Naval Command,
Control and Ocean
Surveillance Center RDT&E Division San Diego, CA 92152–5000

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Technical Report 1502
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Evaluation of Sediment Contamination in Pearl Harbor

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San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

The Pearl Harbor estuary demonstrates a remarkable resilience to natural and human-induced contaminant stresses. Present conditions in the harbor exhibit measurable patterns of improving environmental quality. A review of more than fifty harbor-specific sets of data collected during the past thirty years, reveals a complex contamination and recovery history. The adaptive responses and subsequent recovery of resident harbor organisms to previous contaminant disturbances serve to emphasize the diverse, resilient, and dynamic character of this complex ecosystem.

The present site investigation reported here focuses on environmentally pertinent aspects of Pearl Harbor's contamination source history. Potential sources for environmental contamination in sediment, water, and selected marine organisms are addressed in general terms. Terrestrial impacts and sources of pollution are mentioned where appropriate; however, the harbor's estuarine environment forms the central focus of this assessment.

Siltation represents a major environmental contaminant pathway in Pearl Harbor. Frequent dredging, required in the harbor due to high siltation rates, serves to mitigate the effects of contaminant loading by periodically removing the upper layers of harbor sediment. The responses of organisms used during sediment toxicity and bioaccumulation studies consistently showed negligible effects from sediment toxicity. Environmental quality at an offshore dredge disposal site for the harbor has been described as typical of oceanic conditions off Hawaii, and the site exhibits no measurable adverse effects.

The diversion of major sewage effluent sources from Pearl Harbor in the early-to-mid 1980s has produced significant improvements in harbor water and sediment quality. Reduced sewage nutrient and contaminant loading has improved the overall harbor condition. Contamination by microorganisms, however, continues to be a major problem in the harbor ecosystem.

Pathways of contaminant exposure to the Pearl Harbor ecosystem are primarily those affecting the waterborne migration of pollutants, such as surface runoff and transport via tributary streams. Once contaminants reach the harbor, multiple migration pathways exist for further dispersal. Most contaminants experience extensive physical and chemical modifications after entering the harbor environment. Biological transformation through metabolic processes serves to modify many contaminants.

Several persistent contaminants have recently been measured in sediment samples from certain harbor locations that may warrant further evaluation. Polychlorinated biphenyls (PCBs), petroleum hydrocarbons, and silver are present at sufficiently elevated sediment concentrations to cause environmental concern. Overall sediment quality in Pearl Harbor, however, is considered higher than for many U.S. mainland

coastal bays, ports, and harbors. Based on available data, overall environmental risks for Pearl Harbor are considered moderately low at present. Human health risks attributable to harbor contamination are also considered low.

Further investigation of the abundance and distribution of important marine resources (such as oysters, *nehu*, sport fishes, and crabs) in Pearl Harbor is recommended. An increased understanding of the population dynamics of these harbor resources could enhance decisions related to future harbor uses. As harbor environmental quality continues to improve, there will probably be an increase in marine resources.

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INTRODUCTION

Pearl Harbor is a complex feature located on the south-central coast of Oahu. Its historical record from military, political, socioeconomic, and ecological perspectives is central to understanding present environmental conditions in the harbor. The review and evaluation of available relevant data for Pearl Harbor was an essential part of this effort. The present site investigation reported here focuses on environmentally pertinent aspects of the sources of Pearl Harbor's contamination. Potential sources for environmental contamination in sediment, water, and selected marine organisms are addressed in general terms. Terrestrial impacts and sources of pollution are mentioned where appropriate; however, the harbor's estuarine environment forms the central focus of this assessment. A glossary is included at the end of this report to assist the reader with technical terms and acronyms.

The intended purpose of this investigation is to achieve the following environmental assessment objectives:

1. Review existing environmental information pertaining to the Pearl Harbor region to identify potential contaminants or other environmental hazards present in sediment, water, and selected organisms.

2. Provide a detailed evaluation of present marine environmental conditions in the Pearl Harbor estuary.

3. Assess environmental risks present in Pearl Harbor and adjacent regions.

4. Determine whether Pearl Harbor has been chemically contaminated to the extent that a substantial threat may be posed to human health and/or the environment of the region.

5. Ascertain if sufficient evidence exists to warrant the initiation of remedial investigations in selected regions of Pearl Harbor.

BACKGROUND

HISTORY OF THE HARBOR

The Pearl Harbor Naval Complex has existed for nearly a hundred years. There have been extensive changes since the mid-1800s when "*Pu'uloa*," as Pearl Harbor was known by the ancient Hawaiians, was a large natural inland lagoon. Numerous walled fishponds located inside the harbor were used to cultivate various species of fishes until the 1890s. As one of the finest natural harbors in the Pacific Basin, Pearl Harbor was readily identified as a strategically important military asset.

The U.S. Navy acquired rights to the harbor in an agreement with King David Kalakaua in 1873 (U.S. Department of the Interior, 1969). After 1898, when Hawaii became a territory of the United States, p'ans were developed to dredge the harbor entrance channel and construct docking facilities inside the harbor. In 1901 the U.S. Navy acquired 800 acres of land to establish a Naval Station at Pearl Harbor (U.S. Navy, 1983). The first major dredging of the entrance channel began in 1908, followed by construction of the first drydock in Hawaii at the Pearl Harbor Navy Yard (Nystedt, 1977). After problems were encountered with underground water pressure, Dry Dock #1 was finally completed in 1919 (U.S. Navy, 1983).

During World War I, a dozen warships were repaired and overhauled at the Navy Yard. In 1917–1918 a temporary submarine base was relocated from Magazine Island (*Kuahua Island*) to Quarry Point on the eastern shoreline of Southeast Loch. A Naval Ammunition Depot was commissioned in 1919 at Magazine Island. Around 1920 many walled fishponds still remained intact (figure 1).

During the 1920s and 1930s shore facility developments continued and additional land was acquired by the Navy. Ford Island (formerly known as *Moku'ume'ume*, "island of the little goats") became a naval air station in the early 1920s. Work began on concrete moorings along the south side of Ford Island, which later became known as "Battleship Row." Industrial development was greatly accelerated in the Pearl Harbor area during the late 1930s and early 1940s. A considerable amount of acreage in the Pearl Harbor Naval Complex was created since 1930 by the deposition of dredge spoil materials (U.S. Navy, 1947).

On 7 December 1941 the Japanese Imperial Navy launched a surprise air attack on the U.S. fleet in Pearl Harbor from a task force of 32 vessels, including six aircraft carriers with 350 warplanes. This attack sank or severely damaged 21 of the 86 U.S. naval warships in Pearl Harbor (Lenihan, 1989) and more than 2400 U.S. servicemen were killed. A tremendous salvage, repair, and cleanup effort began within one week after the attack on Pearl Harbor (Lenihan, 1989; U.S. Navy, 1989a). Physical and chemical evidence of this period remain detectable in buried harbor sediments that have not been disturbed by dredging activities (Ashwood and Olsen, 1988). From 1940 to 1943 large amounts of dredged material were placed on Waipio Peninsula and areas adjacent to the Submarine Base (U.S. Navy, 1983). These landfill operations formed the present shoreline configuration of the inner harbor. From 1942 to 1944, the number of facilities and personnel at the Pearl Harbor Naval Complex increased greatly to support the War in the Pacific. Storage facilities for ordnance and materiel filled nearly all available land regions near Pearl Harbor. By mid-1943 civilian employment at the Navy Yard rose to 24,000 personnel (U.S. Navy, 1983).

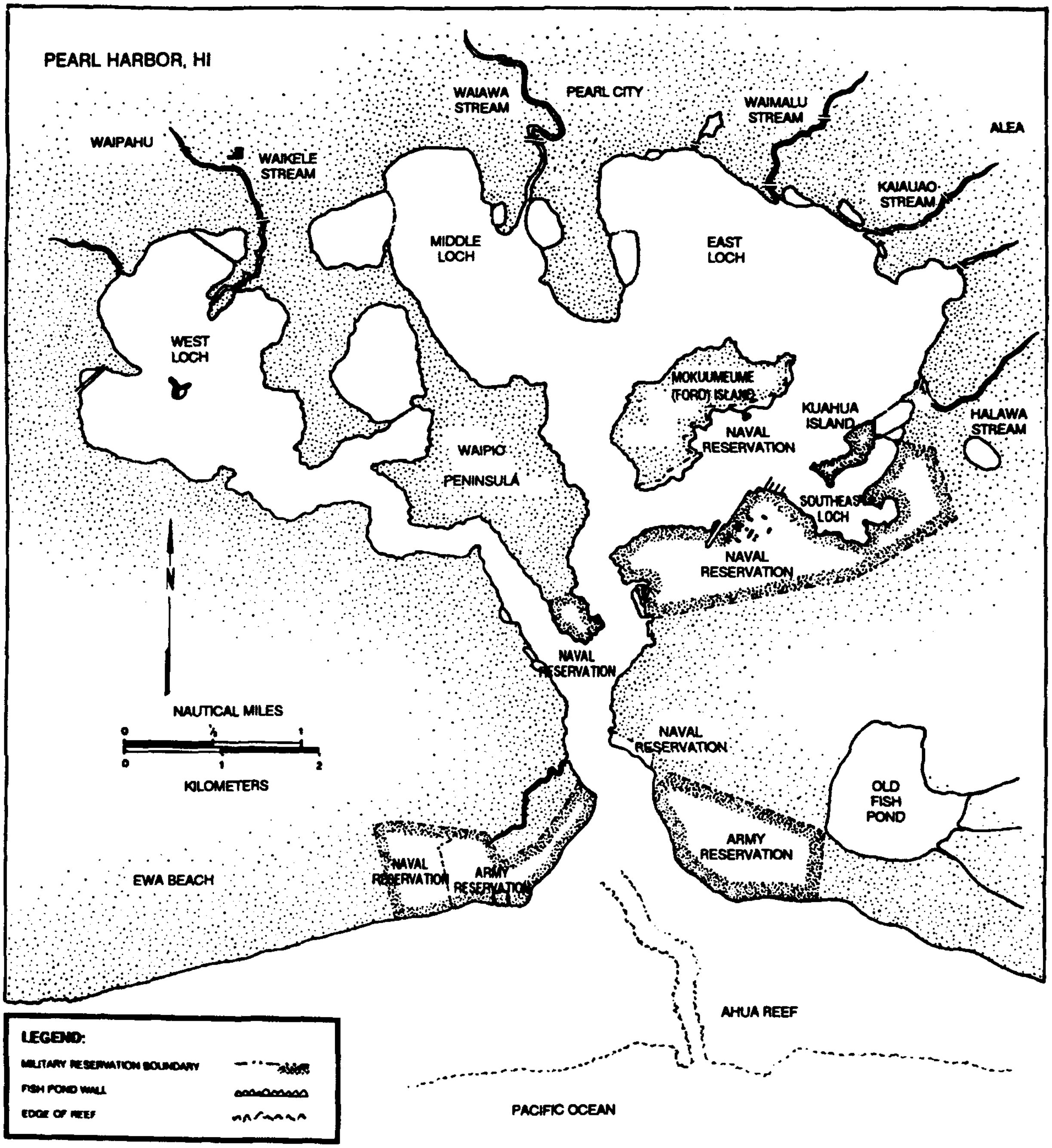

Figure 1. Shoreline configuration in Pearl Harbor circa 1920. (Redrawn from undated Oahu Fisheries Chart obtained from B. P. Bishop Museum.)

After World War II and throughout the late 1940s, the number of service personnel and active facilities at Pearl Harbor decreased markedly. During the Korean War and the Vietnam Conflict, operations and support personnel at the Pearl Harbor Naval Complex increased in response to the nation's defense requirements, but never to the same extent as during World War II. Today Pearl Harbor is a major fleet homeport for nearly 40 warships, service-force vessels and submarines, with their associated support, training, and repair facilities. The region is listed as a National Historic Landmark.

SITE DESCRIPTION

Pearl Harbor is a natural estuary situated midway along the southern coast of the island of Oahu in the Hawaiian Islands. The harbor is under the jurisdiction of the U.S. Navy. Major facilities include a shipyard, naval station, submarine base, naval supply center, public works center, and an inactive ship maintenance facility. Pearl Harbor consists of three primary regions: East, Middle, and West Lochs (figure 2). Southeast Loch is the hub of naval activities in the harbor (figure 3). Vessels using the harbor on a regular basis include—

- U.S. Navy surface ships, submarines and harbor craft
- U.S. Army cargo transport vessels
- U.S. Coast Guard buoy tenders and patrol vessels
- U.S. National Park Service USS *Arizona Memorial* tour craft
- foreign naval vessels
- commercial freighters and tankers
- commercial tour craft
- commercial fishing sampans (to collect baitfish)
- recreational vessels (sailboats and motorized vessels)

Rainbow Bay Marina is a recreational small-boat moorage facility with a capacity of about 70 small vessels, located in the east–northeastern region of the harbor. Iroquois Point Lagoon Marina (see figure 2) with a capacity of about 45 small vessels is located through a narrow inlet along the western side of the harbor's entrance channel, north of Iroquois Point. These two small marinas represent the only pleasure-boat moorage facilities in Pearl Harbor.

Pearl Harbor contains 21 km^2 (8 mi^2) of surface water area and 58 km (36 miles) of linear shoreline. The mean depth in Pearl Harbor is 9.1 meters (30 feet), with the deepest area located off Waipio Peninsula in the main channel adjacent to the U.S. Navy Degaussing Station at a depth of 28 meters (92 feet). Tidal flow and circulation in Pearl Harbor are weak and variable, with a mean tidal current velocity of 0.15 m/s (0.3 knot) and a maximum ebb flow of 0.3 m/s (0.6 knot) in the entrance channel (U.S. Department of Commerce, 1986). The mean annual tidal range for Pearl harbor is approximately 0.5 meter (1.6 feet) (U.S. Department of Commerce, 1989). Surface water circulation is driven primarily by northeasterly trade winds. Maximum residence time for bottom waters has been calculated as about six days in Middle Loch.[1] In major channel areas and throughout East Loch, however, surface water residence times average one to three days. Vessel traffic has been identified as a major harbor-water-mixing mechanism.

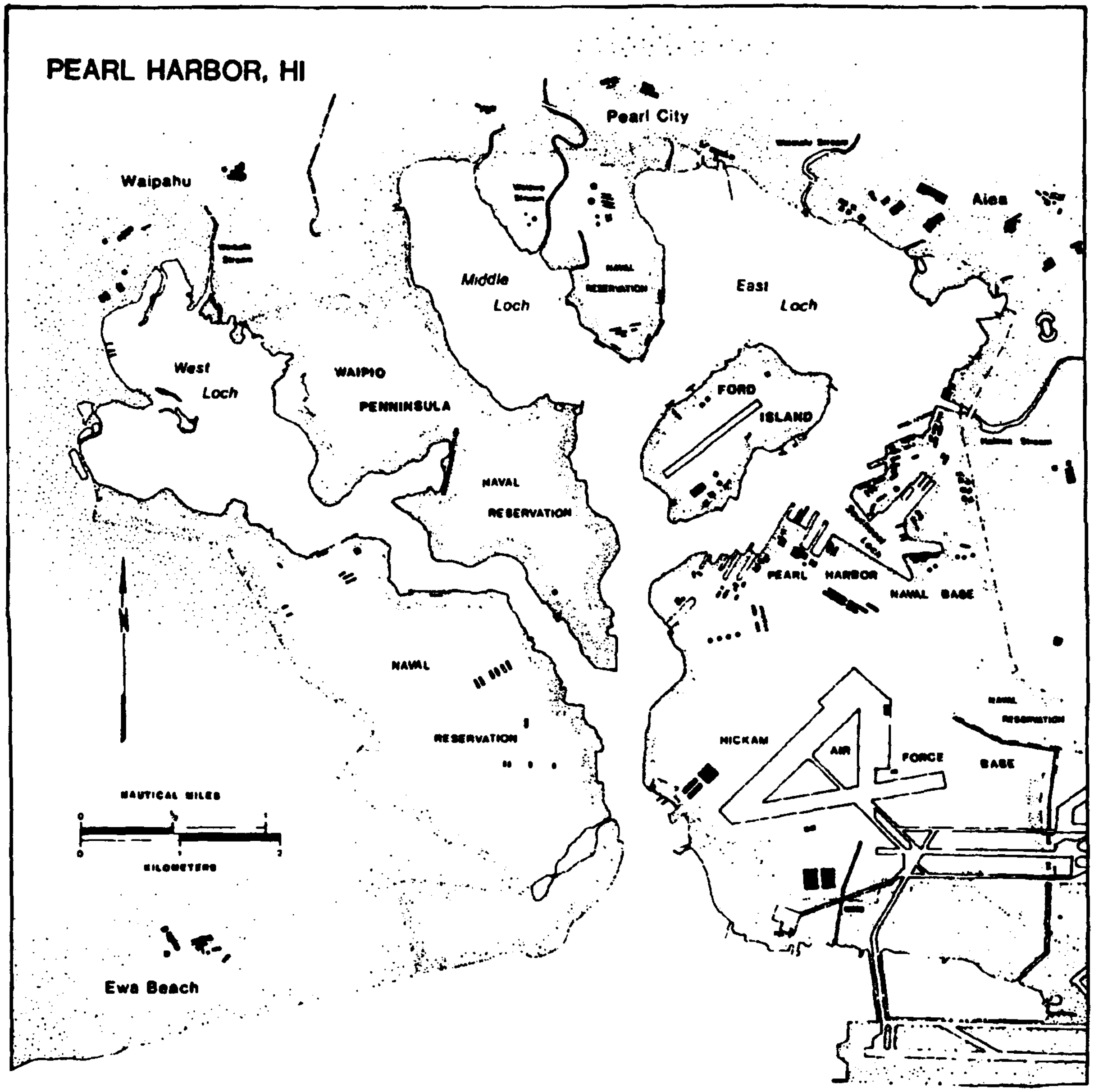

Figure 2. Pearl Harbor plan showing reference locations existing circa 1990.

[1] Evans, E. C., III (ed.), 1974. *Pearl Harbor Biological Survey*. NUC Technical Note 1128. Naval Undersea Center, San Diego, CA. §3.3, pp. 39 (figure) and 76. Technical notes are working documents and are usually not distributed outside of NRaD; however, this extensive, data-rich report (including >700 pp.) has received limited distribution to outside agencies and is a major reference document for the Pearl Harbor ecosystem. For further information, contact the author at NRaD, Code 522.

