Petroleum products can also cause cancer and impair immune response in fish and other aquatic life.

Bacteria
Many scientific studies have shown that boats and runoff from marinas can be a significant source of fecal coliform bacteria in areas of high boat density and poor water flushing. High bacteria concentrations are a public health threat. People can contract diseases or even die from coming into contact with contaminated waters or by consuming shellfish from waters with elevated bacteria levels. High bacteria concentrations have closed shellfishing areas and swimming beaches near marinas.

Reduced Water Flushing
Marinas that restrict water flushing and movement can contribute to low dissolved oxygen levels and a build up of toxic compounds.

Disruption of Sediment and Habitat
Inappropriate boat operation and dredging can destroy habitat, re-suspend bottom sediment, and reduce water clarity. Constructing marinas, ramps, and related facilities can physically alter or destroy wetlands, shellfish beds and other bottom communities. Re-suspending bottom sediments during dredging often reintroduces toxic substances into the water column. As the sediments settle back down, they can bury benthic organisms, suffocating them. Cloudy, or turbid water, blocks light from reaching aquatic plants, such as submerged aquatic vegetation (SAV), reducing their photosynthetic activity. SAV provides valuable habitat for many important fish and shellfish, such as crabs.

Shoaling and Shoreline Erosion
Shoaling and shoreline erosion result from physical transport of sediment due to waves and/or currents. Increased boat traffic can cause unnatural wave action that erodes coastal shorelines, introducing added sediment into the water column.

Section C4: Overusing Water to Maintain Urban Landscapes

Information obtained directly from:
http://www.epa.gov/OW/you/chap2.html

The overuse of water to maintain urban landscapes results in direct and indirect types of non-point source pollution. Direct non-point source pollution problems associated with water overuse for landscape maintenance include increased nutrient and soil runoff from the landscaped area, as well as other pollutants from urban and developed lands. Indirect pollution problems include increasing overall demand for additional development and use of water supply reservoirs.

Decreasing the amount of water used for landscape maintenance and implementing pesticide management plans can reduce the entry of these pollutants into surface and ground waters.

Failed or Failing Onsite Disposal Systems

Overusing water in the household can lead to the failure of onsite sewage disposal systems (OSDS), as well as increased addition of pollutants associated with household water uses to surface and ground waters (Table 3 below). Because many OSDS soil absorption field failures are attributed to hydraulic overload, reducing water use at many locations in the average household leaking toilets and other fixtures, showers and baths, inefficient appliances such as dishwashers or washing machines will ease hydraulic loading.

Table 3. Daily domestic water use and pollutant loadings by sources.

Water Use	Volume (gal/capita)	BOD (grams/capita)	Suspended Solids (grams/capita)	Total Nitrogen (grams/capita)	Total Phosphorus (grams/capita)
Garbage Disposal	1.2	10.8	15.9	0.4	0.6
Toilet	16.2	17.2	27.6	8.6	1.2
Basins and Sinks	22.4	22.0	13.6	1.4	2.2
Miscellaneous	6.6	0.0	0.0	0.0	0.0
Total	46.4	50.0	57.1	10.4	4.0

Source: USEPA, 1980.

Section C6: Lake Tahoe Regional Planning Agency, The Relationship Between Boating Activity on Lake Tahoe and Contamination from Polycyclic Aromatic Hydrocarbons (PAH)

Information obtained directly from:
http://www.trpa.org/default.aspx?tabid=126

Motorized watercraft can be a source of a range of water quality contamination, not only from the operation of the engine, but also from fuel spills, discharges of oil and grease, and other sources. The contamination from engines is due to the fact that outboard motors discharge their exhaust directly into the water, and inboard/stern drive motors typically discharge their exhaust below or at the water line. Marine engines emit hydrocarbons and oxides of nitrogen, typically nitrogen oxide and nitrogen dioxide. Some portion of these nitrogen oxides, which are directly emitted into the Lake, can potentially be converted to nitrate. The nitrogen oxides that enter the atmosphere are potentially available to be transformed into nitrate through atmospheric processes that can result in atmospheric deposition of nitrate. No marine engines (outboards or inboards, gasoline or diesel powered) have had to comply with the emissions regulations for automobiles.

EPA studies have indicated that carbureted two-stroke outboard engines exhaust, unburned, one-quarter of the fuel they consume. On a per-gallon basis, personal watercraft can emit a minimum of 23 percent more ambient hydrocarbon emissions than other two-stroke engine watercraft. Increased discharge impacts created by incomplete combustion due to the effects of high altitude can occur. Two and four-stroke engines do not perform as designed when incorrectly tuned for Lake Tahoe's elevation, which contains 28 percent less air at Standard Temperature and Pressure than found at sea level. The lower air pressure causes fuel to burn incompletely in vessels whose carburetors are tuned for a lower altitude. The un-tuned two-cycle outboard consumes about three times as much fuel as a tuned two-stroke engine.

Studies by scientists in the 1960s determined that fuel concentrations as low as one part per million (ppm) in seawater can be detected by smell. This indicates that one gallon of fuel will taint one million gallons of seawater. Eight parts per million will taint the flesh of fish (Nelson, 1994). Although the toxicity of the oil and gas mixture burned by outboards appears to be low, the combustion process can potentially lead to the formation of PAH. PAH can remain in the micro-layer on the surface of the water, which is a breeding ground for small organisms that form the base for aquatic food chains. They can also be found bound to the sediments at the bottom of bodies of water.

EPA, 2003 has designated fifteen PAHs, having three rings or greater, as priority pollutants because of their suspected harmful health effects on humans (EPA, 2003) (see) 7. PAHs have been found to be toxic to aquatic organisms, even in very low concentrations. The larger molecules, with more rings, tend to be much less water-soluble, biodegradable, and volatile than those containing fewer rings. Although the greater solubility of the smaller molecules makes them more available to organisms, their low persistence reduces the time that these organisms are exposed to them. The larger molecules, on the other hand bind strongly to tissues of exposed organisms. In general, the lighter molecules are more of an acute threat while the heavier molecules are a more persistent or chronic threat. In addition, some of these PAHs are modified in the presence of sunlight causing toxic effects in the cells of exposed organisms. This is termed "phototoxicity", and it is a significant potential problem in Lake Tahoe and other high elevation ultra-oligotrophic lakes due partly to the unique clarity, altitude, and other qualities of the lake waters. Giesy (UNR, 2003) indicated that enhancement of toxicity is as much as 50,000 times greater in sunlight than in dark conditions.

Appendix D
Marina Siting Standards References and Supporting Information

Section D1: Tennessee Valley Clean Marina Guidebook, Tennessee Valley Authority, Section 5, Marina Siting, Design, and Maintenance

Information obtained directly from:
http://www.tva.gov/environment/water/boating.htm

Marina siting and design play important roles in determining how good water quality within a marina basin will be. Marina location affects circulation in a marina basin, and, therefore, how well it flushes. Marina design, especially the configuration of the basin and its orientation to prevailing winds, waves, and currents, affects the retention of pollutants in the marina and the movement of pollutants out of a basin.

Existing marinas can improve water and habitat quality in the marina basin through application of BMPs. A marina designed with the important points of the management measures in mind will probably have better water quality and fewer water-pollution-related problems during its life of operation, and economic benefits may result from making such improvements. Simple yet effective forms of monitoring that provide valuable information about the conditions in the water can be done by someone knowledgeable of the marina and the surrounding waterbody. Visual inspections of the abundance and appearance of aquatic plants in and around the marina, use of the marina and surroundings by ducks and geese, the appearance of bottom sediments, the general clarity of the water near docks, and the abundance of fish can provide all the information necessary to judge the health of the water. All of these characteristics are indicators of the health of the waters.

Water quality assessments are generally done as a part of marina development or significant expansion. The widespread use and proven effectiveness of water quality assessments in determining the suitability of a location for marina development, the best marina design for ensuring good water quality, and the causes and sources of water quality problems make this management measure broadly applicable to marina management.

This management measure also includes assessments of how marinas can incorporate natural habitats into their siting and design. If a marina is properly designed and located, aquatic plants and animals should be able to continue to use the marina waters for the same activities that occurred in the waters before the marina's presence.

Section D2: Managing Nonpoint Source Pollution from Boating and Marinas, Pointer No. 9 EPA841-F-96-004I

Information obtained directly from:
http://www.epa.gov/owow/nps/facts/point9.htm

Managing Siting and Design for Marinas

The siting and design of marinas are two of the most significant factors impacting marina water quality. Poorly planned marinas can disrupt natural water circulation and cause shoreline soil erosion and habitat destruction. To reduce activities that cause NPS pollution, marinas should be located and designed so that natural flushing regularly renews marina waters. In addition, predevelopment water quality and habitat assessments should be conducted to protect ecologically valuable areas. Grass and ground cover planting or, where necessary, structural stabilization measures can help prevent erosion during and after marina construction. Stormwater runoff can be controlled by implementing pollution prevention strategies and properly containing hull maintenance areas. Marina fueling and sewage collection stations should be maintained and designed to make cleanup of spills easier. When completed, the final marina design should deliver the most desirable combination of marina capacity, services, and access, while minimizing environmental impacts and onsite development costs.

Section D3: Management Measures for Marinas and Recreational Boating, Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters, Section II, Marina Flushing Management Measure

Information obtained directly from:
http://www.epa.gov/owow/nps/MMGI/Chapter5/ch5-1.html#Toxicity.

Site and design marinas such that tides and/or currents will aid in flushing of the site or renew its water regularly.

This management measure is intended to be applied by States to new and expanding marinas. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal nonpoint source programs in conformity with this measure and will have some flexibility in doing so. The application of management measures by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

Description

The term *flushing* or *residence time* is often misused in that a single number (e.g., 10 days) is sometimes given to describe the flushing time of an estuary or harbor. In actuality, the flushing time ranges from zero days at the boundary to possibly several weeks, depending on location within the marina waterbody.

Maintaining water quality within a marina basin depends primarily on flushing as determined by water circulation within the basin (Tsinker, 1992). If a marina is not properly flushed, pollutants will concentrate to unacceptable levels in the water and/or sediments, resulting in impacts to biological resources (McMahon, 1989; NCDEM, 1990, 1991). In tidal waters, flushing is primarily due to tidal advective mixing and is controlled by the movement of the tidal prism into and out of the marina waterbody. A large tidal prism relative to the mean total volume of the waterbody indicates a large potential for flushing because more of the "old" water has a chance to become mixed with the "new" water outside the boundary or opening to the waterbody.

In nontidal coastal waters, such as the Great Lakes, wind drives circulation in the adjacent waterbody, causing a velocity shear between the marina basin and the adjacent waterbody and thereby producing one or more circulation cells (vortices). Such cells can have a flushing effect on water within a marina. The current created by local wind conditions is influenced by its persistence in terms of velocity and direction. The depth of the affected water layer is controlled by temperature and how the salinity changes with depth. Several hours of consistent wind are required for full development of wind-driven currents. These currents can be 2 percent of the wind's velocity and are generally downwind in most shallow areas (Tobiasson and Kollmeyer, 1991). In many situations wind-driven currents will provide adequate flushing of marina basins.

The degree of flushing necessary to maintain water quality in a marina should be balanced with safety, vessel protection, and sedimentation. Wave energy should be dissipated adequately to ensure that boater safety and protection of vessels are not at risk. The protected nature of marina basins can result in high sedimentation rates in waters containing high concentrations of suspended solids. Methods for assessing and mitigating sedimentation rates are available (NRC, 1987).

Management Measure Selection

The measure was selected because it has been shown that adequate flushing will greatly reduce or eliminate the potential for stagnation of water in a marina and will help maintain biological productivity and aesthetics (Tsinker, 1992; SCCC, 1984). Presented below are some illustrative examples of flushing guidelines in different coastal regions and different conditions. In areas where tidal ranges do not exceed 1 meter, as in the southeastern United States, a flushing reduction (the amount of a conservative substance that is flushed from the basin) of 90 percent over a 24-hour period has been recommended. For example, a flushing analysis for a proposed marina/canal on the St. Johns River, Florida, was conducted to predict how an effluent would disperse and to determine the configuration that would provide for maximum flushing of a hypothetical conservative pollutant (Tetra Tech, 1988). The selected design provided the recommended flushing reduction of 90 percent over a 24-hour period. This study showed that employing modeling to demonstrate how to achieve the recommended flushing rate is effective at avoiding adverse water quality and other environmental impacts. In the Northwest, a minimum flushing reduction of 70 percent per day was judged to be adequate (Cardwell and Koons, 1981). The 70 percent value, which represents the overall mean flushing rate for the marina basin, was based on the prevailing 1.82-meter tidal range for a 24-hour period. However, if the marina was in a protected area, such as an estuary or embayment, where tidal ranges never attain 1.82 meters, then a minimum flushing reduction of approximately 85 percent per day was recommended.

Practices

As discussed more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require implementation of these practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

A. Site and design new marinas such that the bottom of the marina and the entrance channel are not deeper than adjacent navigable water unless it can be demonstrated that the bottom will support a natural population of benthic organisms.

Existing water depths can affect the entire marina layout and design. Therefore, if depth information is not available, bathymetric surveys should be conducted in the proposed marina basin area as well as in those areas that will be used as channels, whether existing or proposed (Schluchter and Slotta, 1978). Flushing rates in marinas can be maximized by proper design of the entrance channel and basins. For example, in areas of minimal or no tides, marina basin and channel depths should be designed to gradually increase toward open water to promote flushing (USEPA, 1985a). Otherwise, isolated deep holes where water can stagnate may be created (SCCC, 1984).

Good flushing alone does not guarantee that a marina's deepest waters will be renewed on a regular basis. Several studies have concluded that deep canals and holes deeper than adjacent waters are not adequately flushed by tidal action or by wind-generated forces and thus cause stagnant or semi-stagnant conditions (Walton, 1983; Barada and Partington, 1972). Lower layers in canals and basins can act as traps for fine sediment and organic detritus and exhibit low dissolved oxygen concentrations. Lower-layer stagnation can occur in holes of depths less than 10 feet (Murawski, 1969). The low DO concentrations, resulting from an oxygen demand exerted by resuspended sediments and decaying organic matter, can impact aquatic life in the warmer months when the normal DO concentration is lower because of higher temperatures (Sherk, 1971). Fine sediments trapped in deep holes may form a thin surface ooze, which gives poor internal oxygen circulation and leads to oxygen reduction both within the sediments and in the overlying water (USEPA, 1976).

B. Design new marinas with as few segments as possible to promote circulation within the basin.

Flushing efficiency for a marina is inversely proportional to the number of segments. For example, a one-segment marina will not flush as well as a marina in open water, a two-segment marina will not flush as well as a one-segment marina, and so forth. Figure 5-1 presents examples of marinas with one segment and more than one segment. The physical configuration of the proposed marina as determined by the orientation of the marina toward the natural water flow can have a significant effect on the flushing capacity of the waterway. The ideal situation is one in which the distance between the exchange boundary and the inner portion of the basin is minimized. As the shape of the basin becomes more elongated (i.e., more than one segment) with respect to total surface area, the tidal advective or other dispersive mixing processes become more confined along a single flow path, and it takes longer for a water particle originating in the inner part of the basin to travel the greater distance to the boundary.

The marina's aspect ratio (the ratio of its length to its breadth) should be used as a guideline for marina basin design with respect to flushing. This ratio should be greater than 0.33 and less than 3.0, preferably between 0.5 and 2.0 (Cardwell and Koons, 1981). For rectangular marinas with one entrance connected directly to the source waterbody, the length-to-breadth ratio should be between 0.5 and 3.0 to eliminate secondary circulation cells where mixing and tidal flushing are reduced (McMahon, 1989).

Marina configurations that promote flushing exhibit, in general, better dissolved oxygen conditions than those with restrictions or stagnant areas such as improper entrance channel design, bends, and square corners (NCDEM, 1990). These areas also tend to trap sediment and debris. If debris are allowed to collect and settle to the bottom, an oxygen demand will be imposed on the water and water quality will suffer. Therefore, square corners should be avoided in critical downwind or similar areas where this is most likely to be a problem. If square corners are unavoidable because of other considerations, then points of access should be provided in those corners to allow for easy cleanout of accumulated debris.

In tidal waters, marina design should replace conventional rectangular boat basin geometry with curvilinear geometry to eliminate the stagnation effects of sharp-edged corners and to exploit the natural hydraulic patterns of flow and prevent the occurrence of areas where flushing is negligible (Cardwell and Koons, 1981). By combining these elements in the design of a marina, analytical studies have suggested that a strong internal basin circulation system could develop, resulting in acceptable water quality levels (Layton, 1991).

C. Consider other design alternatives in poorly flushed waterbodies (open marina basin over semi-enclosed design; wave attenuators over a fixed structure) to enhance flushing.

In selecting a marina site and developing a design, consideration of the need for efficient flushing of marina waters should be a prime factor along with safety and vessel protection. For example, sites located on open water or at the mouth of creeks and tributaries usually have higher flushing rates. These sites are generally preferable to sites located in coves or toward the heads of creeks and tributaries, locations that tend to have lower flushing rates.

In poorly flushed waterbodies, special arrangements may be necessary to ensure adequate overall flushing. In these areas, selection of an open marina design and/or the use of wave attenuators should be considered. Open marina designs have no fabricated or natural barriers, which tend to restrict the exchange of water between ambient water and water within the marina area. Wave attenuators improve flushing rates because water exchange is not restricted. They are also attractive because they do not interfere with the bottom ecology or aesthetic view. Other advantages include their easy removal and minimization of potential interference with fish migration and shoreline processes (Rogers et al., 1982).

The effectiveness of wave attenuators is usually dependent on their mass (Tobiasson and Kollmeyer, 1991). The greater the horizontal and draft dimensions, the greater their displacement and effectiveness. Floating wave attenuators have limitations on their use in extreme wave fields, and site-specific studies should be performed as to their suitability.

D. Design and locate entrance channels to promote flushing.

Entrance channel alignment should follow the natural channel alignment as closely as possible to increase flushing. Any bends that are necessary should be gradual (Dunham and Finn, 1974). In areas where the tidal range is small, it is recommended that the marina's entrance be designed as wide as possible to promote flushing while still providing adequate protection from waves (USEPA, 1985a). In areas where the tidal range is large, however, a single narrow entrance channel, if properly designed, has proven to provide adequate flushing (Layton, 1991).

Entrance channel design and placement can alleviate potential water quality problems. In tidal and nontidal waters, marina flushing rates are enhanced by wind action when entrance channels are aligned parallel to the direction of prevailing winds because wind-generated currents can mix basin water and facilitate circulation between the basin and the adjacent waterway (Christensen, 1986).

Shoaling may be significant in areas of significant bed load transport if the entrance channel is located perpendicular to the waterway. Increased shoaling could require extensive maintenance dredging of the channel or create a sill at the entrance to the marina basin. Shoaling at the marina entrance can lead to water quality problems by reducing flushing and water circulation within the basin (Tetra Tech, 1988; USEPA, 1985a). In Panama City, Florida, a study of bathymetric surveys before and after the construction of an artificial inlet showed that the areas of deposition and erosion in the natural bay rapidly changed as a result of alterations of channel positions and depths (Johnston, 1981).

The orientation and location of a solitary entrance can impact marina flushing rates and should be given consideration along with other factors impacting flushing. When a marina basin is square or rectangular, a single entrance at the center of a marina produces better flushing than does a single corner-located asymmetric entrance (Nece, 1981). This results in part because the jet entering the marina on the flood tide is able to circumnavigate a greater length of the sub-basin perimeter associated with each of the two gyres than it could in a single-gyre basin with an asymmetric entrance. If the marina basin is circular, an off-center entrance channel will promote better circulation. Off-center entrance channels also promote better circulation in circular canals.

E. Establish two openings, where appropriate, at opposite ends of the marina to promote flow-through currents.

Where water-level fluctuations are small, alternatives in addition to the ones previously discussed should be considered to ensure adequate water exchange and to increase flushing rates (Dunham and Finn, 1974). An elongated marina situated parallel to a tidal river can be adequately flushed using two entrances to establish a flow-through current so that wind-generated currents or tidal currents move continuously through the marina. In situations where both openings cannot be used for boat traffic, a smaller outlet onto an adjacent waterbody can be opened solely to enhance flushing. In other situations a buried pipeline has been used to promote flushing.

F. Designate areas that are and are not suitable for marina development;

i.e., provide advance identification of waterbodies that do and do not experience flushing adequate for marina development.

For example, the physical characteristics of some small tidal creeks result in poor flushing and increased susceptibility to water quality problems (Klein, 1992). These characteristics include:

- Bottom configuration: flushing is retarded when a depression exists that is lower than the entrance to the waterway.
- Entrance configuration: a constricted entrance will decrease flushing.
- Tributary inflow: higher freshwater inflow will increase flushing.
- Tidal range: increased tidal range will increase flushing.

Appendix E

Sediment Re-Suspension by Recreational Watercraft

Lake and Reservoir Management 19(1):15-25, 2003

Stirring up Trouble? Resuspension of Bottom Sediments by Recreational Watercraft

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ABSTRACT

Beachler, M. M. and D. F. Hill. 2003. Stirring up trouble? Resuspension of bottom sediments by recreationalwatercraft. Lake and Reserv. Manage. 19(1):15-25.

An experimental and theoretical study of the hydrodynamic impacts of recreational watercraft in shallow waterbodies is presented. Of particular interest is the ability of turbulent prop or jet wash to resuspend bottom sediments. Intuition suggests, and the experiments confirm, that this ability is a strong function of boat speed and water depth.

The results of this study demonstrate that boats operating at high speed have no greater impact on the lake bed than boats travelling at idle speeds. The greatest impact is seen when boats are travelling at 'near-plane' speeds. This critical speed is a function of boat size and water depth.

To increase the usefulness of the observations, a theoretical model of the flow underneath a passing boat was developed and validated with the data. Relying on only a few input parameters, the model can be used to estimate, for example, the minimum operating depth required for a given boat to prevent sediment resuspension.

Discussion of the relevance of this work in the context of setting use restrictions for watercraft is provided.

Key Words: boating, recreational conflicts, sediment resuspension, hydrodynamics.

Waterways such as rivers, estuaries, and lakes are valuable natural resources, as they support municipal, navigational, industrial, and recreational uses. In response to historically increasing levels of use, proper management of waterways is vital. For were a water body allowed to degrade significantly, the very qualities that made it initially an attractive resource would vanish. The balance between resource conservation and utilization, therefore, is a delicate one and one which is by no means unique to water resources. The role of science in this discussion is to provide objective data which can be incorporated by policy makers into their decision making process.

One of the many potential sources of waterway impacts is recreational boating. This issue attracts attention for several reasons. First of all, according to the National Marine Manufacturer's Association (http://www.nmma.org), boating registrations in the United States have increased from 5 to 15 million over the past 25 years. Moreover, today's boats are bigger and more powerful than those of yesterday. The NMMA reports that the average horsepower of outboard motors sold increased from 65 in 1985 to 86 in 2000. Finally, the popularization of personal watercraft (PWC), with their exceptionally shallow drafts, has brought boating activity to regions of water bodies which have historically seen little boating traffic.

The potential impacts of watercraft fall into the categories of fuel and exhaust emissions, noise pollution, direct contact with flora and fauna, and hydrodynamic impacts such as wake-induced shoreline erosion and turbulent prop wash. Useful reviews are given by Liddle and Scorgie (1980), Wagner (1991), and WHOI (1998). As an example of hydrodynamic impacts, note first that wakes generated by boat traffic can grade and redistribute sediment (Kirkegaard et al. 1998, Parchure et al. 2001, Parnell and Kofoed-Hansen 2001). Johnson (1994) correlated boat waves to an increase in shoreline erosion and stirring of bottom sediments in the Upper Mississippi River System (UMRS). Additional work by Bhowmik et al. (1992) in the UMRS considered the evolution of a wake packet as it propagated away from the sailing line.

Turbulence produced by prop wash has numerous potential impacts as well. The mortality rate of fish eggs due to turbulence was investigated by Killgore et al. (1987). Similarly, Morgan et al. (1976) studied the mortality rates of perch eggs due to boat-induced shear stress in the Chesapeake and Delaware Canals. Finally, Sutherland and Ogle (1975) exposed salmon eggs to forces equivalent to those induced by passing boats, concluding that jet boats operating in very shallow rivers could cause substantial mortality.

Prop wash also plays a role in resuspending bottom sediments. This may lead to erosion, internal nutrient loading, or elevated levels of turbidity and heavy metals in the water column. For example, Hamill et al. (1999) have studied the 'scour' patterns that develop due to displacement vessels operating in shallow water. Yousef et al. (1980) clearly demonstrated increases in nutrient levels in response to boat stirring in Florida lakes. Arruda et al. (1983) and Breitburg (1988) both discussed how aquatic wildlife feeding patterns could be disrupted by elevated turbidity levels. Finally, Francisco et al. (1999) have identified commercial ferry traffic as the main source of resuspension of contaminated sediments in Elliot Bay, Seattle.

