# THE
# ENVIRONMENTAL IMPACTS OF DREDGED MATERIAL DUMPING
# AT
# THE ALCATRAZ DUMPSITE, SAN FRANCISCO BAY, CALIFORNIA
# A PRELIMINARY ASSESSMENT

BY

Douglas A. Segar, Ph.D.

Senior Research Scientist

Romberg Tiburon Centers

Technical Report No. 10

November 1988

Romberg Tiburon Centers

Center for Environmental Studies

San Francisco State University

P.O. Box 855

3150 Paradise Drive, Tiburon, CA

## TABLE OF CONTENTS

# EXECUTIVE SUMMARY

Within San Francisco Bay, there are numerous navigation channels, and berthing areas that have been dredged to depths that are suitable to enable vessels to enter, navigate, and berth within the Bay. At present, all dredged material from San Francisco Bay, with the exception of small quantities disposed upland, is dumped at one of three dumpsites in the Bay. Of these three dumpsites, the Alcatraz dumpsite located immediately south of Alcatraz Island, receives by far the largest quantity of dredged material, including essentially all dredging from South and Central Bay and most of San Pablo Bay.

The quantity of dredged material dumped at the Alcatraz dumpsite is very large. In 1986, 5,185,000 cubic yards of dredged material were dumped at Alcatraz. Five million cubic yards of dredged material is more than enough to fill 10 Olympic-sized swimming pools every day for a year. Dumping of this quantity of material in the Bay is clearly a major activity that could adversely affect the Bay's ecology, particularly as much of the dredged material dumped at the Alcatraz dumpsite is contaminated with various toxic trace metals and organic compounds.

Dredged material is a mixture of sediment solids and associated water. The solid material consists of varying amounts of several components including sand, silt, and/or clay particles, organic matter, and chemical compounds, such as sulfides and hydrous iron oxide. Most of this material is naturally occurring and can be found in prehistoric layers of sediment in the Bay. However, more recent sediments are contaminated by human activities with a range of pollutants including toxic metals (e.g., cadmium, lead, chromium, copper, mercury, nickel, and silver), and toxic organic compounds (e.g., chlorinated hydrocarbons, such as DDT and PCBs, and polycyclic aromatic hydrocarbons and other petroleum products).

In general, the most contaminated dredged material is mud and fine silt rather than sands. Finer grained sediments are generally found concentrated in areas where current velocity near the Bay floor is low. Since many dredged harbors and a substantial percentage of the dredged channels within San

Francisco Bay have relatively low bottom current velocities, these areas tend to accumulate contaminated fine-grained sediments.

The composition, particularly the toxics concentrations, of dredged material is highly variable and only limited sampling and analysis of dredged materials from San Francisco Bay has been performed. Therefore, it is difficult to estimate accurately the quantities of various contaminants dumped at the Alcatraz dumpsite annually. However, estimates of the annual quantities of several toxic metals, PCBs, and PAHs dumped at Alcatraz annually have been made. These estimated loadings can be compared to the estimated total input of these same metals to the Bay-Delta from industrial and municipal discharges, urban and non-urban runoff, riverine input, and atmospheric fallout. These estimates demonstrate that dredged material disposal at the Alcatraz dumpsite releases quantities of potentially bioavailable toxics which are very large compared to other inputs. For example, dredged material inputs for several metals exceeds the total inputs of these contaminants from all of the more than 100 municipal and industrial discharges to the Bay-Delta combined.

When dredged material is released into the water column at the Alcatraz dumpsite, a variety of physical and chemical processes occur before the dredged material reaches a resting place on the Bay floor or is transported from the Bay. Physical processes occurring during and after the dredged material dumping event at the Alcatraz site fractionate contaminants preferentially to the surface sediment layer and the suspended sediments. There is little information on the long-term fate of the contaminant-laden suspended particulates. Dredged material particles entering the suspended sediment regime at the Alcatraz dumpsite are carried by currents away from the dumpsite and are subject to cycles of deposition and resuspension as they are transported. Particles will tend to be deposited on surface sediments where tidal and other current velocities are low and resuspended again when these currents increase. These cycles will continue in the Bay until the particles deposit in areas of consistently low current velocities, or are carried out to sea. The available evidence suggest that the toxic contaminant containing suspended sediments created by dredged material dumping at the Alcatraz dumpsite remain in the suspended sediment regime (and thereby in contact with fish, shellfish, and other biota) of western Central San Francisco Bay for an average length of time that exceeds several tidal cycles and probably several days or weeks.

Toxic organics and many of the toxic trace metals in dredged material are preferentially associated with organic rich particles, or coatings on particles, in the dredged material. These organic particles or coatings are a potential source of food for many types of Bay biota ranging from bacteria to filter feeding zooplankton and juvenile fishes. Relatively little is known about the importance of this mechanism as a route for transfer of dredged material toxics into the biota, particularly in San Francisco Bay. However, studies at other dredged material dumpsites suggest that the toxic contaminants in dredged material disposed at the Alcatraz dumpsite are probably concentrated by Bay biota from the suspended sediments. Since the toxics in dredged material dumped at the Alcatraz dumpsite remain in the suspended sediment regime in the Bay for extended periods and are transported throughout wide areas of the Bay, it is probable that dredged material toxics are responsible, in part, for the high concentrations of a variety of toxics found in Bay biota particularly in Central Bay.

In view of the diversity of, and complex relationships among, chemical and physical reactions taking place during the initial dispersal of dredged material in the marine environment, it is not surprising that the resulting distribution of chemical contaminants between water and sediments cannot be predicted at present with confidence. Very limited field studies of the fate of contaminants during San Francisco Bay disposal operations have been carried out. In these studies, significant increases were observed in dissolved concentrations of lead, cadmium, copper, and chlorinated organics, including PCBs and DDE (a toxic DDT decomposition product). Although the elevated concentrations did not exceed current State Water Quality Objectives, these data indicate that a significant quantity of these and other toxics are released to solution during dumping of dredged material in San Francisco Bay and are almost certainly bioavailable.

The impacts and potential impacts of dredged material dumping at the Alcatraz dumpsite are varied and complex. Some categories of impacts, such as the effects on benthic organisms in the site sediments, are well understood. However, most potential impacts are poorly understood, because appropriate studies have not been performed or, in some cases, are technically unfeasible at the Alcatraz site and in the surrounding Bay environment. The very limited understanding of many of the potential impacts that are possible is based upon 1) chemical analyses, bioassays, and bioaccumulation testing of some of the dredged materials dumped, 2) more extensive, but still limited, laboratory studies of dredged materials from areas other than San Francisco Bay, and 3) often limited field studies at dredged material dumpsites in other parts of the United States. Unfortunately, much of this information is not fully applicable to impacts at the Alcatraz dumpsite because studies in the laboratory and at other sites, and the test procedures that are based on these studies, were designed to evaluate impacts at dredged material dumpsites that are accumulative in nature or at sites where flushing (as opposed to dispersion) of the area surrounding the site is extremely effective. Assessment of the potential impacts, particularly the cumulative impacts of continuous dredged material disposal at the Alcatraz dumpsite must take into account its unique characteristics: a highly dispersive site in an enclosed estuary with limited flushing (compared to open ocean sites), particularly during the summer/fall dry season.

The benthos at the Alcatraz site have been substantially impacted by historical and ongoing dumping. The principal impacts have been caused by the burial of the existing bottom sediments throughout the 2,000-ft. diameter circular site and in areas outside the site to approximately 2000 feet beyond the perimeter of the site. Within this area, populations of benthic organism are highly variable in composition and density and are characterized by species that are tolerant of rapidly changing environmental conditions and that are capable of rapidly recolonizing altered sediments. The extent to which the benthos of the Alcatraz dumpsite and the surrounding area are degraded by dredged material dumping is difficult to assess because of 1) the lack of studies of the site before dumping, 2) the naturally variable nature of the benthic communities in western Central San Francisco Bay, and 3) the paucity of detailed studies of the impacts of dumping on the benthos, particularly studies of the effects of dumping on bottom fish that feed on the benthos. However, dredged material dumping at other dumpsites has been found to 1) reduce the biomass, 2) eliminate many benthic infaunal species known to be important in supporting commercially and recreationally important fish and shellfish polulations, and 3) reduce populations of bottom feeding fish. It is certain that these effects have also occurred, to some extent, at the Alcatraz dumpsite. However, these impacts are not necessarily permanent, particularly at a highly dispersive site, such as the Alcatraz dumpsite and may be reversible if dumping were terminated. While the area of degraded sediments in and near the Alcatraz dumpsite is small compared to the Bay as a whole, it is a significant fraction of the area of the Bay that is occupied by a deepwater, oceanic influence regime that is of critical importance to a variety of bottom fish and shellfish species.

The depositional areas most likely receiving and accumulating the largest quantities of dredged material suspended sediments from dredged material dumping, (dredged channels nearest to the Alcatraz dumpsite, enclosed harbors and wharf areas of the San Francisco shoreline and Richardson Bay) are known to have finer-grained sediments with relatively high levels of a broad spectrum of contaminants. In some of these areas, such as Hunter's Point, the level of contamination in the sediments is very high and local sources of contamination are important. However, in most of these areas, particularly Richardson Bay, there are only limited local sources of toxic contamination and the contamination of the sediments reflects high toxics concentrations in the suspended sediments of the adjacent higher energy areas of the Bay. This and other evidence supports a conclusion that dredged material dumping at the Alcatraz dumpsite is probably a substantial, and possibly a dominant, source of accumulating sediments and their associated toxics contaminant loads in wide areas of the Bay, particularly embayments along the San Francisco waterfront from the Golden Gate to the Bay Bridge (and possibly to the south of the Bay Bridge), and in Richardson Bay and other accumulative locations along the southern Marin County shoreline. It is highly probable that over a period of time toxic contaminant concentrations would be reduced in sediment in these areas if dredged material disposal were terminated in Central San Francisco Bay.

While the impacts of dredged material dumping on benthic communities within the dumpsite are relatively well studied and understood, impacts on free-swimming or floating organisms are much less well studied and understood, partly because of the greater technical difficulties associated with studies of such impacts. Impacts on benthic organisms that reside outside the immediate area of the dumpsite but that are exposed to dissolved or suspended particulate components of the dredged material are also difficult to study and poorly understood.

Because of these difficulties, the regulatory evaluation of potential impacts in the water column relies heavily on short-term bioassay tests and water quality evaluations that address lethal effects within the dredged material plume during the first four hours after dumping. The required tests are a suspended sediment bioassay and an "elutriate" test.

The elutriate test is performed by shaking the dredged material with water from the disposal site, and measuring the increase in concentrations of various dissolved contaminants. For most dredged material samples from San Francisco Bay, these tests show that a variety of contaminants are released to solution. However, the resulting concentrations of toxics rarely exceed the applicable water quality objectives. Even when water quality criteria are exceeded in the elutriate, dilution at the dumpsite would reduce the toxic concentration below the water quality objective within a few minutes after dumping. These data suggest that acute toxicity to non-benthic organisms may be unlikely. However, it must be remembered that this test does not address the potential for 1) acute toxicity due to the combined effects of several toxic contaminants, 2) acute toxicity due to the combination of dissolved and suspended particulate toxics, and the physical effects of suspended solids, and 3) the potential for long-term and/or chronic effects due to continuous dumping at the Alcatraz dumpsite.

The potential for these other types of impacts is investigated through suspended phase bioassays. There are many problems with the interpretation and application of the results of these suspended sediment bioassays since the tests do not properly reproduce the actual conditions that occur at the

Alcatraz dumpsite. The suspended phase bioassays probably underestimate the toxicity of dredged material plumes dispersing at the Alcatraz dumpsite.

Suspended sediment bioassays show that many San Francisco Bay sediments exhibit both lethal and sublethal toxicity to several different species. Until recently, it was thought that the observed suspended sediment toxicities were sufficiently low that dredged materials would not exceed the limiting permissible concentrations because of the rapid dilution of the suspended phase at the dumpsite immediately after dumping. However, erroneous assumptions have recently been identified in the modeling calculations used to calculate dilutions of the suspended phase. When these errors are corrected, many of the dredged materials tested are found to be sufficiently toxic that they exceed the limiting permissible concentrations. Since violation of these limiting permissible concentrations is taken by regulation to be presumptive proof that unacceptable biological impacts may occur, this finding raises concern that the suspended sediment phase of dredged materials dumped at Alcatraz may adversely impact the biota of Central Bay. This is an important finding that requires detailed further scientific review.

Since 1986, the Corps of Engineers has required that, as far as possible, dredged material dumped at the Alcatraz dumpsite should be "slurried" to reduce the accumulation of dredged material and shoaling of waters at the dumpsite. One effect of this requirement is to increase the quantities and concentrations of suspended sediments transported from the dumpsite into the Central Bay water column and suspended sediment regime. Recreational fishermen have reported that during the 2 years since the slurry requirement was introduced, the frequency of high turbidity conditions in Central Bay has increased and the sport fisheries have been adversely affected. The fishermen's observations have been examined the California Department of Fish and Game and the National Marine Fisheries Service. These agencies have concluded that there is strong evidence that the slurry requirement may have caused higher turbidity in Central Bay that, in turn, may have caused a decline in fish stocks. However, the Corps of Engineers claims that turbidity resulting from dredged material dumping is of short duration and cannot have caused either a general increase in turbidity or deleterious effects on fish. This latter view neglects to take into account the the cumulative impacts of multiple continuous dumps.

Re-examination of the available data indicates that 1) turbidity and/or the persistence and frequency of turbid plumes has probably increased in west Central Bay during 1986 and 1987, 2) fishing success for several species has substantially declined in Central Bay during 1986 and 1987, 3) dredged material disposal is a major, perhaps dominant, contributor to the suspended sediment loads of west Central Bay, and 4) the slurry requirement established in 1986 undoubtedly caused an increase in the percentage of dredged materials introduced to the suspended sediments at the Alcatraz dumpsite and, therefore, an increase in the loading rate of suspended sediments in the area. Considerably more evidence would be necessary to unequivocally demonstrate or reject the existence of a cause-and-effect relationship between the slurry requirement and reduced fish populations and fishing success. However, the available evidence suggests that such a relationship is at least possible. An alternate hypothesis is that the fisheries decline may be caused by toxics in the suspended sediment phase released at the dumpsite. Increased concentrations of dredged material derived toxics in the suspended sediments regime of Central Bay are a certain consequence of the slurry requirement. This fact and the observed toxicity of the suspended solid phase of dredged materials dumped at Alcatraz lend support to such a hypothesis. Clearly, this issue requires considerably more detailed and extensive research.

In addition to the possibility that dredged material toxics in suspended sediments are sublethally toxic to benthos and non-benthos of the bay, there exists the additional possibility that these toxics may enter the food chain in significant quantities and contribute to the high levels of a variety of toxics found in the tissues of Bay biota. It is very difficult to assess the contribution of dredged material disposal to the toxics loadings of Bay biota. Scientific research studies, although admittedly difficult, have simply not addressed this question at a dispersive dumpsite like the Alcatraz dumpsite. In addition, laboratory tests which could aid assessment of this question have not been performed on dredged materials dumped in San Francisco Bay. Despite the paucity of studies, several observations can be made concerning the potential contribution of dredged material toxics to the elevated toxics loading of Bay biota.

1) the dumping of dredged material at the Alcatraz dumpsite introduces (or reintroduces) very large quantities of toxics compared to any other individual source.

2) toxic contaminant concentrations in organisms from west Central San Francisco Bay are generally similar to those found in other parts of the Bay where almost all of the other major toxics inputs are located. If dredged material inputs of bioavailable toxics were not substantial the concentrations of toxics in biota of Central Bay would be lower than upstream in the Bay because of the diluting influence of clean ocean water.

3) No bioaccumulation tests have been performed on the suspended sediments phase of dredged materials dumped at the Alcatraz dumpsite. However, solid phase tests show significant bioaccumulation of a variety of toxics, and studies from areas other than San Francisco Bay show that bioaccumulation of toxics from dredged material suspended particles does take place.

From these observations, it is clear that there is a high degree of probability that dredged material dumping at the Alcatraz dumpsite is a contributing factor and perhaps the dominant factor, in creating and sustaining high concentrations of various toxics in Bay biota, particularly in west Central Bay and adjacent areas.

