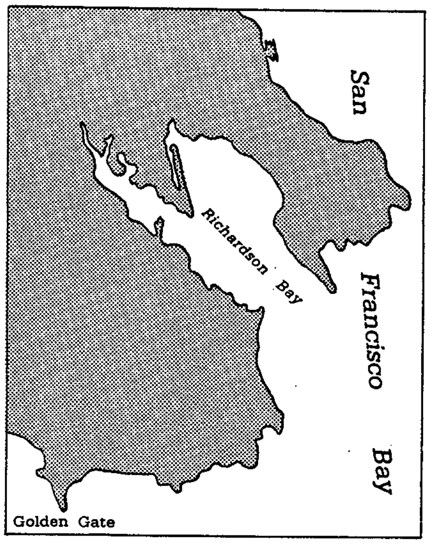
THE SEDIMENT HYDRAULICS OF RICHARDSON BAY



by

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Prepared for the

Richardson Bay Special Area Plan Study

September 1983

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PREPARING A RICHARDSON BAY SPECIAL AREA PLAN

Richardson Bay, part of the San Francisco Bay system, is situated in southern Marin County. Five local governments have jurisdiction over the water body and its shoreline: Marin County and the cities of Sausalito, Mill Valley, Tiburon, and Belvedere, as does the San Francisco Bay Conservation and Development Commission. Richardson Bay is experiencing an increased demand for pleasure boat marina and houseboat marina use. In addition, many vessels used as residences are anchoring out in the Bay. Recognizing the need for a unified set of planning policies and regulatory controls by the local governments and the Bay Commission for Richardson Bay and its shoreline, the agencies agreed that they should jointly prepare a Richardson Bay Special Area Plan which would recommend such unified policies and regulatory controls for adoption by each agency. This report, prepared by Philip B. Williams and Associates, Consultants in Hydrology, is the third in a series of planning background reports that will be used by the Richardson Bay Steering Committee, composed of representatives of each of the local governments and the Bay Commission, in preparing a recommended Richardson Bay Special Area Plan.

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1. Introduction and Summary

Because of its sheltered location, its size, and its proximity to Sausalito and San Francisco, Richardson Bay is especially suitable as an anchorage and harbor for recreational and small commercial vessels. It has had a long history of maritime uses since the first settlement of the Bay Area, being used as a watering station, for careening, whaling, fishing, shipbuilding. Since the second world war however, recreational boating has grown to become the major maritime use of the Bay. There are now approximately 1900 recreational marina berths, primarily located in five marinas that have been constructed by dredging the shallows along the Sausalito waterfront. In addition there are approximately 550 houseboats, again mainly located in four houseboat marinas located along the waterfront.

At present there are proposals to add an additional 1000 recreational marina berths of which 260 already have construction permit approval.

Until the last few years, the long term maintenance dredging requirements for these marinas and their navigation channels have not been a major consideration for permit granting authorities. This is partly because most marinas have been constructed in the last 30 years, and only now is the need for long term maintenance dredging becoming apparent. However, with the dramatic increase in dredging costs in the last decade and the increasing concern over the adverse environmental effects of dredge spoil disposal, BCDC, Marin County, the City of Sausalito and other agencies are interested in evaluating the overall maintenance dredging requirements for Richardson Bay both now and with future development. Furthermore, tied in with the maintenance dredging question is the need to identify the present and future navigation problems and opportunities caused by the concentration of the boating activity in close proximity to existing and proposed marinas, particularly along the Sausalito waterfront.

The purpose of this investigation is to provide the following information to Marin County and BCDC for use in developing the Richardson Bay Special Area Plan.

1. A description of the natural physical processes affecting siltation, dredging and navigation.
2. Identification of siltation rates and maintenance dredging requirements.
3. Identification of navigation problems and opportunities.
4. Recommendations for a navigation and maintenance dredging plan that minimizes costs and adverse environmental affects.

This report finds that sedimentation rates for marinas in Richardson Bay are markedly lower than marinas elsewhere in San Francisco Bay and average about 0.2 ft/year. Sedimentation rates in artificial navigation channels average about 0.5 ft/year. However, these sedimentation rates will ultimately require a long term average annual maintenance dredging of about 60,000 cubic yards per year in order to maintain existing boat use of the marinas and channels; and 76,000 cubic yards per year if all presently proposed marinas are constructed. Dredging costs for marinas in Richardson Bay are comparatively low because of their proximity to the Alcatraz dredge spoil disposal site.

Navigation problems are occurring in Richardson Bay, largely due to the high concentration of boating activity and marinas along the Sausalito waterfront and unregulated anchorages in the navigation lanes.

In order to improve the situation a navigation and maintenance dredging plan is proposed in this report. This plan, which incorporates the Sausalito Fairways Plan prepared by the Sausalito Fairways and Anchorages Committee provides for dredging the Marinship launching basin area and a dredged navigation channel extending to the Kappas Marina. It also provides for unmaintained but marked navigation channels extending to the Cove Marina and the Shelter Bay Marina.

2. The Natural Setting

A) Geomorphology

Prior to the melting of the ice caps at the end of the last ice age, Richardson Bay was a 'V' shaped valley draining east to what was then the Sacramento River that discharged through the Golden Gate. With the rapid rise in sea level due to the melting icecaps, salt water invaded San Francisco Bay 10 to 11,000 years ago (Atwater et al, 1977).

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* Throughout this report Mean Lower Low Water(MLLW)datum is used. Minus refers to below MLLW, plus to above MLLW.

By about 6000 years ago, when the rate of sea level rise declined from about 20mm per year to about 2 mm per year, most of what is now Richardson Bay would have been inundated.

Over time, the submerged stream valley has been filled with estuarine sediments that are discharged into San Francisco Bay, mainly by the Sacramento River, and then redistributed by tidal currents and wind action. These sediments are primarily flocculated clays and silts, carried into Richardson Bay by the tide and settle out at slack water. Sedimentation rates can be very high and may well have kept pace with the rate of sea level rise 6000 to 10,000 years ago. Up to about 150 ft of estuarine sediments have now accumulated in the submerged valley, (Connor 1982). This has formed a broad, flat, gently sloping bottom extending from the head to the mouth of the Bay between Sausalito Point and Belvedere Island. In its natural state, this shallow, underwater "plain" was remarkably uniform in depth and sediment type (Means 1965). It is interrupted only by a single bedrock outcropping at Cone Rock.

At the mouth of the Bay the slope steepens and drops to the deep water of Raccoon Straits. As Raccoon Straits is approached, the sediments change in character from silty clays to silt, and finally sands.

Fig. 1 shows Richardson Bay in 1915 before the area was extensively modified by man's activities.

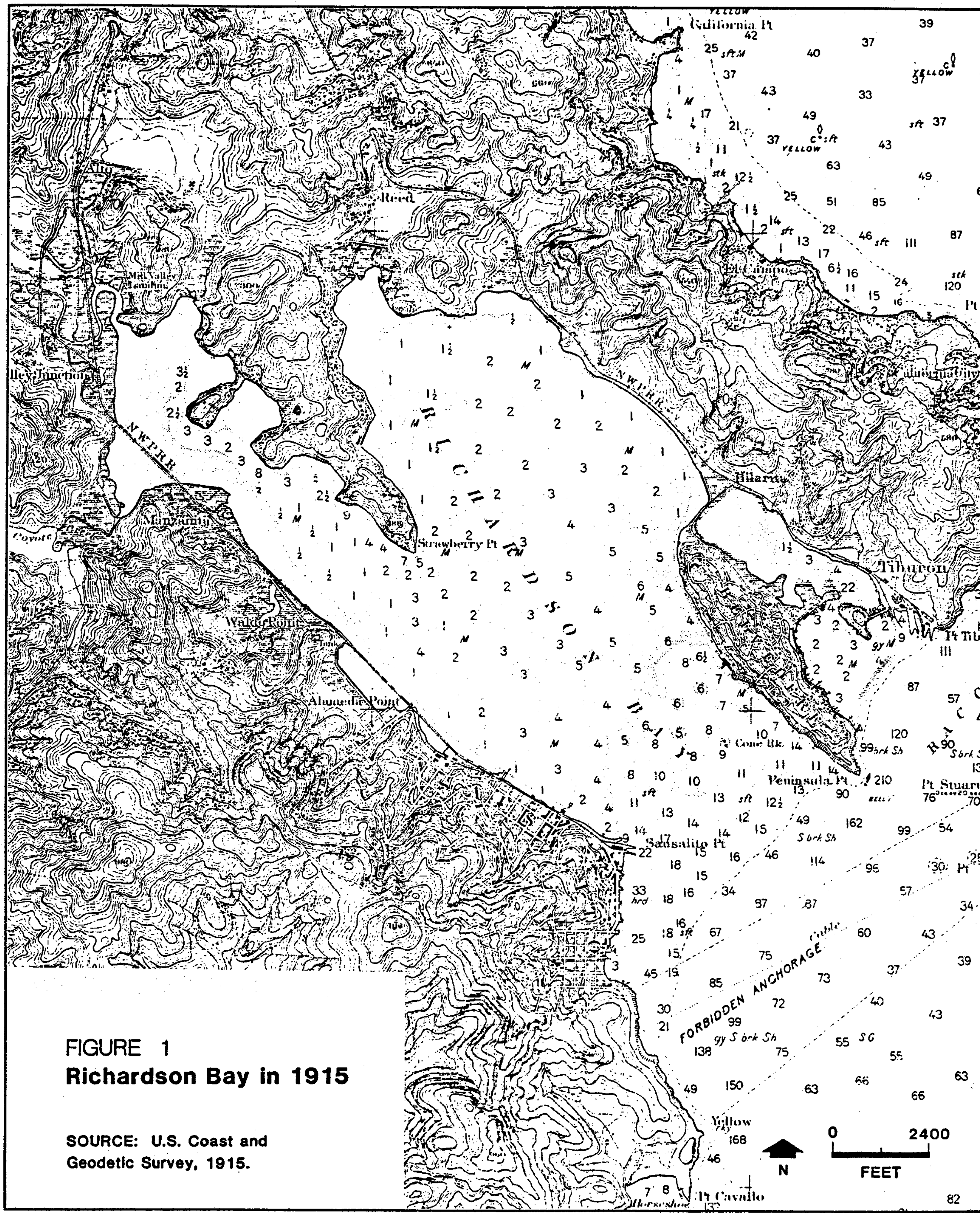

FIGURE 1
Richardson Bay in 1915

SOURCE: U.S. Coast and Geodetic Survey, 1915.

