or potentially affect bay resources and activities. Therefore, the intent of the SOI is to identify existing and future uses compatible with the Plan recommendations within its boundary.

Mission Statement: Based on the aforementioned needs and purpose, the Mission Statement developed for the Humboldt Bay Management Plan is to:

> *"Provide a comprehensive framework for balancing and integrating conservation goals and economic opportunities in a cooperative manner for the management of Humboldt Bay's resources."*

Plan Development as of March 2004

As the database was nearing completion, Harbor District staff and consultants were in place and the planning boundary and mission statement had been defined. The Task Force then moved ahead with Plan development.

The Harbor District's Board of Commissioners wanted to involve bay stakeholders in the planning process at an early stage so that the public was given the opportunity to provide input into the Plan. In addition, the Task Force could develop management actions based on this input rather than merely receiving comments on the final document (as in a "top-down" approach). Using this "bottom up" approach, the Task Force identified a number of bay user stakeholder groups and scheduled a series of workshops to obtain stakeholder input for the Plan. Stakeholder workshops were held in 2001–2002 to address the following topics:

- Commercial and industrial waterfront development
- Agriculture
- Environment
- Recreation
- Education
- Commercial Fishing
- Mariculture

Citizen participation at these workshops is detailed in Table 1 and led to over 350 ideas, which the Task Force boiled down into the following issue categories for the Plan to address:

- Habitat and Living Resources
- Human Activities and Competing Uses
- Water Quality and Sediment Quality
- Public Participation and Education
- Research and Monitoring

Following the conclusion of the stakeholder meetings, in May 2002 the Harbor District staff began assimilating the comments and reviewing preliminary summaries of the information with each of the Task Force's stakeholder representatives. Based on stakeholder and Task Force input, the first internal draft of the Humboldt Bay Management Plan was produced in January 2004.

Document Format

Early drafts of the Plan were organized to contain the following components:

1. Executive Summary
2. Volume I: Introduction
3. Volume II: State of the Bay
4. Volume III: Management Strategies
5. Appendix

Volume I—Introduction contained the background and history for the need and origin of the Plan. In addition, Volume I described the role and make-up of the Plan Task Force and Plan development process, and introduced its structure by briefly describing the contents of each volume. Generally, both the State of the Bay and the Management Strategies were divided into the Harbor District's three main areas of focus, namely Harbor, Recreation and Conservation. These three foci were further subdivided into geographic regions of Humboldt Bay: North Bay, Middle Bay (or Entrance Bay) and South Bay.

Volume II—State of the Bay consisted of three parts:

1. Part A—Summary of Physical and Biological Characteristics of the Humboldt Bay Region
2. Part B—Land Use, Planning, and Environmental Policies Affecting Humboldt Bay
3. Part C—Focused Considerations for Humboldt Bay Management Plan Elements

Volume II, Part A presented a general summary of the physical and biological conditions in Humboldt Bay based on previously published documents and the database developed early in this planning process. It also reflected general changes in understanding that arose in recent years about the relative significance of information either previously unknown or considered insignificant. New information was incorporated, based on recent publications and ongoing studies and research. This discussion did not attempt to be encyclopedic, but provided a synthetic portrait of what is now generally known about Humboldt Bay, its watershed, and adjacent Pacific Ocean.

The Plan required a basic portrayal of the policy framework in which it was embedded. The Harbor District operated within its own legislatively established mandates, in a larger context that included other, independent local agencies (following their own planning policy framework), state agencies carrying out established state programs and federal agencies carrying out the provisions of federal programs.

Part B summarized the relative roles and requirements of the range of programs affecting the Plan's implementation. The information addressed in Part B was abstracted from existing adopted planning documents, as well as through consultations with staff from relevant agencies.

Part C addressed specific setting conditions that were important for the policy framework laid out in Volume III and were divided into the Harbor District's three focus areas of Harbor, Recreation and Conservation. Much of the information required in the Harbor section was abstracted from the Humboldt Bay Harbor Revitalization Plan and other planning documents.

The Recreational summary of Part C identified those uses and opportunities throughout the Humboldt Bay watershed. The content of this section was based on adopted plans and addressed the requirements of local, state and federal laws with respect to recreational opportunities.

