ASSESSMENT OF ALTERNATIVE STRATEGIES FOR SLUDGE DISPOSAL INTO DEEP OCEAN BASINS OFF SOUTHERN CALIFORNIA

Final Report

To

City of Los Angeles
County Sanitation Districts of Los Angeles County
County Sanitation Districts of Orange County

Through

Los Angeles/Orange County Metropolitan Area
Regional Wastewater Solids Management Program

by

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PREFACE

This study is part of EQL's ongoing research on the assessment of various strategies for ocean disposal of digested sewage sludge, with particular reference to the Southern California Bight. Two reports have been issued previously, supported in part by the Ford Foundation.[1]

This report presents work in progress since early 1977, with support of the Rockefeller Foundation and three local sewerage agencies (City of Los Angeles, Sanitation Districts of Los Angeles County, and Sanitation Districts of Orange County). The latter contract[2] covers LA/OMA sub-element 5.2[3] except for limited field work being done under a separate contract by the Southern California Coastal Water Research Project. SCCWRP's report of field work is included as an attachment to this report.

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[1]Faisst, W. K., Digested Sewage Sludge: Characterization of a Residual and Modeling for its Disposal in the Ocean off Southern California, Environmental Quality Laboratory Report No. 13, California Institute of Technology, Pasadena, California, June 1976.

Isaacson, M. S. and N. H. Brooks, eds., Report on Mini-Conference on Sludge Disposal Alternatives in the Ocean off Southern California, 8 September 1976, Environmental Quality Laboratory Memorandum No. 19, California Institute of Technology, Pasadena, California, December 1976.

[2]See Appendix 5 for copy of scope of work in EQL's contract.

[3]Regional Wastewater Solids Management Program, Los Angeles/Orange County Metropolitan Area (Whittier, California), Phase I Report, August 1976, VII-46, 47.

The general framework of engineering alternatives for regional ocean sludge disposal is well described in a report by Raksit,[4] and will not be repeated here. The various ocean disposal alternatives are less costly than all land-disposal and incineration/pyrolysis systems studied.[4,5] Even though ocean sludge disposal is currently contrary to both state and federal regulations, it is hoped that this study will advance our scientific and engineering knowledge of the behavior and effects of sludge discharge in deep water, in case the regulatory policy is reexamined in the future.

The structure of the study is reflected in the organization of the report. Chapter I, Introduction, gives a brief overview. Chapter II is a physical description of the deep marine basins of the Southern California Bight, which have been the focus of much of this research project as potential sites for sludge disposal. Surface water disposal by barge far offshore is another alternative, but we treated this only briefly in Chapter IX, as it was not within the contractual scope of work.

A brief qualitative overview of the water exchange processes and mixing in the basins is given in Chapter III, with detailed mathematical analysis of the processes relegated to Appendix 2, Sections II-IV. Natural fluxes and some observed anthropogenic increments of these fluxes are given

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[4] Raksit, S. K., "Initial Analysis of Ocean Disposal as a Sludge Management Candidate System," Report, c/o LA/OMA Project, P.O. Box 4998, Whittier, California 90607, May 1977.

[5] CH_2M Hill, Inc., "Initial Analysis of Candidate Systems and Preliminary Site Identification," Report to LA/OMA, April 1977.

in Chapter IV. Chapter V and Appendix 3 present the basic data on projected sludge discharges, including trace contaminants, for the three major sewerage agencies in southern California. Also covered is some chemical information on trace metal precipitates and rates of dissolution in various dilutions of seawater. An extensive review of chemical reactions important in the analysis of sludge particles in seawater is given as Appendix 1. Additional sources of data, and some profile data for the basins, is given in Appendix 4. These chapters (I-V) and appendices (1, part of 2, 3, and 4) provide the basis information and literature review for working the sludge modeling problem.

There are two distinct modeling approached used, each based on certain simplifying assumptions, and emphasizing different processes. Sedimentation modeling (developed by Koh in Chapter VI) predicts the relative bottom deposits for various particle fall velocities in the presence of non-isotropic turbulent spreading in three directions over a sloping seabed. But to deal with these complexities of the physics, we had to neglect all the chemistry and biology; it is essentially equivalent to assuming the sludge particles are completely non-reactive. The results of this chapter give us a good prediction of the approximate size of the bottom patches defined by various criteria.

The other modeling approach (developed by Jackson in Chapter VII and Appendix 2) is a one-dimensional basin model (vertical), including the appropriate chemical and biological reactions; but physically, we could not use the elaborate three-dimensional sedimentation analysis developed in Chapter VI. Instead it is assumed that all properties are fully mixed horizontally throughout the basin; therefore, conclusions about impacts may be underestimates near the discharge point, and overestimates far away. Dissolved oxygen profiles are derived to show the impacts of discharging all the sludge (as specified in Chapter V) into various depths (800 m, 600 m, and 400 m). The incremental concentrations of key trace metals in the water column are also predicted, as well as the fate of the particulates (sedimentation, oxidation, or flushing from the basin).

Following the major modeling chapters (VI and VII), we predict in Chapter VIII the biological impacts in case all the region's digested sludge is discharged to the Santa Monica-San Pedro Basin. For this, we draw on the results of the limited biological surveys conducted by SCCWRP under a separate contract (see attachment for SCCWRP report). However, there is still considerable uncertainty in biological predictions (as in physical and chemical) because of gaps in current knowledge of the processes in the deep basins.

Chapter IX is a brief discussion and comparison of alternative methods for disposal of digested sludge in the ocean. There are three zones in the water column, two options for sludge density (heavier or lighter than seawater), and two kinds of delivery systems (outfalls and barges). Using results of the previous chapters, the twelve possible methods are narrowed down to the two most attractive for engineering feasibility analyses and conceptual design.

Chapter X gives recommendations for further study to improve predictions of the impacts of sludge discharges in the ocean.

A brief statement of conclusions precedes Chapter I.

With this report we hope we have demonstrated the potential and difficulties of some new modeling techniques for predicting the effects of sludge discharge in the ocean. In the future, we believe it will be possible to formulate policy of ocean sludge discharges with much better case-by-case predictions of impacts for comparison with other alternatives (such as land disposal), not only for the Los Angeles/Orange County areas, but for all coastal urban areas.

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SUMMARY AND CONCLUSIONS

The basic question underlying this study is: *What new alternatives for ocean discharge of digested sewage sludge are most attractive considering environmental impact for the Los Angeles/Orange Counties area?* We do not attempt to compare ocean discharge with other methods (that is the overall task of the LA/OMA project), but rather to narrow down the ocean alternatives to the best ones. This report focuses on environmental impacts of general methods of disposal, rather than specific engineering works.

Ocean and Sludge Characteristics

Classification of coastal waters. In discussing the possible alternatives and their impacts it is useful to categorize the offshore basin waters in three parts:

a. Lower basin water: the body of water which is within topographic depressions, and below the lowest of the sills surrounding a basin.

b. Upper basin water: those waters which are in layers that are partially enclosed in basins, perhaps with an opening at one end but contained along the sides and at the opposite end by submarine mountain ranges and sills.

c. Shelf water: the water mass which is generally above the submarine mountain ranges so that its lateral flow and circulation are relatively unimpeded by the basin topography.

Characteristics of Santa Monica-San Pedro Basin Waters. The important characteristics of the water in the Santa Monica-San Pedro Basin, geographically closest to the sludge sources, are as follows:

a. Lower basin water (below 740 meters depth): dissolved oxygen in water column very low (less than 0.3 mg/ℓ); little density stratification (uniform temperature and salinity); principal water exchange caused by dense water inflows over the end sills; sediments may be aerobic in the top few centimeters but below that generally anaerobic.

b. Upper basin water (740 to 300 meters depth): some slight density stratification due to a modest temperature gradient; dissolved oxygen still very low but gradually increasing toward the top of the layer due to downward diffusion; greater horizontal water exchange with ocean waters than for the lower basin water.

c. Upper shelf water (300 meters depth to surface): dissolved oxygen concentration now rapidly approaches saturation with decreasing depth; temperature increases more rapidly; horizontal currents believed to be much stronger than in basin waters, with significant exchange with the open ocean.

Sludge density. The digested sludge has a bulk density slightly lighter than seawater as it comes from the digester, but it could be thickened somewhat to make it slightly heavier than seawater. When introduced into the ocean it may either rise or sink depending on its density, but because of the density stratification in the water column it will rise or sink only a limited distance (about 50 m) before the resulting sludge-seawater mixture will stop and spread out at the level of neutral density. (For other sludge characteristics, see Chapter V.)

Delivery systems. The delivery systems to be considered are outfalls and barges. Simply put, outfalls introduce the sludge at the sea floor, whereas barges discharge at or near the surface. Barges should use a pipe hanging down from the barge for a pumped discharge at depth, but the engineering and logistics problems are such that we presume such a hanging pipe would be limited to approximately 100 meters. According to the water classification above, such a discharge would still be into the shelf waters.

Scientific Findings

With the one-dimensional basin model of chemical and physical effects, we assessed (in Chapter VII) changes that would result for discharge into one of three depths in Santa Monica-San Pedro Basin: 800 m (below sill depth), in a low-oxygen, slowly renewed environment; 600 m (above sill depth) in the upper basin with faster renewal but also in a low-oxygen region; and 400 m (near the top of the basin), in a zone of high oxygen concentration and fastest water renewal.

Discharge at 600 or 800 m could virtually deplete oxygen in the water between the sludge injection depth and the basin bottom at about 900 m according to our model. Adverse effects on animals within this depth range would probably eliminate these deep discharge depths from further consideration.

Discharge at 400 m would not have the same adverse effects as discharge at 600 or 800 m: high oxygen concentrations and high exchange rates would lower oxygen depletion and increase sludge oxidation; trace metal concentrations would increase substantially for metals such as copper and chromium but basin-wide averages at all levels should still be substantially lower than receiving water standards in the 1978 Water Quality Control Plan for Ocean Waters in California; most of the oxidizable sludge would oxidize before leaving the basin or settling to the bottom. The incremental concentration of sludge particulate carbon in the water column below 400 m would be several times greater than that occurring naturally. The ecological significance of this increase for plankton should be examined. Substantially more information must be gathered before a definitive statement can be made about fates of sludge disposed in offshore marine basins or all of the ecological effects associated with it. (See Chapter X, Recommendations for Further Study.)

Sludge discharge at 400 m would seem to have few large scale impacts. It would impact a community whose sensitivity to sewage solids has not been experimentally tested -- the mid-water animals. Lack of reported zooplankton kills caused directly by sludge disposal would suggest that this would not be a problem; caution at causing high sludge concentrations in a slowly mixed region with a poorly studied fauna suggests that these factors should be checked.

Sedimentation rates. Sedimentation rates are difficult to predict because of inadequate data on settling of sludge particles in the ocean.

However, a parametric three-dimensional study of particle settling and deposition rates is given in Chapter VI. For representative sludge-particle fall valocity of 10^{-3} cm/s and 1985 sludge discharge rates (full secondary), the predicted deposition rates (as oxygen consumed per unit area and time) would equal or exceed natural sedimentary oxygen demand (10^4 moles-O_2/km^2 day) over an area of approximately 120 km^2. But on the basis of total mass of solids deposited, the increment due to sludge equals or exceeds natural (26 mg/cm^2 yr) over only 60 km^2, which is relatively small compared with the area of 2500 km^2 for the Santa Monica-San Pedro Basin at the 737 m sill level. The depositional areas would be elliptical, extending several times further along the contours compared with normal to the contours. These estimates of deposition rate are conservative upper limits, as they neglect particle decay during settling and resuspension from the bottom.

Environmental Evaluation of Engineering Alternatives

Possible Alternatives. Given three zones of receiving water, two sludge-density possibilities, and two types of delivery systems, there are actually 12 types of disposal systems. Of these, only four may be acceptable possibilities based on environmental or engineering considerations, and are worthy of further study. They are shown in the following table. The last column indicates that the strategy for the first three options (A, B, C) is basically "dispersal," i.e., spread the sludge over a wide area to minimize impacts at any one place by having sludge-caused increments in water column concentrations or sediments approach background levels. The fourth (D) is a containment option where we seek to minimize dilution and contain the effects (at a higher level) in a limited area of a deep basin dedicated to sludge disposal.

	Receiving Water zone; depth, m	Sludge Density (relative to seawater)	Delivery System	Strategy
A	Shelf, 100-300 m	Lighter	Outfall	Dispersal
B	Upper basin, 300-400 m	Lighter	Outfall	Dispersal
C	Shelf, 50-100 m	Heavier	Barge	Dispersal
D	Lower basin, > 700 m	Heavier	Outfall	Containment

Alternate A. Alternate A is an outfall discharge of buoyant sludge in the uppermost layer within the range 100 to 300 m (the surface 100 m is excluded as being too close to shore and the water surface). At 100 m depth the Hyperion sludge outfall is already a prototype in operation, and the effects are documented elsewhere. As the discharge point is moved offshore to deeper water, the impacts would be reduced gradually because the biomass decreases with depth. Throughout this depth the dissolved oxygen is ample, and would not be noticeably depressed by the BOD of the sludge particles.

Alternate B. Alternate B is an outfall discharge of buoyant sludge into the top part of the upper basin water within the range 300

*See various publications (including annual reports of the Southern California Coastal Water Research Project (SCCWRP), 646 West Pacific Coast Highway, Long Beach, California 90806.

to 400 m. The detailed one-dimensional basin modeling (Chapter VII) for discharge depths of 400, 600, and 800 m clearly shows that the dissolved oxygen (naturally very low, but not zero) is depleted significantly as the discharge depth increases. It is concluded that 400 m is the maximum depth of discharge which keeps the dissolved oxygen in the entire water column above 4 μM, a threshold for all life. To provide a reasonable margin for error, 300 m (1000 feet) depth is considered the maximum practicable depth which should be considered for an outfall. (This depth, 1000 feet, is within the range of engineering feasibility and is the basis of engineering cost estimates by Raksit (1977) and given in Chapter 9.)

Alternate C. Alternate C is a barge discharge of thickened sludge (heavier than seawater) into the shelf water in the range of 50 to 100 m depth by means of a hanging discharge pipe. The advantage of barging is the flexibility of location including the ability to discharge in the surface or shelf water at a considerable distance from shore. Although the study did not encompass a detailed analysis of this alternative, it is clear that this option warrants further study if ocean disposal is adopted.

The advantages of the barge option are that it will provide the widest dispersal of settling particles (and thus the least increment of bottom sedimentation), the least impact on dissolved oxygen, and the greatest practicable distance from shore.

Alternate D. Alternate D is the only possible option for a containment strategy, using outfall discharge of thickened sludge into the bottom of the basin. The discharge would flow out as a gravity or density current and deposit the sludge particles in a rather limited area where the impact would be much stronger locally than the other options. The advantage is that the effects would be less extensive both in the water column and on the bottom.

Considering the engineering difficulties of construction to 740 m (2400 ft) depth or more, and the lack of assurance that the containment would be effective, this alternative is given a low chance of becoming viable.

Recommendation

If it is desired to reduce the environmental effects below those experienced around the present Hyperion sludge outfall at 100 m depth, it is recommended that engineering feasibility analyses, conceptual designs, and further environmental studies (specified in Chapter X) be undertaken and focused on the following alternatives:

(1) Sludge outfall(s) with discharge depth of about 300 m (1000 ft); and

(2) Barging with submerged pumped discharge between 50 m and 100 m below the surface by means of a hanging pipe; a likely fixed location would be near the center of the San Pedro Basin, although a "roving" discharge location should be considered.

Other possibilities are judged less attractive or less feasible.

This exploratory research project has been focused primarily on prediction of the environmental effects of possible discharges of digested sludge from submarine outfalls into the deep basins off southern California.

More field data and investigations on environmental interactions (as described in Chapter X) are needed in order to reduce the uncertainties and improve the predictions.

If sludge outfall pipes are favorably considered on the basis of environmental effects, then the next step is to define one (or more) specific engineering projects for feasibility study and conceptual design. Possible outfall alignments to evaluate are shown on Fig. IX-1 to Fig. IX-3, pages 114-116. The cost of construction for these outfalls is estimated to be sixteen million (1979) dollars.

Discharge from barges received little emphasis in the scope of work for the study, probably because the cost of barging sludge is unquestionably several times as high as pumping through sludge outfall(s) (Raksit, 1977). If the barging alternative becomes a serious competitor, more environmental analyses as well as engineering feasiblity studies should be made for surface-layer discharge far from shore.

A table is included on the next page which presents a summary of the predicted environmental impacts from sludge outfalls discharging at 300 to 400 m depth in the format requested by the sponsoring agency.

SUMMARY OF THE EVALUATION OF MARINE BIOLOGICAL RESOURCES UNDER CONDITIONS OF DISCHARGE AT FULL SECONDARY TREATMENT SLUDGE INTO SANTA MONICA - SAN PEDRO BASIN AT 300-400 M DEPTH

COMPONENT OF THE MARINE ECOSYSTEM	NEUTRAL IMPACTS	BENEFICIAL IMPACTS	ADVERSE IMPACTS				BASIS FOR EVALUATION
	DESCRIPTION	DESCRIPTION	DESCRIPTION	UNAVOIDABLE YES/NO	SHORT TERM/ LONG TERM	IRREVERSIBLE COMMITTMENT OF RESOURCES	
● THE FLORA AND FAUNA ● ORGANISMS THAT INHABIT THE WATER COLUMN ▶ Pelagic Plankton and Necton - This would include invertebrates and fishes. The depth precludes there being any plants (phytoplankton). Many of the animals survive by scavanging particles, including fecal material, raining down from surface waters.		Some planktonic organisms may be able to use sludge as food. The importance of this has yet to be demonstrated.	Various toxins, including trace metals and chlorinated hydrocarbons, might injure organisms ingesting sludge particles. Trace metal concentrations in solution would be less than the maximum allowable under the California Ocean Plan* and should therefore not be a problem. Decreases in oxygen concentrations of about 15% could cause range shifts for sensitive species. High concentrations of sludge particles may affect some species. Importance of this effect is unknown.	Yes. Extent of effect is sensitive to sedimentation rate. The toxins and their particulate form are intrinsic to sludge, but can be limited by effective source control on releases to sewers.	Both	No	Proper evaluation will require experiment to determine the extent of interactions between planktonic organisms and sludge. The depth of discharge places the effects in a planktonic community for which there is little information.
● BENTHIC MARINE ORGANISMS ▶ Benthic Infauna - This includes organisms living in the sediment, some of which feed in the overlying waters.			Benthic infauna are most affected by sludge disposal. Settling sludge particles can increase the food supply, but they also increase concentrations of toxic trace metals, halogenated and non-halogenated organic compounds, and sulfides. Areas of sludge accumulation around present outfalls contain fewer animal species, present in greater abundance. Similar results can be expected for deeper disposal.	Yes. Changes caused by toxic trace metals and organics can be limited by limiting their concentrations in sludge. Changes in species composition are, however, intrinsically related to the organic content of sludge, which acts as food for some organisms and, in high concentrations, causes oxygen depletion and sulfide formation in the sediments.	Both	No	This evaluation is based on effects of discharge around present waste outfalls.
▶ Demersal Fish and Epibenthic Invertebrates - This includes fishes and invertebrates living at the sediment-water interface. They feed on benthic infauna and organisms and other material in the water.			Changes in types and abundances of benthic infauna affect the epibenthic animals that feed on them; disappearance of a benthic amphipod around a discharge site, for example, will affect those fishes feeding on it. Other changes could be caused by the association of epibenthic organisms with toxic substances present in sediments.	Yes. Effects of trace metals and various toxic organics can be minimized by source control. Effects due to high organic input and subsequent sulfide formation can be modified by engineering practices that disperse inputs. However, sludge disposal will always result in some accumulation around a fixed outfall site.	Both	No	This evaluation is based on results of studies of present waste outfalls.
● AQUATIC RESOURCE UTILIZATION ● HARVESTING OF MARINE ORGANISMS ▶ Fishing - The only fishery reported in southern California waters at depths of 400 m or deeper is sable fish. Present activity is at depths of 200-600 m in the outer banks area of southern California Bight. The presence of sable fish in nearshore basins makes a fishery there possible.			Effects on any fishery cannot be predicted at present.	(No fishery presently active in discharge area.)		No	See SCCWRP 1978 Annual Report.

*1978 Water Quality Control Plan for Ocean Waters of California (Water Resources Control Board, Sacramento).

I. INTRODUCTION

Disposal of human wastes has always involved an impact on the environment. Treatment of digested sewage waste for ten million people in the Los Angeles/Orange County area yields a sludge that can be disposed of on land, in the ocean, or in the atmosphere. It is necessary to explore the environmental costs associated with each disposal possibility.

Availability of deep water close to shore in southern California has stimulated oceanic discharge of sewage effluent and sludge. Discharge systems in surface waters adequately meet the classical design criteria of maintaining aquatic oxygen concentrations and of satisfying bathing water standards, but have had documented effects on marine benthic ecosystems. While the significance of these ecological changes is not understood there are plans being made to change sludge disposal practices. Federal policy is to stress land disposal. Higher costs involved in land disposal make comparisons with ocean disposal desirable. One option which might have minimal environmental impact is disposal in deep oceanic basins off southern California. Present low oxygen concentrations in basin waters have made them relatively devoid of animal life. Discharge of sewage sludge into such locations may have minimal effect on such ecosystems. We assess the likely consequences of such a discharge in this report.

Although oceanic disposal of organic wastes has had an impact on marine ecosystems, the magnitude of effects, mechanistic causes, and their significance are either unknown or controversial. Uncertainty at all levels of environmental study, be they physical, chemical, or biological, makes it difficult to understand or predict completely the environmental effects of marine waste disposal. However, we can predict three important ways that sewage sludge can affect organisms, namely: by decreasing oxygen content in the water; by increasing sulfide concentrations in the sediments and in the waters; and by changing trace metal concentrations. We can assess the aspects of a proposed sludge disposal scheme by using our knowledge of the chemical processes that influence oxygen, sulfide, and trace metal concentrations.

Santa Monica and San Pedro Basins are the basins nearest Los Angeles. Properties of basin waters are controlled in part by communication with open ocean waters at the San Pedro Basin sill depth of 737 m. The interconnected basins have an area of 2460 km^2 at sill depth and a volume of 290 km^3 below that sill depth. Oxygen concentrations in the basins are about 0.2 ml/liter or 9μM (surface concentrations are about 7 ml/liter or 0.3 mM). Low oxygen concentrations in the basins result from the presence of the oxygen minimum in the oceanic water at the sill depth as well as organic matter decay in the basins. Benthic surveys have shown the lower basins to be depauperate but not dead.

Sludge disposal into Santa Monica-San Pedro Basin would have several predictable effects. More importantly, the oxygen concentration of an already low-oxygen environment would be further lowered and the small number of organisms present would decrease. The extent of the oxygen decrease would depend on mixing rates between basin and overlying waters, on exchange rates for water from Santa Monica-San Pedro Basin and adjacent basins, on rates of sedimentation and on rates of oxygen utilization. By using mixing rates derived from hydrographic data, oxygen utilization data, and sedimentation models, we predict oxygen and trace metal changes.

This study on the effect of sludge disposal in marine basins included the collection of field data by the Southern California Coastal Water Research Project (SCCWRP) and the analysis of this data, and the prediction of sludge disposal effects by the Environmental Quality Laboratory of the California Institute of Technology. SCCWRP was to determine animal distribution in the basins and to collect current and hydrographic data. The latter were to be used for the determination of exchange rates between Santa Monica-San Pedro Basin with other basins and for the estimation of dispersion rates at potential sludge disposal sites. The report on organism distributions is reproduced as an attachment.

It was originally intended that SCCWRP make ocean current measurements on two occasions using two current meters: once at the sill location for assessing the transport and exchange between basins; once at a potential discharge site to provide heretofore unavailable time series data to permit estimation of transport and dispersion from postulated discharges. Unfortunately, the first attempt with the current meters deployed at the sill location resulted in the loss of the current meters. A new meter, however, was installed later at a potential discharge site and provided a one-month period of current data 50 meters off the bottom. This information was used in the sedimentation modeling in Chapter VI.

Previous studies of sewage waste disposal in southern California marine waters have focused on the more dramatic effects on benthic communities around outfalls and have generally neglected planktonic studies (e.g. SCCWRP, 1977). Discharge into California surface waters does not seriously deplete oxygen in the receiving water but can add significant amounts of plant nutrients. Possible effects on the planktonic community, such as from zooplankton ingesting sewage particles or from interference with chemoreceptors used to find food, have not been studied.

This study assesses sludge, oxygen, and trace metal concentrations in the water column and estimates the benthic area over which particles would fall should sludge be discharged in Santa Monica-San Pedro Basin. Discharge was assumed to be from a submarine outfall. Once discharged, the fresh water-suspended solids mixture of sludge would rise due to its buoyancy and entrain ambient seawater until it reaches a level of neutral buoyancy, which is expected to be about 50 meters above the discharge pipe. The depth at which the plume stops rising is considered as the injection depth in basin-wide chemical modeling. This sludge-seawater mixture will spread horizontally, its particles will start to rain out on the sediments below, bacteria will begin to consume it, and its trace metal containing particles will start to dissolve. The rise and mixing of the sludge plume means that it cannot be considered as safely put on the bottom but must be considered in the water as well; bacterial degradation of this suspended sludge removes oxygen from an already oxygen-poor environment.