RICHARDSON BAY
SPECIAL AREA PLAN

As the sea level rose, it advanced up the valleys of tributary drainages. During winter storms, these tributary drainages discharged sediment eroded from the surrounding watershed into the Bay. However, the total amount of sediment discharged into the Bay from the natural watershed would have been very small compared to estuarine sedimentation.

At the upper end of the Bay and in inlets sheltered from wave action, the rate of estuarine sediment accumulation was highest. The deposited sediment would have provided suitable elevations for the establishment of marsh vegetation. In the upper part of the Bay salt marshes developed and extended, forming pickleweed marsh plains with elevations at about mean higher water (+4.7' MLLW). At the mouths of creeks draining into Richardson Bay small deltas of coarse sediment formed. Over time these raised the marsh plain, converting salt marsh to meadowland.

B) Erosion and Sedimentation

In its natural state, the water depths in Richardson Bay were determined by the net long term sedimentation rate and sea level rise. The net long termsedimentation rate is determined by the balance between sedimentation and erosive forces.

The sediment particles in Richardson Bay are extremely small (in the range of 6 to 20 microns) (Means, 1965) and form cohesive electrochemical bonds with each other, forming "flocs." Sedimentation occurs when the settling velocity of these flocs of individual particles is greater than upward movement of sediment due to the turbulence of flowing water. Turbulence is related to the shear stress of the water moving over the bed. There is thus a particular shear stress below which sediment will start to deposit. This shear stress is referred to as the critical shear stress for deposition and is roughly 0.8 dynes/cm^2 for typical San Francisco Bay sediments (Krone 1962). For water depths of about 5 to 10 ft whenever velocities drop below about 0.7 ft/sec the shear stress is lower than the critical shear stress and deposition occurs. Sedimentation, therefore, occurs throughout the Bay during slack water at times when there is little wave action and water velocities are low.

The erosion of deposited cohesive sediment is complicated by the electrochemical bonds that form between the freshly deposited flocs and the bed. As the bed compacts over time, these bonds become stronger. This means, for example, that as the flow velocity increases during the ebb after high tide slack water, first the deposition rate decreases, and then ceases after the deposition velocity is exceeded. However, erosion does not occur until the shear stress exceeds a critical value sufficiently high to break the electrochemical bonds. This value is about 4 dynes/cm^2 (Krone 1969). For Bay muds this occurs at velocities of about 2 ft/sec for typical depths of about 5 to 10 ft. As the velocity increases further the erosion rate increases, but the erosion rate is eventually limited as the upper layers of freshly deposited sediment are stripped away, exposing more consolidated sediments below. These are sediments that have been compacted by the weight of sediment above and which have had time to form strong electrochemical bonds with each other. Generally, consolidated sediments require extremely high velocities to erode them and such high velocities do not usually occur naturally due to tidal or wave action. With compaction the shear strength of bay muds increases by up to two orders of magnitude (Krone and Ariuthuria 1977).

The bathymetry of a bay like Richardson Bay, therefore, evolves as a cyclical process of sedimentation and scouring of freshly deposited sediments. In areas that are sheltered from wave action, or do not have strong tidal currents, there is a net accumulation of sediment year by year. If this accumulation exceeds the rate of sea level rise, which in San Francisco Bay is presently approximately 2 mm/year (Atwater et al 1977), then net shoaling eventually converts open water into mudflats and marshes.

In Richardson Bay the primary natural erosive mechanism is wave action. Strong summer sea breezes from the west-northwest and winter storms from the southeast can generate sufficient wave action to scour and resuspend sediments deposited on the bottom during periods of calm. However, there is an equilibrium established between wave action and sedimentation rates. As an area gets shallower the waves are able to erode the sediments easier by exerting greater shear stresses on the deposited sediments. Thus the bottom depths in the wide shallow expanse of Richardson Bay represent a balance between erosive wave action and sedimentation. The result of this balance can be seen in the current hydrographic map (Fig 2) where bottom depths are slightly

deeper on the eastern side of the bay, which is directly exposed to wave action from west-northwest winds.

Another important natural erosive mechanism separate from wave activity is the action of tidal currents. Because of the deeper depths on the eastern side of the bay, tidal current velocities are higher, causing scouring and deeper channels to develop in a few places where tidal flows are concentrated. Further upstream in the shallow areas protected from wave action tidal currents are the major erosive mechanism, and tidal current velocities maintain distinct slough channels that meander through mudflats and salt marshes.

Bioturbation, the movement of sediment by benthic organisms such as molluscs and worms, can also be a very important factor in resuspending sediments. These organisms not only loosen consolidated sediments, making them easier to erode by wave action and tidal currents, but also directly resuspend sediment during feeding. No data is available for Richardson Bay; however, in the South San Francisco Bay worms resuspend sediment particles about 15 times before they are finally deposited permanently on the bed, moving them several kilometres (Hammond 1983).

C. The Hydraulics of Richardson Bay

The movement of water in Richardson Bay is dictated primarily by the ebb and flow of the tides and the bottom topography. It is also affected by wind action, freshwater inflows, storm surges and very infrequently by tsunamis or "tidal waves."

Because of its location close to the Golden Gate, the tides in Richardson Bay are very similar to those measured at the Presidio. Even at the head of the Bay there appears to be very little attenuation or amplification of the tidal cycle. The mean diurnal tidal range (the difference between mean higher high water and mean lower low water) is 5.5 ft (see Table 1).

Due to its location Richardson Bay is somewhat isolated from the general circulation system of San Francisco Bay. For most of the year, during a typical flood tide, Pacific ocean water enters the Golden Gate and flows in a strong current through Raccoon Straits to the northern San Francisco Bay. It is mainly this water with low suspended sediment concentrations that enters Richardson Bay during the flood tide. When the tide turns, more turbid San Francisco Bay water flows back out of Raccoon Straits and through the Golden Gate. There appears to be little mixing of these strong ebb flows with the slow-moving Richardson Bay water across what is often a visible "shear" line. Only for a short period near slack water before the ebb does the turbid water from the northern part of San Francisco Bay circulate into Richardson Bay. Belvedere Cove is also in the same semi-isolated position relative to the rest of San Francisco Bay.

This partially isolated circulation system is very important in considering sedimentation processes. Pacific Ocean water has

Table 1

TIDAL CHARACTERISTICS OF RICHARDSON BAY[1]

		NGVD Datum ft	MLLW Datum ft
100-yr high tide		5.6[2]	8.4[2]
MHHW	mean higher high water	2.6	5.5
MHW	mean high water	1.9	4.7
MTL	mean tide level	0	2.8
MLW	mean low water	-1.9	1.0
MLLW	mean lower low water	-2.8	0

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[1] Sausalito and Vicinity tide gage No. 85.

[2] National Oceanic and Atmospheric Administration

low suspended sediment concentrations (less than about 10 mg/litre), whereas water from the northern part of San Francisco Bay can have high concentrations (up to 100 mg/litre (Conomos et al, 1979). Most of the tidal water entering Richardson Bay, therefore, has a low suspended sediment concentration.

The sediment concentrations of the flood tides can be expected to increase during periods of high freshwater runoff from the Sacramento River in the winter and spring. In this case turbid water will mix with Pacific Ocean water in the Golden Gate and be carried back into Richardson Bay in the flood tide. In addition, the lower salinity, more turbid water will mix with the higher salinities in Richardson Bay. Salinity variation in Richardson Bay is probably similar to that of the Golden Gate, with an average of 32 ppt total dissolved solids in the summer and 28 ppt in the winter (Conomos et al 1979).

Wind action also affects circulation in Richardson Bay. During the summer the west-northwest breezes would tend to set up a clockwise circulation current in the Bay.

D) Historic Changes in Richardson Bay

Richardson Bay probably retained its natural character until about the 1850s, when with the rapid growth of San Francisco, extensive clear-cut logging occurred on the slopes of Mt. Tamalpais. While it is uncertain as to how an extensive an area was affected, the result was increased erosion and sedimentation in the upper part of the Bay. Whereas originally lumber schooners could sail up the slough channel of Arroyo Corte Madera del Presidio at high tide to Mill Valley, this rapidly became unnavigable, as can be seen by comparing the 1858 and 1895 hydrographic surveys. In addition, salt marsh areas in the upper part of the Bay have been converted to upland meadows by sedimentation.

As the area became settled, filling and diking of the surrounding marshes took place. The construction of the two branches of the Northwest Pacific Railroad (NWPRR) along the Tiburon and Sausalito shores also cut off tidal action to these salt marshes (See Fig 1). Now only approximtely 100 acres of saltmarsh remain out of about 700 acres existing a century ago.

Sedimentation and filling of marshes in the upper part of the Bay reduced the tidal prism (the volume of water between high and low tides), and, hence, the scouring action of the tides; consequently, the slough channels in this area silted up.

The major changes in Richardson Bay's morphology have taken place in the last 50 years. The 1948 hydrographic survey (Figure 3) shows somewhat shallower depths in the main part of the Bay, about a foot less than the 1895 survey. This shoaling pattern is in common with similar surveys in other parts of Northern San Francisco Bay and was probably due to increased suspended sediment concentrations throughout the Bay system resulting from the after-effects of hydraulic mining in the Sierra. This sediment "wave" was first deposited in Suisun Bay about 100 years