The discussion in the Conservation section was focused on specific environmental conditions and "resources" that were the subject of policy considerations in Volume III. That is, the topics in this section were "key issues" for the policy document (Volume III). As in the general discussion, this section was not intended to be encyclopedic in coverage, but to present instead the current understanding of basic and applied scientists, agency staff and informed members of the public regarding ecological processes, and the biological and physical conditions in Humboldt Bay that were needed to carry out informed consideration of the policy framework in Volume III.

Volume III—Policy Document consisted of three parts:

1. Part A—Overview; Harbor District Relationships With Other Planning Efforts
2. Part B—Management Plan Policies
3. Part C—Implementation

Volume III, Part A established the overall Plan framework. The "three-bay" focus provided a unifying thread or theme to help readers grasp the underlying Plan structure and the focus of its efforts to identify a policy focus for the various "resources" in Humboldt Bay. The "three bays" were defined as:

1. North Bay and a focus on Environmental Resources and Mariculture
2. Entrance Bay and a focus on Port Uses and Environmental Resources
3. South Bay and a focus on Environmental Resources and Port Uses

In general, Parts B and C of Volume III identified the responsibilities and interrelationships of the Harbor District and other jurisdictions in managing Humboldt Bay.

Part B identified a policy focus for the Harbor District's management actions in Humboldt Bay. The Harbor District's responsibilities and implementation tasks in the three primary areas (Harbor, Recreation and Conservation), as identified by the Task Force, were the focus. As requested by the Task Force, each section of the policy document cross-referenced relevant policies in other sections.

The Recreational portion of Part B addressed the interrelationships of the Harbor District's jurisdiction with those of other local agencies, including access "across" the shoreline. The requirements of various state and federal acts were considered. To the extent possible, long-range plans for recreational improvements were incorporated.

The growing attention to the ecological or conservation importance of Humboldt Bay—regionally, nationally and internationally—required a policy framework that embedded the Bay's management in the larger context. The policy framework in the Conservation section of Part B, nonetheless, addressed the Harbor District's responsibilities and powers, while attending to the statewide and national policy framework that was of interest to many Humboldt Bay stakeholders.

Part C included specific implementation actions recommended for action by the Harbor

District's Board of Commissioners in order to enact and enable the Plan's recommendations. In March 2004, these implementation recommendations were underway.* However, the Task Force discussed the following generalized implementation sequence:

1. Draft Plan reviewed by the Task Force. Policy issues were amended to reflect Task Force views.
2. The Harbor District Board of Commissioners reviewed the Amended Plan. Policy issues were amended to reflect Board views.
3. Harbor District staff prepared an environmental review document pursuant to the CEQA. This document outlined mitigation measures for any potentially significant effects of the Plan's policy proposals.
4. Harbor District Board of Commission ers reviewed final CEQA document and Plan, approved the CEQA document, and adopted the Plan.
5. Harbor District staff carried out the Implementation Program identified in the Plan.

Appendix: This was divided into two major components. The first component contained text references of relevant bay management laws, and rules and regulations from the Harbor District, as well as all other relevant agencies. This portion of the Appendix contained a list of all appropriate agency and stakeholder contact information.

The second component of the Appendix contained a variety of species guides. These guides were intended for reference and educational purposes and contained relevant pictures and life history information of all invertebrates, fishes, birds and plants that inhabit Humboldt Bay.

Conclusion

The Plan seeks not only to provide information to resource managers on the current state of Humboldt Bay's biological and physical resources, but also to provide a guideline for future resource management strategies that will ensure compatibility with Humboldt County's search for economic stability.

When the various management strategies for the Plan are implemented,* the results monitored, and additional scientific information gathered, this Plan will evolve and, like Humboldt Bay, will be a living and changing entity.

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*The Humboldt Bay Management Plan was adopted by the Harbor District Board in August 2006.