A recent research program on the effects of disposal of dredged material in Long Island Sound conducted jointly by the Corps of Engineers and the Environmental Protection Agency provides valuable evidence to support the conclusion that dredged material dumping is detrimental to the San Francisco Bay ecosystem. This program applied state-of-the-art research techniques in an intensive study of the fate and effects of contaminated dredged material dumped at a site that was remote from other sources of toxic contamination. These state-of-the-art studies in Long Island Sound have established evidence that toxic contaminants in dredged material suspended particulates are significantly bioaccumulated by various species of marine organisms, and that this bioaccumulation or other effects of dredged material suspended particulates causes various sublethal detrimental biological effects on these species.

It is, as yet, unclear whether the observed bioaccumulation and sublethal effects in the Long Island study are evidence that dredged material disposed has a major deleterious effect on the Long Island Sound ecosystem. In addition, there can be no certainty that the effects observed in the Long Island Sound study would also be observed in San Francisco Bay, unless similar studies are performed in San Francisco Bay and on Bay dredged materials. However, the Long Island studies provide strong evidence that the suspended sediments and their toxics loads introduced to the Bay can, and most likely do, bioaccumulate, cause negative biological effects and, therefore, degrade water quality. These negative effects may be partially or largely responsible for the observed degradation of the Central Bay ecosystem and the decline of its fish and shellfish populations. This hypothesis, contradicts the prior Corps of Engineers conclusion that suspended dredged material particulates have no significant environmental impact in the San Francisco Bay ecosystem. This Corps of Engineers conclusion is based on limited and technically unsophisticated studies and inadequate testing data. Clearly, state-of-the-art studies are critically needed in San Francisco Bay.

To summarize, we know little about the effects of dredged material dumping on the quality of Bay waters and biota except that 1) there have been adverse impacts on the benthic biota of a significant fraction of the Bay's deep water environment at and around the dumpsite, and 2) the rapid dispersion of dredged material at the site reduces dissolved toxics concentrations below those that are likely to be lethally toxic. However, the overwhelming weight of evidence that is available suggests that dredged material disposal at the Alcatraz dumpsite plays a major role in maintaining elevated toxics concentrations in the environment and biota of west Central Bay and probably beyond. The evidence also suggests that the dumping may cause sublethal or long-term lethal effects on Bay biota and, therefore, that the dumping contributes substantially to the observed environmental degradation of the Bay.

# I. INTRODUCTION

Within San Francisco Bay, there are numerous navigation channels, and berthing areas for both commercial and recreational vessels that are not naturally deep enough to accommodate the vessels using these facilities. These many channels and harbor areas have been dredged to depths that are suitable to enable vessels to enter, navigate, and berth within the Bay. As cargo, cruise, and military vessels and tankers have grown larger and as the number of commercial and recreational vessels using the Bay has risen, there has been a continuing process of deepening existing channels and providing new channels and berthing areas within the Bay. For example, recent dredging projects have deepened the navigation channels in several areas between the Golden Gate and Sacramento to enable larger vessels to transport goods more economically to and from Sacramento and upper Bay ports such as Benicia. Several major new projects are likely to be dredged in the near future. These include the deepening of Oakland Harbor and its approaches to accommodate the new generation of much larger container ships, and the deepening of several berthing areas (including areas at Hunter's Point) to accommodate the homeporting of several additional navy vessels in the Bay, including the Battleship Missouri.

Without dredging to deepen channels, the Bay area would not have become the major commercial center that it is. Since the size of commercial vessels and the number of vessels of all types using the Bay will continue to increase, future dredging projects will undoubtedly be needed. However, even if no new dredging projects were needed in the Bay, dredging would continue, since existing channels continuously fill with sediments from inputs such as stormwater discharges, erosion, and industrial and municipal discharges and with sediments from other parts of the Bay carried by wave, tide, and wide-induced currents. The periodic redredging of existing channels is called maintenance dredging.

The weight and volume of material dredged in each maintenance or new work project in San Francisco Bay varies greatly depending on the area of each dredged channel or berthing area, the depth to which new dredging takes place, and the rate of accumulation of new sediment in maintained areas. However, the volume of material dredged annually in the Bay is very large - millions of cubic yards. Once dredged, this huge volume of material must be disposed of. The normal disposal technique in recent decades has been to dump the material at another location in San Francisco Bay. Historically, large quantities of dredged materials have been used as fill material in wetlands of the Bay, but now that the environmental value of the remaining wetlands of the Bay is acknowledged, this disposal option is no longer available. Only two other disposal options exist for dredged material, upland disposal in landfills, and ocean dumping. Upland disposal is very expensive and, for large quantities of dredged material, would be difficult, if not impossible, to achieve without unacceptable environmental impacts on the terrestrial environment or ground or surface waters. In any event, it is not likely that sufficient suitable land could be found in the Bay area for the millions of cubic yards of dredged material disposed each year. Even the use of dredged material to rebuild and strengthen levees in the San Francisco Bay Delta would accommodate only a small fraction of the dredged material to be disposed. Ocean dumping is an environmentally sound disposal option for most dredged material, if the dumpsite is carefully selected, and the dumping managed properly. Ocean dumping is the environmentally preferred option for disposal of dredged material from many of the nation's estuaries and numerous ocean dumpsites are located in the Pacific and Atlantic Oceans and the Gulf of Mexico. However, primarily on the grounds that transport of the dredged material to an appropriate ocean dumpsite outside the Bay would increase the cost of dredging, this option has not been considered for San Francisco Bay dredged material until very recently. At present, all dredged material from San Francisco Bay, with the exception of small quantities disposed upland, is dumped at one of three dumpsites in the Bay, a dumpsite in the Carquinez Strait, a dumpsite in central San Pablo Bay, and the Alcatraz dumpsite. Of these three dumpsites, the Alcatraz dumpsite receives by far the largest quantity of dredged material, including essentially all dredging from South and Central Bay and most of San Pablo Bay.

The Alcatraz dumpsite is a circular area of 2000-foot diameter located immediately south of Alcatraz Island, about 1000 yards from the San Francisco shore at Fisherman's Wharf and Aquatic Park (Fig. 1). The geographical coordinates for the center of the site are $34^{o}49'17''N$ and $122^{o}25'23''W$. Water depths within the area range from about 100 ft. to about 40 ft. The site has been in use for dredged material dumping continuously since 1894.

The quantity of dredged material dumped at the Alcatraz dumpsite is very large. In 1986, 5,185,000 cubic yards of dredged material were dumped at Alcatraz. Each year since at least 1965, at least 2 million cubic yards of dredged material have been dumped at the Alcatraz dumpsite, with approximately 4 million cubic yards or more disposed in most years. It is difficult to envision just how much dredged material this represents. However, if 5,000,000 cubic yards of dredged material were piled up in a column the length and width of a football field, the column would reach almost one-half mile high, or about twice the height of the world's tallest building. Looked at another way, 5,000,000 cubic yards is more than enough material to fill 10 Olympic-sized swimming pools every day for a year. Dumping of this quantity of material at one location in the Bay is clearly a major activity that could adversely affect the Bay's ecology, particularly as much of the dredged material dumped at the Alcatraz dumpsite is contaminated with a variety of toxic trace metals and organic compounds.

## II. COMPOSITION OF DREDGED MATERIALS DUMPED AT THE ALCATRAZ DUMPSITE

Dredged material is a mixture of sediment solids and associated water. The solid material consists of varying amounts of several components including sand, silt, and/or clay particles, organic matter, and chemical compounds, such as sulfides and hydrous iron oxide. Most of this material is naturally occurring and can be found in prehistoric layers of sediment in the Bay. However, more recent sediments are contaminated to a greater or lesser degree by human activities. In general, human activities lead to increases in the proportion of fine-grained material in the sediments. This fine-grained material comes primarily from increased erosion and discharges of large quantities of organic matter in municipal sewage. In addition, recent sediments are contaminated to varying degrees with a wide range of pollutants including toxic metals (e.g., cadmium, lead, chromium, copper, mercury, nickel, and silver), and toxic organic compounds (e.g., chlorinated hydrocarbons, such as DDT and PCBs, and polycyclic aromatic hydrocarbons and other petroleum products). Most pollutants are bound to the solid organic material and the clay particles in the dredged sediment. Since clay particles are generally very small and organic particles are of low density compared to quartz or shell sand grains, the pollutants are generally concentrated in the fine-grained and/or low density fraction of the dredged material. As we discuss below, preferential concentration of toxics in these fractions of the dredged material has important consequences for the fate and possible impacts of pollutants in dredged material dumped at Alcatraz.

In general, the most contaminated dredged material is mud and fine silt rather than sands. Finer grained sediments are generally found concentrated in areas where current velocity near the Bay floor is low. Since many harbors and a substantial percentage of the dredged channels within San Francisco Bay have relatively low bottom current velocities, these areas tend to accumulate fine-grained sediments. Therefore, there is a tendency for contaminants entering the Bay from discharges and runoff to be transported, in association with suspended sediments, into areas likely to be dredged and into other depositional areas, such as wetlands. In addition to this tendency of dredged areas to capture contaminated fine-grained suspended sediment, many dredged areas are adjacent to major sources of contaminants. Until relatively recent years, most contaminant discharges were unregulated and often took place through short pipes or shoreline outfalls where industrial facilities are located and where municipal wastewater and street runoff were channeled. Industry and other discharge sources tend to be concentrated around ports and harbors and, therefore, sediments deposited around these harbors in the era of unregulated discharges are often grossly contaminated with a variety of toxic metals and organics (Citizens for a Better Environment, 1987). Although most discharges are now controlled and long pipelines carry many effluents into the more dispersive areas of the Bay, ports and harbors are still the source of substantial contamination including spills and street run-off and a large proportion of the contaminants from these sources is scavenged to the sediments that accumulate in previously dredged harbors and channels.

There are two general categories of dredged material dumped at the Alcatraz dumpsite - maintenance dredged material and new work dredged material. Maintenance dredged material is from channels and harbors that have previously been dredged, the maintenance dredging removing sediments that have accumulated since the previous dredging. Since this sediment is accumulated from particulate material in the active suspended sediment regime of the Bay ecosystem, its contaminant contents generally represent the background contamination level in the region of the Bay where the project is located. Exceptions may occur where unusual local inputs of contamination have occurred at or near the dredging site since the last dredging. Because of its origin, maintenance dredged material tends to be generally fine-grained with relatively high water content and, within any given period of years and region of the Bay, relatively invariable in its contaminant concentrations. In contrast, new work dredging which takes sediment from harbors and channels which are dredged to deeper depths than before, produces dredged material which can be widely divergent in its physical characteristics and degree of contamination. Where deep sediments are dredged in new work projects in some areas, the dredged material can be uncontaminated if the dredging enters layers of sediments laid down before civilization reached the Bay. However, in those areas where new work dredging cuts into layers of sediments laid down during the period since substantial human settlement of the area, the dredged material can consist of anything from relatively coarse-grained uncontaminated erosional sediments to grossly contaminated, highly toxic, fine-grained sediments laid down during periods of uncontrolled release of toxics from industry or municipalities. Areas containing this latter type of sediment are often called toxic hot spots (Citizens for a Better Environment, 1987).

The wide range of sediments encountered in new work dredging projects is illustrated by the data in Tables 1, 2, and 3. The seven stations represented in these data are all located in the inner Oakland Harbor within about 2000 ft. of each other. Table 1 shows that the physical characteristics of dredged sediments can vary widely. For example, sediments at site S1 are predominantly fine-grained whereas sediments at S2 only a few hundred feet away are primarily sand and silt. Table 2 shows the concentrations of several toxic metals in these same sediments. Mercury concentrations in these sediments range over more than an order of magnitude. Percentage variations in the concentrations of other metals are somewhat smaller, but still substantial. Table 3 shows the concentrations of a range of organic toxicants, including PCBs (Arochlors) and a range of aromatic petroleum hydrocarbons. Some of these organic toxicants are found in relatively uniform concentrations throughout the small area sampled (e.g., pyrene, benzo(K)fluoranthene and Arochlor 1254), whereas others are extremely variable (e.g., fluoranthene, anthracene, and Arochlor 1248). The wide variability of contaminant concentrations in dredged sediments is further illustrated in Table 4 which presents the range of concentrations of selected metal and organic contaminants in sediments from several different locations within the Bay.

Because of the high variability of dredged sediment composition and toxics concentrations and the limited sampling of dredging sites, it is difficult to estimate accurately the quantities of various contaminants dumped at the Alcatraz dumpsite annually. This difficulty is compounded by the complete lack of toxics concentration data for dredged materials from many maintenance projects. Until recently, Corps of Engineers requirements for dredged material testing were extremely lax and many projects, including some which may have dredged highly contaminated sediments, were not required to perform comprehensive chemical analysis of the dredged material disposed. Even under current guidelines, comprehensive chemical analysis is not required for dredged material from all projects.

Despite these difficulties, estimates of the annual quantities of several toxic metals, PCBs, and PAHs dumped at Alcatraz annually have been made. These estimated loadings can be compared to the estimated total input of these same metals to the Bay-Delta from industrial and municipal discharges, urban and non-urban runoff, riverine input, and atmospheric fallout (Table 5). For all inputs, except dredged material, the range of inputs given in Table 5 reflects inadequacies in the data used to calculate the total input from that source. These limits reflect a range within which the annual input probably lay during the base year examined (a different year in mid 1980's was used for different inputs). The original report of these data (Gunther et al., 1987) did not calculate a similar range for dredged material inputs. Instead, a single most probable number was calculated. This single value is included in Table 5 as the dredged material input. Some proportion of the toxic contaminants in the dredged material will be buried in the mounds at the Alcatraz dumpsite and a fraction of the toxic metals will be bound so strongly to mineral grains in the dredged material that it will not be bioavailable even in the fraction transported from the dumpsite. Gunther et al (1987) allowed for these factors by arbitrarily assuming that no more than 10% of any toxic contaminant dumped at the Alcatraz dumpsite would be bioavailable. This simplistic assumption is scientifically unsupportable and led to a gross underestimate of the magnitude of dredged material toxics inputs to the Bay compared to other inputs. The potentially bioavailable dredged material input estimates listed in Table 5 are calculated by making make more accurate, scientifically-justified, adjustments to the total dredged material inputs to account for burial at the dumpsite and non-bioavailability due to extremely strong bonding of the toxicant to mineral grains. The adjusted dredged material input estimates assume that 20% of the dredged material dumped at the Alcatraz dumpsite is permanently buried at the site as estimated by the Corps of Engineers (US Army Corps of Engineers, 1987a). The adjusted estimates in Table 5 also utilize a scientifically accepted approximation that metals in the residual phase left after a defined laboratory leaching process constitutes the non-bioavailable fraction. The percentages of metals remaining in this phase in Bay sediments are estimated from leaching data for Bay sediments from Eaton et al (1979) and U.S. Army Engineer District San Francisco (1979b). The adjusted estimates of potentially bioavailable toxics dumped annually at the Alcatraz dumpsite (Table 5) are, therefore, conservatively <u>underestimated</u> compared to the ranges shown for other inputs. The conservative nature of these estimates is reinforced by the following considerations:

a) even those metals that are bound in the residual phase of dredged material may be bioavailable (e.g., bacteria are known to convert mercury in residual phases to bioavailable organic forms),

b) toxic metals are known to be preferentially released from dredged material mounds either during disposal or from the mounded sediments (Dayall et al, 1981) and, therefore, less than 20% of the toxics will be retained at the Alcatraz dumpsite even though 20% of the total mass of dredged material is retained, and

c) a fraction of the toxic metals in each of the other inputs listed in Table 5 is associated with mineral particles in "non-bioavailable" residual fractions and adjustments have not been made for this factor.

In summary, Table 5 underestimates the relative magnitude of potentially bioavailable toxics released to the Bay ecosystem in dredged material compared to other inputs. Therefore, it is highly significant that these estimates demonstrate that dredged material disposal at the Alcatraz dumpsite releases estimated quantities of potentially bioavailable toxics which are very large compared to other inputs. For example, dredged material input for several metals exceeds the total input of these contaminants from all of the more than 100 municipal and industrial discharges to the Bay-Delta combined (Table 5).