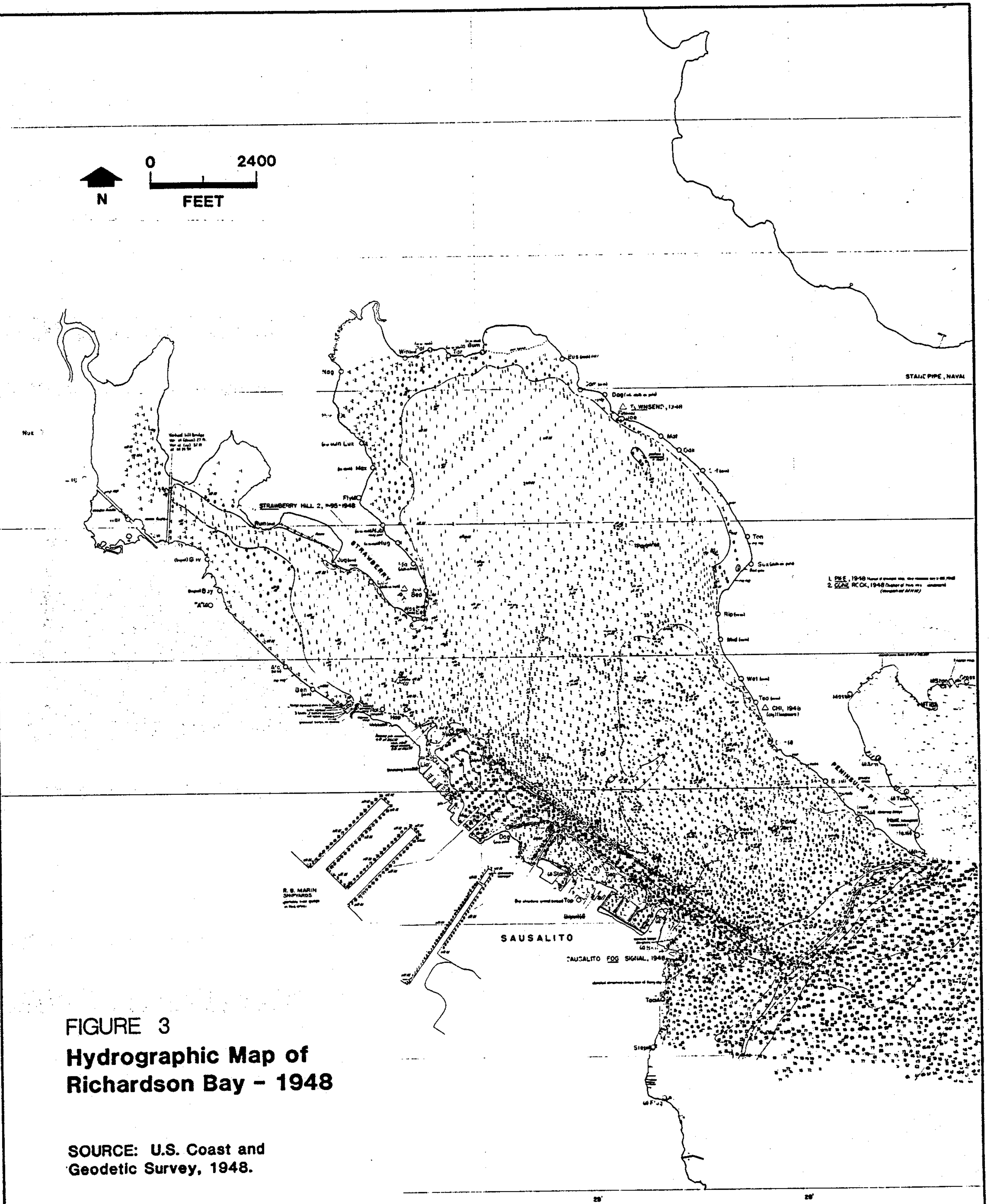

FIGURE 3
Hydrographic Map of Richardson Bay - 1948

SOURCE: U.S. Coast and Geodetic Survey, 1948.

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ago, and over the years migrated seaward, reaching Northern San Francisco Bay about 40 years ago (Krone 1979). The most recent hydrographic survey (1978), Fig 2, indicates that the "wave" has now passed through the system and water depths in the main part of Richardson Bay are deeper and similar to those occurring 80 years before. (In Belvedere Cove however, water depths are now about 2 ft deeper than they were 80 years ago).

During the second world war, the Marinship liberty ship construction yard was built in Sausalito. This required extensive dredging for both a deep launching basin and a 20 ft-deep approach channel to deep water. Since the war, a portion of the yard has been used by the Corps of Engineers as a base for its dredges. Although most of the launching basin has been abandoned, a portion of it and the approach channel are now dredged to about 30 ft by the Corps. The existence of this artificial, deep channel has a significant effect on circulation in the Bay, as it concentrates the ebb and flow currents along the Sausalito shore, rather than along the Belvedere shore as probably occurred naturally.

In addition to the Corps of Engineers' Sausalito Channel, other significant changes have been made to Richardson Bay. The dredging of the Salt Works Canal and Strawberry Lagoon created Strawberry Spit in the 1950s. Although the Salt Works canal has largely silted in, it still concentrates strong tidal currents along the shore of Strawberry Spit.

In the upper part of Richardson Bay the slough channels of Arroyo Corte Madera del Presidio and Coyote Creek were straightened for flood control purposes and adjacent marshes filled. Filling in the 1950s and early 1960s also took place at Shelter Bay, along the Highway 101 and on the marshes around the fringe of the Bay. With the cessation of filling in 1965, several remnant marshes were preserved that had been disconnected from their natural tidal drainage by fill. These marshes, such as the Goodman Marsh and the Mill Valley Middle School Marsh, now have limited tidal circulation.

In the last 30 years, major changes have occurred along the Sausalito waterfront with the construction of marinas, piers and breakwaters, and the placement of fill for parking and development. This has provided additional protection from wave action along the shoreline west of Sausalito Point, resulting in increased shoaling. Of particular importance is the placement of Kappas Spit in the early '60s. This spit comprising partly fill and partly sunken barges extends three quarters of the way across the half-mile wide Bay at Strawberry Point. It, therefore, shelters the mudflat areas from wave action on either side and effects circulation in the upper part of the Bay, both by constricting the Bay and by concentrating tidal flows adjacent to Strawberry Point.

Recent urban development in the surrounding watershed has increased the amount of sediment delivered directly into Richardson Bay by local streams.

E) <u>Future changes in Richardson Bay</u>

Over the next 100 years, several changes will occur that affect sedimentation and tidal circulation in Richardson Bay.

The construction of dams on Sierra Rivers have reduced high flood flows, diverted a substantial portion of the Delta outflow, and trapped sediments in their reservoirs. This will reduce the amount of sediment delivered to San Francisco Bay. Between 1960 and 2020, the total sediment delivery is expected to be reduced by 50% (Krone 1979). In addition, the reduction of high flood flows will reduce the mixing of turbid freshwater into Richardson Bay. These effects would tend to reduce shoaling rates.

At the same time, however, the urbanization and modification of the surrounding watershed will continue to provide higher levels of sediment to the Bay than occurred naturally. This would tend to increase shoaling rates. The net effect on average suspended sediment concentration is uncertain.

Sea level will continue to rise. The rate of rise over the last 6000 years has been about 2mm/year. At this rate sedimentation will probably keep pace with sea level rise, maintaining fairly closely the existing bathymetry of the Bay. Some scientists argue that this rate will accelerate over the next 100 years to an average of about 10 mm/year due to the rise in atmospheric CO_2 levels and consequent warming of the global climate (Hoffman 1983). This would cause dramatic long term changes in the morphology of Richardson Bay, flooding low lying areas in Sausalito, Mill Valley and Tiburon.)

3. Sedimentation Rates

A. Shoaling Rates in Marinas.

In its natural state, sedimentation rates in Richardson Bay are high; however, they are largely balanced by high erosion rates due to wave action, and only the slow rise in sea level causes an accretion of sediments while maintaining an equilibrium water depth in most areas of the Bay. Wherever erosion rates are artificially reduced by sheltering against wave action, sedimentation can occur unimpeded. Therefore, the historic long term accumulation of sediment in existing marinas can give a good indication of average annual sedimentation rates that may be used in projecting future maintenance dredging requirements.

The accumulation of sediment can be measured in two ways: 1) by maintenance dredging records, and 2) by periodic hydrographic surveys.

Table 2 is a summary of historic major dredging activities carried out in Richardson Bay. It can be seen that only in two locations--for the Sausalito Yacht Harbor and the Corps of Engineers channel--has there been maintenance dredging. Unfortunately, the actual volume and area dredged for the Sausalito Yacht Harbor is not well documented for either of these locations.

Table 3 summarizes observed shoaling rates at various locations in Richardson Bay, based on the hydrographic surveys listed in Table 4. It can be seen that typical marina shoaling

Table 2

SUMMARY OF HISTORIC MAJOR DREDGING ACTIVITIES, RICHARDSON BAY

Location	Date	Depth	Volume	Remarks
Marinship turning basin	1942	-13	?	Initial
Marinship channel	1942	-20	?	"
Sausalito Yacht Harbor	1948	-10	?	"
Salt Works Channel	~1955	-8	?	"
Clipper #2	~1955	-8	?	"
Mill Valley small craft Harbor (Pickleweed inlet)	1968	-8	660,000	" Actually dredged to -7
Clipper #3	1957	-8	?	"
Shelter Bay Apts	~1957	-6	?	"
Clipper #4	1967	-8	66,000	"
Kappas	~1964	-8	?	"
Cove Apts	1963	-5	?	"
Sausalito Y.C.	1972	-8	9500	Maintenance
Pelican	~1978	?	9500	Initial
Sausalito Y. H.	1978	-8	?	Maintenance
Deak	1978	-4?	10,500	Initial
Sausalito Y.H.	1983	-8	?	Maintenance
Corps of Eng. Channel	1946-83	-28	?	Maintenance

Table 3

SUMMARY OF OBSERVED SHOALING RATES

Location	Initial Date	Initial Depth	Final Date	Final Depth	Time Period	Depth of Shoaling	Shoaling Rate ft/yr	Average Depth	Remarks
S.Y.H.	1948	-9	1971	-6	23	3	0.13	-7.5	
Clipper #1	1951	-17	1978	-9	27	8	0.30	-13.0	
Marinship	1948	-13	1978	-8	30	5	0.17	-10.5	
Launching	1978	-8	1982	-7	4	1	0.25	-7.5	
Basin	1948	-13	1982	-7	34	6	0.18	-10.0	
Clipper #2	1955	-8*	1978	-3	23	5	0.22	-5.5	
Clipper #4	1967	-8*	1978	-3	11	5	0.45	-5.5	
Kappas	1964	-8*	1968	-7	4	1	0.25	-7.5	
	1968	-7	1982	-4	14	3	0.21	-5.5	
	1964	-8*	1982	-4	18	4	0.22	-6	
Shelter Bay	~1963	-6*	1978	-4	15	2	0.13	-5	
Mill Valley Sm. Craft H.	1968	-7	1978	-4	10	13	0.30	-5.5	Influenced by tidal currents
The Cove	1963	-5*	1978	-1	15	4	0.27	-3	
Beckwith Channel	~1964	-8*	1978	-1	14	7	0.50	-4.5	Channel
Cove channel	~1964	-6*	1978	-1	14	5	0.36	-3.5	Channel
Salt Works Canal	~1965	-8*	1978	-2	13	6	0.46	-5	Channel

*Design depth

Table 4

Index of hydrographic surveys used in determing shoal rates

No.	Date	Description	Source	Scale	Resolution, ft
	1895-6	Richardsons Bay	USC & GS	10,000	+ or - 0.25
1	1948	Richardson Bay H-7704	NOS	10,000	+ or - 0.25
2	10/31/51	Corps channel, before dredging	COE	2,400	+ or - 0.25
3	11/28/51	Corps channel, after dredging	"	"	+ or - 0.1
4	9/63	Saucelito Canal	"	"	+ or - 0.1
5	11/9/67	Corps channel before dredging	"	"	+ or - 0.1
6	1/22/68	Corps channel after dredging	"	"	+ or - 0.1
7	4,5,6/68	Saucelito Canal	"	"	+ or - 0.1
8	7/23/71	Sausalito Yacht Harbor	Towill, Inc.	2,400	+ or - 0.5
9	1978	Richardson Bay H-9793	NOS	10,000	+ or - 0.25
10	9/23/81	Operations Base	C of E	2,400	+ or - 0.1
11	1/11/82	" "	"	"	"
12	6/30 and 7/1/82	" "	"	"	"
13	10/8/82	Saucelito Canal	Towill, Inc.	"	"

rates for sheltered basins as opposed to navigation channels are about 0.2 ft/year. The shoaling rate of 0.45 ft/year for Clipper #4 is probably higher than normal, because it is only partially enclosed and tidal flows pass through it into the Waldo Point area and upper Richardson Bay. Therefore, in every tidal cycle a greater volume of sediment-laden water passes through it than for the more enclosed basins.