With the one-dimensional basin model of chemical and physical effects, we assessed changes that would result for discharge into one of three depths in Santa Monica-San Pedro Basin: 800 m (below sill depth), in a low-oxygen, slowly renewed environment; 600 m (above sill depth) in the upper basin with faster renewal but also in a low-oxygen region; and 400 m (near the top of the basin), in a zone of high oxygen concentration and fastest water renewal (Chapters VII and VIII).

With the particle sedimentation model in three-dimensions, but without chemistry, the fallout patterns were predicted for depths of discharge at 100 m, 400 m, and 900 m (Chapter VI).

The results are summarized in the preceding section "Summary and Conclusions." The discussion of ocean discharge alternatives is given in Chapter IX.

We proceed now with Chapters II-V, giving a description of the natural setting and the characteristics of the sludge to be discharged.

II. DESCRIPTION OF BASINS

Beneath the sea surface off southern California there lies a series of mountain ranges and valleys (Fig. II-1). Mountain peaks break the ocean surface to form the offshore islands; valleys, some deeper than 2000 m, form isolated marine basins. High valley walls limit exchange of basin waters with the open ocean (Fig. II-2). Water that does enter from the open ocean at depths of 500 m or greater enters with low oxygen concentration. Oxidation of organic matter decreases the oxygen to a level where the inshore basins of Santa Barbara, Santa Monica, and San Pedro have low densities of animal life in their depths (Fig. II-3).

The inshore basins are the most accessible for sludge disposal, the best studied, and have the most depauperate fauna in their lower depth. The traditional definition of a marine basin is a bathymetric depression which is totally cut off from horizontal water exchange (e.g. Emery, 1960) by mountain ridges or sills. Above the classical basin are additional volumes of water partially isolated from the open sea by ridges around most of the periphery; for our analysis, it is important to consider those as part of the basins also. The totally isolated part of a basin will be called the lower basin; the overlying water which is in a dead-end canyon will be known as the upper basin. Above this is water which flows easily over (or around) the physical obstructions; this will be called upper shelf water or flow-through zone (see Fig. II-4). See Appendix 2 for more discussion.

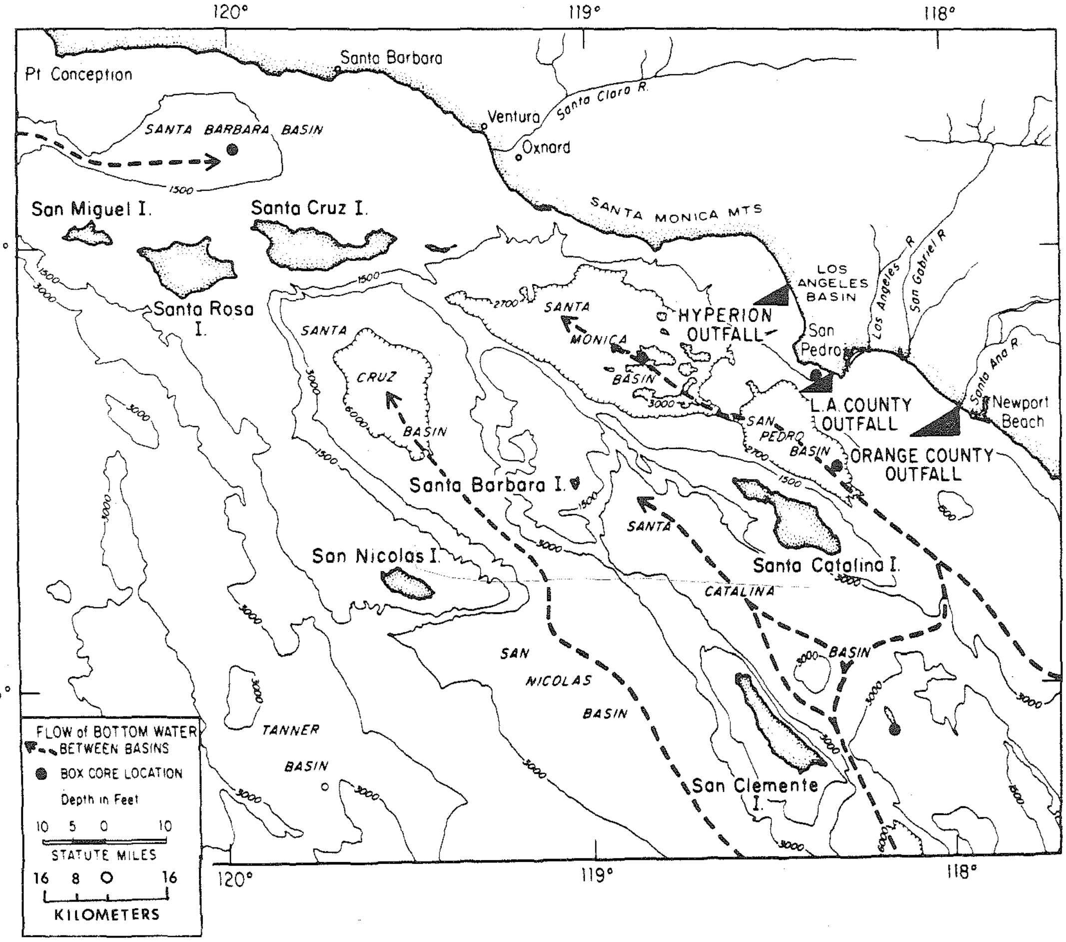


Figure II-1 The Marine Basins of Southern California
(from Bertine and Goldberg, 1977)

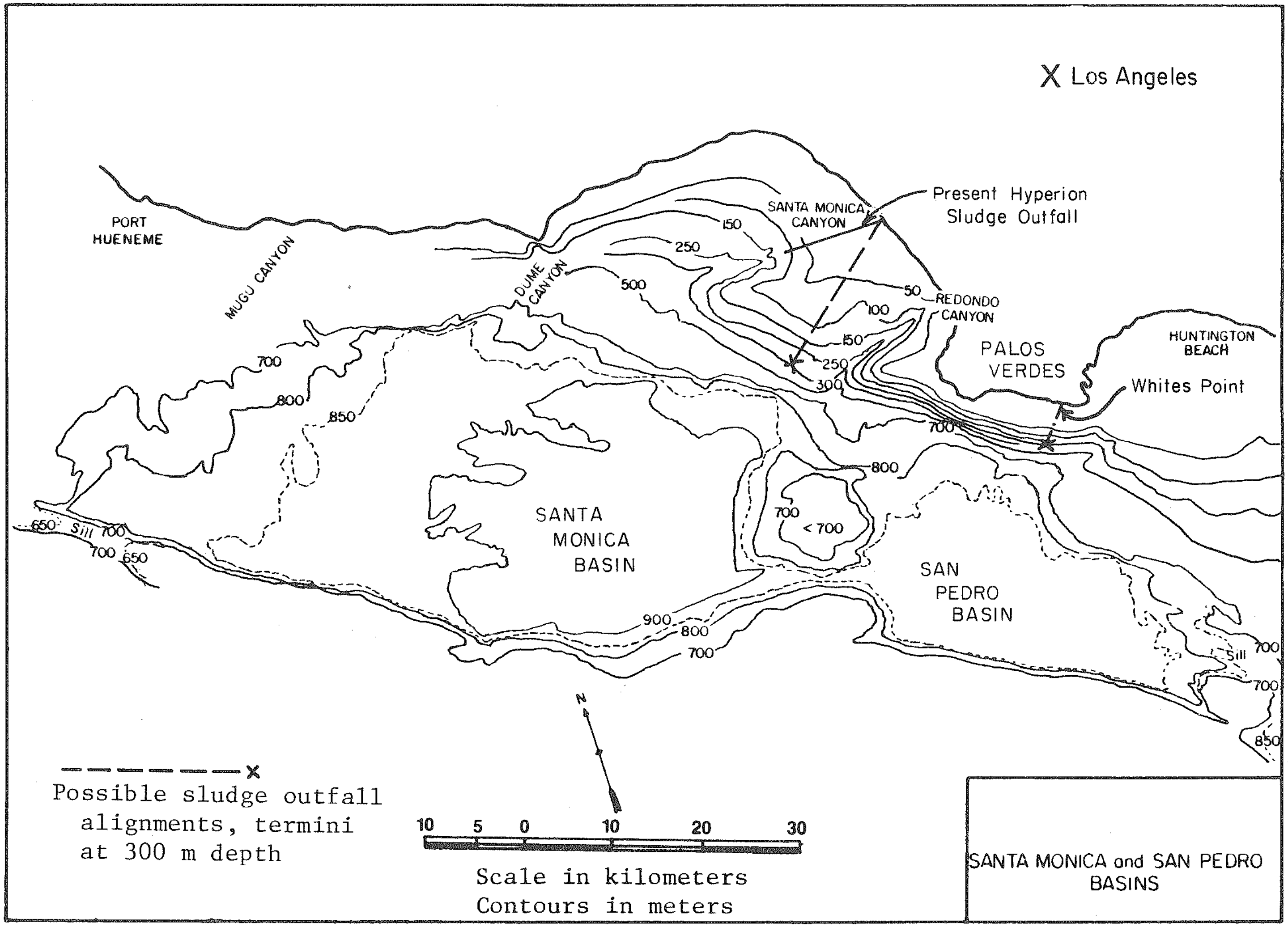


Figure II-2 Basin bathymetry.

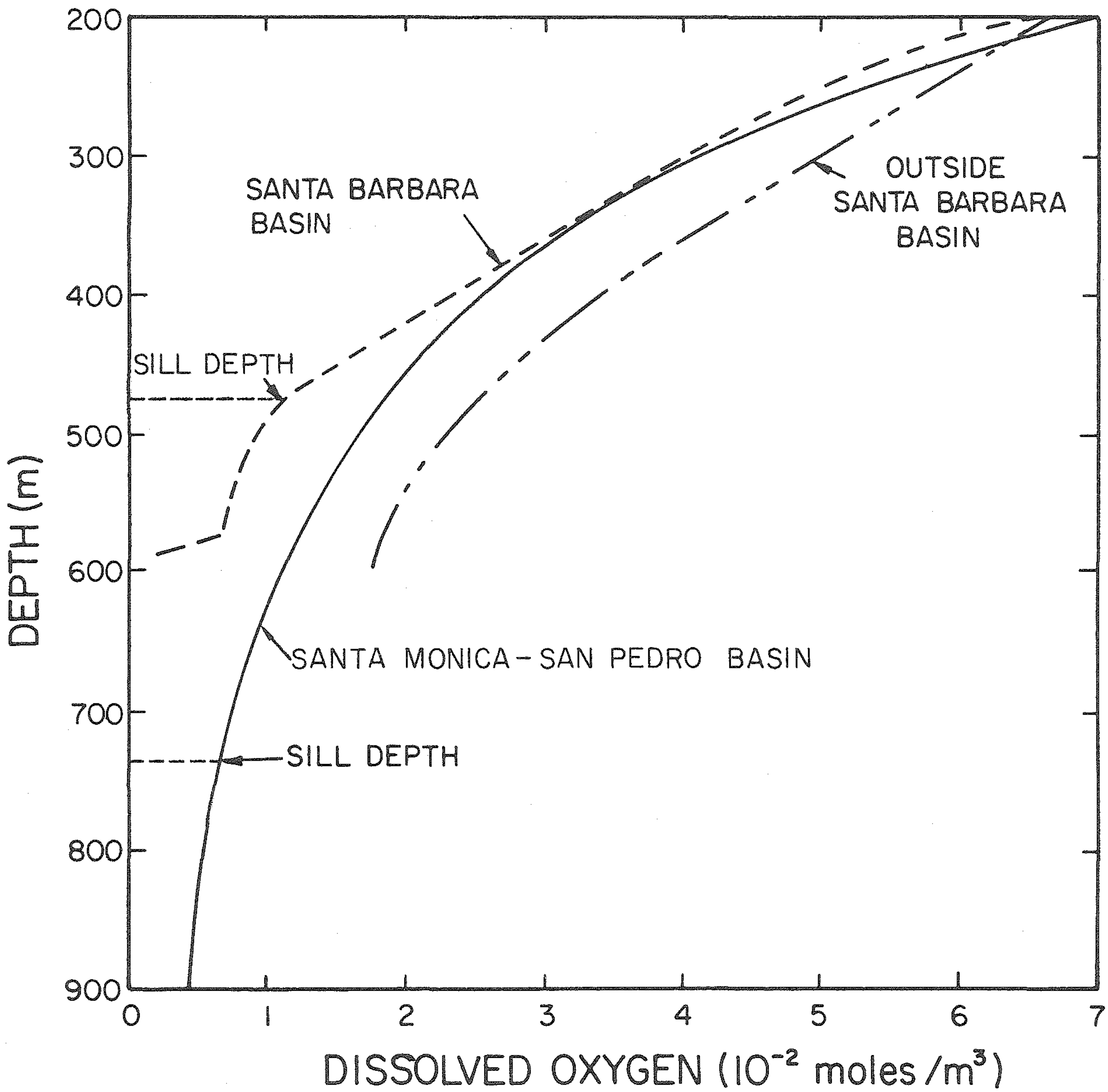


Figure II-3 Typical Oxygen Profiles Off Southern California

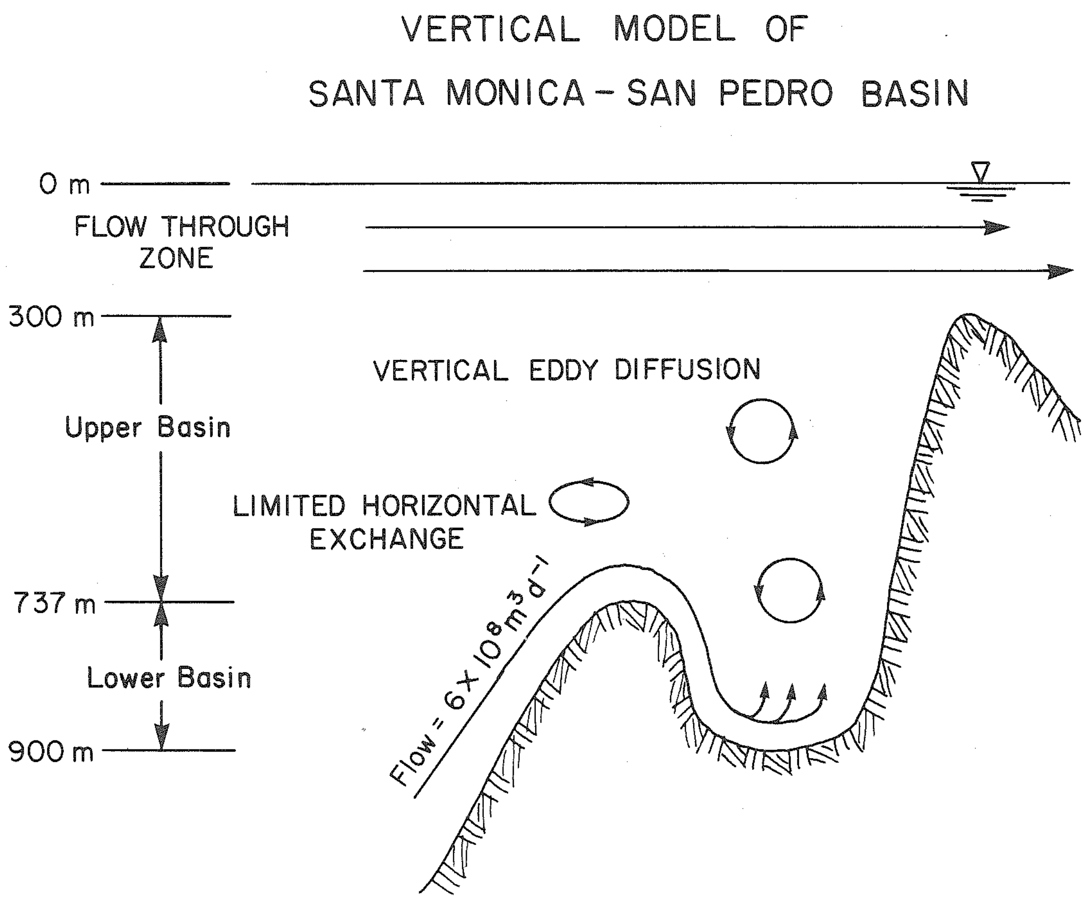

VERTICAL MODEL OF
SANTA MONICA - SAN PEDRO BASIN
0 m
FLOW THROUGH ZONE
300 m
Upper Basin
737 m
Lower Basin
900 m
VERTICAL EDDY DIFFUSION
LIMITED HORIZONTAL EXCHANGE
Flow = 6×10⁸ m³d⁻¹

Figure II-4

The three basins most thoroughly discussed here are the Santa Barbara, Santa Monica, and the San Pedro Basins. The Santa Barbara Basin has been the most extensively studied and has provided information on the basin mixing processes. Santa Monica and San Pedro Basins are closest to the Los Angeles metropolitan area and are therefore the primary sites for basin disposal of sludge. Because the exchanges in the lower parts of these two basins are controlled by the same sill at the south end of San Pedro Basin and because vertical profiles of chemically-important quantities suggest that the two basins are horizontally well mixed, we have considered them to be one basin (Table II-1).

TABLE II-1

Nearshore Basins

	Santa Barbara	Santa Monica-San Pedro
Lower Basin		
Sill depth (m)	475.	737.
Maximum depth below sill (m)	114.	165.
Average depth below sill (m)	65.	118.
Area at sill (m^2)	6.6×10^8	$25. \times 10^8$
Volume below sill (m^3)	4.3×10^{10}	$29. \times 10^{10}$
Upper Basin		
Depth at top (m)	250.	300.
Depth at bottom (m)	475.	737.
Area at top (m^2)	$19. \times 10^8$	$39. \times 10^8$
Volume (m^3)	$31. \times 10^{10}$	$149. \times 10^{10}$

For area-depth graphs, see Fig. 2-5 in Appendix 2.

Basin sediments consist of interbedded layers of green claylike silts and coarser sands (Gorsline and Emery 1959, Hulsemann and Emery, 1961). The clay and silt settles fairly uniformly throughout the basins; sand and coarse silt flow down from the coast through underwater canyons or are sloughed from shelf edges, settling out in the landward sides of the basins (Fig. II-5, curves 1, 2, 3 compared to 4 through 7). Sedimentation rates in the inshore basins range between 0.08 and 0.9 cm/yr. These are high compared to those in the outer basins of San Clemente and Santa Catalina, where 5 cm of sediment accumulates every 1000 years (Bruland et al., 1974; Bertine and Goldberg, 1977).

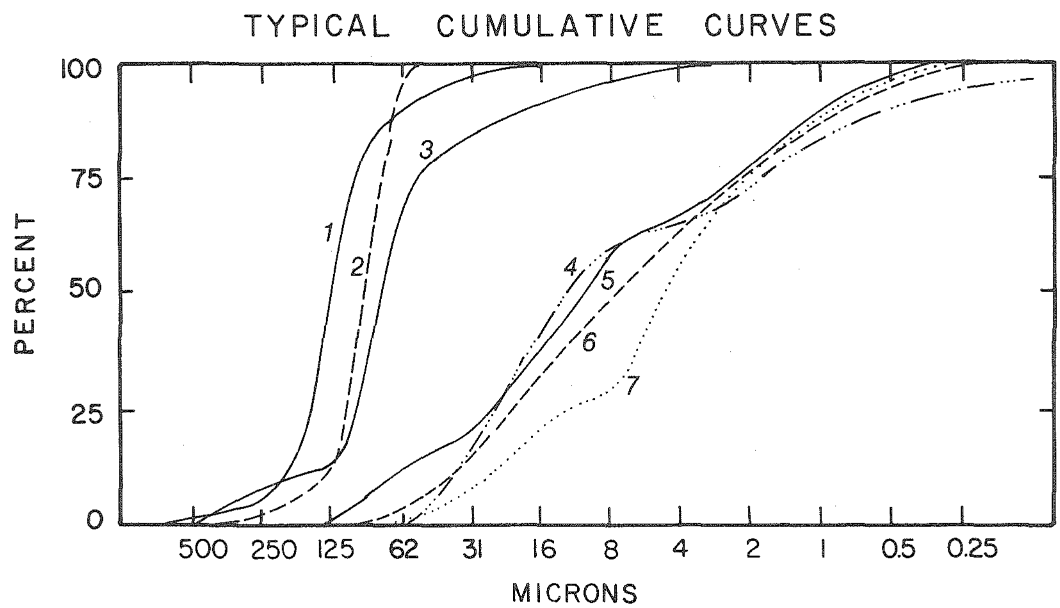


Figure II-5 Typical size distribution curves for various samples from the Santa Monica-San Pedro Basin sediment (from Gorsline and Emery, 1959).

Interstitial water deeper than a few centimeters is devoid of oxygen, high in sulfides and inhospitable for animals. Their absence keeps the top 10-cm layer from being stirred, as would be the case with sufficient oxygen. As a result, the sediments provide a record of the level of surficial animal activity through time. Varves (sediment microlayers) and radioactive profiles indicate that the Santa Barbara and Santa Monica-San Pedro Basins are at present relatively devoid of animal life (Hulsemann and Emery, 1961; Bertine and Goldberg, 1977). Varving patterns in the Santa Barbara Basin indicate that periods of high and low sediment mixing alternate. Organism remains deposited in the two different phases also differ (Hulsemann and Emery, 1961). The implication is that oxygen concentrations were periodically higher, permitting the sustenance of burrowing animals. Historic evidence for animals reworking the Santa Monica-San Pedro Basin sediments has also been reported (Gorsline, 1958), but there have been no recent detailed investigations. Further study of basin histories could show what the mechanisms for changes in basin circulation are, whether these are the same for the different basins, and how sensitive basins are to changes in organic imputs.

Typical profiles for temperature and density for the Santa Monica-San Pedro Basin are given in Figs. 2-1 and 2-3 in Appendix 2.

III. WATER EXCHANGE AND MIXING IN BASINS

The purpose of this chapter is to give a very brief overview of water exchange and mixing in an offshore basin. The quantitative modeling of the basin circulation and mixing processes in the Santa Monica-San Pedro Basin is presented in detail in Appendix 2, Sections II-IV.

The dominant basin water exchange mechanism below sill depth is the fairly regular (but slow) influx of relatively dense water over basin sills. This high oxygen water flows down to the basin bottom, gradually displacing water upward and thereby causing new upward advection (see Fig II-4). Also important is the flux supplied by vertical mixing. These processes maintain the movement of water and its various associated substances to the lower basins. Oxygen concentration is determined by the balance of physical processes that supply oxygen and the chemical and biological processes that deplete it.

Upper basin circulation involves not only these vertical processes but also the more important horizontal ones. Horizontal water exchange can occur through eddy processes occurring at basin entrances exchanging water with that of other basins or through currents bringing outside water in at one end and taking basin water out at another. However, the underwater topography of the basins combined with density stratification tends to limit the flushing of the basins by currents. Horizontal exchange replaces water on a time scale that ranges from about 100 days at 300 m to about 500 days at 700 m (Appendix 2, Section III).

Further exchange is provided by large changes in basin thermal structure as in upwelling or downwelling events. Changes in vertical temperature profiles suggest possible vertical water movements of 100 m for water initially at 150 m, 50 m for water at 300 m, and lesser distances for deeper waters. Such vertical movements in a basin are accompanied by inward flow of makeup water from other basins. Under most conditions this flow is less than from horizontal exchange processes. It can be important to a shallow lower basin such as that of Santa Barbara Basin when upwelling external to the basin brings new water above sill depth that is denser than that already in the lower basin. The result is the rapid replacement of water in the lower basin with new water from outside (Sholkovitz and Gieskes, 1971). This overturn of water in the lower Santa Barbara Basin can have dramatic effects on oxygen concentration, increasing it by a factor of four. However, oxidation processes reduce these concentrations by half within a month. They play only a small part in the total oxygen budget of a basin.

No evidence of this overturning phenomenon has been observed in the deeper Santa Monica-San Pedro Basin, probably because variations in isopycnal depth are smaller at the deeper sill depth, 740 m, than at the 470 m Santa Barbara Basin sill depth.

IV. NATURAL FLUXES IN BASINS

Sedimentary Processes

Measured sedimentation rates or fluxes for various substances are shown in Table IV-1. Note that almost all sedimentation processes occur faster in Santa Barbara Basin than in Santa Monica-San Pedro Basin when rates are normalized with respect to area.

Also note that heavy metal sedimentation rates have increased greatly as a result of anthropogenic processes. Bruland et al. (1974) suggest that the likeliest source for much of this is waste water discharge. Bertine and Goldberg (1977) examined sedimentation in marine basins further from the coast and decided that the considerably lower values found there were more suggestive of atmospheric fallout than of sewage discharge. Their conclusion did not explain the extremely high concentrations of some heavy metals found in Santa Monica-San Pedro Basin. It is still possible that the high anthropogenic fluxes there are the result of waste discharge, although urban runoff and atmospheric fallout are also likely sources.