The inputs of toxics in dredged material are not as large as total inputs from urban and non-urban runoff and riverine input. However, the riverine input enters the Bay-Delta already diluted in massive volumes of water compared to the much smaller total volume of dredged material, and urban and non-urban runoff are distributed throughout hundreds of miles of Bay-Delta shoreline. In contrast, the dredged material input takes place entirely within a 30-acre area of Central Bay - the Alcatraz dumpsite. Clearly, the dumping of dredged material at the Alcatraz dumpsite constitutes a major source of contaminant release to San Francisco Bay and is almost certainly by far the largest, single, geographically-limited source, or "point" source, of toxic contaminants in the Bay-Delta. Since most toxics inputs to the San Francisco Bay-Delta other than dredged material are distributed primarily outside Central Bay, dredged material disposal is certainly the dominant source of release of most toxics into the waters and suspended sediments of Central San Francisco Bay.

## III. FATE OF DREDGED MATERIAL DUMPED AT THE ALCATRAZ DUMPSITE

When dredged material is released into the water column at the Alcatraz dumpsite, a variety of physical and chemical processes occur before the dredged material reaches a resting place on the Bay floor or is transported from the Bay. These include physical fractionation and dispersion, the release of pore fluids, adsorption and desorption reactions, ion exchange processes, and chemical oxidation. The dredged material has several potential effects on the biosphere during the initial settling period when it remains in the suspended sediments of the Bay ecosystem: 1) contaminants released to solution may be taken up by and affect organisms in the dispersion zone; 2) contaminants associated with the sediments may become biologically available even if not released to solution; 3) increased turbidity will restrict light penetration and may reduce the rate of primary production; 4) the increased quantity of particles may impair the respiratory exchange of higher organisms; and 5) chemical species of a reduced nature in the dredged material may remove dissolved oxygen from the water column. In order to assess the relative importance of these effects, it is necessary to understand the physical and chemical processes that occur during and immediately following dumping. The brief description of these processes that follows is taken from Segar (1978) updated with information from numerous more recent reports of dredged material dumping research studies, and interpreted to apply to the specific conditions found at the Alcatraz dumpsite.

## A. Physical Processes Occurring After Dumping

The process of physical dispersion of the dredged material after its introduction to the water column is complex and depends upon such factors as water depth and density stratification, composition of the dredged material, and dumping vessel operating techniques.

The nature of the physical dispersion process is well understood. The density of the bulk dredged material is greater than that of the water into which it is introduced. Therefore, it immediately sinks through the water column as a density plume. Since neither the water column nor the dredged material has a uniform density, the dredged material begins to fractionate. If this dredged material is from a fresh water or a lower-salinity environment than the Alcatraz dumpsite, as will most often be the case, the pore waters are of lower density than the dumpsite water and they immediately begin to separate out of the density plume and have a greater tendency to disperse horizontally than does the solid dredged material. Therefore, dissolved components in pore waters of dredged material are distributed in some proportion throughout the depth of the water column at the Alcatraz dumpsite after a dump.

The solid fraction of dredged material is itself heterogeneous and also fractionates. The sand or mineral particles of larger grain size and higher density sink more rapidly than the finer particles, which are predominantly authigenic and organic matter. The extent of fractionation of solids is dependent upon the water depth at the dumpsite. The shallower the depth, the less fractionation occurs before initial impact of the density plume on the bottom sediments. If the water is sufficiently deep, the density plume dissipates before reaching the substrate and becomes a collection of individual particles, each settling at their characteristic velocity (Clark et al, 1971). The depth necessary to dissipate the density plume is a function of dredged material composition, nature of the dumping process, water column density and stratification, and other factors. The water column at the Alcatraz dumpsite is relatively shallow. Therefore, it is likely that: 1) dredged material dumped at the site impacts the bottom sediments as a density plume; 2) the proportion of pore water released during the dredged materials initial fall to the bottom is small; and 3) fractionation of the solids in the dredged material during the initial fall to the bottom is minimal. However, the recent Corps of Engineers requirement that dredged material dumped at Alcatraz must be a slurry of high water content will tend to enhance pore water loss and fractionation during advective descent of the dumped dredged material.

When the density plume of dredged material impacts the bottom sediments, the kinetic energy of the plume is partially dissipated by resuspension of the upper layers of sediments at the impact site, and partially translated into a horizontal plume which disperses near and along the bottom, away from the initial impact site. During resuspension of the upper layers of sediment at the impact site, the pore waters of these sediments (which are primarily dredged material from earlier dumps) are released to the water column. Following initial impact and resuspension, the suspended matter, which is dispersed over a large area of the sea floor (typically tens to hundreds of thousands of square meters), settles out at a characteristic velocity that depends primarily on the particles size and density and the extent of turbulence in the water column at the dumpsite. Dense mineral grains such as coarse sands will settle out rapidly, while the lighter fractions (including organic matter) will remain suspended for a longer period. Therefore, the lighter dredged material is preferentially dispersed (diluted and spread like a smokestack plume as it rises on a windless day) and advected away (carried by currents like a smokestack plume is carried away from the stack by the wind) from the disposal site compared to the denser dredged material (Basco et al, 1974). The Alcatraz dumpsite is specifically selected because its fast tidal currents maximize this dispersion and advection and prevent all but the coarsest dredged material from remaining on the bottom at the dumpsite. The slurry requirement further increases dispersion and advection by preventing cohesive lumps of dredged material from falling all the way to the bottom without breaking up.

The less dense authigenic and organic fractions of dredged sediments contain proportionately larger quantities of the trace metal and organic contaminants introduced to the environment by human activity than do the coarser mineral fractions (e.g., Chen at al, 1976, U.S. Army Engineer District San Francisco, 1975a). Therefore, the net effect of the physical processes occurring during and after the dredged material dumping event is to fractionate these contaminants preferentially to the surface sediment layer and the suspended sediments. Any dredged material permanently buried by continued dumping is enriched in coarse sands compared to the original dredged material. In summary, the dumping process at Alcatraz preferentially fractionates fine materials containing higher contaminant levels to the suspended sediments which are then transported throughout Central San Francisco Bay and beyond (see below). Therefore, although 20% of the total mass of solids in the dredged material are accumulated in the sediments at the Alcatraz dumpsite (U.S. Army Engineer District San Francisco, 1987) the 80% of the solids that are dispersed as suspended sediment contain more than 80% of all the toxic contaminants in the original dredged material.

While the short-term physical fate of the dredged material in the minutes following dumping is well understood and documented, there is little information on the longer-term fate of the contaminant-laden suspended particulates that constitute the bulk of the dredged material. Dredged material particles entering the suspended sediment regime at the Alcatraz dumpsite are carried by currents away from the dumpsite and, like all suspended sediments, are subject to cycles of deposition and resuspension as they are transported. Particles will tend to be deposited on surface sediments where tidal and other current velocities are low and resuspended again when these currents increase. These cycles will continue in the Bay until the particles deposit in areas of consistently low current velocities, or are carried out to sea.

Currents at the Alcatraz dumpsite are dominated by oscillating tidal currents with maximum speeds of about 2.9 knots (150 cm/sec). These currents flow almost due west toward the Golden Gate on the ebb tide, and almost due east toward Treasure Island on the flood tide (Dames & Moore, 1971; Rubin and McCulloch, 1979, Goddard et al, 1985; Winzler and Kelly, 1985). Dredged material dumping at the Alcatraz dumpsite takes place at random times with respect to the stage of the tide. Therefore, suspended solids from an individual dump will be carried away from the site initially in a direction and at a rate determined by the tidal stage when dumping occurred. Dredged material particulates from dumps taking place at slack tide would tend to remain at the dumpsite and accumulate temporarily in the sediments until they are resuspended and/or transported by the increasing currents associated with the next falling or rising tide. Laboratory resuspension studies have shown that maximum tidal current velocities at the Alcatraz dumpsite are sufficiently high to resuspend most of the dredged material particles initially deposited at slack water at the Alcatraz dumpsite, provided that the dredged material that is dumped has a density of 1.3 $g/cm^3$ or less (Teeter, 1987). The fine-grained contaminant-rich fraction of dredged materials has a density of less than 1.3 $g/cm^3$ and is, therefore, resuspended provided it is not in cohesive clumps of mud with low water content. The Corps of Engineers requirement that materials be slurried before disposal at the Alcatraz dumpsite is intended to ensure that clumps of high density mud are broken up and mixed with water (or not dumped). Therefore, during the two years since this requirement was established, essentially all of the fine-grained, contaminant-rich, solid particles dumped in dredged materials at the Alcatraz dumpsite are resuspended and transported by tidal currents away from the dumpsite and into the Bay suspended sediment regime.

The Corps of Engineers states that the typical tidal excursion (the average distance traveled by any parcel of water between high and low tide) through the central and northern reaches of the Bay is about 10 km (5.4 miles) (U.S. Army Corps of Engineers, 1988). However, based on the current meter data for the Alcatraz dumpsite (Winzler and Kelly, 1985), the tidal excursion from the Alcatraz dumpsite (neglecting topography effects) is estimated to be approximately 5 km for near bottom waters and approximately 6 km for surface waters. The differences in these estimates are of critical importance. If the tidal excursion of water from the Alcatraz dumpsite is only about 5 km, then the maximum distance traveled by dredged material suspended particulates before experiencing current direction reversal would only take the particles to about the Golden Gate Bridge if dumping took place exactly at slack high tide, and to about the Bay Bridge if dumping took place exactly at slack low tide. Therefore, contaminated suspended sediment from Alcatraz dredged material would tend to remain in the Central Bay suspended sediment regime for a longer period of time than if the excursion were sufficient to carry the suspended sediment several kilometers into the ocean or into South Bay. The Corps of Engineers have used the hydraulic Bay Model to investigate the fate of dredged material dumped at Alcatraz (Schultz, 1965; U.S. Army Corps of Engineers, 1988). Using these model studies, they estimate that 47% of the material is eventually transported to the ocean, 27% deposits in Central Bay, 22% in upper South Bay, and 2% in San Pablo bay. This study is unreliable since the hydraulic model does not accurately reproduce critical processes such as the resuspension of sediments, the vertical differences in current velocity, and the vertical movements of suspended particles in response to their characteristic settling velocity and turbulence. However, the model study does support a conclusion that a considerable proportion of the contaminated suspended dredged material solids remains for some time in the active suspended sediment regime of Central Bay where biological uptake of contaminants can take place.

Although there is very limited reliable information concerning the long-term fate of suspended dredged material particles in

Central Bay, certain characteristics of this fate can be inferred from basic knowledge of the behavior of suspended particles, following dumping in the marine environment and of the water circulation of the Bay.

First, the contaminated suspended sediments will tend to be concentrated and transported in near bottom water as opposed to surface waters. This is a consequence of 1) the initial dumping process which tends to inject the bulk of the dredged material into the near bottom water with proportionately less in the surface layers, and 2) the tendency of suspended particles to sink to the sediments during low current periods and to be resuspended into the near bottom waters when current velocities rise.

Second, the suspended dredged material particles will tend to be transported and widely dispersed within the western portion of Central Bay (generally to the west of a line drawn from Treasure Island to Angel Island) and to remain in the active suspended sediment regime within this area until it is a) accumulated in sediments of areas where tidal currents are low, including harbors and pier areas of the San Francisco shoreline (particularly between the Bay and Golden Gate Bridges) and Richardson Bay and other embayments on the Marin shoreline; b) transported out to the ocean; c) transported south of the Bay Bridge. Hydraulic model studies have indicated that a substantial proportion (22%) of the dredged material is eventually transported south of the Bay Bridge. These same studies also indicated that a substantial proportion (47%) of the suspended dredged material is eventually transported to the ocean. However, this conclusion is less reliable because the hydraulic model does not accurately reproduce the vertical structure of currents. The suspended dredged material tends to be transported in near bottom waters and, particularly when river flow rates are very low as in the summers of 1986 and 1987, the tendency for estuarine circulation to occur at the Golden Gate (i.e., mean flow out of the Bay at the surface and mean flow into the Bay in bottom waters) will tend to retain the suspended particulates in the Bay. The bulk of the toxics in dredged material dumped at the Alcatraz dumpsite, therefore, remains in the active suspended sediment regime for some time until it is accumulated in quiescent areas along the San Francisco and Marin shorelines. Jenkins and Skelly (1986) have provided experimental evidence that much of the dredged material dumped at Alcatraz most likely accumulates in boat basins along the San Francisco shoreline. There is no direct evidence of accumulation along the Marin shoreline. However, the tidal characteristics of the Bay are such that San Pablo Bay tides begin to rise while South Bay tide is still ebbing. This will lead to mixing and transport of water from the Alcatraz dumpsite toward the Golden Gate by South Bay ebb flow and to the north into Richardson and Elliott Bays and past Angel Island by the flood flow through the Golden Gate. Significantly, toxic contaminant concentrations in sediments in these areas are elevated despite limited local inputs.

In summary, available evidence suggest that 1) the toxic contaminant containing suspended sediments created by dredged material dumping at the Alcatraz dumpsite remain in the suspended sediment regime (and thereby in contact with fish, shellfish, and other biota) of western Central San Francisco Bay for an average length of time that exceeds several tidal cycles and probably several days or weeks, and 2) a large proportion of the toxics containing suspended sediments are eventually deposited in embayments along the San Francisco and lower Marin County shorelines inside the Bay, contributing to the contamination of these sediments.

B. Release of Toxics in Pore Waters and Suspended Particulates.

During the initial dispersal and settling out of the dredged material after dumping, the pore waters dredged with the sediments from their original site, and the water entrained with the sediments during dredging, are dispersed and diluted with disposal site water. The mixed pore waters and entrained dredging site water (hereafter the mixture is referred to as pore fluids) are usually of lower salinity (and density) than the water at the disposal site. Therefore, some of the pore fluids will disperse in the surface waters at the dumpsite. The remainder of these fluids is entrained with the initial convective descent of the dredged material mass and will be mixed upwards into the water column when the dredged material mass impacts upon the Bay floor.

The dispersal of pore fluids during dredging has not been studied extensively in the field. However, the available evidence suggests that the major fraction of the pore fluids is entrained with the solids during convective descent and disperses in the deeper waters, particularly at dumpsites as shallow as the Alcatraz dumpsite. Acoustic studies suggest that rising convective plumes of pore fluids containing fine-grained suspended solids are formed after the breakup of the dredged material mass upon its impact with the sea floor (Proni, personal communication, Proni and Hansen, 1981). It would appear that the dredged material pore fluids are dispersed throughout the water column at the dumpsite. However, the dispersal is not uniform vertically, and it is probable that the major fraction of the dissolved components of the pore fluids is dispersed into the near-bottom waters at the shallow Alcatraz dumpsite.

The pore waters of dredged material may have significant concentrations of both toxic trace metals, organic compounds, and ammonia. Some trace metals may accumulate in the pore waters of sediments to concentrations substantially in excess of those in the overlying water. The available data show that, with the exception of manganese and iron, the concentrations of trace metals in sedimentary pore waters are generally less than ten times higher than the concentrations of the same metal found in coastal sea water (e.g. Elderfield and Hepworth 1975, Blom et al, 1976, Chen et al, 1976). However, the variability of metal concentrations in pore waters at different locations is large, and sediments dredged from any particular region may have anomolously high pore water concentrations of one or more metals. Dilution factors of greater than ten times, should be achieved within minutes after dumping at the Alcatraz dumpsite, effectively reducing the concentration of the released pore water trace metals to concentrations close to the ambient background. Nevertheless, toxic metals released in pore waters are almost certainly totally bioavailable. Therefore, considering the large volumes of dredged material dumped at the Alcatraz dumpsite, pore water release could constitute a significant source of bioavailable toxic metals at the site, and could contribute significantly to the elevated background concentrations of these toxics in Central Bay waters.