Siltation rates in enclosed and sheltered basins remain fairly constant until the bottom approaches the low tide level. Then the rate of shoaling decreases and the erosive power of wave action increases. A further decline in the shoaling rate occurs when the bottom rises above the low tide level and the tidal prism is reduced. Figure 4 shows the change in siltation rates in an enclosed basin with a tidal range of 5.5 ft, that has deep water siltation rates of 0.2 ft/year equivalent to a mean annual suspended sediment concentration of 120 mg/litre. A "mean annual suspended sediment concentration" is merely an index useful in characterizing shoaling rates (see discussion in technical appendix). The actual suspended sediment concentration would always vary considerably according to many factors such as tidal stage, wind conditions and salinity.

In the range of depths encountered in most marinas, -8 ft MLLW to -4 ft MLLW, the rate of siltation does not vary significantly and is about 0.2 ft/year.

The siltation rates shown in Fig. 4 ignore the effect of side slopes around the edge of the marina basin. Sediment

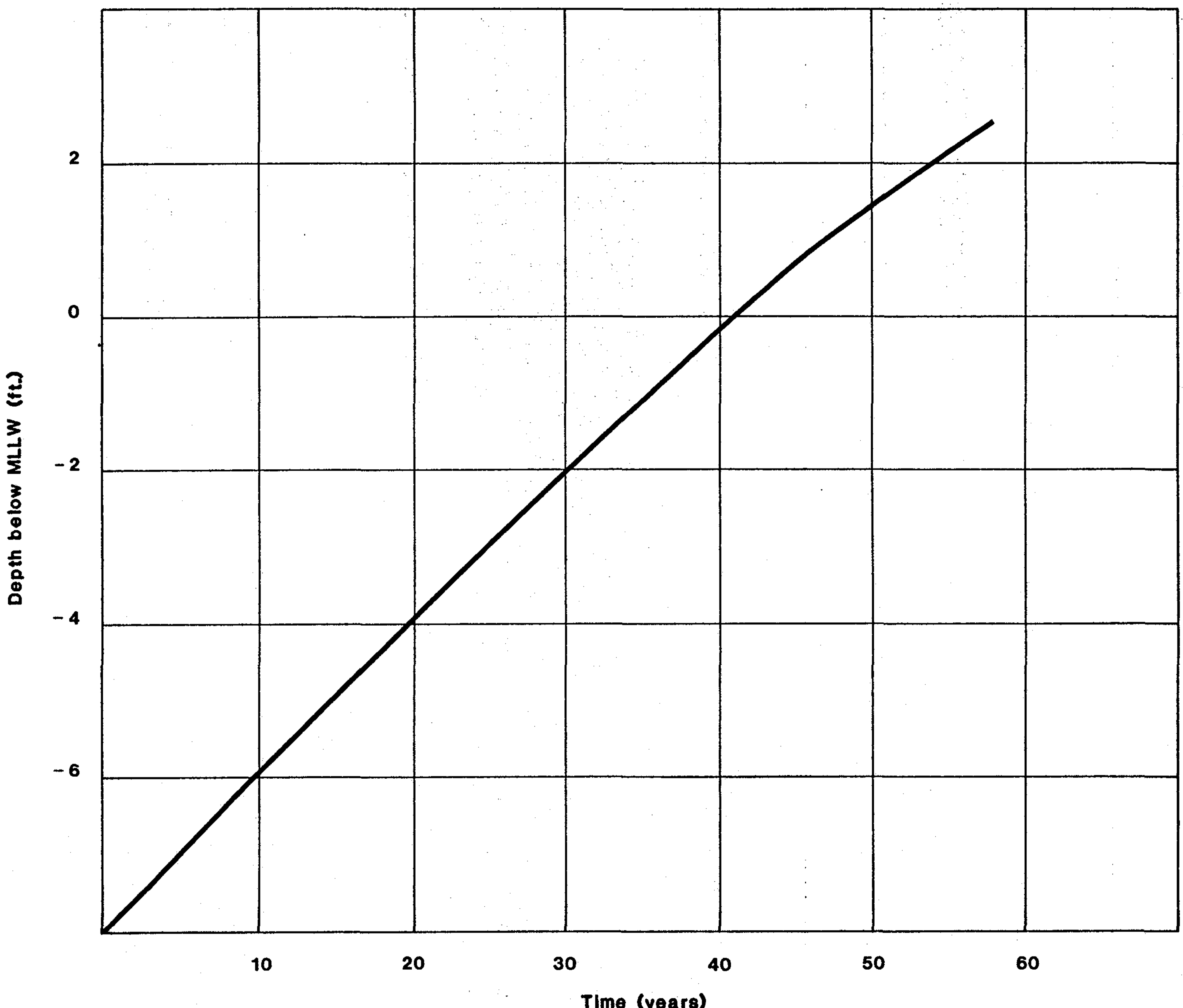

FIGURE 4

Change in Shoaling Rate with Depth for Closed Basins

Average Annual Suspended Sediment Concentration: 120 MG/L

accumulating on side slopes tends to flow or slump into the basin. Side slopes can, thus, act to enlarge the "catchment" area of the marina basin, increasing shoaling rates where the basin is deepest. For most marina basins in Richardson Bay the sideslope effect would be small.

B. Shoaling rates in houseboat marinas.

The houseboat marinas at Waldo Point and Gates 6 and 6 1/2 have not been dredged and are located on the undisturbed shallow bottom of Richardson Bay. Based on the 1948 hydrographic survey , the equilibrium depth in these areas, where erosion by wave action is balanced by siltation, appears to have been about +1 ft MLLW in the Gate 6 and 6 1/2 marinas and about -1 ft MLLW in the Waldo Point area.

The construction of the Kappas Spit and the Clipper #4 Marina in the 1960s provided sheltering from wave action. In the most sheltered portions of the houseboat marinas, the eastern end of Gate 6, the shoreward end of Gate 6 1/2, the shoreward part of the Yellow Ferry Harbor, and the shoreward part of the Waldo Point area, about one foot of shoaling has occurred in the last 20 years, making a net shoaling rate of roughly 0.05 ft/year. It should be noted that such low shoaling rates are difficult to identify on hydrographic maps whose accuracy is within plus or minus 0.5 ft.

Once the intertidal mudflats are raised above an elevation of about +2 ft, they are susceptible to colonization by spartina or cordgrass. When this occurs, sedimentation rates will increase, both because wave action is reduced and due to the "stirring" effect of the plant stems in increasing flocculation. Cordgrass is already colonizing the landward portions of the houseboat marinas at Gate 6 1/2 and in the Waldo Point area.

However, no net measurable siltation appears to have occurred in the more exposed areas of the Waldo Point, Gate 6, and Gate 6 1/2 areas, as shown by the 1978 hydrographic survey. Shallow water areas elsewhere in Richardson Bay, not sheltered against wave action, have eroded by about 1 ft in the last 30 years, indicating that the normal equilibrium depth has lowered by about 1 ft except in these sheltered marinas.

C. Shoaling Rates in Channels.

Shoaling in channels is increased by sediment slumping from adjacent side slopes. For example, a 50-ft wide channel with 4:1 side slopes dredged to -8' MLLW through shallows at -2 MLLW has an effective "catchment" width of 96', and might be expected to double the normal sedimentation rate because of the sideslope effect. In addition, shoaling is further increased by high suspended sediment concentrations in flows conveyed by the channels from adjacent shallows. On the other hand, increased erosion can occur in channels due to increased tidal scouring.

In the Salt Works canal there appears to have been a net shoaling of about 5 ft since the last dredging in 1965. The channel is now only about 1 ft deeper than the adjacent shallows.

However, this channel now conveys ebb and flow tidal currents and the existing channel is probably self maintaining.

The natural deepwater channel in the upper part of Richardson Bay also appears to be in equilibrium. Detailed surveys in 1963 and 1968 showed no significant change in the period immediately after substantial filling of marshland in Mill Valley.

The Corps of Engineers channel is frequently dredged to depths of between 27 to 30 ft. Unfortunately siltation rates cannot be estimated directly from hydrographic maps, because the dredgers based in Sausalito will often remove sediment from the channel on their way out to another site in San Francisco Bay. The Corps of Engineers has reported an annual average dredging of 25,000 cubic yards (Corps of Engineers 1975), which is equivalent to a sedimentation rate of about 0.5 ft/year. This rate is similar to those occurring in other channels in Richardson Bay and is higher than the sedimentation rate in sheltered marinas, probably because of the sideslope effect and because of low tidal current velocities in the channel.

Measuring sedimentation rates in channels by comparing hydrographic surveys can be complicated by the erosive effects of boats' propellers. In some instances, for example, along the Salt Works Canal, this has been used from time to time as a method of dredging.

Although scouring by tidal currents appears to be weak in comparison to wave action in most of Richardson Bay, in the upper part of the Bay in Mill Valley localized scouring could be increased if the tidal prism were increased by restoring tidal circulation to adjacent marshes.