Oxygen Consumption

Oxygen is consumed in the sediments and in the water column. Jenkins (1977) reported an oxygen consumption rate of 2.5×10^{-5} mole-O_2 $m^{-3}d^{-1}$ (0.2 liter m^{-3} yr^{-1}) in the water column of the Sargasso Sea at a depth of about 100 m. Morita, Geesey, and Goodrich (1974) reported carbon utilization rates among bacteria of the Oregon coast in 100 m depth were,

TABLE IV-1

Sedimentary Inputs to Lower Basins
Values from Bruland et al. (1974), and Hulsemann and Emery (1961)

	Santa Barbara Basin			Santa Monica-San Pedro Basin		
	Rates or Fluxes		TOTAL	Rates or Fluxes		TOTAL
	Natural	Anthropogenic	tons/year	Natural	Anthropogenic	tons/year
Sedimentation Rate						
mm yr^{-1}	4.			0.8	-	
gm-solids $m^{-2} yr^{-1}$	900.		600,000	260.	-	640,000
Fluxes						
Organic carbon gm $m^{-2} yr^{-1}$	45.		30,000	13.		31,000
Organic nitrogen gm $m^{-2} yr^{-1}$	3.		2,000	0.4		1,000
Heavy metals mg $m^{-2} yr^{-1}$						
Pb	10.	21.	20	2.5	12	36
Cr	107.	29.	90	25.	28	130
Zn	97.	22.	80	30.0	20	123
Cu	26.	14.	26	11.	12	56
Ag	1.1	1.0	1.4	0.4	0.9	3.2
V	135.	78.	141	35.	20	135
Cd	1.4	0.7	1.4			
Mo			-	0.8	8	22
Ni	41.		27	15.		37
Co	10.		6.6	3.0		7
Mn	100.		66	240.		590
Fe	12,000.		7,900	30,000.		74,000
Al	17,000.		11,000	50,000.		120,000

at their highest, equivalent to 3.6 x 10^{-5} mole-O^2 $m^{-3}d^{-1}$ (for an O_2:C ratio of 1). Oxygen utilization is widely believed to decrease rapidly with increasing depth. For instance, Morita et al., found maximum carbon uptake in Antarctic waters at 100 m depth and were unable to detect any uptake at 500 m. Therefore, it is surprising that Skolkovitz and Gieskes (1971) reported oxygen utilization rates in the low Santa Barbara Basin as great as 2.2 x 10^{-4} mole-O_2 $m^{-3}d^{-1}$, a factor of 6 greater than the maximum uptake near the Oregon surface waters.

Oxygen consumption rates in the Santa Barbara Basin are more reasonable when computed as sediment uptake rate of 14 mmole-O_2 $m^{-2}d^{-1}$ (320 ml $m^{-2}d^{-1}$). Smith (1974) measured sediment oxygen consumption in 20 m deep sandy bottom off southern California as high as 44 mmole-O_2 $m^{-2}d^{-1}$ (1000 ml $m^{-2}d^{-1}$); he measured a rate of 2.6 mmole-O_2 $m^{-2}d^{-1}$ (58 ml $m^{-2}d^{-1}$) in the San Diego Trough. The similarity of oxygen consumption in the Santa Barbara Basin to benthic respiration rates suggests that sedimentary oxygen uptake is predominant over water column uptake.

The exact rate of which sediments consume oxygen in Santa Monica-San Pedro Basin is unknown. A mass balance on oxygen entering and leaving the lower basin yields an oxygen consumption rate of 1.7 mmoles-O_2 $m^{-2}d^{-1}$ (38 ml-O_2 $m^{-2}d^{-1}$). This might be equivalent to a rate of 3.8 mmoles $m^{-2}d^{-1}$ (85 ml-O_2 $m^{-2}d^{-1}$) if the lower basin had a higher oxygen concentration (Appendix 2). Oxygen uptake rate in the upper basin should be between this (3.8 mmole $m^{-2}d^{-1}$) and 45 mmole $m^{-2}d^{-1}$ measured in 20 m depth (Fig. IV-1). Smith (1974) calculated from a relation suggested by

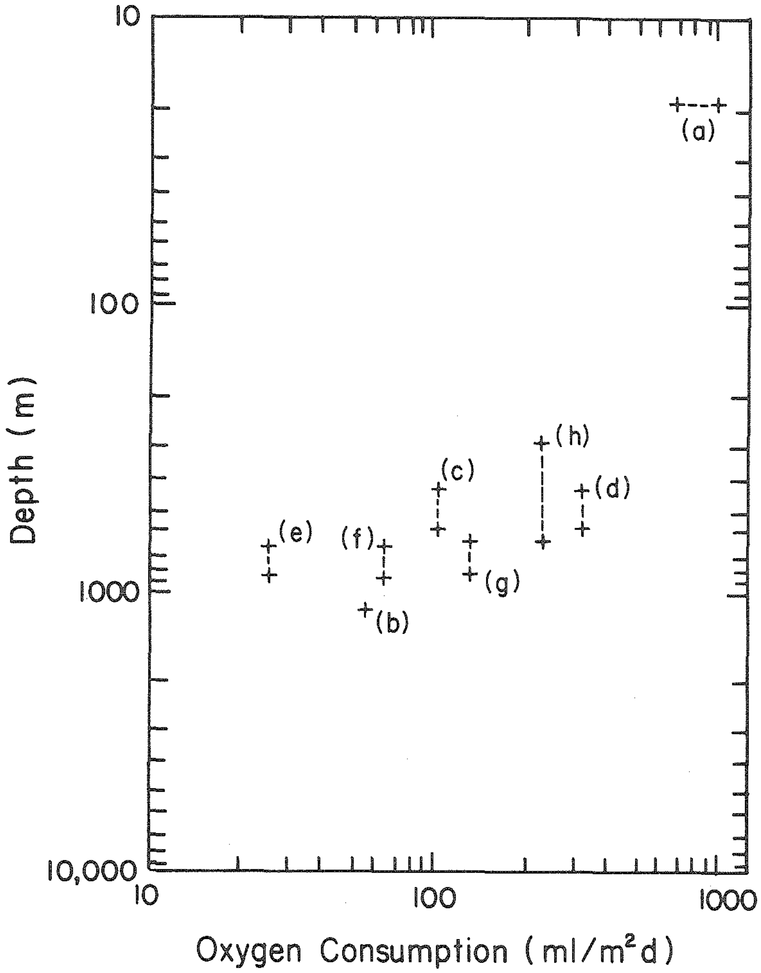


Figure IV-1 Sediment Oxygen consumption rates:

a) Scripps pier (1974), Smith (personal communication).
b) San Diego Trough, Smith (1974).
c) Santa Barbara Basin, Sholkovitz and Gieskes (1971).
d) Santa Barbara Basin, ℓ_{max} as calculated from (c) as in Appendix 2.
e) Lower Santa Monica-San Pedro Basin, actual rate (Appendix 2).
f) Lower Santa Monica-San Pedro Basin, ℓ_{max} calculated for oxygen uptake independent of nitrate uptake.
g) Lower Santa Monica-San Pedro Basin, ℓ_{max} calculated for oxygen + nitrate uptake.
h) Upper Santa Monica-San Pedro Basin, assumed ℓ_{max}.

Hargrave (1973) that respiration in the sediments of southern California should be 240 ml-O_2 $m^{-2}d^{-1}$ (10.7 mmole $m^{-2}d^{-1}$). We have assumed that oxygen consumption in the upper Santa Monica-San Pedro Basin is 10.7 mmole $m^{-2}d^{-1}$ (240 ml-O_2 $m^{-2}d^{-1}$).

Nitrate Consumption

Nitrate reduction rates in the lower Santa Monica-San Pedro Basin are as large or larger than oxygen reduction rates (Appendix 2). A mass balance of nitrate entering and leaving the lower basin gives a nitrate reduction of 1.5 mmoles-NO_3 $m^{-2}d^{-1}$, equivalent to 1.9 mmoles-O_2 $m^{-2}d^{-1}$ if nitrate is being reduced to N_2.

V. SLUDGE INPUTS

Trace metals are predominantly in particulates in treated sewage effluents (both primary and secondary) discharged to the ocean (Chen et al., 1974; Morel et al., 1975), and in digested sludge (Faisst, 1976). Theoretical calculations show that under reducing conditions of sewage, most trace metals can form sulfide or oxide precipitates (see Table V-1).

Studies on the dissolution of sewage particulates are not consistent. Rohatgi and Chen (1975) found that more than half of the cadmium, zinc, and nickel had been released from sludge particulates five weeks after sludge had been mixed with seawater (Table V-2). However, when Faisst (1976) performed similar experiments, he found that nickel was the only metal to solubilize to any measurable extent over a period of four weeks. Both sets of experiments did show that the majority of copper, chromium, lead, iron and manganese remained in particulate forms over short times.

Fate of metals discharged into the ocean is linked with their particulate and dissolved distributions. For a strategy of containment, in which the goal of ocean discharge is to have the trace metals collect and stay in limited areas of the basin bottoms, it would be desirable for metals to settle quickly to the bottom, or be discharged as a denser-than-seawater mass on the bottom, with little release to the water column. For a strategy of dilution, trace metals should be widely enough dispersed so that: (a) the impact of the water column is minimal (i.e., by

TABLE V-1

Equilibrium Speciation in a Sludge Digester Organic Model[1]
$p\varepsilon = -4.40$, pH = 7.9
(from Faisst, 1976)

metals	total conc	free conc	COMPLEXES[2]										SOLIDS	
ligands →			CO_3	SO_4	Cl	NH_3	S	PO_4	SiO_3	CN	AC	OH		
total conc →			1.60	---	2.38	1.63	2.03	2.42	3.78	3.81	1.78	---		
free conc →			3.48	2.93	2.38	2.82	11.4	8.40	10.0	6.23	1.78	5.91		
Ca	2.60	4.38	5.04	6.04	---	7.30	---	7.80	---	---	5.67	8.99	$Ca_3(PO_4)_2$	3.31
Mg	2.21	2.59	3.22	4.15	---	5.31	---	5.52	---	---	3.79	6.20	$Mg_2(PO_4)_2$	3.03
K	2.60	2.60	---	4.95	---	---	---	---	---	---	---	---		
Na	2.11	2.11	4.90	4.86	---	---	---	---	---	---	---	---		
Fe^{3+}	1.90	23.7	---	24.1	25.4	---	---	21.5	19.4	18.8	20.1	15.0	Fe_3O_4	2.63
Fe^{2+}	---	6.93	---	8.59	8.92	8.45	---	3.36	---	8.71	5.52	7.94	FeS	2.28
Mn	3.93	5.90	6.14	7.56	7.69	8.02	---	8.33	---	---	7.05	8.41	$MnCO_3$	3.94
Cu^{2+}	3.30	25.8	23.4	27.5	25.8	23.5	---	27.9	---	---	25.8	26.1	CuS	3.30
Cu^{1+}	---	19.2	---	---	18.7	14.0	---	---	---	8.13	---	---		
Cd	4.72	16.3	15.4	18.0	17.0	16.6	12.9	22.4	---	17.1	16.0	18.7	CdS	4.72
Zn	2.70	10.1	9.33	11.8	11.2	10.6	---	13.0	---	18.7	10.6	11.5	Zn	2.70
Ni	3.36	10.4	9.40	12.1	12.8	10.5	---	13.6	---	4.44	11.5	11.5	NiS	3.70
Pb	3.82	16.4	13.3	17.7	17.6	---	---	---	---	31.6	16.2	16.5	PbS	3.82
Ag	5.11	19.6	---	21.9	19.0	---	14.2	---	---	11.2	21.0	23.8	Ag_2S	5.41
Cr	2.86	10.8	---	12.5	13.1	---	---	7.78	---	---	---	3.66	$Cr(OH)_3$	2.94
H^+	---	7.9	1.63	9.09	---	1.66	5.75	4.46	3.79	5.12	4.88	---		

(1) All values as p[X] = -log (molar concentration of X).

(2) Concentrations of complexes are sums of all complexes of a given Metal Me, with a given ligand L. $\sum_{k,j} [Me_k L_j]$ where k,j are the stoichiometric coefficients.

dissolution of metals during sludge particle sedimentation); and (b) the loading in natural sediments is light over a large area. Particle settling rates are an important factor in this. Faisst (1976) has measured sludge particle settling rates and found that the particles exhibit a broad distribution of settling velocities (see Fig. VI-4).

TABLE V-2

Percentage of Trace Metals Released After Five Weeks From the Particles in Digested Hyperion Sludge (from Rohatgi and Chen, 1975)

Metal	50:1 Dilution[1]	100:1 Dilution[1]	200:1 Dilution[1]
Cd	93.0	95.0	96.0
Cu	5.0	5.6	9.0
Cr	2.0	2.0	3.8
Fe	0	0	0
Mn	31.8	34.7	35.7
Ni	49.0	58.0	64.0
Pb	37.8	35.4	35.4
Zn	18.0	24.4	58.7

(1) Sludge was diluted with filtered natural seawater.

This range of sedimentation rates might represent the worst situation with regard to disposal in the marine basins because neither containment nor dilution works completely. A vertical flow of water will keep suspended those particulates with settling velocities less than the upward water flow velocity. At a vertical water velocity of 0.2 m d^{-1} calculated in the Santa Monica-San Pedro Basin at the level of the sill, approximately 30-40 percent of the sludge might stay suspended with the rest settling out (Fig. V-1),* and the strategy of containment in the lower basin might not work. However, if the sludge coagulates upon discharge, the settling rates would increase and the sludge would be taken to the bottom much more efficiently.

An alternative strategy for disposal in the marine basins would be to discharge in the upper basin or upper shelf waters. Consequences of this are developed later in this report.

The amounts of trace metals and oxygen-consuming organics that can be expected if sludge were to be discharged into the basin are shown in Table V-3. These numbers are the estimates of suspended solids to be discharged in 1985. Table V-4 gives a comparison of projected sludge outputs of metals to the present estimates of trace metal accumulation rates in the sediments of the lower Santa Monica-San Pedro Basin; the ratios range from 3 to 9 times as great. The differences between sludge inputs from full secondary treatment and from marine secondary treatment are relatively small. ("Marine secondary treatment" is defined by Table 3-1 in Appendix 3 as secondary treatment for only part of the flow to be discharged to the ocean by each agency, with the remainder having only (advanced) primary treatment.)

*A quartz particle of about 2μ sedimentation diameter would also settle at about 0.2 m d^{-1}.

TABLE V-3

Projected Sludge Discharges, 1985[1]

a) Full Secondary Treatment

	Hyperion[3]	JWPCP[3]	OCSD[3]	Total
Sludge quantity,[b] dry tons d^{-1}	370	475	300	1145
BOD of sludge,[2] 10^6 moles-$O_2 d^{-1}$	8.1	10.5	6.6	25.2
Trace metals, kg d^{-1}				
As	7	—	—	> 7
Hg	4	2	—	> 6
Ag	36	18	7	61
Cd	41	34	34	109
Ni	94	155	46	295
Pb	59	328	138	525
Cr	506	777	189	1472
Cu	486	460	392	1338
Zn	545	1407	474	2426
Trace organics, kg d^{-1}				
DDT's	.10	2.45	0.04	2.59
PCB's	.64	2.73	1.25	4.62
TICH	.73	5.45	1.30	7.48
Chlorinated benzene	21.36	30.45	14.55	66.36

1. Values provided by LA/OMA (See Appendix 3).

2. BOD calculated using relationship of 1 dry ton sludge = 2.2×10^4 moles O_2.

3. Hyperion (Treatment Plant, City of Los Angeles).
JWPCP (Joint Water Pollution Control Plant, Los Angeles County Sanitation District).
OCSD (Orange County Sanitation Districts).

TABLE V-3
(continued)

Projected Sludge Discharges, 1985

b) Marine Secondary Treatment

	Hyperion	JWPCP	OCSD	Total
Sludge quantity, dry tons d^{-1}	285	440	225	950
BOD of sludge, 10^6 moles-$O_2 d^{-1}$	6.3	9.7	5.0	21.0
Trace metals, kg d^{-1}				
As	6	—	—	> 6
Hg	3	2	—	> 5
Ag	25	16	6	47
Cd	31	29	22	82
Ni	75	141	40	256
Pb	43	290	107	440
Cr	344	692	120	1156
Cu	375	412	290	1077
Zn	438	1281	363	2082
Trace organics, kg d^{-1}				
DDT's	0.10	2.34	.03	2.47
PCB's	0.47	2.50	.85	3.82
TICH	0.54	5.09	.87	6.50
Chlorinated benzene	15.91	24.85	8.82	49.58

TABLE V-4

Comparison of Lower Santa Monica-San Pedro Basin Sedimentation with Projected Sludge Discharge

Substance	(A) Lower SM-SP Basin Flux[1]	(B) Projected Sludge Discharge: Full Secondary Treatment	B/A	(C) Projected Sludge Discharge: Marine Secondary Treatment	C/A
Organic C (BOD 10^9 moles - O_2/yr)	2.6[2]	9.2	3.5	7.7	3.0
Heavy Metals (tons/yr)					
Cd	--[3]	40.	--	30.	--
Cr	130	537.	4	422.	3
Cu	56	488.	9	393.	7
Pb	36	192.	5	161.	4
Hg	--[3]	> 2.2	--	> 1.8	--
Ni	37	108.	3	93.	3
Ag	3	22.	7	17.	6
Zn	123	886.	7	760	6

1. From Table IV-1, total present fluxes including anthropogenic.
2. Assuming complete oxidation of all C.
3. No estimate available.

VI. SEDIMENTATION MODELING

Introduction

This chapter discusses the physical aspects of the fate of the particulates in sludge if it is discharged into the Santa Monica-San Pedro Basin. For definiteness, it will be assumed that a pipeline is terminated at approximately 400 meters depth, although the analysis is similar for other depths as well as other modes of discharge. The 400-meter depth appears more favorable than deeper depths according to the biological modeling results given in Chapter VII.

When sludge first exits from a pipeline (whether or not equipped with a diffuser), it will undergo a phase of motion which is influenced by its momentum and buoyancy as well as the ambient current and density stratification. This phase typically lasts only a matter of minutes and results in a certain initial dilution and equilibrium height of rise. During this phase, the ambient conditions can be considered steady (since the time scale of changes in ambient conditions is on the order of hours) and the particulates can be assumed to be part of the discharged fluid (since fall velocities are very small). The phenomenon of flocculation may take effect during this time. However, no method is available to estimate its importance.

Following this initial phase, the diluted mixture is advected and dispersed by the currents and turbulence in the ocean while the particulates slowly fall down (or float up, as the case may be).

We shall not be concerned with the details of how the dispersion occurs on any given day, but rather will attempt to estimate the longer-term fallout pattern of the particulates when the effects are integrated over a long time (such as months and years).

It is clear that in order to do this, we must have the following information:

(i) The fall velocities of the particulates

(ii) The ocean currents and density stratification near the site

(iii) The flow rate and other characteristics of the discharge.

Unfortunately, we have little information on either the fall velocities or the currents. It is thus impossible to make reliable estimates. The best that can be achieved would be a parametric estimation of orders of magnitude.

In principle, a computer simulation approach could be applied where a particle is released at a given height (sampled from a distribution) with certain fall velocity (sampled from a distribution) and permitted to be transported with a certain velocity field (sampled from a population). When the particle reaches the bottom, its location can be recorded. By repeating this procedure many times, an estimate can be made as to the sedimentation distribution. This procedure tends to be costly in practice because the total settling times are much larger than the time scale of current fluctuations resulting in the need for a large number of simulation steps. Inasmuch as we have, at best, only rough estimates of the required information, an alternative method will be employed based on the advective diffusion equation. This is basically the same as replacing the random walk approach in Brownian motion by solving the diffusion equation.

Formulation

Consider a single particle of sludge with fall velocity w situated as position x_o, y_o, z_o at time $t = 0$ in an infinite ocean. We seek the probability density $p(x,y,z,t;x_o y_o, z_o)$ such that

$$p \; dxdydz$$

is the probability of finding that particle in the interval x to $x + dx$, y to $y + dy$, z to $z + dz$ at time t. We assume stationarity and postulate that p is Guassian of the form

$$p = \left(\frac{1}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z}\right) \exp\left\{-\frac{(x - x_o)^2}{2\sigma_x^2} - \frac{(y - y_o)^2}{2\sigma_y^2} - \frac{(z - (z_o - wt))^2}{2\sigma_z^2}\right\} \qquad \text{(VI-1)}$$

where σ_x, σ_y are functions of t only; $\sigma_z = \sqrt{2\varepsilon_z t}$, ε_z = vertical diffusion coefficient and where it has implicitly been assumed that x, y, z are along principal axes of the stochastic velocity field.

In the present case, there is an ocean bottom given by $z = z_b(x,y)$. We now make the intuitive assumption that the relative rate of particle fallout on $z = z_b(x,y)$ is given by

$$E = wp\big|_{z=z_b} + \varepsilon_z \frac{\partial p}{\partial z}\Big|_{z=z_b} \tag{VI-2}$$

This assumption is admittedly simplistic and is used only as a rough approximation. Physically it means that the probability p is unaffected by the bottom (i.e., the bottom is transparent to the particles) and that the fallout is given by the net downward vertical transport implied by p evaluated at $z = z_b$. Substitution Eq. VI-1 into Eq. VI-2 yields

$$E = \frac{1}{4\pi\sigma_x\sigma_y\sqrt{\pi\varepsilon_z t}} \left(\frac{z_o - z_b + wt}{2t}\right) \exp\left\{-\frac{(x-x_o)^2}{2\sigma_x^2} - \frac{(y-y_o)^2}{2\sigma_y^2} - \frac{[z_o - z_b - wt]^2}{4\varepsilon_z t}\right\} \tag{VI-3}$$

which represents the probability that a particle with fall velocity w which was originally at x_o, y_o, z_o at time $t = 0$ will get to the bottom at position x,y in time t. If, in addition, we know the distribution of heights $g(z_o)$ and fall velocities $f(w)$, then the fallout distribution on the bottom is

$$B = \int_0^\infty dt \int_0^\infty dw \int_0^H dz_o E(x,y,t;x_o,y_o,z_o,w) f(w) g(z_o) \tag{VI-4}$$

where $z_o = H$ is at the water surface.

Distribution of Fall Time

Consider the special case $z_b(x,y) = 0$, i.e., the bottom is flat and is chosen to coincide with the x,y plane. Then

$$E = E_{xy} \frac{1}{2\sqrt{\pi\varepsilon_z t}} \left(\frac{z_o + wt}{2t}\right) \exp\left\{\frac{-(z_o - wt)^2}{4\varepsilon_z t}\right\} \tag{VI-5}$$

where E_{xy} accounts for the variation in the x,y plane.

Let

$$e(t;z_o,w) = \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dx \quad E(x,y,t;x_o,y_o,z_o,w) \tag{VI-6}$$

which can be shown to be simply E/E_{xy}. It represents the fallout probability regardless of x,y position. In other words,

$$e(t;z_o,w)dt$$

is the probability that a particle with fall velocity w at original height z_o will reach the bottom in time t to t + dt. Define

$$\theta(t;z_o,w) = \int_0^t e(t';z_o,w)dt' \tag{VI-7}$$

which is the fraction of the particles originally at z_o having fall velocity w which have reached the bottom by time t. Recalling the basic assumption made wherein we ignored the presence of the bottom and recognizing that $\theta(t;z_o,w)$ can be interpreted as the integral $\int_{-\infty}^{0} p\, dz$, we see that this will underestimate the actual fallout.

We now examine the function $e(t;z_o,w)$ in some more detail. Define $t_o = z_o/w$, $\tau = t/t_o$. Then it can be shown that

$$e(\tau;\eta) = \frac{\eta}{2\sqrt{\pi}} \left(\frac{1+\tau}{\tau\sqrt{\tau}}\right) \exp\left[-\frac{\eta^2(1-\tau)^2}{\tau}\right] \qquad \text{(VI-8)}$$

where
$$\eta = \sqrt{\frac{wz_o}{4\varepsilon_z}} \qquad \text{(VI-9)}$$

and the interpretation of $e(\tau;\eta)$ is that $e(\tau;\eta)d\tau$ is the probability of reaching bottom in time τ to $\tau + d\tau$. Eq. VI-8 gives a one parameter family of probability density functions and is shown plotted in Fig. VI-1. It should be noted that $\tau = 1$ implies that $t = t_o \equiv z_o/w$ which is the time for pure falling a distance z_o at velocity w. If there were no vertical diffusion ($\varepsilon_z \to 0$, or $\eta \to \infty$) then we expect $e(\tau,\infty) \to \delta(\tau - 1)$ where δ denotes a delta function. The parameter η therefore measures the relative importance of falling against vertical diffusion. For z_o = 50 meters, $w = 10^{-3}$ cm/sec, and $\varepsilon_z = 1$ cm^2/sec, $\eta \sim 1$. It is of interest to note from Fig. VI-1 that for η small, a significant fraction of the particles would have reached bottom within only a small fraction of time z_o/w.