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Figures and Table

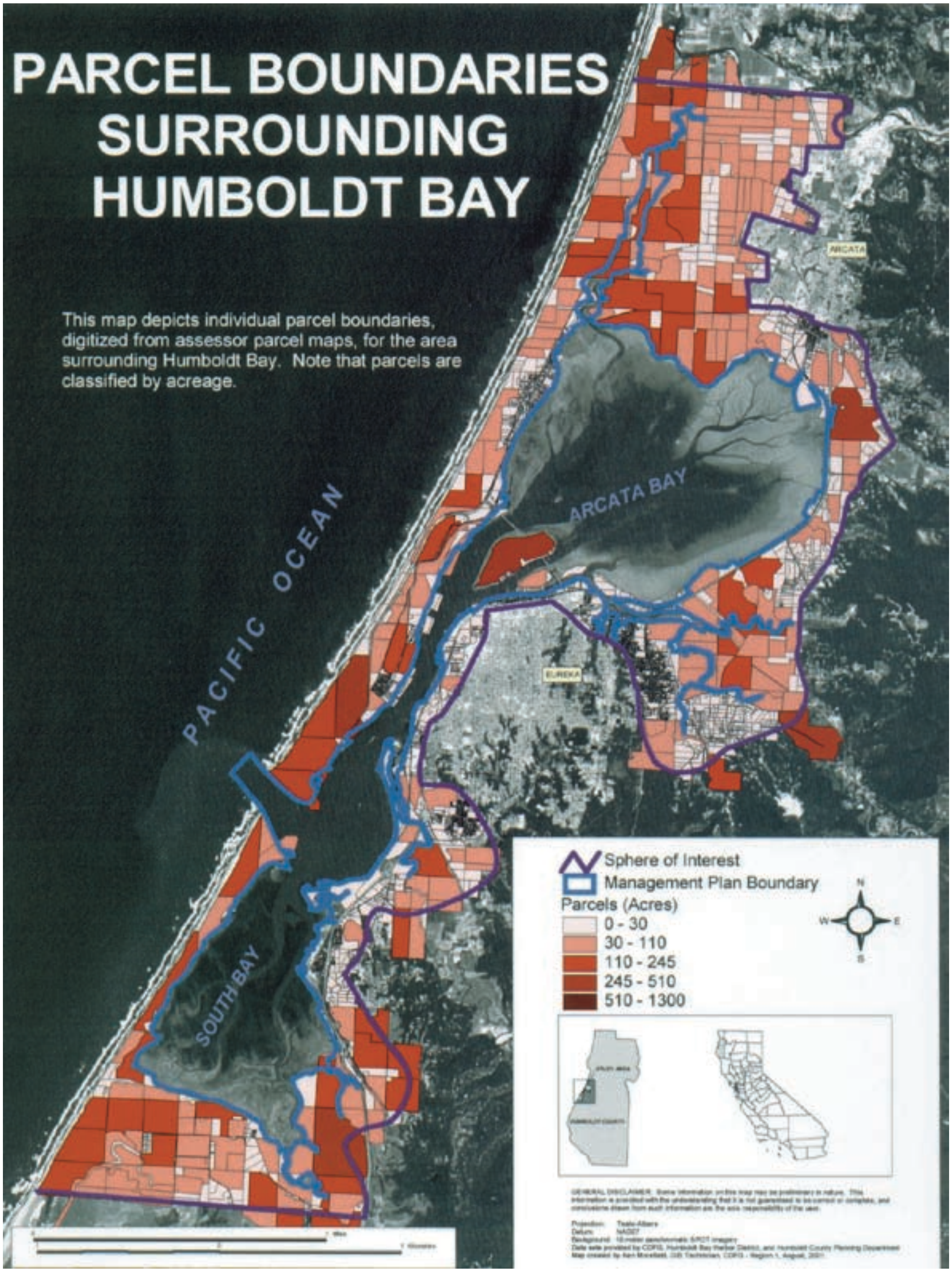

Figure 1. Humboldt Bay Parcel Boundaries.