D. Shoaling due to sedimentation from surrounding watershed.

The average amount of sediment delivered to the Bay from the surrounding watershed is small compared to the amount carried in by the tides. Unfortunately, no detailed sediment budget has been prepared for Richardson Bay. However, it is very roughly estimated that an average of about 25,000 tons per year is delivered to the Bay from the surrounding watershed, as compared to about 250,000 tons carried in by the flood tide. Only a small fraction of these amounts is actually deposited in the Bay. The rest is flushed out by the ebb tide.

During a very high runoff year, such as 1982, the amount of eroded material delivered to Richardson Bay can be up to many times that of an average year, due in large part to mudflows and landslides. When this happens, appreciable sedimentation occurs. For example, verbal reports indicate about 3 inches of shoaling took place immediately after the January 4, 1982 storm in some areas along the Sausalito waterfront. In exposed areas of the Richardson Bay wave action will resuspend these freshly deposited fine silts and clays redistributing them throughout the Bay system. In sheltered marinas the sediments remain. Because of its dependence on these major storms, siltation from the upstream watershed varies greatly from year to year. (It should also be noted that siltation from suspended sediment carried in by the tides varies from year to year, but not to the same extent as that brought in by local runoff. Suspended sediment concentrations in San Francisco Bay in the winter and spring of 1983 were considerably higher than normal, due to high Sierra runoff).

Siltation from the surrounding watershed may also cause extensive local shoaling as sand and gravel bars at the mouths of creeks and storm drains. Such coarse sediments usually cannot be moved by the weak wave and tidal forces acting on them. Although their total volume is not large, several of these sand bars have formed where storm drains discharge into marinas and can cause local navigation problems.

E. Impact of marina development on sedimentation rates

The primary impact of marina development on sedimentation rates is to increase net siltation by the reduction of wave-induced erosion. Breakwaters, piers, floating docks, and moored vessels reduce wave energy and shelter the areas downwind. This not only increases net siltation within the marina but also in adjacent protected areas. Thus, the high concentration of marinas, moorings and filings along the Sausalito waterfront has resulted in the shoaling of areas the formerly were 5 to 6 ft MLLW to -3 to -4 ft.

Another phenomena that increases sedimentation locally is the stirring effect of eddies created by pilings, mooring lines, boats and other obstructions. The increased stirring increases flocculation of clay particles resulting in a more rapid rate of settling.

In some instances breakwaters or spits can obstruct natural tidal currents reducing water circulation upstream. When this happens scour holes and shoals often occur at the end of the breakwater. The Kappas Spit is a typical example of this process.

4. Existing Navigation Requirements

A. Depths.

Although there is quite a variation in the size and type of boat using Richardson Bay, the typical vessel can be characterized as a yacht with auxiliary motor, 30 to 40 ft in length and with a draft to the bottom of the keel of about 5 ft. In addition, there are motor cabin cruisers typically drawing 2 to 3 ft and commercial fishing vessels with drafts to 10 ft. Houseboat drafts vary depending on type of construction, but 3 to 4 ft of water is generally required for floatation. The Corps of Engineers channel is maintained to accommodate the 22 ft draft of the dredge "Biddle" (Corps of Engineers, 1975).

The tidal characteristics of Richardson Bay are given in Table 1, and the frequency distribution of tidal elevations are shown in Figure 5. This shows that, for a boat drawing 5 ft, a depth of -7 ft MLLW is required for floatation 100% of the time, allowing for inaccuracies in dredging of about 1 ft. This means that basins and channels need to be maintained at -8 ft MLLW.

Although most of the marinas were originally dredged to -8 ft MLLW, they have been allowed to silt in over the years to about -4 ft MLLW. This does not appear to have significantly impaired the marina operation, because, as can be seen from Figure 5, a -4 ft MLLW depth allows flotation 83% of the time for a 5 ft draft boat. Some parts of the Kappas and Clipper marinas apparently now have depths of -3 ft MLLW.

The Salt Works Canal has silted to about -3 ft MLLW, limiting the navigation of 5 ft draft boats berthed in Strawberry Lagoon to 70% of the time.

In the Cove and Shelter Bay Marinas shoaling limits the depth to about -1 ft MLLW. However, mainly cabin cruisers are kept in these harbors. A 2 ft draft vessel would, therefore, be able to navigate approximately 83% of the time.

For houseboats the only "navigation' requirement would be the ability to move the boat for relocation or repair. This could be done at high tide. Therefore, provided depths are no shallower than about + 2 ft MLLW for a 4 ft draft houseboat, there would be little difficulty moving it in a spring tide.

B. Channels, Fairways and Anchorages.

At present there is only one actively maintained navigation channel in Richardson Bay. This is the Corps of Engineers channel to its operations base and turning basin (see

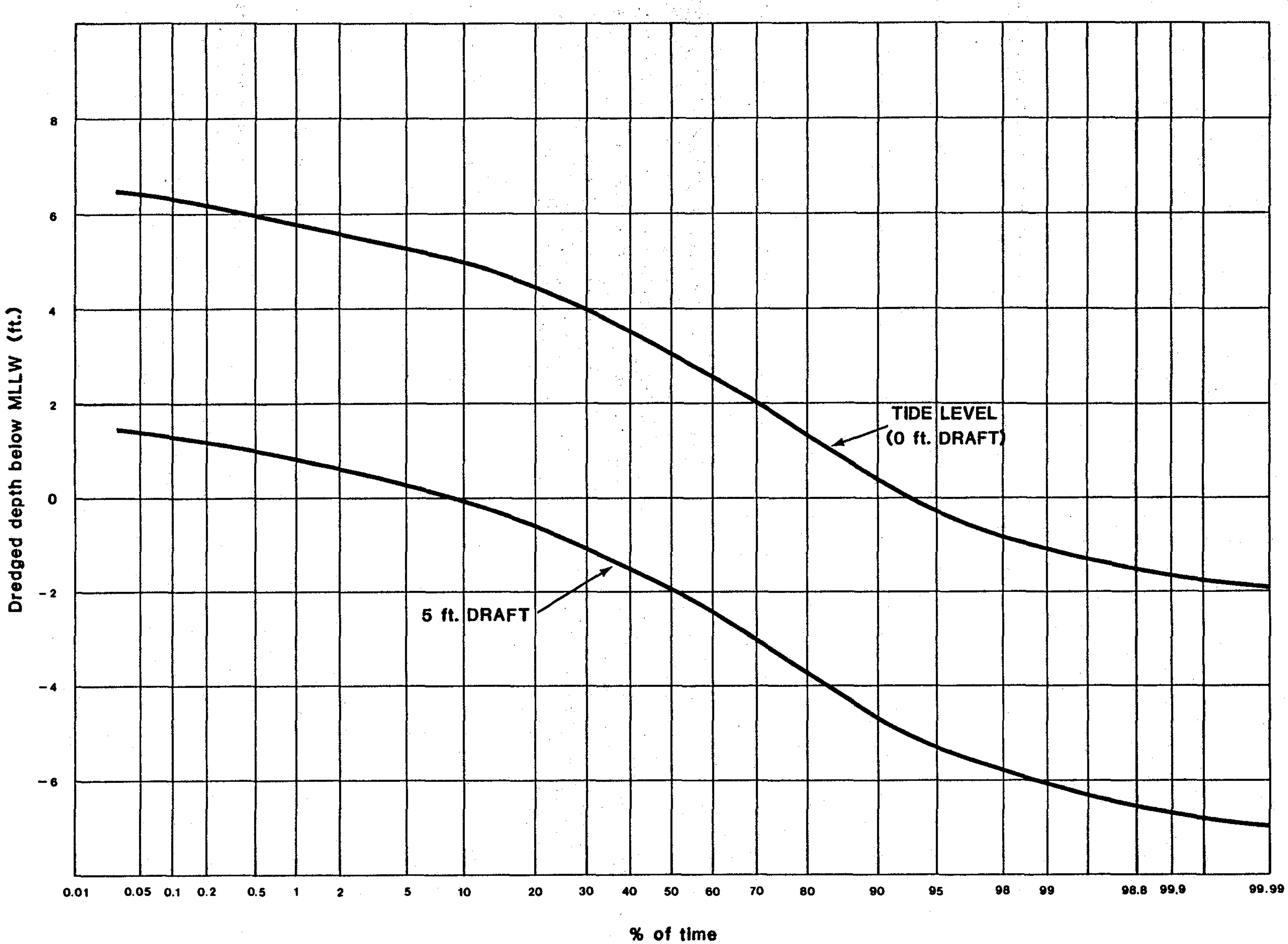

FIGURE 5
Navigibility of Channels

Figure 6). The channel is about one mile long, 300 ft wide and officially maintained to -23 ft MLLW (Corps of Engineers 1975). However, it is actually dredged deeper to between -27 and -30 ft MLLW. Unlike other Corps of Engineers' maintained channels this is not a congressionally authorized project, but is considered to be part of the maintenance expense of the operations base. The channel is denoted by navigation marks placed along its northern side and maintained by the U.S. Coast Guard.

The maintenance of the Corps channel in an area that would naturally have depths of about -4 ft MLLW to -5 ft MLLW is very important for the operation of all the marinas along the Sausalito shoreline. Boats using the marinas to the east of the operations yard can sail directly into the channel and out into San Francisco Bay. The Marinship Yacht Harbor, the Clipper #2, #3 and #4 marinas to the west have direct access to the channel via the deeper water of the former Marinship launching basin, formerly dredged to -13 ft MLLW, but now silted in to -7 ft MLLW. Boats in the Kappas marina have to navigate the shallows before reaching the former launching basin. If they use the deeper natural channel along Strawberry Point, the limiting depth is about -4 ft MLLW. Further upstream, boats in the Shelter Bay Marina are limited by depths of about -1 ft MLLW in the natural channel.