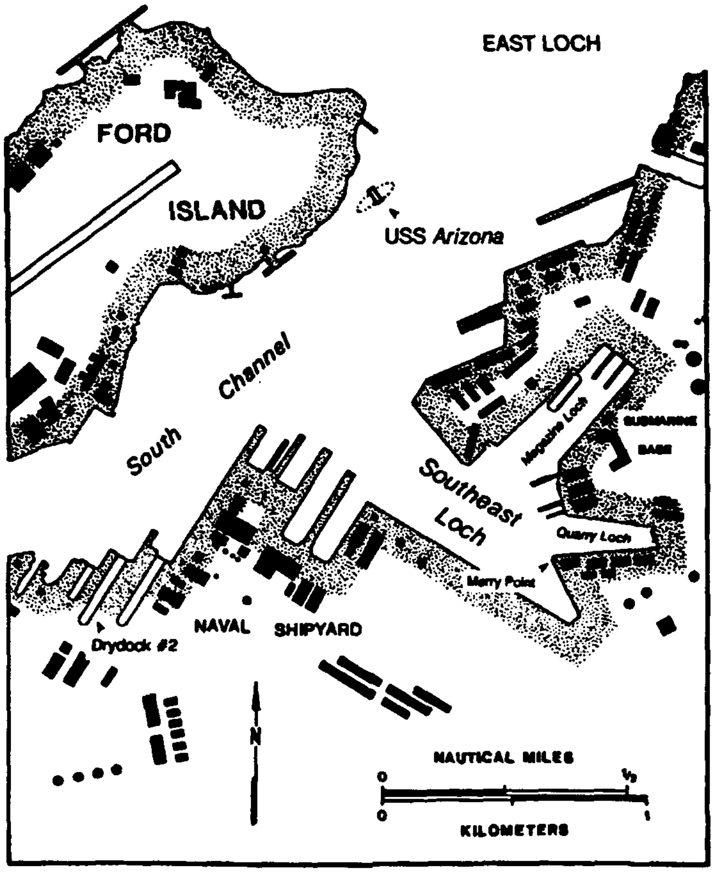

Figure 3. Expanded view of major naval facilities in Pearl Harbor.

Salinities in Pearl Harbor range from 10 to 37.5‰, with a yearly average of 32.8‰. Harbor water temperatures annually range from 22.9 to 29.4°C (mean of 25.7°C) and dissolved oxygen values range from 2.8 to 11.0 mg/l (mean of 5.7 mg/l). The lowest dissolved oxygen values have been measured from bottom waters in Middle and West Lochs. Harbor pH ranges from 7.8 to 8.4, with a mean of 8.1 pH in this well-buffered system. Pearl Harbor is most appropriately described as a high-nutrient estuary. Water transparency ranges from 0.5 to 3.5 meters (1.6 to 11.5 feet) with a mean of about 2.5 meters (8.2 feet) as measured by Secchi disk. Severe coliform bacterial contamination in surface waters and oyster tissues was reported during the 1960s and 1970s in certain harbor regions, primarily at stream mouths, in West Loch and in Middle Loch (U.S. Department of the Interior, 1969; Cox and Gordon, 1970). Certain trace element concentrations in Pearl Harbor sediments have been described as typical for many worldwide coastal harbors exposed to ship repair and industrial activities.[2]

Pearl Harbor is characterized by high biological complexity and productivity for plankton, fouling, benthic, and fish assemblages. During comprehensive field studies

[2] Evans, E. C., III (ed.), 1974. *Ibid.*, §5.0, p. 25.

more than 90 species of marine fishes, 114 species of benthic organisms, 71 species of micromollusks and 88 species of piling (*aufwuchs*) organisms were identified from the harbor ecosystem.[3] The estuary provides important nursery areas for many marine fish species and remains an economically important location for the Hawaiian anchovy (*nehu*) bait fishery (Somerton, 1990).

SUMMARY OF ENVIRONMENTAL INVESTIGATIONS

Many studies have been performed in the Pearl Harbor estuary and adjacent regions. Studies especially pertinent to this evaluation are summarized in table 1.

Only the leading author for each study is listed; however, full citation information for each study may be found in the annotated list of references at the end of this report. Many of these investigations addressed environmental concerns at specific locations within the harbor. Ten studies obtained spatially comprehensive data from many harbor regions ("location" has been listed as "entire" in those cases).

ENVIRONMENTAL CHARACTERIZATION

TOPOGRAPHY

Oahu consists of two parallel mountain ranges, the longer Koolau Range to the east and the higher Waianae Range to the west. A plateau separates these two ranges by about five miles. A large, relatively level coastal plain borders the Schofield Plateau along the south (Stearns and Vaksvik, 1935). Pearl Harbor exists as a true coastal plain estuary within this region. Its three primary lochs represent drowned valleys of major streams which traversed the coastal plain and united to form a single channel. This river flowed to the sea in the now-flooded valley which, today, forms the entrance channel for Pearl Harbor (Cox and Gordon, 1970). The lochs have been considerably altered in shape by sea-level changes, erosion, sedimentation, landfill activities, and dredging. Land near all harbor waterfront areas is very flat (less that 20 feet above sea level), rising slightly across Kamehameha Highway to 80 feet at the rim of Makalapa Crater to the east (U.S. Navy, 1983). To the north of East and Middle Lochs, elevations rise rather abruptly to about 100 feet above sea level. To the west along the Ewa Plain and to the south along Hickam AFB, the topography remains relatively flat.

[3] Evans, E. C., III (ed.), 1974. *Ibid.*, §5.0, pp. 1-20.

Table 1. Summary of Pearl Harbor site-specific environmental investigations.

Author/Organization	Date	Study/Type	Measurements	Location	Remarks
Akazawa/DOH	1978	Env.Monitoring	Sed-Tissues	WestLoch	Poll. Study
Akazawa/DOH	1981	Env.Monitoring	ChlorHydr/PCB	Several	Poll. Study
Aqua Terra Tech, Inc./ for PACDIV	1988	LandfillHazWst	Sed-Tis-Water	PearlCty	IR/Confirm
Ashwood/ORNL	1986	TraceMetalAssmt	Sediments	MidLoch	InactShips
Ashwood/ORNL	1989	TraceMetalAssmt	Sediments	MidLoch	InactShips
B-K Dynamics,Inc/for HECo	1972	PowerPlantEnvSt	Temp-Sal-Bio	EastLoch	Waiau Plant
Brock/City & Co Hono	1980	Dredging	Sed:bioassay	WestLoch	No Toxicity
Chave & Miller/NAVFAC	1978	DredgeDispSite	Env.Baseline	Offshore	Ecology
Evans/NavalUnderseaCntr	1972	Biolog.Survey	Heavy Metals	Entire	Assessment
Evans/NavalUnderseaCntr	1974	Env.BaselineSur	Sed-Wat-Biota	Entire	Assessment
Grovhoug/NUC	1976	Env.SurveyTech.	Sed-Wat-Biota	Several	Bioindicator
Grovhoug/NOSC/PacDiv	1979	Env.Assessment	Biota-Water	Several	Plankton
Grovhoug/NOSC	1980	MarineFouling	Biota	Several	Assessment
Grovhoug/NOSC	1980	MarineBorers	Biota	Several	Assessment
Grovhoug/NOSC	1984	Env.Status	Sediment Types	Entrance	Assessment
Grovhoug/NOSC	1987	Env.Monitoring	Wat-Sed-Tis	Entire	TBTAFPaint
Grovhoug/NOSC	1989	Env.Monitoring	Wat-Sed-Tis	Entire	TBTAFPaint
Grovhoug/NOSC/PacDiv	1990	Env.Monitoring	Sed-Wat-Biota	Several	BRCC-EIS
Guinther/AECOS,Inc.	1982	Maint.Dredging	Sed:bioassay	Mag.Loch	No Toxicity
Guinther/AECOS,Inc.	1990	Maint.Dredging	Sed:bioassay	Entire	No Toxicity
Henderson/NOSC	1982	Env.Status	Benthic Metab.	Several	HullClean
Henderson/NOSC	1985	Microcosm	Bioassay	Ford Is.	TBT Paint
Henderson/NOSC	1988	Microcosm	Bioassay	Ford Is.	TBT Paint
Henderson/NOSC/PacDiv	1991	DredgingDisposal	Sed:Bioassay	Ford Is.	No Toxicity
Inter Tech Corp./for PacDiv	1990	Landfill/HazWste	Sed-Wat-Tis	PearlCty	IR/Confirm
Kennedy Engineers/PacDiv	1979	Indust. Wastes	Chemicals	Several	Sources
McCain/ for HECo	1974	Env.Survey	Temp-Sal-Biot	EastLoch	Waiau Plant
Somerton/NMFS/NOAA	1990	Fisheries/Nehu	Distribution	Entire	Baitfish
Sunn, Low, Tom & Hara, Inc	1967	Indust. Wastes	Chemicals	Several	Sources
U.S. Dept of Interior (FWPCA)	1969	Pollution Study	Wat-Bact-Nutr	Entire	Assessment
U.S. EPA/Off.Rad.Progr.	1987	Radiological	Co-60, K-40, γ	Entire	PHNavShpY
U.S. NAVY/NEESA	1983	NACIP/IAS	Chemicals	Entire	HazMatls
U.S. NAVY/PacDiv	1990a	BRCC (EIS)	Wat-Sed-Tis	Several	Assessment
Youngberg/for PacDiv	1973	Sed-Soil Survey	Chemicals	Entire	Assessment

GEOLOGY AND SOILS

The island of Oahu was formed by volcanic activity along a ridge in the Pacific Ocean and consists of the eroded remnants of two shield volcanoes (Youngberg, 1973a). The geologic history of the harbor has been outlined in detail by Stearns and Vaksvik (1935). The west side of the harbor is composed primarily of limestone reef material, while the primary geologic element on the eastern side is volcanic tuff. Volcanic basalt forms the bulk of rock material to the north. Marine and terrestrial sediments occur around the perimeter of the harbor (Youngberg, 1973b).

Soils within the Pearl Harbor basin are primarily comprised of materials known as the Lualualei-Fill Land-Ewa Soil Association (U.S. Department of Agriculture, 1972). This mixed material consists of well-drained, fine-textured or moderately fine-textured soils present on fans and in drainageways on the southwestern coastal plain of Oahu. The soils are formed in alluvium and are nearly level to moderately sloping. The fine-grained materials are primarily inorganic clays of high plasticity. This association makes up about 14% of Oahu soils (U.S. Navy, 1984).

Dredge spoil fill material is common in areas adjoining Pearl Harbor. The dredge spoils in the Southeast Loch area consist of semiconsolidated shell and coral fragments mixed with silty muds. A typical subsurface soil profile along the eastern shoreline of Pearl Harbor consists of sand, silty clay and various types of rubble and debris resulting, in large part, from fill operations dating back to the 1930s (U.S. Navy, 1984).

SURFACE WATER

The freshwater supply for Pearl Harbor is derived from five perennial streams (Halawa, Kalauao, Waiawa, Waikele, and Waimalu) and three intermittent streams (Aiea, Honouliuli, and Waiau) (U.S. Department of Interior, 1969). The perennial streams have headwaters in the high-rainfall forest reserve region of the Koolau Range. These streams drain agricultural and newly urbanized lands before passing through highly urbanized areas near the harbor where they remain brackish for short distances upstream (Cox and Gordon, 1970). Stream discharges are supplemented by flows from five large springs emerging at the toes of bedrock ridges between the streams, where coastal plain sediments were modified by wave erosion. Some of the discharge from springs is diverted for taro and watercress irrigation (Cox and Gordon, 1970). Freshwater also enters Pearl Harbor from artesian springs and shallow aquifers. Total freshwater inputs to Pearl Harbor (Cox and Gordon, 1970) are summarized in table 2. The volume of freshwater entering Pearl Harbor has been estimated at 50 million gallons per day (mgd) during dry periods, and greater than 100 mgd during rainy periods (Cox and Gordon, 1970; B-K Dynamics, 1972). The total drainage area for Pearl Harbor is estimated to be 285 km^2 (110 mi^2) and is shown in figure 4. Siltation rates are highest in Middle and West Lochs, which both receive larger stream flows than East Loch. The entire harbor becomes a "red water" area during and after significant storms (AECOS, 1979; observations by the author).

Table 2. Estimated total annual freshwater inputs to Pearl Harbor estuary. Modified from Cox and Gordon (1970). Refer to figure 2 for reference locations.

(a) Tributary Stream Flows

Loch	Stream	Est. Max. Flow(MGD)	Est. Min. Flow(MGD)
West	Waikele	26	6
Middle	Waiawa	16	2
East	Waimalu	5	0
	Kalauao	1	0
	Halawa	8	0
Total		56	8

(b) Tributary Spring Flows

Loch	Spring	Mean Flow (MGD)	Minimum Flow(MGD)
West	Waikele	22	5
Middle	Waiawa	14	11
East	Waimanu-Waiau	32	21
	Kalauao	19	14
Total		87	51

(c) Annual Freshwater Estimates for Dry/Wet Years

Source	DryYear Flows (MGD)	Wet Year Flows (MGD)
Streams	8	56
Springs	31	87
Wells	5	8
Shallow aquifers	6	10
Total	50	161

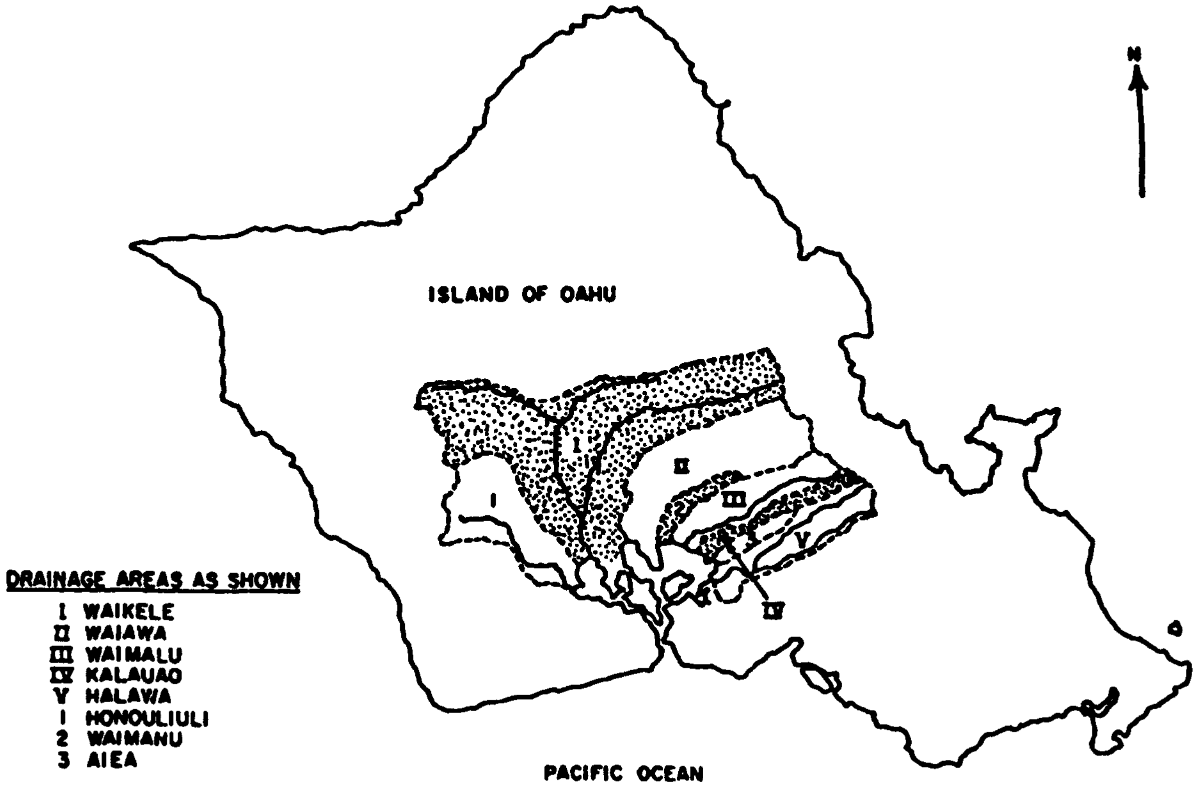

Figure 4. Pearl Harbor Drainage Basin (from FWPCA, Pearl Harbor Pollution Survey, 1969).

GROUND WATER

The movement of groundwater is controlled by local hydrologic conditions which influence the supply and distribution of water (Youngberg, 1973b). The Pearl Harbor area has both sedimentary caprock aquifers and basaltic aquifers. Sedimentary caprock lies atop an unconfined aquifer in which water moves downward to the zone of saturation (water table). The caprock is underlain by an impermeable stratum which overlies and confines the basaltic aquifer. The Koolau basalt aquifer is still artesian in the Pearl Harbor area (U.S. Navy, 1983). Contaminants have a potential migration pathway, because overlying basalts and soils are highly permeable except in areas overlain by sedimentary caprock. During tests performed at landfill sites adjacent to Pearl Harbor, it was concluded (Youngberg, 1973) that landfill operations at the Pearl City Landfill (bordering Middle Loch) and the City and County Landfill (Waipio Peninsula bordering West Loch) had no perceptible deleterious effects upon the water quality of Pearl Harbor. More recent studies at the Pearl City Peninsula Landfill Site (Aqua Terra Technologies, Inc., 1988; International Technology Corporation, 1990) have suggested that a moderate potential exists for groundwater contamination at this site.

CLIMATE AND METEOROLOGY

The Pearl Harbor Naval Complex is influenced by relatively moderate meteorological conditions due to its low elevation on the leeward side of Oahu. Northeast tradewinds that average 10–12 mph over Pearl Harbor prevail during most of the year. During infrequent, isolated "Kona" storms from the south, wind velocities up to 40 mph occur. These south winds are usually accompanied by wet tropical air masses, resulting in heavy shower activity. Rainfall averages about 25 inches per year for the Pearl Harbor Naval Complex region. The heaviest precipitation usually occurs during winter months (November to April), especially during Kona storms.

Air temperatures generally range from 70 to 90°F (21.1 to 32.2°C) during summer months and 60 to 80°F (15.2 to 26.7°C) during winter months. Low winter temperatures are generally caused by a shallow layer of cold air that flows down from the Koolau Mountains over lowland areas during reduced wind periods. Relative humidity at Pearl Harbor Naval Complex varies from 55 to 80% throughout the year. Higher humidity usually occurs during weather front passages or during episodes of Kona wind conditions. Mean daily humidities range from 62 to 65%.