Distribution of Initial Height, $g(z_o)$

To obtain an estimate of the distribution if initial height $g(z_o)$ we appeal to the body of literature on buoyant jets and plumes in a stratified fluid. We assume that the discharge is buoyancy-dominated and use the results of Wright (1977) to estimate the equilibrium height z_e:

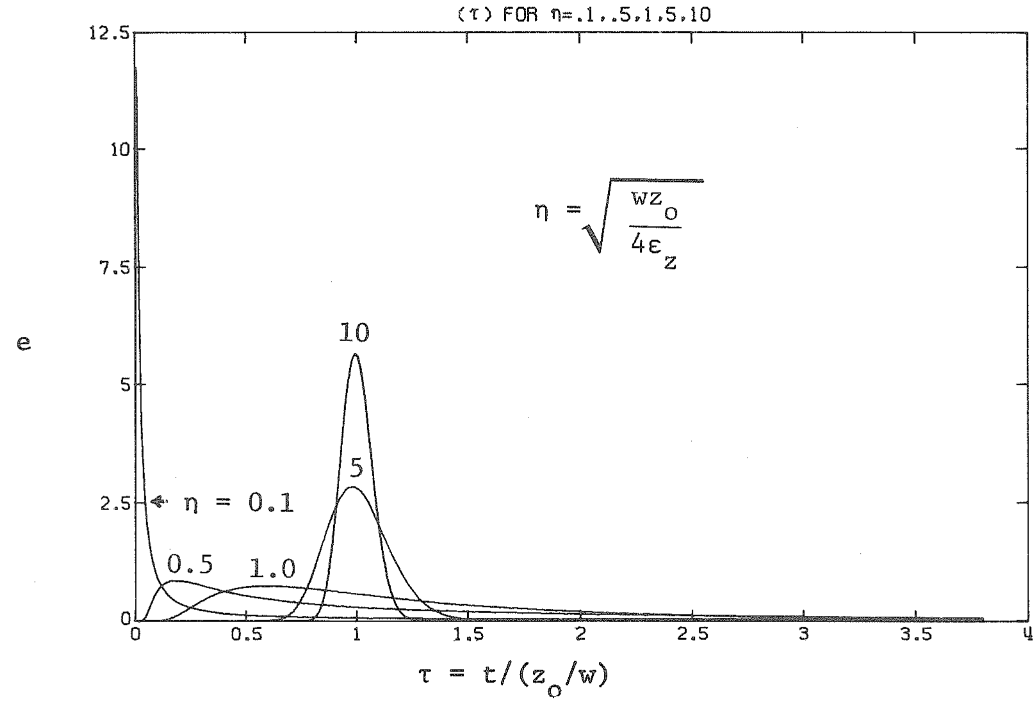


Figure VI-1a Distribution of fall time (actual time to reach the bottom compared to nominal time z_o/w).

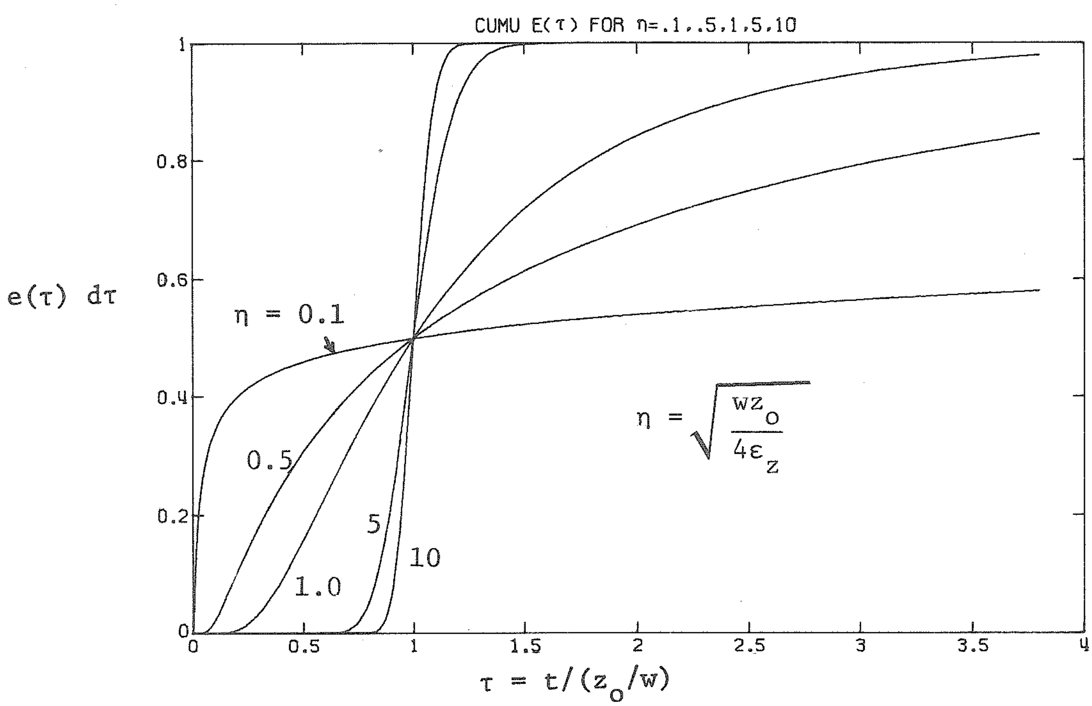


Figure VI-1b Cumulative distribution of fall time (integrals of curves in Fig. VI-1a).

$$\frac{z_e}{\ell_b} = C_{12}\left(\frac{\ell_a}{\ell_b}\right)^{2/3} \qquad \text{(VI-10)}$$

where
$$\ell_b = gQ_o \frac{\Delta\rho_o}{\rho} \Big/ u^3$$

$$\ell_a = u \Big/ \sqrt{\frac{g}{\rho} \left|\frac{d\rho}{dz}\right|}$$

From Wright, C_{12} can be approximated by 1.8 for all his data regardless of whether the experiment was buoyancy-dominated near- or far-field.

In addition, if there were no ambient current, we use the result based on buoyant plume theory

$$z_e = \alpha(3.98) \left(Q_o \frac{\Delta\rho_o}{\rho}\right)^{1/4} \left[\frac{g}{\rho} \left|\frac{d\rho}{dz}\right|\right]^{-3/8} \qquad \text{(VI-11)}$$

where α is a numerical factor to account for the difference between equilibrium height and maximum height of rise.

For application to the present problem, we use the following typical data (same as in Faisst, 1976, pp. 119-120):

$$Q_o = 5 \text{ mgd}$$

$$\frac{1}{\rho}\frac{d\rho}{dz} = 1.5 \times 10^{-6} \text{ meters}^{-1}$$

$$(\Delta\rho)_o = 24.5 \times 10^{-3} \text{ gm/cc}$$

and take $\alpha = 0.8$ for definiteness. Eqs. VI-10 and VI-11 then reduce to

$$z_e = 46\, Q_o^{1/3} \left(\frac{1}{u}\right)^{1/3} \qquad \text{(from Eq. VI-10)} \qquad \text{(VI-12a)}$$

$$z_e = 145\, Q_o^{1/4} \qquad \text{(from Eq. VI-11)} \qquad \text{(VI-12b)}$$

The value of z_o which applies should be the smaller of the two.

The value of Q_o in Eqs. VI-10 and VI-11 is subject to some control through design. For example, if ten (non-interfering) plumes result from a diffuser, the Q_o would only be 0.5 mgd for each.

By using Eqs. VI-10 and VI-11, and using the current data measured in Santa Monica-San Pedro Basin, the distributions shown in Fig. VI-2 are obtained. (The current data will be further discussed in a later section.) It is seen that the rise height decreases as Q_o decreases but can range over several tens of meters. The overall range is about 10 to 100 meters.

Distribution of Fall Velocities f(w)

Figures VI-3 and VI-4 show distributions of fall velocities of sludge particles as determined in the laboratory by several investigators. The range is very wide and there is some indication that flocculation is at play. More definitive determination of fall velocities is required. For our present purposes, we can only parameterize and bracket the range as less than a few tenths cm/sec with the bulk in the range 10^{-4} to 10^{-2} cm/sec. It is interesting to note that with $w = 10^{-3}$ cm/sec, and $z_o = 50$ meters, the time z_o/w is about 58 days.

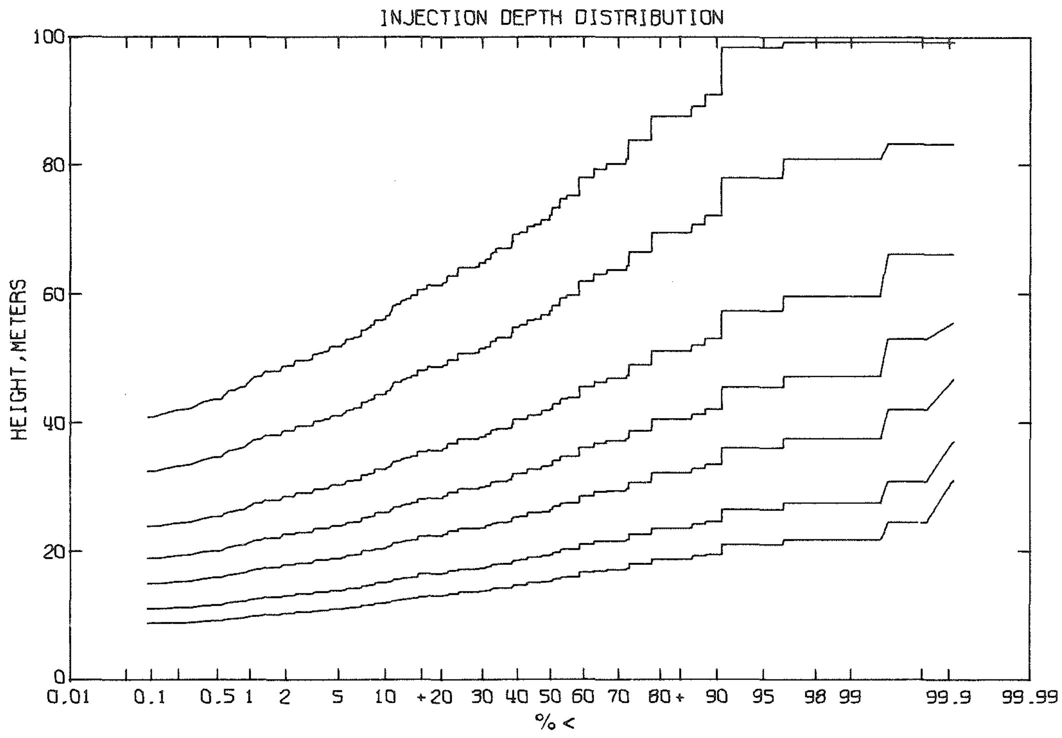


Figure VI-2 Distribution of height of rise of discharged plumes for various port flows, derived from an ambient current distribution. Stratification is fixed at a typical value.

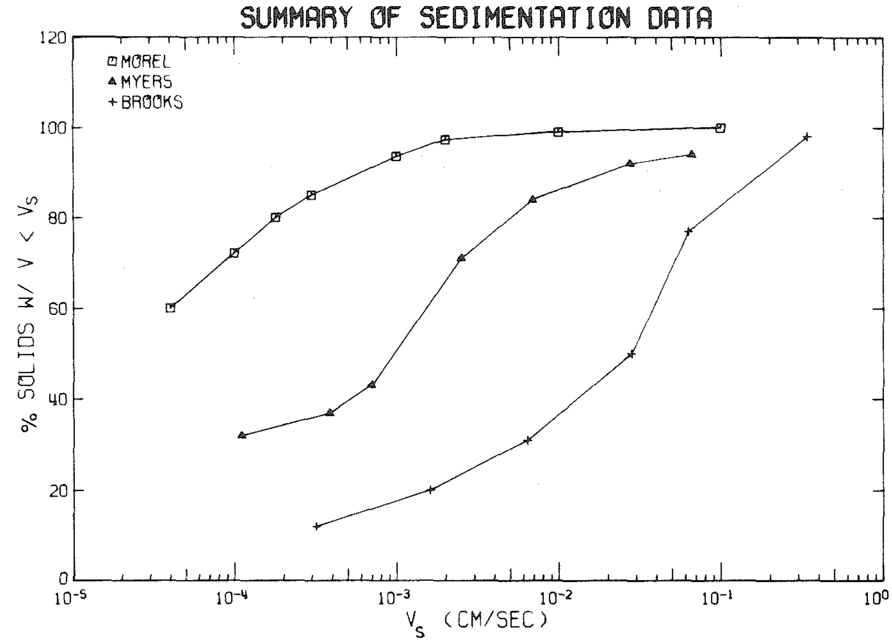


Figure VI-3 Distribution of fall velocity of wastewater solids (digested sludge: Myers and Brooks; sewage effluent solids, Morel).

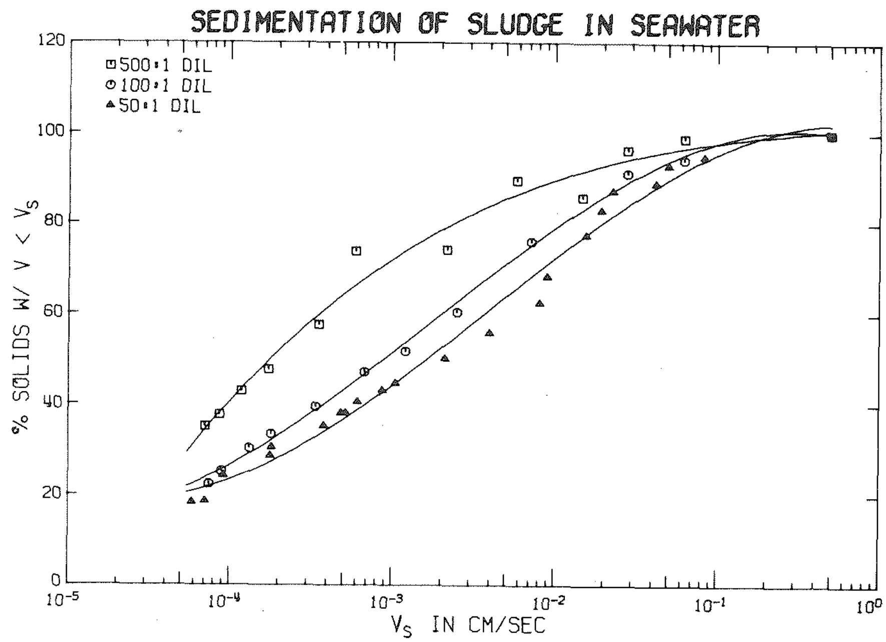


Figure VI-4 Distribution of fall velocity of sludge particles at various dilutions (from Faisst, 1976).

Estimation of Horizontal Diffusion from Ocean Current Measurements

Since the expected time of residence of sludge particles in the water column is quite long (due to the small fall velocities), it is of interest to examine the horizontal diffusion of the particulates.

An effort was made to measure the currents in selected locations in Santa Monica Basin. Unfortunately, the first attempt to make current measurements at the basin sill resulted in the loss of the current meters. The second attempt was successful and resulted in the current data plotted in Fig. VI-5. This was taken in water of 470 m depth with the current meter about 40 meters above the bottom. Examination of the data reveals that there is a great disparity between the component toward N100°E and the component N190°E. The former is effectively parallel to the local bottom contours while the latter is perpendicular. The fact that the current appears to be predominantly along the bottom contours is not surprising. The current component perpendicular to the bottom contour contains much high frequency fluctuations while the other component shows much more energy in the lower frequencies. Figure VI-6 shows power spectral estimates of the currents. It can be seen that with the exception of a spectral peak at the semidiurnal frequency, the perpendicular component has effectively a level power spectrum. The parallel component, on the other hand, shows spectral peaks at both the diurnal and semi-diurnal periodicities. It can also be seen from Fig. VI-5 that the character of this current component exhibited the occurrence of some "event" during the period May 8 to May 21, 1978. It is not known what caused this marked difference in character.

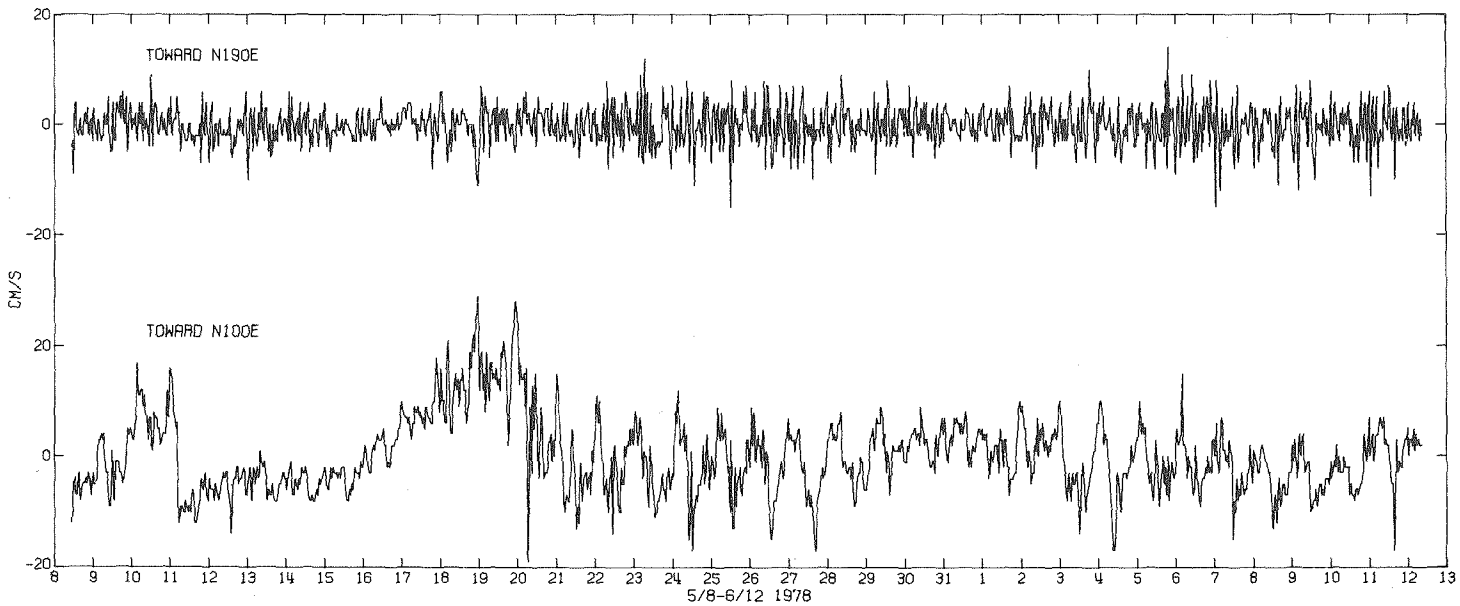
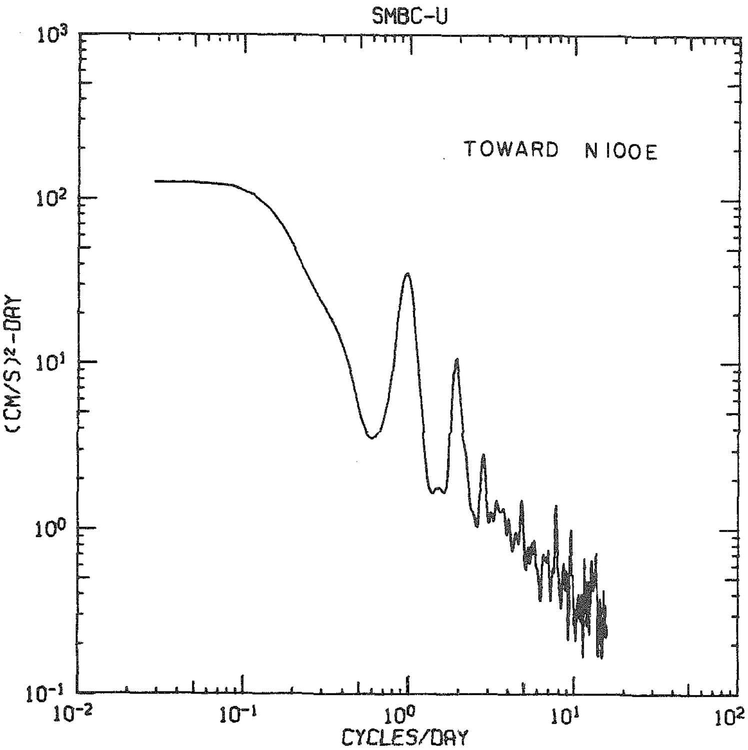


Figure VI-5 Ocean currents measured in Santa Monica Basin slope in water of 470 m depth. Meter depth 430 m.



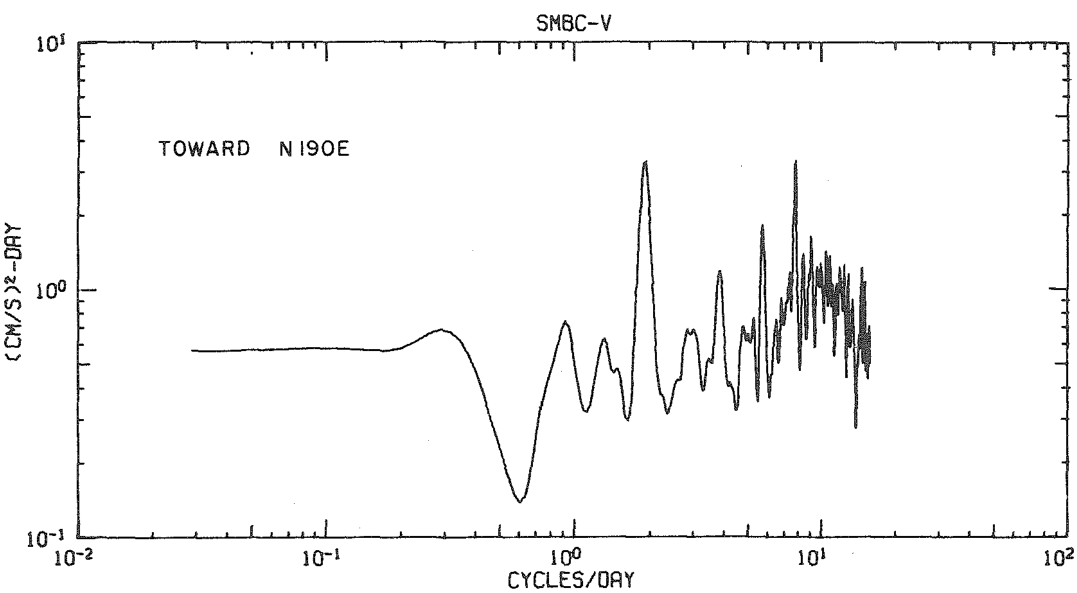


Figure VI-6 Power spectral estimates of current components (see Figure VI-5).

It will first be assumed that there is no mean motion. Any estimate of the mean is likely to be quite poor based on the available data. Next, the current meter records are high-pass filtered to remove long-term variations for which the data cannot be expected to be representative. We chose a digital filter with the half power cutoff at 0.09 cycles/day. The filtered data are shown in Fig. VI-7. It may be noted that only the very long-term variations have been removed. In fact, the general appearance of the data is almost identical to the actual measurements.

In an attempt to deduce the dispersive characteristics, we appeal to Taylor's Theorem and apply it to the two components of the velocity separately since they are effectively uncorrelated. Taylor's Theorem states that for a stationary process, the mean square dispersion σ^2 along a given axis x is given by

$$\sigma^2 = 2\int_0^t (t-\tau)C(\tau)\,d\tau$$

where $C(\tau)$ is the Lagrangian autocovariance of the velocity at lag τ. We assume that the Lagrangian autocovariance function can be estimated by the autovariance functions of the two components in Fig. VI-7. (In other words, we are replacing the Lagrangian autocovariance function by the Eulerian one.) The data for the parallel component was divided into two parts containing the first twelve days (the"event") and the remainder of the data samples. Autocovariance estimates were made for the two parts separately as well as for the entire piece of data. Taylor's Theorem was then applied to yield estimates of the variances σ_x^2 as

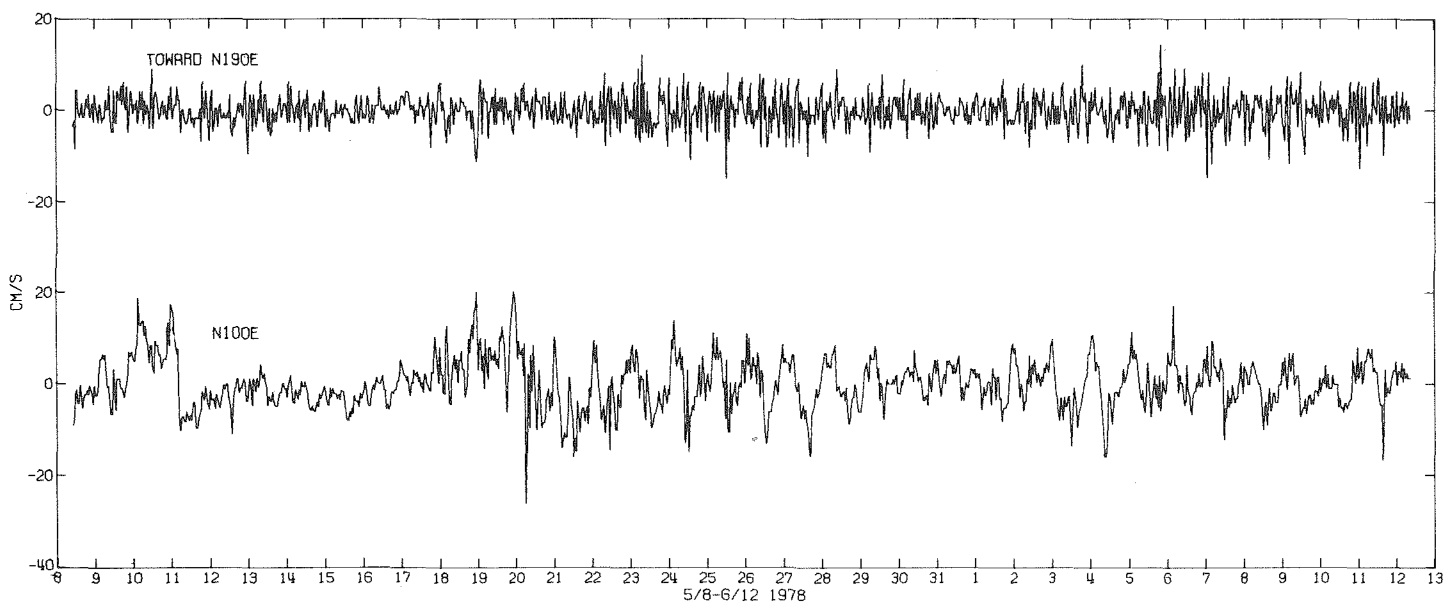


Figure VI-7 High pass filtered current components functions of time. Figures VI-8 and VI-9 show autocovariance estimates and $\sigma_x^2(t)$ respectively for the u (parallel) component of the current. It can be seen that the variance grows at a rate somewhat higher than linear in time. At 1 day, $\sigma_x^2 \approx 5$ km^2, and at 3 days, $\sigma_x^2 \approx 15$ km^2. If an overall Fickian diffusion coefficient were to account for this it would be on the order of 2.5 km^2/day.