Several investigators have considered the mechanics of bottom stirring by boats. For example, Herbich (1984) used basic momentum conservation and incipient sediment motion relations in his discussion of propeller-induced resuspension. However, few examples were given and no data were cited for comparison. Gucinski (1982) conducted scale-model laboratory experiments of propeller flows in order to complement field observations of boat-induced turbidity in the Chesapeake Bay. His conclusions were that boat-induced resuspension can occur in depths less than 3 meters, but is likely to be of minor consequence until depths are 2.2 meters or less. He further notes that smaller, planing boats will have much less impact than heavy, displacement (deeper draft) boats.

Yousef et al. (1978) used pressure sensors to measure the hydrodynamic signal of boat passage at the level of the lake bed. Their observations were incorporated into an empirical design procedure predicting the 'critical' depth of operation, based upon sediment grain size and boat power. Finally, Maynord (1998) provides some useful analysis of propeller flows and bottom shear stress, albeit in the context of larger displacement vessels.

The present paper discusses a recent field study, coupled with a simple mathematical model, that seeks to elaborate upon the mechanism of bottom stirring of sediments by recreational watercraft. The specific objectives of the field measurements are to document the velocity and turbidity that are induced, near the bed of a lake, by the passage of watercraft. Of particular interest is how these quantities vary with parameters such as boat speed and water depth. The specific objective of the modelling is to develop the mathematical capability to reproduce the observations, thereby broadening the applicability of the present work.

Theoretical Model

An understanding of the disturbance of a lake bed by a passing watercraft has two main components. First, the unsteady velocity field that is induced in the water as a boat passes overhead must be known. Second, the interaction of this velocity field with the water-sediment interface at the bed must be known. The scope of the present paper is largely limited to the first component, but, before proceeding, a brief discussion of the second is warranted.

Sediment Dynamics

For cohesionless soils, the parameters most relevant to incipient motion include sediment grain size, shape, and density. Fall velocity, which is really an aggregate measure of these individual parameters is a frequently used measure as well. To give some numeric context, a round sand grain having a diameter of 1 mm and a specific gravity of 2.65 will attain a terminal fall velocity of roughly 15 cm·s^{-1}. On the other hand, a 50 μm grain of the same material will settle out at the much lower velocity of 2 mm·s^{-1}.

In the past, extensive attention has been paid to determining how the minimum, or 'critical', bed shear stress required to initiate motion varies with these parameters. The bulk of existing laboratory results are relevant to flat beds of monodisperse particles exposed to a steady current. In the field environment, application of these results is often complicated by the presence of bedforms, polydisperse sediments, and turbulent, unsteady flows. In addition, many soils have a significant fraction of very fine particles or mineral content (e.g., kaolinite), either of which can render the soil 'cohesive', thereby increasing the critical stress required for motion.

These complicating factors do not change the fundamental approach, however, which is to express a non-dimensional critical shear stress as a function of a non-dimensional particle Reynolds number. In other words,

$$\frac{\tau_c}{gd(\rho_s - \rho)} \equiv \psi = f\left(\frac{u_{*c}d}{\nu}\right), \qquad (1)$$

where τ_c is the critical bed shear stress required for motion, g is gravity, d is particle diameter, ρ_s and ρ are the densities of the sediment and water, ψ is the Shields parameter, u_{*c} is the critical shear velocity, and ν is the fluid kinematic viscosity. The unknown functional dependence between the two dimensionless variables must then be established through laboratory experimentation. The original data of Shields and those of numerous other authors are reviewed by Yalin and Karahan (1979).

To cite a numerical example, consider the uniform flow of water, 1 m in depth, over a smooth bed of cohesionless sand of 0.3 mm diameter and 2.65 specific gravity. It is straightforward to show (Sturm 2001) that the depth-averaged minimum velocity required for sediment motion is 37 cm·s^{-1}. Given the boundary layer structure of the velocity profile in the vertical direction, the value of the velocity in the vicinity of the bed will of course be less than this average value.

Alternative approaches to the description of incipient motion include consideration of the balance of lift and drag forces on a single sediment grain (Cacchione and Southard 1974). Their analysis suggests, for 1 mm sand, a critical velocity of 15 cm·s^{-1}. As yet another example, Yousef et al. (1978) utilize an equation for critical near-bed velocity, rather than shear stress, and determine that 25 cm·s^{-1} is required to move 0.3 mm sand. These figures are all noteworthy as they are consistent with the observations of the present field experiment.

Axisymmetric Turbulent Jets

The induced flow underneath a planing boat is clearly extremely complex. There are components associated with the displacement of the hull and with the propulsion. The fine details of these effects are controlled by hull geometry, propeller geometry, motor trim and a variety of other parameters. Additionally, there is significant entrainment of air such that the flow is two-phase in the near field.

For any model to be useful in widespread application, it should be as general and as simple as possible. To that end, it was decided to (i) neglect hull displacement effects and to (ii) model the prop wash flow as an axisymmetric turbulent jet. While the latter assumption is justifiable in the case of a PWC or a jet-driven boat, its validity in satisfactorily modelling swirling propeller flows is not immediately obvious. As shown in Fig. 1, a jet is created when a fluid stream of initial 'slip' velocity V_s (i.e., velocity relative to the ambient fluid) discharges from an orifice of some diameter D. After an initial 'zone of establishment', the streamwise mean velocity field $u(x,r)$ is very well described by (Fischer et al. 1979):

$$u(x, r) = 7\,\frac{M_0^{1/2}}{x}\exp\left[-\left(\frac{r}{0.107x}\right)^2\right] \qquad (2)$$

where $M_0=\pi V_s^2 D^2/4$, x is the streamwise coordinate, and r is radial distance from the jet axis. Some characteristics of this velocity field are that the velocity along the centerline of the jet decays by $1/x$ and that the variation of velocity in the lateral direction is Gaussian (i.e., a bell shape).

To help illustrate what this means in terms of velocities that can be induced on a lake bed by a passing boat, consider a boat travelling in water of 1.5 m depth. Assume that the prop sweeps out a circular area 37.5 cm in diameter and that the prop axis is 25 cm below the water surface. Finally, assume that the slip velocity V_s=5 m·s^{-1}. Fig. 2 illustrates the expected velocity on a 20 m wide and 100 m long patch of lake bed. The location of the boat is at x = 0, z = 0 and it is travelling to the left. Assuming that 25 cm·s^{-1} is needed to disturb the sediment of our example lake, it is clear that there is a significant 'footprint' of lake bed that will be disturbed in this case. Of additional interest is the fact that the region of greatest impact is not directly underneath the boat, but instead lags the boat by several meters.

Finally, note that (2) applies *only* to a fluid of infinite extent and is therefore not applicable to a shallow fluid layer bounded by a sediment bed on the bottom and a free surface on the top. However, the well-known method of images can be used to satisfy the requisite no-flow conditions at these boundaries. One effect of this is that the velocity profile in the vertical direction is no longer Gaussian.

Model Application

To apply this model, one needs to know the propeller/jet diameter and draft, figures that are readily obtained. The crucial, and more elusive, parameter is V_s. Recall that this is the velocity of the jet, at its source, relative to the ambient fluid. One method of obtaining V_s, for a propeller-driven boat, is to record speed and

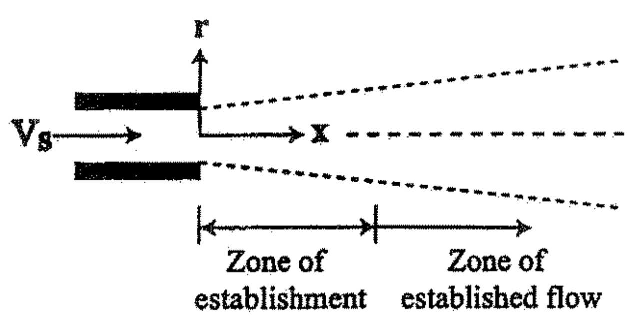

Figure 1.–Schematic of an axisymmetric turbulent jet. The velocity at the jet source is V_s and the velocity field downstream is a function of the streamwise coordinate x and the lateral coordinate r.

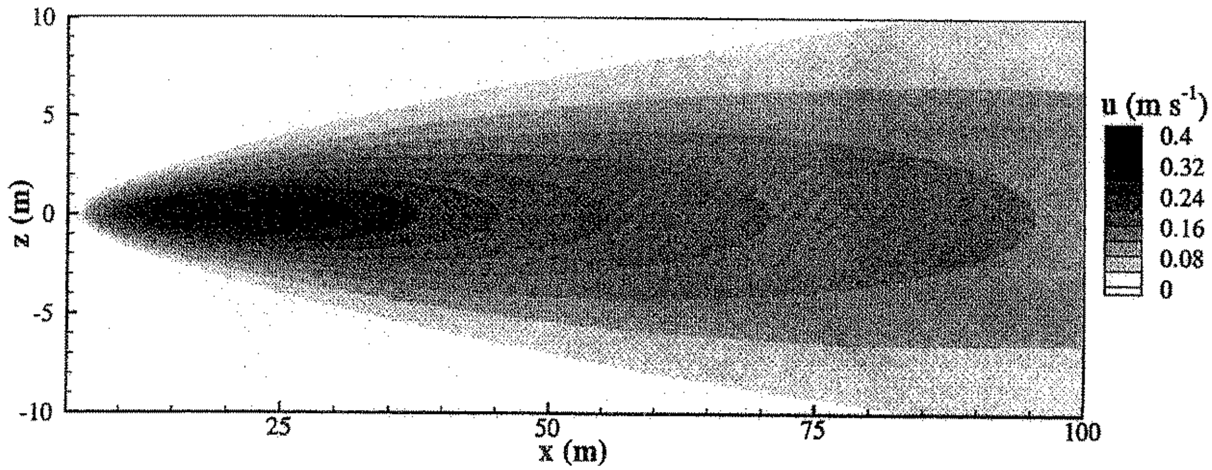

Figure 2.–Contours of horizontal velocity u on a lake bed in 1.5 m of water. V_s=5 m·s^{-1}, D = 37.5 cm. The jet source is located at x = 0 m, z = 0 m, is travelling from right to left, and is at a depth of 25 cm below the free surface.

rpm data for the boat. This is easily done, provided that the boat has both a speedometer and tachometer. In lieu of an accurate speedometer, a GPS unit may be used. Once this data is obtained, the slip velocity, in meters per second, is given by

$$V_s = \omega P - V_b \qquad (3)$$

where ω is the *propeller* angular velocity in revolutions per second, P is the pitch of the propeller in meters, and V_b is the boat speed in meters per second. As a sample, rpm and V_s data for a typical boat are given in Fig. 3. Note that the pitch of a propeller is typically stamped somewhere on the body of the propeller and that the propeller angular velocity is reduced from the tachometer reading by a gear ratio, typically in the range of 1.5 to 2.0.

Determination of V_s for a PWC or a jet-driven boat is also possible, in principle. These craft are essentially driven by a centrifugal pump, the flow rate through which is a function of rotational rate and imposed head. If the pump-performance curve can be either obtained from the manufacturer or measured through experimentation, determination of V_s as a function of boat speed is straightforward.

Field Study

To test the predictions of the model, field experiments were conducted during a two-week period in July, 2001. The main objective of the field study was to gain information on how the induced velocity and turbidity on a lake bed varied with the speed of the passing boat and with the depth of the water. A secondary objective was to test different types of boats to see if there was any significant variation with drive type.

The experiments were performed on Franklin and Butternut Lakes, located in Forest County, Wisconsin, USA. The lakes were selected not for any perceived boating-related problems but, rather, for the ease of access to a wide variety of facilities that they provided. Franklin and Butternut Lakes have, respectively, surface areas of 3.61 km^2 and 5.23 km^2 and maximum depths of 14.0 m and 12.8 m. The average depths of the two lakes are in the range of 4-5 m. Bottom material spans a wide range of grain sizes, from fine (~50 μm) mud to coarse (~15 cm) rubble.

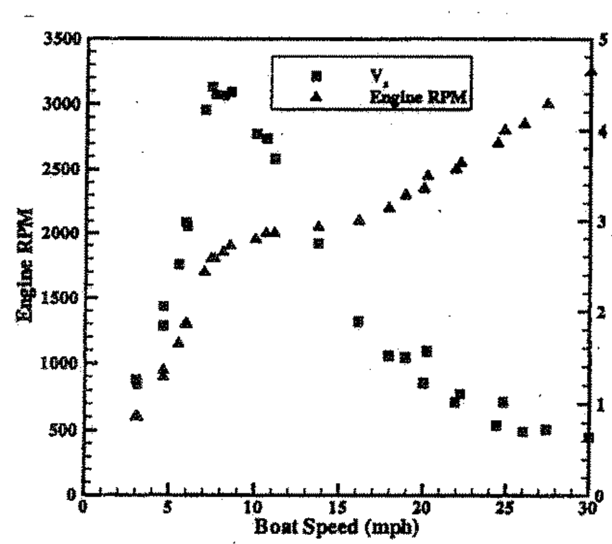

Figure 3.–Measured values of engine rpm and calculated values of V_s for a typical recreational watercraft.

Study Design

The general experimental methodology began with the selection of an appropriate study site. Here, 'appropriate' refers to a site characterized by a relatively flat, debris-free bottom, in water of a desired depth. Next, a series of gates was constructed in order to guide the watercraft directly above the instrumentation, as illustrated in Fig. 4. The buoys were 2 m apart laterally for the boat trials and 1.2 m apart for the PWC trials. In all cases, the gate spacing was roughly 20 m in the streamwise direction. Note that while a perfectly flat bottom is a laboratory ideal not achievable in the field, effects due to variations in water depth were minimized by (i) choosing sites with widely spaced depth contours and (ii) aligning the path of travel of the boats parallel to the contours.

With the course set and the instrumentation installed on the lake bed, a boat was then navigated, at a constant specified speed, through the course while data on velocity and turbidity were collected. After completion of a run, and a waiting period of several minutes, to allow for any lingering transients to die out, the next run was conducted. In this fashion, numerous runs, at a wide range of speeds were carried out. The gates were then set up in a different water depth and the trials were repeated.

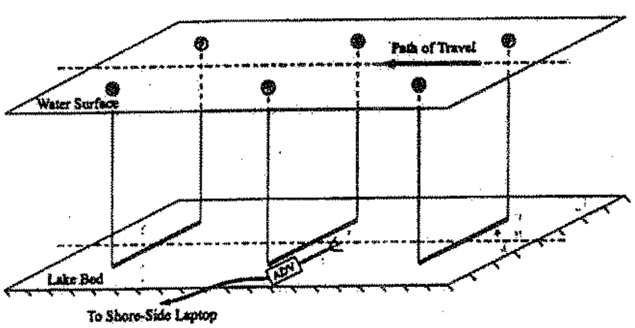

Figure 4.–Schematic of field experiments.

Facilities and Instrumentation

A total of three different watercraft were utilized in this study, a 1980's vintage Hydrostream Ventura outboard boat, a 1993 Correct Craft Ski Nautique inboard boat, and a 1988 Yamaha Waverunner PWC. General characteristics of these craft are summarized in Table 1. Boat speed measurements, in the case of the inboard, were made with an onboard speedometer while in the cases of the outboard boat and the PWC, a handheld GPS unit was used.

Fluid velocity measurements were made with a Sontek Acoustic Doppler Velocimeter (ADV), which allows for the continuous acquisition of three components of velocity, at a point, at a rate of up to 25 Hertz. The ADV uses the Doppler shift of sound waves, scattered off of small particles in the water, to deduce the velocity of the water itself. The measurement volume of the ADV is quite small, on the order of 1 cm^3, and the ADV was mounted horizontally on the lake bed such that the measurement volume was 10 cm above the bed. In this configuration, the three components of velocity, (u,v,w) corresponded to the streamwise, vertical, and lateral directions.

Turbidity measurements were made with a Downing & Associates Optical Backscatter Sensor (OBS-3). This instrument emits infrared radiation and uses receiving optics to measure the amount of radiation scattered back by particles suspended in the water. If local sediment samples are collected, the voltage output of the sensor can then be calibrated to suspended sediment concentration (SSC). For the present study, sediment samples were collected at each study site where the OBS-3 was used and a laboratory calibration was performed, as detailed by Beachler (2002). Grain size distributions for these samples are given in Fig. 5. The conical sampling volume for the OBS-3 is larger and less well defined than that of the ADV, but the instrument was mounted approximately 2.5 cm above

Table 1.–Physical properties of the watercraft utilized in the field experiments.

Watercraft	Propulsion Type	Power (hp)	Length (m)	Mass (kg)	Prop/Jet dia. (cm)	Prop Draft (cm)	Gear Pitch (cm)	Gear Ratio
Hydrostream Ventura	Outboard propeller	150	5.0	450	35.6	54.6	48.3	1.86
Ski Nautique	Inboard propeller	240	5.9	1180	35.6	43.2	40.6	1.26
Yamaha Waverunner	Jet drive	~75	~2.5	~150	8.25	0	n/a	n/a

the lake bed in an effort to register the entrainment of sediment from the bed itself.

Sample transient velocity and SSC data, for the outboard boat, are given in Fig. 6. These data are intended to be illustrative only and they are not from the same run; hence the lack of synchronization of the time axis. As shown in part (a), the passage of a boat is indicated by a forward surge in velocity (due to the displacement of the hull) followed by a backward surge in velocity (due to the prop wash). Of key importance to the present study is how the maximum reverse streamwise velocity near the bed, v_{bmax}, varies with boat speed and water depth. As shown in part (b), the disturbance at the bed is manifested in the form of a severe 'pulse' of resuspended sediment. As the sediments in the study areas were fairly sandy (d_{50} ~ 0.3 mm), they resettled fairly quickly. Other studies (Garrad and Hey 1987) in areas characterized by finer sediments have noted far longer resettlement times subsequent to boat passage.

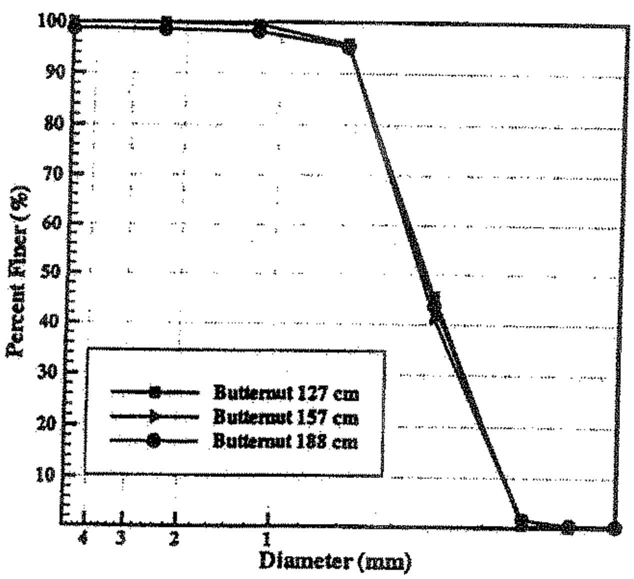

Figure 5.–Grain size distributions of the three study sites on Butternut Lake.

Results

Velocity Data

A summary of the variation of maximum bed velocity, v_{bmax}, with boat speed and water depth, for the outboard boat, is provided in Fig. 7. In addition to the experimental measurements, the model predictions are given. First of all, note that the error bars reflect a ~10% uncertainty in the measurements. This uncertainty is not dominated by instrument resolution, but rather by the ability of the boat driver to consistently navigate the boat *directly* over the instrumentation and at a constant specified speed.

Regarding the first of these sources of error, due to the sharp lateral gradients exhibited by a Gaussian profile, even small deviations of the boat from the established sailing line can lead to significant under-

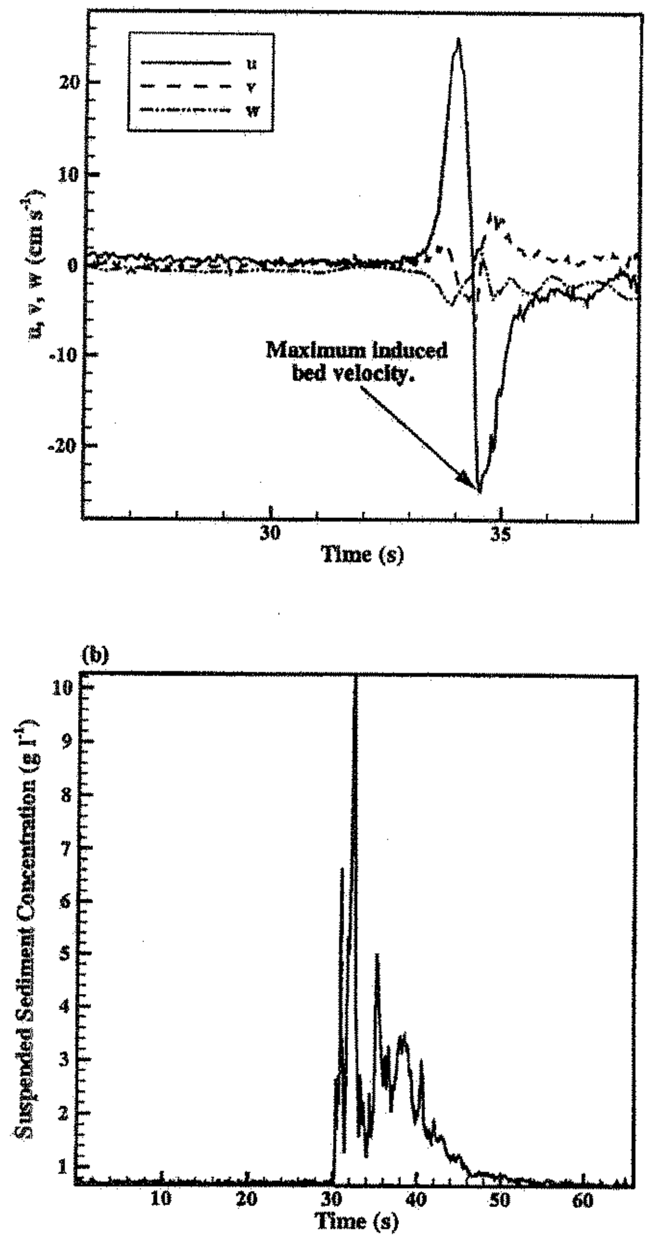

Figure 6.–Sample transient data obtained for the outboard boat. (a) - near-bed induced velocity components (u,v,w). (b) - near-bed induced suspended sediment concentration.

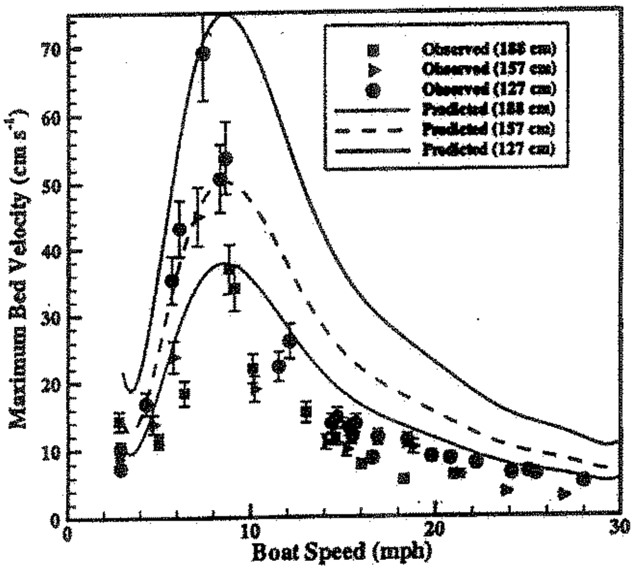

Figure 7.–Observed and predicted values of maximum bed velocity, as functions of water depth and boat speed, for the outboard boat.

estimates of v_{bmax}. The tightly spaced guide buoys, designed to minimize this systematic error, limited these deviations, to the driver's estimation, to 25 cm to either side of the instrumentation.

Regarding the second source of error, while inboard boats excel at holding a set speed, the resolutions of onboard speedometers are generally limited to ±1 mph. For the outboard and PWC trials, the available ±0.1 mph accuracy of the GPS was more than negated by the fact that these craft are much more difficult to hold at set speeds, particularly in the near-plane band. As such, the uncertainty in boat speed for the outboard and PWC trials was estimated to also be ±1 mph.

The 10% uncertainty figure comes from tests of repeatability conducted as follows. At a selected boat speed, six trials were conducted and a value of v_{bmax} was determined for each realization. The mean of the ensemble and the standard deviation of the ensemble about the mean were then computed. Repeating this procedure for numerous values of boat speed, it was found that the standard deviations averaged ~10\% of the means (Table 2).