LAND USES

Land use within the controlled area of the Pearl Harbor Naval Complex is primarily limited to operational and industrial activities, unaccompanied personnel housing, and related administrative, training, and support facilities (U.S. Navy, 1984). Encroachment issues for the operational areas of Pearl Harbor are minimized because the miltary controls all the harbor waters and most of the harbor shoreline.

Land use in private or public areas adjacent to Pearl Harbor has shifted from primarily agricultural (including sugar cane, pineapple, taro, and watercress farming) to commercial, industrial, and residential. A marked increase in urban development on leeward Oahu is reflected by recent extensive housing development in the Pearlridge, Waimalu, and Waiau areas of Pearl City since 1970. Waipahu and Ewa Beach regions have experienced greatly increased residential growth in the past few years. Commercial or light industrial complexes have also accompanied this growth. The construction of the Honolulu International Airport reef runway during 1973–1977 required extensive land filling activities (an estimated 19 million yd3 of dredged material) which modified water circulation patterns and the marine habitat near the harbor entrance channel (AECOS, 1979).

CRITICAL ENVIRONMENTS

Several wetland areas are located adjacent to Pearl Harbor in East Loch, Middle Loch, and West Loch and on the Waipio Peninsula. The Pearl Harbor National Wildlife

Refuge has two units located at Honouliuli in West Loch and at Waiawa on Pearl City Peninsula (State of Hawaii, 1979). These areas are known habitats for several endemic and endangered waterbird species, including the Hawaiian stilt, "A'eo" (*Himantopus knudseni*), the Hawaiian coot, "Alae Ke'oke'o" (*Fulica americana alai*), the Hawaiian duck, "Koloa" (*Anas wyvilliana*), and the Hawaiian gallinule, "Alae 'ula" (Gallinula chloropus sandvicensis)(U.S. Navy, 1982 and 1989b). The endemic Hawaiian or Short-eared Owl, "Pu'eo" (*Asio flammeus sandwichensis*) also hunts in the area. This owl is very rare on Oahu and has been listed as endangered by the State of Hawaii (U.S. Navy, 1989b).

All lands and waters within the Pearl Harbor Naval Complex are listed for the conservation and management of fish and wildlife resources in a cooperative agreement between the U.S. Navy, U.S. Fish and Wildlife Service, National Marine Fisheries Service, and Hawaii State Department of Land and Natural Resources (U.S. Navy, 1983).

Quiet waters in the upper regions of all major Pearl Harbor lochs provide excellent habitats for the Hawaiian anchovy, "nehu" (*Encrasicholina purpurea*), a species used as a baitfish in the offshore tuna, "aku," fishery. This species is the most important baitfish resource in Hawaii, and Pearl Harbor provides a primary harvesting area in the state (Grovhoug, 1979). For these reasons, the U.S. Navy issues permits for insured commercial aku boats to collect baitfish from certain regions of Pearl Harbor.

The importation of eastern oysters (*Crassostrea virginica*) into Pearl Harbor began as early as the 1870s; however, these initial transplantation efforts did not succeed in establishing viable populations. Additional introductions of this species in the 1890s and 1920s (Sparks, 1963) resulted in the establishment of an enormous population of eastern oysters in West Loch by the middle of the twentieth century. Sparks conservatively estimated that over 35 million live oysters were present in West Loch in 1962. This resource has not been harvested commercially due to severe and chronic bacterial contamination. In July 1972 an oyster-specific microbial infestation caused massive mortality in the West Loch oyster population. Present oyster abundances in West Loch are considerably lower than those of the 1960s.

Field observations made during previous intensive sampling and diving operations revealed that two major groups of organisms are not found inside Pearl Harbor. Hermatypic (i.e., stony) corals are present throughout most bays and harbors on Oahu, yet are remarkably absent from Pearl Harbor. One species of soft coral (*Telesto riisei*) is common in Pearl Harbor.[4] This shallow-water Atlantic species was probably introduced into the harbor from the hulls of ships. Sea urchins (echinoids) are another group that is absent from the harbor. The specific reason for the absence of these otherwise common Hawaiian taxa, is uncertain, although both groups are known to be relatively

[4] Evans, E. C., III (ed.), 1974. *Ibid.*, Appendix 1, p. 1.

sensitive to the effects of siltation and freshwater. Corals and sea urchins are present in Honolulu Harbor, a heavily industrialized harbor on Oahu. Minimal siltation and freshwater effects are present, but high levels of industrial contaminants exist there.

POTENTIAL SOURCES OF ENVIRONMENTAL CONTAMINATION

WASTE CHARACTERIZATION

Pollutants in many forms and from multiple sources enter the Pearl Harbor ecosystem. This section presents an overview of the pollution history for the estuary. A summary is provided of the types, harbor locations, and estimated amounts of various contaminant substances, with references to detailed environmental or engineering studies (table 3). The present site investigation focuses on environmentally pertinent aspects of the sources of Pearl Harbor's contamination. Potential sources for environmental contamination in sediment, water, and selected marine organisms are addressed in general terms. Detailed listings of contaminant discharges affecting Pearl Harbor are available (U.S. Navy, 1983; Kennedy Engineers, 1979; GMP Associates, 1990). Terrestrial impacts and sources of pollution are mentioned where appropriate; however, the harbor's estuarine environment forms the central focus of this assessment. Categories of contaminants are described in the following sections.

Sedimentation/Siltation

Siltation is a principal contaminating process in the Pearl Harbor ecosystem (U.S. Navy, 1977; AECOS, 1979). Freshwater streams annually transport an estimated 96,300 tons (or 180,000 yd^3) of sediment into Pearl Harbor (Nystedt, 1977). From 1959 to 1990, U.S. Navy maintenance dredging in Pearl Harbor removed approximately 9 million yd^3 of bottom material from the harbor.* Maintenance dredging is required on a four-to-five-year cycle.

Water transparency measurements made during April–May 1990, (U.S. Navy, 1990a) verified that harbor waters continue to be turbid in the upper layer of the water column. A harborwide average Secchi disc reading of 2.5 meters (or 8.2 feet) is consistent with measurements taken previously; however, many harbor areas exhibit turbid water conditions, especially after periods of heavy rainfall. Persistent turbidity in Pearl Harbor results from the combined effects of siltation, nutrient loading, plankton abundance, and vertical mixing in the water column caused by wind- and vessel-driven sediment resuspension.

* Personal communication with Mike Lee, Operations Division, U.S. Army Corps of Engineers, Feb 1991.

Table 3. Major categories of potential environmental contaminants in Pearl Harbor. Refer to figures 2 and 3 for locations.

Contaminant Type	Locations*	Est. Amount	Approx. Dates	Refs**
Bacteriological (pathogenic)	WL,ML,EL,CH,RBM	High	1930s-Now	DoH,PWC IAS,PHBS
Heavy Metals	EL,SEL,NSY, ML,RBM	Low	1910s-1980s	PHBS,IAS DoH
Hydrocarbons	CH,EL,SEL,ML	Moderate	1920s-Now	IAS,PHBS
Ordnance Wastes	West Loch	Low	1940s-1980s	IAS
Radiological	NSB,NSY,WL	Very Low	1960s-Now	EPA,IAS
Sewage (from municipal/ship-board sources)	CH,WL,ML,EL,RBM	Low	1950s-1980s	DoH,IAS, PHBS, NOSC
Siltation	All Lochs	Very High	1800s-Now	USGS,IAS
Toxic Organic Compounds	NSY,EL,SEL,ML,WL, CH,RBM	Moderate	1950s-Now	IAS,PHBS DoH

*Locations:
- CH = Entrance Channel (up to Hospital Point).
- EL = East Loch, Ford Island, North & South Channels.
- SEL = SouthEast Loch.
- ML = Middle Loch.
- NSB = Naval Submarine Base, Pearl Harbor.
- NSY = Pearl Harbor Naval Ship Yard.
- RBM = Rainbow Bay Marina, Aiea Bay.
- WL = West Loch.

**Data Sources:
- DoH = Hawaii State Department of Health (1978). "Distribution of Heavy Metals, Chlorinated Pesticides, and PCB's in Hawaiian Estuarine Environment."
- EPA = U.S. Environmental Protection Agency (1987). "Radiological Survey of the Pearl Harbor Naval Shipyard and Environs."
- IAS = U.S. NAVY (1983). "Initial Assessment Study of Pearl Harbor Naval Base, Oahu, Hawaii."
- NOSC = Naval Ocean Systems Center (Hawaii Laboratory) (1983). R.S. Henderson, unpublished data compiled from various Navy, City, & County of Honolulu sources.
- PHBS = Naval Undersea Center, Dr. Evan C. Evans III (1974). "Pearl Harbor Biological Survey-Final Report," TN 1128.
- PWC = U.S. Navy Public Works Center, Industrial Testing Laboratory (X-11) (1990). Unpublished data, RBM.
- USGS = U.S. Geological Survey (1990) various related sedimentation data.

In 1977 a specialty conference was convened by the U.S. Navy, offering a forum to discuss the problems of sedimentation, erosion, and tributary flow into Pearl Harbor (U.S. Navy, 1977). During panel discussions, repeated references were made to the recurring siltation impact in Pearl Harbor. Several land-use solutions were suggested to reduce the effects of sedimentation and erosion in the Pearl Harbor watershed areas which consist primarily of forest, agricultural lands, and more recently, suburban housing development. New grading ordinances and soil erosion control measures have been implemented. Sediment trapping devices were suggested to delay the transport of upland materials via tributary streams into the harbor. Changes in agricultural practices, such as drip irrigation to reduce erosion and sedimentation, were also discussed. As a natural wetland, marsh and swamp environment, Pearl Harbor has historically existed as a natural sedimentation basin. The harbor ecosystem that developed under these circumstances propagated organisms which were compelled to adapt to a turbid, high-sediment-loading environment.

Microorganisms

The contamination of waters and shellfish (primarily oysters) by pathogenic bacteria and other microorganisms has been a persistent condition in Pearl Harbor for many years. Streams and sewage effluent discharges serve as primary pathways for the introduction of bacteria into the harbor. High levels of coliform bacteria have been documented for West Loch (Sparks, 1963; U.S. Department of the Interior, 1969; Morris et al., 1973). The revised State of Hawaii 1989 Water Quality Regulations (Title 11, Chapter 54) state that "fecal coliform content shall not exceed a geometric mean of 200 per one hundred milliliters..." and that "enterococci content shall not exceed a geometric mean of 7 per one hundred milliliters...." These standards are regularly exceeded in West Loch and several other harbor regions as a direct result of nonpoint source pollution (State of Hawaii, Department of Health, 1990a, b). Pearl Harbor is listed as one of 14 Water Quality Limited Segments (WQSLs) in the State. WQSLs are waterbodies within the State which, without additional action to control nonpoint sources of pollution, cannot reasonably be expected to attain or maintain State Water Quality Standards.

Toxic Organic Compounds

Toxic organic compounds include organic pollutants not associated with petroleum products such as solvents, paints, pesticides, and polychlorinated biphenyls. An Initial Assessment Study (U.S. Navy, 1983) performed under the Installation Restoration (IR) Program lists various estimates for previous discharges of these types of chemicals. Throughout the harbor, some regions exhibit elevated concentrations of toxic organic compounds in sediments. Maintenance dredging activities serve to partially mitigate the effects of sediment contamination in the harbor environment by periodically removing upper layers in the sediment column (U.S. Navy, 1983).

Pesticide contamination in the Pearl Harbor ecosystem has primarily been caused by surface water runoff from agricultural areas in the watershed. Changes in agricultural practices and the urbanization of large areas of previous agricultural lands on central Oahu have probably lessened pesticide impact during recent years; few studies, however, have addressed this potential source of contamination (Akazawa, 1978; Henderson, unpublished data, 1981).

Polychlorinated biphenyls (PCBs) have been introduced into the harbor from various industrial sources, primarily in the naval shipyard region, where several transformer accidents have occurred. During May 1990 personnel from the Hawaii Laboratory of the Naval Ocean System Center (NOSC) collected sediment samples from South Channel and Southeast Loch and analyzed them for PCB concentrations (see Appendix B). The measurements of Aroclor 1260—mean concentration of 510.73 μg/kg (ppb) dry weight (s.d.=332.52; n=15)—correspond with concentrations reported during maintenance dredging environmental studies (AECOS, 1990) from the same harbor region.

Antifouling Coatings And Wood Preservatives

Antifouling paints contain toxic materials to prevent the growth of marine organisms on ship hulls. The slow leaching of toxicants from the paint matrices provides long-term antifouling capabilities. Thus, toxic material is steadily released into harbor waters from the antifouling coatings on ship hulls. During the past several decades various paint formulations have been tested by exposing test panels in Pearl Harbor's high fouling environment (Grovhoug and Rastetter, 1980a). A David Taylor Research Center/PHNSY paint test site is located near Drydock #4 (on the seaward side of Hospital Point). And in the lower West Loch the Naval Civil Engineering Laboratory has tested methods that use various toxic compounds to preserve wooden pilings. The moderate incidence of marine borer activity in Pearl Harbor (Grovhoug et al., 1980b) mandates the use of protective measures for wooden structures exposed to the harbor environment.

Copper-based antifouling paints are used on most U.S. Navy vessels at this time. Because copper is not entirely effective as an antifoulant, periodic hull cleaning is required. These hull-brushing operations are performed by divers at several locations in Pearl Harbor, primarily in Southeast Loch. In-water hull cleaning operations release variable amounts of paint residue and fouling debris (depending on the condition of the paint and the amount of fouling growth) into harbor waters. The Navy is currently studying the potential environmental and operational consequences of hull cleaning activities in Pearl Harbor and San Diego Bay.

During 1986–1989 the Navy used Pearl Harbor as a test site for the evaluation of the possible fleetwide use of organotin paints (Grovhoug et al., 1989). Three navy vessels were painted in the Pearl Harbor Naval Shipyard with a newly developed, low-leaching antifouling paint. Comprehensive harbor monitoring was performed to evaluate the effect of organotins on the Pearl Harbor environment (Grovhoug et al., 1989). This study concluded that there would be minimal impact in the Pearl Harbor estuary from the fleetwide implementation of low-release-rate organotin paints when specified application and drydock cleanup procedures were used.

Hydrocarbons

Hydrocarbon contaminants include all petroleum-based fuel products such as diesel, JP-5, JP-4, AVGAS, bunker fuel, gasoline, oils, sludges, and lubricants. Pearl Harbor has been exposed to chronic hydrocarbon contamination during the past fifty years (U.S. Navy, 1990a). The USS *Arizona* continues to release small amounts of bunker fuel contained within the ship when she was sealed as a memorial to those men who perished on December 7, 1941. During the last several years there have been several spills from both civilian and U.S. Navy sources. Nonpoint source inputs from chronic surface runoff, underground regions of pipe or container leakage, barge and oil/water separators, and vessel bilge water are existing pathways for hydrocarbon introduction into the harbor. East Loch (including Southeast Loch) has been the harbor region most impacted by hydrocarbon contamination.

Trace Metals

Various concentrations of trace metals such as silver (Ag), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) have been reported for sediments, waters, and tissues of organisms from Pearl Harbor (Bathen, 1971; Akazawa, 1978; U.S. Navy, 1990a). Trace element burdens in harbor samples are generally the result of inputs from streams, ships, and industrial activities. Some of the trace metal concentrations reported for Pearl Harbor are likely derived from natural processes (Turner, 1975). Chromium and nickel are related to basaltic mineral deposits. Iron, zinc, lead, and copper are correlated with the occurrence of anaerobic bottom conditions (Turner, 1975). Surface and bottom water trace metal concentrations measured recently from nine locations throughout the harbor (U.S. Navy, 1990a) were within water quality standards set by the state (State of Hawaii, Department of Health, 1989). Akazawa (1978) reported that heavy metal concentrations in fish and shellfish tissue samples collected from Pearl Harbor in most instances were comparable to measurements in other Hawaiian harbors.

Domestic/Shipboard Sewage Effluents

Sewage was a major long-term source of contamination in Pearl Harbor until pipeline construction projects diverted most sewage treatment plant (STP) effluents from the harbor (Henderson, unpublished NOSC data, 1983). Additionally, U.S. Navy vessels stopped releasing shipboard wastewater effluents into the harbor after collection, holding, and transfer (CHT) tank systems were installed during the mid-1970s (Harrison, 1988). Table 4 presents a summary of the sewage treatment plant diversion, nutrient concentrations, and flow data related to Pearl Harbor. Ford Island STP effluent (0.4 MGD) has been diverted to the Fort Kamehameha plant for 10 years. The

Iroquois Point STP ceased discharges into the entrance channel in 1984 (U.S. Navy, 1990a). The Fort Kamehameha plant discharges secondary-treated sewage effluent into the entrance channel adjacent to Iroquois Point. Nutrient data from a monitoring station near this outfall are shown for 1984–1989 in figure 5.

Only a small percentage of this effluent is estimated to enter inner harbor areas, based on reported surface and bottom water circulation patterns (Bathen, 1972). While some municipal sewage may enter the inner harbor in upper loch regions via seepage and stream flows, the exposure is notably less than in the past. During heavy rainfall periods or extended power outages, municipal raw sewage effluent has occasionally been diverted into several streams entering the harbor. Tributary streams and sewage effluent provide a rich source of organic materials to Pearl Harbor. This organic loading can often exert major biochemical oxygen demand (BOD) effects which stress certain benthic organisms.

Table 4. Listing of Pearl Harbor sewage treatment plant (STP) diversion, nutrient concentrations and flow data.

STP	*Diversion Date*[1]	*Total Kjeldahl N*	*Total Nitrogen*	*Total Phosphorus*	*Flow (MGD)*
Pearl City	Jan 1983	ND	18.0	30.0	8.1
Waipahu	Jan 1982	21.4	21.7	6.5	3.0
Mililani	Nov 1983	18.6	25.2	8.9	2.0
Pacific Palisades	Sep 1982	24.9	26.7	7.0	0.5
Halawa	Dec 1982	ND	21.0	10.0	0.4
Iroquois Pt	Jan 1984	ND	ND	ND	ND
Fort Kamehameha	NONE	6.5	5.0[2]	5.0[3]	6.5

Legend:
[1] Sewage diversion out of Pearl Harbor, except Ft. Kam STP
[2] NH_4 rather than Total Nitrogen
[3] PO_4 rather than Total Phosphorus
ND = No Data

Notes: Data compiled by NOSC Hawaii Laboratory personnel via phone contacts with City and County Sewers Division, Hawaii State Department of Accounting and General Services, and Fort Kamehameha Sewage Treatment Plant personnel; flow data provided by Mr. Klein/Mr. Hustace at Fort Kamehameha STP and BRCC Final Environmental Impact Statement (US Navy, 1990).