The v (perpendicular) component of the current was analyzed in the same way. There is no reason to break the record up into two pieces since the "event" did not appear to be manifested in this component. Figures VI-10 and VI-11 show autocovariance estimates and $\sigma_y^2(t)$ respectively for this component. It can be seen that the variance grows effectively linearly with time with a Fickian diffusion coefficient of 0.1 km^2/day. There is thus a 25 to 1 ratio in the horizontal dispersive coefficients in the two directions. This alone would result in a 5 to 1 ratio of the lengths of the zone of significant fallout of particulate matter.

Horizontal Distribution of Fallout Pattern

We return now to Eq. VI-3 and permit z_b to be a function of the horizontal coordinates x and y. We further assume $\sigma_x = \sqrt{2\varepsilon_x t}$ and $\sigma_y = \sqrt{2\varepsilon_y t}$, i.e., that the horizontal diffusion is Fickian in nature. It is believed that these are probably justified since we can have at best only an order of magnitude estimate of ε_x and ε_y. The equation (VI-3) can then be written

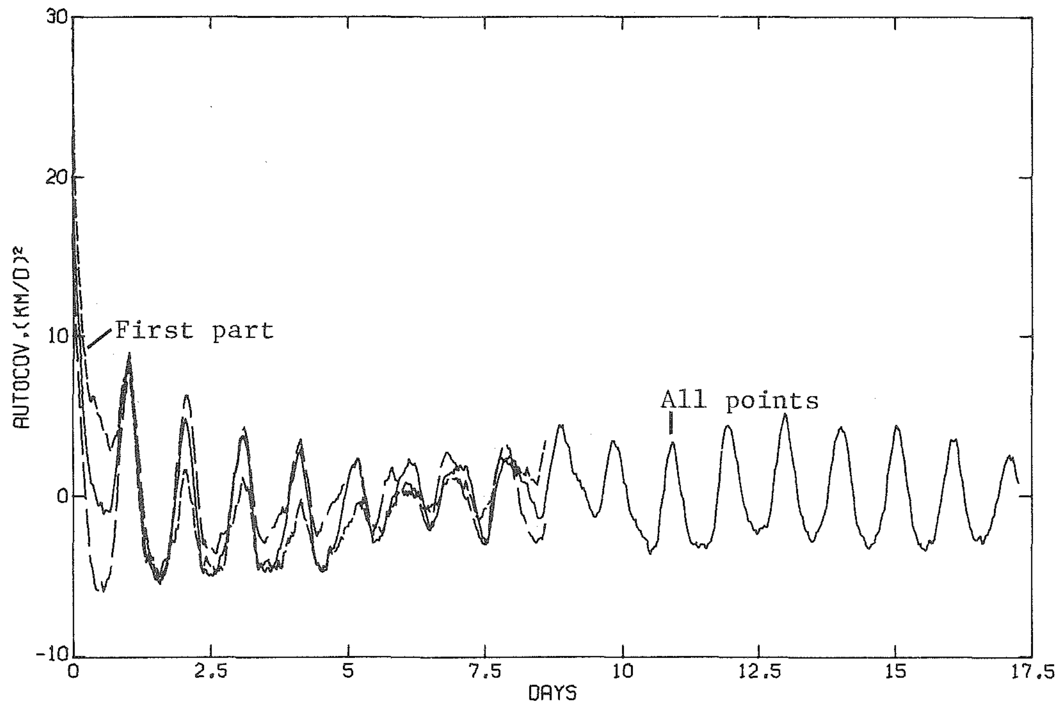


Figure VI-8 Autocovariance of current component toward N100E shown in Fig. VI-7.

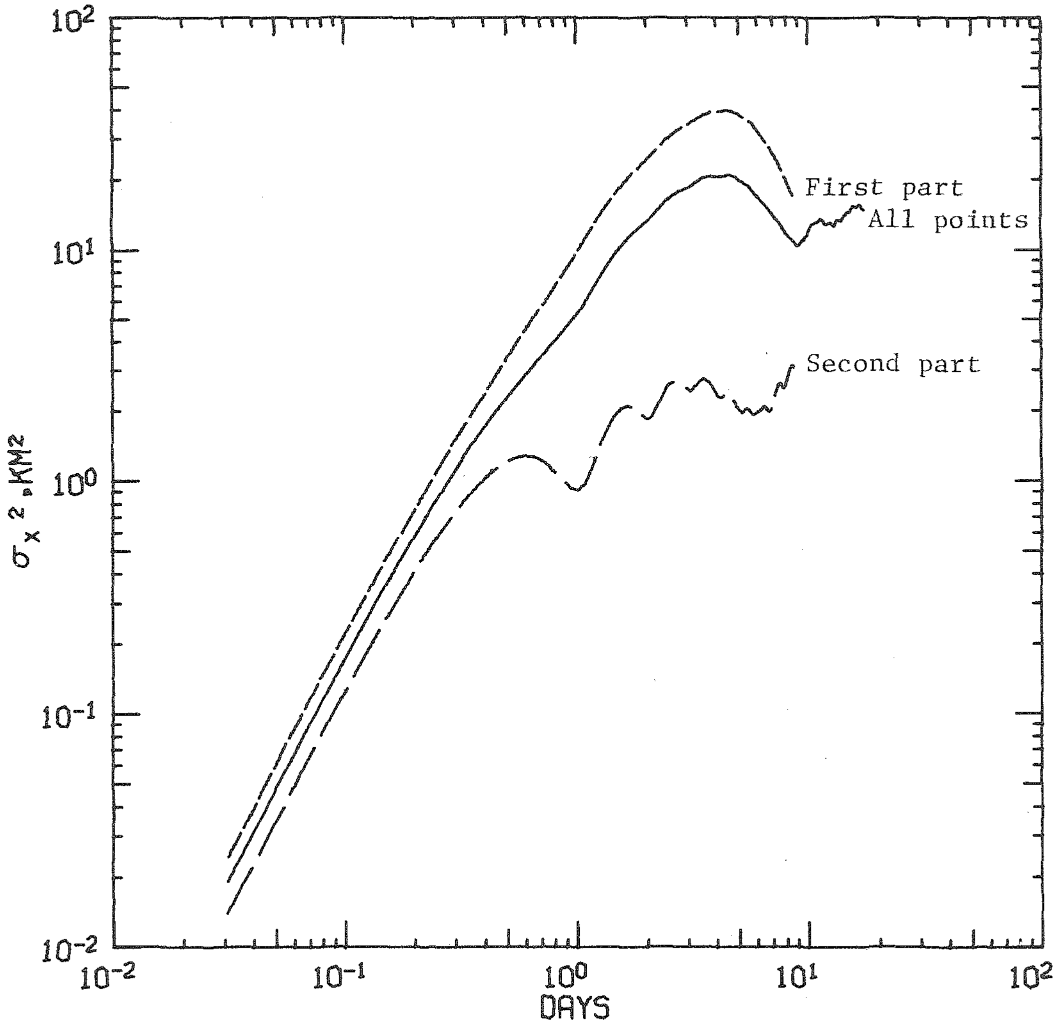


Figure VI-9 Growth of variance (by Taylor Theorem) of current component toward N100E (shown in Fig. VI-7).

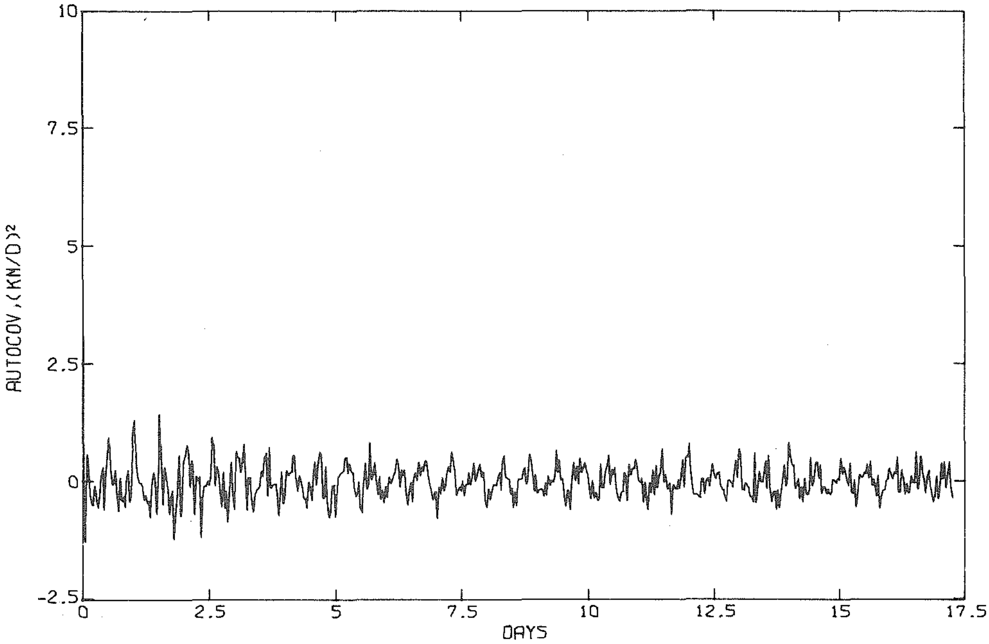


Figure VI-10 Autocovariance of current component toward N190E shown in Fig. VI-7.

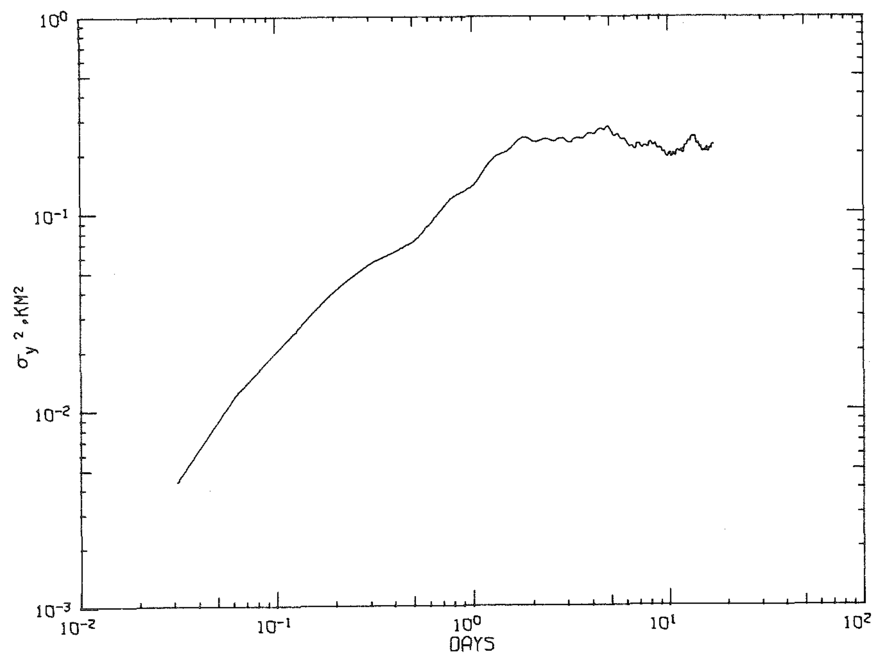


Figure VI-11 Growth of variance (by Taylors Theorem) of current component toward N190E (shown in Fig. VI-7).

$$E = \frac{1}{A}\left[\frac{z_o - z_b}{t^{5/2}} + \frac{w}{t^{3/2}}\right] \exp[X] \qquad \text{(V1-13)}$$

where

$$A = 16\pi^{3/2}\sqrt{\varepsilon_x \varepsilon_y \varepsilon_z}$$

and

$$X = -\frac{(x - x_o)^2}{4\varepsilon_x t} - \frac{(y - y_o)^2}{4\varepsilon_y t} - \frac{(z_o - z_b - wt)^2}{4\varepsilon_z t}$$

$$= -\frac{1}{4t}\left\{\frac{(x_o - x)^2}{\varepsilon_x} + \frac{(y_o - y)^2}{\varepsilon_y} + \frac{(z_o - z_b)^2}{\varepsilon_z}\right\} - \frac{t}{4}\frac{w^2}{\varepsilon_z} + \frac{w(z_o - z_b)}{2\varepsilon_z}$$

(VI-14)

so that

$$E = \frac{1}{A}\left[\frac{z_o - z_b}{t^{5/2}} + \frac{w}{t^{3/2}}\right] \exp\left\{\frac{-\phi}{4t} - t\frac{w^2}{4\varepsilon_z}\right\} \exp\left\{\frac{w(z_o - z_b)}{2\varepsilon_z}\right\} \qquad \text{(V1-15)}$$

where

$$\phi = \frac{(x_o - x)^2}{\varepsilon_x} + \frac{(y - y_o)^2}{\varepsilon_y} + \frac{(z_o - z_b)^2}{\varepsilon_z} .$$

Since E is the rate of settling to the bottom, the quantity

$$F = \int_0^t E\, dt \qquad \text{(VI-16)}$$

is the amount which has reached the bottom at x, y by time t. Letting the upper limit tend to ∞ then gives F_∞ as the amount which would ultimately settle out as a function of the horizontal coordinates.

It may be shown that for $\beta > 0$, $\gamma > 0$

$$\int_0^\infty x^{\nu-1} e^{-\frac{\beta}{x} - \gamma x} dx = 2\left(\frac{\beta}{\gamma}\right)^{\frac{\nu}{2}} K_\nu(2\sqrt{\beta\gamma}) \qquad \text{(VI-17)}$$

where K_ν is the modified Bessel function. Using the expressions

$K_{3/2}(r) = \sqrt{\frac{\pi}{2r}}\, e^{-r}\,(1+\frac{1}{r})$ and $K_{1/2}(r) = \sqrt{\frac{\pi}{2r}}\, e^{-r}$, it is found that

$$F_\infty = \frac{2\sqrt{\pi}}{A}\, e^{\left\{\frac{w(z_o - z_b)}{2\varepsilon_z} - \frac{w}{2}\sqrt{\frac{\phi}{\varepsilon_z}}\right\}} \left[\frac{w(z_o - z_b)}{\phi\sqrt{\varepsilon_z}}\left(1 + \frac{2}{w}\sqrt{\frac{\varepsilon_z}{\phi}}\right) + \frac{w}{\sqrt{\phi}}\right] \tag{VI-18}$$

Let

$$R = \frac{w}{2}\sqrt{\frac{\phi}{\varepsilon_z}} \tag{VI-19}$$

$$S = \frac{z_o - z_b}{\sqrt{\phi\varepsilon_z}} \tag{VI-20}$$

then

$$F_\infty = \frac{4\sqrt{\pi\varepsilon_z}}{A\phi}\, e^{(RS - R)}\,[RS + S + R] \tag{VI-21}$$

$$= \frac{RS + R + S}{4\pi\phi\sqrt{\varepsilon_x\varepsilon_y}}\, e^{RS - R}$$

The physical interpretation of $F_\infty(x,y;z_o,w,\varepsilon_x,\varepsilon_y,\varepsilon_z)$ is simply the fraction of particulates which would fall per unit area at x,y as a result of injection height z_o, fall velocity w and diffusion coefficients ε_x, ε_y, and ε_z. The expression for F_∞ in Eq. VI-21 is obtained based on various assumptions and must be regarded as providing no more than a rough estimate. However, inasmuch as the basic variables such as w, z_o, $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are only known to a rough approximation, it is believed that the assumptions leading to Eq. VI-21 are justified since it provides at least a rational method of estimation of the fallout distribution. Moreover, the evaluation of F_∞ given the parameters $z_o, w, \varepsilon_x, \varepsilon_y, \varepsilon_z$ and $z_b(x,y)$ can be made very rapidly and simply without any iterations so that Eq. V-21 provides a very convenient (though rough) starting point in the investigation of the problem.

Horizontally Isotropic Diffusion in Ocean of Constant Depth

We first apply the method to investigate the simpler case of horizontally isotropic diffusion in an ocean of constant depth. We shall find F_∞ for various values of the parameters $z_o, \varepsilon_x, \varepsilon_y, \varepsilon_z$ and w. Since there are substantial uncertainties associated with each of these parameters, it is highly desirable to select a "basic" set of values about which each of the parameters will be varied in turn but one at a time. Based on the discussion in previous sections of this chapter, the following set of basic values will be selected:

z_o	50 meters
w	10^{-3} cm/s
ε_x	2.5 km^2/day = 2.9×10^5 cm^2/s
ε_y	2.5 km^2/day = 2.9×10^5 cm^2/s
ε_z	1 cm^2/s

Note that even though measurements of ocean current at candidate site of sludge discharge shows that ε_x and ε_y might bear a ratio of 25 to each other, we cannot justify them to be different in the present parametric case of a horizontal ocean bottom. The case of non-isotropic horizontal diffusion in a non-horizontal ocean bottom will be discussed in a later section.

Figure VI-12 shows the function $F_\infty(r)$ (where $r = \sqrt{x^2 + y^2}$) for various values of the parameters. Six graphs are presented in the figure, each one corresponding to a set of values of the parameters. Within each graph, four curves are shown, one for each of the four fall velocities 10^{-1}, 10^{-2}, 10^{-3} and 10^{-4} cm/s. The graph at the upper left corresponds to the basic set of values for the parameters. By comparing these graphs, the effect of each of the parameters can be appreciated. Note that the ordinate is F_∞ which is the fraction of particles falling per km^2 at the various distances away from the discharge. Thus if Q is the rate of particulates being imparted into the ocean (say in tons/year), then QF_∞ is the equilibrium rate of sedimentation in tons/(km^2·year). It can be seen that in the basic case (10^{-3} cm/sec in upper left graph), $F_\infty(0)$ is 6.5 x 10^{-4} km^{-2} and it decreases by a factor of 10 at about 40 km away. Increasing ε_z increases $F_\infty(0)$ because more particles would reach bottom by vertical diffusion. Increasing z_o or ε_x decreases $F_\infty(0)$ as expected.

Figure VI-13 shows the quantity $G_\infty(r)$ defined by

$$G_\infty(r) = \int_o^r F_\infty(r')2\pi r'dr' \qquad \text{(VI-22)}$$

representing the fraction of particulates which is contained in a disc with radius r centered at the discharge. The six graphs are arranged in the same way as in Fig. VI-12.

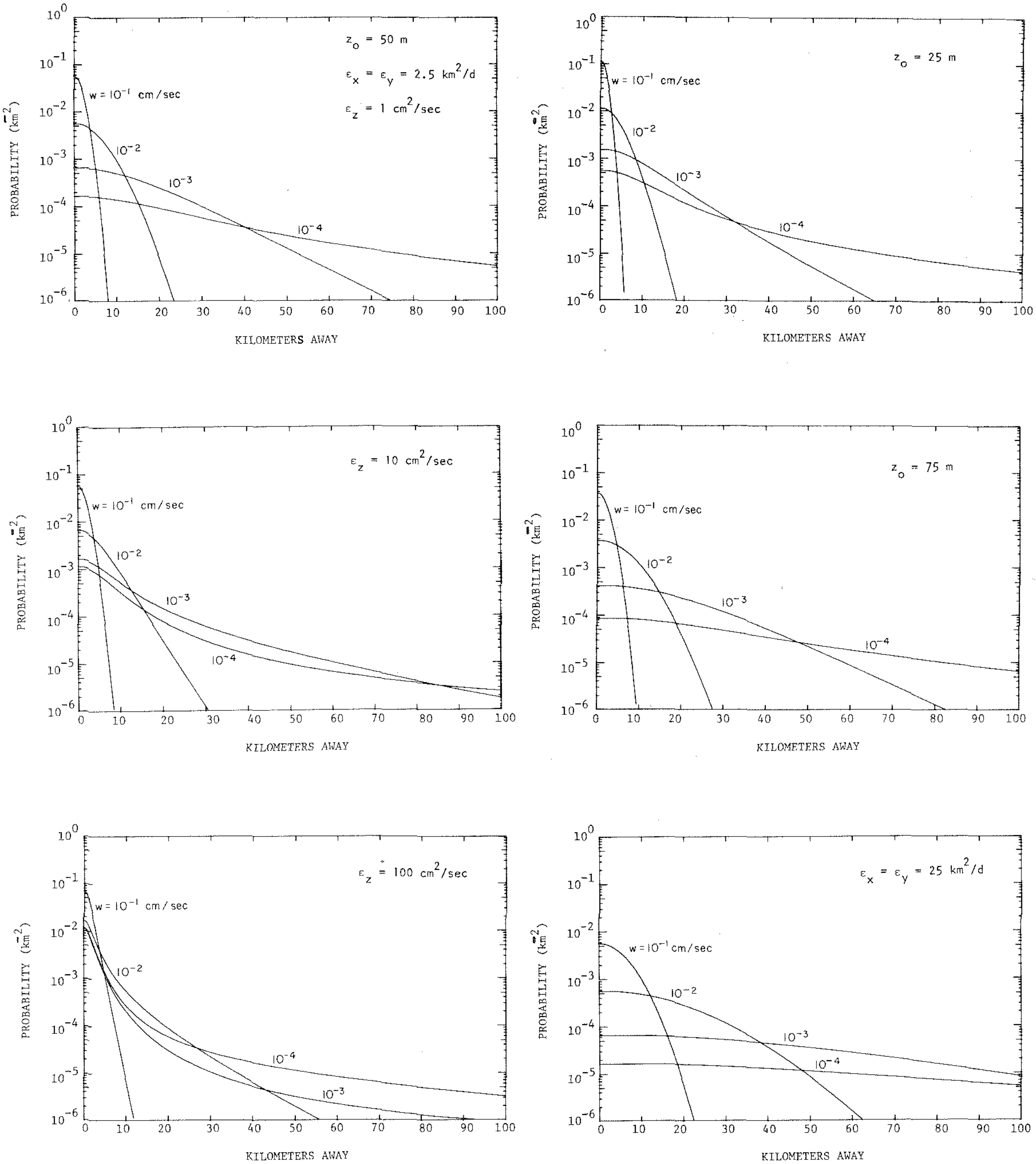


Figure VI-12 Effects of parameters on distribution function F_∞ = ratio of sedimentation (per km^2) to source input versus distance from source. Parameters are varied from basic set of upper left graph as indicated.