Humboldt Bay Harbor District
Board of Commissioners

Harbor District Administrative Core Team

Board Advisory Committee:
Commissioners Ron Fritzsche/Ronnie Pellegrini/
Dennis Hunter

Chief Executive Officer: David Hull

Conservation Specialist: Jeff Robinson

Environmental Consultants:
Chad Roberts/Bruce Kemp

Task Force Representatives

City of Eureka: Gary Bird

City of Arcata: Juli Neander

County of Humboldt:
Supervisor: Jimmy Smith
Community Development: Kirk Girard

Bureau of Land Management: Bruce Cann

Humboldt Bay National Wildlife Refuge: Shannon Smith

California Department of Fish and Game:
Region 1: Mark Wheetley
Marine Region: Vicki Frey

Humboldt County Resource Conservation District: Otis Skaggs

Consumptive Recreational User Group Representative: Pat McNeil

Non-consumptive Recreational User Group Representative: Pete Oringer

Environmental Representative: Jim Clark

Commercial/Industrial Representative: Andy Westfall

Mariculture Industry Representative: Greg Dale

Commercial Fishing Industry Representative: Ken Bay

Education Representative: Bill Schaser

California Coastal Conservancy: Sheila Semans, Jim King

U.S. Environmental Protection Agency: Gail Louis

Figure 2. Humboldt Bay Management Plan Project Organization.