Next, note that v_{bmax} is a strong function of boat speed. At low (idle) speeds, there is little disturbance at the lake bed. More surprisingly, at high speeds, there is equally little disturbance at the bed. Indeed, operation of the boat at 30 mph is observed to have less impact than operation at 3 mph. In a fairly broad band of 'near-plane' speeds, from 5-13 mph, however, very large near-bed velocities are observed. Assuming that ~25 $cm \cdot s^{-1}$ of velocity is required to resuspend cohesionless medium sand, as discussed previously, it is clear that operation of this boat in the depths described

Table 2.–Calculated mean values and standard deviations about the mean of v_{bmax}.

Boat speed (mph)	$\bar{v}_{bmax}$ $(cm \cdot s^{-1})$	$\sigma \bar{v}_{bmax}$ $(cm \cdot s^{-1})$	Coefficient of Variation (%)
8	27.9	2.5	9
10	43.5	4.9	11
12	27.2	3.2	12
14	27.2	5.0	18
16	23.4	1.2	5
18	24.2	1.9	8
21	19.4	1.9	10
23	16.9	1.2	7

here has the potential for resuspending significant amounts of sediment.

Finally, note that the agreement between the measurements and the predictions is reasonably good, particularly in the 'near-plane' band of speeds. The calculated correlation coefficients for the 127, 157, and 188 cm depths are 0.91, 0.85, and 0.91 respectively. At higher speeds, the model over-predicts the near-bed velocity. This is due, in part, to the fact that as a boat planes, it (and hence the propeller axis) moves vertically upward and therefore further away from the lake bed. This effect is not accounted for in the model.

The experimental and theoretical results for the Nautique inboard boat are shown in Fig. 8 and are qualitatively similar to those of the outboard boat. Note that, for comparable depths, the inboard induces a slightly lower velocity at near-plane speeds. This is likely due, in part, to the fact that inboards do not 'nose up' nearly as much as outboard boats when climbing onto plane. It is also partly due to the fact that the Nautique has a slightly smaller draft than the outboard. On the other hand, the induced bed velocities at higher speed are greater for the inboard. With regards to the predictions, the model again performs qualitatively well, with a correlation coefficient of 0.86, but consistently over-predicts the near-bed velocity.

Finally, the experimental results for the WaveRunner are shown in Fig. 9. Model predictions are not included as the authors were unable to obtain quantitative flow rate vs. engine rpm data for the PWC used in the present study. It is hoped that future studies with a different PWC will allow for this comparison to be made. Regardless, the experimental results are qualitatively similar to those of the other boats, showing a rapid decrease in observed bed velocity with increasing craft speed. Note that while the observed velocities are similar in magnitude to those obtained for the boats,

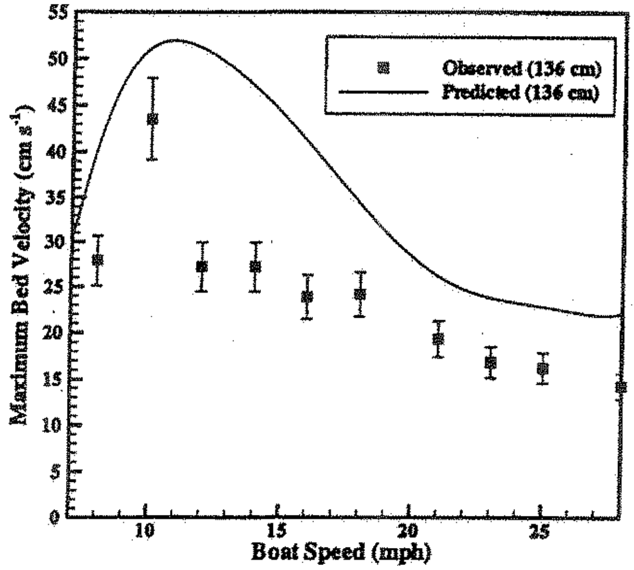

Figure 8.–Observed and predicted values of maximum bed velocity, as functions of boat speed, for the inboard boat.

the PWC trials were in much shallower water. The logical conclusion is that, given equal water depth, a PWC will cause much less disturbance at the lake bed.

Suspended Sediment Concentration Data

As the ultimate goal of this research is to establish the capability to predict sediment resuspension, the trials with the OBS-3 were significant from a verification point of view. Due to time constraints, the OBS-3

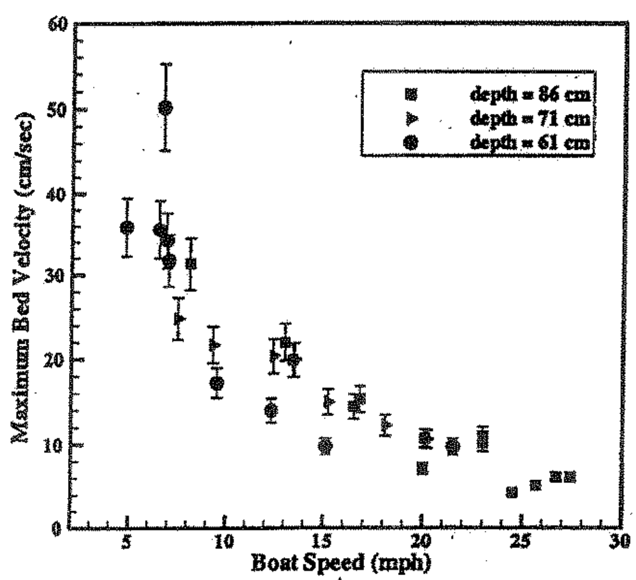

Figure 9.–Observed values of maximum bed velocity, as functions of water depth and boat speed, for the personal watercraft.

studies were limited to trials with the outboard boat. As shown in Fig. 10, the maximum observed suspended sediment concentrations follow the same trends as the maximum observed near-bed velocities, peaking at 'near-plane' speeds and falling off rapidly with increasing boat speeds. Beyond boat speeds of 12 mph, the OBS-3 failed to register any suspended sediment whatsoever, even at the shallowest study site. Next, if the SSC and v_{bmax} data are compared, it is seen that sediment resuspension occurs only when the induced near-bed velocity exceeds roughly 25 cm·s^{-1}. This critical

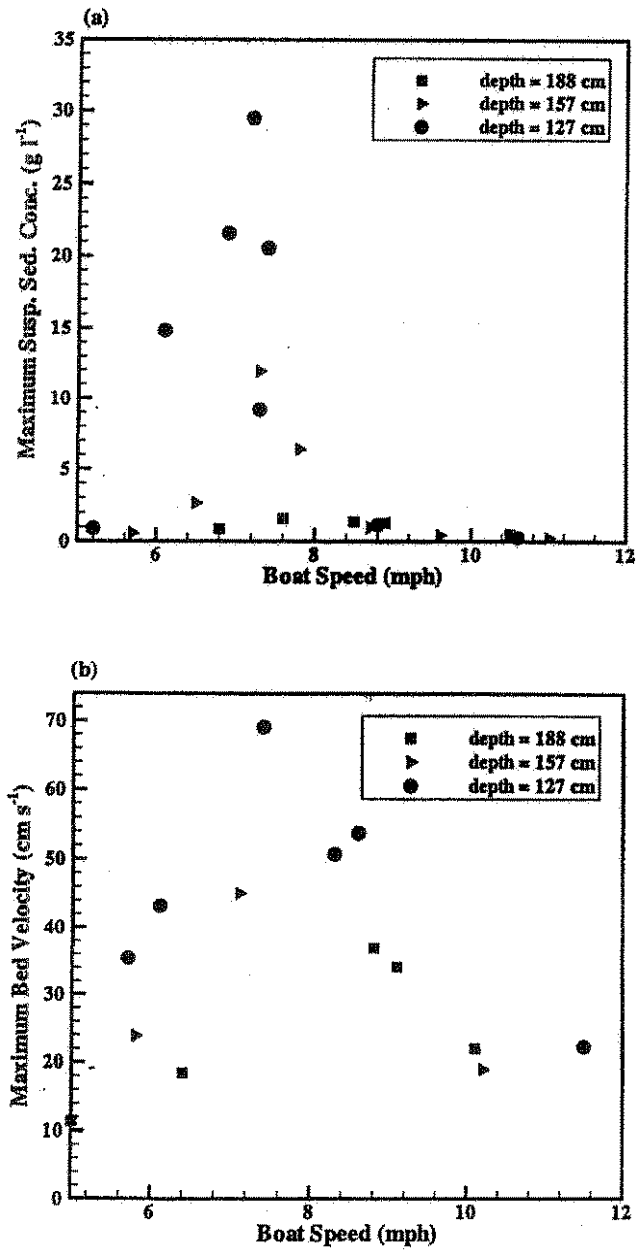

Figure 10.–Variation of (a) observed maximum bed velocity and (b) observed maximum suspended sediment concentration with water depth and boat speed for the outboard boat.

velocity is consistent with the values discussed earlier for cohesionless medium sands.

Discussion

The observed variations in v_{bmax} with boat speed are readily explained by considering the similar variations in wave heights with boat speed that have been documented extensively (Sorenson 1973, Bhowmik et al. 1992, Kirkegaard et al. 1998, Parnell and Kofoed-Hansen 2001). The main controlling parameter in this case is the dimensionless depth-based Froude number:

$$Fr_h = \frac{V_b}{\sqrt{gh}} \tag{4}$$

where V_b is the boat speed, g is gravity, and h is the water depth. If $Fr_h \ll 1$, the boat is said to be operating in 'sub-critical' (i.e., displacement) mode, and wave heights are relatively small. If $Fr_h \gg 1$, the boat is in 'super-critical' (i.e., planing) operation and wakes are similarly small. In the neighborhood of $Fr_h \sim 1$, where the boat speed is at the 'critical' value of $\sqrt{gh}$, wave heights are at a maximum.

As wave drag is a significant energy sink for recreational boats, it is clear that the efficiency of a boat's propeller should be inversely proportional to the wake heights. At trans-critical speeds, where the wakes are at a maximum, the propeller will have to work very hard, leading to a large slip velocity V_s to overcome the resistance. On the other hand, for a boat fully off or fully on plane, where wakes are minimal, the propeller is fairly efficient, leading to low values of V_s (recall Fig. 3).

For the present study, the Butternut site depths of 127, 157, and 188 cm correspond to critical speeds of 7.9, 8.8, and 9.6 mph. Recalling Fig.7, it is clear that these expected speeds of maximum impact are consistent with the observations of the field experiment.

A second controlling parameter is the dimensionless length-based Froude number:

$$Fr_l = \frac{V_b}{\sqrt{gl}} \tag{5}$$

where l is the boat length. In this case, if $Fr_l \sim 0.5$, wake heights, and therefore bottom-stirring potential, will again be maximized. A worst-case scenario therefore occurs when the water depth, boat length, and boat speed are such that $Fr_h \sim 1.0$ and $Fr_l \sim 0.5$ simultaneously. For boats 5 to 6 m in length, such as those used in the current study, the critical boat speeds corresponding to the latter condition are 7.8-8.6 mph, indicating that such an overlap was indeed occurring.

Management Implications

Having demonstrated the relative success of the present model, it is worth briefly discussing its use. As a preface, several limitations of the present analysis should be noted, in order to better clarify its scope. First, it does not directly consider the quantification of a threshold for incipient motion itself; that is taken to be an input to the problem. As discussed previously, this specification of a critical near-bed velocity is complicated by the fact that real soils are polydisperse and often cohesive and that lake bed bathymetry often possesses both high- and low-wavelength spatial variability. Second, it does not address the issue of whether or not bottom stirring is detrimental to a specific lake. That is clearly a site-specific question that must take into account the chemical composition of the sediment. Third, it does not quantify how much sediment will be resuspended under certain conditions, only whether or not this resuspension is likely to occur.

What *can* be arrived at, by using the present analysis, is the establishment of a 'minimum operating depth' for a given boat. Put another way, if the objective is to prevent altogether resuspension of bottom sediment by boating activity, the minimum water depth required to achieve this can be estimated.

This concept is illustrated in Fig. 11, where the predictions of bed velocities, as induced by the outboard boat, are shown for several different water depths. For the sake of this example, and as suggested by the data of Fig. 10, assume that roughly 25 cm·s^{-1} is required to disturb the 0.3 mm sand comprising the bed. It is clear that, as the water depth increases, the band of boat speed that induces near-bed velocities greater than this value is steadily shrinking. Beyond a depth of approximately 2.75 m, the near-bed velocity never exceeds this critical value and, therefore, there is minimal potential for impact.

This minimum depth will be a function of boat size and power and sediment grain size. Regarding the latter, consider the outboard boat of the present study operating above a lake bed characterized by 50 μm silt. It is found that the minimum depth in this case is 4.6 m. For coarser bed material, say 1.0 mm sand, this depth is found to be 1.8 m. For boats of lesser horsepower, it is intuitive that these depths will be reduced, but the present data set does not allow for that conclusion to be tested directly. Also, note that this depth is a rather conservative measure as it seeks to prevent bottom stirring for *all* boat speeds. In reality, boats do not spend all of their time operating at the worst-case near-plane speeds.

In closing, it is worth noting that blanket policies such as universal speed limits are perhaps not the optimal choice for nearshore management. A limit

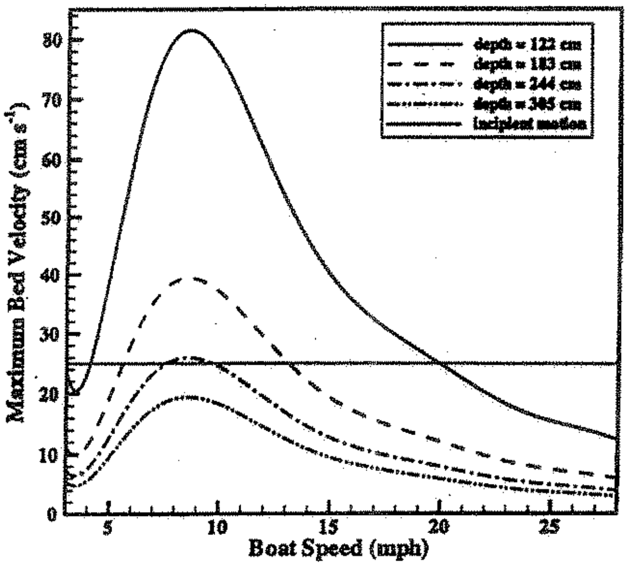

Figure 11.–Model predictions of V_{bmax} variation with boat speed for several water depths for the outboard boat.

that is designed for a boat of a certain size operating in a certain depth of water might be wholly adequate in preventing bottom stirring for that situation. However, the same speed limit imposed in water of a different depth might inadvertently place the same boat at the worst possible (Fr_h ~1.0) speed for that depth. Alternatively, limits designed for one size of boats may place boats of a different size at an undesirable value of length-based Froude number. No-wake zones, provided that they are enforced as truly no-wake zones are likely to be far superior in terms of mitigating the effects of both sediment resuspension and wake impacts on the shoreline.

Conclusions

In summary, this study has investigated the mechanism of bottom stirring by recreational watercraft through a combination of field experimentation and mathematical modelling. Prior to this work, investigations of this problem have considered only one or the other methodology independently. Moreover, the modelling attempts to date have been empirical, rather than based on physical principles, and the authors are unaware of any previous attempts to directly measure the induced velocity field in the near-field of planing craft. Therefore, the present work represents an important advance in theunderstanding and prediction of this phenomenon.

The present velocity measurements indicate that the variation of induced near-bed velocity with boat speed is controlled by depth and length based Froude numbers, with peaks near Fr_h ~1.0 and Fr_l ~0.5. This parallel with the behavior of boat wake height is logical as wave resistance represents a major component of the overall drag to be overcome by the propulsion source of a boat. The turbidity measurements exhibited a similar response and supported well-known relations describing the onset of cohesionless sediment motion.

A simple, physically-based model was developed in order to generalize the study beyond the conditions studied in the experiments. Based upon well-known relations for a turbulent jet, the model requires, as input, only simple, easily obtainable parameters describing the boat and its performance characteristics. An additional requirement for predictive use is that the near-bed velocity required to disturb the sediment in the area of interest must be known. When applied to the conditions of the present field measurements, the model was found to perform reasonably well.

Future extensions and refinements of this work should include (i) experimentation on a much broader cross-section of boats, (ii) turbidity measurements in a lake characterized by much finer sediments, and (iii) testing of the model against PWC or jet-driven boats.

ACKNOWLEDGMENTS: Funding for this work was provided by the Pennsylvania State University and the United States Department of the Interior. Assistance with the facilities utilized in the field study was provided by Charles and Constance Hill, Georgianna Starz, Albert Goodman, and John Rodemeier.

References

Arruda, J., G. Marzolf and R. Faulk. 1983. The role of suspended sediments in the nutrition of zooplankton in turbid reservoirs. Ecol. 64(5);1225-1235.

Beachler, M. 2002. The hydrodynamic impacts of recreational watercraft on shallow lakes. Master's thesis, The Penn. State Univ.

Bhowmik, N., T. Soong, W. Reichelt and N. Seddik. 1992. Waves generated by recreational traffic on the Upper Mississippi River System. Techn. Rep. EMTC 92-S003, Ill. State Wat. Surv. Champaign, IL.

Breitburg, D. 1988. Effects of turbidity on prey consumption by striped bass larvae. Trans. Am. Fish. Soc. 117:72-77.

Cacchione, D. and J. Southard. 1974. Incipient sediment movement by shoaling internal gravity waves. J. Geophysical Res. 79(15):2237-2242.

Fischer, H., E. List, R. Koh, J. Imberger and N. Brooks. 1979. Mixing in Inland and Coastal Waters. Academic Press, Inc., New York.

Francisco, M., C. Ebbesmeyer, C. Boatman and T. Michelsen. 1999. Resuspension and transport of contaminated sediments along the Seattle waterfront, part 2: resuspension and transport mechanisms. J. Marine Env. Eng. 5:67-84.

Garrad, P. and R. Hey. 1987. Boat traffic, sediment resuspension and turbidity in a broadland river. J. Hydrol. 95:289-297.

Gucinski, H. 1982. Sediment suspension and resuspension from small-craft induced turbulence. U.S. EPA Chesapeake Bay Program, EPA 600/3-82-084.

Hamill, G., H. Johnston and D. Stewart. 1999. Propeller wash scour near quay walls. J. Waterway, Port, Coastal, and Ocean Eng. 125(4):170-175.

Herbich, J. 1984. Sediment movement induced by ship propellers. Marcel Dekker, Inc., New York.

Johnson, S. 1994. Recreational boating impact investigations – Upper Mississippi River System, Pool 4, Redwing, Minnesota. Techn. Rep. EMTC 94-S004, Minn. Depart. of Nat. Resources.

Killgore, K., A. Miller and K. Conley. 1987. Effects of turbulence on yolk-sac larvae of paddlefish. Trans. Am. Fish. Soc. 116:670-673.

Kirkegaard, J., H. Kofoed-Hansen and B. Elfrink. 1998. Wake wash of high-speed craft in coastal waters. P. 325-337. *In:* Proc. 26th Coastal Engineering Conf., ASCE, Copenhagen, Denmark.

Liddle, M. and H. Scorgie. 1980. The effects of recreation on freshwater plants and animals: A review. Biol. Conserv. 17:183-206.

Maynord, S. 1998. Bottom shear stress from propeller jets. P. 1074-1083. *In:* Proc. Ports '98 Conference, ASCE, Long Beach, CA, USA.

Morgan, R., R. Ulanowicz, V. R. Jr. L. Noe and G. Gray. 1976. Effects of shear on eggs and larvae of striped bass, *Morone Saxatilis*, and white perch, *M. Americana*. Trans. Am. Fish. Soc. 106:149-154.

Parchure, T., W. M. Jr. and A. Teeter, 2001. Desktop method for estimating vessel-induced sediment suspension. J. Hydraul. Eng. 127(7):577-587.

Parnell, K. and H. Kofoed-Hansen. 2001. Wakes from large high-speed ferries in confined coastal waters: Management approaches with examples from New Zealand and Denmark. Coastal Manage. 29:217-237.

Sorenson, R. 1973. Water waves produced by ships. J. Waterways Harbors and Coastal Eng. Div. 99(2):245-256.

Sturm, T. 2001. Open channel hydraulics. McGraw Hill, New York.

Sutherland, A. and D. Ogle. 1975. Effect of jet boats on salmon eggs. New Zealand J. Marine and Freshwat. Res. 9(3):273-282.

Wagner, K. 1991. Assessing impacts of motorized watercraft on lakes: Issues and perceptions. P. 77-93. *In:* Proc. of a National Conf. on Enhancing States' Lake Management Programs, Northeastern Illinois Planning Commission.

WHOI. 1998. The environmental impacts of boating. Techn. Rep. WHOI-98-03, Woods Hole Oceanographic Institution, Woods Hole, MA. Proc. of a workshop held December 7-9, 1994.

Yalin, M. and E. Karahan. 1979. Inception of sediment transport. ASCE J. Hydraulics Div. 105(11):1433-1443.

Yousef, Y., W. McLellon, R. Fagan, H. Zebuth and C. Larrabee. 1978. Mixing effects due to boating activities in shallow lakes. Techn. Rep. ESEI N. 78-10, FL Technol. Univ.

Yousef, Y., W. McLellon and H. Zebuth. 1980. Changes in phosphorous concentrations due to mixing by motorboats in shallow lakes. Wat. Res. 14:841-852.

Appendix F

USACE Design Manual

Engineering and Design
Environmental Engineering for Small Boat Basins

CECW-EH-W Engineer Manual 1110-2-1206	Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	EM 1110-2-1206 31 October 1993
	Engineering and Design ENVIRONMENTAL ENGINEERING FOR SMALL BOAT BASINS	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-1206

CECW-EH-W

Manual
No. 1110-2-1206

31 October 1993

Engineering and Design
ENVIRONMENTAL ENGINEERING FOR SMALL BOAT BASINS

1. Purpose. The purpose of this manual is to incorporate environmental considerations into the planning, engineering, design, construction, operation, and maintenance of small boat basins. Much of this guidance is general in nature with many references to appropriate Corps manuals and other design guides. However, specific design guidance is provided for areas involving basin design and operation.

2. Applicability. This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having Civil Works responsibilities.

3. General. Small boat basins, which are located on coastlines, estuaries, lakes, and riverbanks, provide direct access to each boat, parking, technical services, shops, and other amenities. The increasing prosperity of the world population has resulted in an increased popularity of and need for small boat basins. The development of small boat basins is a concern to environmental groups and local residents because of the potential effects of these basins on the quality of rivers, lakes, estuaries, and ocean shorelines. The goal of this manual is to provide general environmental considerations guidance during the planning and design stage.

FOR THE COMMANDER:

WILLIAM D. BROWN
Colonel, Corps of Engineers
Chief of Staff

CECW-EH-W

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, D.C. 20314-1000

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Engineering and Design
ENVIRONMENTAL ENGINEERING FOR SMALL BOAT BASINS

Table of Contents

Chapter 1
Introduction

1-1. Purpose

Small boats are classified as recreational craft, fishing boats, or other small commercial craft with lengths less than 100 ft (31 m). A small boat basin is a place to obtain essential supplies such as food, fuel, and drinking water. Small boat basins provide direct access to each boat, adequate depth of water, parking, toilet facilities, technical services, shops, and other amenities. Small boat basins are found on coastlines, estuaries, lakes, and riverbanks. The increasing prosperity of the world population has resulted in an increased popularity of and need for small boat basins. The development of small boat basins is a concern to environmental groups and local residents because of the potential effects of these basins on the quality of rivers, lakes, estuaries, and ocean shorelines. This manual provides general guidance for incorporating environmental considerations into the planning, engineering, design, construction, operation, and maintenance of small boat basins. When these facilities are poorly planned and/or managed, they may pose a threat to the health of aquatic systems and may pose other environmental hazards.

1-2. Applicability

This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having Civil Works responsibilities.

1-3. References

Required and related publications are listed in Appendix A.

1-4. General Study Authority

The U.S. Army Corps of Engineers (USACE) has the general authority to investigate the need for navigation improvements under Section 107 of the River and Harbor Act of 1960, as amended (U.S. Army Corps of Engineers 1989). The investigations are limited to determining means to satisfy immediate and future needs for small craft refuge. Desirable sites and facility alternatives are formulated and evaluated, and the best plan is selected based on sound engineering design, economics, and environmental and cultural acceptability. The evaluation criteria used are based on principles and guidelines established by the U.S. Water Resources Council.