The concentrations of toxic organic contaminants in pore waters of sediments are less well-documented than those of trace elements in general. The extremely soluble chlorinated insecticides, toxaphene, and 2,4-D, are present in very small concentrations in some pore waters (e.g. Fulk et al, 1975). In addition, PCB compounds may be present in significantly higher concentrations in pore waters than in the overlying water (Fulk et al, 1975). Since most toxic organic compounds have only limited solubility in water they are generally not released in substantial quantities in dredged material pore waters (Fulk et al, 1975, Lee et al, 1975, Chen et al, 1976). However, toxic organics are preferentially released to the water column in association with suspended sediments during dredged material dumping (Fulk et al, 1975). The suspended toxic organic containing suspended sediment settles out of the water column to the sediments in laboratory experiments where there is no turbulent mixing (Fulk et al, 1975). At the Alcatraz dumpsite, where water column turbulence is high, it is probable that almost all of the toxic organic contaminant load of materials dumped at the dumpsite is carried away from the dumpsite into the suspended sediment regime of the Bay. The toxic organics are preferentially associated with organic rich particles or coatings on particles in the dredged material as are many of the toxic trace metals (Fulk et al, 1975). These organic particles or coatings are a potential source of food for many types of Bay biota ranging from bacteria to filter feeding zooplankton and juvenile fishes. Relatively little is known about the importance of this mechanism as a route for transfer of dredged material toxics into the biota, particularly in San Francisco Bay. However, field studies elsewhere have shown that both toxic organics and toxic trace metals are taken up and concentrated by filter feeding mussels at a dredged material dumpsite during the period when active disposal (and, therefore, exposure to suspended particulates) was taking place (e.g. Nelson at al, 1987, also see section 4.C below). This suggests that the toxic contaminants in dredged material disposed at the Alcatraz dumpsite are probably concentrated by Bay biota from the suspended sediments. Since the toxics in dredged material dumped at the Alcatraz dumpsite remain in the suspended sediment regime in the Bay for extended periods and are transported throughout wide areas of the Bay, it is probable that dredged material toxics are responsible, in part, for the high concentrations of a variety of toxics found in Bay biota particularly in Central Bay.

C. Chemical Processes Affecting Dredged Material Toxics in the Alcatraz dumpsite Environment.

When dredged material is introduced to marine waters, a variety of chemical reactions occur. The dredged material is under the influence of one set of physicochemical conditions (pH, redox potential, ionic strength, temperature) at the dredging site. These conditions are altered during the dredging process and then again upon entry of the dredged material into the disposal environment. Most commonly, the dredged material is subjected to higher pH, redox potential, and ionic strength, and lower temperature at the Alcatraz dumpsite than at the dredging site. One effect of the increased ionic strength is to cause the flocculation of colloidal particles (the so-called "salting out" effect). Upon mixing following the dump, colloidal organic and inorganic matter in the dredged material pore waters will aggregate if the ionic strength of the pore waters is lower than that of the disposal site water (as it will be for a substantial proportion of the dredged material dumped at the Alcatraz dumpsite). The aggregates may contain significant quantities of organic and inorganic contaminants, and they are probably used as a food source by planktonic, nektonic and benthic animals. Therefore, the formation of such aggregates constitutes a mechanism whereby contaminants may be transferred from the dredged material directly into the food chain. However, very little information exists to permit an assessment of the significance of such a pathway in the Alcatraz dumpsite environment.

The altered physicochemical conditions experienced by the dredged material at the disposal site have significant effects on the equilibria between solid and solution phases of the dredged material and mixing water, and as a consequence, various chemical reactions take place. Some of these reactions can have the effect of introducing chemical species to solution, while the reverse (removal of dissolved species) will be the effect of others. The transfers of chemical species between dissolved and solid phases are not instantaneous, but can continue during and after the initial dispersion of the dredged material particulates beyond the boundaries of the dumpsite. Reactions that occur during dispersal of dredged material particulates in saline waters include:

i) Ion exchange. Sediment particles have many ion exchange sites on their surfaces. The metals bound at these exchange sites are determined by the chemical composition of the aqueous phase surrounding them and the nature of the particle surface. As the chemical composition of the water at a dumpsite is different from the water at the dredging site, ion exchanges take place when the sediment particles are subjected to the new environment. These exchanges can be complex. When particles from lower salinity dredging sites are dumped at Alcatraz ion-exchange would generally favor the release to solution of toxic trace transition metals which would be replaced on the particles by the major cations of sea water (e.g. sodium, calcium, strontium). However, since most dredged material dumped at Alcatraz is from relatively high salinity environments the quantities of toxic metals released will be small.

ii) Adsorption-desorption. In addition to ion-exchange sites on the surfaces of sediment particles, there are adsorption sites which can bind inorganic species. Exchanges similar to those occurring at ion exchange sites will occur at these binding sites during the disposal of sediments.

iii) Complexation reactions. Organic compounds and metals, particularly transition metals, form complexes with each other, usually in ring compounds termed chelates. The complexes can be of diverse strengths and solubilities according to the nature of the organic compound involved. The complexes can be dissolved or associated with particles. Some of the toxic metals in such complexes in the dredged material may be released from the complex when mixed with the disposal site water and may become more biologically available and/or toxic. Alternatively some metals may be complexed with organic compounds found in the dumpsite waters and may be rendered less toxic. Little is known about the importance of these processes at dredged material dumpsites.

iv) Redox reactions and precipitation. The altered physicochemical conditions at the disposal site usually include an increase in both the redox potential and the pH. These changes favor the oxidation of sulfide and reduced metal ions and the formation and precipitation of hydroxides. Anoxic dredged material may contain large concentrations of sulfides and reduced metal ions in solution in the pore waters. Oxidation of these is initiated during dredging and transport to the disposal site and continues as the dredged material is dispersed at the dumpsite. If the dredged material contains substantial quantities of oxidizable matter, oxidation at the dumpsite can lead to a drop in the oxygen concentration (or oxygen "sag") in the dumpsite water column. In severe cases where there is little mixing at the dumpsite to resupply oxygen this can lead to anoxia. Oxygen sags have been observed in the near bottom waters of the Alcatraz dumpsite immediately after dumping. However, mixing is very efficient at the Alcatraz dumpsite and these temporary sags do not lead to anoxia. There is little cause to believe that oxygen loss due to dredged material disposal at the Alcatraz dumpsite is sufficiently large to cause harm to the biota. Beside the possible effects on dumpsite dissolved oxygen concentrations, oxidation reactions are important because the principal metals that are oxidized, iron and manganese, both form insoluble hydrated oxides that form colloidal particles or coatings on other particles which may coprecipitate other metals and organic compounds (see v).

v) Coprecipitation. Under appropriate conditions, colloidal hydroxide precipitates are extremely effective scavengers for many of the dissolved trace trace metals and organics of seawater. Trace quantities of various elements and organic compounds are adsorbed and occluded in the hydroxide lattice during its precipitation. This phenomenon is termed coprecipitation. Hydrated iron oxides are formed rapidly after dumping while the oxidation of manganese is slower and hydrated manganese oxides will take several hours to fully form after dumping. Since both of these hydrated oxides can remove a variety of trace metals and organic compounds from solution their precipitation in the dumpsite environment can have the effect of removing toxics from dispersed pore water, toxics released by other mechanisms from dredged material particles, or even toxics from the dumpsite water. Removal of toxics from solution in hydrated oxides may, therefore, reduce the potential toxicity of the dredged material. However, little is known about the importance of this possible toxicity reduction mechanism in the dumpsite environment. Additionally, the biological availability of toxics may be reduced by hydrated oxide coprecipitation, marine organisms including bacteria are known to be capable of re-releasing these toxics from the hydrated oxides.

In view of the diversity of, and complex relationships among, chemical and physical reactions taking place during the initial dispersal of dredged material in the marine environment, it is not surprising that the resulting distribution of chemical contaminants between waters and sediments cannot be predicted at present with confidence. Very limited field studies of the fate of contaminants during San Francisco Bay disposal operations have been carried out (U.S. Army Engineer District San Francisco, 1975b). The data from these studies are limited by the logistic problems of sampling a transient event by the sampling and analysis techniques that were employed in this decade-old study. These techniques are now acknowledged to be poor and somewhat unreliable.

In these studies, 7 hopper dredge loads of polluted sediments from the Oakland Inner Harbor were dumped at an experimental dumpsite about 1 mile east of Angel Island in Central Bay. Immediately after dumping significant increases were observed in dissolved concentrations of lead, cadmium, copper, and chlorinated organics, including PCBs and DDE (a toxic DDT decomposition product). The lead, cadmium, and copper concentrations were elevated 9, 6, and 4 times over background concentrations while PCBs were elevated 10 times and DDE (a toxic, persistent DDT decomposition product) 3 times over background. Although the elevated concentrations did not exceed current State Water Quality Objectives, these data indicate that a significant quantity of these and other toxics are released to solution during dumping of dredged material in San Francisco Bay. These dissolved toxics are almost certainly bioavailable. The elevated concentrations observed in the Corps San Francisco Bay study (U.S. Army Engineer District San Francisco, 1975b) were reduced to background concentrations at the dumpsite within 1 to 1 1/2 hours. However, the Corps conclusion that this reduction was due to dilution or resorbtion by sediments is almost certainly incorrect. Instead, these data reflect the movement of the contaminated cell of water away from the dumpsite (and, therefore, beyond the Corps sampling locations) by tidal currents. This contaminated cell of water was undoubtedly diluted during its transport away from the dumpsite, but most probably was not diluted to background concentrations within little more than an hour as concluded by the Corps. Although the Corps study (U.S. Army Engineer District San Francisco, 1977b) was unsophisticated, it does indicate that dissolved toxic contaminants are released in significant quantities from the dredged material during the dumping process. This would suggest that the continuous dumping of large quantities of dredged material at the Alcatraz dumpsite contributes significant quantities of dissolved toxics to wide areas of San Francisco Bay. Unfortunately, the Corps study has not been repeated at the Alcatraz dumpsite and there are no appropriate data to enable a direct assessment to be made of the quantities of toxics released at the Alcatraz dumpsite.

Laboratory studies of net chemical transfers occurring between sediments and water during dispersal and settling of the sediments in seawater cannot reproduce field conditions. However, these studies may be useful to indicate (qualitatively) the types of processes that may be present in the field. The most exhaustive of these studies are reported by Lee et al (1975). Fulk et al (1975), Blom et al (1976) and Chen et al (1976). Their findings are in agreement with the preceding description of processes occurring at the Alcatraz dumpsite. In summary, their findings include:

i) The initial oxygen demand (first hour) of dredged material after its disposal is significant. If dilution is not rapid and if the ambient water column oxygen concentration is low, regions of anoxic water at the bottom are created. These anoxic regions persist until relieved through mixing and dispersion. In general, mixing rates are high enough to preclude the persistence of anoxia for periods in excess of an hour or more, especially in high-energy environments such as the Alcatraz dumpsite.

ii) Substantial quantities of ammonium ion are released to solution. The concentration of ammonium ion in the disposal site water may reach toxic levels if dilution is not efficient. Phosphate is not normally released to solution, but can be released from certain sediments (particularly if anoxic conditions persist).

iii) Manganese is released to solution in significant quantities. The behavior of other metals depends upon the physical and chemical conditions of the mixing water and the nature of the dredged sediment. In general, other metals are not released to solution in substantial quantities if the dispersion water remains oxygenated. Some metals (particularly zinc) may actually be removed from the dilution water. These data are consistent with the hypothesis that hydrated iron oxide precipitation effectively and immediately removing metals released by other chemical reactions. Cadmium appears to be released slowly (but in significant quantities) from dredged material solids after the initial dispersion, if oxygenated conditions persist as they do at the Alcatraz dumpsite.

iv) Chlorinated insecticides and PCBs are not released to solution when dredged material solids are dispersed in seawater. However, these compounds are preferentially fractionated into suspended particles during dumping. The quantity of the chlorinated compounds in the residual suspended particles increases with increasing concentrations of hydrocarbon contaminants in the original sediments.

v) Significant quantities of as yet unidentified organic compounds are released to solution during the initial dispersion of dredged material.

vi) Differential settling and resuspension of particulates tends to segregate the more contaminated fractions of the sediments into the suspended-sediments and to bury the less-contaminated, coarse sand or mineral grains at the dumpsite.

Based on the results of laboratory studies, including those discussed above, the Corps of Engineers has established the "elutriate" test as a component of their required testing of dredged materials for ocean (and Alcatraz) disposal. This test is intended to simulate the net effect of all the physical and chemical processes acting on toxics within the dredged material during the disposal process. The test is performed by mixing dredged material with water from the dumpsite, then removing the sediment and measuring any increases in the concentrations of dissolved contaminants. Elutriate tests performed on San Francisco Bay dredged materials indicate that significant quantities of some toxic metals and organic compounds are released to solution from most dredged material dumped at Alcatraz. However, the concentrations reached in the elutriate tests seldom exceed State water quality objectives (U.S. Army Corps of Engineers, 1988, U.S. Navy, 1987). Elutriate test data indicate that, although concentrations of toxic contaminants will be elevated in the water column at the Alcatraz dumpsite as a result of dredged material dumping, they will probably not exceed applicable water quality criteria or standards. However, the tests are inadequate for accurate assessment of the quantities of contaminants released to solution. In particular, they do not address the potential for longer-term release of toxics from the dredged material particles that are held in suspended sediments for long periods of time following dumping, as are most of the contaminated dredged material particles dumped at the Alcatraz dumpsite. Unfortunately, the elutriate test more closely reproduces the conditions found at accumulative dumpsites than at dispersive dumpsites like the Alcatraz dumpsite. Yet another limitation of the elutriate tests is that they provide no information about the biological availability of toxics that remain associated with suspended sediment particles after initial mixing with dumpsite waters.

## IV. IMPACTS OF DREDGED MATERIAL DUMPING AT THE ALCATRAZ DUMPSITE

The impacts and potential impacts of dredged material dumping at the Alcatraz dumpsite are varied and complex. Some categories of impacts, such as the effects on benthic organisms in the site sediments, are well understood. However, most potential impacts are poorly understood, because appropriate studies have not been performed or, in some cases, are technically unfeasible at the Alcatraz dumpsite and in the surrounding Bay environment. The very limited understanding of many of the potential impacts that are possible is based upon 1) chemical analyses, bioassays, and bioaccumulation testing of some of the dredged materials dumped, 2) more extensive, but still limited, laboratory studies of dredged materials from areas other than San Francisco Bay, and 3) field studies at dredged material dumpsites in other parts of the United States. Unfortunately, much of this information is not fully applicable to impacts at the Alcatraz dumpsite because studies in the laboratory and at other sites, and the test procedures that are based on these studies, were designed to evaluate impacts at dredged material dumpsites which are accumulative in nature or at sites where flushing (as opposed to dispersion) of the area surrounding the site is extremely effective. Assessment of the potential impacts, particularly the cumulative impacts of continuous dredged material disposal at the Alcatraz dumpsite must take into account its unique nature as a highly dispersive site in an enclosed estuary with limited flushing (compared to open ocean sites), particularly during the summer/fall dry season.

Potential biological impacts of disposal at the Alcatraz dumpsite can be separated into 1) impacts on the benthic community at the dumpsite itself, 2) impacts on benthic communities in accumulative sites of San Francisco Bay to which the dredged material is transported, 3) impacts on the community living in the water column of the Bay.

A. Impacts on Benthos at the Alcatraz Dumpsite

At most dredged material dumpsites, the major biological impact of dumping is on the communities of organisms that live on the surface of and in the bottom sediments. Benthic communities are highly sensitive to a number of interrelated physical and chemical characteristics of their environment including 1) the grain size distribution of the sediments, 2) the amount of organic matter in the sediments, 3) the oxygen or sulfide content of the interstitial and overlying water, 4) the concentrations of toxic contaminants, 5) the stability of the sediments with respect to current and wave-induced suspension, and 6) the rate of accumulation of the sediments. Dumping of dredged material can cause alterations of each of these parameters within and immediately adjacent to the dumpsite. Each of these characteristics has been altered to some extent in sediments of the Alcatraz dumpsite as a result of the continuous historical dumping. The changes that have taken place are not well documented but include some degree of change in each of the characteristics listed above.