Notes: Data compiled by NOSC Hawaii Laboratory personnel via phone contacts with City and County Sewers Division, Hawaii State Department of Accounting and General Services, and Fort Kamehameha Sewage Treatment Plant personnel; flow data

provided by Mr. Klein/Mr. Hustace at Fort Kamehameha STP and BRCC Final Environmental Impact Statement (U.S. Navy, 1990).

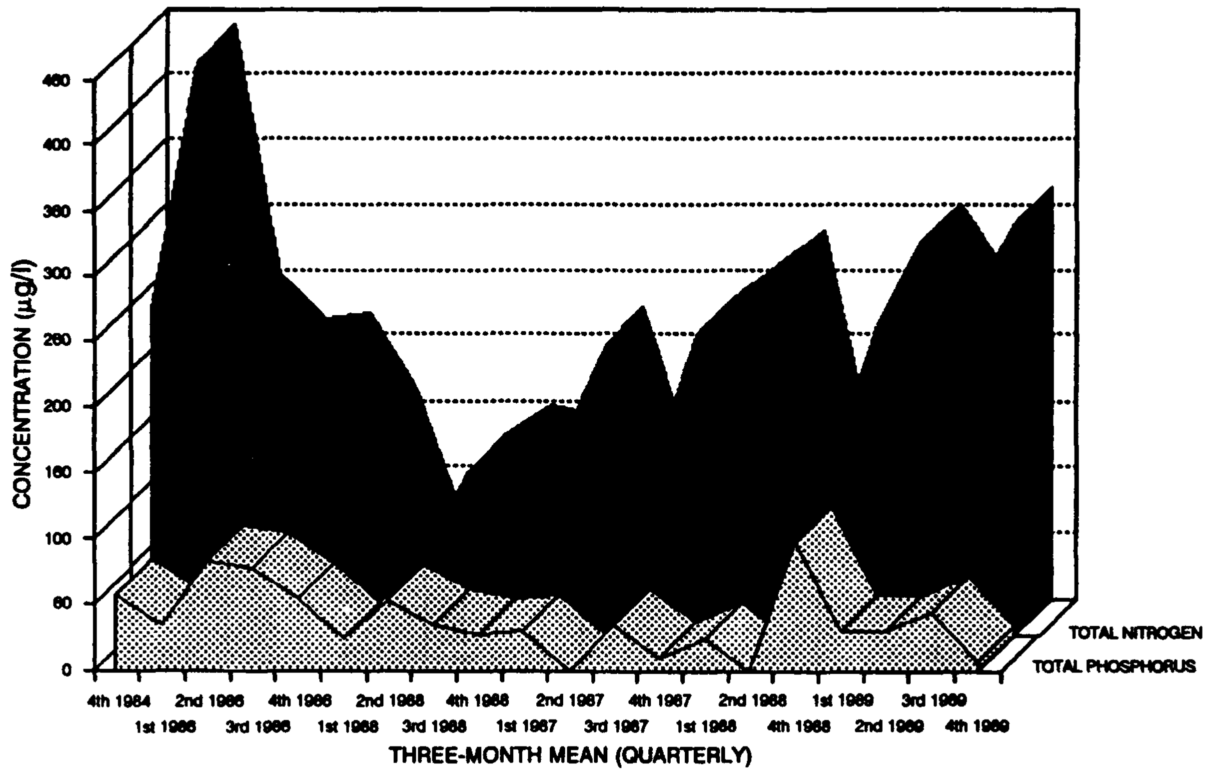

Figure 5. Fort Kamehameha STP effluent discharge data (nutrient loading) at Pearl Harbor entrance channel during 1984–1989.

Ordnance Wastes

The category of ordnance wastes includes explosives compounds such as RDX, TNT, picric acid, tetryl, nitrobenzene, ordnance casings and other munitions components (Johnston et al., 1989). The primary harbor region for potential contamination by this category is located in West Loch. In order to document the presence of ordnance-related contamination, specifically designed collections and analyses would be required. However, in the absence of specific study data, it is generally estimated that the probability for serious ordnance contamination in water, sediment, or tissues of organisms in Pearl Harbor is low. After extensive field observations (Grovhoug, 1979; Grovhoug and Rastetter, 1980a; Grovhoug et al., 1980b, 1987, 1989) investigators ranked the general environmental quality in West Loch higher than many other regions of the harbor.

Radiological Material

The operation of U.S. Navy nuclear propulsion plants on vessels berthed in Pearl Harbor suggests potential radiological contamination in the harbor environment.

However, detailed surveys (M&E Pacific, 1983; U.S. Environmental Protection Agency, 1987) concluded that no significant radiological contamination was present in water, tissue, or sediment samples in the harbor.

CONTAMINANT TOXICITY CONSIDERATIONS

The toxicological characteristics of organic and inorganic chemical compounds present in Pearl Harbor sediment and water have not been well documented, a realistic evaluation of the acute or chronic toxicity for a single contaminant (or complex of toxic substances) on test organisms dictates the precise consideration of many factors. The sole reliance on toxicological data or environmental concentrations reported from other geographic locations should be avoided (U.S. Environmental Protection Agency, 1989a). The degree of toxicity of and the magnitude of exposure to major contaminants must be considered to adequately address toxicological risks to the Pearl Harbor environment. Since various organisms respond to the same contaminant dose in different ways (Phillips, 1980), site-specific, multispecies microcosm bioassays offer the best method of evaluating biological response to various contaminants (Henderson and Smith, 1978). A microcosm facility was operated intermittently on the west side of Ford Island during the period 1984–1989 (Henderson, 1985; Henderson and Salazar, 1991b). Multispecies bioassays were conducted to examine butyltin toxicities during this period.

ENVIRONMENTAL SIGNIFICANCE OF CONTAMINANT EXPOSURE

The biological availability of various contaminants varies among organisms and chemicals (U.S. Environmental Protection Agency, 1989a; Phillips, 1980). Bioavailability is influenced by environmental factors such as temperature, salinity, pH, redox potential, particle size distribution, and organic carbon concentration. Because biota accumulate contaminants differentially in their tissues, environmental concentrations and uptake rates will not necessarily predict biotic concentrations (U.S. Environmental Protection Agency, 1989a).

Bioassays have been performed using resident Pearl Harbor biota (Brock, 1980; AECOS, 1982; AECOS, 1983; Henderson, 1985) and standard U.S. mainland bioassay test organisms (AECOS, 1990; Henderson, 1991a) as part of dredge disposal permit requirements. The minimal toxicity demonstrated during these tests represents a notable trend observed in all available sediment bioassay data from Pearl Harbor. Sediments from all major regions of the harbor have consistently produced negligible effects on test organism survivability. Bioaccumulation studies conducted in conjunction with the toxicity bioassays resulted in significant uptake in only one of 32 cases (Henderson, 1991a). Additionally, extensive dredge disposal site investigations (Chave and Miller, 1978a–1978d) concluded that adverse environmental effects were not measurable. Baseline environmental studies at this disposal site, located at a depth of 200 fathoms off the entrance to Pearl Harbor, consisted of bathymetric, bottom sediment, mineralogic, water quality, zooplankton, micronekton, benthic fauna, and photographic analyses.

FATE AND EFFECTS OF HAZARDOUS SUBSTANCES

POTENTIAL EXPOSURE PATHWAYS

Contaminant exposure pathways for the Pearl Harbor ecosystem (including the human population) are primarily those pertaining to the waterborne migration of pollutants. Surface and groundwater, as well as sediment transport from the watershed, provide the most probable pathways for contaminant migration into the harbor. Fortunately, two former pathways of pollutant transfer, sewage and industrial outfalls (Duce et al., 1974), have been significantly reduced for Pearl Harbor since the early 1980s (U.S. Navy, 1983; U.S. Navy, 1990a; Henderson, unpublished NOSC data, 1983).

Airborne contaminants exhibit only minor influence on the harbor's marine environment. Paint application and grit blasting operations at the Pearl Harbor Naval Shipyard may have some localized effects. A city and county of Honolulu incinerator, located adjacent to the Waipahu Landfill, ceased operation in the mid-1970s. The location of Campbell Industrial Park and sugar cane fields (where controlled burning occurs) to the west and the dispersion effect of predominant northeasterly tradewinds serve to minimize exposure from these sources.

Once contaminants reach the harbor, multiple migration pathways exist. Particulate trace metals may be enriched in the surface microlayer by transport on the surface of bubbles or foam (Duce et al., 1974). Dispersion throughout the harbor by wind-driven surface currents has been measured.[5] The migration of contaminants through harbor waters into the bottom sediments readily occurs. The remobilization of contaminants from the sediments during dredging or the movement of large vessels in the harbor has also been suggested.[6] Resident organisms such as fishes, algae, plankton, and sessile and benthic biota may incorporate contaminants into their tissues from the water column, sediment, or diet media. Pearl Harbor organisms such as certain fishes, crabs, oysters, and algae provide a potential human exposure pathway through consumption as food.

Most contaminants experience extensive chemical and physical changes after entering the marine environment (Phillips, 1980). These complex modifications result from a combination of interactions with such physical conditions as variations in particulate

[5] Evans, E. C., III (ed.), 1974. *Ibid.*, §3.3, pp. 1-76.
[6] Evans, E. C., III (ed.), 1974. *Ibid.*, §5.0, pp. 23-24.

loading, temperature, salinity, dissolved oxygen, and pH parameters. Chemical processes such as oxidation, reduction, and complexation have profound effects on the behavior and environmental fate of various contaminants, particularly in the sediment. Biological transformation through the metabolic activities of organisms modifies many pollutant substances. The bioaccumulation of contaminants by marine organisms such as oysters, clams, crabs, shrimp, and fishes has been documented in Pearl Harbor (AECOS, 1979; Grovhoug, 1989; Henderson, 1991a). The bioconcentration of pathogenic bacteria in West Loch oysters has been observed (Sparks, 1963; Department of the Interior, 1969). Contaminant migration through the harbor food web is another viable migration pathway. The burrowing activities (bioturbation) by bottom-dwelling organisms such as snapping shrimp, mantis shrimp, worms, and certain fishes promote the migration and transport of various contaminants in the bottom sediments. A summary of potential contaminant exposure pathways for Pearl Harbor is provided in table 5.

Table 5. Potential contaminant exposure pathways for Pearl Harbor.

Major Pathway	Contaminant Source	Remarks
Air	Paint Application Overspray	DryDocks, RAV Piers
	Sandblasting Grit	DryDocks, SE Loch, Middle Loch, Oscar Pier
	Volcanism (Atmospheric)	During "Kona" Wind Conditions (from South)
	City & County Incinerator	Heavy Metals Discharged
Water (Ground)	Landfill Leachates, USTs	Landfills
Water (Surface)	Tributary Streams	Sedimentation
	Sewage Discharges	Ft. Kam STP (Channel), Streams, Seepage
	Storm Drains & Runoff	Nonpoint Sources
	Spills & Pipeline Leaks	Shipyard, East Loch
	Dry Dock Discharges	All Four Graving Docks, AFDM
	In-Water Hull Cleaning	B, M, & S Piers
Soils/Sediments	Maintenance Dredging Activities	Channels, Turning Basins, and Pier Areas
	Ship Movements in Harbor	Remobilization of Toxics
	Biological Activity	Burrowing, Bioturbation
Tissues	Fish & Shellfish	Consumption by Humans
	Algae	Consumption by Humans

These routes of exposure have been observed in the Pearl Harbor environment during the past twenty years and postulated in the open literature (Duce et al., 1974; Phillips, 1980; U.S. Environmental Protection Agency, 1988a; U.S. Environmental Protection Agency, 1989a–1989c).

BIOLOGICAL RECEPTORS

Certain Pearl Harbor organisms which are harvested and consumed by humans may contain chemical or biological contamination. Fishes, shellfish, and algae are major groups in this category. Goatfishes, mullet, surgeonfishes, and jacks from many areas of Pearl Harbor have been collected and consumed by humans. Oysters, crabs (several species), and occasionally lobsters are known to be taken from Pearl Harbor waters (primarily West Loch) to be used as food. Several species of edible algae (*limu* in Hawaiian) are regularly collected from accessible shorelines of East, Middle, and West Loch regions of the harbor. Environmentally sensitive populations in Pearl Harbor, notably plankton, diatoms, sea anemones, feather duster worms, Hawaiian anchovy (*nehu*), shorebirds, certain fish species, and larval forms of many resident biota, may be adversely affected by certain contaminants. Siltation, nutrient loading, hydrocarbons, toxic organic compounds, heavy metals, nutrient availability, freshwater presence, and many other factors influence the abundance and distribution of these biotic populations within the harbor.

SUMMARY OF ENVIRONMENTAL FIELD AND LABORATORY DATA

The following discussion summarizes several sets of data which examine trends in the present environmental status of Pearl Harbor. These studies consist of sediment bioassays, water and sediment quality measurements, population studies of baitfish, butyltin measurements and sediment trace metal concentrations. These data sets are considered by the author to represent the most rigorously collected and scientifically defensible of many reports examined. Investigations providing quantitative environmental data for Pearl Harbor have been summarized in table 1. Complete citations for these studies may be found in the references.

DATA QUALITY

The quality of data sets reviewed during this study, varied from excellent to questionable. Many of the reports examined represent significant contributions to a further understanding of certain aspects of the dynamic and complex ecosystem in Pearl Harbor. Several local scientists who have extensive knowledge and experience with ecological evaluations in Hawaii provide valuable insights into various aspects of harbor status and functions. Some reports represented simply a reiteration of older original data with minimal analysis or interpretation. Data in this category were considered to be of marginal value. Wherever possible, original data were obtained for this evaluation. Sets of data used during this investigation were considered suitable if collected, analyzed, and reported using established and validated methods.

DATA DESCRIPTIONS

Henderson (1991a) evaluated sediment toxicity during mortality and uptake studies before planned U.S. Navy dredging in South Channel adjacent to Pier F-5 in Pearl Harbor. Solid-phase ten-day bioassay and bioaccumulation tests were performed with adult clams (*Mercenaria mercenaria*) and adult shrimp (*Penaeus vannamei*) in a flow-through seawater system. Adult brine shrimp (*Artemia salina*) and postlarval shrimp (*Penaeus vannamei*) were used in a 96-hour suspended particulate phase static study. Analyses for chemical contaminants in sediments and bioaccumulation tests were performed in accordance with current requirements (U.S. Army, 1990; U.S. Environmental Protection Agency/Corps of Engineers, 1977). The results of these tests are summarized below:

1. Statistical analysis of the 96-hour bioassay and ten day bioaccumulation data demonstrated no significant differences between control and test biota in the survival of test organisms.

2. No significant bioaccumulation of measured contaminants was noted except for total butyltins in clams.

3. Priority pollutant levels measured in test sediments were insufficiently elevated to represent cause for concern.

4. The overall toxicity and biological contamination potential of sediment characteristics in this region of Pearl Harbor is considered extremely low based on the lack of organism mortality and bioaccumulation in only 1 of 32 test cases.

This study verifies the consistent trend of minimal sediment toxicity observed in previous bioassay and bioaccumulation investigations throughout Pearl Harbor (Brock, 1980; AECOS, 1982; AECOS, 1983; AECOS, 1990). Independent teams of investigators have reached similar conclusions regarding the pronounced lack of toxicity and bioaccumulation potential from most Pearl Harbor sediments.

Field data from Pearl Harbor were collected in April and May 1990 to support the preparation of a Base Realignment and Closure Commission (BRCC) Final Environmental Impact Statement for proposed developments in the Pearl Harbor area (U.S. Navy, 1990a). Sampling locations are shown in figure 6.

The primary areas investigated were the proposed Ford Island Causeway location between Bowfin Park and the eastern end of Ford Island (3 stations), Pier F5 as a future site for battleship berthing (1 station), Southeast Loch and shipyard area (3 stations), and 2 channel "control" stations. Seven of the 9 sampling locations were identical to those in the 1971–1973 Naval Undersea Center study.[7] Harbor sampling emphasized the collection of comparative water quality, benthic biota, and fish population data to facilitate an analysis of possible changes in marine environmental quality since the early 1970s. Observations and preliminary data indicate that overall environmental quality has improved since the comprehensive study in the early 1970s.

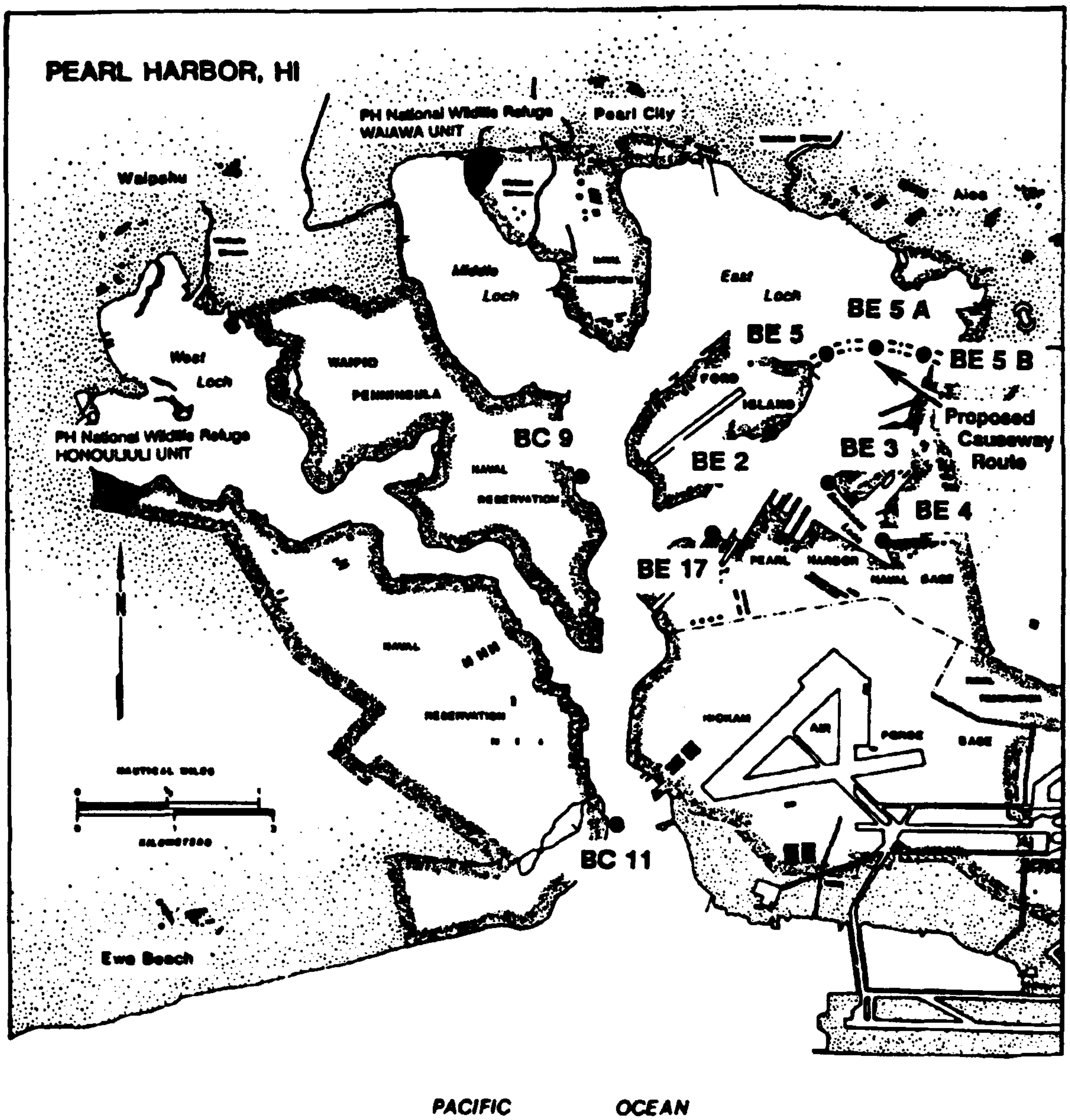

Figure 6. Pearl Harbor BRCC/battleship homeporting sampling stations (April–May 1990).