1-5. Permit Processing

Because of the possible environmental impact of developing small boat basins, the activities must be consistent with national environmental policies. These policies can be complex and confusing when dealing with the variety of Federal, state, and local regulations concerning small boat marina development in coastal areas and inland waters. Appendix B lists several Federal statutes, executive orders, and USACE regulations that often require studies of existing and future environmental conditions.

a. Federal agencies. The USACE is the Federal agency with direct permitting authority for coastal marinas. Section 10 of the River and Harbor Act of 1899 and Section 404 of the Clean Water Act give USACE permitting authority for these facilities. Section 10, in conjunction with other environmental laws, provides USACE authority to control, through its permit program, construction and excavation or deposition of any material in navigable waters. The Section 404 program is designed to protect water quality, aquatic resources, and wetlands. It provides USACE with authority to issue permits for the discharge of dredged or fill material into waters of the United States. Guidelines developed by the U.S. Environmental Protection Agency (USEPA) state that no discharge will be permitted if it will result in significant adverse impacts on municipal water supplies, recreation, and economic and aesthetic values. The USEPA does not typically exercise direct permitting control over marina development whenever disposal of dredged and fill material is an issue. However, Section 404 gives the USEPA authority to veto dredged and fill permits proposed by USACE.

(1) The overall process followed by USACE in reviewing permit applications is shown in Figure 1-1. This diagram generally illustrates overall USACE responsibilities and decision points. Typically, when a USACE application form is used, only one form is submitted for both Sections 10 and 404 approval. Once USACE receives the permit, a preliminary assessment is conducted to determine the type of environmental review required. Based upon the potential extent of adverse impacts on the natural and man-made environment, this environmental review may range from a categorical exclusion to a full Environmental Impact Statement. The next step in the permit process is a public notice, which goes out to all interested parties and agencies. The U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS) are interested in the impact to fish and wildlife resulting from potential water resource

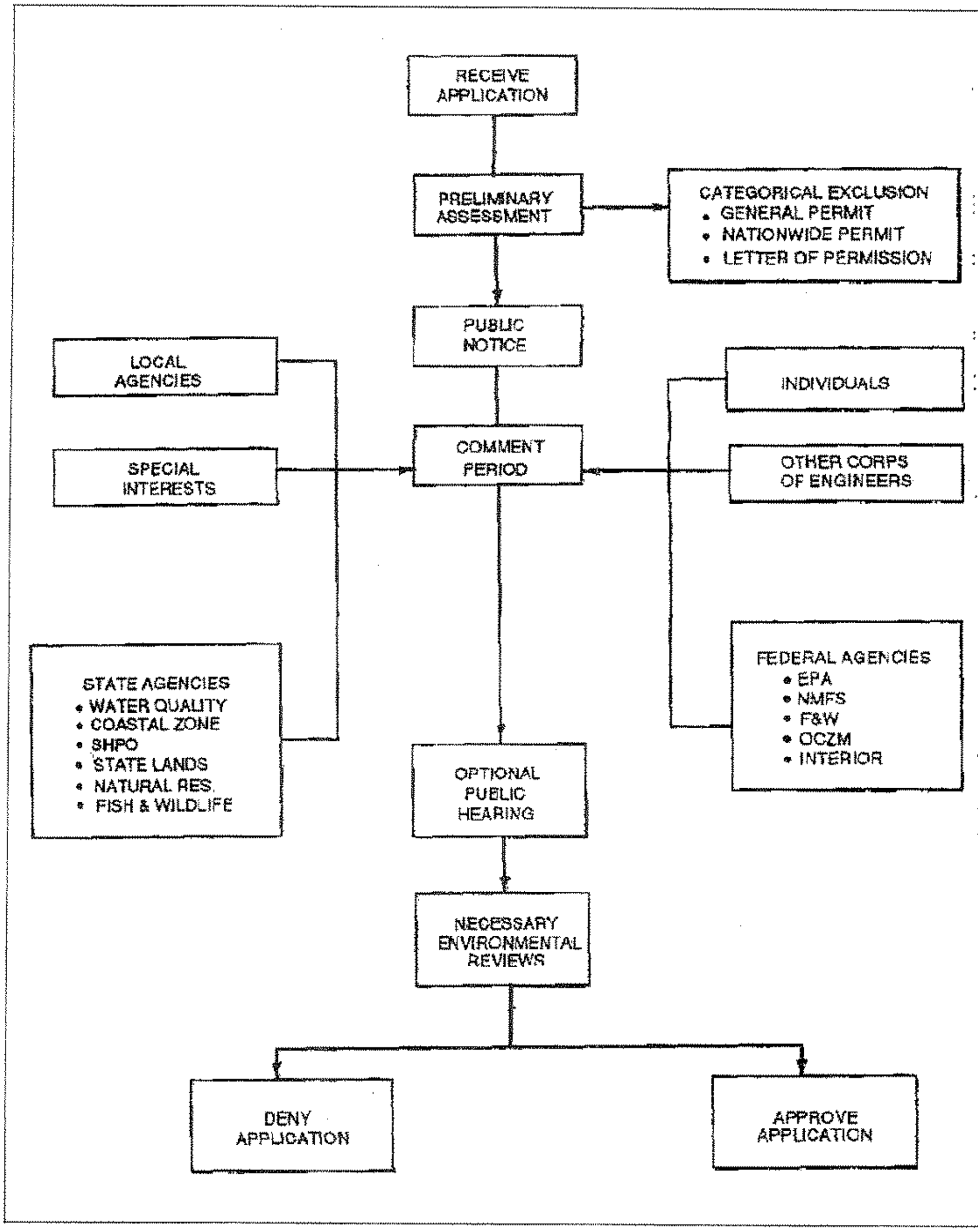

Figure 1-1. U.S. Army Corps of Engineers permitting process

development activities. When permits are reviewed, the USFWS considers whether alternative, non-wetland sites are available and whether construction can be accomplished without adverse impact to fish and wildlife in aquatic, terrestrial, or wetland habitats. The NMFS reviews applications for potential impacts to aquatic and wetland resources as they affect commercial fisheries. Both agencies' comments are quite important in the decisionmaking process; they are, therefore, reviewed extensively. Another agency interested in the permitting process is the U.S. Coast Guard, which regulates marine sanitation devices (MSD). The Clean Water Act prohibits discharges from MSD into freshwater lakes and rivers except those bodies that support interstate navigation. For vessels operating in saltwater estuaries and territorial seas, new vessels operating after January 1980 must have no discharge or have an MSD capable of limiting fecal coliform bacteria to 200 most probable number (MPN) per 100 ml and suspended solids to 150 mg/ℓ. Older boats are still allowed to operate MSDs with lower levels of coliform and solids removal but are not permitted to use pump-through devices. The Coast Guard also reviews applications with respect to boating safety and navigation. If it is determined necessary by comments received from the public notice, the next step is a public hearing. The permit application is then evaluated and the necessary environmental review, as determined in the preliminary assessment, is conducted. The final step in the permit process is to either issue or deny the permit based on the completion of the environmental review.

b. State agencies. States play a major role in the permitting of marina developments. There is broad variation from state to state in the type of approval required and the way in which regulatory programs are administered.

(1) The minimum level of state involvement is review and comment on Section 10 permit applications. When Section 404 permits are required, the states must provide a certification to the Corps that the proposed activity will not violate the state's water quality standards throughout construction and subsequent operation of the facility. The state must also indicate that any other required state licenses, permits, or approvals can be secured. The USACE will not approve the 404 permit without this assurance.

(2) Another level of state involvement is a consistency review of the USACE permit action under the state Coastal Zone Management Program (CZMP) (if applicable). In states where a CZMP has been approved by the Secretary of Commerce, an applicant for a Federal license or permit to conduct any activity affecting a coastal zone must furnish a certification that the activity will be consistent with the goals of the state's CZMP. Some states are zoning land areas adjacent to water with restrictions favoring commercial fishing, sport fishing, water recreation, water conservation, and commercial development. The USACE will deny the 404 permit unless the state is in agreement.

(3) The highest level of state involvement is where a state has developed a separate regulatory program controlling marina development. Different states have taken different approaches to direct regulation of marina activities. Some states have developed a wetland or coastal area permit, while other states have developed separate wetland or marshland permitting programs. Some states have developed dredge and fill permit programs. Some states claim ownership of submerged lands.

c. Local agencies. Local agencies exercising control over marina development may include regional authorities, counties, and cities. Generally, these agencies are not involved in the comprehensive evaluation of the suitability of a marina based on environmental water quality issues. The local agencies are generally intended to complement the state and Federal regulations applicable to a given area. Local regulations usually take into account special characteristics of the local environment that may require special restrictions on construction or development. Examples of such local concerns include land use controls, building codes, subdivision ordinances, and provision and operation of public facilities. Additional local regulations may also be implemented to reduce damage from hurricanes, tornadoes, earthquakes, and extreme weather conditions.

Chapter 2
Water Body Designations

2-1. Salt Water

a. Saltwater harbors supporting deep-sea fishing are generally located within 15 miles (24 km) of open water. A 5-ft (1.5-m) minimum channel depth is usually maintained. Navigation to and from the marina should be relatively easy, with numerous aids to navigation. There are usually no restrictions on speed or wake, except within the immediate vicinity of the marina. Estuarine harbors are typically located within 5 miles of suitable fishing waters. A 4-ft (1.2-m) minimum channel depth is usually maintained. Navigation is normally easy, with readily identifiable landmarks and numerous guides to navigation (Chamberlain 1983).

b. It is desirable to locate coastal marinas or small boat basins in protected waters such as tidal rivers, bays, estuaries, lagoons, inlets, and coves. However, unprotected coastal environments may also be suitable if breakwaters or artificial harbors are constructed to protect the marina against waves and currents. Facilities constructed in such high energy environments require a more detailed design and are more costly to construct, as compared to a marina in a more protected environment.

c. Small boat basins are designed to provide safe and secure vessel mooring with quick, convenient access to navigable waters. The design should be appropriate for local weather conditions, i.e., wind, precipitation, ice, fog, etc. A deep-water site with maximum natural protection will minimize alterations of the site and adverse impacts of construction. Dredging and maintenance of the facility will be minimized by locating the harbor in an area with these natural physical features. In the past, marshes and mangroves were often selected for marina sites, as they possess environmental requirements desirable for a small boat basin (that is, protection from waves and strong currents). These wetland environments should be avoided because of their high biological value and the "no net loss" policy related to wetlands.

d. Small boat basins usually occupy several tidal zones extending from terrestrial through the subtidal zone in order to accommodate land facilities, automobile parking, boat dry storage, launching ramps or lifts, boat docks, fueling docks, bulkheads, breakwaters, and jetties or groins (see Figure 2-1). Due to concerns over construction in wetlands, intertidal, and nearshore zones, and the lack of suitable sites, some small boat basins have been excavated in upland areas with connecting channels to navigable waters (U.S. Fish and Wildlife Service 1980). Such sites have their own unique environmental problems that should be thoroughly investigated prior to selecting a site for a small boat basin.

2-2. Fresh Water

Freshwater recreational fishing is supported by marinas, harbors, and access facilities on natural lakes, reservoirs, and inland waterways. Facilities for lake and reservoir fishing are often on the shoreline. Waterway harbors are located within 5 miles of fishing waters. Minimum depth for channels is 4 ft, with easy navigation resulting from readily identifiable landmarks and numerous guides to navigation (Chamberlain 1983).

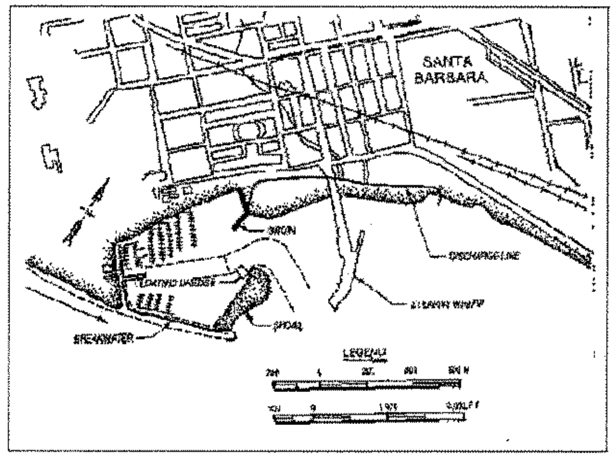

Figure 2-1. Breakwater protecting recreational harbor, Santa Barbara, CA

2-3. Great Lakes

a. An appropriate site for a small boat basin along the Great Lakes, as well as other locations, must have convenient access to water supply, electric power, and suitable transportation to nearby business or residential centers. However, physical attributes of the proposed site must be considered if the boat basin is to function in its intended manner. High water and dangerous currents from nearby rivers can be hazardous to navigation and mooring facilities. Strong winds could cause water damage and could be hazardous to the facility and moored boats.

b. Longshore currents driven by wind-generated waves carry large volumes of sand (usually from the northeast toward the southwest) along much of the shoreline of the Great Lakes (Wood and Davis 1978). In order to maintain a natural balance between destructive and constructive wave forces, this movement of sand should not be interrupted. However, when a barrier is placed across the active transport zone, an imbalance occurs that can result in sedimentation on the updrift side and severe erosion on the downdrift side. A breakwater placed to protect the entrance to a small harbor can disrupt this natural flow of sediments along the shoreline. Negative effects can be reduced if a proposed boat basin is located in a natural harbor. However, dredging on the updrift side and beach nourishment on the downdrift side may be the only suitable solutions to this problem. Maintenance-free boat basins are an unreasonable goal along the Great Lakes. However, facilities can be located where damage from wind and high water is unlikely. If a natural breakwater or cove is unavailable, the small boat marina facility will have to be constructed.

Chapter 3
Basin Design and Operation Criteria

3-1. Basin Design Criteria

a. Harbor function. The function that a harbor is to provide will determine its design requirements. Sembler et al. (1969) categorize harbors according to the following functions: harbors of refuge, commercial, fishing boat moorage, convenience harbor, recreational center, and yacht club.

(1) Harbor of refuge. When a remote harbor is provided specifically to accommodate transient small boats rather than as a home port for the local boats of the immediate area, it is designated as a harbor of refuge. Such harbors need not have all the refinements of a home port, but must have an entrance that is navigable in adverse weather, access to emergency aid, and appropriate facilities to accommodate the transient boater. Depending on the class of boat and characteristics of the region, the safe cruising distance for small boats is usually between 20 and 40 miles, or two hours cruising time. In remote areas, harbors of refuge meeting just the needs of the transient boaters often are subsidized. In these instances, the harbor of refuge may possibly be made self-sustaining by berthing a small number of home-based boats in addition to meeting the periodic needs of transient boats; it may not survive economically on either type of boat alone.

(2) Commercial. Small boat harbors are designed for various commercial fishing fleets, barges, and small boat transportation terminals, including berths for excursion craft of various kinds. Small boat facilities are often within or adjacent to harbors built primarily for deep-draft cargo or passenger vessels. In such cases, large ships and small craft will move through the same waters. Planning criteria must be adopted to reduce the collision hazard to a minimum without curtailing the activities of either class more than is essential for navigational safety (Dunham and Finn 1974).

(3) Commercial fishing boat moorage. Harbors for commercial fishing boats may be considered a special type of installation. This is due largely to the type of usage, the characteristics and habits of commercial fishery, and equipment requirements. Because a fishing boat is a work boat and the operator's work in port is essentially preparation for the next trip, utility usually supersedes appearance.

(4) Convenience harbor. The convenience harbor is generally designed as an enroute stopover point and provides a minimum of services. Such harbors may serve for overnight stays, temporary tie-ups for repairs and obtaining supplies, and similar usages. Facilities of this type should generally be located at or near population centers for availability of food, fuel, and amusement. Some degree of harbor protection is necessary, but moorage facilities can be minimal and services limited. Because of the lack of direct revenue from a harbor of this type, it is anticipated that it would be installed at community expense with few, if any, charges, its benefit to the community coming from other business generated.

(5) Recreational. Small boat harbors are designed for various recreational craft, including: sailboats, rowboats, pedal craft, and air-cushion vehicles. Other exotic craft are not specifically covered, although the basin and entrance design techniques described will be found satisfactory for all classes of small boat. The development of a recreational harbor will require not only the best weather protection, but also waterside and landside facilities that are best suited for its function. Boaters may patronize a deluxe restaurant, a pleasant bar, and various concessions. They may support boat sales, boat repair facilities, a marine supply store, clothing shops, and other similar establishments. They may use facilities for dancing, skating, bathing, skin diving, and water-skiing, if available. However, they usually demand the most in conveniences, utilities, and services, and a well-managed, clean, and attractive marina.

(6) Yacht clubs. In many areas, boating enthusiasts group together into yacht clubs. These are usually, by their nature, private installations accessible to members only. Yacht clubs may be somewhat meager in their facilities and appointments or may be quite lavish. Of prime importance will be a clubhouse at the water's edge with a good dining room and bar, and an assembly place for races and regattas. These races and regattas constitute one of the major interests in boating of a large segment of small boat owners. These are classed as amateur sports and can be sponsored only by a recognized yacht club. On this basis, the yacht club performs a desirable function and one or more of these should be considered in the planning and design of any recreational type of small boat harbor.

b. Site selection.

(1) Site selection for a small boat basin is probably the single most important aspect of developing a marina in an

environmentally sound manner. A site selected to complement the marina concept and to permit maximum use of the natural attributes can facilitate the entire development process from permit application through completion of construction. For example, wetlands and island refuges may be developed through the construction process.

(2) Selection of a site that has favorable hydrographic characteristics and requires the least amount of modification can reduce potential impacts. Any future modification or expansion should be considered in the design phase. One method is to set a basin perimeter when the basin is constructed. Thereafter, modifications that occur within that perimeter (such as dock reconfiguration) are considered not significant. Another method is to set a limit, such as a 25-percent increase in the number of slips or a set number of slips (such as an increase of more than five slips). The final method is a combination of the above methods.

(3) Small boat basins should not be located in or immediately adjacent to wetlands. In addition, development of small boat basins should not disrupt unique areas such as mouths of streams, isolated aquatic plant beds, or small areas with valuable rock/rubble substrate. These areas should be avoided, or at least small boat basin design and subsequent operation should be implemented to minimize disruption to these habitats. Suitable habitat evaluation techniques are available for wetlands (Adamus et al. 1988).

(4) Site selection considerations for recreational harbors are intended to ensure that a site provides usable land and water resources for marina operation. Chamberlain (1983) recommends that at a minimum, the land area should be at least 10 acres and above the local floodplain. The usable water area should be approximately equal to available land area. The site should offer protection from wave action in the adjacent body of water and at least some protection from wind. The water depth should not be less than 8 ft (2.4 m) at mean low water and not over 20 ft (6.1 m) at mean high water. Figure 3-1 illustrates desirable and undesirable site locations for boat basins.

(5) A major requirement in designing a small boat basin is that it be located and sized to accommodate present and future user needs and related harbor facilities. It must be located in adequate depths for safe vessel operation and be accessible to a nearby navigation channel. Alternative measures and sites for developing a small boat basin must be evaluated and compared for impacts on the natural environment, as mandated by the National Environmental Policy Act and other environmental Policy Act and other environmental statutes and guidelines.

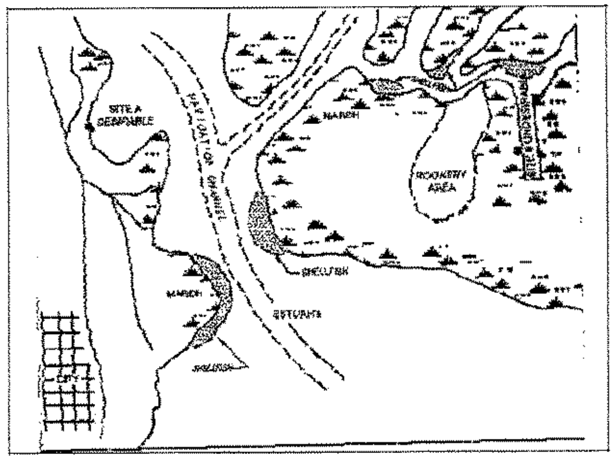

Figure 3-1. Desirable and undesirable site characteristics

(6) Physical factors that must be considered in locating a small boat basin are circulation and current patterns, bottom conditions, wave action, tides, sedimentation and shoaling, and prevailing winds (Brockwell 1987). If conditions are not suitable, major environmental problems may result. Hazardous conditions for small craft operating out of the basin because of waves, currents, and shoaling may be created. Water quality may be degraded if tides and currents are not adequate to flush the basins. The potential for flushing of marina waters should be the prime consideration in selecting a site. Sites on open water or at the mouth of creeks and tributaries generally have higher flushing rates than those in coves and toward the head of creeks and tributaries that have lower flushing rates.

(7) Dredging and maintenance can also be minimized by selecting deep sites with low sediment transport potential. The land topography at inland sites should be suitable to provide protection to the boat basin from winds, tides, and river flow.

(8) A small boat basin should have the following site characteristics:

(a) Easy access to open water.

(b) Accessibility from roads and waterways.

(c) Location in protected waters.

(d) Location near navigable water.

(e) Access to areas suitable for dredged material disposal.

(f) High tides and flushing rates.

(g) Compatibility with existing land and water uses.

(h) Good water quality.

(i) Absence of commercial shellfish beds.

(j) Low value as a fish and wildlife habitat.

(k) Absence of rare, threatened, or endangered species.

c. Site conditions. The natural elements of a site for constructing a small boat basin, such as local weather conditions, ice conditions, tides, currents, waves, and shoaling factors all have to be investigated.

(1) Weather factors. Weather factors such as precipitation, wind, and fog must be considered when evaluating a site.

(a) Precipitation. Maximum rainfall or snowfall present no serious problems for small boat basin operations, although all surface drainage measures have to be considered in marina planning. Drainage facilities have to be designed to be capable of draining or diverting a maximum amount of rainfall. In regions where snowfall is heavy, land-based structures must be designed to withstand these snow loads.

(b) Wind. The prevailing wind is a wind blowing from one general direction for a major portion of the year. Prevailing winds are not the strongest winds. Winds of greater intensity, which occur less frequently, come from other directions. A wind rose may be used to graphically represent the direction, frequency, and intensity of winds at a particular location over a period of time. Heavy wind may affect water levels in the marina basin, raising or lowering the water level. Land-based structures must be designed to withstand the unusually heavy forces. Heavy wind may generate waves or move sand located in dune areas which may shoal the basin or the entrance to the marina. Breakwaters are constructed to protect the entrance to the basin. Planting grass or construction of sand fences may be used to stabilize sand movement.

(c) Fog. Fog may be a serious navigational problem if it reduces visibility. Many marinas have occasional foggy conditions, and for this reason, channels in a small boat basin should be as straight as possible. In regions where fog is a problem, marker buoys and other channel-marking devices have to be installed.

(2) Ice.

(a) In northern climates ice is a serious problem in the operation of small boat basins. In areas with moving ice sheets, marinas must be located in protected areas, because these ice sheets may crush not only boats but also marine structures. Protection is provided by locating the entrance to the marina oriented away from the direction of the prevailing wind or current. This will encourage ice floes to move out of the marina during breakup. The marina should be located as close as possible to an industrial complex so that any available waste heat may be utilized. Although thin ice formation cannot damage boats, they are usually removed from the water during the winter, even in protected marinas. In protected marinas, thick, unbroken ice sheets forming around piles which support marina piers may lift these piles when the water rises, and thus bring the whole structure out of alignment. Repeated freezing and thawing may eventually jack piles completely out of the ground. In large natural basins, wind-driven ice floes may crash onto marine structures as the ice melts in spring, causing considerable damage to these structures.

(b) In Finland, small boat basins have been built with considerable success having piers and quays with a width of 1.5-3.0 m supported by wooden batter piles (Kivekas and Sarela 1985). Batter piles provide better stability in the foundation soil. When water fluctuates steadily, the ice attached to the shore (to a wall of a solid type construction or to a dense row of piles) will break easily at that location when the water changes level. However, in tidal zones, ice could easily build up on vertical surfaces of structures that are fixed on the bottom, thus creating a destabilizing buoyancy force or an additional load on the foundation.

(3) Waves.

(a) Natural phenomena such as waves may be caused by winds, tides, earthquakes, or by disturbances caused by moving vessels. A designer should be interested in waves produced by wind and moving vessels, since they have the most influence on site selection and basin design. Passing ships may generate waves which are sometimes of greater length than wind waves. Small boat basins on rivers experience the passing of ships or barges that may generate damaging waves. The effect of waves will depend on the height of the wave generated and the distance between the ship and the project site. As a rule of thumb, it can be assumed that the wave height is equal to twice the amount of vessel squat. The wave height at the riverbank is then computed using refraction and diffraction techniques. The wave length is equal to approximately one third of the vessel length (EM 1110-2-1615). If ship-generated waves are considered to be the design wave, model tests or prototype measurements are needed to verify or adjust the predictions. Additional information on the possible impact of vessel wakes may be obtained from Camfield, Ray, and Eckert (1980).

(b) Marina sites need to be protected from adverse wave effects. Some sites may be protected by one or more islands which shield the entrance from waves. If the site does not have natural protection against wave action, breakwaters or other wave-dissipating devices are used at the entrance or inside the marina.