As a result of these changes, the benthos at the site have been substantially impacted. The principal impacts have been caused by the burial of the existing bottom sediments throughout the 2,000-ft. diameter circular site and in areas outside the site to approximately 2000 feet beyond the perimeter of the site (U.S. Army Corps of Engineers, 1988). Within this area, the sediments are highly variable and the changing grain size and chemical composition reflect the continuous dumping of new dredged material and the continuous reworking and movement of the deposited dredged material by currents. In response to this variable and changing substrate and the periodic reburial caused by successive dumps, populations of benthic organism are also highly variable in composition and density. The benthos are characterized by species which are tolerant of this rapidly changing environment and which are capable of rapidly recolonizing altered sediments (Liu et al., 1975; Kinnetic Laboratories, 1985).

The extent to which the benthos of the Alcatraz dumpsite and the surrounding area are degraded by dredged material dumping is difficult to assess because of 1) the lack of studies of the site before dumping, 2) the naturally variable nature of the benthic communities in western Central San Francisco Bay due to naturally variable environmental conditions, and 3) the paucity of detailed studies of the impacts of dumping on the benthos, particularly time series studies and studies of the effects of dumping on bottom fish that feed on the benthos. However, the decreased median grain size, increased variability, and increased contamination of the sediments has been found at other, better studied, dumpsites to 1) reduce the biomass, 2) eliminate many benthic infaunal species known to be important in supporting beneficial food chains (to commercially and recreationally important fish and shellfish populations), and 3) reduce populations of bottom feeding fish. It is certain that these effects have also occurred, to some extent, at the Alcatraz dumpsite. However, these impacts are not necessarily permanent, particularly at a highly dispersive site, such as the Alcatraz dumpsite.

The degradation of benthic communities within and surrounding the Alcatraz dumpsite caused by dredged material disposal is undisputed. However, the Corps of Engineers claims that this degradation is not significant because the area affected is only a small fraction of the Bay bottom and because the bottom is already degraded by ongoing and past dumping. In contrast, the Corps of Engineers has stated that "[i]f disposal activities cease, recolonization would be probable with recruitment of a diverse group of opportunistic bottom species" (U.S. Army Corps of Engineers, 1988). In addition, while the area of degraded sediments in and near the Alcatraz dumpsite is small compared to the Bay as a whole, it is a significant fraction of the area of the Bay that is occupied by a deepwater, oceanic influence regime. This regime is restricted to western Central Bay and parts of San Pablo and South Bay and is of critical importance to a variety of bottom fish and shellfish species, including Dungeness crab, speckled sanddabs, diamond and curlfin turbots, sand and English soles, and starry flounder (Armor and Herrgesell, 1985).

B. Impacts on Benthic Communities in Accumulative Sites Remote From the Alcatraz Dumpsite.

As discussed above, the fate of dredged material carried away from the Alcatraz dumpsite as suspended sediments is not well known. However, it is known that the finer-grained, more contaminated dredged material is carried in the suspended sediment regime until it is transported to the ocean or to low energy depositional areas of the Bay. The depositional areas receiving the largest quantities of dredged material suspended sediments are undoubtedly the bottom of the dredged channels nearest to the Alcatraz dumpsite, the enclosed harbors and wharf areas of the San Francisco shoreline and Richardson Bay. These areas are known to have finer-grained sediments with relatively high levels of a broad spectrum of contaminants. In some of these areas, such as Hunter's Point, the level of contamination in the sediments is very high and local sources of contamination are important. However, in most of these areas, particularly Richardson Bay, there are only limited local sources of toxic contamination and the contamination of the sediments reflects high toxic concentrations in the suspended sediments of the adjacent higher energy areas of the Bay. Contaminated suspended sediments are contributed to the Bay from many different sources so that it is not possible to identify the specific source or sources of contamination of sediments in any area of the Bay. However, the following observations are relevant to an assessment of the relative contribution of dredged material dumping:

1) A large proportion of many toxic contaminants entering the Bay (other than through dredged material dumping) are initially transported to and accumulate in low-energy sedimentary environments near the input location. This is the reason for the existence of sediment toxics "hot spots" in many locations within the Bay (Citizens for a Better Environment, 1987).

2) The non-dredged sources of contaminants are primarily located outside of western Central Bay and, therefore, direct inputs of contaminated suspended sediments to this area are small.

3) The quantities of contaminated suspended sediment transported by currents into western Central Bay from South Bay, San Pablo Bay, and eastern Central Bay are highly variable and depend on river flow rate and wind and tide induced mixing. However, the quantity transported is probably not large except during high river flow rates.

4) The quantity of suspended sediment that is estimated (U.S. Army Corps of Engineers, 1988) to be transported annually from the Bay through the Golden Gate to the ocean (1.8-4 million cubic meters) is substantially smaller than the quantity of dredged material dumped annually at the Alcatraz dumpsite (approximately 5-6 million cubic meters).

5) An estimated 120 million cubic meters of sediment are resuspended annually in San Francisco Bay. However, most of this resuspension takes place in shallow areas of South, East Central, and San Pablo/Suisun Bay due to wind-induced mixing (Krone, 1979) and this material is mostly redeposited within these same areas after the winds abate. Therefore, while it is true that dredged material dumping is a small addition to the total suspended sediment regime of the Bay (U.S. Army Corps of Engineers, 1988), the Corps of Engineers has overlooked the fact that dredged material dumping is almost certainly the dominant source of suspended sediments in western Central San Francisco Bay during most of the year.

6) Dredged materials are often substantially more contaminated with a variety of toxics than are the average sediments and suspended sediments of the Bay.

Based on these factors, it is justifiable to conclude that there is a high degree of probability that dredged material dumping at the Alcatraz dumpsite is a substantial, possibly dominant, source of accumulating sediments and their associated toxics contaminant loads in wide areas of the Bay, particularly embayments along the San Francisco waterfront from the Golden Gate to the Bay Bridge (and possibly to the south of the Bay Bridge), and in Richardson Bay and other accumulative locations along the southern Marin County shoreline.

Little is known about the biological effects of the toxic contaminants in these sediments, and it is not known whether these sediments are otherwise chemically or physically altered by the accumulation of dredged material suspended particles. However, sediments in some of these areas are known to be toxic through bioassays and these areas are known to have benthic biota populations that are substantially altered or degraded compared to historical conditions. It is certain that dredged material dumping has contributed to these changes. It is also highly probable that over a period of time toxic contaminant concentrations would be reduced in sediment in these areas if dredged material disposal were terminated at the Alcatraz dumpsite and not moved to another Central Bay location.

C. Impacts on Water Quality, Plankton, and Nekton

While the impacts of dredged material dumping on benthic communities within the dumpsite are relatively well studied and understood, impacts on free-swimming or floating organisms are much less well studied and understood, partly because of the greater technical difficulties associated with studies of such impacts. Impacts on benthic organisms that reside outside the immediate area of the dumpsite but that are exposed to dissolved or suspended particulate components of the dredged material are also difficult to study and poorly understood. The difficulty of studying impacts beyond the dumpsite sediments is caused by several factors primarily 1) the mobility of planktonic and nektonic organisms that prohibit sampling of organisms in the field that have a known history of exposure to the dredged material plume, 2) the difficulty of performing laboratory studies which can reproduce the variable exposure to the dredged material plume that is experienced by the organism in the natural environment, 3) the lack of suitable dumpsites for study where the dispersing dredged material plumes are transported within a known area that is not also impacted by other anthropogenic influences, and 4) the subtlety of the anticipated sublethal and/or long-term impacts and the consequent difficulty in observing such effects in the naturally highly variable ecosystems around most dredged material dumpsites including the Alcatraz dumpsite. Because of these difficulties, the regulatory evaluation of potential impacts in the water column relies heavily on short-term bioassay tests and water quality evaluations that address lethal effects within the dredged material plume during the first four hours after dumping. The required tests are a suspended sediment bioassay and an "elutriate" test.

The elutriate test is performed by shaking the dredged material with four times its volume of water from the disposal site, removing the solids and measuring the concentrations of various contaminants in the remaining solution. These concentrations are then compared with water quality standards or objectives and with the concentration of contaminants in water from the dumpsite. For most dredged material samples from San Francisco Bay, these tests show that a variety of contaminants are released to solution resulting in higher concentrations in the elutriate than in the untreated dumpsite water. However, the resulting concentrations of toxics in the elutriate rarely exceed the applicable water quality objectives. In these rare instances where the elutriate concentration exceeds the water quality objective, the actual concentration is such that the dilution likely to occur at the dumpsite within a few minutes after dumping would reduce the toxic concentration below the water quality objective. Based on these data, it is concluded that acute toxicity to non-benthic organisms due to the release of contaminants to solution is unlikely to be caused by dredged material dumping at the Alcatraz dumpsite. While this is a valid conclusion, it must be remembered that this does not address the potential for 1) acute toxicity due to the combined synergistic effects of several toxic contaminants in solution each at concentrations below their water quality objectives, 2) acute toxicity due to the combination of dissolved and suspended particulate toxics, and the physical effects of suspended solids, and 3) the potential for long-term and/or chronic effects due to continuous dumping at the Alcatraz dumpsite.

The regulatory evaluation processes attempt to address the potential for these other types of impacts through suspended phase bioassays, including the application of a "safety factor" to the results of these bioassays. There are many problems with the interpretation and application of the results of these suspended sediment bioassays to the Alcatraz dumpsite. First, the tests do not properly reproduce the actual conditions that occur at the Alcatraz dumpsite. The suspended sediment phases used in these tests are prepared by mixing dredged materials with four times their own volume of water from the dumpsite (or often from some other "comparable" location), allowing the mixture to settle in a laboratory container for an hour (or allowing less settling time, but centrifuging) and then decanting the water carefully off the deposited sediments. The decanted water is called the "suspended sediment phase." This procedure is probably adequate to simulate the suspended sediment phase at accumulative dumpsites where currents are slow. However, it does not accurately reflect the suspended sediment phase formed at the Alcatraz dumpsite where the majority of the dredged material particles enter the suspended sediments. It is likely that the concentrations of toxic contaminant containing, fine-grained solids, particularly in near bottom waters that are transported away from the Alcatraz dumpsite, remain substantially higher than the concentrations in the "suspended sediment phase" tested (corrected for initial dilution) for a considerable time after each dump. The suspended phase bioassays, therefore, probably underestimate the toxicity of dispersing dredged material plumes transported away from the Alcatraz dumpsite either immediately after dumping or by tidal current induced resuspension of material temporarily deposited at the Alcatraz dumpsite. Since the suspended sediment concentrations of the "suspended sediment phase" used for suspended sediment bioassays is not reported, and the suspended sediment measurements in the water column at and around the Alcatraz dumpsite are poor, it is difficult to assess the degree to which the suspended sediment bioassays may underestimate the toxicity of suspended dredged material sediments in Central Bay.

Suspended sediment bioassays performed on sediments from San Francisco Bay show that the "suspended sediment phase" from many of these sediments does exhibit both lethal and sublethal toxicity to several different species (U.S. Army Corps of Engineers, 1988; U.S. Navy, 1987; Word et al., 1988a, 1988b). Regulations require that this phase should be non-toxic after four hours of dispersion following a dump. There is a possibility that test species are less sensitive to toxicity than species found in the Bay, and that chronic toxicity may occur at concentrations below those at which laboratory acute or chronic toxicity is observed. To allow for this, the Ocean Dumping regulations require that the concentration of the suspended phase after 4 hours of dispersion be less than 0.01 times (100 times more diluted) than the lowest concentration shown to cause a lethal or sublethal response in 50% of the test organisms. While this "safety factor" is not required by the more lenient Clean Water Act regulations that apply to dumping at the Alcatraz dumpsite, the Corps of Engineers has adopted a policy that this safety factor must be met at this estuarine dumpsite. To determine compliance with this requirement, a mathematical model is used to calculate the dilution of the suspended phase achieved in 4 hours after dumping at the Alcatraz dumpsite. This concentration is then compared to a limiting permissible (maximum allowable) concentration calculated by applying the safety factor to the minimum concentration shown by the bioassays to cause a detrimental response in 50% of the test organisms of the most sensitive species tested.

Although dredged materials dumped at Alcatraz almost all show toxicity in suspended sediment bioassays, until recently, it was thought that all such dredged materials did not exhibit sufficiently high toxicity to violate the limiting permissible concentrations. However, Segar (1988) has recently identified erroneous assumptions in the modeling calculations used to calculate 4-hour dilutions of the suspended phase at the Alcatraz dumpsite. When these errors are corrected, many of the dredged materials tested are found to be sufficiently toxic that they exceed the limiting permissible concentrations. Since violation of these limiting permissible concentrations is taken by regulation to be presumptive proof that unacceptable biological impacts may occur, this finding raises concern that the suspended sediment phase of dredged materials dumped at Alcatraz may adversely impact the non-benthic biota of Central Bay. This is an important finding that requires detailed further scientific review particularly as:

1) the suspended sediment bioassay test procedures probably underestimate the suspended dredged material sediment concentrations in plumes leaving the Alcatraz dumpsite,

2) the modeling calculations used to compute the dilutions achieved within 4 hours after dumping probably underestimate the actual dilution in near bottom waters due to the highly dispersive nature of the site, and

3) the persistence of high concentrations of the suspended phase at and surrounding the Alcatraz dumpsite is probably much greater than accounted for in the test procedures due to a) the cumulative impact of continuous multiple dumping, and b) the tendency of suspended sediment plumes to be transported in such a manner that, after initial dilution, they revisit the Alcatraz dumpsite on successive tidal cycles (particularly when river flow is low).

Since 1986, the Corps of Engineers has required that, as far as possible, dredged material dumped at the Alcatraz dumpsite should be "slurried" to reduce the accumulation of dredged material and shoaling of waters at the dumpsite. One effect of this requirement is to increase the quantities and concentrations of suspended sediments transported from the dumpsite into the Central Bay water column and suspended sediment regime. There has been considerable controversy concerning the effects of this increased dispersion of suspended solids from the dumpsite. Recreational fishermen have reported that during the 2 years since the slurry requirement was introduced, the frequency of high turbidity conditions in Central Bay has increased and the sport fisheries for striped bass, salmon, halibut, shark, perch, founder, croaker, and sturgeon in this area have been adversely affected (United Anglers, 1987). The fishermen's observations of fisheries decline and higher turbidity in Central Bay have been supported by data analyses performed by the Department of Fish and Game, State of California (1987). Both the Department of Fish and Game, State of California (1987) and the National Marine Fisheries Service (1987) have concluded that there is strong evidence that the slurry requirement may have caused higher turbidity in Central Bay that, in turn, may have caused a decline in fish stocks.

However, the Corps of Engineers claims that turbidity resulting from dredged material dumping is of short duration and cannot have caused either a general increase in turbidity or deleterious effects on fish.

The Corps of Engineers arguments are supported by a) their observations that the increased turbidity created at the Alcatraz dumpsite immediately after a dump disappears rapidly and, b) by their contention that the suspended sediment loading due to dredged material dumping is very small compared to the Bay's total suspended sediment load. Both of these observations, while correct according to the data presented, are misleading. First, while the turbidity plume created immediately following a dump does undoubtedly both disperse and disappear from the site within an hour or two after dumping, its disappearance is most likely due to transport of the plume away from the site by tidal currents. Turbidity may remain high in the plume as it is transported from the site beyond the turbidity monitoring network at the dumpsite. If dumping takes place at slack tide, the turbid plume may be reduced by temporary sedimentation but a turbid near-bottom plume will be created during subsequent periods of high tidal current velocity. In addition, most observations of the turbid plume at and near the Alcatraz dumpsite are made in surface waters, not in the near-bottom waters where the turbidity concentrations will be highest. Second, although the dredged material suspended solids load due to dredged material dumping is small compared to the Bay's total suspended sediment load, the dredged material suspended solids load is probably by far the dominant source of suspended sediments in west Central Bay. The vast majority of the Bay's suspended sediment load is maintained in the water column of shallow areas of Berkeley Flats, South Bay, San Pablo Bay, and Suisun Bay. The predominantly deeper, oceanic-influenced west Central Bay should, in the absence of dredged material disposal, have much lower turbidity than other parts of the Bay, except during high outflow periods. The high background turbidity observed in west Central Bay is most likely caused at least partially by the dredged material particulates dumped at the Alcatraz dumpsite that "are expected to remain suspended for a considerable time due to the water currents existing within the Bay" (U.S. Army Corps of Engineers, 1988).