[7] Evans, E. C., III (ed.), 1974. *Ibid.*, §1.0, pp. 1–26.

Surface to bottom water profiles at 1-meter increments throughout the water column measured conductivity, temperature, depth, pH, dissolved oxygen, and salinity. Concurrently, Secchi disk (water transparency) measurements were taken and harbor water nutrient samples collected (from 1 meter below the surface and 1 meter above the bottom). Samples were analyzed at the University of Hawaii by an autoanalyzer for phosphate (PO_4) and ammonia (NH_4), and by the ultraviolet method for total phosphorus (P) and total nitrogen (N). Additionally, water column samples (surface and bottom layers) were collected and analyzed by using inductively coupled plasma atomic emission spectrometer (ICP/AES) techniques at the University of Hawaii for the following trace metals: silver (Ag), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), and zinc (Zn) content. Cold vapor atomic adsorption analyses were used for mercury (Hg) and arsenic (As) concentration determinations.

Benthic biota were sampled by using a 0.1 m^2 Van Veen bottom grab. Samples were preserved in a 10% formalin–seawater solution in the field and transported to the laboratory for analysis. Sediment samples were screened through 0.5-mm sieves and then acid-digested (if necessary) to reduce the amount of calcium carbonate debris in the sample before laboratory analysis.

Fish traps and gill nets were deployed at several stations to qualitatively sample fishes and macroinvertebrates (crabs). Fish traps were normally set for a 72-hour period, while gill nets were deployed overnight at selected stations. Traps and gill nets were checked during each sampling day. All organisms collected were identified, counted, and measured.

Water quality data for nine stations in Pearl Harbor sampled during May 1990 are summarized in table 6 (physical–chemical and nutrients) and table 7 (trace metals). Light extinction coefficients were estimated from secchi disk data. These data were well within expected ranges for the harbor. Comparisons with earlier studies reveal no significant adverse changes in general harbor water quality conditions. Conversely, recent data reveal improving water quality conditions for Pearl Harbor.

Mean total phosphorus levels during the BRCC survey series ranged from 12 to 16 $\mu g\ l^{-1}$ at the surface and from 12 to 15 $\mu g\ l^{-1}$ at the bottom, well below the State of Hawaii standard of 60.00 $\mu g\ l^{-1}$ for the geometric mean level. Total nitrogen concentrations ranged from 95 to 180 $\mu g\ l^{-1}$ at the surface and 93 to 140 $\mu g\ l^{-1}$ at the bottom, also within the State of Hawaii standards for the Pearl Harbor Estuary (table 6). Mean water column ammonia (NH4) concentrations ranged from 0.66 to 14 $\mu g\ l^{-1}$ at the surface and from 0.54 to 7.6 $\mu g\ l^{-1}$ at the bottom. With only two exceptions, trace metal concentration data from surface and bottom waters were far below State of Hawaii standards for chronic levels in seawater, and all were below the acute concentration values.

Table 6. Pearl Harbor water qualtiy summary (May 1990). K = light extinction coefficient. Dissolved oxygen (DO) concentrations in μg l^{-1}. Nutrient concentrations in μg l^{-1} (mean ± s.d.). n = 3, except as noted.

Station	Water Layer	K (mean)	Temp (C)	pH	DO	Salinity (‰)	PO_4	NH_4	Total P	Total N
BE2	Surface	.543	25.64	7.98	6.67	33.8	23 ± 7.5	8.2 ± 7.2	14 ± 2.3	110 ± 18
	Bottom		25.48	8.01	6.13	34.5	19 ± 3.8	7.6 ± 2.8	13 ± 1.1	100 ± 12
BE3	Surface	.403	25.50	8.02	6.74	34.3	18 ± 1.9	2.2 ± 2.3	14 ± 0.78	110 ± 13
	Bottom		25.14	8.02	5.87	34.7	17 ± 2.9	3.0 ± 2.5	14 ± 0.18	100 ± 16
BE4	Surface	.553	25.70	7.99	5.84	34.3	25 ± 6.7	14 ± 5.7	17 ± 1.7	120 ± 2.0
	Bottom		25.27	8.02	5.61	34.6	19 ± 2.0	2.5 ± 2.4	14 ± 0.65	110 ± 10
BE5	Surface	.735	25.56	8.00	6.36	34.2	17 ± 2.9	0.66 ± 0.55	14 ± 1.9	110 ± 12
	Bottom		24.97	7.99	5.53	34.6	20 ± 3.6	3.1 ± 2.3	15 ± 2.2	140 ± 48
BE5A	Surface	.818	25.82	7.99	6.54	34.1	17 ± 4.4	0.72 ± 0.94	12 ± 2.1	96 ± 1.5
	Bottom		24.90	7.97	5.29	34.8	20 ± 2.2	2.2 ± 2.6	14 ± 0.82	110 ± 20
BE5B	Surface	.910	25.65	7.96	6.16	34.2	18 ± 1.5	1.2 ± 1.2	13 ± 0.64	95 ± 1.5
	Bottom		25.25	7.97	5.29	34.8	18 ± 2.7	3.8 ± 3.9	13 ± 0.65	120 ± 26
BC9	Surface	.647	25.09	8.03	6.74	33.7	15 ± 5.3	3.1 ± 3.7	13 ± 2.2	120 ± 13
	Bottom		24.84	8.04	5.72	34.7	16 ± 1.5	3.0 ± 2.3	12 ± 0.72	110 ± 24
BC11	Surface	.770	25.97	8.02	7.52	33.1	18 ± 12	2.2 ± 2.5	15 ± 6.7	180 ± 56
	Bottom		24.68	8.06	6.20	34.9	12 ± 1.9	3.4 ± 3.6	12 ± 2.8	110 ± 17
BE17	Surface	.760	25.69	8.03	8.09	33.5	19 ± 9.6	5.5 ± 3.6	13 ± 3.1	100 ± 15
	Bottom		25.21	8.05	6.23	34.6	17 ± 4.7[a]	0.54 ± 0.51[a]	12 ± 1.1[a]	93 ± 7.1[a]
Hawaii Standard[b]	Mean	.800	1°C[e]	6.8≤x≤8.8	≥60% Saturation	10%[e]	NS	10.00	60.00	300.00
	<10%[c]	1.60						20.00	130.00	550.00
	<2%[d]	2.50						30.00	200.00	750.00

NS = No standard.
[a] n= 2.
[b] State of Hawaii Department of Health Water Quality Standard, Pearl Harbor Estuary.
[c] Not to exceed the given value more than ten percent of the time.
[d] Not to exceed the given value more than two percent of the time.
[e] Shall not vary more than the given value from ambient conditions.

Table 7. Concentrations of trace metals in Pearl Harbor waters (May 1990). Metal concentrations in $\mu g\, l^{-1}$ (ppb).

		Metal								
Station	**Layer**	**Ag**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**
BE2	Surface	0.2	0.5	0.31	0.6	2.12	ND	2.5	3.3	4.4
	Deep	0.1	ND	0.03	0.6	2.31	ND	2.4	ND	7.4
BE3	Surface	0.3	ND	0.27	0.9	2.23	ND	3.2	ND	4.5
	Deep	0.2	0.5	3.24	1.7	2.96	ND	16.0	0.8	ND
BE4	Surface	0.2	1.0	0.10	0.7	2.24	ND	53.4	ND	2.3
	Deep	0.2	0.5	0.32	1.7	2.11	1.0	5.1	ND	29.7
BE5	Surface	0.1	ND	0.21	0.6	1.67	ND	2.4	ND	4.8
	Deep	0.1	0.5	0.12	0.5	2.14	ND	1.4	ND	1.0
BE5A	Surface	0.2	ND	0.13	1.1	1.69	ND	4.0	ND	8.8
	Deep	0.2	0.5	0.08	0.8	2.17	ND	2.9	ND	1.6
BE5B	Surface	0.2	0.5	0.05	0.9	2.48	ND	3.2	0.3	11.5
	Deep	0.2	0.5	0.07	0.9	2.32	ND	4.4	ND	11.2
BC9	Surface	0.2	0.5	0.21	0.5	1.84	ND	1.6	ND	1.3
	Deep	0.1	ND	0.12	0.7	1.63	ND	2.4	ND	0.9
BC11	Surface	0.2	ND	0.09	0.9	2.13	ND	5.9	1.0	8.8
	Deep	0.2	ND	0.75	0.5	1.47	ND	1.1	ND	4.4
BE17	Surface	0.2	0.5	0.31	1.1	2.44	ND	3.1	ND	2.6
	Deep	0.2	0.5	0.05	0.6	2.27	ND	2.0	ND	4.6
Detection Limit		0.07	0.5	0.05	0.33	0.19	1.0	0.52	0.62	0.5
Hawaii Standard[a]	Acute	2.3	69	43	1100	NS	2.1	75	140	95
	Chronic	NS	36	9.3	50	NS	NS	8.3	NS	86

ND= Not determined.
NS= No standard.
[a] State of Hawaii Department of Health Water Quality Standard.

Field observations and collections made during April and May 1990 indicate that the inner harbor continues to maintain diverse fish and benthic biotic assemblages. Three series of gill net and trap catches from stations on the east (station BE05) and west (station BC09) sides of Ford Island and Pier F5 (BE02) yielded 60 individuals from 13 different species of fishes and 11 swimming crabs from 3 species. A species list for organisms collected during this survey is provided in table 8.

Table 8. Species list of fishes and crabs collected in Pearl Harbor (April 1990).

Station	Species	Common Name	Number	Mean Length [a]
BE02	*Arothron hispidus*	Soft puffer	1	19.5
	Gymnothorax undulatus	Moray eel	1	88.5 [b]
	Lutjanus fulvus	Black-tail snapper	1	22.5
	Naso brevirostris	Surgeonfish	3	18.3
BE05	*Arothron hispidus*	Soft puffer	2	28.3
	Parupeneus porphyreus	Goatfish, "kumu"	8	34.7
	Sphyrna lewini	Hammerhead shark	1	59.0 [b]
	Upeneus arge	Goatfish, "weke"	1	28.0
BC09	*Albula vulpes*	Bonefish, "O'io"	18	37.0
	Arothron hispidus	Soft puffer	1	21.5
	Caranx ignobilis	Jack, "papio"	1	22.5
	Caranx mate	Jack, "omaka"	1	24.5
	Carcharhinus limbatus	Shark, "mano"	1	
	Diodon hystrix	Spiny balloonfish	1	
	Elops hawaiiensis	Hawaiian tarpon,"awa"	1	52.0
	Lutjanus fulvus	Black-tail snapper	1	24.0
	Podophthalmus vigil	Hawaiian crab	2	
	Portunus sanguinolentus	White crab	8	
	Sphyrna lewini	Hammerhead shark	11	56.4 [b]
	Thalamita crenata	Stone crab	1	
	Upeneus arge	Goatfish, "weke"	5	29.6

[a] Fork length in cm.
[b] Total length in cm.

Benthic infauna population analyses from 8 deep water stations and 4 shallow water stations were also performed during this study. A data summary for these analyses is shown in table 9. Shallower regions of the harbor contain a greater diversity and abundance of benthic infaunal organisms because of enhanced substrata availability. Harbor channel areas exhibited less benthic biotic diversity, which may partially be attributable to recent maintenance dredging operations in the harbor, although homogeneous silt substrata generally support less diverse benthic populations.

Somerton (1990) performed a comprehensive two year study in Pearl Harbor to assess baitfish stocks (including abundance and distribution) using an egg production method for analysis. Biomass of the Hawaiian anchovy ("nehu"), *Encrasicholina purpurea,* was estimated weekly at 39 stations throughout the entire harbor during 3 April 1986 to 7 April 1988. Over the study period, *nehu* spawning stock biomass ranged between 0.5 and 5.0 metric tons and was clearly associated with the variation in rate of bait catches by aku boat fishing. The Pearl Harbor *nehu* population fluctuated seasonally with maximum abundance in March–April and minimum abundance in November. Seasonal fluctuation in larval production was similar to the pattern observed for mean water temperature and the density of crustacean zooplankton. The total mortality rate of adult *nehu* is the sum of both natural and fishing mortalities. During this two year period, natural mortality appeared to be "nearly constant over time" (Somerton, 1990).

Table 9. Benthic infauna populations in Pearl Harbor (April 1990).

A. Deep Water Sediments

	Taxa				
Station	***Nematoda***	***Polychaeta***	***Copepoda***	***Gammaridea***	***Natantia***
BE02	77	710			79
BE03	500	820			
BE04	87				
BE05	450	1,100			
BE05B	4,800	1,500	170	86	
BC09	5,700	3,800	320		
BE17	3,000	1,400			170

B. Shallow Water Sediments

	Station			
Taxa[a]	**BE02**	**BE05**	**BE05B**	**BC09**
Porifera	present	present		
Actinaria	470	950		
Turbellaria	310	1,600		
Nematoda	16,000	11,000	650	16,000
Bivalvia	13,000	11,000		610
Gastropoda	470	1,100		150
Polychaeta	65,000	270,000	3,000	28,000
Sipuncula	470	3,200		920
Ophiuroidea	470			150
Copepoda	150	270		
Cumacea		140		
Tanaidacea	4,700	27,000		1,700
Isopoda	150			
Gammaridea	4,800	110,000		150
Natantia	310			
Brachyura	630	810		
Tunicata		present		present

[a] Number of individuals per square meter.

This study is considered an important indication of the present ecological conditions in Pearl Harbor. The Hawaiian anchovy is a rather fragile harbor organism which has recently been used as a bioassay test organism in Pearl Harbor (Henderson and Salazar, 1991b). The Hawaiian anchovy spends its entire life cycle (pelagic egg, larval, and adult phases) in Pearl Harbor.Somerton's study evaluated the population dynamics of *nehu* at a time when most pollution abatement efforts were in effect. This species is sustaining a viable and reproducing population in many harbor regions. These data indicate toxic contamination does not adversely affect this commercially important resource in the harbor.

From 1984 to 1990 field sampling operations and laboratory bioassays were performed in Pearl Harbor in support of the Navy's butyltin monitoring program (Grovhoug et al., 1987; Grovhoug et al., 1989; Henderson, 1985; Henderson and Salazar, 1991b). During these investigations the primary focus was a detailed evaluation of the environmental fate and effects of tributyltin (TBT) based antifouling coatings. Numerous water, sediment, and oyster tissue samples were collected and analyzed during these studies. Many additional observations were made and data collected related to Pearl Harbor ecosystem dynamics. Harborwide water column profiles have been recorded on a quarterly basis since October 1989. For each major region in Pearl Harbor, conductivity, temperature, depth, salinity, dissolved oxygen and pH were recorded at 1-meter increments from surface to bottom. Butyltin compounds were analyzed in sediment and oyster tissue samples from each major harbor region on a semiannual basis. These collection activities afforded repeated opportunities for the field team to make synoptic observations of general harbor conditions. Qualitative field observations of harbor conditions (such as sediment texture and color, water turbidity, and the abundance of terrestrial and marine biota) and the lack of the visual presence of potential contamination (such as oil spills, red tides, fish kills, and other significant events) have supported the general impression of improving environmental quality throughout the harbor.

Sediment contaminant concentrations for three sampling periods (1990, 1982, and 1972) are summarized in tables 10, 11, and 12, respectively. The sources for these data are AECOS (1990), AECOS (1983), and Evans et al. (1974) [see footnote 1]. Trace metal levels in sediments from major harbor regions are available for the three periods. Unfortunately, only the most recent study provides detailed data for other toxic organic compounds. A significant temporal pattern has been observed in the trace metal content of harbor sediments. Data from four regions of the harbor are summarized in Appendix A. Since 1972 there has been a significant decrease in cadmium, chromium, copper, lead, mercury, silver, and zinc sediment concentrations.

Table 10. Average regional contaminant concentrations in Pearl Harbor sediments collected December 1989–January 1990 during dredging bioassay/bioaccumulation studies (Source: AECOS, 1990). Concentrations in µg/g (ppm) for trace metals; units for organic compounds as indicated. All concentrations in dry weight. Regional data represent composited grab samples (numbers of sampling sites shown in parentheses). Refer to figure 2 for reference locations.