(4) Tides. Tides and tide-like effects (e.g., water level change in inland lakes and rivers due to spring and fall flood) often play an important role in water quality control. The current-producing exchange of water by water fluctuation action may be essential to the marine ecology and the prevention of stagnation conditions. Water circulation is an important component in marina design and can be accomplished by the effective use of the tidal prism of the water. In inland lakes and rivers, water fluctuates in a slower cycle, and although it occurs too slowly to produce substantial water exchange effects, these effects have to be taken into account for the design.

(5) Currents.

(a) Currents are essentially horizontal movement of the water. At coastal locations, currents or flow of tides or freshets moving at only a few tenths of a knot generally cause no serious problems to marina operations. However, in swiftly moving rivers (with a speed of several knots) where seasonal floods are expected, or in large open bodies of water, where wind-generated current may be damaging to the marina, marinas should be in protected locations, e.g., secluded inlets, bays or lagoons, or breakwaters must be installed. Apart from the possibility of direct interference with marina operation, currents may also present other adverse functional effects such as scouring, deposition of sediments, and increased erosion rates.

(b) Currents may cause changes in wave effects, and in the impact of ice and flotsam (floating debris), as well as hampering construction operations. In tidal estuaries, the current can be expected to reverse. The value of tidal current velocity for many locations around the world may be obtained from tables that are published annually by the National Oceanic and Atmospheric Administration (NOAA). Depending on location as well as importance and cost, current velocity measurements may be considered for the project (Coastal and Ocean Engineering 1990).

(6) Shoaling.

(a) A principal cause of shoaling at entrances to marina basins is littoral drift, which is mainly the result of wave and/or current action. Any structure that interferes with wave or current action would cause abnormalities in the wave or current pattern and could substantially affect the shoaling process. Dunham and Finn (1974) suggested the following example. If the unprotected approach channel is dredged through a beach into an inner basin, the wave impinging on either side at the mouth will be refracted in such a way as to cause changes in the wave pattern approaching the lips of the channel. If the approach of the prevailing waves is normal to the shore, the initial effect will be a movement of the littoral material from the lips inward along each flank of the channel, thus eroding the lips and shoaling the inner channel fed by material from the beach on either side of the entrance. Unless tidal currents are strong enough to maintain an opening against the forces tending to shoal the entrance, the channel will soon be blocked. Where the prevailing wave approach is oblique to the shoreline, sediments being transported along the shore by littoral currents will be interrupted at the channel opening near the updrift lip, and that lip will soon begin to accrete. As the wave-induced longshore current again begins to "feel" the shore downdrift of the channel mouth, it attempts to reacquire its sediment load. As a result, at the same rate as the updrift lip accretes, the channel mouth will migrate in the downdrift direction. In each of these cases, the forces of nature are attempting to re-establish the littoral balance that was present before the channel was excavated. The above example is an oversimplified version of an extremely complex process, and excludes consideration of the effects of sandbar formation, eddy currents, and tidal channel meandering (Coastal and Ocean Engineering 1990).

(b) The customary solution to entrance shoaling is the construction of jetties along each flank of the channel from the lips of the mouth seaward beyond the breaking zone. The structural features of the jetties must be such that the materials will not be washed through or over the structure into the channel. A typical section of a sand-tight, rubble-mound jetty is shown in Figure 3-2. If the littoral transport from one direction predominates and the entrance is stabilized by jetties, accretion will occur along the updrift shore and erosion along the downdrift shore.

(c) The entrance to off-river marinas is often subject to shoaling because of sediment deposition in the quiet water area and to eddy currents that might be created by the entrance configuration and the flowing water in the river. Although shoaling cannot be prevented, it is often reduced by proper entrance design. For example, a flat area on the downstream lip of the entrance could be provided from which a dragline can excavate deposits from the bottom of the entrance channel and cast them into the river downstream of the entrance (Figure 3-3). The entrance must be kept as narrow as practical to permit such an operation, and a training dike at the upstream lip is helpful in reducing the deposits (Coastal and Ocean Engineering 1990).

d. Marina design.

(1) General. Design considerations for a marina may include boat slips, water supply, sanitation, structural integrity, and esthetics of structural/environmental compatibility.

(a) Boat slips. Slip sizes are determined by the size the boats intended to use them. Table 3-1 shows the recommended widths and lengths for fixed and floating slips. The water acreage required for slip use is shown as the maximum number of boats per acre in Table 3-2. Alignment of the slips should be parallel to the current. Configuration of boat slips efficiency is achieved by use of single or double-wide slips with access from walkways attached to the shore. Walkways between rows of slips should be oriented perpendicular to the shoreline. Slips generally should be perpendicular to the main walkway. Designs that use curved walkways or curved slips are not efficient in use of water area, promote damage to boats, and are more expensive to build and maintain. If slips of different widths are off the same walkway, the slips should be arranged symmetrically by width on either side of the walkway to ensure symmetrical transmission of stresses to the walkway. Smaller slips should be placed closer to the shore. Double-wide slips can be used, saving money and water space and allowing more flexibility, but increasing the possibility of damage to boats by boat operators or wave action. Figure 3-4 shows a generalized layout of boat slips (Chamberlain 1983).

(b) Walkways. Walkways should be designed to be above the water level at all times and should be structurally sound and safe, kept free of mud, ice, snow, and grease. Walkways should be constructed perpendicular to the shoreline. Walkways less than 200 ft (61 m) long should be straight, while those greater than 200 ft (61 m) can jog or angle at the halfway point. This change

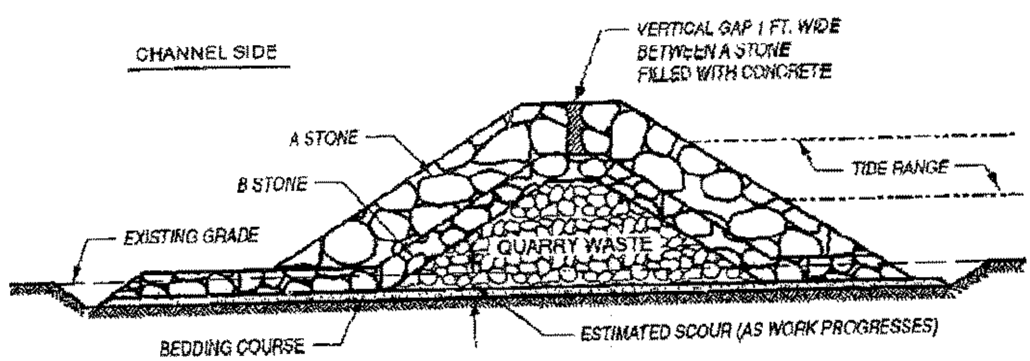

Figure 3-2. Typical cross section of a rubble-mound jetty

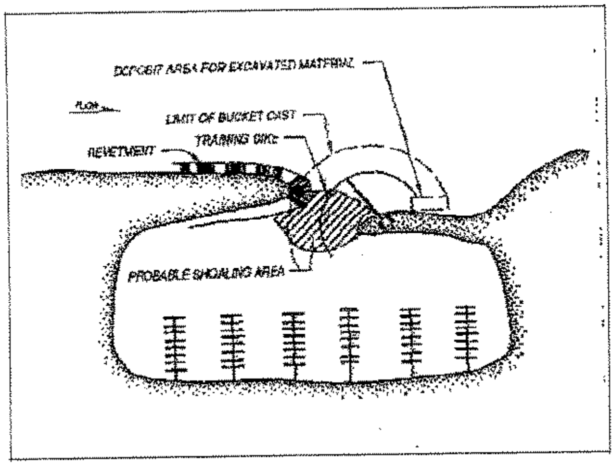

Figure 3-3. Maintenance of entrance to off-river marina basin with land-based equipment

Table 3-1
Recommended Slip Widths for Various Slip lengths

	Slip Length								
	25	30	35	40	45	50	55	60	65
Width, floating slips	10	11	12	14	15	17	18	18	19
Width, fixed slips	11	12	14	16	18	19	19	20	22

Table 3-2
Maximum Number of Boats Per Acre

Fairway Width Boat Length (L)	Floating Slips 1.25 X L	Floating Slips 1.5 X L	Fixed Slips 1.5 X L
25	90	87	93
30	69	66	72
35	50	47	52
40	38	37	41
45	32	31	32
50	26	25	27
55	21	21	25
60	20	19	22
65+	17	16	18

improves lateral stability and modifies the impression of a long pier. Curved or star arrangements for walkways are wasteful of water space, conducive to boat damage, and are expensive to build and maintain. For floating walkways, the finger walkways should extend the full boat length. The finger walkways should not be less than 3 ft wide. A "T" should be placed at the end of a walkway for lateral stability of the pier, and should be at least as long as the slips on either side of the main walkway.

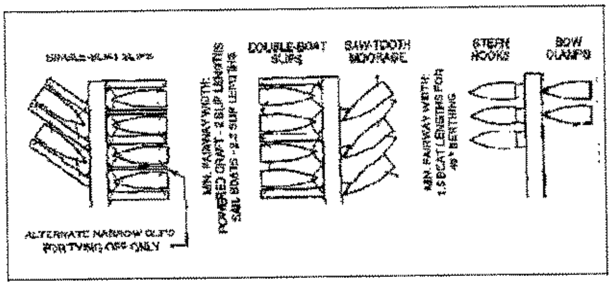

Figure 3-4. Small-craft berthing system (Sembler et al 1969)

Main walkway widths should be a minimum of 4 ft wide. If vehicles such as golf carts are anticipated, a minimum width of 8 ft (2.4 m) should be allowed for turning. Additionally, if significant pedestrian traffic is expected, the width should be at least 8 ft (2.4 m). Finger walkways may need widths greater than 3 ft (0.9 m) for stability (floating) or for strength and rigidity. Finger walkways do not have to extend the length of the slip (Chamberlain 1983, National Water Safety Congress 1988).

(c) Moorings. Mooring piles at the outmost end of the slip allow stern-to-bow mooring (Figure 3-5). For slips longer than about 25 ft (7.6 m), an additional mooring pile should be placed about halfway down the length of the slip. This additional pile, called a spring pile, helps restrain the fore and aft motion and provides protection between boats of adjacent slips. Additionally, a spring pile can be substituted for every other finger walkway (Chamberlain 1983).

(d) Fairway. The width of the area between adjacent rows of slips, i.e., the fairway, should be 1.5 times the length of the longest slip. If the current parallel to the long dimension of the slip exceeds 2 to 3 knots, even temporarily, the fairway should be widened to 1.75 to 2.00 times the length of the longest slip to allow for maneuvering in the down current (Chamberlain 1983).

(e) Basin shape. Natural basins are often used for marina development, taking advantage of natural protection for boat slips. In some cases, it is necessary to construct a basin for protection from waves or high water levels. Surrounding the mooring area with a breakwater or other protection will provide the necessary protection. Marina basins should be rectangular in shape to utilize space and for design purposes, the shorter side should be a multiple of 200 to 250 ft (61 to 76.3 m). The use of vertical bulkhead walls should be minimized and interior

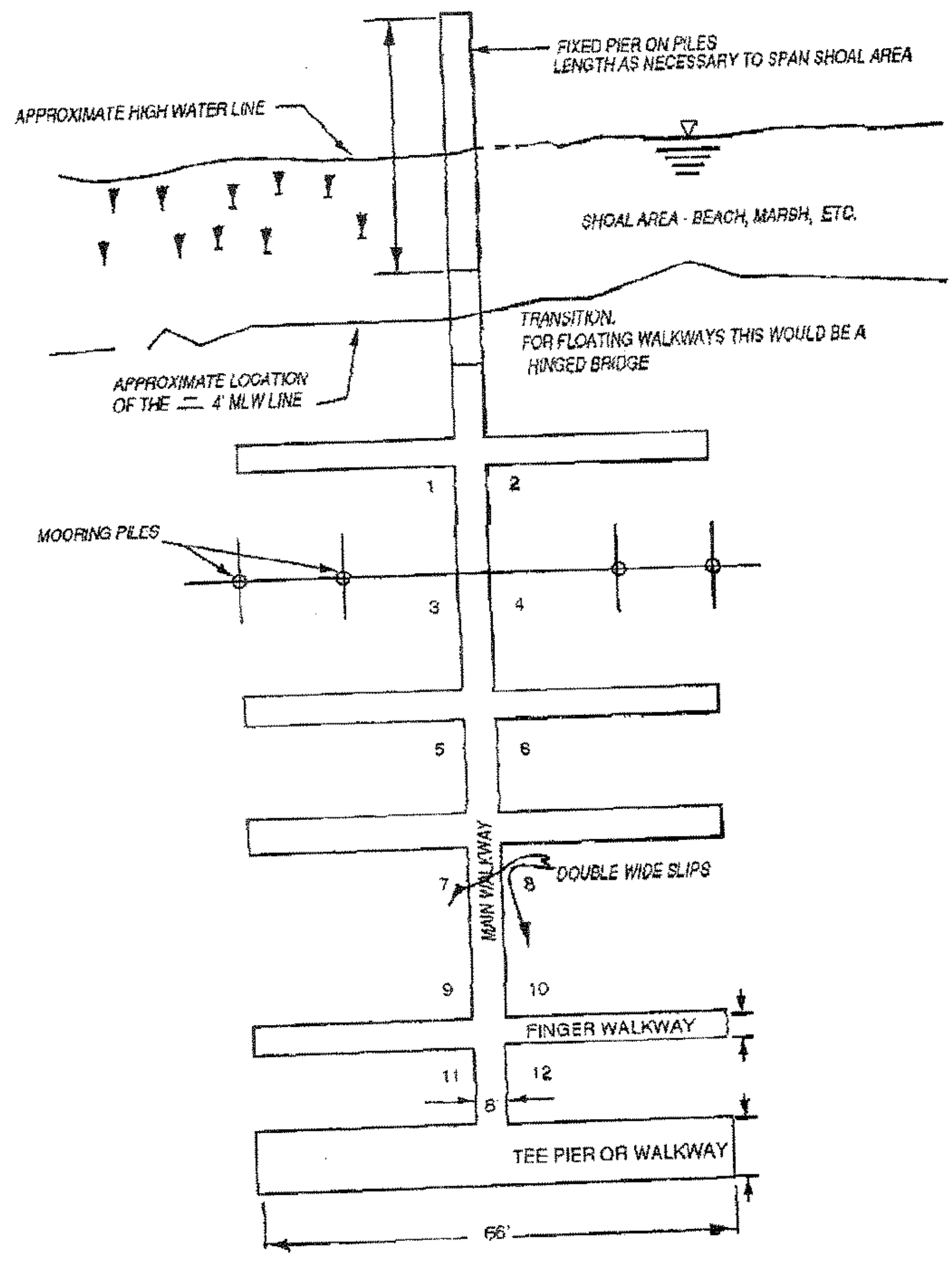

Figure 3-5. Basic layout for marina walkways (Chamberlain 1983)

corners should be gently rounded, preferably with constantly changing radii. Such designs result in the most efficient use of water area and promote water circulation. The basin bottom should be sloped toward the exit and the waterway outside the marina. In designing a basin, concern should be given to preserving or encouraging all natural flushing activities. If necessary, artificial flushing should be considered (Chamberlain 1983).

(f) Channels. Channel entrances and the channel leading to a marina should be as large as possible so as to provide safety and ease of passage in times of storm, fire, or other emergency, and to promote flushing. Where possible, the entrance should be located to avoid the direct entry of waves. Any bends that are necessary should be gradual (Dunham and Finn 1974). A breakwater can be constructed to protect channel entrances from the direct entry of waves (Chamberlain 1983).

(g) Harbor entrance channel. Harbor entrance channels should be at least 60 ft (18.3 m) wide or four times the beam of the widest boat berthed in the marina.

(h) Channel leading to the marina. A clear width of twice the entrance channel width, but not less than 60 ft (18.3 m), should be required.

(i) Channel turning. Required widths for turning are 2.25 times the length of the longest boat. For sites with frequent onshore winds or a large number of single screw power boats, the allowance for turning width should be increased from 2.5 to 2.75 times the longest boat.

e. Dead-end canal.

(1) General. Small boat dead-end canals are generally constructed for access to residences with docking facilities. Construction typically consists of excavation of an access channel through wetlands by widening an existing creek or excavating a totally new watercourse. The access channel provides easy access to the ocean, coastal waterway, river, reservoirs, or lake. Perimeter canals are often connected to the access canals to increase the density of home sites. Christensen and Snyder (1978) provide classification of existing canal systems; most canal systems in the classification terminated in dead ends.

(2) Environmental impact. The major environmental impact of early canal design was loss of wetlands. The dead-end configurations inhibited mixing and exchange of canal waters with the parent water body. As a consequence, storm-water pollutants and domestic wastes accumulated in the canals, resulting in nuisance plant growth and depressed dissolved oxygen. Because of the resulting environmental degradation, most regulatory agencies prohibit the construction of new residential canals until it can be shown that such systems are compatible with the site, that the environment will not be degraded, and that all regulatory criteria are met. Several techniques have recently been developed for reestablishment of wetlands and sea grasses that can be used to mitigate for habitat losses and create new habitat. These techniques are discussed in EM 1110-2-1204 and EM 1110-2-5026.

(3) New canal design. New canal design recommendations that are less damaging to the environment have been suggested (USEPA 1975, Morris 1981, U.S. Army Corps of Engineers 1983):

(a) Canal developments should be restricted to nonwetland areas.

(b) Flow-through or indented boat slip designs are preferable to dead-end canals due to their superior circulation characteristics. To the extent possible, dead-end features should be eliminated from canal systems.

(c) Canal depths for shallow draft pleasure craft should be no more than 4-6 ft below mean low water. It has been observed that "deep" canals are not adequately flushed by tidal action and that lower layers act as a trap for sediments and organic material. It has also been observed that canals that are very shallow (under 4 ft) may have poor flushing characteristics, poor navigability, and increased turbidity due to boat traffic.

(d) The grade of the canal bottom should be such that no sills are created at any point in the system. When a canal is first dredged, before connection to the receiving water body, a plug is often left in place. Upon removal, a sill may remain which impedes the circulation of the bottom waters.

(e) Canals should be designed to maximize wind-induced mixing, i.e., maximum width, minimum length, and orientation with prevailing winds.

(f) Canal design should contain some shallows. Intertidal and littoral vegetation consume nutrients from the water; thus, the canal may improve the quality of the receiving waters by reducing nutrient content and possibly raising the level of dissolved oxygen.

(g) Surface drainage patterns should be designed with swales, contours, and shallow depressions for water retention, to minimize direct runoff into canal waterways.

(h) For residential sewage treatment, package plants or lagoon systems are recommended.

f. Launching ramps.

(1) General. If properly placed and designed, launching ramps should have a minimal impact on aquatic and terrestrial resources. Under some conditions there may be concern over the effects of wave wash on bank stability and vegetation. If adjacent areas are shallow, bottom-dwelling organisms and their habitat can be disrupted if boats run aground or scrape the substrate. Valuable habitats and their biota may be protected if well-marked routes to the launching ramp are established and recreational craft are kept away from sensitive areas. If ramps have to be located near valuable areas, breakwaters, bank protection devices, or speed warnings may be required.

(2) Ramp design. Direct access to water areas should be prevented by designing boat launching ramps that require a deliberate turn from any access roads. Boat ramp designs vary depending upon their usage (U.S. Fish and Wildlife Service 1980). Ramps are usually constructed adjacent to deep water for easy launching of boats on trailers. They may range in widths from 10 ft to over 50 ft (3-15 m). The length of a ramp may be over 60 ft (18 m). The slope should be between 12 and 16 percent above the waterline and 15 to 20 percent below the waterline (EM 1110-1-400, National Water Safety Congress 1988). It is recommended that a ramp be paved to about 5 ft (1.5 m) below the extreme low tide. There should also be a level, gravel shelf at the end of the ramp. The most common construction technique for a ramp is to use a gravel foundation covered by 3 to 6 in. of concrete. Piers should also be provided for boarding and holding a boat while launching. It is recommended that piers be provided on both sides of the ramp. The ramp should be placed in a well-protected area with minimal currents, but one that is well flushed to avoid the buildup of exhaust, petrochemicals, and other pollutants associated with boating operations. The ramp should have a washdown facility. Oil, grease, and other pollutants washed off a boat should be discharged into the sewer system rather than into the boat basin.

(a) Ramp safety designs. To provide adequate traction, the surfaces of the ramp should be scored or patterned. Deep grooves in the concrete should be perpendicular to the slope of the ramp to provide good vehicular traction. Where drop-offs exist or could form, retaining curbs should be incorporated at the lower end of the ramp and on the outside edges or ramps. Consideration should be given to providing chock blocks, where feasible. Operation plans should include plans to keep ramps free of algae growth and siltation (National Water Safety Congress 1988).

(b) Ramp area design. For boat trailer parking, a general rule is 25 car and trailer parking spaces per lane, except where demand or site conditions require deviations. A minimum of one 75-ft- (23-m-) diam vehicular turnaround should be provided for each ramp. Courtesy loading docks should be provided to allow for safe loading and unloading of persons and gear (EM 1110-1-400, National Water Safety Congress 1988).

(c) Security lighting. Adequate security lighting should be provided. Appropriate signs should be placed to encourage safe boating practices. Overhead power lines crossing the water should be posted (National Water Safety Congress 1988).

(3) Environmental impacts.

(a) If not properly designed, the construction of a boat ramp and associated parking facilities can result in both immediate and long-term environmental effects. Construction of a ramp and parking facilities can cause increased erosion and associated turbidity as a result of altering the shoreline and intertidal habitats, smothering of benthic animals, and release of toxic substances used in the construction material. A possible solution is the planting of marsh grasses and sea grasses (EM 1110-2-1204 and EM 1110-2-5026). Ramp site selection should avoid, if possible, wetlands, and highly productive intertidal habitats (i.e., shellfish beds, sea grasses, nursery habitat, etc). The construction of a ramp will displace shoreline and aquatic habitats and in most cases replace it with less productive habitat, particularly if the ramp is heavily used. Construction can also result in increased noise and air pollution.

(b) Long-term impacts are associated with dredging and channel deepening to accommodate the ramp, protective structures that may be required, parking facilities that require clearing and grading the land, and increased human usage of the area. Increased operation of boats in association with the ramp will increase turbulence of the water, petrochemical pollution, and noise which may affect fish and wildlife resources and humans in the area. Generally, channel depths providing a clearance of 2-3 ft between the propeller of a vessel and the channel bottom during low waters, will be sufficient to prevent increased turbidities (NOAA 1976). It is also possible that a greater number of boats and their wakes may increase shoreline erosion, requiring additional protective shoreline structures. If the ramp becomes a popular boat launching area, it may attract other commercial facilities that could further increase habitat alterations.

(4) Alternatives.

(a) An alternative that should be considered in place of a boat ramp is a hoist that can pick a boat up off a trailer and place it in the water. A hoist usually requires a pier or other structure to allow access to navigable waters. The hoist would be appropriate where the water is deep close to the shore. In areas where there is a narrow band of marsh or shallow water separating the shore from deep water, a dock or pier could be used to span these areas.

(b) A marine way (dolly) is another alternative to a boat ramp. This operation requires lifting the boat onto a rail and lowering the boat down the rail into the water. Its advantage is that boats can be launched in areas with a shallow slope at low tides.

3-2. Basin Operating Criteria

a. Periods of Operation.

(1) Under certain conditions, it is often possible to restrict dredging, construction, or related activities to appropriate times of the year so as not to negatively affect certain biota (LaSalle 1988, Sanders and Killgore 1989). Boat ramps are usually constructed during low water periods when banks are dry and construction will not be impeded by high water. There are probably fewer negative effects to aquatic biota during late summer and fall when aquatic plants have senesced, reproduction of fishes and macroinvertebrates has taken place, and many aquatic insects have emerged. Water clarity is usually highest during late summer and early fall, so the effects of sedimentation may appear great, although impacts to spawning or nursery areas will be minimal.

(2) It may be virtually impossible to restrict access to boat ramps during selected times of the year. When fish spawning and plant growth are maximal (i.e., during the spring), recreation use is often at a peak. Rather than attempt to restrict access, boat ramps and facilities should be designed so that sensitive areas will not be damaged. The use of buoys and breakwaters, placing boat lanes so that they are straight and do not encroach on valuable areas, and enforcement of reduced speed zones are all methods of protecting biota regardless of season. Seasonal restrictions on dredging and construction activities are based on perception or concern that such activities will have a negative impact on biological resources. The major concerns are related to impacts on migrating waterfowl, shore and wading birds, fish migration, and larval and juvenile fish and shellfish. Restrictions may be justified in cases where there are known occurrences of the animals in the vicinity of the construction site during specific seasons. Project activities should be scheduled to minimize interference with reproduction, rearing, and migration of these biological resources (Cardwell and Koons 1981). Careful planning and scheduling of dredging and construction can minimize these impacts.

b. Water quality impacts.