An extension of The Corps channel to a proposed harbor in Mill Valley, refered to as the Saucelito Canal, was authorized by Congress in 1970, but was never dredged because of its high

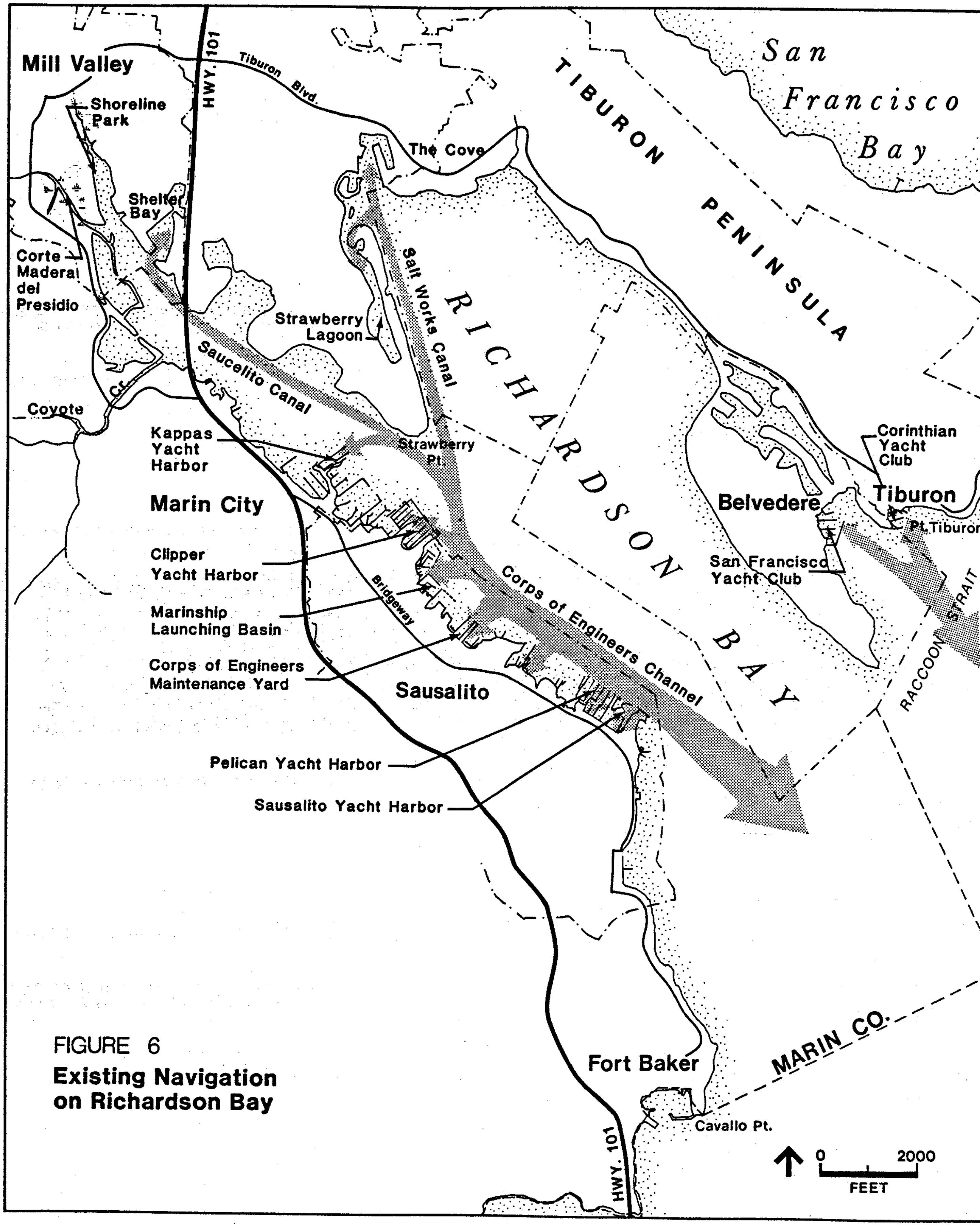

FIGURE 6
Existing Navigation on Richardson Bay

cost, and is now considered an "inactive" Corps of Engineers project. This channel was to have been maintained to -8 ft MLLW (see Figure 7).

The Salt Works canal is neither authorized by the Corps nor maintained; however channel markers have been placed to assist in navigation and to help minimize intrusion on the seal haulout on Strawberry Spit. The channel is approximately 80 ft wide and was originally dredged to -8 ft MLLW primarily to provide fill material for Strawberry Spit.

The limiting water depth for boats travelling to Strawberry Lagoon is the -3 ft MLLW of the Salt Works canal. For boats travelling to the Cove Marina the limiting depth is about -1 ft MLLW in the channel outside.

At present sailboats travelling from upper Richardson Bay typically motor to the launching basin area before raising their sails. The large size of the launching basin, its sheltered location, and its orientation to the prevailing west-northwest winds is ideal for this purpose. Also, the only fuel dock in Sausalito is located in the launching basin area.

The entire Richardson Bay is designated by the U.S. Coast Guard as a "special anchorage," which means that small craft need not display anchorage lights except in "designated channels." The only presently designated channel is the Corps of Engineers channel. Within Richardson Bay there are no other designated

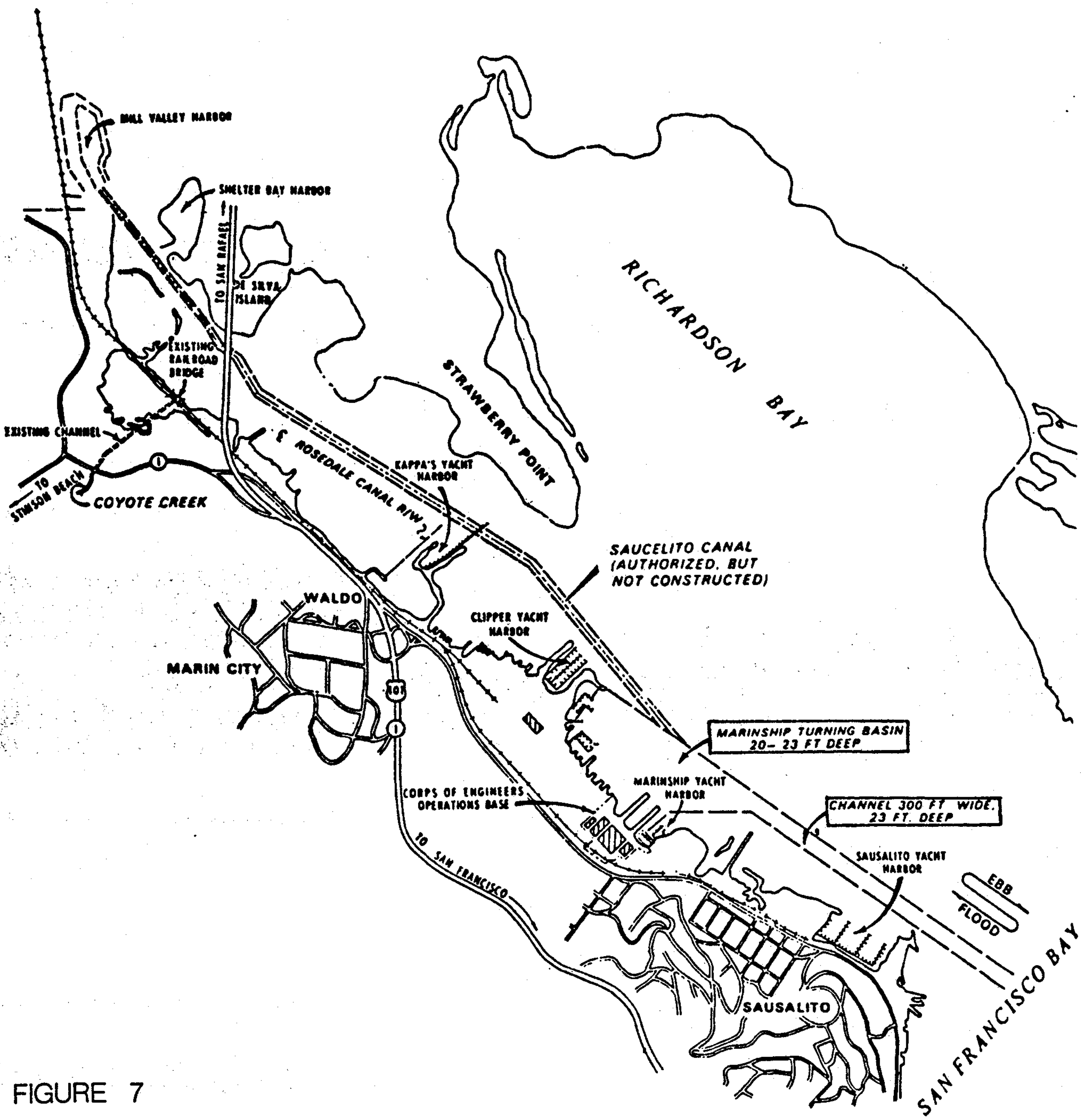

FIGURE 7

Saucelito Canal

SOURCE: U.S. Army Corps of Engineers, San Francisco District, 1975

N 0 2000 FEET

RICHARDSON BAY
SPECIAL AREA PLAN

moorings or regulation of anchorages. The preferrable anchorages for small boats are the most sheltered areas in the lee of Kappas Spit and in the launching basin. However, moorings in these two locations often conflict with navigation requirements, both for boats using Kappas Marina, upper Richardson Bay and the Salt Works canal, and for all boats using the launching basin to set sail or to fuel. The conflict is sometimes aggravated by boats and houseboats in these areas, using of long mooring lines tied to privately installed anchorages.

5. <u>Existing Maintenance Dredging Requirements</u>.

A. <u>Dredged volumes</u>.

Maintaining the existing level and type of boat use in Richardson Bay will eventually require continued maintenance dredging for the following:

1. The marina basins
2. The former Marinship launching basin
3. The Corps of Engineers channel and basin

Assuming no substantial change in average siltation rates or acceleration in sea level rise, and assuming -4 ft MLLW to be the minimum acceptable depth for the typical 5 ft draft boat, the total long term average annual dredging requirement will be approximately 60,000 cubic yards per year, of which 25,000 cubic yards per year is required for the Corps channel. This total is broken down as shown in Table 5.