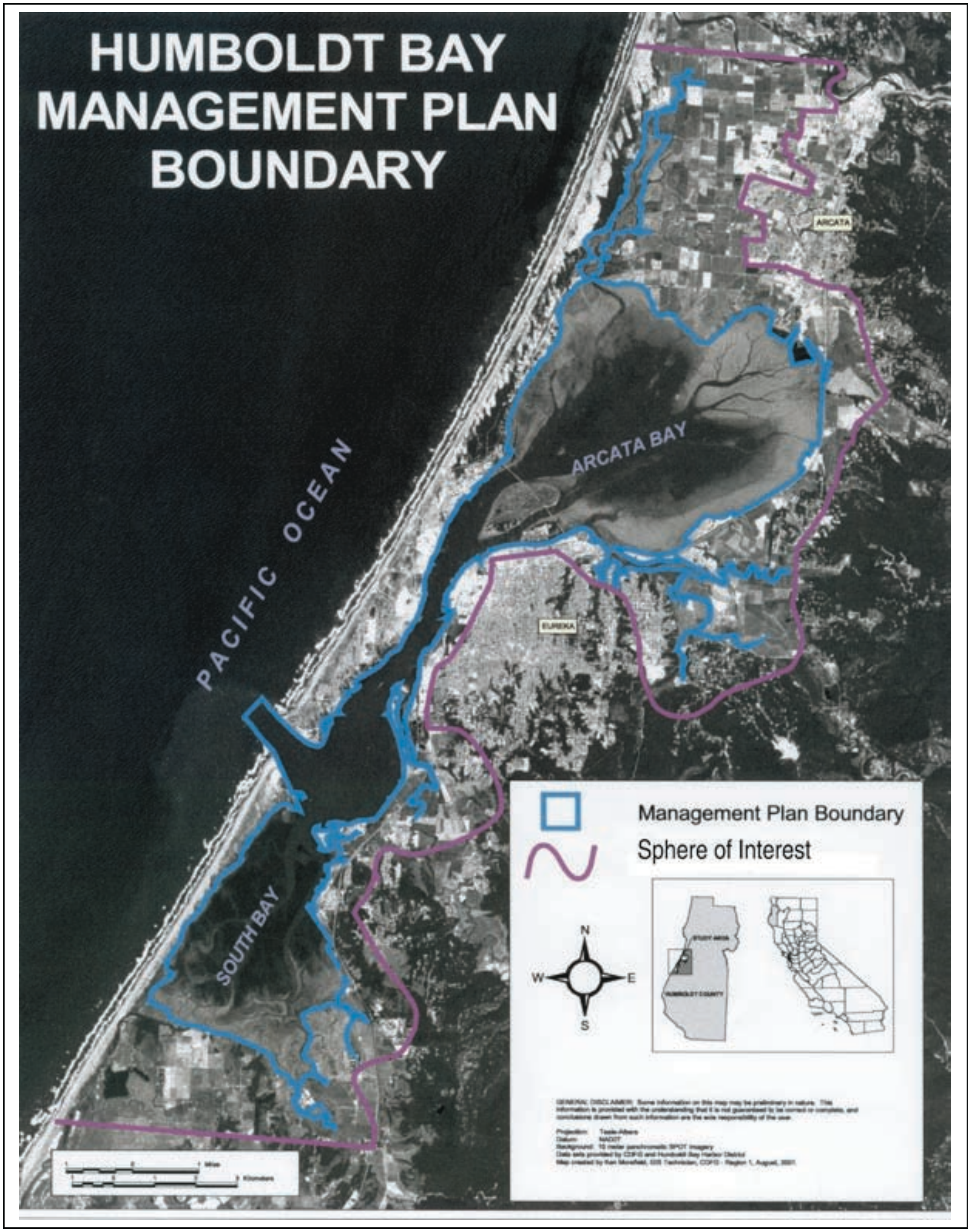

Figure 3. Humboldt Bay Management Plan Boundary and Sphere of Interest.

Table 1. Stakeholder Group Information.

Stakeholder Group	Workshop Date	Attendees	Comments/Actions Suggested
Commercial/Industrial	12.11.01	16	44
Agriculture	1.8.02	31	41
Environmental	1.22.02	24	79
Recreation	2.12.02	26	61
Education	2.26.02	5	44
Commercial Fishing	3.12.02	13	38
Mariculture	4.9.02	9	51
Total Attendees		124	
Total Comments/Actions Suggested			358

Panel Discussion Summary

Susan Schlosser[1]
California Sea Grant Extension Program

Participants

Biological Perspective	Milton Boyd, Ph.D.
Physical Science Perspective	Steve Costa, Ph.D.
Aquaculture Perspective	Greg Dale
California Coastal Commission Perspective	Lesley Ewing
Resources Agency Perspective	Vicki Frey
Harbor District Perspective	David Hull
U.S. Army Corps of Engineers Perspective	Nicholas Kraus, Ph.D.
Environmental Perspective	Tim McKay
Physical Science Perspective	Adele Militello, Ph.D.
Commercial Fisheries Perspective	Aaron Newman/Troy Nicolini

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[1] 2 Commercial Street, Suite 4, Eureka, California 95501

Each panel member gave comments on the symposium presentations and identified those data gaps that were important to address from their perspective.

David Hull, Executive Director of the Humboldt Bay Harbor Recreation and Conservation District, noted current high interest in the Bay. He thought there had been a gap in community interest in the Bay from about 1980 to 1996. Data gaps important to the Harbor District are being addressed by the U.S. Army Corps of Engineers (USACE)/Humboldt Bay Shoreline Monitoring Project, but it will be a few years before sufficient data are collected for analysis. NOAA and the Center for Integrated Coastal and Ocean Research and Education at Humboldt State University (HSU) will add directional capabilities to buoy data that are important for navigational safety. Hull said it is important for contemporary studies to use methodology comparable to historic studies whenever possible. Light Detection and Ranging (LIDAR) data are now in a usable format and provide topographical bathymetric data for Humboldt Bay. He noted other useful studies currently in process such as the Humboldt Bay Cooperative Eelgrass Project that conducts eelgrass surveys twice a year. Hull would like to see statewide requirements for shipboard treatment of ballast water exchange to reduce invasive species introductions.

Troy Nicolini of the Humboldt Fisherman's Association (and National Weather Service hydrologist) fishes part-time for anchovy, herring and sardine in Humboldt Bay. He recommended fisheries biologists work with local fishermen to develop methodology for targeted fish studies. This is especially useful as fishermen can provide knowledge on timing of species occurrence.

Greg Dale thought the Indian Island restoration project deserves support and it would be useful to compile or archive resources such as Don Tuttle's photographs. He would like to see bathymetric LIDAR data used to develop an electronic chart. Dale also noted the lapse in Humboldt Bay studies and suggested strong support for HSU research and generally using more local expertise. The symposium was important, but action is needed on information presented and integration of bay and watershed studies and activities.