Region → Contaminant ↓	Entrance Channel (3)	Alpha Docks (7,	Lower W.Loch (5)	Upper W.Loch (4)	Hospital Point (4)	W. and Ford Is (8)	Middle Loch (6)	North Channel (10)	Lower E.Loch (7)	South Channel (6)	Naval Shipyard (10)	So.East Loch (7)
Cadmium (Cd)	1.5	1.5	1.0	0.4	1.2	0.9	0.3	0.4	0.3	0.6	0.8	1.3
Chromium (Cr)	20.2	23.5	25.7	35.4	25.4	27.7	19.4	35.5	13.9	7.4	28.3	17.6
Copper (Cu)	11.0	37.7	24.3	28.2	36.5	24.2	3.7	25.4	6.6	24.9	79.4	23.9
Lead (Pb)	31.6	40.2	51.3	15.5	41.6	31.5	8.6	18.2	19.3	13.1	47.2	55.3
Mercury (Hg)	0.09	0.17	0.23	0.15	0.25	0.19	0.08	0.12	0.10	0.12	0.49	0.26
Silver (Ag)	3.7	3.5	2.3	0.8	2.0	1.2	0.6	0.5	0.4	1.1	1.0	1.6
Zinc (Zn)	23.8	58.2	81.8	47.0	51.2	73.3	67.7	59.4	49.5	71.5	107.3	88.2
PCB (1260) (ppb)	<150	<150	<150	<150	180	<150	<150	<150	170	420	710	900
Σ Organotins (ppb)	356	34	27	25	37	21	21	80	23	33	91	44
Σ Petroleum Hydrocarbons (ppm)	50	300	290	<50	400	230	54	50	72	100	1100	360
Σ PAH	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Σ Chlordane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Σ DDT	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Note: BDL = Below detection limit.

Detection Limits (mg/kg)
Σ PAH [1.0]
Σ Chlordane [0.3]
Σ DDT [0.03]

Table 11. Average trace metal concentrations in Pearl Harbor sediment data collected in 1982 for dredging bioassay/bioaccumulation studies (Source: AECOS, 1983). Concentrations in mg/kg dry weight. Regional data represent mean values (numbers of sampling sites shown in parentheses). PHNSY = Pearl Harbor Naval Shipyard. ND = not detected.

Region → Contaminant ↓	Entrance Channel (12)	Upper Ent.Ch. (6)	Middle Loch (15)	North Channel (14)	Lower E.Loch (7)	S.Channel/PHNSY (7)	So.East Loch (9)
Cadmium (Cd)	0.15	0.2	0.3	ND	ND	0.8	0.2
Chromium (Cr)	23	35	127	78	81	63	43
Copper (Cu)	16	36	103	72	88	262	78
Lead (Pb)	17	36	41	35	44	125	46
Mercury (Hg)	0.1	ND	0.5	0.5	0.3	0.5	0.3
Zinc (Zn)	66	215	197	181	188	424	128

Table 12. Average trace metal concentrations in Pearl Harbor sediment data collected in 1971–1972 (Source: Evans, et al., 1974). Concentrations in mg/kg dry weight. Regional data represent mean values (numbers of sampling sites shown in parentheses). PHNSY = Pearl Harbor Naval Shipyard.

Region → Contaminant ↓	Lower West Loch (5)	Upper West Loch (10)	Hospital Point/DD#4 (6)	Middle Loch (6)	Lower E.Loch (16)	PHNSY/ SE Loch (39)
Cadmium (Cd)	0.70	0.47	1.3	0.22	0.45	1.7
Chromium (Cr)	68	120	67	170	34	100
Copper (Cu)	120	72	550	120	34	240
Lead (Pb)	90	2.0	320	42	29	210
Mercury (Hg)	1.6	0.31	1.9	0.92	0.52	2.0
Silver (Ag)	3.6	2.0	5.0	2.6	3.1	6.6
Zinc (Zn)	330	160	730	210	92	350

As previously discussed, the biological availability of sediment contaminants is highly variable. At the inception of this study, the author anticipated making comparisons between environmental concentrations of toxic contaminants in harbor sediments and toxicity data gathered during dredge disposal bioassay tests. However, because of the absence of organism toxicity experienced during sediment bioassay studies (Brock, 1980; AECOS, 1982; AECOS, 1983; AECOS, 1990; Henderson, 1991a), the anticipated calculation of Apparent Effects Threshold (AET) values (Long and Morgan, 1990; Barrick et al., 1989) for Pearl Harbor was not feasible. As can be seen from recent NOAA National Status and Trends Program data, which are summarized in table 13, sediment contaminant concentrations recorded recently from Pearl Harbor (AECOS, 1990) are, except for PCBs and silver, below national averages.

Table 13. Summary of National Status and Trends Program sediment effects data (Sources: Long and Morgan, 1990; O'Connor, 1990). Concentrations of trace elements in ppm; all other compounds in ppb.

Chemical Analyte	Low Effects Range Concentration[a]	Median Effects Range Concentration[b]	Overall AET[c] Estimate	Subjective Degree of Confidence	"High" NS&T Conc.[d]
Cadmium (Cd)	5	9	5	High	1.3
Chromium (Cr)	80	145	None	Moderate	230
Copper (Cu)	70	390	300	High	87
Lead (Pb)	35	110	300	Moderate	87
Mercury (Hg)	0.15	1.3	1	Moderate	0.51
Silver (Ag)	1	2.2	1.7	Moderate	1.2
Zinc (Zn)	120	270	260	High	280
Chlordane	0.5	6	2	Low	5.5
Σ PCB's	50	400	370	Moderate	200
Σ PAH's	4000	35,000	22,000	Low	3900
Σ DDT	3	350	None	Low	40

[a] Represents the lower 10th percentiles in effects-based NOAA data.
[b] Identifies the median in effects-based NOAA data.
[c] Overall Apparent Effects Threshold Estimates, subjectively determined concentrations, at or above which biological effects were usually or always observed.
[d] Sediment concentrations whose logarithmic value is more than the mean plus one standard deviation of the logarithms for all concentrations.

Comparisons between the data shown in tables 10 and 13, when viewed in the perspective of harbors nationwide, reveal important characteristics of Pearl Harbor sediment toxic burdens. Concentrations of total polynuclear aromatic hydrocarbons (PAHs) are common in many industrialized harbors throughout the U.S. (Long and Morgan, 1990). These compounds were undetected in sediments collected from twelve regions in Pearl Harbor. Pesticide levels (chlordane and total DDT in this comparison) were below detection limits in 1990 Pearl Harbor sediment data. Silver is the single trace metal which showed elevated concentrations in the entrance channel region. Sewage effluent from Fort Kamehameha STP is a likely source of contamination.* The cumulative effects of washing silver flatware and discharging photographic processing wastes into municipal sewage systems have increased the likelihood of silver contamination at outfall sites. Polychlorinated biphenyl concentrations are substantially elevated in shipyard and Southeast Loch sediments. Two sets of PCB sediment data collected during 1990 are included in Appendix B.

* Dr. Donald Crosby, toxicologist, U.C. Davis, personal communication, March 1991.

ASSESSMENT OF ENVIRONMENTAL RISK

The process of assigning magnitudes and probabilities to adverse environmental effects caused by chemicals or other hazards forms a contemporary paradigm for environmental risk assessment (Barnthouse and Suter, 1986; Suter, 1990). Risk assessment requires explicit endpoints for which probability statements can be made. The following assessment endpoints are suggested as valid criteria for the present evaluation of potential contamination in Pearl Harbor:

1. A reduction in the abundances of harvestable marine resources in Pearl Harbor (specifically, for *nehu*, food fishes, crustacean, bivalve (oysters), and plant populations in or adjacent to the harbor).

2. A reduction in the resident wildlife populations (especially threatened or endangered shorebird species) adjacent to or inhabiting Pearl Harbor.

3. An increasing frequency of algal or red tide "blooms" within Pearl Harbor (which affect harbor water ecological or aesthetic qualities).

4. Increases in the incidence of histopathological phenomena in resident marine biota (such as lesions, tumors, and parasitic infestation).

5. Increased adverse human health effects attributable to Pearl Harbor (through contact with harbor water or sediment, consumption of marine life, symptoms of environmentally caused toxicological reactions, etc.).

Data relating to each of these endpoints, where available, have been examined. Based on available information, the assessment of environmental risk for present conditions in Pearl Harbor is considered to be semiquantitative at this time. A need exists for additional information relating to biotic population dynamics within the Pearl Harbor ecosystem. Data and observations relating to suggested endpoints are further discussed below. Estimated risk assessment parameters are summarized in table 14.

Abundances of harvestable marine resources in Pearl Harbor are estimated to be consistent with previous quantities. Somerton (1990) provided detailed estimates of nehu populations in the harbor. Field collections of fishes, crabs, and benthic invertebrates (U.S. Navy, 1990a) at selected locations in the harbor indicate that diverse and abundant assemblages of these groups are present. Oyster populations in certain regions of the harbor have been observed as plentiful (Grovhoug et al., 1989; additional observations by the author). Aquatic and terrestrial plant distributions in Pearl Harbor appear to be steady or increasing (especially for mangroves along many shoreline areas). Algal harvesting has been recently observed along Waipio Peninsula shoreline areas.

Table 14. Environmental risk estimates for Pearl Harbor.

Endpoint Category	Data Uncertainty	Analytical Uncertainty	Overall Assessment of Risk
Marine Resources	Moderate	Low	Low
Wildlife Populations	Moderate	Low	Low
Algal or "Red Tides"	Low	Low	Very Low
Histopathology in Marine Biota	Low	Low	Very Low
Human Health Effects	Moderate	Low	Low

Selected wildlife distribution data have been obtained from the Hawaii State Department of Land and Natural Resources. As an indication of general population trends, visual census data of waterbirds for three areas adjacent to the harbor were analyzed and are presented in Appendix C. Three endangered species of waterbirds were selected for presentation. The Honouliuli Unit of the Pearl Harbor National Wildlife Refuge (see figure 6 for location) supports viable populations of all three waterbird species. Relationships between harbor sediment contamination and waterbird abundance are not well established. Habitat modification is probably responsible for the decreases seen in waterbird numbers on Waipio Peninsula. Generally, resident wildlife adjacent to Pearl Harbor appears to be at minimal risk from the effects of sediment contamination.

There have been no reported increases in the occurrence of algal or "red tide" blooms in Pearl Harbor. Conversely, the frequency of observed red tide conditions in the harbor has decreased markedly since the diversion of major sewage outfalls, presumably related to decreased nutrient availability (Henderson, personal communication, and long-term observations by the author).

Observations by the author of resident marine biota inhabiting Pearl Harbor during the last twenty years have revealed no indication of histopathological phenomena attributable to contaminants in the harbor. Observations in Puget Sound, San Francisco Bay, and off the southern California coast have revealed the presence of lesions and tumors in benthic fish populations (Malins et al., 1984; MacDonald, 1989; Southern California Coastal Water Research Project, 1982). Similar histopathological phenomena have not been reported in Pearl Harbor biota.

CONCLUSIONS AND RECOMMENDATIONS

After an extensive review of information pertaining to the Pearl Harbor environment, the following conclusions and recommendations have been reached:

CONCLUSIONS

- Pearl Harbor is a complex estuarine system which has been the center of U.S. Navy activities in the mid-Pacific for nearly one hundred years.
- The contamination history of the harbor is the result of inputs from natural, agricultural, urban, industrial, and military sources.
- Pearl Harbor supports diverse biological assemblages of organisms (including humans) which respond in various ways to the general effects of environmental contamination.
- The concentrations of contaminants in sediment, tissue, and water samples collected from Pearl Harbor are present at or below levels measured in other Hawaiian bays and harbors and are generally lower than the average concentrations reported for U.S. mainland harbor areas.
- The frequent dredging of Pearl Harbor sediments serves to mitigate potentially adverse effects of sediment contamination through physical removal.
- The responses of bioassay test organisms used during sediment toxicity and bioaccumulation studies demonstrated minimal effects attributable to sediment contamination.
- An evaluation of the environmental status at the offshore dredge disposal site indicates no adverse impacts from nearly thirty years of disposal activities.
- Critical environments such as wetlands and habitat for baitfish within the harbor are sustaining viable populations of organisms and are considered to be under minimal risk from sediment contamination.
- Marine resources within the harbor, such as fishes, crabs, and benthic invertebrates, have demonstrated substantial population stability.
- The decline of red tide blooms in Pearl Harbor during recent years is propbably the result of decreased nutrient loading.
- The diversion of most sewage outfalls from Pearl Harbor has significantly enhanced water quality through reduced nutrient and contaminant inputs.
- Sedimentation and nonpoint source pollution are chronic contaminating processes affecting the Pearl Harbor estuary.
- Several sediment contaminants (including silver, PCBs and petroleum hydrocarbons) presently occur in sufficiently elevated concentrations at certain harbor locations (see table 10) to warrant potential environmental risk.

- The overall environmental risks from sediment, water, and organism contamination in Pearl Harbor are considered moderately low at this time.
- The human health risks attributable to harbor contaminants are considered low.

RECOMMENDATIONS

- Further investigation of the abundance and distribution of potentially harvestable marine resources in Pearl Harbor (such as algae, oysters, fishes, and crustaceans) is essential to further identify important biotic population characteristics and dynamics. A series of research efforts should be explored and initiated (possibly through agreements with the University of Hawaii or other research institutions). Through cooperative scientific investigation, the unique and diverse character of Pearl Harbor's ecosystem can be better understood.
- A detailed characterization of sediment and tissue loading for PCBs in the harbor is suggested. Elevated sediment concentrations have been recently detected at certain harbor locations. A detailed study should be initiated to identify the distribution, fate, and effects of elevated polychlorinated biphenyl concentrations in the harbor.
- The U.S. Navy should actively participate in nonpoint source minimization efforts to reduce chronic contaminant inputs to the Pearl Harbor ecosystem. An appropriate initial phase of this effort would be to identify study areas on naval properties in the watershed which may be used as test sites for Best Management Practice (BMP) demonstrations.
- Pearl Harbor should be included in the State of Hawaii's Main Hawaiian Islands Marine Resources Investigation (MHI-MRI). This program is undertaking the assessment of important inshore and nearshore marine resources in Hawaii. The development of better management measures is expected to enhance viable fishery resources around the state. Since 1990 this effort has been developed and administered by the Division of Aquatic Resources of the Department of Land and Natural Resources.

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GLOSSARY OF TERMS

Acute Toxicity. The ability of a substance to produce systematic damage in an organism from a single, short duration exposure.

AFDM. U.S. Navy floating drydock.

Aku. Hawaiian name for skipjack tuna, *Katsuwonus pelamis*.

Aku boat. A commercial fishing boat (usually sampan configuration) largely engaged in the taking of skipjack tuna (*aku*) after purse seining for baitfish (*nehu*) in estuaries such as Pearl Harbor.

Algae. A group of lower photosynthetic plants varying greatly in color and habitat; may live in a variety of environments and range in size from microscopic, planktonic species to macroscopic, obvious forms.

Alluvium. Sedimentary material such as sand, silt, and mud deposited by flowing water, as in a riverbed or delta.

Amphipod. A relatively small, shrimp-like crustacean of the order *Amphipoda*; members of the planktonic, epifaunal, and infaunal benthic communities.

Antifoulant. An agent which prevents or retards the attachment and growth of epiphytic marine organisms; usually consists of a biocide incorporated into a paint matrix.

Aquifer. Ground water contained in water-bearing rock formations.

Artesian well. A well drilled through impermeable strata to reach water capable of rising to the surface by internal hydrostatic pressure.

Assemblage. A naturally occurring association of living forms in a specific environment.

Aufwuchs. Term used to describe the community of organisms which live attached to hard substrata such as piers, pipes, piling, and ship hulls; epifaunal community.

Benthos. That portion of the marine environment inhabited by organisms which live permanently on or in the bottom substrata; also called benthonic; bottom-dwelling.

Benthic. Of or relating to the benthos.

Bioaccumulation. Any uptake of chemical residues from dietary and external environmental sources by metabolic processes in organisms; includes bioconcentration.

Bioaccumulation potential. A predicted estimate of significant elevations in biotic tissues caused by exposure to specific contaminants; used in dredge material ocean disposal studies.

Bioassay. A toxicity testing method which subjects test organisms to contaminants and measures the effects (usually expressed as mortality, morbidity, or other adverse biological responses).

Bioavailability. The tendency of a contaminant to partition into forms conducive to uptake by organisms; this will vary among chemical and organisms and is influenced by such environmental factors as temperature, salinity, pH, redox potential, particle size distribution, and organic carbon concentrations.

Bioconcentration. A process of bioaccumulation in which chemical substances enter aquatic organisms through the gills or epithelial tissue directly from ambient water.

Biological Oxygen Demand (BOD). A measure of relative uptake of oxygen by wastewaters, effluents, or sediments under standard laboratory conditions; commonly expressed in mg O_2 uptake per liter of water or gram of sediment over a five-day period.

Biomass. The mass of living material; frequently expressed on a per unit area or volume basis for a given environment.

Biota. The animal (faunal) and plant (floral) forms of a given environmental region.

Biotic. Relating to the biota.

Bioturbation. Disturbance in sediment strata by the burrowing activities of marine benthic organisms.

BRCC. Base Realignment and Closure Commission.

CERCLA. Comprehensive Environmental Response, Compensation and Liability Act.

CFR. Code of Federal Regulations; codification of the general and permanent rules published in the Federal Register by the executive departments and agencies of the federal government.

Chronic toxicity. The ability of a substance to produce systematic damage in an organism from long-term, low-level exposure.

CHT. Collection, holding, and transfer system (for shipboard sewage and waste water).

Contaminant loading. The measured amount of a deleterious chemical in a specific environment.

CTD. Conductivity, temperature, and depth; usually measured in vertical increments in the water column.

COE. Corps of Engineers, U.S. Army; responsible for regulating dredging in harbors and coastal areas.

Diatoms. Algal components of the marine environment; distinguished from all other algae by enclosure in a siliceous wall; usually microscopic; very abundant in marine environment.

Dinoflagellate. A member of a group of single-celled, minute organisms which are often responsible for red tide phenomena; some species are toxic and may cause mass mortality to marine organisms.

DOH. Department of Health, State of Hawaii.

DTRC. David Taylor Research Center; a U.S. Navy research and development facility located in Annapolis, Maryland, and Washington, D.C.

Echinoderms. A group of spiny-skinned marine animals such as starfish, sea cucumbers, sea urchins, and sand dollars.

Ecological endpoints. (1) An Assessment Endpoint is a formal expressions of the actual environmental values that are to be protected; environmental characteristics, which, if they are found to be significantly affected, would indicate a need for remediation and (2) a Measurement Endpoint is a quantitative expression of an observed or measured effect of a hazard; a measurable environmental characteristic that is related to the valued characteristic chosen as an assessment endpoint.

Ecosystem. A functional, natural unit composed of living organisms and the nonliving environment with which they interact to produce a balanced system in which the exchange of materials between living and nonliving components follows a circular path; generally four components are recognized: abiotic elements, producers, consumers and decomposers.

EPA. U.S. Environmental Protection Agency.

Epifauna. Animals living on various surfaces; for instance, on the surface of, rather than in the bottom sediments.