In the houseboat marinas gradual siltation will continue to occur in the most sheltered areas resulting in the formation of

Table 5

Summary of long term maintenance dredging requirements

Location	Siltation Rate ft/yr	Existing Area acres	Existing Annual Vol cy/yr	Future Area acres	Future Annual Vol cy/yr
Sausalito Yacht Harbor	0.2	20.2	6500	20.2	6500
Pelican	"	5.6	1800	5.6	1800
Zacks	"	1.0	300	1.0	300
Ducorp	"	-	-	2.5	800
Clipper #1	"	1.3	400	1.3	400
South Pier	"	-	-	2.5	800
Jerry's Marinship	"	4.4	1400	4.4	1400
Clipper #2	"	4.6	1500	4.6	1500
Clipper #3	"	7.0	2200	7.0	2200
Clipper #4	"	6.9	2200	6.9	2200
Kappas	"	5.0	1600	5.0	1600
Shelter Bay	"	3.0	1000	3.0	1000
Strawberry Lagoon	"	2.5	800	5.0	1600
The Cove	"	3.0	1000	3.0	1000
Corinthian	"	11.5	3700	11.5	3700
Tiburon	"	4.0	1300	4.0	1300
(Zacks)	"	-	-	11.0	3500
(Dorade)	"	-	-	3.0	1000
(Schoonmaker)	"	-	-	5.0	1600
(Deak)	"	-	-	3.0	1000
Marinship Launching Basin	"	-	-	20.0	6500
Saucelito Canal(part)	0.5	11.5	9300	11.5	9300
Corps channel	0.5	-	25000	-	25000

salt marshes around the boats in these locations. In order to prevent some of the houseboats from being immobilized, it is estimated that an average of about 2000 cubic yards per year of sediments would have to be removed. However, it is more likely that because of potential water quality problems due to pollutants in the muds, no dredging will take place and some of these houseboats will eventually be surrounded by salt marsh, preventing their removal or replacement. Therefore, the 2000 cubic yards/year has not been included in the total maintenance dredging requirement.

In the deeper part of the houseboat marinas where there is sufficient wave energy to maintain existing water depths there probably will not be any need for maintenance dredging.

B. Dredge Spoil Disposal.

The major constraints on dredge spoil disposal are the presence of contaminants in the mud and the availability of a suitable disposal site. Provided the level of contaminants in the dredged mud is not excessive, the Alcatraz disposal site or the experimental disposal site in Raccoon Strait could be used. If contaminant levels were high as determined by mud elutriate tests carried out in accordance with Corps of Engineers procedures, dredge spoils would have to be disposed of on land or outside the Golden Gate beyond the 100 fathom line.

Generally, the major water quality problems are those resulting from the reintroduction of heavy metals contained in the sediment, such as mercury, lead, and cadmium, back into the sea water where it can pass into the food chain. The highest concentrations of heavy metals usually occur where urban runoff sediments haze accumulated over a long period of time, e.g., adjacent to storm drain outlets, or where industrial processes such as shipbuilding have taken place. This is reflected in mud samples taken by the Corps of Engineers in Richardson Bay, which generally show higher heavy metal concentrations at the upper end of the Bay by the Highway 101 bridge and adjacent to the Marinship site. Heavy metal concentrations for these samples lie within the range of 3 to 89 ppb for lead, 13 to 10.5 ppb for mercury and 0.33 to 2.4 ppb for cadmium (Corps of Engineers 1975).

After the initial dredging, mud from later maintenance dredgings is usually of better quality because of the shorter period of time of accumulation and the elimination of many pollutant sources. Only in the most industrialized parts of San Francisco Bay such as the Oakland Estuary, have there been problems with polluted muds from maintenance dredgings. Therefore, it is unlikely there will be water quality restrictions in disposing of maintenance dredge spoils at the Alcatraz site. The only locations where problems could possibly arise would be in shallow water areas adjacent to storm drain outfalls or in the first maintenance dredging of the Marinship launching basin.

C. Dredging Costs

The major cost in dredging is the expense of transportation to the disposal site. Because of the proximity to the Alcatraz dredge disposal site, which is located only about four miles from the Sausalito waterfront, dredging costs should be low and typically in the $5 to $6/cubic yard range. A conventional clam shell dredging operation loading directly into barges can be used for all the existing maintenance dredging requirements, except for any deepening required for houseboat areas. Here the dredging operation may be restricted by shallow depth to periods of high tides. Therefore, overall maintenance dredging costs for houseboat marinas would be higher.

Dredging costs would be lower for the Belvedere Cove maintenance dredging if the experimental Raccoon Straits disposal site is eventually approved. At present the major concern with this disposal site is whether there is adequate dispersion of sediments.

6. Future Navigational Requirements

The proposed new marinas at Zack's, Ducorp, and Schoonmaker will be located immediately adjacent to the Corps channel and, consequently, would not change the existing navigational requirements. However access channels from the proposed marina basins to the navigation channel would have to be dredged and maintained.

Completion of the Deak marina will require access to the Corps channel via the Marinship launching basin. This launching basin is silting up and, in any event, will require maintenance dredging in the future. The increased use of the area by boats from the Deak Marina and the expanded Kappas Marina will add to congestion and conflicts between moored boats, houseboats and vessels under way. Furthermore, boats from the new Zack's, Ducorp, and Schoonmaker Marina will probably need to use the fuel dock, also adding to the congestion.

The expanded Kappas Marina will require a navigational channel to the turning basin area--this, too, will create additional conflicts between moored boats and boats using the marina.

The proposed development on Strawberry Spit would change the existing navigational access for boats presently using the Salt Works Canal. The current design proposal is to excavate a navigation channel across the base of the spit, converting it to an island. Because of the depth of water in Strawberry Lagoon, this may result in diversion of the main ebb and flow tidal currents from the Salt Works Canal through the Lagoon. As this could probably result in the silting up of the Salt Works Canal, boats from the Cove Marina would have to be afforded unrestricted access through the lagoon. Maintenance dredging of a channel through the lagoon would also reduce any dredging requirements for the private boat docks along the western shore of the lagoon. Diversion of boat traffic from the Salt Works canal would also reduce intrusion on the seal haul-out area on Strawberry Spit.

There have been proposals to dredge both the Saucelito Canal to the Shelter Bay Marina, and the Salt Works canal to the Cove Marina. The extension of the Saucelito Canal beyond Kappas

Marina would be about 1.4 miles and the Salt Works canal would also be approximately 1.4 miles. If channels were maintained 100 ft wide to -8 ft MLLW, the average annual maintenance dredging requirement would be approximately 14,000 cubic yards for each. These channels are not used by significant numbers of deep draft boats and no additional future increase in boat use is likely. Because of the high costs dredging of these channels is not recommended.

7. Proposed Navigation and Maintenance Dredging Plan

A proposed navigation and maintenance dredging plan is shown in Figure 8. This plan is intended to provide for navigational access to marinas and other boat facilities and suitable areas for anchorages while minimizing maintenance dredging requirements and costs.

Its main features are as follows:

1. Continuation of dredging of the existing Corps channel and turning basin to be maintained at the present depths and width in any event or no shallower than -10' MLLW.
2. Designation of navigational fairways and anchorages as recommended by the Sausalito Fairways and Anchorages Committee (see Figure 9). Maintenance dredging to be carried out in those fairways not included in the Corps channel or private marinas to a minimum depth of -8 ft MLLW.
3. Designation of a 200' wide Saucelito Canal along the natural deep water channel along the northern side of

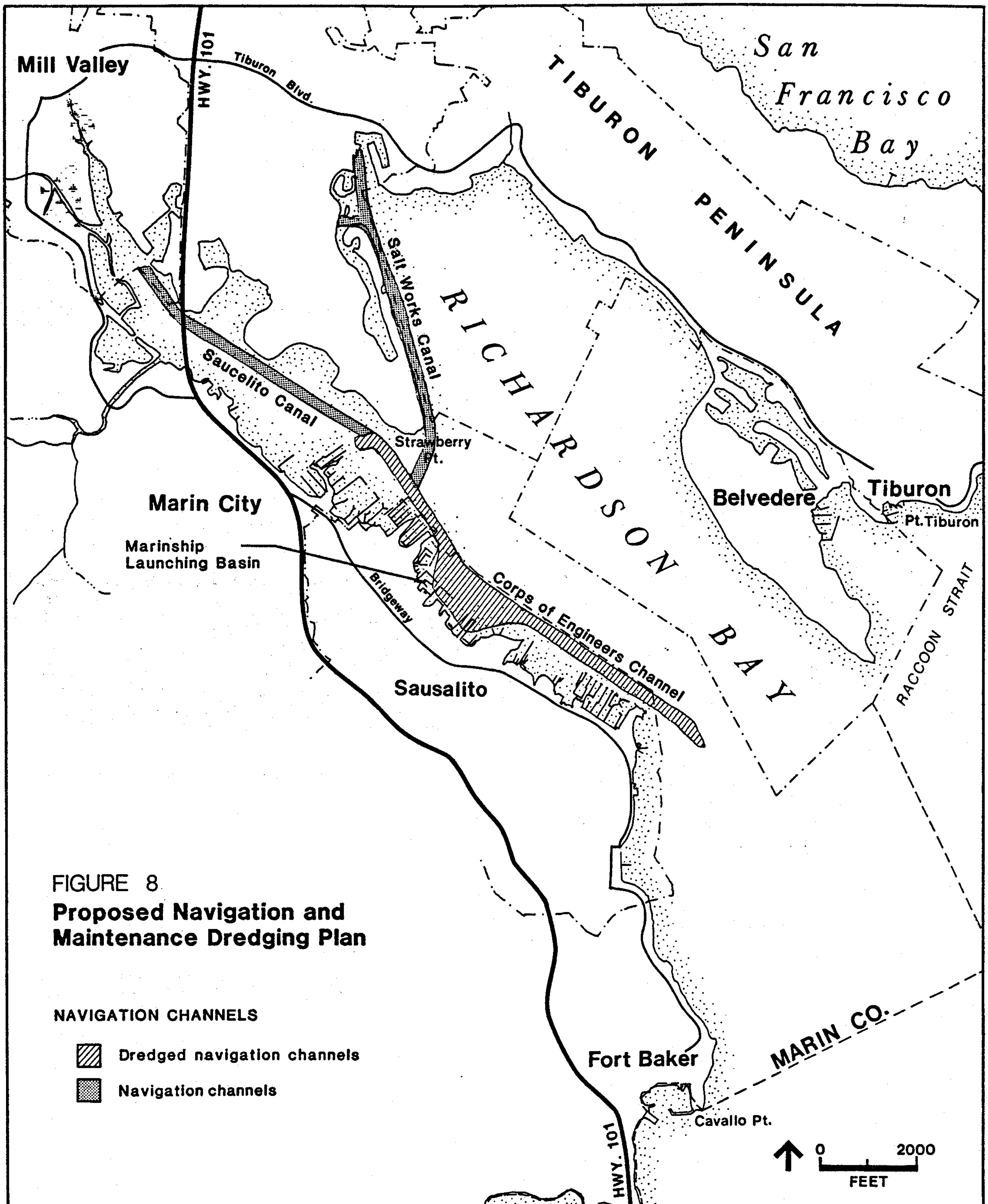

FIGURE 8
Proposed Navigation and Maintenance Dredging Plan

NAVIGATION CHANNELS

- Dredged navigation channels
- Navigation channels

the upper Bay from Shelter Bay to Strawberry Point and the Marinship launching basin. The upper part of the Saucelito Canal beyond Kappas Marina would not be dredged.