(1) Flushing. Water quality impacts of small boat basins can be attributed to excess input of pollutants and/or inhibited flushing. Flushing is a concept of how long a constituent remains in the water body. The term "flushing" is often misused in that a single number (e.g., 10 days) is sometimes used to describe the flushing time of a harbor. In actuality, the flushing rate ranges from 0 days at the boundary to several weeks depending on location within the marina water body. A decrease in flushing increases the time that a constituent exerts its influence on the water quality. Site selection, basin design, and operation procedures are the most effective ways to minimize possible water quality impacts. Objectives should include minimization of pollution sources and maximization of flushing. Evaluation of water quality impacts involves an assessment of the input of pollutants and flushing of the water body.

(2) Pollutant sources. The term pollutant refers to either naturally occurring or synthetic materials that may occur in sufficient quantity to adversely affect water quality. The major sources of pollution include storm water runoff, sanitary wastes, and wastes from boat operation and maintenance. In addition, pollutants may be introduced through dredging and dredged material disposal during either construction or maintenance.

(a) Rainfall creates runoff from roofs, parking lots, roads, fields, forests, lawns, etc. The runoff may carry a variety of pollutants that may degrade water quality. These pollutants include sediment, nutrients, pesticides, oil and grease, metals, and pathogens.

(b) Sanitary wastes cause an increase in the nutrient supply, an increase in biochemical oxygen demand, and introduction of disease-causing viral and bacterial organisms. Pollutants from this source can enter small boat basins in wastewater directly discharged from boats or from improperly functioning or poorly located septic systems that allow sewage effluents to leach into the basin.

(c) Other wastes from boat operation and maintenance include pollutants such as gasoline, oil, and grease; solid waste; trash; lead; copper; and detergents.

(3) Predictive techniques. Application of predictive techniques to assess the water quality impacts (e.g., depressed dissolved oxygen (DO)) of these pollutants requires an estimate of pollutant loading. If actual values for various loadings are not available, the USEPA (1985) provides estimates of constituent concentrations for urban runoff and contribution from boats.

(4) Flushing and DO. The water quality in harbors is generally lower than the water quality of the parent water body. However, successful control of water quality is usually dependent upon periodic exchanges of harbor water with the parent water body. Dunham and Finn (1974) suggested that for single entrance marine harbors, an average daily exchange of water equivalent to about one-third of the harbor's mean tidal volume is usually sufficient to prevent water stagnation. Boozer (1979) stated that for marine harbors, turnover times of 2-4 days will generally prevent stagnation or the buildup of high pollution concentrations. By correlating hydraulic model estimates of flushing with water quality measurements in five Puget Sound Marinas, Cardwell, Nece, and Richey (1980) suggest that a mean exchange coefficient of 30 percent was necessary to prevent serious fluctuations in DO. The mean exchange coefficient is the percentage of water in a basin that is removed and replaced with ambient water during each tidal cycle. Although the three methods use different techniques, the results are nearly equivalent. Importantly, the three exchange estimates are for marinas for which tidal action is the dominant factor.

(a) Rivers and lakes. In flowing rivers, potential water quality problems are minimized because the river currents will induce circulatory flow. In lakes, small craft harbors are typically constructed in coves; the use of floating docks minimally affects the existing circulation and thus the exchange with the parent water body.

(b) Marinas. Marinas may be located near the ocean where solid breakwaters may be used for protection. The harbor construction may significantly affect the water exchange with the parent water body. Nece et al. (1979) used physical models to study geometric effects of marina design and suggested design features for maximum flushing: the best design of a rectangular basin for optimal tidal flushing would have a length/breadth ratio between 0.5 and 2.0, rounded corners, and a centered entrance. However, asymmetric basins within the same length/breadth ratio and with rounded corners also exhibit adequate flushing characteristics. Little guidance was found on designs with multiple entrances; however, parent water body circulation could be used to enhance water exchange. Two openings at opposite ends of the marina could establish flow-through water currents. Other design considerations for enhancing flushing include (Boozer 1979): marinas should have wide and deep entrances with depth gradually decreasing toward the inner reaches of the marina; marinas should never be deeper than either the open water or channels to which they are connected and never deeper than their own access channels; and marinas should use floating breakwaters to dampen incoming waves yet allow less restricted water circulation. Most of the early designs of marina systems were based on a simple flushing analysis. The flushing analyses were a variant of the tidal prism method (Walton 1983). Such an approach for marinas is a reasonable "back-of-the-envelope" calculation to obtain an idea of the exchange of water between the marina and adjacent waterway. The procedure is described in Chapter 4 of the *Coastal Marinas Assessment Handbook* (USEPA 1985). In studying South Beach Marina in Oregon, Callaway (1981) used a simple flushing model to simulate mixing. His results showed excellent agreement with a physical model of the system, but showed that both the physical and flushing models overestimated the flushing time when compared to field data.

(c) Residential canals. Tidal prism analysis is not applicable to canal systems because the assumption of complete mixing is not valid. The use of the one-dimensional model DYNTRAN (Moore and Walton 1984) provides a relatively rapid, conservative, and inexpensive procedure for assessing flushing and DO. The procedure is conservative because the physical mixing processes due to wind, density-induced currents, and secondary currents are not included in the model. Several basin design features that promote flushing are basin depths that are not deeper than the open water, two openings at opposite ends of the marina to establish flow-through currents, minimal vertical walls, a rectangular basin with single entrances that are centered, and basin depths that gradually increase toward open water.

(5) DO analysis. The level of DO is used to characterize water quality because it serves as an integrated

measure of physical, chemical, and biological processes. DO is included in all state water quality standards. The procedure for DO analysis consists of two phases. The first phase consists of a flushing analysis for estimates of flushing rates or flows. The second phase consists of the use of the flushing rate estimates for the solution of mass balance equations relating DO to sources such as reaeration and sinks such as biochemical oxygen demand (BOD) decay. A procedure is outlined in the Coastal Marinas Assessment Handbook (USEPA 1985). Two- and three-dimensional numerical hydrodynamic and water quality models are available (Hall, Dortch, and Bird 1988) that can address the flushing and water quality of small boat basins. Although not justified in the past, due to the rapid decrease in computational costs and the capability to run some applications on microcomputers, the application of numerical models for analyses of small boat basins is now feasible.

(6) Water exchange. Water exchange does not always ensure good water quality. A significant factor in water quality control is the elimination of direct sources of pollution: storm-water runoff, sanitary wastes, and wastes from boat operation and maintenance.

c. Control of adjacent land and water use. Planning for adjacent land and water use should be documented in a master plan and in provisions of permits for marinas. The master plan should consider trash and garbage pickup, and provision of a boat maintenance area for washing boats. The need for maintenance dredging to minimize siltation and to ensure adequate channel depth and alignment should be evaluated. Maintenance dredging should be scheduled to minimize impacts on current paths and wave action and impacts to adjacent beaches and wetlands (Chamberlain 1983).

Chapter 4
Attendant Problems and Responsibilities

4-1. Boat Discharges

Due to the limited circulation in most small boat basins, the discharge of pollutants from boats can have adverse environmental impacts. Primary boat discharges include sanitary wastes and boat motor emissions.

a. Sanitary waste.

(1) Sanitary waste discharges from boats pose a health risk and can potentially violate state water quality standards, especially for boat basins located near bathing or shellfishing waters. Boat sewage can be visually repulsive (Chmura and Ross 1978) and may contribute to increased BOD in receiving waters (NOAA 1976). BOD is a measure of the DO required to stabilize the decomposable matter present in a water body by aerobic biochemical action. When BOD increases, DO available for aquatic organisms decreases. Anaerobic waters create a sump for pollutants and organics resulting in stagnant, sulfide-odorous, and slow-decaying (due to low DO) conditions.

(2) The most serious effect of discharging fresh fecal material is the potential for introducing disease-causing viruses and bacteria (pathogens). Problems may occur if boat sewage is released in the vicinity of shellfish (clam or oyster) beds or into enclosed waterways with limited flushing. Shellfish require clean water to be microbiologically safe for human consumption, regardless of whether they are eaten raw or partially cooked (USEPA 1985).

(3) Management of boat sanitary waste discharges includes the installation and proper use of equipment onboard the vessels and onshore equipment for collection and disposal. The onboard equipment is referred to as marine sanitation devices (MSD). Another means of managing boat sanitary waste discharges would be to educate boaters about the potential health risks associated with the discharge of sewage. Boat toilet use would be reduced if marinas discouraged "live-aboards" and provided well-maintained shoreside restroom facilities of sufficient quantity to accommodate above-average boating populations. Shoreside facilities must be convenient to the docks (Chmura and Ross 1978). USEPA does not require a National Pollutant Discharge Elimination System permit for: "Any discharge of sewage from vessels, effluent from properly functioning marine engines, laundry, shower, and galley sink wastes, or any other discharge incidental to the normal operation of a vessel." However, this exclusion doesnot apply to permanently moored vessels.[1] Permanently moored vessels could be discouraged from marinas in order to avoid potential discharge of any sewage from all vessels into aquatic habitats by applying to the USEPA Administrator for issuance of a regulation prohibiting discharge into well-defined shellfish growing waters (USEPA 1985).

b. Boat motor emissions.

(1) Boat motor emissions include hydrocarbons and lead. Once exhausts are released from outboard motors, some of the hydrocarbons become suspended in the water column while others evaporate at the surface (Kuzminski, Jackivicz, and Bancroft 1973). Clark, Finely, and Gibson (1974) suggested that small amounts of hydrocarbons from outboard motor wastes may adversely affect mussels and oysters. They found that mussels were more sensitive to two-cycle outboard motor effluent than oysters, and that cumulative mortality in mussels after 10 days was 66 percent compared with 14 percent for oysters.

(2) The major source (approximately 88 percent) of lead that enters a basin through subsurface outboard motor exhaust was the combustion of leaded gasoline, which is no longer available (May and McKinney 1981). Lead is very toxic to most plants and is moderately toxic to mammals, where it acts as a cumulative poison (Bowen 1966). The aquatic organisms most sensitive to this metal are fish (Mathis and Kevern 1975). Boat motor emissions can be reduced through the increased use of unleaded fuels and by manufacturer research and development aimed at reducing the pollutants in emissions and increasing fuel efficiency. Public education directed toward the importance of well-tuned engines in reducing emissions and increasing efficiency is another mitigative measure to be considered (USEPA 1985).

4-2. Water Quality Monitoring and Maintenance

a. Sewage discharge from vessels moored in a boat basin is normally a minimal pollution problem. However, the development of recreation facilities will result in replacement of existing lands with impervious surfaces, increases in contaminants and surface runoff, and increased siltation.

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[1] Letter from Roger O. Olmstead, Program Manager, Shellfish Sanitation, USFDA, Atlanta, GA to J. David Clem, Chief, Shellfish Sanitation Branch, 1 December 1982.

If small boat basin design results in a confined basin, there is the potential for stagnation and eventual accumulation of pollutants. This can result in decreases in dissolved oxygen levels below acceptable levels. The basin should be oriented so that flushing currents are introduced. Design components to encourage flushing include taking advantage of prevailing winds; elimination of corners or projections in basin design; and shaping and sloping of the bottom of the basin. In severe cases, flushing can be achieved by pumping water from an adjacent area or by aerating the basin.

b. Water quality monitoring can be expensive. The most economical alternative compared to field monitoring may be the use of a numerical model. All models require some field data for proper calibration. Tetra Tech (1988) determined that a better and more cost-effective approach would be a combination of both water quality monitoring and numerical modeling. These models may be used to predict flushing time and pollutant concentrations without site-specific data. Another advantage of numerical models over field monitoring is the ability to perform sensitivity analyses to establish a set of design criteria. Numerical models may be used to evaluate different alternative designs to determine the configuration that would provide for maximum flushing of pollutants. These models may also be used to perform sensitivity analysis on the selected optimum design.

4-3. Environmental Effects of Structures

Breakwaters and jetties associated with marinas, boat ramps, or harbors can benefit aquatic biota. Gravel and cobble provide substrate for small plants, crustaceans, and molluscs, which are food for fishes and waterfowl (Miller 1988, Payne 1989). In addition, rock structures create quiescent areas that are used by larval and juvenile fishes, as well as freshwater mussels and crustaceans. Jetties and other rock structures may be particularly beneficial if they are placed in lakes or estuaries where substrate consists mainly of fine-grained sands and silts. The negative effects of these structures probably originate from improper construction practices. Heavy equipment should be kept clear of shallow aquatic habitats, wetland vegetation, and unstable banks. Coarse rock and riprap are the best materials for construction of jetties and other rock structures. Although automobile bodies and rubble from construction can be used in place of riprap, this material is unsightly and can be dangerous forswimmers and may be a source of toxicants or nuisance flotsam.

a. Marinas.

(1) The impacts of small boat basins are dependent on the sensitivity of the site selected, the design of the marina, and the extent of the impacts on the environment. The nature of a small boat basin dictates the need for protected waters that are conducive to stagnation and associated water quality problems. Basins that contain dead-end canals and are inadequately flushed may create major water quality problems. Stagnation may result in higher temperatures and salinities in the basin than in unmodified areas. Poor circulation may also result in the buildup of debris, organic material in the water and sediments, phytoplankton blooms, depletion of oxygen in the water, and associated fish kills (de La Cruz 1983; McBee and Breham 1979). There are a number of design features that can be considered to improve the environmental quality of a harbor. The shape of the basin is important. It should fit the flow patterns of the area if possible. This requires avoiding square-shaped basins and dead-end canals that create dead-water areas. Basins should be constructed so that they are not deeper than their access channel. The most desirable design would be a marina with a wide deep entrance channel with gradually decreasing depths toward the inner harbor (NOAA 1976). This design would provide improved flushing rates in the marina. With this design, larger vessels could be moored toward the mouth of the marina and shallower draft vessels in inner portions of the harbor. Flow-through designs would also be desirable. Open piles and floating breakwaters would be more conducive to water circulation in a basin. Where an open flow-through design is not feasible, breaches or culverts should be considered to enhance circulation and flushing of the basin. A small boat basin should not be located near sewage or industrial outfalls that may compound potential water quality problems.

(2) Water quality in the harbor may be further impacted by boating activities. Petroleum products may be released in the water from boat engines. Boating operations may also add to the turbidity of the water in the basin if it is shallow and may result in a reduction of photosynthesis and dissolved oxygen in the water. Generally, a water depth of 2-3 ft between the propeller of a vessel and the bottom during low water should prevent these problems (NOAA 1976). Other water quality problems may result from oil spills, sewage disposal, and land runoff into the basin. Contamination may also result from protective paints (copper) on boats.

(3) Noise and air pollution from construction and/or operation of a marina may also disturb aquatic and terrestrial animals and humans in the immediate area.

b. Jetties.

(1) Jetties associated with marinas are structures used to stabilize the position of the navigation channel, to shield vessels from wave forces, and to control the movement of sand along the adjacent beaches so as to minimize the movement of sand into the channel (EM 1110-2-1204). The sand transported into a channel will interfere with navigation depth. Because of the longshore transport reversals common at many sites, jetties are often required on both sides of a channel to achieve complete channel protection. It is the impoundment of sand at the updrift jetty that creates the major physical impact. When fully developed, the impounded sand extends well updrift on the beach and outward toward the tip of the jetty.

(2) Another major physical impact of a jetty is the erosion of the downdrift beach. Before the installation of a jetty, nature supplies sand by intermittently transporting it along shore. The reduction or cessation of this sand transport due to the presence of a jetty leaves the downdrift beach with an inadequate natural supply of sand to replace that carried away by littoral currents.

(3) To minimize the downdrift erosion, some projects provide for periodically dredging the sand impounded by the updrift jetty and pumping it through a pipeline to the downdrift eroding beach. This pumping provides nourishment of the downdrift beach and also reduces shoaling of the channel. If the sand impounded at the updrift jetty extends to the head or seaward end of the jetty, sand will move around the jetty and into the channel, causing a navigation hazard. Therefore, the purpose of sand bypassing is not only to reduce downdrift erosion, but also to help maintain a safe navigation channel.

(4) One design alternative for sand bypassing involves a low section or weir in the updrift jetty over which sand moves into a sheltered, predredged deposition basin. By dredging the basin periodically, channel shoaling is reduced or eliminated. The dredged material is periodically pumped across the navigation channel to provide nourishment for the downdrift shore.

c. Breakwaters.

(1) Breakwaters are wave energy barriers designed to protect any land form or water area behind them from the direct assault of waves (EM 1110-2-1204). Because of the higher cost of these offshore structures, breakwaters have been mainly used for harbor protection and navigational purposes. In recent years, shore-parallel, detached, or segmented breakwaters have been used for shore protection structures.

(2) Breakwaters have both beneficial and detrimental effects on the shore. All breakwaters reduce or eliminate wave action in the lee (shadow). However, whether they are offshore, detached, or shore-connected structures, the reduction or elimination of wave action also reduces the longshore transport in the shadow of the breakwater. For offshore breakwaters, reducing the wave action leads to a sand accretion.

(3) Shore-connected breakwaters provide protection to harbors from wave action and have the advantage of a shore arm to facilitate construction and maintenance of the structure (Figure 4-1).

(4) At a harbor breakwater, the longshore movement of sand generally can be restored by pumping sand from the side where sand accumulates through a pipeline to the eroded downdrift beach.

(5) Offshore breakwaters have also been used in conjunction with navigation structures to control channel shoaling. If the offshore breakwater is placed immediately updrift from a navigation opening, the structure impounds sand in its lee, prevents it from entering the navigation channel, and affords shelter for a floating dredge plant to pump out the impounded material across the channel to the downdrift beach.

d. Physical considerations.

(1) Jetty, breakwater, and marina construction are invariably accompanied by localized changes in the hydrodynamic regime, creating new hydraulic and wave energy conditions. The initial disruption of the established dynamic equilibrium will be followed by a trend toward a new set of equilibrium conditions. Rapid dynamic alterations in the physical environment may occur in the short-term time scale as the shore processes respond to the influence of the new structures. Slower, more gradual, and perhaps more subtle changes may occur over the long term.

(2) In light of the dynamic character of shore processes, assessment of the effects of coastal engineering projects on shorelines is a difficult task. Shoreline changes

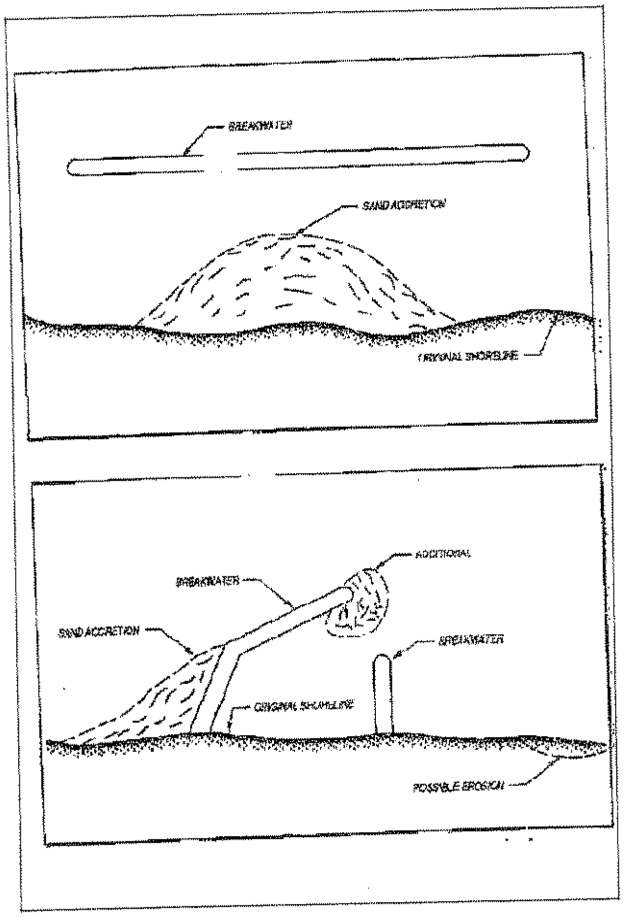

Figure 4-1. Erosion and accretion patterns in association with detached and attached breakwaters

induced by the presence of a structure may be masked by wide annual or seasonal fluctuations in natural physical processes. Several events, however, can be predicted in response to jetty, breakwater, and marina construction with reasonable certainty. For example, by creating wave-sheltered areas, construction will result in changes in the erosional and depositional patterns along adjacent beaches, both inshore and offshore. A jetty or shore-connected breakwater will form a barrier to longshore transport if the structure extends seaward beyond the surf zone. Spatial extent of the ensuing shoreline alteration will depend on the structure's effectiveness as a sediment trap, which is a function of its orientation to the prevailing wave climate. Updrift accretion of sediments will continue until the sink area is filled to capacity and the readjusted shoreline deflects longshore transport past the seaward terminus of the jetty. The volume of sediment trapped by the structure represents material removed from the natural sand bypassing process. Consequently, the downdrift shoreline will be deprived of this sediment and become subject to erosion. In circumstances where waves are refracted around the structures in a proper manner, accretion can occur along the seaward side of a downdrift jetty. Reflection of waves from a jetty or breakwater may also cause erosion of adjacent shorelines. However, erosion further down the shoreline is not precluded. Planning for adequate sand bypassing is, in view of the above considerations, a critical requirement of coastal construction.

(3) Erosion related to jetties will not necessarily be limited to downdrift shorelines. Jetties confine flows through a channel such that current velocities are increased. An enhancement of ebb jet flows will result in displacement of sediments from between the jetties in a seaward direction to deeper waters.

(4) Shore-connected breakwaters of a small boat basin affect shorelines in much the same manner as jetties. Accretion occurs along the updrift junction of shore and structure and continues until longshore transport is deflected around the free end to the breakwater (Figure 4-1). Calm waters in the protected lee of the breakwater provide a depositional area that can rapidly shoal. Sediments trapped in the accretional area and terminal shoal are prevented from reaching downdrift beaches, and substantial erosion may result.

(5) Offshore breakwaters create depositional areas in their "shadows" by reflecting or dissipating wave energy (Figure 4-1). Reduction of wave energy impacting a shoreline in the lee of the structure retards the longshore transport of sediments out of the area and accretion ensues. The extent of accretion will depend on the existing balance of shore processes at a given project site. Generally, a cuspate spit will develop between the shoreline and the structure as the system approaches a new equilibrium. However, if the breakwater is situated in the littoral zone such that it forms a very effective sediment trap, a complete connection will eventually form, merging the shoreline with the structure. A tombola associated with an offshore breakwater may present a severe obstruction to littoral transport and trap a significant volume of sediment. Extensive downdrift erosion may result.

(6) By modifying the cross-sectional area of a channel, jetty construction potentially can alter the tidal prism, or volume of water entering or exiting through a channel in one tidal cycle. Enlarging a channel can increase the tidal range within a harbor. In connection with channel deepening, seawater may intrude further into the harbor than occurred under pre-project conditions. Circulation

patterns within a basin may be altered as a consequence of modified floodwater current conditions. Thus, the area physically affected by jetty construction might be extended appreciable distances from the actual project site.

e. Water quality considerations.

(1) Suspended sediments. During the construction and dredging of a small boat basin, suspended sediment concentrations may be elevated in the water immediately adjacent to the operations (EM 1110-2-1204, U.S. Army Corps of Engineers 1989, NOAA 1976). In many instances, however, construction and dredging will be occurring in naturally turbid estuarine or coastal waters. Plants and animals residing in these environments are generally adapted to, and are very tolerant of, high suspended sediment concentrations. The current state of knowledge concerning suspended sediment effects indicates that anticipated levels (generally less than 1,000 mg/l) generated by construction and dredging do not pose a significant risk to most biological resources (U.S. Army Corps of Engineers 1989). The adaptability of the animals to high turbidities may minimize environmental impacts. However, turbidity control is always in the best interest of the environment during construction or dredging activities. Although estuaries and coastal waters are generally more turbid than coral reefs, they are not insensitive to potentially indiscriminate construction practices. High levels of suspended sediment concentrations remain a concern in construction projects. Limited spatial extent and temporal duration of turbidity fields associated with these construction activities reinforce this assessment. However, when construction and dredging are to occur in a clear-water environment, such as in the vicinity of coral reefs or sea grass beds, precautions should be taken to minimize the amounts of resuspended sediments. Organisms in these environments are generally less tolerant to increased siltation rates, reduced levels of available light, and other effects of elevated suspended sediment concentrations (U.S. Army Corps of Engineers 1983, EM 1110-2-1204). Potential negative impacts can be somewhat alleviated by erection of a floating silt curtain around the point of impact when current and wave conditions allow. However, high-energy conditions usually preclude the use of silt curtains (NOAA 1976, EM 1110-2-1202).

(2) Other water quality impacts. Indirect impacts on water quality may result from changes in the hydrodynamic regime. The most notable impact of this type is associated with breakwaters which form a semi-enclosed basin used for small boat harbors or marinas. If the flushing rate of the basin is too slow to provide adequate removal of the contaminants, toxic concentrations may result (USEPA 1985, NOAA 1976, U.S. Fish and Wildlife Service 1980, EM 1110-2-1204). Also, fluctuations in parameters such as salinity, temperature, dissolved oxygen, and dissolved organics may be induced by construction or due to altered circulation patterns. Anticipated changes in these parameters should be evaluated with reference to the known ecological requirements of important biological resources in the project area.

f. Biological considerations.