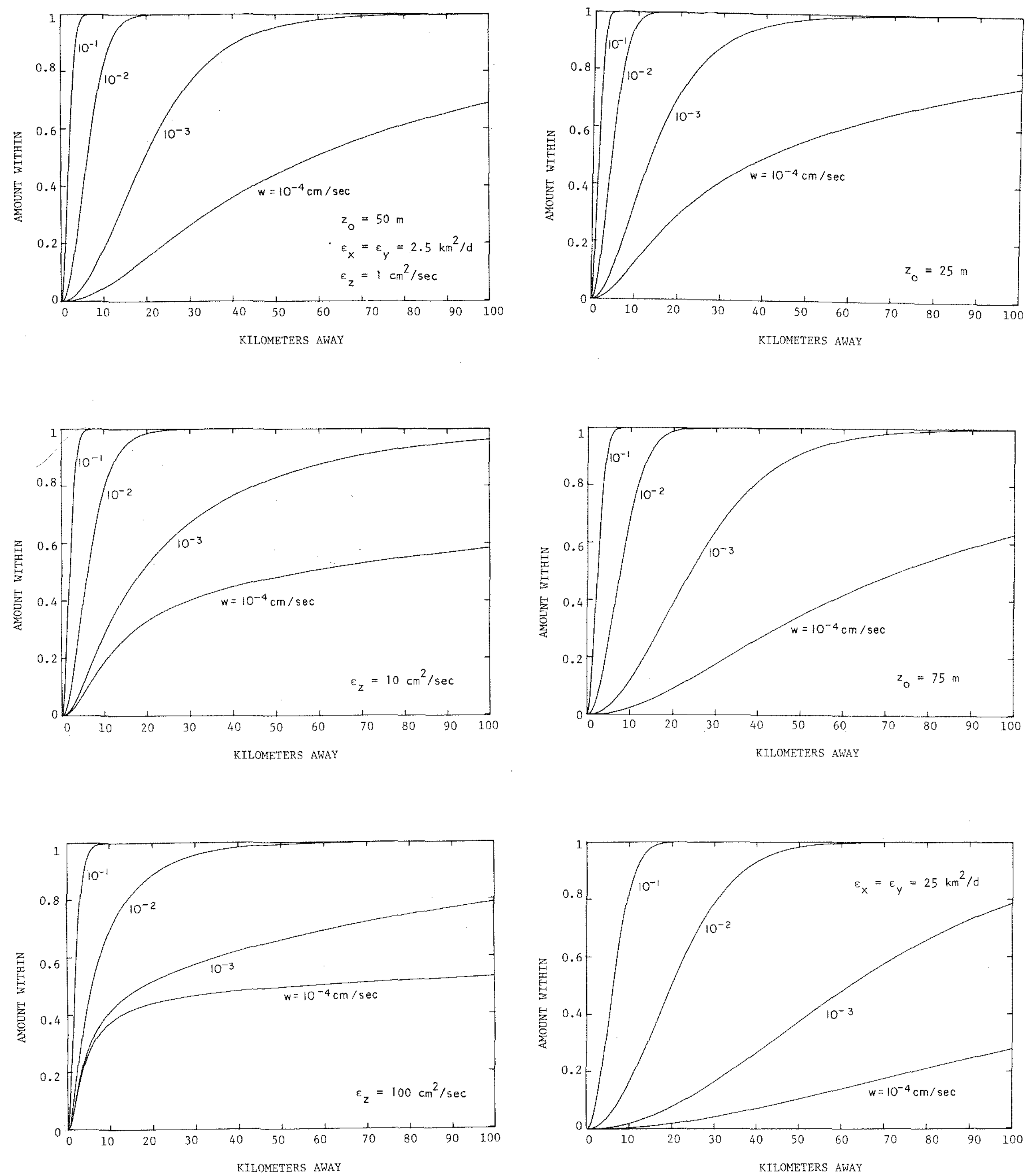


Figure VI-13 Cumulative distribution function G_∞ = integral of F_∞ by Eq. VI-22.

In order to gain further insight into the problem, the parameter w will be eliminated by assuming that the particulates consist of

$$\begin{aligned} 8\% &\text{ with } w = 10^{-1} \text{ cm/sec} \\ 20\% &\text{ with } w = 10^{-2} \text{ cm/sec} \\ 35\% &\text{ with } w = 10^{-3} \text{ cm/sec} \\ 17\% &\text{ with } w = 10^{-4} \text{ cm/sec} \end{aligned}$$

Note that this adds up to only 80%. The other 20% is assumed to be of neutral buoyancy or less so that they do not settle to the bottom. The functions G_∞ for the various fall velocities can then be combined to yield the results shown in Fig. VI-14. From this, we expect that a few percent of the particulates would settle within a kilometer, and a significant fraction (say 10% to 50%) would settle within a radius of 10 km. This result is predicted on the assumption of horizontally isotropic diffusion and no mean ocean drift.

Horizontally Non-Isotropic Diffusion in Ocean of Variable Depth

From the analysis of ocean current time series presented previously it was found that the horizontal diffusion coefficients which can be inferred from the data are highly non-isotropic. This is not surprising since the measurements were taken fairly close to the bottom (about 40 meters from the bottom in water depth of 470 meters). The choice of the meter placement was guided by the preliminary results of this study and represents a likely location for the placement of the discharge terminus if it was decided to employ ocean disposal by submarine outfall.

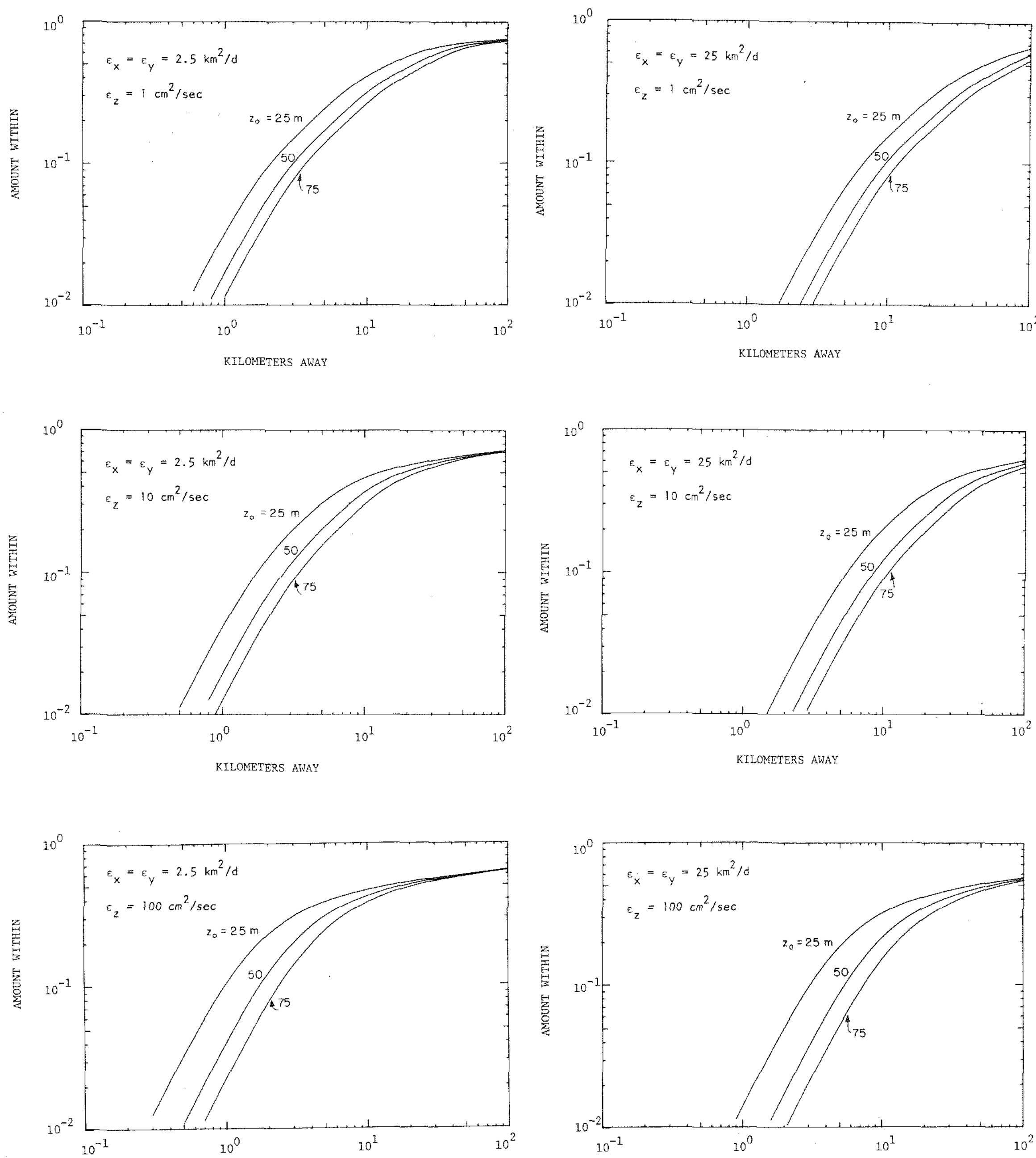


Figure VI-14 Distribution functions G_∞ for specific fall velocity distribution (see text for explanation).

Examination of the bathymetry at the site and taking into consideration the distance from shore to reach each depth, it was found that to reach a depth on the order of 400 to 500 meters, the pipeline would most likely be located such that the terminus is on the slope of the basin rather than near the Santa Monica submarine canyon. The local bottom topography can be approximated by a two-dimensional succession of planes as shown in Fig. VI-15. The approximate method developed in this section on the estimation of bottom fallout rates was applied to this case and the results shown in Figs. VI-16, VI-17 and VI-18. In each of these figures, two contour maps of bottom fallout rates are shown for the fall velocities of 10^{-3} and 10^{-2} cm/sec. The contour values represent fractions per km^2. Because of symmetry about the y-axis, only half of each deposition pattern is shown. Figure VI-16 shows the case when the discharge is made at a depth of about 100 meters; Fig. VI-17 at a depth of about 400 meters and Fig. VI-18 at a depth of about 900 meters. The non-isotropic nature of the pattern can be clearly seen. Also it can be noticed that more material settles in deeper depths than the discharge depth as would be expected due to the sinking of the particulates.

Figure VI-19 shows perspective plots of the deposition pattern for the cases when the discharge depth is 400 meters. In Fig. VI-20 the results in Fig. VI-19 are truncated at 5×10^{-4} km^2 to show both the zone within which the deposition rate exceeds 5×10^{-4} km^2 (the plateau) and the rate of decrease of deposition rate away from the discharge.

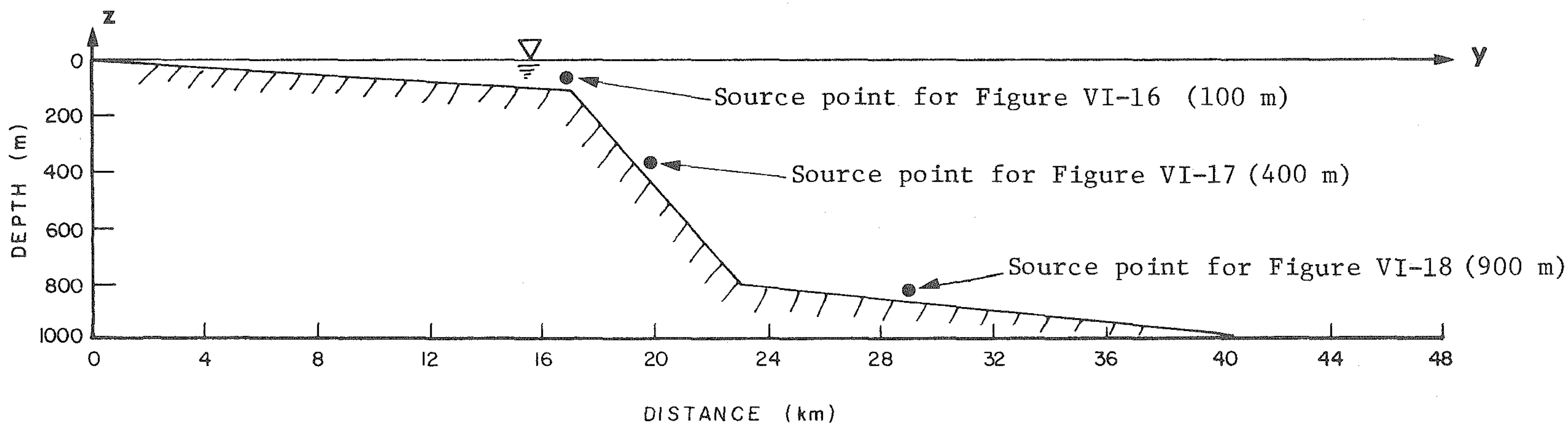


Figure VI-15 Idealized profile of Santa Monica shelf used in sedimentation modeling (assumed uniform along the coast).

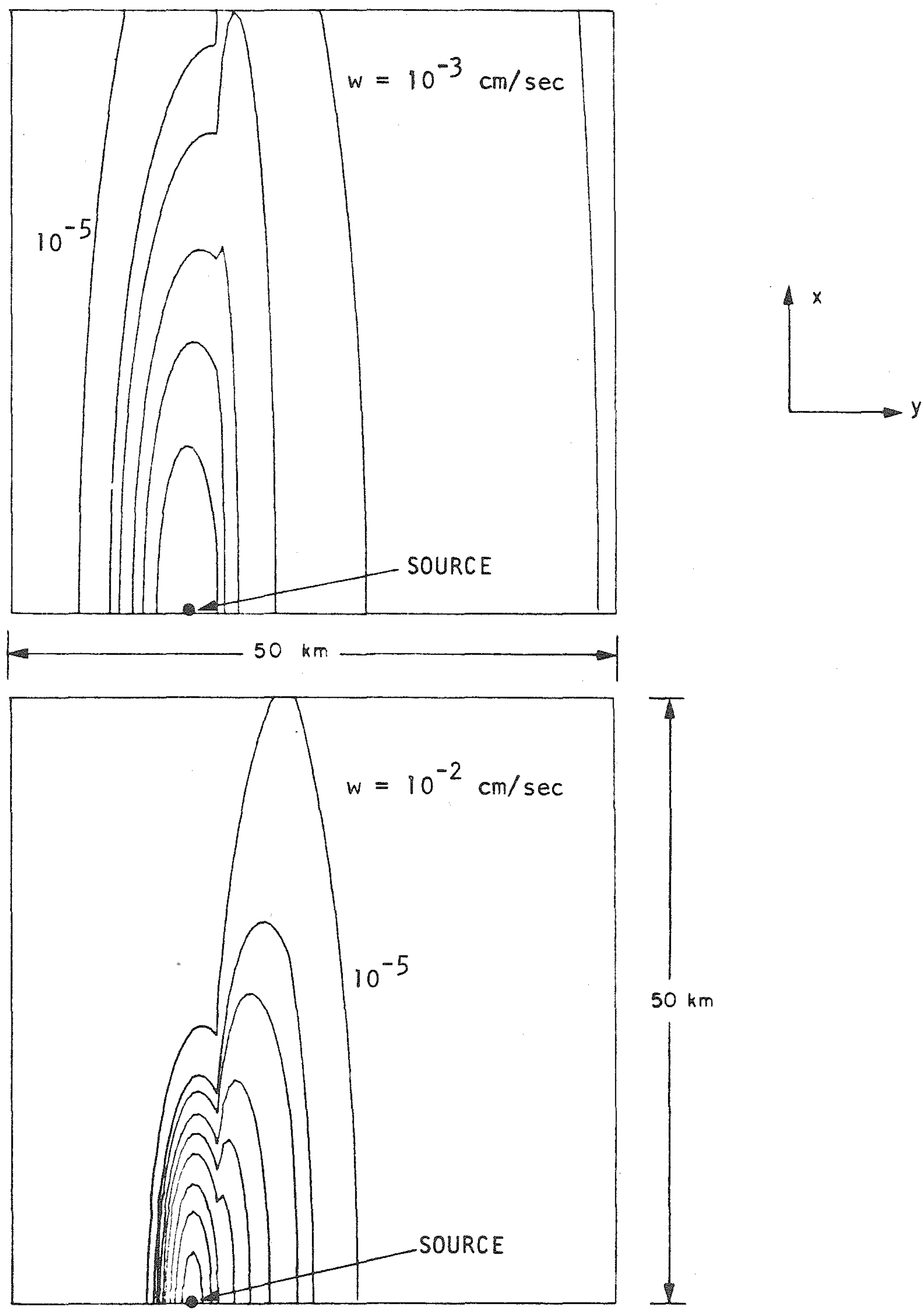


Figure VI-16 Particle fallout probability distribution (in km^{-2}). Contour values at 10^{-5}, 10^{-4}, 2×10^{-4}, 5×10^{-4}, 10^{-3}, 2×10^{-3}, 5×10^{-3}, 10^{-2}, 2×10^{-2}. Parameters $\varepsilon_x = 2.5\ km^2/d$, $\varepsilon_y = 0.1\ km^2/d$, $\varepsilon_z = 1\ cm^2/s$, $z_o = 50$ meters. Depth of discharge point = 100 meters.

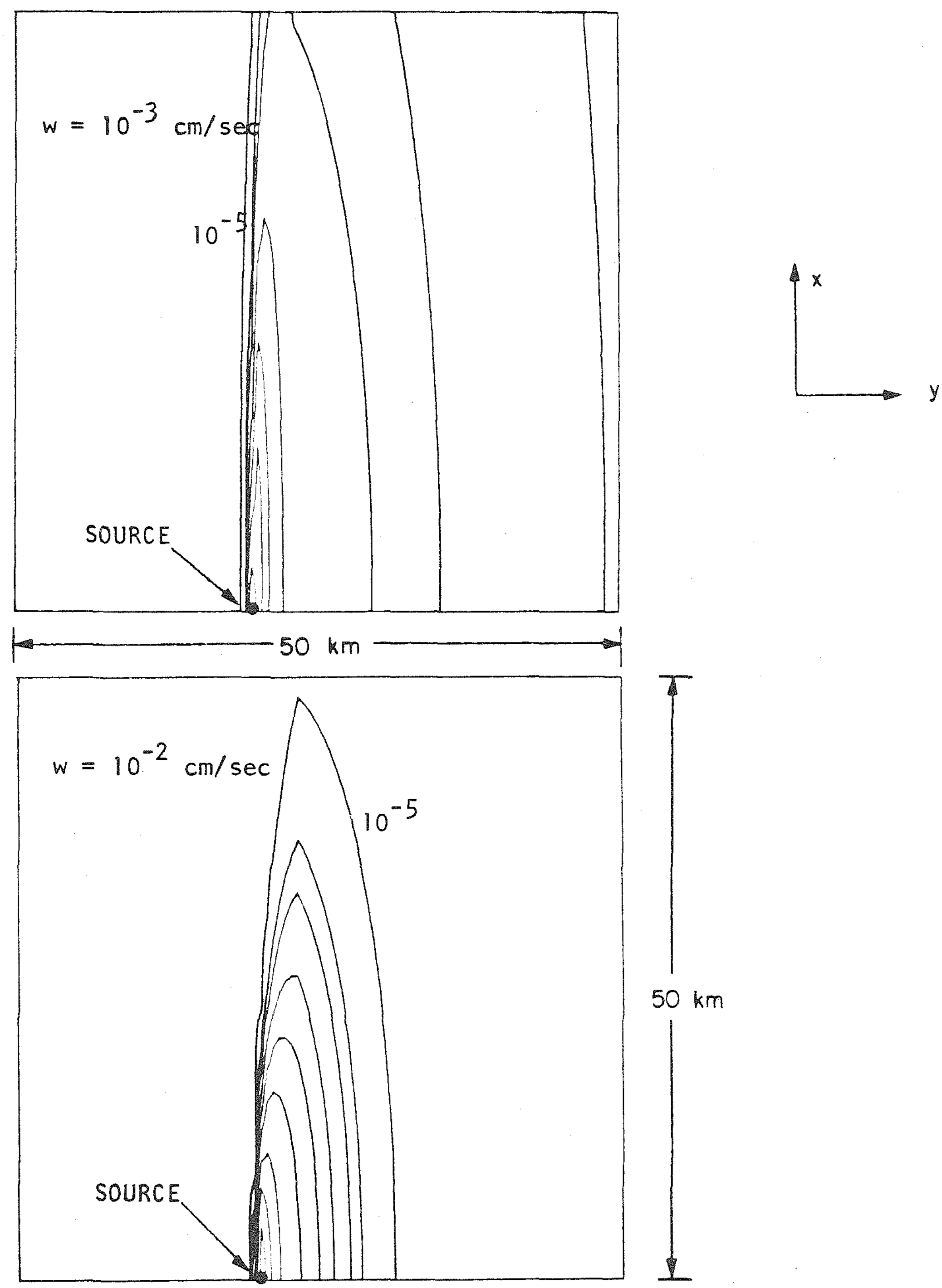


Figure VI-17 Particles fallout probability distribution (in km^{-2}). Contour values at 10^{-5}, 10^{-4}, 2×10^{-4}, 5×10^{-4}, 10^{-3}, 2×10^{-3}, 5×10^{-3}, 10^{-2}, 2×10^{-2}. Parameters ε_x = 2.5 km^2/d, ε_y = 0.1 km^2/d, ε_z = 1 cm^2/s, z_o = 50 meters. Depth of discharge point = 400 meters.

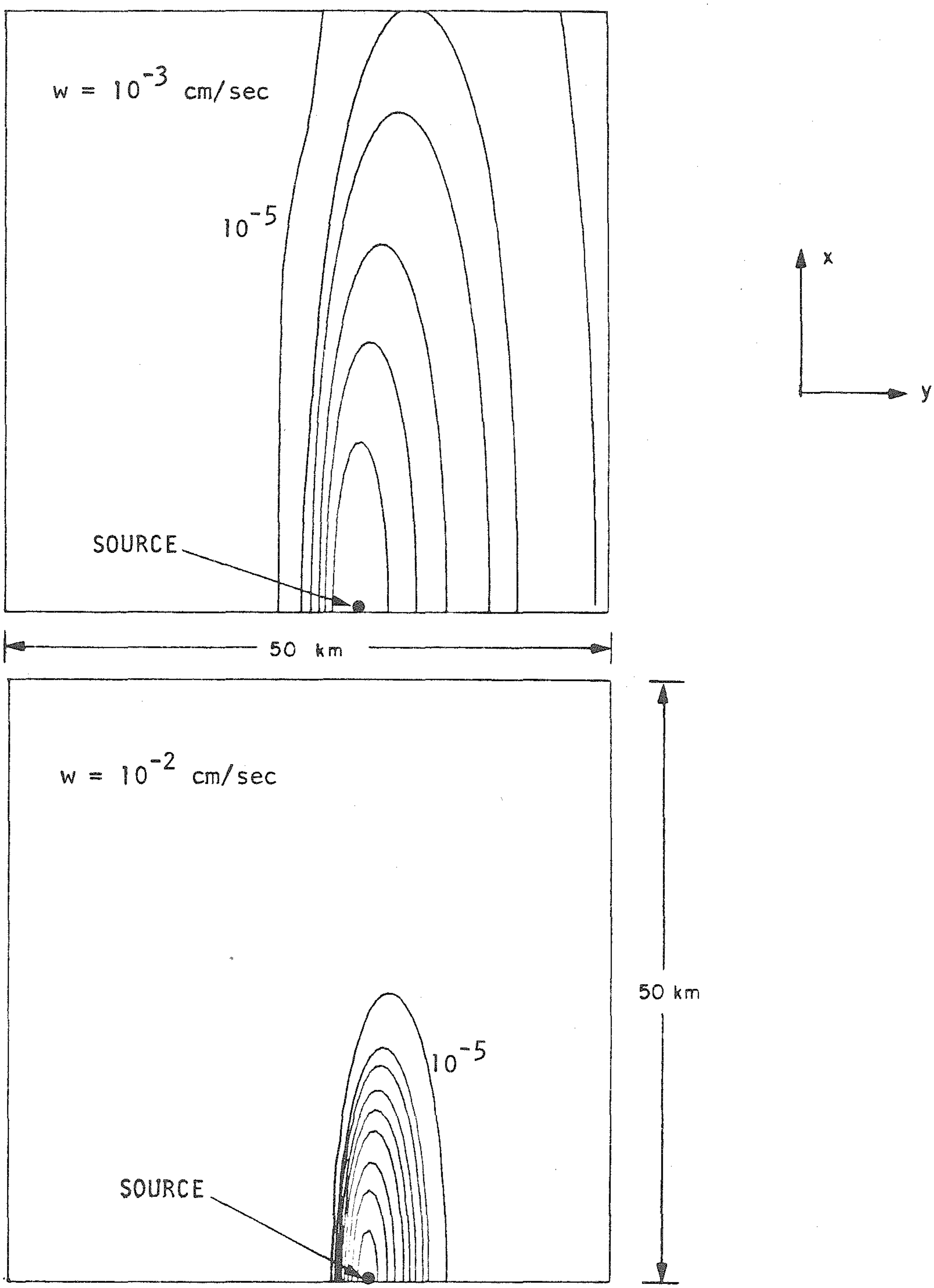


Figure VI-18 Particle fallout probability distribution (in km^{-2}). Contour values at 10^{-5}, 10^{-4}, 2×10^{-4}, 5×10^{-4}, 10^{-3}, 2×10^{-3}, 5×10^{-3}, 10^{-2}, 2×10^{-2}. Parameters ε_x = 2.5 km^2/d, ε_y = 0.1 km^2/d, ε_z = 1 cm^2/s, z_o = 50 meters. Depth of discharge point = 900 meters.