4. Designation of a navigation channel from Kappas Marina to the Saucelito Canal and dredging of this channel and the Saucelito Canal to the turning basin to -8 ft MLLW approximately 100 ft wide.

5. Designation of a 200' wide navigation channel from the Cove through Strawberry Lagoon to connect with the Saucelito Canal. This channel would not be dredged.

The proposed navigation and maintenance dredging plan would be administered by a harbor authority whose responsibility would be to plan and supervise dredging activities, to ensure that all regulatory agency conditions were met, to ensure that navigation channels were kept free of moorings, pilings, boat docks or sunken vessels and to install and maintain navigational aids. Such an authority would be able to coordinate dredging activities so as to achieve economies of scale and also to minimize procedural delays which would also help reduce costs.

8. Conclusions and Recommendations

A. The western shore of Richardson Bay is a very suitable location for small boat harbors because of its sheltered position and proximity to the Golden Gate.

B. Sedimentation rates in marinas are markedly lower in Richardson Bay than elsewhere in San Francisco Bay, primarily because of its partial isolation from the main circulation system of the rest of San Francisco Bay.

C. Typical average sedimentation rates in Richardson Bay marinas amount to about 0.2 ft per year.

D. Typical average sedimentation rates in artificial channels in Richardson Bay amount to about 0.5 ft per year.

E. Water depths in most of Richardson Bay appear to be stable and in equilibrium with natural sedimentation and erosive forces. In fact, the natural shallows and mudflats of Richardson Bay appear to be experiencing a small net rate of erosion over the last 30 years, probably because the effects of the Sierra hydraulic mining on suspended sediment concentrations in San Francisco Bay have now been dissipated.

F. With the existing marinas and pattern of boat use, long term maintenance dredging requirements for Richardson Bay will be approximately 60,000 cubic yards per year, of which approimately 25,000 cubic yards per year is attributed to maintaining the Corps of Engineers channel to its operations base.

G. With future additional marinas the long term maintenance dredging requirements for Richardson Bay will be approximately 76,000 cubic yards per year.

H. Dredging costs for marinas in Richardson Bay are comparatively low, due to their proximity to the Alcatraz dredge spoil disposal site.

I. The former Marinship launching basin, last dredged in the 1940s, acts as a focal point for boating activities, and will need to be dredged in the future.

J. Unregulated anchorages in the launching basin area and in the channel leading from the Strawberry Spit and the upper part of Richardson Bay are an impediment to navigation.

K. Navigation channels to the Kappas Marina, Shelter Bay, Strawberry Lagoon and the Cove Marinas should be designated and marked to help prevent obstruction of navigation in the natural deepwater channels.

L. Maintenance dredging of the Salt Works Canal and the Saucelito Canal beyond Kappas Marina are not recommended because of high cost For 100-ft wide channels, an average of approximately 28,000 cubic yards of sediment would have to be removed per year.

M. Depths in both the existing Salt Works Canal and in the natural channel to the upper part of the Bay appear to be in equilibrium with the tidal currents so that additional shoaling is not anticipated.

N. The proposed channel from Strawberry Lagoon across the base of Strawberry Spit would divert tidal action from the Salt Works Canal, probably resulting in its shoaling. However, this effect can be compensated for by allowing for navigation access from the Cove Marina through Strawberry Lagoon.

O. If a channel is dredged from the launching basin to the Kappas Marina, its natural scouring would be improved if the Clipper #4 harbor was enclosed with a bulkhead. In addition, this would probably reduce sedimentation within the Clipper #4 harbor.

P. Continued maintenance of the Corps of Engineers channel and turning basin is vitally important for the long term future of maritime activities in Sausalito.

Q. The optimal maintenance dredging depth for marinas and channels appears to be about -8 ft MLLW allowing siltation to -4 ft MLLW, and, therefore, requiring maintenance dredging about every 20 years.

R. Although suspended sediment concentrations in tidal waters in San Francisco Bay are projected to decrease over the next 50 years, increased sediment loads are entering Richardson Bay from its surrounding watershed. Therefore, erosion control of development in the surrounding watershed could be a factor in reducing long term dredging costs.

S. Improvement in tidal flushing in the upper bay might be achieved by increasing the tidal prism of the salt marshes in the area. This also might improve scouring of the natural channel adjacent to Shelter Bay.

T. Encroachment of boat docks on natural deep water channels is an impediment to navigation.

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TECHNICAL APPENDIX

ANALYSIS OF SEDIMENTATION RATES

IN RICHARDSON BAY

Introduction

As part of the preparation of the navigation and maintenance dredging plan, Philip Williams & Associates examined the physical processess affecting sedimentation in Richardson Bay. At first the use of a hydrodynamic computer model was evaluated to calculate the tidal currents and consequent sedimentation rates throughout the Bay. However, analysis of channel sedimentation rates showed that in the areas of interest tidal current scouring was not the major factor influencing siltation. Furthermore, the majority of the marinas and channels that will require maintenance dredging are located in relatively sheltered areas with both low tidal current velocities and limited wave action. As an approximation, therefore, a simple sedimentation model was used that assumed the marinas and channels behaved similar to a closed basin subject to the influx of sediment laden water during a diurnal tidal cycle.

This appendix describes the equations for cohesive estuarine sedimentation used in this model. By applying these equations to the conditions in Richardson Bay, the long term siltation rates are calculated and the causes of siltation are examined. In particular, the equations are used to show that sedimentation rates are strongly dependent on suspended sediment concentrations which appear to be significantly lower in Richardson Bay than the rest of San Francisco Bay because of Richardson Bay's location.

Siltation in Closed Basins

The deposition of cohesive sediments is influenced by three factors: 1) the probability that an individual particle will stick to the bed, 2) the settling velocity of the sediment particles, and 3) the shear stress on the bed.

The shear stress results from the force of the water moving over the bottom of the bay, either due to tidal currents or waves. The shear stress due to water flowing over a bed is analagous to the force exerted by a brick sliding down an inclined plane.

Since it is a force on the channel bed, the shear stress has a direct impact on sedimentation rates. When there are large shear stresses (i.e., large forces on the bottom), freshly deposited sediment cannot remain on the bed without being eroded. When the shear stress drops below a particular value known as the critical shear stress for deposition, sediment can accumulate on the bed without being eroded. The critical shear stress for San Francisco Bay muds is in between 0.6-0.8 dynes/cm^2 (Krone 1962).

Given that the shear stress is less than the critical value, the probability that a particle will stick to the bed can be expressed as:

$$P = 1 - \frac{\tau_o}{\tau_{cd}}$$

Where P = the probability that a particle will stick to the bed

τ_o = shear stress due to wave action and tidal currents

τ_{cd} = critical shear stress

The settling velocity has a large impact on sedimentation rates as it determines how fast particles will fall through a column of water and settle on the bottom. At high suspended sediments concentrations, cohesive sediments bond together into larger aggregates, known as flocs, which have a much higher settling velocity than the individual particles. This relationship is evident in the equation for settling velocities:

$$V_s = C^{1.33} \cdot K$$

Where V_s = the average settling velocity of the particles and flocs

C = suspended sediment concentration

K = an empirical constant evaluated at 0.55

Through experimentation, Ariathurai and Krone (1977) found that the settling velocities and probability of particles sticking to the bed are related to sedimentation rates by the following equations.

$$\frac{dc}{dt} = -\frac{P V_s C_o}{d}$$

which can be solved to give

$$C = 10^{-\left(\frac{V_s P t}{2.3 d}\right)}$$

where $\frac{dc}{dt}$ = change in suspended sediment with time

C_o = initial suspended sediment concentration

C = new suspended sediment concentration

t = time

d = average depth through which the sediment settles

These two equations were used to compute the sedimentation rates in closed basins with tidal and suspended sediment characterisitcs similar to Richardson Bay. Since we assumed there was no significant wave action, there was no shear stress and, thus, P was set equal to 1. The long-term sedimentation rates for Richardson Bay are shown in Figure 4.

Before the calculations could be made, the equations had to be calibrated on an average annual suspended sediment concentration for Richardson Bay. This was evaluated by determining what average annual suspended sediment concentration would produce the observed sedimentation rates of 0.2 ft/yr at depths of about -8 ft MLLW in Richardson Bay. This value was calculated to be approximately 120 mg/l.

Because it has an exponential relation to the settling velocity, which in turn is exponentially related to the sedimentation rate, the average annual suspended sediment concentration has a large impact on siltation rates. This relationship is shown in Table A-1 where a little more than a threefold increase in sediment concentrations produces an order of magnitude increase in sedimentation rates.

In other words, the period of high suspended sediment concentrations, e.g. winter storms are far more important than the low ones for producing long term siltation. The average annual suspended sediment concentration for Richardson Bay is thus a median value which falls between the high concentrations during periods of intense wave action or winter runoff and low concentrations at other times.

Although the average annual suspended sediment concentration of 120 mg/l that correlates with observed siltation rates in Richardson Bay is lower than concentrations elsewhere in San

Francisco Bay, it is considerably higher than typical suspended sediment concentrations of waters in Raccoon Straits which are generally in the range 10 to 40 mg/l. Therefore, it appears that the sediments of the mudflats and shallows of Richardson Bay are resuspended and locally recirculated within the Bay. Consequently, the artificial marinas and channels are acting as sinks to trap these sediments in the recirculation process.

Because of the low average annual suspended sediment concentration, the variation in siltation rate with depth shown in Figure 4 is not very significant within the normal navigible depth range. For example, at -8 ft MLLW the annual siltation rate is 0.20 ft/year, whereas at -2 ft MLLW it is 0.19 ft/year. Consequently, unlike other areas of San Francisco Bay with higher average annual suspended sediment concentrations there is no significant advantage in maintaining marina basins to a shallower depth in order to reduce maintenance dredging requirements.

Table A-1

SILTATION RATES AT DIFFERENT SUSPENDED SEDIMENT CONCENTRATIONS*

Siltation Rate	Average Annual Suspended Sediment Concentration
0.20 ft/yr	120 mg/l
0.48 ft/yr	175 mg/l
1.07 ft/yr	250 mg/l
1.61 ft/yr	300 mg/l
3.04 ft/yr	400 mg/l

*All siltation rates are for -8 ft MLLW closed vertically sided