Estuary. An area where a river or stream (or system of tributaries) meets the ocean (e.g., Pearl Harbor); characterized by water whose salt content (salinity) is between that of fresh water and marine environments; an area inhabited by a distinct assemblage of organisms.

FEIS. Final Environmental Impact Statement.

Fouling Organisms. plants or animals that attach to the surface of submerged, man-made or introduced objects such as ship hulls, piers, and pipes.

FWPCA. Federal Water Pollution Control Act; or Federal Water Pollution Control Administration, forerunner to the Environmental Protection Agency.

HECo. Hawaiian Electric Company (Waiau Plant located in upper East Loch).

Histopathology. The pathology of changes in diseased tissues.

IAS. Initial Assessment Study under the U.S. Navy Installation Restoration (IR) Program.

Infauna. Bottom-dwelling organisms that live within the bottom substratum such as clams, snails, worms, and burrowing shrimp.

Loch. An arm of a harbor which is constricted at its entrance; a lobe.

Microcosm. A laboratory simulation of a simplified ecosystem; a community (of organisms) which is a model of a larger system.

Microorganisms. An animal or plant of microscopic size; in this report, bacteria, viruses, and protozoans.

Mollusc. A group of soft-bodied animals usually in shells such as clams, oysters, snails, squids, and octopi.

Moribund. being in the state of dying; approaching death.

Mortality. the state of death; frequency of number of deaths in proportion to a population or sample.

NACIP. Navy Assessment and Control of Installation Pollutants.

Nehu. Hawaiian anchovy, *Encrasicholina purpurea*, used as baitfish in the skipjack tuna (*aku*) fishery.

NMFS. National Marine Fisheries Service, National Oceanic and Atmospheric Administration.

NOAA. National Oceanic and Atmospheric Administration.

Nonpoint source (NPS) polllution. Derived from a nondefinable source (such as agricultural runoff).

NOSC. Naval Ocean Systems Center; a U.S. Navy research and development facility.

Organotin. A man-made compound synthesized by attaching several organic (carbon–based) butyl groups to the tin molecule; tributyltin (TBT), a toxic form, is used as a marine biocide.

‰. Parts per thousand.

ppm. Parts per million; e.g., mg/kg, µg/g.

ppb. Parts per billion; e.g., ng/g, $\mu g\ l^{-1}$.

pptr. Parts per trillion; e.g., ng/l (or $ng\ l^{-1}$).

PCBs. Polychlorinated biphenyls.

Pelagic. Free-swimming throughout the water column with depth preference; residing in open water.

Phytoplankton. Microscopic plant (floral) components of the plankton population.

Piling Organisms. The assemblage of biota that tends to inhabit vertical substrata; primarily epifauna.

Plankton. Drifting or slowly swimming animal or plant life that is a vital primary source of food for larger biota; usually microscopic organisms including eggs, larvae, and adult forms; also includes jellyfish, and comb jellies of all sizes.

POL. Petroleum–Oil–Lubricant.

Polychaetes. A class of annelid (segmented) worms with parapodia (appendages) bearing numerous bristles (setae).

Population. Statistically: that set of all similar entities from which a sample is drawn; ecologically: the total number of a particular group inhabiting a given region.

PWC. Public Works Center (U.S. Navy).

RAV. Restricted Availability (used in upkeep and maintenance of naval vessels).

Redox Potential. A water quality parameter used when examining a sample to measure changes in contained inorganic matter.

Sampan. A distinctive vessel hull configuration, consisting of a V-shaped bottom and flat stern; *aku* boats are of this type.

Sample. In this report, collection of data at a specific location at a specific time.

SARA. Superfund Amendments and Reauthorization Act.

SARA III. Superfund Amendments and Reauthorization Act, Title III (Emergency Planning and Community Right-to-know Act).

Sea Urchin. See urchin.

SECCHI Disc. A weighted disc (usually white or black and white) used to measure vertical transparency of the water column; distance measurements of visibility are obtained using this device.

Sedentary. Referring to animals that seldom move about or are permanently attached to a substratum; not migratory.

Sessile. Attached to a substratum; e.g., barnacles or tube worms growing on ship hulls.

Station. In this report, a geographic location in Pearl Harbor.

STP. Sewage Treatment Plant.

Stratum. Layer, as in geological formation.

Substratum. A material within or upon which an organism resides (e.g., pier piling, bottom sediments, water column, and mangrove root system).

Taro. Hawaiian plant from which "poi," a staple Hawaiian starchy paste is produced.

Taxa. A specific group of organisms; usually at the *species* level of discussion.

TOC. Total Organic Carbon.

Toxicant. Environmental pollutant.

Toxin. Plant or animal secreted poison.

Trophic Levels. Functional components of the food web such as grazers (herbivores), consumers (carnivores), detritivores, scavengers (such as crabs and lobsters).

Turbidity. Reduced water clarity resulting from presence of suspended matter.

Urchin. A member of the echinoderm class, *Echinoidea*; possessing sucker-like tube feet and usually a thin, spine-covered calcareous shell.

USFWS. U.S. Fish and Wildlife Service.

USGS. U.S. Geological Survey.

UST. Underground storage tank, primarily for POL products.

Variability. The way in which an observed parameter changes with time or with repeated observation and measurement.

Water quality standards. Standards and related implementation plans that have been adopted by each state and approved by the Office of Water Programs of the EPA pursuant to the FWPCA as amended.

Appendix A
TRACE METAL TRENDS IN PEARL HARBOR SEDIMENT

Table A-1. Sediment trace metal trends in selected Pearl Harbor areas (concentrations in mg/kg dry weight).

PHNSY/SE LOCH

Trace Metals	1972	1982	1990
Cadmium	1.7	0.5	1.05
Chromium	100	53	22.95
Copper	240	170	51.65
Lead	210	85.5	51.25
Mercury	2	0.4	0.38
Silver	6.6	NO DATA	1.3
Zinc	350	276	97.75

MIDDLE LOCH

Trace Metals	1972	1982	1990
Cadmium	0.22	0.3	0.3
Chromium	170	127	19.4
Copper	120	103	3.7
Lead	42	41	8.6
Mercury	0.92	0.5	0.082
Silver	2.6	NO DATA	0.6
Zinc	210	197	67.7

LOWER EAST LOCH

Trace Metals	1972	1982	1990
Cadmium	0.45	ND	0.3
Chromium	34	81	13.9
Copper	34	88	6.6
Lead	29	44	19.3
Mercury	0.52	0.3	0.1
Silver	3.1	NO DATA	0.4
Zinc	92	188	49.5

HOSPITAL POINT/DRYDOCK #4

Trace Metals	1972	1982	1990
Cadmium	1.3	0.2	1.2
Chromium	67	35	25.4
Copper	550	36	36.5
Lead	320	36	41.6
Mercury	1.9	ND	0.25
Silver	5	NO DATA	2
Zinc	730	215	51.2

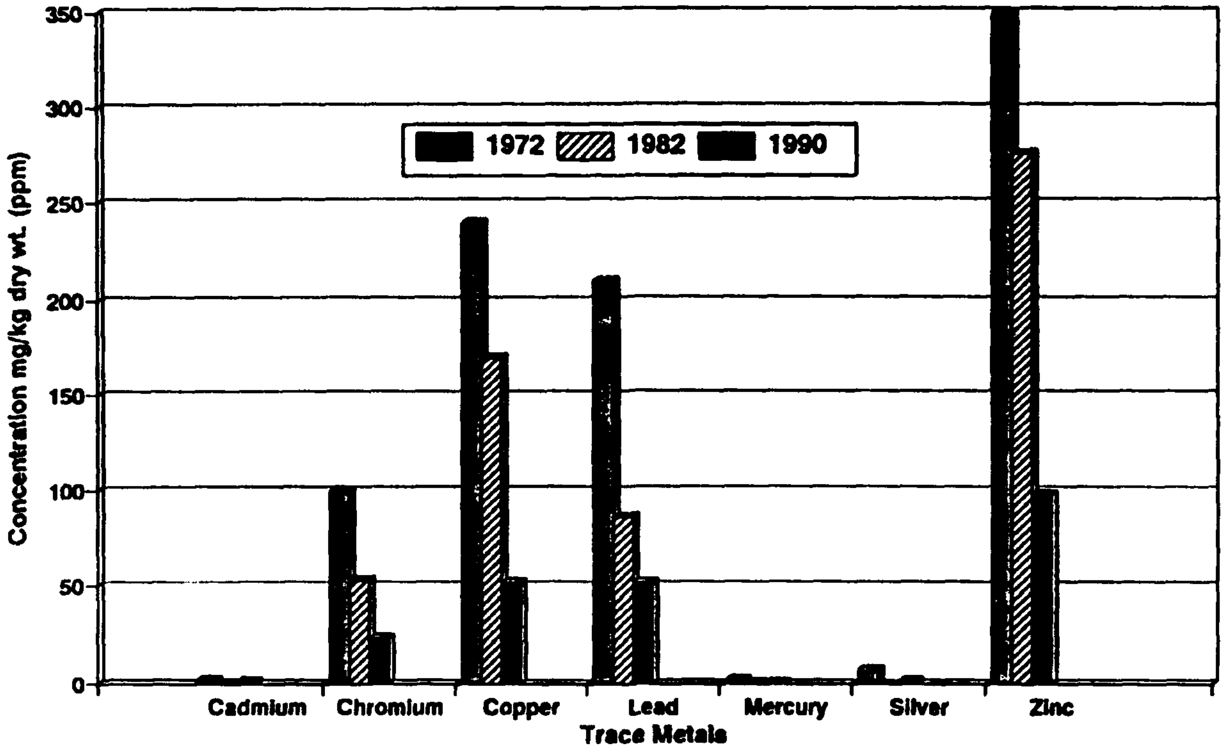

Figure A-1. Trace metal concentrations in Pearl Harbor sediments, Naval Shipyard/ Southeast Loch.

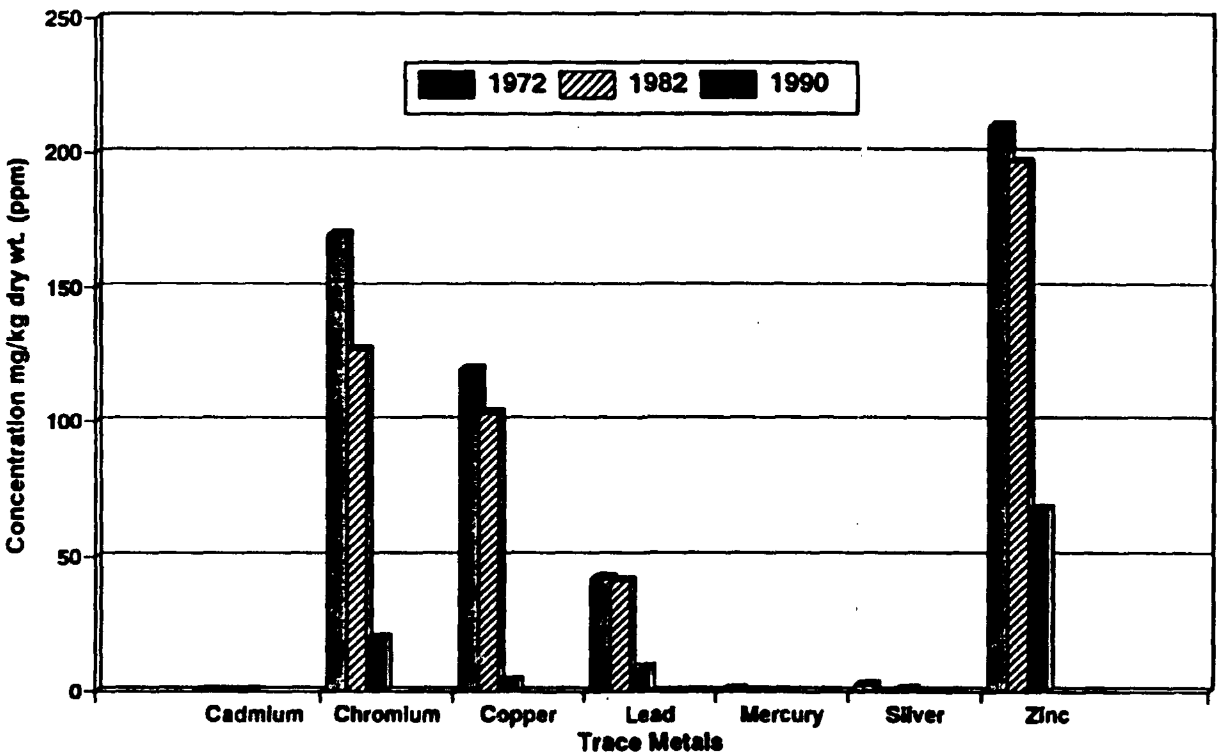

Figure A-2. Trace metal concentrations in Pearl Harbor sediments, Middle Loch.

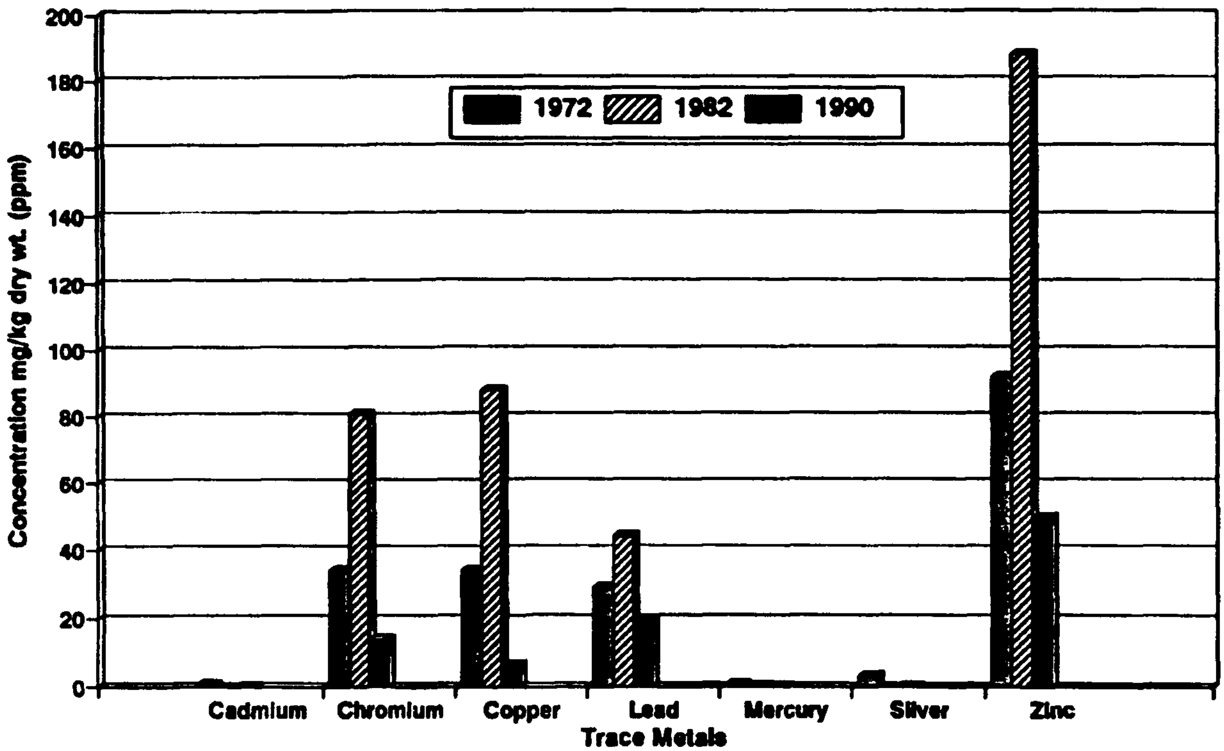

Figure A-3. Trace metal concentrations in Pearl Harbor sediments, lower East Loch.

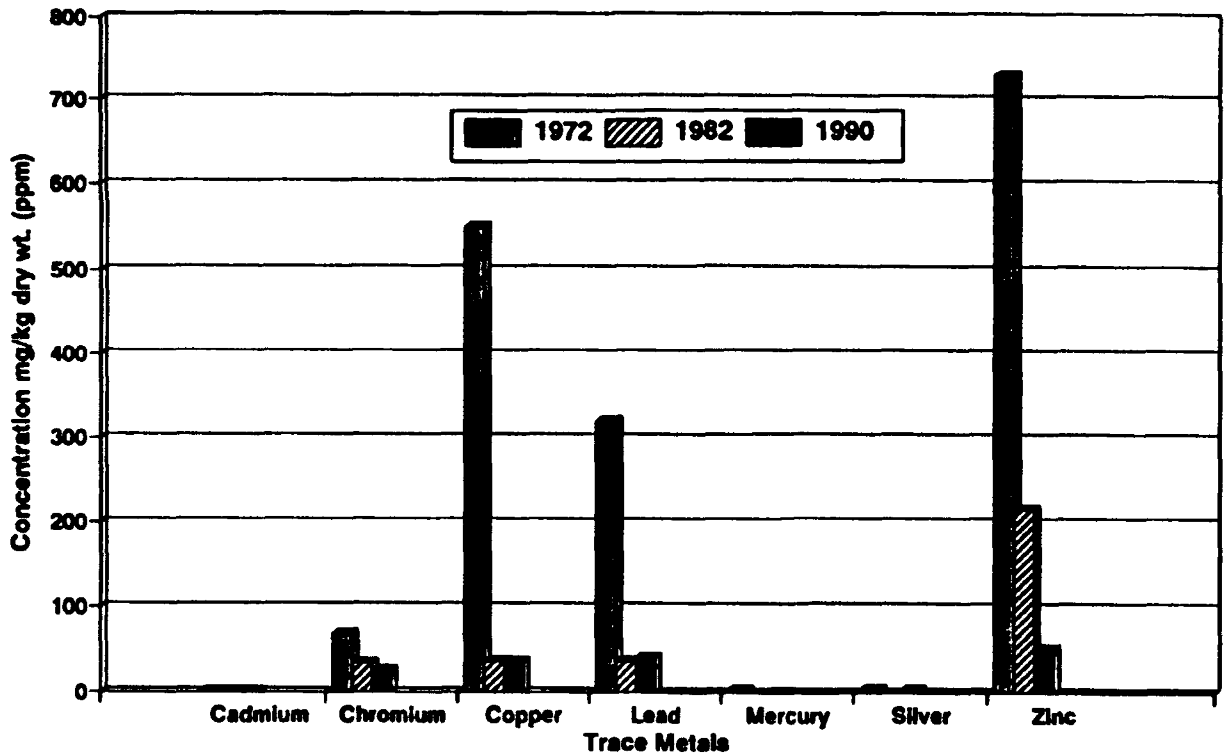

Figure A-4. Trace metal concentrations in Pearl Harbor sediments, Hospital Point/ Drydock #4.