It appears that considerable evidence exists that 1) turbidity and/or the persistence and frequency of turbid plumes has increased in west Central Bay during 1986 and 1987, 2) fishing success for several species has substantially declined in Central Bay during 1986 and 1987, 3) dredged material disposal is a major, perhaps dominant, contributor to the suspended sediment loads of west Central Bay, and 4) the slurry requirement established in 1986 undoubtedly caused an increase in the percentage of dredged materials introduced to the suspended sediments at the Alcatraz dumpsite and, therefore, an increase in the loading rate of suspended sediments in the area. Considerably more evidence would be necessary to unequivocally demonstrate or reject the existence of cause-and-effect relationship between the slurry requirement and reduced fish populations and fishing success. However, the available evidence suggests that such a relationship is at least possible. It is relevant to point out that such a cause-and-effect relationship may exist even if other factors also contributed to the dramatically decreased fishing success in Central Bay during 1986 and 1987. It is also intriguing to propose an alternate hypothesis that the mechanism involved in such a cause-and-effect relationship may not be related to increased turbidity per se. Instead, fisheries decline may be related to toxics in the suspended sediment phase released at the dumpsite. Increased concentrations of dredged material derived toxics in the suspended sediments regime of Central Bay are a certain consequence of the slurry requirement. The observed toxicity of the suspended solid phase of dredged materials dumped at Alcatraz lend support to such a hypothesis. Clearly, this issue requires considerably more detailed and extensive research.

In addition to the possibility that dredged material toxics in suspended sediments are sublethally toxic to benthos and non-benthos of the bay, there exists the additional possibility that these toxics may enter the food chain in significant quantities and contribute to the high levels of a variety of toxics found in the tissues of Bay biota. It has not been demonstrated unequivocally that the high toxics body burdens of Bay biota are detrimental to the organisms or the ecosystem. However, it is generally acknowledged that detrimental effects due to the high toxics body burdens are likely, and that the elevated toxics concentrations in the Bay and Bay biota may be responsible, at least in part, for the historical population declines of numerous commercially, recreationally, and ecologically important species in the Bay. It is very difficult to assess the contribution of dredged material disposal to the toxics loadings of Bay biota. Scientific research studies, although admittedly difficult, have simply not addressed this question at a dispersive dumpsite like the Alcatraz dumpsite. In addition, laboratory tests which could aid assessment of this question have not been performed on dredged materials dumped in San Francisco Bay. Despite the paucity of studies, several observations can be made concerning the potential contribution of dredged material toxics to the elevated toxics loading of Bay biota.

1) As discussed above, even when corrected to account for burial of some toxics in sediments at the Alcatraz dumpsite and for the non-bioavailability of some proportion of many toxic metals because they are strongly bound to sediment particles, the dumping of dredged material at the Alcatraz dumpsite introduces (or reintroduces) very large quantities of toxics compared to any other individual source. Dredged material disposal is the dominant source of toxics in Central Bay and the only major source in the western portion of Central Bay, an area that is somewhat isolated from rapid mixing with other parts of the Bay.

2) Although data are very limited, toxic contaminant concentrations in organisms (including non-mobile organisms) from west Central San Francisco Bay are generally of the same order of magnitude as those found in other parts of the Bay where almost all of the major toxics inputs (both point and non-point) are located. If dredged material inputs of bioavailable toxics in western Central Bay were small the concentrations of toxics in biota of this part of the Bay should be substantially lower than elsewhere in the Bay because of the diluting influence of clean ocean water. In other words, there should be a pronounced gradient of contaminant concentrations from South Bay and San Pablo Bay toward the ocean. No such gradients have been observed.

3) No bioaccumulation tests have been performed on the suspended sediments phase of dredged materials dumped at the Alcatraz dumpsite. However, solid phase bioaccumulation tests do show significant bioaccumulation of a variety of toxics. This suggests that toxic contaminants associated with the

solids are bioavailable and will be taken up by organisms from dredged material suspended sediments. Suspended sediment bioaccumulation tests are under development and have been applied to highly contaminated sediments from areas other than San Francisco Bay. These tests show that bioaccumulation of toxics from dredged material suspended particles does take place.

From these observations, it is clear that there is a high degree of probability that dredged material dumping at the Alcatraz dumpsite is a contributing factor and perhaps the dominant factor, in creating and sustaining high concentrations of various toxics in Bay biota, particularly in west Central Bay and adjacent areas.

To summarize, we know little about the effects of dredged material dumping on the quality of Bay waters and on the fish and plankton except that the rapid dispersion of dredged material at the site reduces dissolved toxics concentrations below those that are likely to be lethally toxic. However, the overwhelming weight of evidence that is available suggests that dredged material disposal at the Alcatraz dumpsite plays a major role in maintaining elevated toxics concentrations in the environment and biota of west Central Bay and probably beyond. The evidence also suggests that the dumping may cause sublethal or long-term lethal effects on Bay biota and, therefore, that the dumping contributes substantially to the observed environmental degradation of the Bay.

A recent research program on the effects of disposal of dredged material in Long Island Sound conducted jointly by the Corps of Engineers and the Environmental Protection Agency provides valuable evidence to support the conclusion that dredged material dumping is detrimental to San Francisco Bay ecosystem. This program applied state-of-the-art research techniques in an intensive study of the fate and effects of contaminated dredged material dumped at a site that was remote from other sources of toxic contamination. The observations of this study are not directly applicable to the Alcatraz dumpsite because 1) the dredged material dumped at the Long Island Sound site was grossly contaminated with several toxic metals and organics to concentrations that exceed those found in dredged materials dumped at Alcatraz, 2) dumping was not continuous, 3) the quantity of dredged material dumped in Long

Island was very small compared to the annual dumping rate at the Alcatraz dumpsite (50,000 $m^3$ or about 5 days of average dumping at Alcatraz), and 4) the Long Island dumpsite is an accumulative site where bottom currents are slow and a large proportion of the toxics in the dredged material are buried at the site in a dredged material mound. Except for the difference in degree of contamination, these factors would tend to minimize the effects of toxics on biota at the Long Island site compared to the Alcatraz dumpsite. However, since the Long Island dredged material was more heavily contaminated with toxics, the findings of the Long Island study should provide an acceptable qualitative analog of the nature of biological effects and bioaccumulation (other than in benthic biota at the site itself) that occur at the Alcatraz dumpsite and in the west Central Bay dredged material dispersal area. The following are some of the relevant findings of the Long Island study:

1) A variety of toxic metals and organic compounds were significantly bioaccumulated by mussels and worms exposed to dredged material suspended sediments both in the laboratory and at the dumpsite (Lake et al. 1988, Zaroogian et al. 1988). In fact, in the laboratory, "contaminant uptake patterns in M. edulis [mussels] were directly related to BRH [Black Rock Harbor] suspended sediment concentrations" (Lake et al., 1988).

2) Long-term (months to years) bioaccumulation studies may be necessary to determine the extent of bioaccumulation by organisms exposed to contaminated sediments and suspended sediments. PCB concentrations were still increasing in worms after almost two months of exposure to sediments (Lake et al. 1988). Equilibrium concentrations of PCBs were reached in about a month and a half in suspended sediment bioaccumulation tests (Lake et al. 1988). Suspended phase bioaccumulation tests are not performed on dredged materials dumped at the Alcatraz dumpsite. Solid phase bioaccumulation tests for dredged materials dumped at the Alcatraz dumpsite use only a 10-day exposure period.

3) "Negative biological effects" were detected in mussels exposed to very low concentrations of suspended dredged material particles both in the laboratory and in the field (Nelson et al. 1987). Three measures of the health of the

mussels metabolic processes, scope for growth, clearance rates and shell growth rate were all reduced at suspended dredged material particulates at concentrations as low as 1.5 mg/l in the laboratory. Reduced scope-for-growth was observed in the field where exposure was estimated to be to 0.2-0.7 mg/l of suspended dredged material particles (Nelson et al. 1987).

4) Similar negative effects, physiological changes in metabolic rates, were observed in the polychaete worm, Nephtys incisa, exposed to suspended dredged material particles at somewhat higher concentrations both in the laboratory and in the field (Johns and Gutjahr-Gobell, 1988).

5) Laboratory exposure of mussels (Mytilus edulis), amphipods (Ampelisca abdita), and polychaete worms (Nephtys incisa and Neanthes arenaceodentata) to dredged material suspended sediment caused histopathological changes (Yevitch et al. 1986, 1987). Histopathological changes are changes in the microscopic structure of the tissues of various organs that are related to, or cause, negative effects on the growth or reproduction of the organisms. In mussels, histopathological effects were found in gills, gastrointestines, reproductive organs, and kidneys at exposure levels as low as 3 mg/l. Similar adverse effects were not seen in the field where suspended sediment concentrations were lower due to the non-dispersive nature of the dumpsite.

6) Adverse effects on growth, reproduction, and population growth were observed in a shrimp (Mysidopsis bahia) and an amphipod (Ampelisca abdita) exposed to low concentrations of suspended dredged particles (Gentile et al., 1987). Adverse effects on population growth of A. abdita were observed at suspended dredged material particulate concentrations as low as 1.1 mg/l.

7) The polychaete worm (Nephtys incisa) showed evidence of mutagenic effects of exposure to dredged material suspended sediments both in the laboratory and in the field, through application of a cytogenic technique known as sister chromatid exchange (Pesch et al. 1987). The concentrations of the two most likely carcinogens, chromium and benzo(a)pyrene (a petroleum hydrocarbon) in the Black Rock Harbor sediments used in these experiments are not substantially higher than found in dredged materials from some parts of San Francisco Bay.

In summary, the state-of-the-art studies in Long Island Sound have established evidence that toxic contaminants in dredged material suspended particulates are significantly bioaccumulated by various species of marine organisms, and substantial evidence that this bioaccumulation or other effects of dredged material suspended particulates causes a variety of sublethal detrimental biological effects on these species. The disposal of San Francisco Bay dredged dredged materials at the Alcatraz dumpsite is not directly comparable to the dumping of Black Rock Harbor dredged material at the Long Island Sound dumpsite. Because the concentrations of several toxics in Black Rock Harbor dredged material substantially exceed those in dredged materials disposed at the Alcatraz dumpsite both bioaccumulation and biological effects would be expected to be greater at the Long Island Dumpsite than in San Francisco Bay. However, because the Alcatraz dumpsite is highly dispersive and the Long Island dumpsite is non-dispersive, the San Francisco Bay biota is probably exposed to higher concentrations of dredged material suspended solids over a larger area than is biota near the Long Island Sound dumpsite. In addition, exposure in San Francisco Bay is continuous compared to the transient exposure at the Long Island dumpsite where a limited amount of dredged material was dumped over a short period of time and where resuspension of the dredged material after dumping is substantially less than at the Alcatraz dumpsite.

It is, as yet, unclear whether the observed bioaccumulation and sublethal effects in the Long Island study are evidence that the dredged material disposed has a major deleterious effect on the Long Island Sound ecosystem. In addition, there can be no certainty that the effects observed in the Long Island Sound study would also be observed in San Francisco Bay, unless similar studies are performed in San Francisco Bay and on Bay dredged materials. However, the Long Island studies provide strong evidence that the suspended sediments and their toxics loads introduced to the Bay can, and most likely do, bioaccumulate, cause negative biological effects and, therefore, degrade water quality. These negative effects may be partially or largely responsible for the observed degradation of the Central Bay ecosystem and the decline of its fish and shellfish populations. This hypothesis, that is supported by the recent studies, contradicts the prior Corps of Engineers conclusion that suspended dredged material particulates have no significant environmental impact in the San Francisco Bay ecosystem. This Corps of Engineers conclusion is based on older studies and inadequate testing data. Clearly, state-of-the-art studies are critically needed in San Francisco Bay.

## V. SUMMARY

This preliminary assessment of the effects of dredged material dumping at the Alcatraz dumpsite has identified substantial information that is relative to the assessment of these effects that has not been comprehensively analyzed to address cumulative impacts. While this report is not itself such a comprehensive assessment, we have identified a number of areas where our knowledge is relatively sound and a number of areas where significant questions remain.

### A. Major conclusions supported by existing information:

1) The quantity of toxic contaminants dumped at the Alcatraz site in dredged materials is very large. Even when allowances are made for the burial of some fraction of the toxics in sediments at the site and for the non-bioavailability of the fraction of toxic metals that is strongly bound within mineral grains, the quantity of some toxic metals and organics introduced to the Bay's water and suspended sediments annually is larger than quantities introduced annually by all of the municipal and industrial discharges to the entire Bay-Delta system. The Alcatraz site is essentially the largest single point source of toxic pollutants to Bay waters.

2) The majority (approximately 80%) of the dredged material dumped at the Alcatraz site is not permanently deposited in the bottom sediments of the site. Strong tidal currents sweep dredged material away from the site as suspended particulates either before the dredged material settles on the bottom or by resuspension of dredged material temporarily deposited in the dumpsite sediments during slack water periods. Toxic metals and organic pollutants are preferentially concentrated in the fine grained fraction of dredged materials. The fine grained fraction of dredged

material is preferentially resuspended and transported away from the dumpsite compared to the less-contaminated, coarse sand fractions. Therefore, a very large percentage (greater than 80%) of the toxic contaminants in dredged material dumped at the Alcatraz dumpsite enter the suspended sediment regime of Central San Francisco Bay where they may be transported long distances before being deposited permanently in the sediments or transported to sea.

3) Little data exists concerning the fate of the suspended sediments created by dredged material dumping at the Alcatraz site. However, it is apparent that these suspended sediments remain in Central San Francisco Bay for some time and are deposited and resuspended many times before leaving the Central Bay suspended sediment regime. During the extended period of time that the contaminated particles remain in the suspended sediments, the toxic contaminants in these particles are potentially bioavailable. Since most suspended sediment movement takes place in the few meters above the sediments, bottom dwelling or bottom feeding organisms are potentially the most affected.

4) Despite the lack of field data, it is apparent that a large proportion of the contaminated, dredged material suspended particles introduced at the Alcatraz dumpsite are eventually deposited in quiescent areas in Central Bay. These areas include the piers, marinas and embayments along the San Francisco shoreline between the Golden Gate and Bay Bridges, and Richardson Bay and other embayments along the Marin county shoreline. Smaller amounts of the contaminated suspended sediments are probably transported a) south of the Bay Bridge where they may accumulate along the San Francisco shoreline, b) through the Golden Gate to the ocean sediments, and c) to depositional sites on the flanks of the deep channels in the Bay. Dredged material dumping, therefore, contributes to the contamination of the bottom sediments in all these areas.

5) During the dispersion of dredged material as suspended sediments in the Bay, toxic contaminants are released to solution and dissolved oxygen is consumed. Existing data suggest that the rapid initial dispersion and dilution of dredged material in the Bay prevents the dissolved toxics concentrations in the dispersing plume from exceeding water quality objectives and minimizes depletion of dissolved

oxygen. However, because the quantities of dredged material dumped are very large, the total quantities of toxics released to solution are probably substantial and may be sufficiently large to have an influence on the background levels of toxics in Central San Francisco Bay waters.

6) Recent state-of-the-art studies of suspended sediments created by dumping of contaminated dredged material have demonstrated that toxic contaminants that remain associated with particles after initial dispersion are bioaccumulated, and can cause a variety of sub-lethal, adverse responses in organisms living in the vicinity of a dumpsite. These studies were carried out at a dumpsite in Long Island Sound that is not dissimilar to the Alcatraz site. State-of-the-art studies have not been performed in San Francisco Bay. However, suspended sediment bioassays have been performed on many samples of San Francisco Bay dredged materials. There are recently discovered errors in the regulatory interpretation of these test results. When these errors are corrected, the tests show that many of the dredged material samples tested are sufficienty toxic (after allowing for initial dilution at the dumpsite and applying a required regulatory safety factor) that adverse toxic effects on Bay biota due to suspended sediment toxicity at the Alcatraz dumpsite are possible. In fact, many samples of dredged material tested would be prohibited from disposal at the Alcatraz dumpsite because of these test results if dumping at this site was regulated under the Ocean Dumping Act rather than the Clean Water Act that applies within the Bay.