(1) Habitat losses. Measurable amounts of bottom habitat are physically eradicated in the path of a fixed jetty or breakwater during construction of a small boat basin. If a rubble-mound structure with a toe-to-toe width of 164 ft (50 m) is used as an example, 0.6 mile (1 km) of structure removes approximately 12.5 acres (5 ha) of preexisting bottom habitat (EM 1110-2-1204). Once a structure is in place, water currents and turbulence along its base can produce a scouring action, which continually shifts the bed material. Scour holes may develop, particularly at the ends of structures. Scouring action may effectively prevent the colonization and utilization of that habitat area by sediment-dwelling organisms. Effects of scouring are largely confined to entrance channels and narrow strips of bottom habitat immediately adjacent to structures. Usually, only a portion of the perimeter of a structure will be subject to scouring, such as along the channel side of the downdrift jetty. Generally, the amount of soft bottom habitat lost at a given project site will be insignificant in comparison with the total amount of that habitat available. Exceptions to this statement may exist, such as where breakwater construction and dredging of the total enclosed harbor area will displace large acreages of intertidal habitat. Often such habitats function as nursery areas for estuarine-dependent juvenile stages of fishes and shellfish, and the availability of those habitats will be a determining factor in the population dynamics of these species. Most marina projects, however, require only a small amount of dredging. The impacts of these projects will be minor provided marshes, sea grasses, and other critical habitat are not disturbed. Dredged material should be placed on high ground within the marina area, if possible (NOAA 1976). Dredged material can be used to improve coastal ecosystems if it can be disposed in a manner to establish artificial marshes, sea grass beds, and shellfish beds (NOAA 1976, EM 1110-2-5026, Pullen and Thayer 1989). Additional habitat losses may occur when significant erosion of downdrift shorelines impacts spawning or nesting habitats of fishes, shorebirds, or other organisms and when the tidal range of a harbor is

modified by entrance channel modification, which in turn affects coastal habitat. Short-term impacts of this type may also occur during construction activities as heavy equipment gains access to the project site. Small boat basins in some coastal regions are constructed in areas of rocks or other hard bottoms and may require blasting to break up the rocks during construction. Fish kills may result from the blasting. The major damage is to fish with swim bladders. Tests have shown that a force of 40-50 psi from a high explosive charge is usually fatal to adult fish with swim bladders, whereas a charge as low as 2.7 psi will kill juveniles (U.S. Army Corps of Engineers 1989).

(2) Habitat gains.

(a) Losses of benthic (bottom) habitat and associated benthos (bottom-dwelling organisms) due to physical eradication or scouring will gradually be offset by the gain of new habitat represented by the structures themselves and the biological community, which becomes established thereon (NOAA 1976, EM 1110-2-1204). The trade-off made in replacing "soft" (mud or sand) bottom habitat with "hard" (rock, at least in rubble-mound structures) bottom habitat has generally been viewed as a beneficial impact associated with jetty and breakwater projects. Submerged portions of jetties and breakwaters, including intertidal segments of coastal structures, function as artificial reef habitats and are rapidly colonized by opportunistic aquatic organisms. Over the course of time, structures in marine, estuarine, and most freshwater environments develop diverse, productive, reeflike communities. Detailed descriptions of the biota colonizing rubble-mound structures have been made for project sites on the Pacific (Johnson and De Wit 1978), Atlantic (Van Dolah, Knott, and Calder 1984), Gulf of Mexico (Hastings 1979; Whitten, Rosene, and Hedgpeth 1950), and Great Lakes (Manny et al. 1985) coastlines. In some geographical areas, jetties and breakwaters provide the only nearshore source of hard-bottom habitat. Also, exposed portions of detached structures may be colonized by seabirds.

(b) The ultimate character of the biological community found on a jetty or breakwater of a small boat basin will depend on the quality of habitat afforded by the construction materials used. Physical complexity (i.e., rough surfaces with many interstitial spaces and a high surface area to volume ratio) is a desirable feature of rubblemound structures in comparison with the relatively smooth, flat surface of steel sheet-pile, concrete bulkhead, caisson structures (EM 1110-2-1204, NOAA 1976, U.S. Fish and Wildlife Service 1980). The sloping sides of rubble-mound structures also maximize the surface area of habitat created. Structures with sloping sides also provide more habitat within a given depth interval than structures with vertical elements. Where depths are sufficient, the biota on jetties and breakwaters exhibit vertical zonation, with different assemblages of organisms having discrete depth distributions. In general, then, structures built in deep waters will support a more diverse flora and fauna than those in shallow waters. This pattern will be influenced by such factors as latitude and tidal range.

(c) Just as changes in shoreline configuration and beach profile can entail habitat loss, they can also represent habitat gain. Accretional areas, such as exposed bars, and the above-water portion of structures may be used, for example, by wading and shorebirds for nesting, feeding, and resting sites.

(3) Migration of fishes and shellfishes.

(a) Eggs and larvae. Early life history stages, namely eggs and larvae, of many important commercial and sport fishes and shellfishes are almost entirely dependent on water currents for transportation between spawning grounds and nursery areas (EM 1110-2-1204). A concern which has sometimes been voiced by resource agencies in relation to jetty projects is that altered patterns of water flow may adversely affect the transport of eggs and larvae. Those eggs and larvae carried by longshore currents might be especially susceptible to entrapment or delay in eddies and slack areas formed adjacent to updrift jetties at various times in the tidal cycle. Even short delays in the passage of eggs and larvae may be significant because of critical relationships between the developmental stage when feeding begins and the availability of their food items. All aspects of this potential impact remain hypothetical. No conclusive evidence exists to support either the presence or absence of impacts on egg and larval transport. This fact is true even where jetties have been present for relatively long spans of time. The complexity of the physical and biological processes involved would render field assessments of this impact a long-term and expensive undertaking. The results of hydraulic modeling studies related to this question have been inconclusive (U.S. Army Corps of Engineers 1980). Future modeling studies combined with field verification studies may provide insight into resolving the validity of this concern.

(b) Juveniles and adults. Similar concern has been voiced regarding potential impacts of jetties and breakwaters on migration of juvenile and adult fishes and shellfishes. These stages generally have well-developed swimming capabilities, such that physical barriers imposed by these structures are less of a concern than are behavioral barriers. This issue has been raised primarily in association with projects in the Pacific Northwest, and with anadromous fishes in particular (Faurot et al. 1989). Anadromous fishes, including many salmonids, spend much of their adult life in the ocean, then return to fresh water to spawn. Early life history stages spend various lengths of time in fresh water before moving downstream to estuaries where the transition to the juvenile stage is completed. Specific concerns are that juveniles or adults will not circumvent structures that extend for considerable distances offshore. Juveniles in particular are known to migrate in narrow corridors of shallow water along coastlines and may be reluctant, due to depth preferences, to move into deeper waters. The State of Washington has developed criteria whereby continuous structures that extend beyond mean low water are prohibited. Designs of coastal structures there are required to incorporate breaches or gaps to accommodate fish passage (EM 1110-2-1204).

(4) Increase predation pressure. Coastal rubble-mound structures provide substrate for the establishment of artificial reef communities. As such, jetties and breakwaters serve as a focal point for congregations of fishes and shellfishes which feed on sources of food or find shelter there. Many large predator species are among those attracted to the structures in numbers, as evidenced by the popularity of jetties and breakwaters as sites of intense sport fishing. Thus, there is concern, again largely associated with projects in the Pacific Northwest, that high densities of predators in the vicinity of jetties and breakwaters pose a threat to egg, larval, and juvenile stages of important species (Faurot et al. 1989). For example, fry and smelt stages of several species of salmon are known to congregate in small boat harbors prior to moving to the sea. The concern raised is that these young fishes are exposed to numerous predators during their residence near the structures. As is the case with the concern for impacts on migrating patterns, this concern remains a hypothetical one. Conclusive evidence demonstrating the presence or absence of a significant impact is unavailable and will be exceedingly difficult to obtain.

g. *Environmental summary*.

(1) Environmental design.

(a) Every small boat basin project scenario should incorporate engineering design, economic cost-benefit, and environmental impact evaluations from the inception of planning stages. All three elements are interrelated to such a degree that efficient project planning demands their integration. Environmental considerations must not be an afterthought. Structural design criteria should seek to minimize negative environmental impacts and optimize yield of suitable habitat for biological resources. Minimizing impacts can best be achieved by critical comparisons of a range of project alternatives, including the alternative of no construction. From an environmental perspective, site selection is perhaps the single most important decision in the planning process. However, various engineering design features can be incorporated to optimize an alternative from an ecological viewpoint. For example, opting for a floating rather than fixed breakwater design might alleviate most concerns related to impacts on circulation, littoral transport, and the migration of fishes, because passage is allowed beneath the structure. Floating breakwaters are also excellent fish attractions and still provide substrate for attachment and shelter for many other organisms.

(b) In planning small boat harbors, configurations that minimize flushing problems should be examined. Rectangular basins that maximize the area available for docks and piers characteristically have poor water circulation, particularly in the angular corner areas. Designs with rounded corners and entrance channels located so that flood tidal jets provide adequate mixing throughout the basin are desirable. Selection of a less steep rubble-mound side-slope angle will maximize the availability of intertidal and subtidal habitat surface areas. The size class of stone used in armor layers of rubble-mound structures is another engineering design feature that has habitat value consequences. Selection of large-size material results in a heterogeneous array of interstitial spaces on the finished structure. Heterogeneity rather than uniformity enhances the quality of the structure in terms of refuge and shelter sites for diverse assemblages of fishes and shellfishes.

(2) Environmental assessment.

(a) Short-term impacts. Actual construction activities for small boat basins entail a number of potential impacts (Table 4-1). These impacts will vary in type and frequency from project to project. For example, temporary or permanent access roads may have to be built to allow transportation of heavy equipment and construction materials to the site. The access routes may cross marshes, creeks, and other water areas and have the potential for altering water circulation and displacing valuable wildlife habitat. Grading, excavating, backfilling, and dredging operations will generate short-term episodes of noise and air pollution and may locally disturb wildlife such as

Table 4-1
Marina Environmental Impact Matrix (NOAA 1976)

FACILITY COMPONENTS* / IMPACT CATEGORIES**	Alteration of Natural Areas***	Alteration of Water Circulation Patterns***	Turbidity	Release of Sewage	Oil Spills	Land Runoff	Erosion	Shoaling	Dissolved Oxygen Depletion	Air Pollution	Copper Pollution
Access Channels	•	•	•				•	•	•		
Boat Basins	•	•	•				•	•	•		
Piers and Docks	•	•	•								
Boat Moorings	•	•									
Launching Ramps	•					•	•				
Bulkheads	•	•	•				•	•			
Breakwaters	•	•	•				•	•			
Marine Sanitation Devices				•					•		
Pumpout Facilities	•			•					•		
Fuel Docks	•				•						
Boats			•		•		•	•		•	•
Access Roads	•	•				•	•				
Parking Lots and Cars	•					•	•			•	
Dry Storage Areas	•					•	•				
Club Houses	•					•					
Storm Sewer Outfalls			•	•	•	•			•		
Septic Tanks				•					•		
Dredging	•	•	•				•	•	•		
Dredged Material Disposal	•	•	•			•	•	•	•		
Boat Repair & Maintenance Areas	•				•	•					•

Notes:

* All facility components are not necessarily involved in each marina.

** All impact categories are not necessarily produced at each marina.

*** Impacts may be either positive or negative.

Dots indicate a potentially significant relationship between the facility component and impact category during either construction or operation. The component may be either a source or a cause for that impact.

nesting or feeding shorebirds. Project activities should be scheduled to minimize disturbances to waterfowl, spawning fishes and shellfishes, and other biological resources at the project site. Precautions should also be taken to reduce the possibility of accidental spills or leakages of chemicals, fuels, or toxic substances during construction and operation of a marina. Effort should be expended to minimize the production and release of high concentrations of suspended sediments, especially where and when sensitive biological resources such as corals or sea grasses could be exposed to turbidity plumes and increased siltation rates. Dredging of a channel and basin in conjunction with a small boat harbor project presents a need for additional consideration of impacts in relation to suspended sediments and dredged material disposal.

(b) Long-term impacts. Long-term impacts of small boat harbor construction are less definitive or predictable. Ultimate near-field effects on littoral sediment transport can be expected to become evident within several seasonal cycles. These effects will vary according to a given project's environmental setting and specific engineering design. For example, periodic maintenance dredging will be required for catch basins adjacent to weir jetties and in the harbors. The impact that constructing coastal structures will have on far-field shore processes is presently understood only qualitatively.

4-4. Non-Point Source Pollution (Commercial and Recreational Traffic Effects)

a. Passage of commercial or recreational craft can cause drawdown, turbulence, and waves. These disturbances can erode shorelines, resuspend alluvial sediments, and scour shallow areas. Physical effects of traffic are unique in that although they may last only a few minutes, they are often repeated many times during a 24-hr period. Concern has been expressed that the physical effects of movement of commercial vessels could negatively affect aquatic biota (Rasmussen 1983; Nielsen, Sheehan, and Orth 1986). Temporary periods of turbulence or elevated suspended sediments can stress or kill pelagic fish eggs and larvae, bottom-dwelling invertebrates such as mussels, aquatic insects, worms, and crustaceans. Characteristics of large rivers, which include size, shape, bed and bank material grain size, and ambient velocity and suspended sediment concentrations, influence the nature and magnitude of traffic effects. Shallow, narrow, sinuous waterways will be more susceptible to physical forces than large waterways. Sediment is more likely to be resuspended from alluvial substrates than from cobble or bedrock. Sediment resuspension due to commercial traffic is usually most noticeable during low flow since the vessels are physically closer to the sediment. During higher flow, sediment resuspension due to traffic usually cannot be detected since the vessels are further away from the bottom and have less influence.

b. Chemical changes resulting in vessel passage are usually minor. Shifts in oxygen tension in the water column have been associated with tow-induced increases in suspended sediment (Lubinski et al. 1981). In a study by Environmental Science and Engineering (1981) it was concluded that the effects of tow passage on dissolved oxygen, specific conductance, pH, water temperature, and transmissivity adjacent to the navigation channel were nearly undetectable.

4-5. Point Source Pollution

a. General. Point sources of pollution in small boat basins can have an adverse effect on water quality in the basin and adjacent areas. These point sources of pollution may include dredging and disposal operations during harbor construction and maintenance. After construction is complete and the boat basin is in operation, point sources of pollution include storm and sanitary sewer utilities provided with the marina facilities, surface runoff, inadequate control of bilges, fueling facilities, and the dumping of garbage and trash in the harbor waters.

b. Dredging and dredged material disposal considerations. Nearly all harbor development projects will require some dredging operations. Factors influencing the amount of material that must be dredged are water depth, tidal range, size of vessels to be accommodated, distance to main navigation channels, and siltation rates. The environmental impacts associated with dredging are site-specific. Negative environmental impacts associated with dredge and disposal operations include short-term increases in turbidity, temporary reductions in oxygen content, burial of organisms, disruption of existing benthic communities, creation of stagnant water conditions, and resuspension of pollutants (Chmura and Ross 1978).

(1) During the design phase of the project, the environmental effects associated with dredging and dredged material disposal must be considered. Dredging and disposal should be accomplished using the most technically satisfactory, environmentally compatible, and economically feasible dredging and dredged material disposal procedures. The following activities are required to evaluate the environmental impacts of dredging and dredged material disposal in the design phase of the project.

Step	Information Source
(1) Analyze dredging location and quantities to be dredged.	Hydrographic surveys, project maps
(2) Determine the physical and chemical characteristics of the sediments.	Palermo, Montgomery, and Poindexter (1978)
(3) Determine whether or not there will be dredging of contaminated sediments.	Brannon (1978)
(4) Evaluate disposal alternatives.	EM 1110-2-5025
(5) Select the proper dredge plant for a given project.	EM 1110-2-5025
(6) Determine the levels of suspended solids from dredging and disposal operations.	Barnard (1978)
(7) Control the dredging operation to ensure environmental protection.	Barnard (1978)
(8) Identify pertinent social, environmental, and institutional factors.	EM 1110-2-1202
(9) Evaluate dredging and disposal impacts.	Wright (1978) Hirsch, DeSalvo, and Peddicord (1978)

(2) Limitations may be placed on dredging equipment to minimize the environmental impact of the dredging and disposal operation. If upland containment areas are small, the size of the dredge should be restricted to minimize stress on containment area dikes and provide adequate retention time for sedimentation to prevent excessive suspended solids in the weir effluent. Dredged material disposal may also be accomplished through open-water disposal and habitat development. The determination of a disposal alternative is very important in determining the environmental impact of dredging during marina construction and maintenance. Each disposal alternative involves its own set of unique considerations, and selection of a disposal alternative should be made based on both economic and environmental considerations. Detailed guidance for the selection of a disposal alternative is given in EM 1110-2-1202 and EM 1110-2-5025.

(3) The environmental effects commonly associated with dredging operations are increases in turbidity, resuspension of contaminated sediments, and decreases in DO levels. Research results indicate that the traditional fears of water quality degradation resulting from the resuspension of sediments during dredging are for the most part unfounded. More detailed information on the impacts of depressed DO levels is given in EM 1110-2-1202 and EM 1110-2-5025. Regardless of the type of dredging used, there are certain environments (e.g., spawning grounds, breeding areas, oyster and clam reefs, areas with poor circulation) and organisms (e.g., coral, sea grasses, benthos) that may be extremely sensitive to high levels of turbidity and/or burial by dredged material. It is, therefore, necessary to evaluate the potential impact of <u>each</u> proposed operation on a site-specific basis, taking into consideration the character of the dredged material, the type and size of dredge and its mode of operation, the mode of dredged material disposal, and the nature of the dredging and disposal environment. The seasonal cycles of biological activity should also be considered. Techniques to minimize environmental impacts must be employed during dredging activities. Sources of guidance on dredging activities are listed below.

Activity	Information Source
Selecting dredge	EM 1110-2-5025
Improving operational techniques	EM 1110-2-5025 Barnard (1978)
Properly using silt curtains	Barnard (1978)
Selecting appropriate pipeline discharge configurations	Barnard (1978)

(4) Most of the negative aspects of dredging operations can be eliminated or minimized. Dredging can be used to enhance the environmental quality of a water body in some cases by increasing flushing rates. Harbor basin design features that promote flushing are basin depths that are not deeper than connecting waters and gradually increase toward open water, basins with few vertical walls and gently rounded corners, and even bottom contours with no pockets or depressions (*Coastal Marinas Assessment Handbook* (USEPA 1985)). Increased turbidity and burial of organisms by siltation can be minimized by the proper use of hydraulic cutterhead dredges, filters, and silt screens as opposed to unscreened mechanical dredging. The work should be seasonably timed so as to have the least impact on certain life stages of the surrounding biota such as fish larvae or oyster spat. The duration and areal extent of these impacts are a direct function of material particle size and the flushing rate (Burrage 1988). Dredged channels should follow the course of existing channels, and slips for boats with deep drafts should be built in naturally deep water. In all cases, the harbor should not alter tidal circulation patterns, salinity regimes, or change related nutrient, aquatic life, and vegetative distribution patterns (National Marine Fisheries Service 1983). Dredged material should be viewed as a potentially reusable resource, and should include provisions for access to such resources. Permanent, upland disposal sites should be sought in preference to wetland disposal. Areas containing submerged vegetation and regularly flood-emergent vegetation should not be used.

c. Other point source discharges.

(1) Other direct sources of pollution in a small boat basin may occur during marina construction where natural vegetative cover is usually replaced with impermeable surfaces such as parking lots and buildings. These areas reduce the area available for storm-water percolation and increased storm-water runoff and pollutants. These pollutants associated with storm-water runoff may include sediments, pesticides, oil and road dirt, heavy metals, and nutrients. An immediate effect of runoff may be a temporary reduction in DO in the water. Lower DO concentrations can be lethal for most marine species. Boat basins may have low DO concentrations because of reduced water exchange rates and therefore, may be more susceptible to deoxygenating pollutants. Although heavy metals such as zinc, mercury, lead, and cadmium in their pure state usually are not particularly hazardous to marine life, these metals become quite toxic when combined with organic pollutants.

(2) Pesticides and herbicides used at marinas and their associated developments may also be washed into marina waters by runoff. These pollutants are not only harmful to marine life, but may also be accumulated by fish and shellfish and then consumed by humans. Also, petroleum products resulting from fuel spills, parking lots, and bilge draining may be toxic to marine life. Other potentially harmful runoff products include sediments, detergents, and excessive nutrients. These pollutants can result in reduced DO levels, can stimulate algal blooms and the growth of nuisance plants, and can eventually change the texture of bottom substrates and produce a zone of reduced productivity.

(3) Sanitary pollutants can enter marina waters directly discharged as untreated or macerated fecal waste from marine sanitation devices (MSDs) aboard boats or from improperly functioning or poorly located septic systems that allow sewage effluents to leach into marina waters. The most serious effect of discharging sanitary waste may be the potential for introducing disease-causing viruses and bacteria. This problem may occur if boat sewage is released in the vicinity of shellfish (clam or oyster) beds.

(4) Expected pollutant concentrations in marina basins and adjacent waters can be estimated by evaluating the type and quantity of pollutant loadings expected and the dilution and transfer of such pollutants by various flushing mechanisms. Various methods to assess the water quality impacts of marina-derived pollutants on the environment are discussed in detail in the *Coastal Marinas Assessment Handbook* (USEPA 1985).

d. Water quality mitigative measures.

(1) Water exchange does not always ensure good quality, especially in the back basins of a multibasin harbor. Sanitary-sewer and industrial waste discharges into harbor waters can be and must be eliminated in harbor planning. The flushing of sanitary facilities and dumping of pollutants must be controlled by ordinance and by provision of pumping stations and garbage and trash collection services at convenient locations. The disposal services should be capable of handling heavy weekend or seasonal usage. Trash containers should be convenient and secure to prevent litter from falling or blowing into the water. Collection facilities for boat holding tank wastes should be conveniently available at existing fueling stations. The production of boat sanitary wastes can be reduced by providing convenient shoreside restroom facilities of adequate size with hot showers and wash basins. Well-maintained restrooms will reduce boat toilet use. Other

measures to prevent sanitary waste discharges into marina waters are to require all boats with MSDs to be connected to a sanitary waste collection system when moored, sealing boat discharge outlets when they enter the marina, and banning live-aboards or requiring that these boats be permanently connected to a shoreside sanitary waste collection system.

(2) A storm-water management plan that diverts storm water away from the harbor is required to maintain water quality within the marina. If local surface water cannot be diverted from the harbor, extra care should be taken to keep harbor streets, parking lots, and other marginal surfaces reasonably clean. Also, fertilized landscapes should be prevented from overflowing when watered.

(3) Careful attention to boat maintenance and repair activities is also essential to maintaining harbor water quality. Paint spraying, sandblasting, engine repairs, boat washing, and similar maintenance activities should not take place in the harbor or near ramps or railways. These activities should preferably be performed on shore, either indoors or behind canvas screens. Also, the use of non-phosphate detergents can greatly reduce the amount of nutrients entering marina waters.

4-6. Aquatic Plant Control

a. Submersed aquatic plants can interfere with recreation, water supply, and navigation in small boat basins. Although moderate densities of vegetation improve habitat for fishes and waterfowl, nuisance levels usually have to be removed with an appropriate control measure. The following pertains to two methods of controlling submersed vegetation at small boat basins: mechanical harvesting and biological methods.

b. Mechanical harvesting of aquatic plants should be considered when areas are small, or when biological techniques are not appropriate. A mechanical harvester moves through the water, and cuts and processes the plants, which can be placed back in the water or loaded on a barge and shipped to shore for disposal. A computer model that simulates mechanical harvesting has been prepared that provides guidance on the effectiveness of various harvesting methods and the amount of time required for various harvesting strategies (Sabol 1983).

c. The white amur or grass carp (*Ctenopharyngodon idella*) has been used to control certain species of aquatic plants in lakes and ponds (Miller and Decell 1984, Miller and King 1984). Nonreproductive strains of the fish can be purchased and easily transported by truck. The fish do not compete with native fish for food or reproductive sites and are used successfully as control agents. These fish should only be used in small bodies of water where there are dense localized stands of submersed aquatic plants.