Lesley Ewing said the California Coastal Commission (CCC) will apply scientific information on Humboldt Bay to their day-to-day permitting of development and restoration projects. The kinds of questions they ask about projects are: Is something being done to the bay going to be safe? Are there any geological hazards such as erosion or landslides? Regarding shoreline armoring, would natural levees or beaches be useful instead? Are there ways to maintain the shoreline and avoid nonindigenous species invasions? Is sediment and beach nourishment a way to get a more natural bay shoreline? Is dredging being conducted by the USACE enhancing or degrading the bay? We need a bay sediment budget. What is sea-level rise doing to the tidal elevations, subsidence and accretion around the bay? What are the natural dynamics of Humboldt Bay evolution? The more information Ewing has, the easier her work will be.

Steve Costa said there is a dearth of studies on Humboldt Bay. Regarding physical processes, Nick Krause's model could be used to predict the time and speed of currents. This should be integrated with a water quality transport model. For example, if something gets dumped in the bay, what happens? The advantage of models is their ability to answer the "what if" questions. There is a general lack of water-quality and sediment monitoring. Jeff Borgeld's research is great for the sediments that are present now, but we also need to examine toxics that may be in the sediments. Costa also stated the need for a sediment budget to include ocean and watershed sources.

Adele Militello pointed out that the lack of directional wave data for shoreline erosion and accretion models is a huge data gap. Directional data are needed to make effective current models for different seasons, tides and wind direction. Important questions to answer are: How is the shoreline changing? What change in sediment size is occurring? If a new model that included sediment transport were developed, we could calculate bed elevation changes and how components of the system are related. All of this could be applied to dredging practices and management.

Nick Krause recommended a siren for tsunami warnings, as the area is vulnerable to this natural hazard. He endorsed the idea of a directional wave buoy and said in Grays Harbor, Washington, their directional wave buoy costs $45,000 annually to maintain. It would take about $25,000 to upgrade the existing buoy, and he encouraged the CCC and USACE to collaborate and get a directional wave buoy. Krause stressed the importance of regional sediment management. He considered dredge spoils a resource and asked how can we get projects to talk with each other? Beaches are eroding around Humboldt Bay yet we are removing sediment from the bay. Beneficial uses of dredge spoils elsewhere include shoreline restoration of beaches, seagrass habitat creation and shoreline protection. Mounds of dredge spoils can protect nearby levees, form bird islands, or provide a substrate for saltmarsh plants. The new data on currents in Humboldt Bay will be on their Web site. He will request NOAA make new bathymetric projections for an updated chart of Humboldt Bay. He pointed out that the USACE LIDAR data could be used, for example, to determine where to plant eelgrass but could not be used for navigation.

Vicki Frey noted gaps in shoreline monitoring in the bay to prevent erosion without armoring, as erosion occurs at the ends of most armored sections of shoreline. Coordination of LIDAR data between HSU, USACE and the Harbor District for circulation and transport of sediment at the Humboldt Open Ocean Disposal Site (HOODS) site is important. As more dredge spoils are taken to HOODS, what is the site's expected life span? If the harbor is increasingly deepened, what effects and impacts will be seen around the bay? Biological monitoring of the edge of the shipping channel is needed. How are salmonid populations existing in the bay? Do they leave via the eelgrass beds or main channels? How does oyster filtration affect eelgrass? What is the role of oysters on bay ecology?

Tim McKay asked how far do fish go that started out in Humboldt Bay tributaries? He noted the general increase in eelgrass, Brant and Aleutian geese populations recently and the lack of political topics today. A future symposium could address politics and science, especially trying to determine what residents think about Humboldt Bay. How is public access? How is monitoring paid for? McKay thought there is a need to strengthen the public trust in order to use but not abuse natural resources, and encouraged everyone to get involved in the Humboldt Bay Management Plan and CEQA process and express their expertise on Humboldt Bay.

Milt Boyd said South Bay has relatively little human impact and should be protected. We need better ecological service information about the bay, such as how many oysters, fish, birds and salt marshes, etc., are sustained by the bay? This is largely unknown. He encouraged people to get involved with the Humboldt Bay Stewards.

Final note: There was a question raised about establishing a reference condition for Humboldt Bay. It was generally decided that identification of a desirable condition may be more realistic given all that has changed in Humboldt Bay. NOAA Essential Fish Habitat guidelines provide reference conditions for fish.