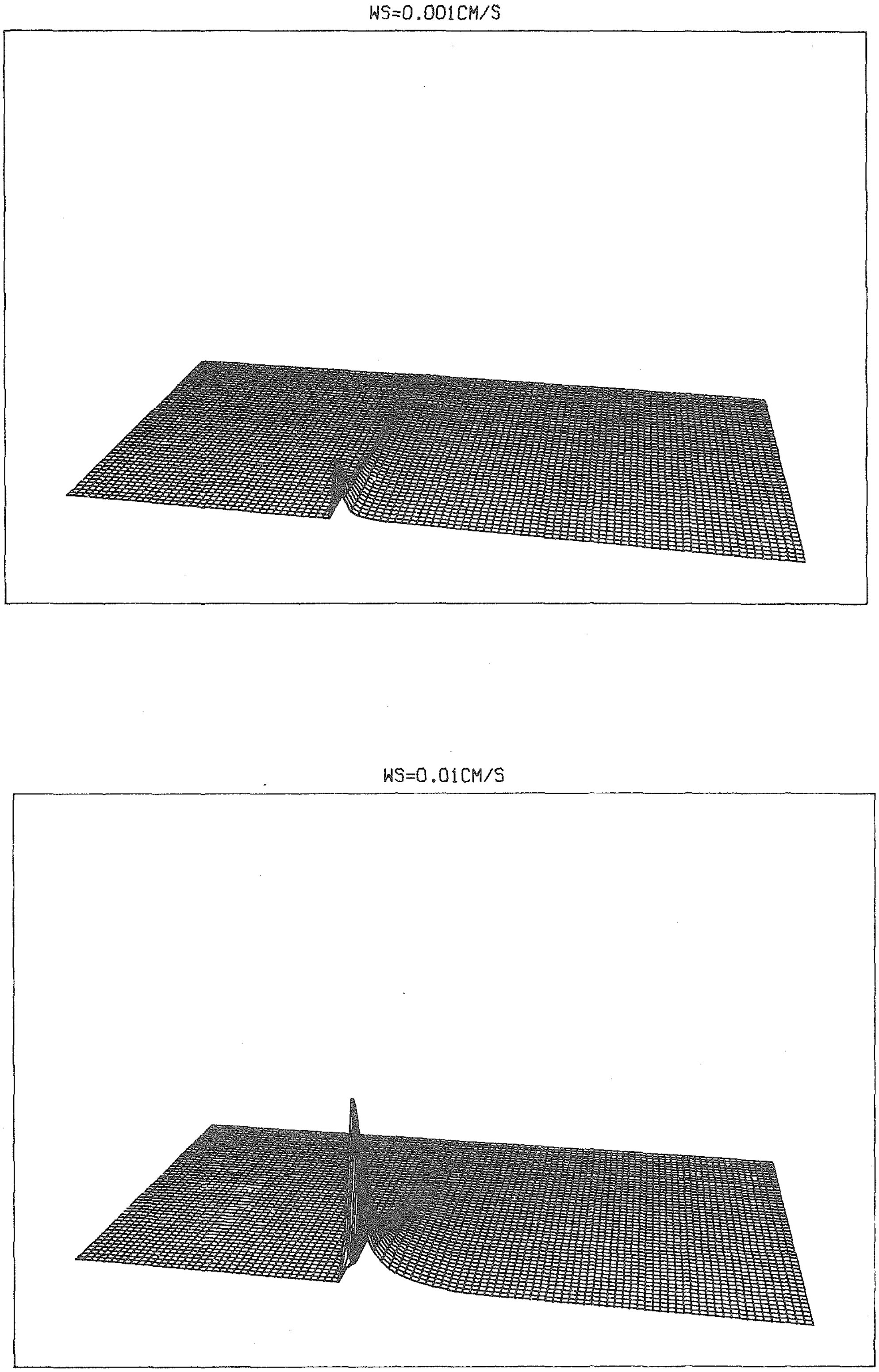
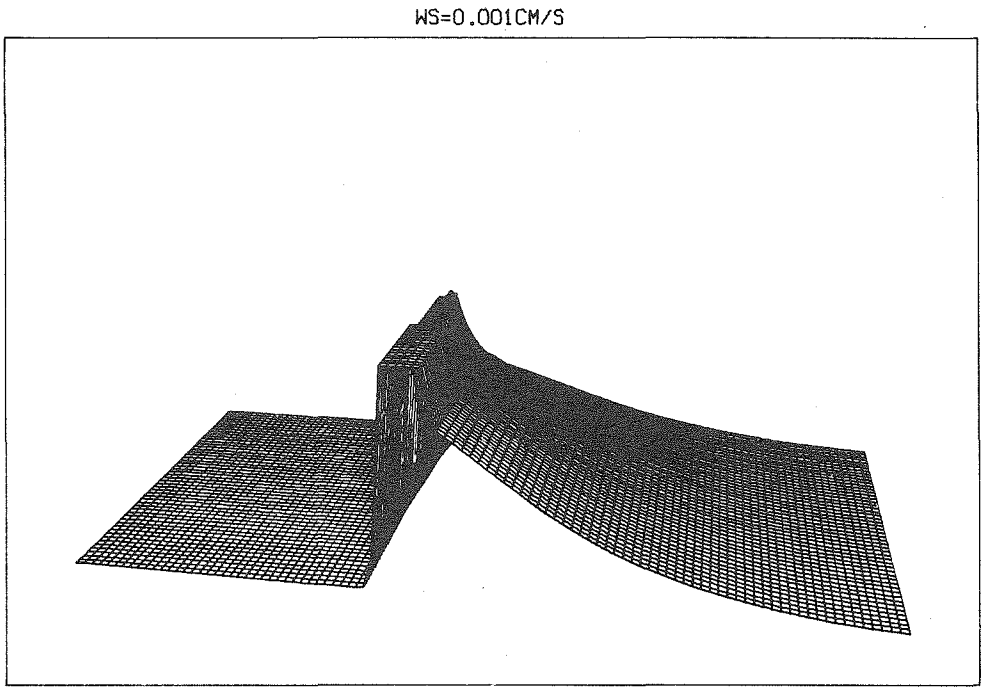


Figure VI-19 Perspective plots of sedimentation distribution corresponding to case shown in Fig. VI-17.



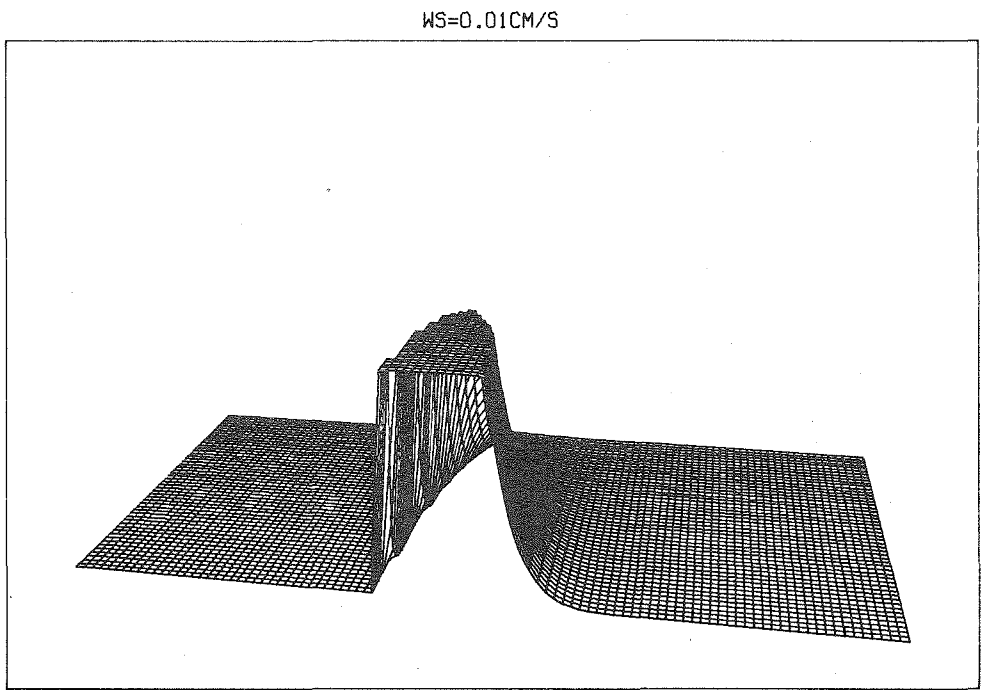


Figure VI-20 Truncated perspective (truncated at 5×10^{-4} km^{-2}) corresponding to case shown in Fig. VI-19.

Discussion

The results presented in the preceeding sections of this chapter show that ocean disposal of sludge to the Santa Monica-San Pedro Basin via submarine outfall will result in the deposition of the particulates in a fairly extensive area on the bottom. A few percent of the particulates would settle out near the outfall terminus (within a kilometer) while the bulk would not. The area over which half the particulates would settle out might be on the order of 100 km^2.

All calculations of deposition presented thus far pertain to a relative fraction per unit area. To use the results to estimate actual deposition rate, it is necessary to multiply by the source rate. If the total organic input from sludge outfall is 2×10^7 moles-O_2/day, and if the background oxidation rate is 10^4 moles/(day-km^2), then the value of the relative deposition F_∞ for the sludge deposition to equal natural oxidation is $10^4/2 \times 10^7\ km^{-2} = 5 \times 10^{-4}\ km^{-2}$. Examination of Fig. VI-17 (discharge at 400 m depth 20 km offshore) reveals that the oblong area enclosed by the 5×10^{-4} contour (for $w = 10^{-3}$ cm/sec) is on the order of 120 km^2.

Alternatively, the total amount of sludge discharged might be estimated as 3×10^5 metric tons/year. The natural sedimentation rate has been estimated as on the order of 30 mg/cm^2·yr = 300 tons/km^2.yr. Thus the value of F_∞ which renders them equal is $300/3 \times 10^5 = 10^{-3}\ km^{-2}$. This is a higher value and the corresponding area in Fig. VI-17 is smaller than that for $5 \times 10^{-4}\ km^{-2}$.

Summary

In this chapter, the local deposition rates of hypothetical sludge discharged into the ocean are examined. In summary, the following points are noted:

1. Available information on the fall velocity distribution of sludge particulates indicates that it is quite variable and may be influenced significantly by flocculation. At present only an order of magnitude of the fall velocity is known.
2. The density stratification and currents at possible discharge sites in Santa Monica Basin are such that the discharged sludge would rise to a distance on the order of 50 meters above the bottom due to buoyancy.
3. Two mechanisms participate in the downward migration and sedimentation of the particulates: (i) falling of the particles, and (ii) downward diffusion of the particles. The second mechanism is significant for particles with small fall velocities ($\sim 10^{-3}$ cm/sec).
4. Approximate estimation of horizontal diffusion using current meter data measured along the slope in the Santa Monica Basin indicates that the phenomenon is anisotropic with diffusion along the bottom contour substantially more energetic than in the perpendicular direction.
5. Based on available data, an approximate determination was made of the bottom fallout pattern for several choices of discharge site. Results indicate that for fall velocity of 10^{-3} cm/sec the areal

extent of the zone where the sedimentation rate is equal to the background oxidation rate is on the order of 120 km^2. This area has an oblong shape with the long axis oriented effectively along the contour.

6. The general conclusion which can be reached is that a few percent of the particulate would settle within a kilometer of the discharge. The bulk would be quite dispersed over an oblong shaped region oriented along the bottom contour.

VII. BASIN-WIDE CHEMICAL EFFECTS OF SLUDGE DISPOSAL

Sludge disposal in marine basins will have local effects more intense than those of ocean-wide scale, such as the sedimentation around an outfall discussed in the previous section. The size of sludge inputs, comparable to those of natural processes, makes it important to examine basin-scale results. Sludge disposal will deplete basin oxygen and possibly nitrate, and will increase trace metal and, perhaps, sulfide concentrations. The exact size of these effects depends on mechanisms and rates of sludge degradation, sludge settling and water mixing and transport. Should oxygen be depleted too greatly, the basins will become inhospitable to animals now present, nitrate regeneration will be retarded and sulfide concentrations could increase. We have calculated basin-wide effects of sludge discharge under a range of strategies and assumptions in order to estimate their magnitude.

We simplified the problem of looking for large effects by assuming that any horizontal layer within the Santa Monica-San Pedro Basin is well mixed (i.e., concentrations are uniform within a layer). Concentrations within a given depth layer are determined by vertical mixing, by upward (or downward) water movement, by chemical reactions, by particles falling into the next layer and by exchange with waters outside the basin. Oxygen and nitrate, which would be consumed by sludge, are already consumed, oxidizing naturally cycling organic matter. Both types of reactions were used. Sludge consists of a fraction (about 70%) which is not oxidized and which would settle on the bottom or be carried out of the basin. This phase was considered only briefly because it did not seem as chemo-biologically important as the oxidizable phase. The system we studied coupled oxygen, nitrate, and sludge chemical interactions with physical processes in a way described further in Appendix 2.

Basin responses are different in the slowly circulating lower basin and in the horizontally exchanging upper basin; within the upper basin, water in contract with high oxygen surface waters should act differently from those with lower oxygen content. We studied effects of sludge disposal in each of these water zones by studying effects of discharge at 800, 600 and 400 m depth.

Discharge at 800 meters

Sludge disposal into lower Santa Monica-San Pedro Basin would deplete oxygen throughout the lower basin to a concentration of less than 4 μM (4 mmoles m^{-3})(Table VII-1; Fig. VII-I). The minimum oxygen concentration predicted for standard assumptions is 1.3 μM, 28% of the present minimum concentration. Sludge would consume oxygen at a rate one-third of the rate at which sediments presently consume oxygen in the whole basin (400-900 m depth).

Sludge discharge would increase dissolved metal concentrations. Increased concentrations would range from 7 times background for chromium to 1.02 times background for cadmium. Copper, to which phytoplankton growth is very sensitive, would become 3.4 times more concentrated.

Oxidizable sludge particles would have a residence time in the basin of 110 days; non-oxidizable particles would have a residence time

TABLE VII-I

Effect of Sludge Discharge at 800 m under Standard Assumptions

	A No Discharge	B Discharge	Ratio: B/A
Total particle content, 10^9 moles BOD	--	2.2	
Residence time, d[1]	--	110	
Oxygen consumption, 10^7 moles d^{-1}			
Sediments	1.59	1.42	0.9
Particles	--	0.46	
Lowest oxygen concentration, μM	4.6	1.3	0.28
Depth region with oxygen less than 4μM	--	745-900m	
Nitrate consumption, 10^7 moles d^{-1}			
Sediments	0.88	0.94	1.1
Lowest nitrate concentration, μM	33.	33.	1.0
Maximum soluble trace metal concentrations, moles m^{-3}			
Cd	9×10^{-6}	9.2×10^{-6}	1.02
Cr	9.6×10^{-7}	7.3×10^{-6}	7.6
Cu	2×10^{-6}	6.7×10^{-6}	3.4
Pb	1.3×10^{-7}	6.9×10^{-7}	5.3
Ni	3.4×10^{-5}	3.5×10^{-5}	1.03
Ag	3.7×10^{-7}	4.95×10^{-7}	1.34
Zn	5×10^{-6}	1.33×10^{-5}	2.7
Particle fates (fraction)			
Settle to bottom		0.76	
Oxidized		0.21	
Flow out of basin		0.03	

[1] Residence time is defined as total sludge particle content of Santa Monica-San Pedro Basin divided by input rate. Residence time of non-degraded particles is 135d.

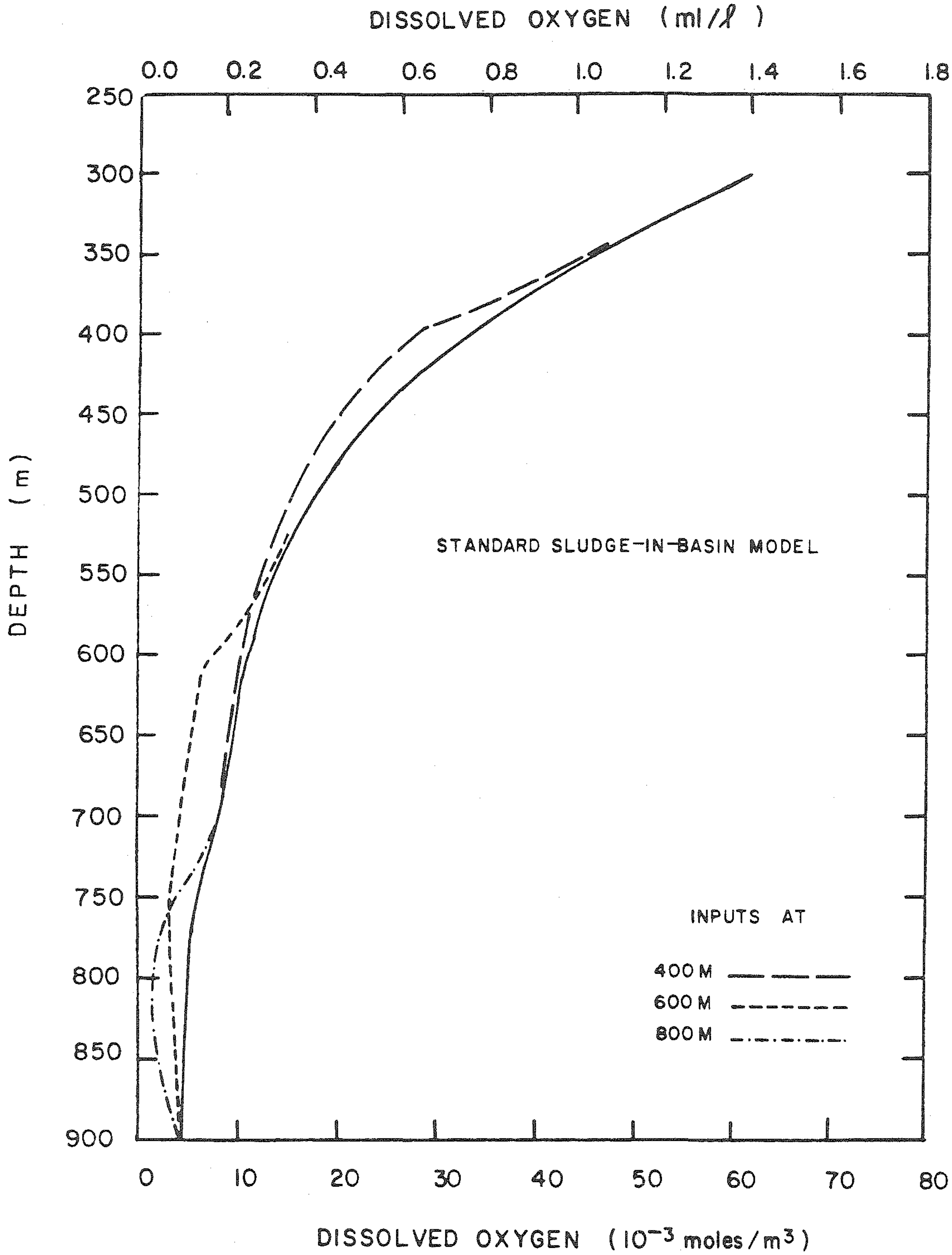


Figure VII-1 Dissolved oxygen concentrations in Santa Monica-San Pedro Basin under standard conditions for discharge at 400, 600, 800 m depth. Solid line represents base line concentration.

of 135 days. Approximately 76% of oxidizable sludge would settle out before being oxidized; 21% would be oxidized in the water column. Thus, for discharge at 800 m, sedimentation on the bottom is the fate for most particles.

These predictions were made using the "standard" or baseline assumptions discussed in Appendix 2. How dependent on the assumptions are they? The effects of variations of several important parameters, such as total sludge BOD (biochemical oxygen demand) and particle fall velocities, are illustrated by Figs. VII-1 through VII-4. The pattern of oxygen depletion is similar in all cases, varying only in degree. Halving the oxygen demand would increase the minimum oxygen concentration, from 1.3 to 2.5 μM, but the lower basin would still be seriously depleted in oxygen (Table VII-2, Fig. VII-3). Particle settling velocities of 6 m d^{-1} (as opposed to the standard 0.78 m d^{-1}) would increase predicted minimum oxygen concentration to 4 μM. However, increased sediment oxygen demand caused by increased organic matter input would decrease oxygen concentration in a way not included in this model.

The conclusion is that a major sludge discharge at 800 m into the lower basin would seriously deplete the supply dissolved oxygen there.

Discharge at 600 meters

Sludge disposal into lower part of upper Santa Monica-San Pedro Basin, at 600 m depth, would put the sludge into a region of greater exchange with other basins and of higher oxygen concentrations. These factors increase the fraction of sludge leaving the basin to 31% and the

TABLE VII-2

Effect of sludge discharge at 800 m for variations on standard assumptions.

	Standard Assumptions	2 x Std. BOD	1/2 x Std. BOD	Fast settling $v_s = 6m\ d^{-1}$	Slow settling $v_s = 0.08m\ d^{-1}$
Total basin particle content, 10^9 moles BOD	2.2	4.7	1.04	0.26	49.
Particle residence time, d	110	113	104	26	243
Oxygen consumption, 10^7 moles d^{-1}					
Sediments	1.4	1.3	1.4	1.5	1.3
Particles	0.5	0.6	0.3	0.1	0.8
Lowest oxygen concentration, μM	1.3	0.5	2.5	4.0	0.5
Region with oxygen < 4μM	745-900m	745-900m	755-895m	--	730-900m
Maximum Cu, 10^{-6} moles m^{-3}					
Soluble	6.7	4.8	8.7	3.1	8.0
Particulate	14.	14.5	13.3	1.8	27.
Particle fates (fraction)					
Fall to bottom	0.76	0.84	0.70	0.96	0.09
Oxidized	0.21	0.13	0.28	0.04	0.35
Go out of basin	0.03	0.03	0.02	0	0.56

[1] Standard assumptions: BOD input = 2×10^7 moles d^{-1}; $v_s = 0.78\ md^{-1} = 0.9 \times 10^{-3}$ cm/sec

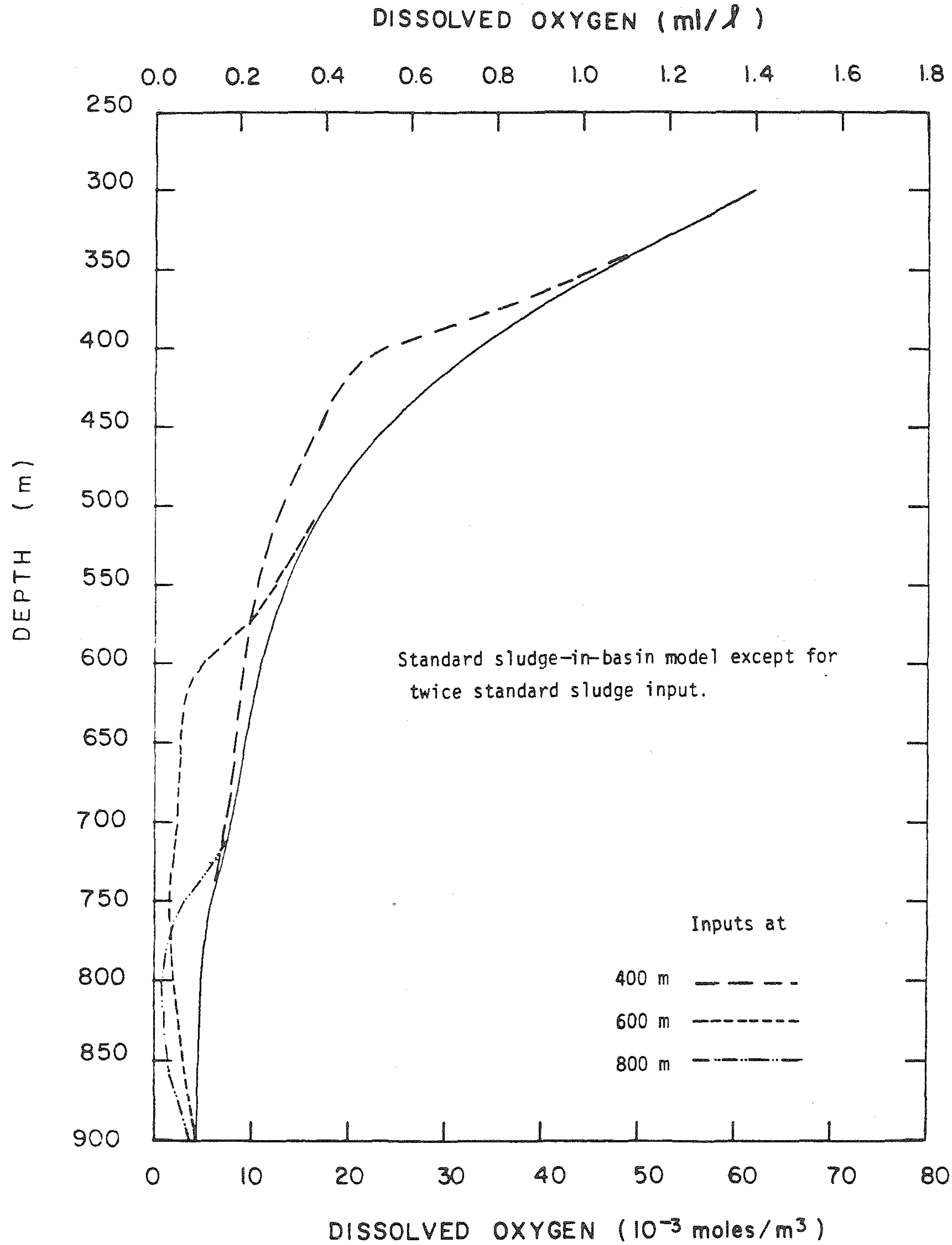


Figure VII-2 Dissolved oxygen concentrations in Santa Monica-San Pedro Basin with input of sludge BOD = 4×10^7 moles-O_2 d^{-1} (twice standard rate).