7) Suspended sediment created by dumping at the Alcatraz dumpsite could contribute to the turbidity of Central Bay waters. If turbidity is high enough, adverse effects on phytoplankton production and sub-lethal effects including avoidance reactions could occur in fish and shellfish. Accordingly, increased turbidity has been implicated in the recent declines of various fisheries stocks in Central Bay. Available evidence shows that the incremental turbidity associated with dredged material plumes is probably too small compared to the normal background range of turbidity in Central Bay to support a conclusion that these adverse effects are caused by dredged material plume turbidity. However, the very large quantities of suspended sediments introduced to the Central Bay suspended sediment regime by dredged material

dumping may be sufficiently large to significantly increase the background levels of turbidity in Central Bay, particularly during the dry season when other source of suspended sediments from outside Central Bay are small. In addition, the suspended sediments introduced to Central Bay by dredged material dumping are toxic (see 6) and it is possible that the observed fisheries declines are at least partly due to this toxicity.

8) The benthic (bottom dwelling) biota in sediments from within the Alcatraz dumpsite and in areas surrounding the dumpsite are degraded by dredged material dumping. The area of degraded sediments is a significant proportion of the deep water habitat of San Francisco Bay that is important to various fish, shellfish, and other species. The degradation is probably not permanent. The benthic ecosystem would most likely recover if dumping were terminated, although the recovery would take a number of years.

B. Major areas where more information is needed

1) Better data is needed to enable more accurate estimates of the total quantities of toxic contaminants dumped at the Alcatraz site. All dredging projects should be sampled adequately and the materials to be dumped analyzed for a wide range of toxic pollutants. Fractionation studies are needed to characterize the fraction of toxic metals in dredged materials that is strongly bound within mineral lattices (and presumably non-bioavailable).

2) More detailed information is needed concerning the fate of dredged material suspended sediments. The processes of deposition and resuspension at the dumpsite throughout a tidal cycle are not well known. Therefore, it is not possible to estimate the suspended sediment concentrations that organisms would encounter in and around the dumpsite particularly in the bottom meter or two where many species live and feed. The movement of suspended sediment particles through the Central Bay suspended sediment regime after initial dispersion is inadequately characterized. Therefore, it is not possible to accurately estimate the contribution of dredged material to the background levels of turbidity, suspended sediments, and suspended sediment toxics loads in Central Bay. It is also not possible to determine the

contribution of dredged material dumping to the siltation of Central Bay shoreline embayments or to the toxics concentrations of sediments in these embayments.

3) State-of-the-art, sub-lethal toxicity and bioaccumulation studies of dredged material dumped at the Alcatraz dumpsite are critically needed. These studies should be performed both under controlled laboratory conditions and in the field at the dumpsite itself. Field studies are essential to an understanding of the cumulative effects of multiple dumps taking place continuously at the site.

4) There is a need for hybrid models of the suspended sediments and dissolved components of Central San Francisco Bay that incorporate existing dispersion and mixing models. These models would provide information necessary to assess the cumulative effects of multiple continuous dumping at the Alcatraz site on the background suspended sediment, turbidity, dissolved and suspended sediment toxics concentrations of Central San Francisco Bay.

Much of the data needed to address the identified research needs undoubtedly already exists. However, the data is scattered in many documents and computer databases, including numerous unpublished and limited-availability, technical reports and permit applications.

## REFERENCES


Armor, C., and P.L. Herrgesell. 1985. Distribution of fishes in the San Francisco Bay estuary between 1980 and 1982. In J.E. Cloern, and F.H. Nichols, eds. Temporal dynamics of an estuary: San Francisco Bay. Hydrobiologia. Vol 129.

Basco, D.R., W.A. Dunlap, and A.H. Bouma. 1974. Assessment of the factors controlling the long-term fate of dredged material deposited in unconfined subaqueous disposal areas. Technical Report D-74-8, U.S. Army Engineer Waterways Experimental Station, Dredged Material Research Program, Vicksburg, Miss.

Blom, B.E., T.F. Jenkins, D.C. Leggett, and R.P. Murmann. 1976. Effects of sediment organic matter on migration of various chemical constituents during disposal of dredged materials. Technical Report D-76-7, U.S. Army Engineer Waterways Experimental Station, Dredged Material Research Program, Vicksburg, Miss.

Chen, K.Y., S.K. Gupta, A.Z. Sycip, J.C.S. Lu, M. Knezevic, and W.W. Choi. 1976. Research study on the effects of dispersion, settling and resedimentation on migration of chemical constituents during open-water disposal of dredged materials. Technical Report D-76-1, U.S. Army Engineer Waterways Experimental Station, Dredged Material Research Program, Vicksburg, Miss.

Citizens for a Better Environment. 1987. Toxic hot spots in San Francisco Bay. Citizens for a Better Environment, San Francisco, California.

Clark, B.D., W.F. Ritall, D.J. Baumgartner, and K.V. Byram. 1971. The barged ocean disposal of wastes: A review of current practice and methods of evaluation. EDP Interim Report, NTIS PB 204 868.

Dames and Moore. 1971. Foundation investigation, North Point submarine outfall line, San Francisco, California. Unpublished report prepared for the City and County of San Francisco.

Dayal, R., M.G. Heaton, M. Fuhrmann, and I.W. Duedall. 1981. A geochemical and sedimentological study of the dredged material deposit in the New York Bight. Technical Memorandum OMPA-3, National Oceanic and Atmospheric Administration, Boulder, Colorado.

Department of Fish and Game, State of California. 1987. Letter from P. Bontadelli, Acting Director, In: Oakland Harbor. Final Supplement 1 to the Environmental Impact Statement, Alameda County. U.S. Army Corps of Engineers, San Francisco District, San Francisco California.

Eaton, A. 1979. Leachable trace elements in San Francisco Bay sediments: Indicators of sources and estuarine processes. Environ. Geol. 2(6): 333-339.

Elderfield, H.W., and A. Hepworth. 1975. Diagenisis, metals and pollution in estuaries. Mar. Pollut. Bull. 6: 85-87.

Fulk, R., D. Gruber, and R. Wullschleger. 1975. Laboratory study of the release of pesticide and PCB materials to the water column during dredging and disposal operations. Technical Report D-75-6, U.S. Army Engineer Waterways Experimental Station, Dredged Material Research Program, Vicksburg, Miss.

Gentile, J.H., K.J. Scott, S.M. Lussier, and M.S. Redmond. 1987. The assessment of Black Rock Harbor dredged material impacts on laboratory population responses. Technical Report D-87-3, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Goddard, T.C., M.L. Stevenson, and G. Gillingham. 1985. San Francisco Bay dredged material disposal site survey. Report prepared for the U.S. Army Corps of Engineers, San Francisco District.

Gunther, A.J., J.A. Davis, and D.J.H. Phillips. 1987. An assessment of the loading of toxic contaminants to the San Francisco Bay-Delta. Technical Report, Aquatic Habitat Institute, Richmond, California.

Jenkins, S.A., and D.W. Skelly. 1986. Site suitability study for sedimentation control. Technical Report prepared for the Port of San Francisco, San Francisco, California.

Johns, D.M., and R. Gutjahr-Gobell. 1988. Bioenergetic effects of Black Rock Harbor dredged material on the polychaete<u>nephtys incisa</u> a field verification. Technical Report D-88-3, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Kinnetic Laboratories Inc. 1985. San Francisco Bay dredged material disposal site survey. Report prepared for the U.S. Army Corps of Engineers, San Francisco District, California.

Krone, R.B. 1966. Sedimentation in the San Francisco Bay System. In T.J. Conomos (ed.) "San Francisco Bay, The Urbanized Estuary. American Association for the Advancement of Science. pp. 85-96.

Lake, J.L., W. Galloway, G. Hoffman, W. Nelson, and K.J. Scott. 1988. Comparison of field and laboratory bioaccumulation of organic and inorganic contaminants from Black Rock Harbor dredged material. Technical Report D-87-6, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Lee, G.F., M.D. Piwoni, J.M. Lopez, G.M. Mariani, J.S. Richardson, D.H. Homer, and F. Saleh. 1975. Research study for the development of dredged material disposal criteria. Technical Report D-75-4, U.S. Army Engineer Waterways Experimental Station, Dredged Material Research Program, Vicksburg, Miss.

Liu, D.H.W., K.D. Martin, and C.R. Norwood. 1975. San Francisco Bay Benthic Community Study. Prepared for "San Francisco Bay Estuary Dredged Disposal Study, Biological Community, Appendix D." U.S. Army Corps of Engineers, San Francisco District, California.

National Marine Fisheries Service. 1987. Letter from E.C. Fullerton, Regional Director, In: Oakland Harbor. Final Supplement 1 to the Environmental Impact Statement, Alameda County. U.S. Army Corps of Engineers, San Francisco District, San Francisco California.

Nelson, W.G., D.K. Phelps, W.B. Galloway, P.F. Rogerson, and R.J. Pruell. 1987. Effects of Black Rock Harbor dredged material on the scope for growth of the blue mussel, <u>mytilus edulis</u> after laboratory and field exposures. Technical Report D-87-7, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Pesch, G.G., C.E. Pesch, A.R. Malcolm, C. Mueller, W.R. Munns, Jr., J. Heltshe, T.C. Lee and A.G. Senecal. 1987. Sister chromatid exchange in marine polychaetes exposed to Black Rock Harbor sediment. Technical Report D-87-5, prepared by the US Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Proni, J.R., and D.V. Hansen. 1981. Dispersion of particulates in the ocean studied acoustically: the importance of gradient surfaces in the ocean. In: B.H. Ketchum, D.R. Kester, P.K. Park, Eds., Ocean dumping of industrial wastes. Plenum Press, New York. pp 161-173.

Rubin, D.M. and D.S. McCulloch. 1979. The movement and equilibrium of bedforms in Central San Francisco Bay. In T.J. Conomos (ed.) "San Francisco Bay, The Urbanized Estuary. American Association for the Advancement of Science. pp. 97-113.

Schultz, E.A. 1965. San Francisco Bay dredge spoil disposal. Report prepared for Committee on Tidal Hydraulics, 53rd meeting, San Francisco, California, May 1965.

Segar, D.A. 1978. A review of the impact of dredged material disposal in the New York Bight Apex, with emphasis on chemical processes. Technical Report. National Oceanic and Atmospheric Administration, Marine Ecosystem Analysis Project, Stony Brook, New York.

Segar, D.A. 1987. Letter to Mr. Andrew Lichterman, Western States Legal Foundation, Submitted to U.S. Army Corps of Engineers in response to Public Notice # 17162S46 regarding the Final Composite Environmental Impact Statement. Battleship battlegroup/cruiser destroyer group. U.S. Navy, Western Division, Naval Facilities Engineering Command, San Bruno, California.

Teeter, A.M. 1987. San Francisco Bay-Alcatraz disposal site erodability. Miscellaneous Paper HL-86-1. Alcatraz disposal site investigation report 3, U.S. Army Engineer District, San Francisco, California.

United Anglers, 1987, Letter from John Buettler, Executive Director, United Anglers of California. In: Oakland Harbor. Final Supplement 1 to the Environmental Impact Statement, Alameda County. U.S. Army Corps of Engineers, San Francisco District, San Francisco California.

U.S. Army Corps of Engineers. 1988. Oakland Harbor. Final Supplement 1 to the Environmental Impact Statement, Alameda County. U.S. Army Corps of Engineers, San Francisco District, San Francisco California.

U.S. Army Engineer District, San Francisco, Corps of Engineers. 1975a. Dredged disposal study San Francisco Bay and Estuary. Appendix I. Pollutant availability study. U.S. Army Engineer District, San Francisco.

U.S. Army Engineer District, San Francisco, Corps of Engineers. 1975b. Dredged disposal study San Francisco Bay and Estuary. Appendix F. Crystalline matrix. U.S. Army Engineer District, San Francisco.

U.S. Army Engineer District, San Francisco, Corps of Engineers. 1987. Long-term management strategy for San Francisco Bay area disposal of dredged material. Unpublished manuscript. Dated June 24, 1987

U.S. Navy. 1987. Final Composite Environmental Impact Statement. Battleship battlegroup/cruiser destroyer group. U.S. Navy, Western Division, Naval Facilities Engineering Command, San Bruno, California.

Winzler and Kelly. 1985. Oceanographic investigation at the Alcatraz disposal site, San Francisco Bay, California. Report prepared for U.S. Army Corps of Engineers, San Francisco District.

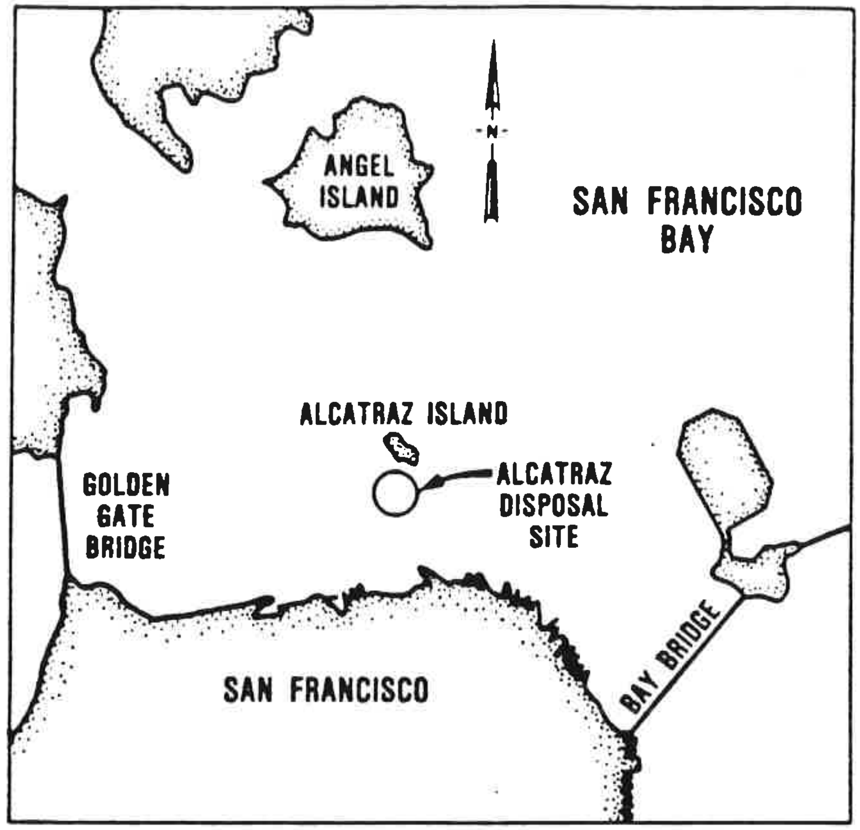
Word, J.Q., J.A. Ward, and D.L. Woodruff. 1988a. Results of bulk sediment analysis and bioassay testing on selected sediments from the Oakland Inner Harbor and Alcatraz disposal site, San Francisco, California. Report on Contract DE-AC06-76RLO 1830. Prepared for U.S. Army Corps of Engineers, San Francisco District.

Word, J.Q., J.A. Ward, C.W. Apts, D.L. Woodruff, M.E. Barrows, V.I. Cullinan, J.L. Hyland, and J.F. Campbell. 1988b. Results of confirmatory sediment analyses and solid- and suspended-particulate-phase bioassay tests on selected sediment from the Oakland Inner Harbor, San Francisco, California. Report on Contract DE-AC06-76RLO 1830. Prepared for U.S. Army Corps of Engineers, San Francisco District.