Appendix B
PCB CONCENTRATIONS IN PEARL HARBOR SEDIMENT

Table B-1. PCB concentrations in Pearl Harbor sediments. Samples collected 4 April 1990 from PHNSY Piers, South Channel, and Southeast Loch.

Sample Number	Location	Concentration (µg/kg dry wt)
1	South Channel	No Detection
2	South Channel	128
3	South Channel	209
4	PHNSY-1010 Pier	472
5	PHNSY-1010 Pier	213
6	PHNSY-1010 Pier	1067
7	SE Loch Mid-Channel	796
8	SE Loch Mid-Channel	597
9	SE Loch Mid-Channel	515
10	Magazine Loch	265
11	Magazine Loch	781
12	Magazine Loch	544
13	Quarry Loch	768
14	Quarry Loch	1053
15	Quarry Loch	253
	Mean Concentration	510.73
	Standard Deviation	332.52

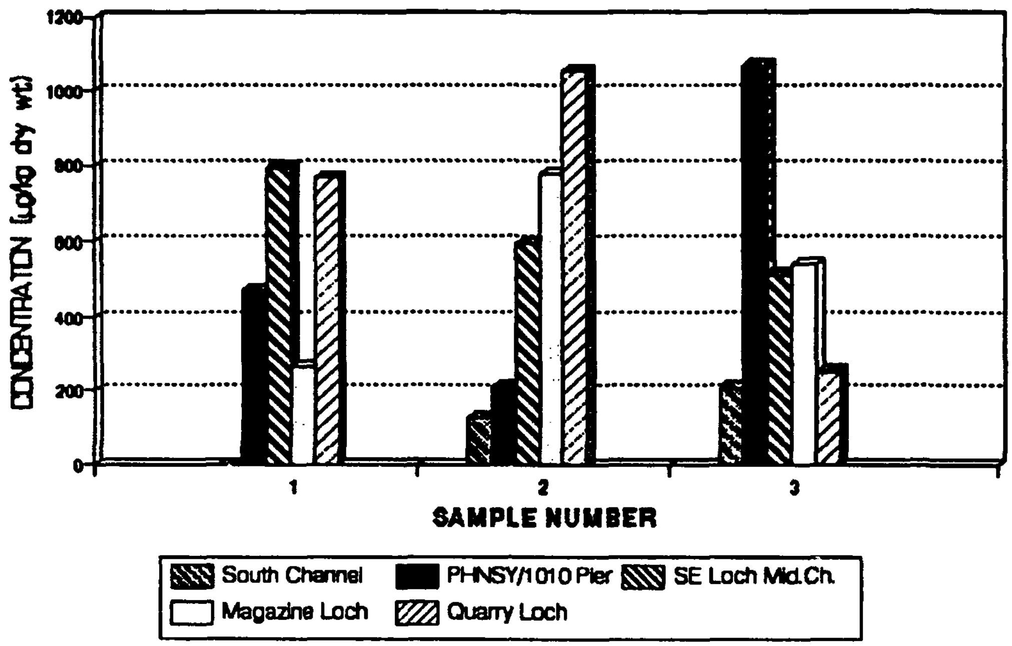

Figure B-1. PCB concentrations in Pearl Harbor sediments.

Table B-2. Pearl Harbor PCB (1260) concentrations. Source: AECOS, 1990.

Location	Concentration (ng/g dry wt)
Lower East Loch (n = 7)	170
South Channel (n = 6)	420
PHNSY (n = 10)	710
Southeast Loch (n = 7)	900
mean	550
standard deviation	321

n = number of samples.
ng/g dry wt = nanograms per gram (ppb).

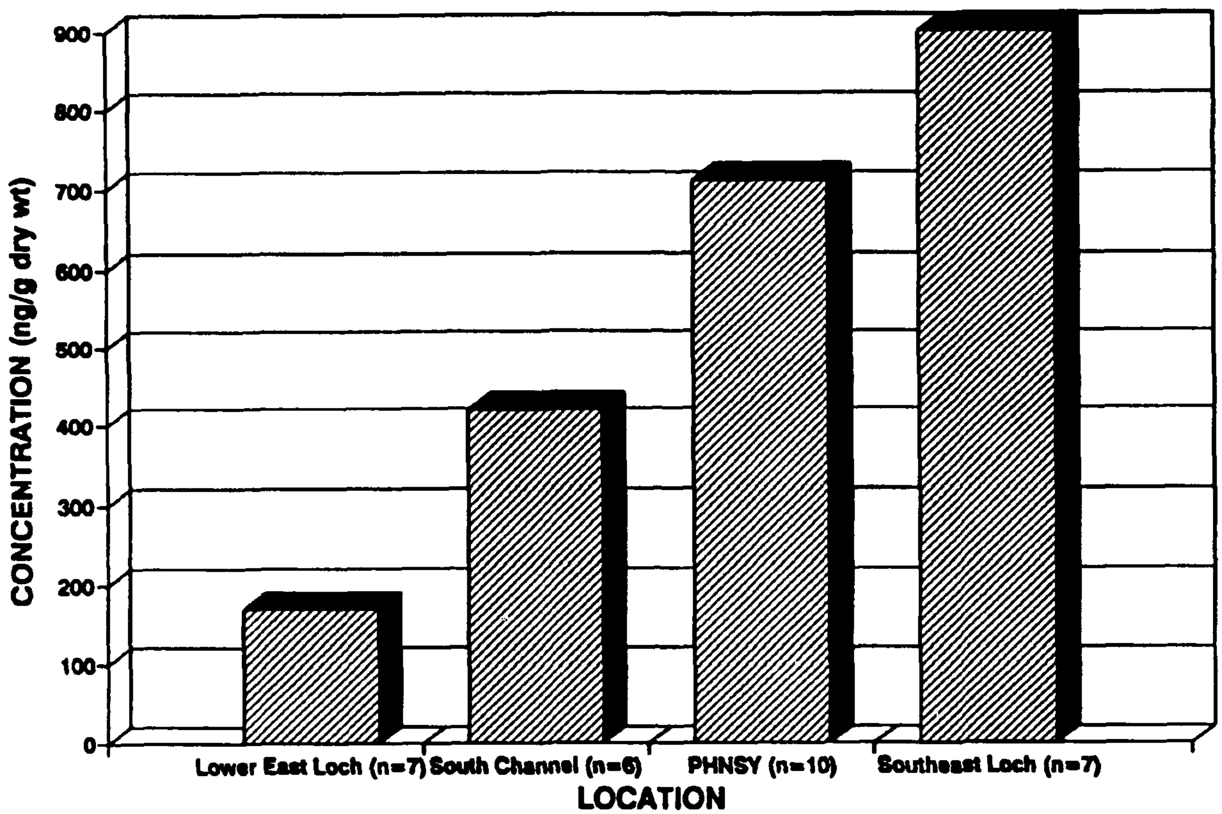

Figure B-2. PCB (1260) concentrations in Pearl Harbor sediments (source: AECOS, 1990).

Appendix C
VISUAL CENSUS DATA OF WATERBIRDS IN PEARL HARBOR

Table C-1. Pearl Harbor endangered waterbird visual census data.

Honouliuli Unit (PH Wildlife Refuge)									
Species	***1/86***	***8/86***	***1/87***	***8/87***	***1/88***	***8/88***	***1/89***	***8/89***	***1/90***
Hawaiian Coot	12	13	12	3	23	0	65	63	73
Hawaiian Duck	18	2	12	0	8	0	0	0	6
Hawaiian Stilt	34	5	17	28	24	24	83	35	17
Waiawa Unit (PH Wildlife Refuge)									
Species	***1/86***	***8/86***	***1/87***	***8/87***	***1/88***	***8/88***	***1/89***	***8/89***	***1/90***
Hawaiian Coot	0	23	0	0	0	NC	28	75	0
Hawaiian Duck	0	0	0	0	0	NC	2	1	0
Hawaiian Stilt	46	29	28	28	0	NC	11	17	0
Waipio Peninsula									
Species	***1/86***	***8/86***	***1/87***	***8/87***	***1/88***	***8/88***	***1/89***	***8/89***	***1/90***
Hawaiian Coot	47	22	6	14	0	10	10	0	1
Hawaiian Duck	5	0	2	0	0	11	0	0	0
Hawaiian Stilt	159	274	113	208	0	27	61	10	22

Source: Hawaii Department of Land and Natural Resources, Division of Forestry and Wildlife

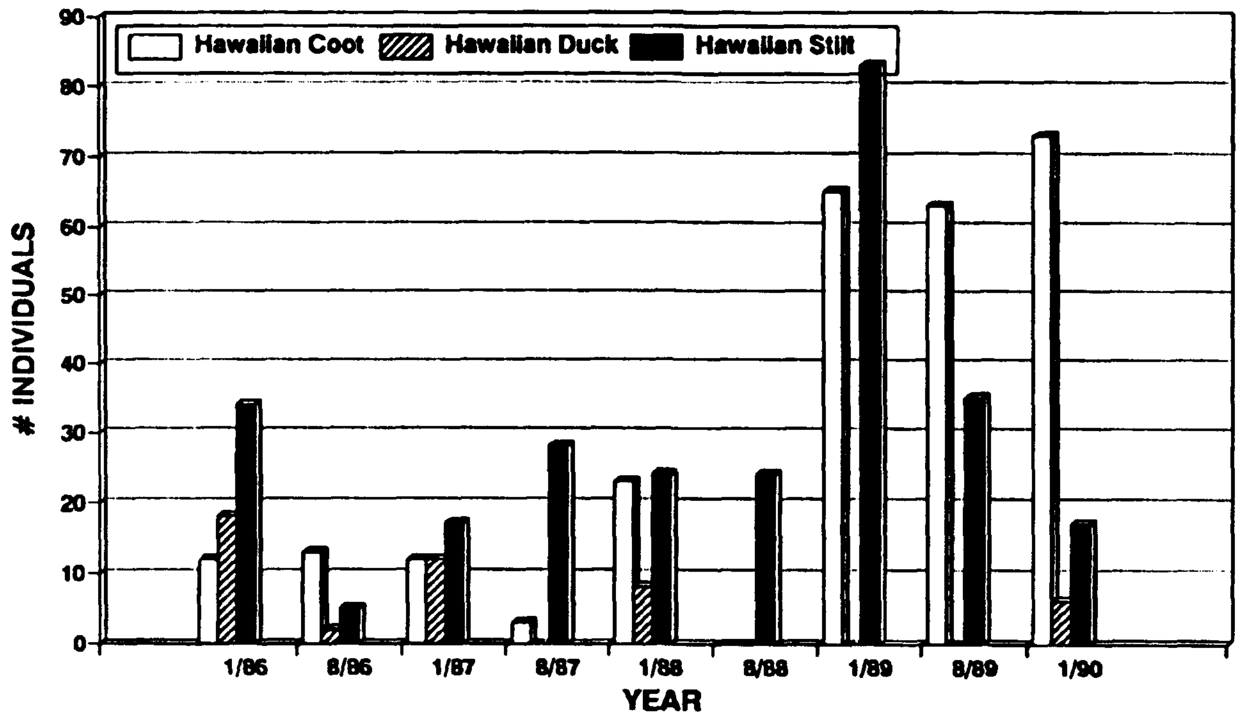

Figure C-1. Pearl Harbor Honouliuli Unit waterbird census data, 1986–1990.

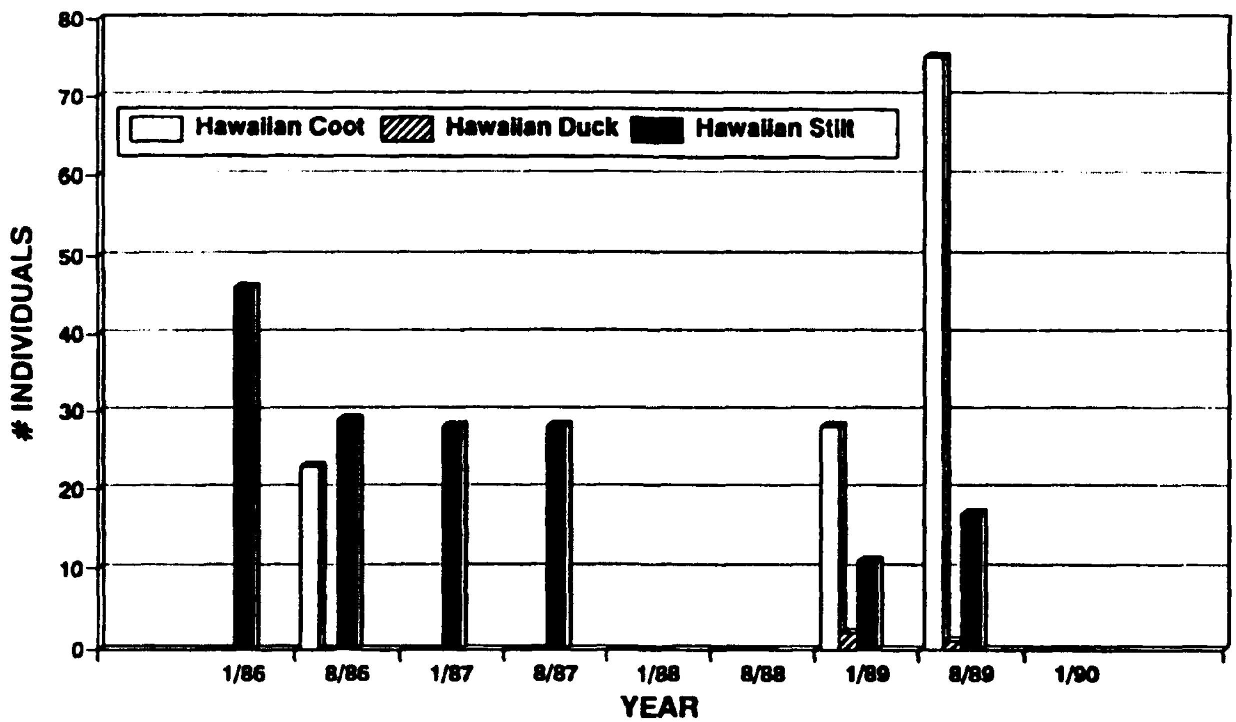

Figure C-2. Pearl Harbor Waiawa Unit waterbird census data, 1986–1990.

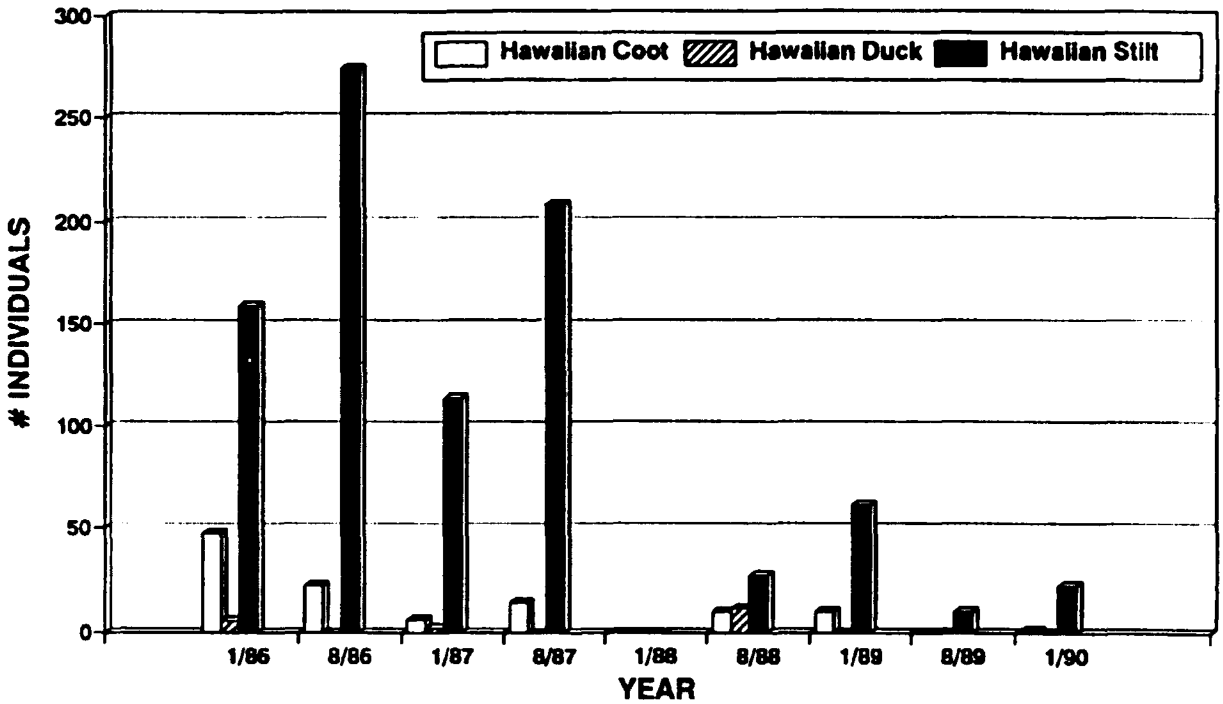

Figure C-3. Pearl Harbor Waipio Peninsula waterbird census data, 1986–1990.

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Pearl Harbor demonstrates remarkable resilience to natural and human-induced contaminant stresses. A review of more than fifty harbor-specific data sets reveals a complex contamination and recovery history. Siltation is a major contaminant pathway in Pearl Harbor. Dredging operations, which are necessary due to high siltation rates, reduce contaminant loading by periodically removing the upper harbor sediment layers. The response of test organisms during sediment toxicity and bioaccumulation studies showed negligible effects from sediment toxicity. The environmental quality at an offshore dredge disposal site for the harbor is not measurable affected. Urban runoff via storm drains and tributaries is an important nonpoint source of contaminant exposure to the Pearl Harbor ecosystem. Most contaminants experience extensive physical, chemical, and biological modification after entering the harbor environment. Certain contaminants, including PCBs, petroleum hydrocarbons, and silver, were reported at sufficiently elevated sediment concentrations to warrant environmental concern in some harbor regions and may warrant further evaluation. The overall sediment quality in Pearl Harbor, however, is less degraded than that of many U.S. mainland coastal harbors. Further detailed study of the abundance and distribution of important marine resources in Pearl Harbor is recommended.

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nutrients	sediment toxicity	trace metals
oysters	sewage treatment plant	U.S. Navy

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