Appendix A
References

A-1. Required Publications

Note: References used in this EM are available on interlibrary loan from the Research Library, ATTN: CEWES-IM-MI-R, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

16 U.S.C. 1451, et seq.
Coastal Zone Management Act of 1972, as amended

16 U.S.C. 1221, et seq.
Estuary Protection Act

16 U.S.C. 1361-1407, et seq.
Marine Mammal Protection Act

40 CFR 230, 33 CFR 209.145 and Corps regulations
U.S. Environmental Protection Agency Guidelines for Specification of Disposal Sites for Dredged or Fill Material

40 CFR 220
Ocean Dumping Criteria

ER 200-2-2
Policy and Procedures for Implementing NEPA

EM 1110-1-400
Recreation Planning and Design Criteria

EM 1110-2-1202
Environmental Engineering for Deep-Draft Navigation Channels Projects

EM 1110-2-1204
Environmental Engineering for Coastal Shore Protection

EM 1110-2-1615
Hydraulic Design of Small Boat Harbors

EM 1110-2-5025
Dredging and Dredged Material Disposal

EM 1110-2-5026
Beneficial Uses of Dredged Material

Adamus et al. 1988
Adamus, P. R., Clairain, E. J., Morrow, M. E., Rozas, L. P., and Smith, R. D. 1988. "Wetland Evaluation Technique (WET) Volume I: Literature Review and Evaluation Rationale," Operational Draft, Technical Report EL-88, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Barnard 1978
Barnard, W. D. 1978. "Prediction and Control of Dredged Material Dispersion Around Dredging and Open-Water Pipeline Disposal Operations," Technical Report DS-78-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Boozer 1979
Boozer, A. C. 1979. "A Review of the Impacts of Coastal Marina Siting, Construction, and Activities as Related to Water Quality Considerations," Publication No. 001-79, South Carolina Department of Health and Environmental Control, Bureau of Field and Analytical Services, Division of Biological and Special Services, Columbia, SC.

Bowen 1966
Bowen, H. J. M. 1966. "Trace Elements In Biochemistry," Academic Press, New York.

Brannon 1978
Brannon, J. M. 1978. "Evaluation of Dredged Material Pollution Potential," Technical Report DS-78-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Brockwell 1987
Brockwell, S. M., Jr. 1987. "Site Analysis Factors For Small Craft Harbors," Marine Design and Engineering Conference, Technical Paper, Boston, MA.

Burrage 1988
Burrage, D. D. 1988. *The Mississippi Oyster Industry: Past, Present, and Future*, Proceedings of a Conference Held in Biloxi, MS, December 1-2, 1988. MASCP-88-048. Mississippi/Alabama Sea Grant Consortium, Ocean Springs, MS, pp 30-40.

Callaway 1981
Callaway, R. J. 1981. "Flushing Study of South Beach Marina, Oregon," *Journal of Waterway, Port, Coastal and Ocean Division*, Vol 107, No. WW2.

Camfield, Ray, and Eckert 1980
Camfield, F.E., Ray, R.E., and Eckert, J.W. 1980. "The Possible Impact of Vessel Wakes on Bank Erosion,"

Report No. CG-W-1-80, U.S. Department of Transportation, Washington, DC.

Cardwell and Koons 1981
Cardwell, R. D., and Koons, R. R. 1981. "Biological Considerations for the Siting and Design of Marina and Affiliated Structures in Puget Sound," Technical Report No. 60, State of Washington, Department of Fisheries.

Cardwell, Nece, and Richey 1980
Cardwell, R. D., Nece, R. E., and Richey, E. P. 1980. "Fish, Flushing, and Water Quality: Their Roles in Marina Design," *Coastal Zone 80, Proceedings of the Second Symposium on Coastal and Ocean Management*, American Society of Civil Engineers, Vol 1.

Chamberlain 1983
Chamberlain, Clinton J. 1983. "Marina Recommendations for Design, Construction, and Management, Volume 1," National Marine Manufacturers Asso., Chicago, IL.

Chmura and Ross 1978
Chmura, Gail L., and Ross, Neil W. 1978. "The Environmental Impacts of Marinas and Their Boats, a Literature Review with Management Considerations," University of Rhode Island Marine Memorandum 45, Narragansett, RI.

Christensen and Snyder 1978
Christensen, B. A., and Snyder, R. M. 1978. "Establishment of Residential Waterfront Property by Construction of Canal Systems in Coastal Wetlands, Problems and Solutions," *Coastal Zone 78*, pp 1301-1315.

Clark, Finely, and Gibson 1974
Clark, R. C., Jr., Finely, J. S., and Gibson, G. C. 1974. "Acute Effects of Outboard Motor Effluents on Two Marine Shellfish," *Environmental Science and Technology*, 8(12), pp 1009-1014.

Coastal and Ocean Engineering 1990
Coastal and Ocean Engineering. 1990. Volume 3: Harbors, Navigational Channels, Estuaries, and Environmental Effects, Gulf Publishing Co., Houston, TX.

de La Cruz 1983
de La Cruz, A. 1983. "Biological Impacts of Shoreline Structures: The Effects of Shapes, Siting, and Construction Materials," BMR Project No. NC-7-81, NOAAA Grant NA 81AA-D-CZ145.

Dunham and Finn 1974
Dunham, J. W., and Finn, A. A. 1974. "Small-Craft Harbors: Design, Construction, and Operation," Special Report No. 2, U.S. Army Engineer Coastal Engineering Research Laboratory, Available from: Technical Information Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Environmental Science and Engineering 1981
Environmental Science and Engineering. 1981. "Navigation Impact Study, Illinois River, Pool 26, August 1980, Mississippi River, Pool 9, October 1980, Phase III, Task 9," Prepared for: Illinois Natural History Survey, Grafton, IL.

Faurot, Landino, Reisenbichler, and Clarke 1989
Faurot, M. W., Landino, S. W., Reisenbichler, A. A., and Clarke, D. G. 1989. "Habitat Utilization By Juvenile Pink and Chum Salmon in Upper Resurrection Bay, Alaska," U.S. Army Engineer Waterways Experiment Station, Technical Report EL-89-17, Vicksburg, MS.

Hall, Dortch, and Bird 1988
Hall, R. W., Dortch, M. S., and Bird, S. L. 1988. "Summary of Corps of Engineers Methodologies for Modeling Water Quality of Estuaries and Coastal Embayments," Miscellaneous Paper EL-88-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hastings 1979
Hastings, R. W. 1979. "The Origin and Seasonality of the Fish Fauna on a New Jetty in the Northeastern Gulf of Mexico," Bulletin of the Florida State Museum, Vol 24, No. 1.

Hirsch, DiSalvo, and Peddicord 1978
Hirsch, N. D., DiSalvo, L. H., and Peddicord, R. 1978. "Effects of Dredging and Disposal on Aquatic Organisms," Technical Report DS-78-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Johnson and De Wit 1978
Johnson, G. F., and De Wit, L. A. 1978. "Ecological Effects of an Artificial Island, Rincon Island, Punta Gorda, California," Miscellaneous Report 78-3, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, VA.

Kivekas and Sarela 1985
Kivekas, L. K., and Sarela, K. 1985. "Boating and Marina Building in Finland," *Proceedings of the*

26th Congress of Permanent Internation Association of Navigation Congresses, Section II, Subject 5, Brussels, Belgium.

Kuzminski, Jackivicz, and Bancroft 1973
Kuzminski, L. N., Jackivicz, T. P., Jr., and Bancroft, D. A. 1973. "Identification and Fate of Organic Compounds Emitted from Outboard Motor Subsurface Exhausts," Progess Report for the Division of Water Pollution Control, Massachusetts Water Resources Commission, Report No. Env. E. 31-73-2, Boston, MA.

LaSalle 1988
LaSalle, M. W. 1988. "Seasonal Restrictions on Dredging: Workshop Summary," Environmental Effects of Dredging, Technical Note EEDP-08-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lubinski, Seagle, Bhowmik, Adams, Sexton, Beohnerkempe, Allgire, Davis, and Fitzpatrick 1981.
Lubinski, K. S., Seagle, H. H., Bhowmik, N. G., Adams, J. R., Sexton, M. A., Beohnerkempe, J., Allgire, R. L., Davis, D. K., and Fitzpatrick, W. 1981. "Information Summary of the Physical, Chemical, and Biological Effects of Navigation," Upper Mississippi River Basin Commission, Grafton, IL.

Manny, Schloesser, Brown, and French 1985
Manny, B. A., Schloesser, D. W., Brown, C. L., and French, J. R. III. 1985. "Ecological Effects of Rubble-Mound Breakwater Construction and Channel Dredging at West Harbor, Ohio (Western Lake Erie)," Technical Report EL-85-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p 30.

Mathis and Kevern 1975
Mathis, B. J., and Kevern, N. R. 1975. "Distribution of Mercury, Cadmium, Lead, and Thallium in a Eutrophic Lake," *Hydrobiologia*, 46(203), pp 207-222.

May and McKinney 1981
May, T. W., and McKinney, G. L. 1981. "Cadmium, Lead, Mercury, Arsenic, and Selenium Concentrations in Freshwater Fish," *Pesticide Monitoring Journal*, 15(1), pp 14-38.

McBee and Breham 1979
McBee, J. T., and Breham, W. T. 1979. "Macrobenthos of Simmons Bayou and an Adjoining Residential Canal," *Gulf Research Reports*, Vol 6, No. 3, pp 211-216.

Miller 1988
Miller, A. C. 1988. "The Value of Wing Dams for Feshwater Mussels," Environmental Effects of Dredging Technical Note EEDP-08-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller and Decell 1984
Miller, A. C., and Decell, J. L. 1984. "Use of the White Amur for Aquatic Plant Management," Instruction Report A-84-1 of the Aquatic Plant Control Research Program, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller and King 1984
Miller, A. C., and King, R. H. 1984. "Large-Scale Operations Management Test of Use of the White Amur for Control of Problem Aquatic Plants, Report 5, Synthesis Report," Technical Report A-78-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Moore and Walton 1984
Moore, C.I., and Walton, R. 1984. "DYNTRAN/TRAN User's Manual," Camp, Dresser, and McKee, Inc., Annandale, VA.

Morris 1981
Morris, F. W., IV. 1981. "Residential Canals and Canal Networks: Design and Evaluation," Report No. 43, Florida Sea Grant College, prepared in cooperation with the Board of Regents of the State of Florida University System and the Board of Commissioners of Palm Beach County, University of Florida, Gainesville, FL.

National Marine Fisheries Services 1983
National Marine Fisheries Services. 1983. *Guidelines for Proposed Wetland Alterations in the Southeast Region of the U.S.*

National Oceanic and Atmospheric Administration 1976
National Oceanic and Atmospheric Administration. 1976. "Coastal Facility Guidelines," National Oceanic and Atmospheric Administration, Office of Coastal Zone Management.

National Oceanic and Atmospheric Administration 1976
National Oceanic and Atmospheric Administration. 1976. "Coastal Facility Guidelines: A Methodology for Development with Environmental Case Studies On Marinas and

Power Plants," U.S. Dept. of Commerce, NOAA Working Paper.

National Water Safety Congress 1988
National Water Safety Congress. 1988. "Guide for the Safe Operation and Maintenance of Marinas," NWSC B-13, Warrenton, VA.

Nece, Richey, Rhee, and Smith 1979
Nece, C. W., Richey, E. P., Rhee, J., and Smith, H. N. 1979. "Effects of Planform Geometry on Tidal Flushing and Mixing in Marinas," Technical Report No. 62, Department of Civil Engineering, College of Engineering, University of Washington, Seattle, WA.

Nielsen, Sheehan, and Orth 1986
Nielsen, L. A., Sheehan, R. J., and Orth, D. J. 1986. "Impacts of Navigation on Riverine Fish Production in the United States," *Polskie Archiwum Hydrobiologii*, Vol 34, pp 277-294.

Palermo, Montgomery, and Poindexter 1978
Palermo, M. R., Montgomery, R. L., and Poindexter, M. 1978. "Guidelines for Designing, Operating, and Managing Dredged Material Containment Areas," Technical Report DS-78-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Payne 1989
Payne, B. S. 1989. "The Value of Gravel Disposal Mounds in River Side Channels for Freshwater Mussels," Environmental Effects of Dredging Technical Note EEDP-07-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Pullen and Thayer 1989
Pullen, E. J., and Thayer, G. W. 1989. "An Evaluation of Habitat Development and Vegetative Shoreline Stabilization," *Beach Preservation Technology '89*, Florida Shore and Beach Preservation Association, Inc., pp 87-100.

Rasmussen 1983
Rasmussen, J. L. 1983. "A Summary of Known Navigation Effects and a Priority List of Data Gaps for the Biological Effects of Navigation on the Upper Mississippi River," prepared for the U.S. Army Engineer District, Rock Island, by U.S. Fish and Wildlife Service, Contract No. NCR-LO-83-C9, Rock Island, IL, p 96.

Sabol 1983
Sabol, B. M. 1983. "Simulated Mechanical Control of Aquatic Plants in Buffalo Lake, Wisconsin," Aquatic Plant Control Research Program Miscellaneous Paper A-83-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sanders and Killgore 1989
Sanders, L., and Killgore, K. J. 1989. "Seasonal Restrictions on Dredging Operations in Freshwater Systems," Environmental Effects of Dredging Technical Note EEDP-01-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sembler, Lee, Dearstyne, Dunham, and Kvammen 1969
Sembler, E. L., Lee, C. E., Dearstyne, S. C., Dunham, J. W., and Kvammen, K. R. 1969. "Small Craft Harbors," American Society of Civil Engineers, New York.

Tetra Tech 1988
Tetra Tech. 1988. "Rive St. Johns Phase II Canal System Water Quality Model Study," Tetra Tech Report TC-3668-04.

U.S. Army Corps of Engineers 1980
U.S. Army Corps of Engineers. 1980. "Oregon Inlet Larval Transport Sensitivity Study," U.S. Army Engineer District, Wilmington, p 29.

U.S. Army Corps of Engineers 1983
U.S. Army Corps of Engineers. 1983. "A Decade of Ecological Studies Following Construction of Honokohau Small Boat Harbor," U.S. Army Engineer District, Honolulu, p 88.

U.S. Army Corps of Engineers 1989
U.S. Army Corps of Engineers. 1989. "Lawsen Bay, Alaska, Small Boat Harbor," U.S. Army Engineer District, Alaska, p 153 and Appendix.

USEPA 1975
USEPA. 1975. "Finger-Fill Canal Studies, Florida and North Carolina," Report EPA 904/9-76-017, Surveillance and Analysis Division, U.S. Environmental Protection Agency, Athens, GA.

USEPA 1985
USEPA. 1985. "Coastal Marinas Assessment Handbook," Report EPA 904/6-85-132, NEPA Compliance Section, U.S. Environmental Protection Agency, Atlanta, GA.

U.S. Fish and Wildlife Service 1980
U.S. Fish and Wildlife Service. 1980. "Biological Impacts of Minor Shoreline Structures on the Coastal

Environment: State of the Art Review" U.S. Dept of the Interior, FWS/OBS -77-51, Vol 1, p 156.

Van Dolah, Knott, and Calder 1984
Van Dolah, R. F., Knott, D. M., and Calder, D. R. 1984. "Ecological Effects of Rubble Weir Jetty Construction at Murrells Inlet, South Carolina; Vol I, Colonization and Community Development on New Jetties," Technical Report EL-84-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p 69.

Walton 1983
Walton, R. 1983. "Computer Modeling of Hydrodynamics and Solute Transport in Canals and Marinas, Literature Review and Guidelines for Future Development," Miscellaneous Paper EL-83-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Whitten, Rosene, and Hedgpeth 1950
Whitten, H. L., Rosene, H. F., and Hedgpeth, J. W. 1950. "The Invertebrate Fauna of Texas Coast Jetties; A Preliminary Survey," Publications of the Institute of Marine Science, University of Texas, Vol 1, No. 2, pp 53-87.

Wood and Davis 1978
Wood, W. L., and Davis, S. E. 1978. "Effectiveness and Environmental Impact of Beach Nourishment at the Indiana Dunes National Seashore," Great Lakes Coastal Research Laboratory, Department of Geosciences, Purdue University, West Lafayette, IN.

Wright 1978
Wright, T. D. 1978. "Aquatic Dredged Material Disposal Impacts," Technical Report DS-78-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

A-2. Related Publications

40 CFR 1500-1508
Council on Environmental Quality Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act of 1969

16 U.S.C. 460-1(12), et seq.
Federal Water Project Recreation Act, as amended

16 U.S.C. 469, et seq.
Archaeological and Historic Preservation Act, as amended

16 U.S.C. 470a, et seq.
National Historic Preservation Act, as amended

16 U.S.C. 661, et seq.
Fish and Wildlife Coordination Act, as amended

16 U.S.C. 1001, et seq.
Watershed Protection and Flood Prevention Act

16 U.S.C. 1271 et seq.
Wild and Scenic Rivers Act, as amended

16 U.S.C. 1531, et seq.
Endangered Species Act, as amended

16 U.S.C. 4601-4601-11, et seq.
Land and Water Conservation Fund Act, as amended

33 U.S.C. 1344, et seq.
Clean Water Act, as amended

33 U.S.C. 1401, et seq.
Marine Protection, Research, and Sanctuaries Act of 1972

33 U.S.C. 401, et seq.
Rivers and Harbors Act

42 U.S.C. 4321, et seq.
National Environmental Policy Act of 1969, as amended

42 U.S.C. 7401, et seq.
Clean Air Act, as amended

E.O. 11988
Floodplain Management

E.O. 11990
Protection of Wetlands

E.O. 12114
Environmental Effects Abroad of Major Federal Actions

ER 1110-2-400
Design of Recreation Sites, Areas, and Facilities

ER 1110-2-1404
Deep-Draft Navigation Project Design

ER 1130-2-400
Management of Natural Resources and Outdoor Recreation at Civil Works Water Resource Projects

ER 1130-2-406
Shoreline Management at Civil Works Projects

ER 1165-2-28
Corps of Engineers Participation in Improvements for Environmental Quality

EP 1165-2-1
Digest of Water Resources Policies

EM 1110-2-1612
Ice Engineering

EM 1110-2-1613
Hydraulic Design of Deep-Draft Navigation Projects

Miscellaneous Paper D-76-17
Ecological Evaluation of Proposed Discharge of Dredged or Fill Material into Navigable Waters: Interim Guidance for Implementation of Section 404(b)(1) of Public Law 92-500 (Federal Water Pollution Control Act Amendments of 1972)," U.S. Army Engineer Waterways Experiment Station (WES).

Chaney 1961
Chaney, C. A. 1961. "Marinas, Recommendations for Design, Construction and Maintenance," National Association of Engine and Boat Manufacturers, Inc., New York.

Engel 1984
Engel, S. 1984. "Restructuring Littoral Zones: A Different Approach to an Old Problem," *Lake and Reservoir Management, Proceedings of the North American Lake Management Society*, EPA 440/5-84-001, Washington, DC, pp 463-466.

Engel 1985
Engel, S. 1985. "Aquatic Community Interactions of Submerged Macrophytes," Technical Bulletin Number 156, Department of Natural Resources, Madison, WI.

Engel 1987
Engel, S. 1987. "The Impact of Submersed Macrophytes on Largemouth Bass and Bluegills," *Lake Reservoir Management*, 3:227-234.

Hynes 1974
Hynes, H. B. N. 1974. "The Ecology of Running Water," University of Toronto Press, Toronto, Ontario, Canada.

LaSalle, Clarke, Homziak, Lunz, and Fredette 1979
LaSalle, M. W., Clarke, D. G., Homziak, J., Lunz, J. D., and Fredette, T. J. 1979. "A Framework for Addressing the Need for Seasonal Restrictions on Dredging and Disposal Operations," U.S. Army Engineer Waterways Experiment Station, Technical Report D-89- , p 110, Vicksburg, MS.

Merezhko 1973
Merezhko, A. I. 1973. "Role of Higher Aquatic Plants in the Self-Purification of Lakes and Rivers," *Hydrobiological Journal*, Vol 9, pp 103-109.

Merezhko, Ryabov, and Tsytsarin 1977
Merezhko, A. I., Ryabov, A. K., and Tsytsarin, G. V. 1977. "The Effects of Macrophytes on Hydrochemistry of the Shallows of the Kremenchug Reservoir," *Hydrobiological Journal*, Vol 13, pp 97-100.

Mitsch and Gosselink 1986
Mitsch, W. J., and Gosselink, J. G. 1986. *Wetlands*, Van Nostrand Reinhold Co., New York.

Payne, Bingham, and Miller 1989
Payne, B. S., Bingham, C. R., and Miller, A. C. 1989. "Life History and Production of Dominant Larval Insects on Stone Dikes in the Lower Mississippi River," Report 18 of the Lower Mississippi River Environmental Program, U.S. Army Engineer Division, Lower Mississippi Valley, Vicksburg, MS.

USAESAM 1983
USAESAM. 1983. "Public Notice: Joint Guidelines on Criteria and Concerns for the Siting, Design, and Evaluation of Freshwater Dead-End Canals," U.S. Army Engineer District, Mobile, AL.

U.S. Army Corps of Engineers 1980
U.S. Army Corps of Engineers. 1980. "Publication Index and Retrieval System," Technical Report DS-78-23, Dredged Material Research Program, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Westerdahl and Getsinger 1988a
Westerdahl, H. E., and Getsinger, K. D. 1988a. "Volume I: Aquatic Plant Identification and Herbicide Use Guide," Technical Report A-88-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Westerdahl and Getsinger 1988b
Westerdahl, H. E., and Getsinger, K. D. 1988a. "Volume II: Aquatic Plant Identification and Herbicide Use Guide," Technical Report A-88-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wiley, Gordon, Waite, and Powless 1984
Wiley, M. J., Gordon, R. W., Waite, S. W., and Powless, T. 1984. "The Relationships Between Aquatic Macrophytes and Sport Fish Production in Illinois Ponds: a Simple Model," *North American Journal of Fisheries Management*, Vol 4, pp 111-119.

Appendix B
Statutes and Regulations

B-1. Statutes and Regulations

Compliance with Federal statutes, executive guidelines, and Corps regulations often requires studies of existing environmental conditions and projections of conditions likely to occur in the future with and without various activities. Major environmental statutes and regulations that are currently applicable to Corps small boat harbors navigation projects are listed in Appendix A. Five statutes that have a major impact on the planning and operation of small boat harbors are: The National Environmental Policy Act; The Clean Water Act; The Marine Protection, Research, and Sanctuaries Act; The Coastal Zone Management Act and Estuary Protection Act; and The Marine Mammal Protection Act.

a. National Environmental Policy Act (NEPA). NEPA is the Federal statute that established national policy for the protection of the environment and set goals to be achieved along with the means to carry out these goals. The NEPA requires preparation of an environmental impact statement (EIS) for certain Federal actions affecting the quality of the human environment. The Corps normally prepares an EIS for legislation, feasibility reports, operations and maintenance activities, regulatory permits, and real estate management and disposal actions. Environmental assessments are prepared for all other Corps actions that may not have a significant impact on the environment except for certain minor actions that are categorically excluded from NEPA review. Emergency activities do not require the preparation of an EIS (refer to ER 200-2-2 for more detailed guidance).

b. Clean Water Act. Section 404 of the Clean Water Act governs the discharge of dredged or fill material into U.S. waters. The Corps regulates these activities by granting Federal permits, and is itself regulated by Section 404 through provisions for coordination with the states and the U.S. Environmental Protection Agency (EPA). Evaluation of the effects of dredged or fill material discharges must be done in accordance with EPA guidelines (40 CFR 230).

c. Marine Protection, Research and Sanctuaries Act - Section 103. Section 103 of the Marine Protection, Research, and Sanctuaries Act authorizes the Corps to issue permits for the transportation of dredged material for dumping in ocean waters. Evaluation must be done in accordance with EPA criteria found in 40 CFR 220. Note that in relation to Sections 404 and 103, Corps Regulation 209.145 also applies.

d. Coastal Zone Management Act and Estuary Protection Act. The Coastal Zone Management Act promotes coordination in the management, beneficial use, protection, and development of the coastal zone (16 USC 1451-1464; PL 92-583 as amended). Development, management, and protection are undertaken through long-term plans implemented by the states and local coastal zone management programs. The Estuary Protection Act is specifically for protection, conservation, and restoration of resources in estuaries (16 USC 1221-1226; PL 90-454). Information from state coastal management programs and local planning agencies can assist in determining what environmental resources exist in the project area and potential impacts of Repair, Evaluation, Maintenance, and Rehabilitation Research Program activities on the coastal zone and estuaries. Compliance with the Estuary Protection Act requires that studies funded by Congress, e.g., Corps planning or construction projects, consider the effect of the project on estuaries and their resources. The Secretary of the Interior, through the Fish and Wildlife Service (FWS), reviews plans and makes recommendations. This review is incorporated into authorization reports to Congress.

e. Marine Mammal Protection Act. The Marine Mammal Protection Act was enacted to protect diminishing populations of certain species of marine mammals (16 USC 1361-1407; PL 92-522 as amended). The Act establishes the Marine Mammal Commission to oversee protection activities. The FWS and NMFS administer the Act (16 USC 1379), but primary administrative responsibilities are delegated to states with marine mammal conservation and protection programs.