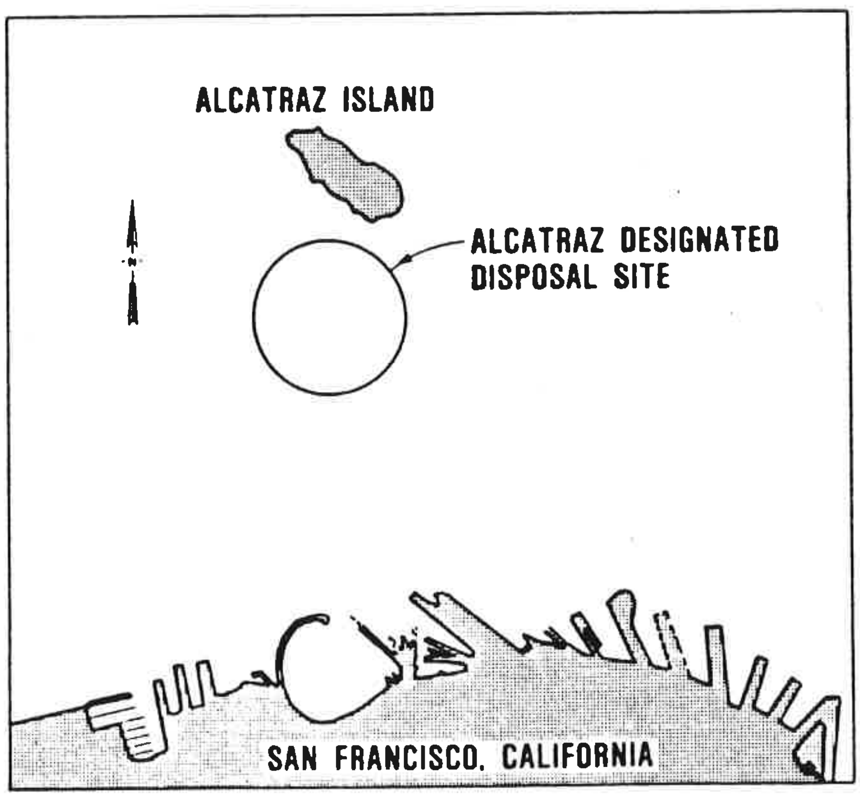
Yevitch P.P, C. Yevitch, G. Pesch, and W. Nelson. 1987. Effects of Black Rock Harbor dredged material on the histopathology of the blue mussel mytilus edulis and polychaete worm nephtys incisa after laboratory and field exposures. Technical Report D-87-8, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Yevitch, P.P., C.A. Yevitch, K.J. Scott, M. Redmond, D. Black, P.S. Schauer, and C.E. Pesch. 1986. Histopathological effects of Black Rock Harbor dredged material on marine organisms. Technical Report D-86-1, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Zaroogian, G.E., P.F.Rogerson, G. Hoffman, M.Johnson, and W.G. Nelson. 1988. A field and laboratory study using adenylate energy charge as an indicator of stress in Mytilus edulis and Nephtys incisa treated with dredged material. Technical Report D-88-4, prepared by the U.S. Environmental Protection Agency, Narragansett, R.I., for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.




a. Location map




b. Vicinity map

Figure 1. Location of Alcatraz disposal site

Table 1. Grain Size of Sediments from Oakland Inner Harbor

| Station | Grain Size | | |
|---|---|---|---|
| | Sand | Silt | Clay |
| Schnitzer Steel | | | |
| S1 | 3.91 | 30.1 | 65.78 |
| S2 | 33.23 | 26.89 | 39.63 |
| S3 | 7.03 | 43.69 | 58.36 |
| Todd Shipyard | | | |
| T4 | 61.46 | 13.28 | 24.92 |
| T5 | 19.61 | 23.75 | 54.33 |
| T6 | 20.56 | 22.62 | 53.92 |
| T7 | 27.41 | 24.67 | 44.06 |

Data from Word et al., 1988b.

Table 2. Metal and Metaloid Contaminant Concentrations in Sediment Samples from Oakland Inner Harbor Concentrations in ug/g (dry weight)

| | Arsenic | Cadmium | Chromium | Copper | Lead | Mercury | Nickel | Selenium | Silver | Zinc |
|---|---|---|---|---|---|---|---|---|---|---|
| Schitzer Steel | | | | | | | | | | |
| S1 | 10.60 | 1.42 | 230.00 | 71.10 | 48.40 | .41 | 129.00 | .38 | .45 | 179.00 |
| S2 | 7.10 | 1.97 | 343.00 | 79.00 | 100.00 | 1.30 | 101.00 | .16 | .57 | 260.00 |
| S3 | 10.50 | 1.05 | 217.00 | 81.40 | 87.60 | .76 | 130.00 | .23 | .63 | 208.00 |
| Todd Shipyard | | | | | | | | | | |
| T4 | 5.90 | .67 | 416.00 | 96.70 | 78.30 | 1.30 | 85.70 | .08 | .33 | 183.00 |
| T5A | 16.30 | 2.02 | 390.00 | 326.00 | 177.00 | 8.30 | 146.00 | .31 | 1.00 | 428.00 |
| T5B | 19.40 | 2.03 | 419.00 | 327.00 | 175.00 | 8.40 | 155.00 | .39 | .99 | 415.00 |
| T6 | 13.30 | 1.16 | 930.00 | 423.00 | 246.00 | 4.20 | 212.00 | .23 | .62 | 549.00 |
| T7 | 9.20 | 1.33 | 437.00 | 224.00 | 174.00 | 2.70 | 155.00 | .31 | .70 | 287.00 |

Data from Word et al., 1988b.

Table 3. Priority Pollutants, Pesticides, and PCB concentrations in Sediments from Oakland Inner Harbor. Concentrations are in ug/kg

| | Schnitzer Steel | | | Todd Shipyard | | | | |
|---|---|---|---|---|---|---|---|---|
| Compound | S1 | S2 | S3 | T4 | T5A | T5B | T6 | T7 |
| Acenaphthene | 0 | 58 | 0 | 0 | 346 | 219 | 0 | 0 |
| Diethyphthalate | 102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fluorene | 0 | 0 | 0 | 0 | 346 | 200 | 91 | 0 |
| Phenanthrene | 261 | 578 | 561 | 252 | 1730 | 1821 | 1299 | 444 |
| Anthracene | 108 | 298 | 0 | 0 | 437 | 710 | 445 | 0 |
| Di-n-Butylphthalate | 46 | 193 | 0 | 0 | 0 | 0 | 260 | 291 |
| Fluoranthene | 541 | 1541 | 1488 | 489 | 3825 | 2004 | 2041 | 803 |
| Pyrene | 1343 | 3327 | 6341 | 2370 | 6011 | 4372 | 6679 | 1880 |
| Butylbenzylphthalate | 90 | 315 | 0 | 0 | 0 | 0 | 0 | 0 |
| Benzo(a)Anthracene | 301 | 578 | 610 | 370 | 2368 | 1639 | 2783 | 650 |
| bis(2-ethylhexyl)phthalate | 501 | 1401 | 0 | 607 | 383 | 328 | 1206 | 547 |
| Chrysene | 561 | 893 | 0 | 637 | 3097 | 2186 | 0 | 0 |
| Benzo(b)Fluoranthene and Benzo(k)Fluoranthene | 922 | 2102 | 2927 | 2370 | 4554 | 3825 | 8349 | 2051 |
| Benzo(a)Pyrene | 601 | 1524 | 2146 | 1289 | 2914 | 2186 | 3896 | 1128 |
| Indeno(1,2,3-cd)Pyrene | 441 | 1068 | 1512 | 637 | 2004 | 2004 | 2783 | 0 |
| Benzo(ghi)Perylene | 561 | 1436 | 2171 | 726 | 2186 | 2186 | 2597 | 701 |
| Arochlor 1016,1242,1248 | 0 | 88 | 0 | 0 | 0 | 0 | 0 | 0 |
| Arochlor 1248 | 0 | 0 | 0 | 0 | 200 | 182 | 186 | 205 |
| Arochlor 1254 | 180 | 158 | 96 | 281 | 328 | 346 | 928 | 1009 |
| Arochlor 1260 | 0 | 88 | 122 | 207 | 128 | 164 | 260 | 222 |

Concentrations below the analytical detection limits are indicated by the value 0.
Data from Word et al., 1988b.
Note: Arochlor's are different formulations of PCBs.

Table 4. Contaminant Concentrations in Sediments of San Francisco Bay/a/

| | San Francisco Pier 94/96/b/ | Central Bay Reference/b/ | Point San Pablo/c/ | Lower San Pablo Bay/d/ | Oakland Inner Harbor/d/ | Islais Creek/d/ |
|---|---|---|---|---|---|---|
| INORGANICS (ppm dry weight unless otherwise noted) | | | | | | |
| Arsenic | <0.1 | <0.1 | — | 44-70 | 49-64 | 57-72 |
| Cadmium | 0.1-0.2 | 0.2 | <9 | <1 | <1 | <1-1 |
| Chromium | 8.9-13.6 | 5 | 27-150 | 72-93 | 85-95 | 110-146 |
| Copper | 5.4-15.5 | 6.4 | 7-110 | 30-53 | 43-51 | 68-130 |
| Lead | 5.3-16 | 7.3 | <20 | 18-25 | 29-33 | 49-223 |
| Mercury | <0.1-0.2 | 0.1 | <3 | 0.09-0.31 | 0.21-0.29 | 0.57-1.2 |
| Nickel | 15.3-22.7 | 9.4 | 27-96 | 76-85 | 72-84 | 88-96 |
| Silver | 0.17-0.36 | .24 | — | 0.9-1.6 | 1.7-2.4 | 4.0-8.6 |
| Zinc | 10.6-28 | 20.3 | 30-170 | 86-114 | 109-122 | 156-321 |
| ORGANICS (ppb dry weight unless otherwise noted) | | | | | | |
| 4,4'-DDD | <14-<140 | <140 | — | 0.21-0.45 | 0.65-1.0 | 0.98-1.44 |
| 4,4'-DDE | <2-<20 | <20 | — | 0.21-0.27 | 0.22-0.29 | 0.46-1.32 |
| 4,4'-DDT | <17-<170 | <170 | — | <0.1 | <0.1-0.24 | 0.4-0.87 |
| PCBs (Total) | <50-<500 | <500 | — | 5.7-17.5 | 26.6-36.8 | 57.3-255.3 |
| Anthracene | <20-69 | 145 | — | 6-29 | 40-60 | 298-1,341 |
| Fluoranthene | <20-181 | 398 | — | 14-183 | 259-37 | 871 -3,712 |
| Phenanthrene | <20-240 | 359 | 4,000/i/ | 20-88 | 128-172 | 301-615 |
| Pyrene | <20-390 | 839 | 5,100/i/ | 68-242 | 320-489 | 1,292-2,666 |
| Benzo(a)Anthracene | <20-631 | 112 | — | 16-62 | 77-153 | 421-1,199 |
| Chrysene | <20 | 299 | 18,000/i/ | 28-94 | 120-194 | 702-2,208 |
| Benzo(a)Pyrene | <20-191 | 512 | — | 18-92 | 104-180 | 365-820 |

/a/ Table adapted from US Navy, 1987, Environmental Impact Statement, Homeporting, Battleship Battlegroup/Cruiser Destroyer Group.

/b/ Data Source: Bendix Environmental Research Inc, 1987, Port of San Francisco Pier 94/96 Sediment Study.

/c/ Data Source: Jefferson Associates & URS Corp, 1987, Chevron USA Richmond Refinery Deep Water Outfall Project, Environmental Impact Report.

Table and footnotes are continued on next page.

Table 4.(Cont.) Contaminant Concentrations in Sediments of San Francisco Bay/a/

| | Alcatraz Dumpsite/e/ | Hunters Point Dry Dock 4/f/ | Hunters Point/g/ | Treasure Island/g/ | Alameda/g/ |
|---|---|---|---|---|---|
| INORGANICS (ppm dry weight unless otherwise noted) | | | | | |
| Arsenic | 0.4-1.2 | 12-13 | 7.9-8.8 | 5.2-12 | 3.7-4.9 |
| Cadmium | 0.5-1.0 | 1.5-1.7 | 2.3-2.5 | 1.4-2.3 | 1.1-1.3 |
| Chromium | 40-74 | — | <0.1/h/ | <0.1/h/ | <0.1/h/ |
| Copper | 4-26 | 40-43 | 62-75 | 29-54 | 16-26 |
| Lead | 10-45 | 14-23 | 43-64 | 22-50 | 16-20 |
| Mercury | 0.01-0.62 | 0.33-0.43 | 0.37-0.42 | 0.06-0.45 | 0.10-0.19 |
| Nickel | 26-50 | 86-91 | 120-130 | 60-110 | 54-64 |
| Silver | 0.40-0.87 | 1.1-1.6 | 1.7-2.1 | 0.9-1.7 | 0.7-1.0 |
| Zinc | 19-58 | 117-127 | 150-170 | 60-130 | 43-63 |
| ORGANICS (ppb dry weight unless otherwise noted) | | | | | |
| 4,4'-DDD | <1-6 | 1-2 | 1.1-1.8 | <0.5-1.4 | <0.5-0.5 |
| 4,4'-DDE | <0.5-3.4 | 1 | 1.7-2.6 | <0.1-1.9 | <0.1-0.5 |
| 4,4'-DDT | <1 | 1 | <0.5 | <0.5 | <0.5 |
| PCBs (Total) | <20 | — | <10 | <10 | <10 |
| Anthracene | <66-390 | <66 | <20 | <20-20 | <20 |
| Fluoranthene | <66-630 | 87-150 | 20-65 | <20-110 | <20 |
| Phenanthrene | <66-1,100 | <66-80 | 20-36 | 20-63 | <20 |
| Pyrene | <66-1,000 | 84-140 | 27-81 | <20-160 | <20 |
| Benzo(a)Anthracene | <66-370 | <66 | <20-24 | <20-49 | <20 |
| Chrysene | <66-430 | <66 | <20-32 | <20-59 | <20 |
| Benzo(a)Pyrene | <66-380 | <66-130 | 20-46 | <20-98 | <20 |

/d/ Data Source: Chapman et al., 1986, NOAA Tech Memo NOS OMA 25.
/e/ Data Source: US Army Corps of Engineers, San Francisco District, 1987, Toxscan Data Reports, Data are wet weight basis.
/f/ Data Source: Marine Bioassay Labs & Env. Sci. Assoc., 1987, Maintenance Dredging Permit Application #16685548, Appendix.
/g/ Data Source: US Navy, 1987, Environmental Impact Statement, Homeporting, Battleship Battlegroup/Cruiser Destroyer Group.
/h/ Hexavalent chromium only.
/i/ ppb, wet weight basis.

Table 5. Inputs of Selected Contaminants to the San Francisco Bay Delta Tonnes per year.

| | Atmosphere | Non-Urban | Riverine | Urban | Point Source | Dredged Material | Bioavailable Dredged Material* |
|---|---|---|---|---|---|---|---|
| Copper | 1.9-3.1 | 51-581 | 203 | 7-59 | 18-31 | 100 | 32 |
| Mercury | N/A | 0.15-1.7 | 1.2-3 | 0.026-0.15 | 0.18-0.8 | 1.0 | 0.16 |
| Cadmium | 0.14-0.35 | 0.52-6 | 5.5-27 | 0.3-3 | 1.9-4.0 | 2 | 1.5 |
| Lead | 6-21 | 31-358 | 30-66 | 30-250 | 11-17 | 100 | 40 |
| Zinc | 16-32 | 126-1435 | 272-288 | 34-268 | 70-74 | 300 | 96 |
| Nickel | N/A | N/A | 74-82 | N/A | 21-29 | 200 | 24 |
| PCB's | 0.75-0.12 | N/A | N/A | 0.006-0.4 | N/A | 0.067 | 0.054 |
| PAH's | 0.8-4.8 | N/A | N/A | 0.5-5 | N/A | 4.7 | 3.8 |

All data from Gunther et al., 1987 except bioavailable dredged material data
N/A - Data not available
* Bioavailable dredged material loadings represent the potentially readily bioavailable toxicants calculated by adjusting total loading estimates from Gunther et al. assuming
  A. 20% of the contaminant is buried in accumulated sediments at the Alcatraz dumpsite
  B. residual phase contaminants are not potentially bioavailable. Residual phase estimated as 60% of total Copper, 80% of mercury, 5% of cadmium, 50% of lead, 60% of zinc 85% of nickel, and 0% of PAHs and PCBs. Data for these estimates was derived from Eaton, 1979 and US Army Corps of Engineers, 1975b.

ACKNOWLEDGMENTS

Most of the funding for this study was supplied by the author. However, the author is grateful for small grants of supplemental support received from Citizens for a Better Environment, the Marin Audubon Society Endowment Fund for Conservation, and the Santa Clara Valley Audubon Society.