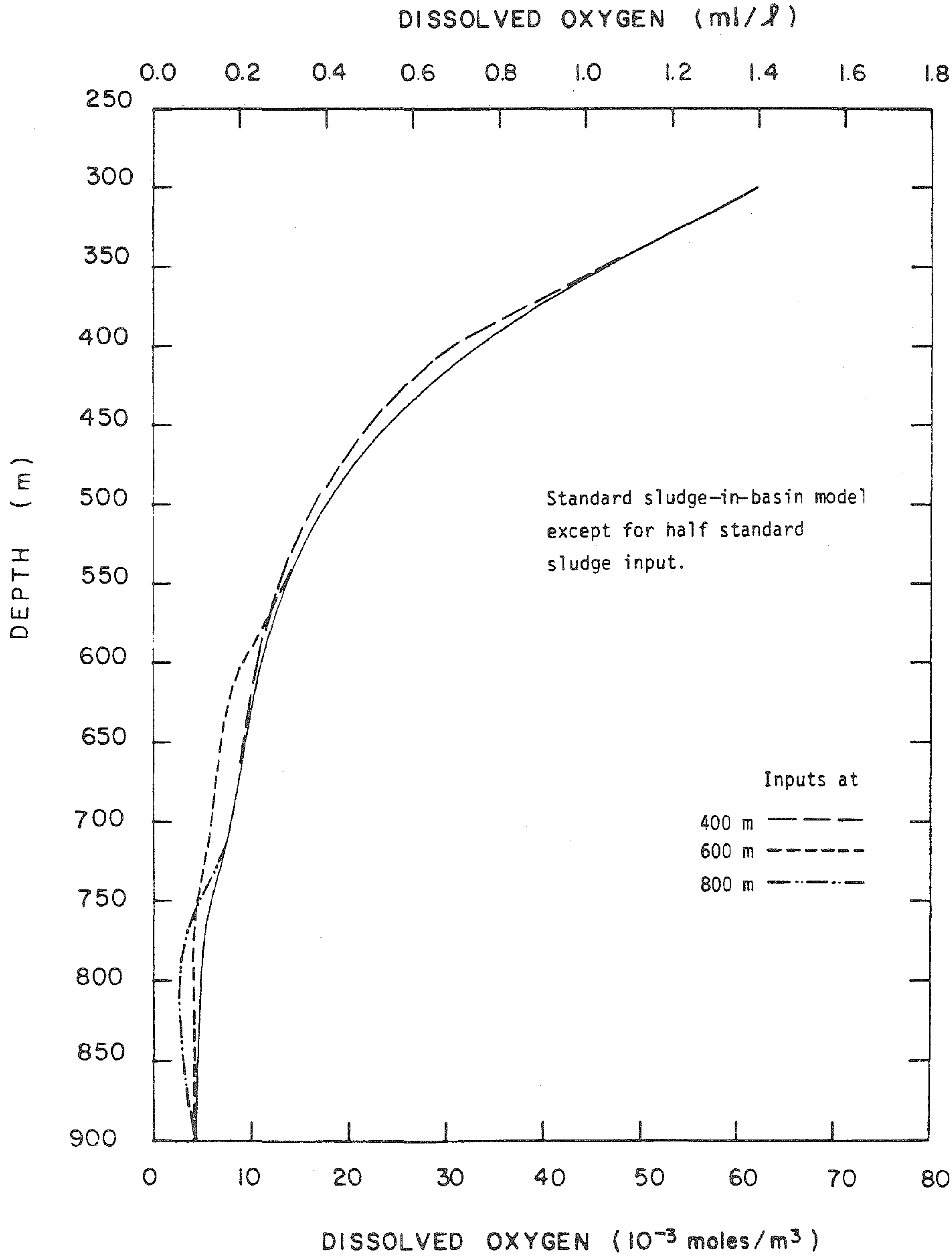


Figure VII-3 Dissolved oxygen concentrations in Santa Monica-San Pedro Basin with input of sludge BOD = 1 x 10^7 moles-O2 d^{-1} (half standard rate).

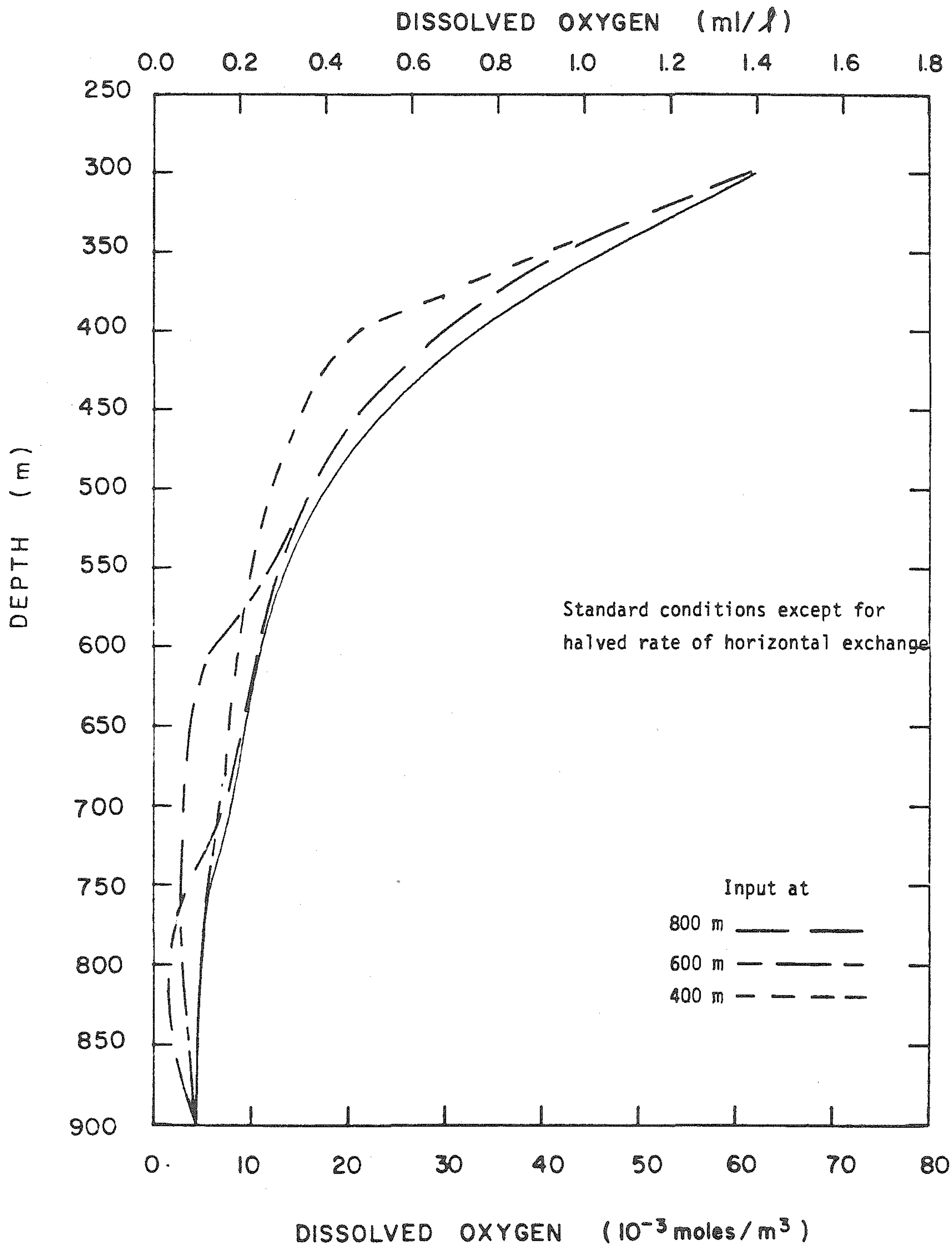


Figure VII-4 Dissolved oxygen concentrations in Santa Monica-San Pedro Basin for half the standard rate of horizontal exchange f_h.

fraction being oxidized to 47% and decrease the fraction settling to the bottom to 22% (Table VII-3). The minimum oxygen concentration becomes a 3.2 μM, greater than the 1.3 μM minimum when sludge is discharged at 800 m. However, this shallower discharge depth increases the distances particles can fall before reaching the basin bottom. The result is that the upper depth of the region with oxygen less than 4 μM rises to 715 m. The effect of discharge at 600 m is to decrease the oxygen depletion intensity but to increase the depth range over which it occurs. Moving from 800 m to 600 m depth of discharge also causes the maximum soluble copper concentration to increase slightly, from 3.4 to 4 times the background value.

Variation of model assumptions shows that conclusions about disposal at 600 m are more tentative than those for disposal at 800 m; half-standard sludge oxygen demand would minimize oxygen depletion, but would increase peak trace metal concentrations; fast settling velocities would again minimize oxygen depletion, and increased horizontal exchange rates, twice standard values, would keep minimum oxygen concentration above 4 μM. There is, however, insufficient evidence to state that disposal at 600 m would have minimal effects.

<u>Discharge at 400 meters</u>

Sludge disposal into the upper part of upper Santa Monica-San Pedro Basin, at a depth of 400 m, would subject sludge to greatest oxidation and fastest dilution with extra-basin waters. Particle residence time is shorter than for disposal at 600 m, 81 days as opposed to 115 days

TABLE VII-3

Effect of sludge discharge at 600m for variations on standard assumptions.
See Figure 2-6 for definition of upwelling, downwelling.

	Standard Assumptions[1]	BOD input		Particle velocity v_s		Particle reactivity r_{max}		Horizontal exchange f_h		Vertical advection, V_z	
		2x std.	1/2x std.	6m d^{-1}	0.08 m d^{-1}	2x std.	1/2x std.	2x std.	1/2x std.	upwelling	downwelling
Total basin particle content, 10^9 moles BOD	2.29	5.1	1.1	0.63	3.5	1.8	2.7	1.8	2.6	3.2	1.6
Particle residence time, d	115	128	107	32	174	88	137	91	132	159	82
Oxygen consumption 10^7 moles d^{-1}											
Sediments	1.3	1.2	1.4	1.5	1.3	1.3	1.4	1.4	1.2	1.1	1.8
Particles	1.0	1.5	0.5	0.3	1.2	1.3	0.6	0.9	0.9	0.9	1.0
Lowest oxygen concentration, μM	3.2	1.6	4.2	4.2	2.7	2.7	3.8	4.1	2.3	2.2	4.2
Region with oxygen < 4μM	715-855m	610-890m	--	--	590-750m	620-860	755-840	--	630-870	580-870	--
Maximum Cu concentration 10^{-6} moles m^{-3}											
Soluble	7.8	6.4	8.5	3.6	12.	10.	5.6	6.1	9.1	8.8	8.
Particulate	7.2	7.3	7.2	1.2	18	6.9	7.5	7.1	7.4	9.9	6.
Particle fates (fraction)											
Fall to bottom	0.22	0.28	0.20	0.79	0.02	0.14	0.31	0.17	0.27	0.28	0.15
Oxidized	0.47	0.37	0.52	0.13	0.60	0.62	0.31	0.45	0.46	0.38	0.53
Go out of basin	0.31	0.35	0.28	0.08	0.38	0.24	0.38	0.38	0.27	0.34	0.32

[1]Standard assumptions: BOD input = 2 x 10^7 moles d^{-1}; v_s = 0.78 m d^{-1}; r_{max} = 0.01d^{-1}, f_h by Figure 2-9.

(Table VII-4). The majority of sludge, 59%, is oxidized within the basin, 35% leaves the basin, and only 6% falls to the bottom. Disposal at 400 m has minimal effect on the oxygen content of the lower basin. Highest soluble copper concentration is, however, 3.7 times the background concentration.

Results for other conditions are similar. Effects on lower basin waters are minimal. With the exception of the high fall velocity case, 6% of the particles or less reach the sediments. Thus, large scale chemical effects of sludge disposal are the least at 400 m.

Nitrate Reduction

These estimates of sludge-caused perturbations were made with the assumption that the sediments are the only nitrate reducers. Nitrate reduction in the water column was omitted because oceanographic evidence suggests that nitrate reduction in the water column does not occur for oxygen concentrations greater than 4.5 μM (see Appendix 2). The expression for nitrate reduction used here considers oxygen inhibition of nitrate reactions at high oxygen concentrations but does not eliminate them. We eliminated nitrate reaction in the water column at high oxygen concentrations by not allowing it at all.

This assumption of no nitrate reaction with sludge particles will not be valid when massive loadings cause oxygen to decrease below 4 μM. We tested the importance of nitrate reduction under those circumstances where there would be heavy oxygen depletion in the lower basin (Table VII-5, Fig. VII-5). Calculations showed that for conditions standard

TABLE VII-4

Effect of sludge discharge at 400m for variations on standard assumptions.

	Standard Assumptions[1]	BOD input 2x std.	BOD input 1/2x std.	Particle velocity v_s 6m d^{-1}	Particle velocity v_s 0.08m d^{-1}	Particle reactivity r_{max} 2x std.	Particle reactivity r_{max} 1/2 std.	Horizontal exchange f_h 2x std.	Horizontal exchange f_h 1/2x std.	Vertical advection, V_z upwelling	Vertical advection, V_z downwelling
Total basin particle content, 10^9 moles BOD	1.6	3.3	0.8	0.9	1.4	1.0	2.4	1.1	2.0	1.6	1.2
Particle residence time, d	81	83	80	44	70	49	121	57	104	80	61
Oxygen consumption, 10^7 moles d^{-1}											
Sediments	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.8
Particles	1.2	2.4	0.6	0.6	1.1	1.5	0.9	0.9	1.4	1.2	1.0
Lowest oxygen concentration, μM	4.6	4.6	4.6	4.5	4.6	4.6	4.6	4.6	4.6	4.5	4.6
Region with oxygen $< 4 \mu M$	--	--	--	--	--	--	--	--	--	--	--
Maximum Cu concentrations 10^{-6} moles m^{-3}											
Soluble	7.5	7.4	7.7	3.6	9.6	10.6	5.4	4.7	12.	6.5	4.6
Particulate	7.0	7.0	6.9	0.1	11.	6.3	7.4	6.4	7.3	8.6	3.3
Particle fates (fraction)											
Fall to bottom	0.06	0.06	0.06	0.61	0	0.03	0.11	0.04	0.08	0.05	0.05
Oxidized	0.59	0.58	0.60	0.25	0.56	0.73	0.43	0.45	0.70	0.58	0.51
Go out of basin	0.35	0.36	0.34	0.14	0.44	0.24	0.46	0.52	0.22	0.37	0.44

[1] Standard assumptions: BOD input = 2×10^7 moles d^{-1}; $v_s = 0.78$ m d^{-1}; $r_{max} = 0.01 d^{-1}$. f_h by Figure 2-9.

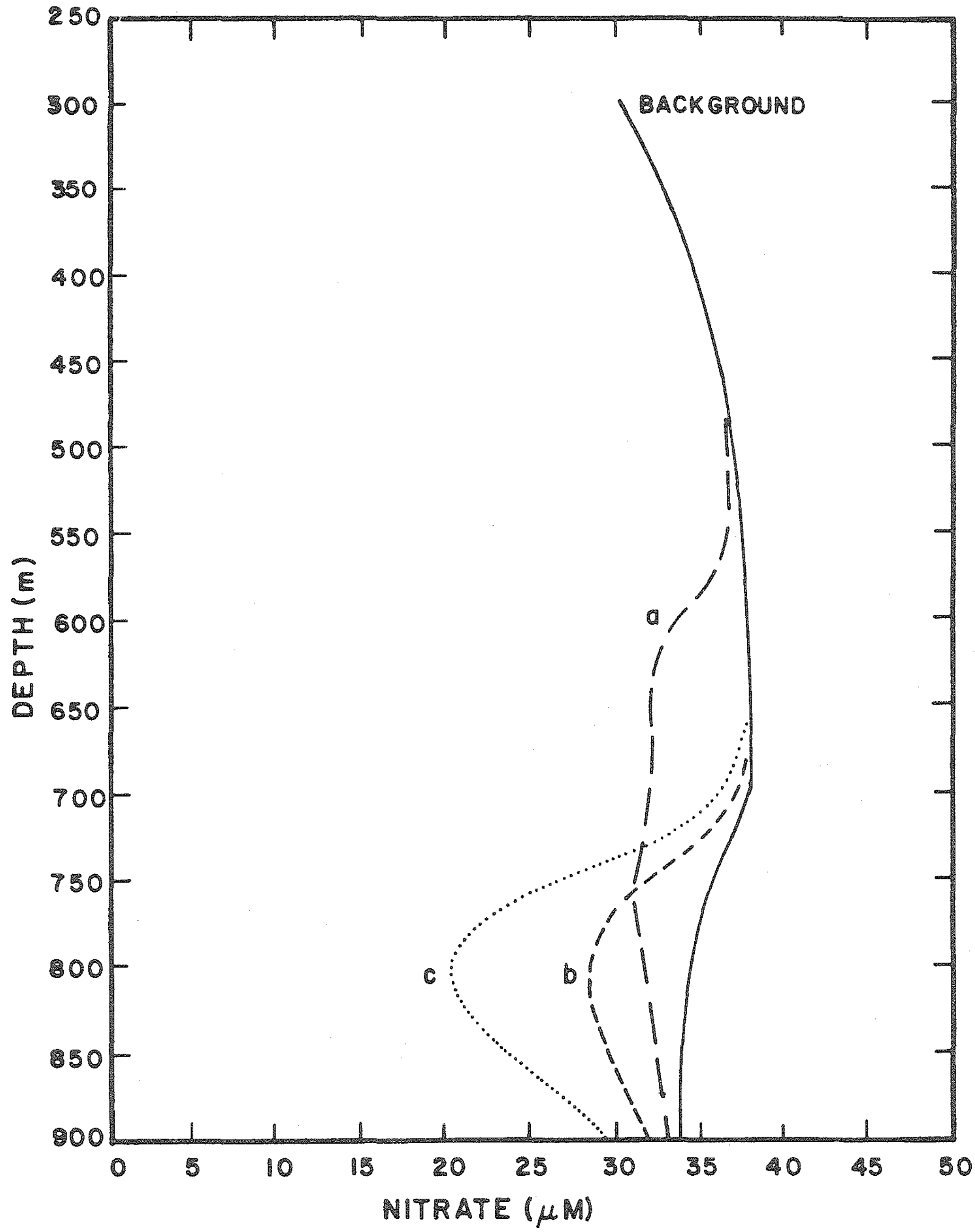


Figure VII-5 Nitrate concentration in Santa Monica-San Pedro Basin with sludge input when nitrate and oxygen oxidize particles:

a) twice the standard BOD input at 600 m;
b) standard BOD input at 800 m; and
c) twice the standard BOD input at 800 m.

except for the nitrate + oxygen reaction with sludge particles, minimum nitrate concentration in the lower basin would decrease to 28 μM from the present 33 μM. Total nitrate reduction in the basin would increase by 56% over the present value. Disposal of sludge with twice the oxygen demand would decrease the minimum lower basin nitrate concentration to 20 μM and increase total nitrate reduction to almost twice the present rate.

TABLE VII-5

Effect of Nitrate + Oxygen Degradation of Sludge Particles As Opposed to Standard Oxygen Only Degradation, With Discharge at 800 m.

	Background	Standard Conditions	Nitrate + Oxygen Degradation of Particles: Standard BOD input	Nitrate + Oxygen Degradation of Particles: 2 x Std. BOD input
Oxygen consumption, 10^7 moles d^{-1}				
Sediments	1.59	1.43	1.49	1.60
Particles	--	0.46	0.31	1.26
Nitrate consumption, 10^7 moles d^{-1}				
Sediments	0.88	0.94	0.88	0.81
Particles	--	--	0.49	0.78
Lowest nitrate concentration in lower basin μM	33.	33.	28.	20.

Sulfide Production

The continued presence of fairly large concentrations of nitrate (at least 20 μM) in basin waters even after oxygen is virtually eliminated indicates that sludge organic matter should not reduce sulfate to sulfide in basin waters. However, sulfides could be produced in the sediments and released into the water column, where they would be oxidized back to sulfate, or they could be released directly from the sludge.

Effects of sludge disposal on sedimentary sulfate reduction and sulfide release are too complex to model at present (Berner, 1974). Sulfate reduction could be increased by organic sedimentation, but whether it would or not depends on other factors as well. For example, Sholkovitz (1973) found strong sulfate reduction in sediments of lower Santa Barbara Basin where oxygen concentration was between 2 and 4 μM, but little sulfate reduction on basin slopes, where sedimentation appeared to be the same, but water oxygen concentrations were about 18 μM. The rate at which sulfides species leave the sediments depends on presence of iron available for formation of pyrites and presence of sufficient oxygen at the water-sediment interface to oxidize sulfides to sulfates. Further study of basin sediments would have to be made to determine rates of sulfide release to the water column.

Sulfides in sludge are mostly in metal sulfide precipitates, with the greatest amount present in FeS(s) (Faisst, 1976). Nelson et al. (1977) investigated the dissolution kinetics of the ferrous sulfide mineral mackinawite. They found that, under oxygen-rich conditions, the ferrous iron was oxidized to ferric and that sulfide was oxidized to sulfur and various higher oxidative states. He could not differentiate between those oxidations taking place while the iron and sulfide were still on the crystal and those oxidations taking place in solution. We shall assume that they take place in solution, that the rate of dissolution of metal-sulfide solids is that of sludge and that the oxidation of sulfide follows the kinetic expression of Cline and Richards (see Appendix 1).

The sulfide oxidation rate in sea water can be described by the equation

$$\frac{d\Sigma S^{=}}{dt} = k[O_2][S^{=}] \qquad \text{(VII-1)}$$

where $k = 3.6 \times 10^{-2}\ \mu M^{-1} d^{-1}$. The concentration of iron in sludge is about 10 times that of copper. If, for discharge at 400 m, the maximum particulate copper concentration is 6.7×10^{-9} M, the maximum particulate iron and, therefore, particulate sulfide concentrations are 6.7×10^{-8} M. This particulate concentration, dissolving at the maximum 0.01 d^{-1} rate, would add 6.7×10^{-10} M sulfide per day to solution. The system, when at steady state, will oxidize sulfide as fast as sulfides dissolve; the dissolution rate just calculated, occurring where particle concentrations are the highest, is the fastest. Therefore,

$$6.7 \times 10^{-8}\ M = k[O_2][S^{=}]$$

For the 400 m discharge, the oxygen concentration is 30 μM and the resulting sulfide concentration is 6.5×10^{-10} M. Thus, the maximum sulfide concentration for disposal at 400 m from sludge dissolution is less than 10^{-9} M. If sulfide oxidation is part of the dissolution process, the concentration would be less than this.

VIII. BIOLOGICAL IMPACTS

Conclusions reached by SCCWRP after surveying life in the basins were (see Attachment);

> "First, the water column, bottom, and, bottom sediments of San Pedro and Santa Monica Basins are not devoid of marine life. At the deepest depth sampled (915 m) there were few live organisms taken, but there were some (one fish and seven species of invertebrates in the trawl and three invertebrates yielding a biomass of 0.5 g/m^2 in the grab).
>
> "Second, while the fauna is lower in abundance and diversity below sill depth (737 m) than above, there appears to be no great sudden drop or faunal discontinuity at sill depth but rather a gradual decline in abundances of most organisms. This lack of sudden drop reflected in the last two columns of Table 8 [Attachment] suggests there are no significant physical or chemical discontinuities here as well ...
>
> "Our review of the midwater fauna is cursory, at best; the data examined do confirm the trend of a general decrease in density and biomass of midwater organisms with depth. There are several reasons why the midwater fauna data base is weak ... As a consequence, estimates of total fish or decapod population sizes in the basins should not be extrapolated from existing catch data."

Biomass Affected

The SCCWRP report shows that the lower Santa Monica-San Pedro Basin is not dead. However, inadequate information on the ecology and physiology of animals there limits the predictions that can be made. We can estimate, very crudely, population sizes that will be affected by different disposal strategies.

One approach is to argue that animals cannot survive in water with less than a given oxygen concentration. If a certain area/volume would have its oxygen concentration lowered below that value, then all of the animals within that area would be affected. If it was known which would be affected, then their biomass within that area can be calculated. We have not tried to estimate which species would be eliminated because of our ignorance as to whether a species range might only be shifted to higher oxygen-containing waters. We have calculated the biomass that would be displaced/eliminated, assuming all the biomass used in our estimates (Table VIII-1) would be affected.

We have chosen to use an oxygen concentration of 4 μM as the critical oxygen concentration below which no animals live. Several observations, physiological and environmental, support this. Childress (1975) measured the critical concentration at which animal respiration began to decrease with decreasing oxygen concentrations. He found a critical concentration as low as 4.5 μM in one of the midwater crustaceans and fishes that he tested. This concentration, he argued, would represent the lower limit at which the animals could function aerobically. Judkins (personal communication) observed that 90% of the zooplankton avoided a layer of water with oxygen concentrations of 4.5 μM (.1 ml/liter) off the Peru coast. Data for lower Santa Monica-San Pedro Basin, which has oxygen concentrations as low as 4.5 μM, suggest that oxygen concentrations there are barely large enough to sustain some animals. We chose 4 μM as the critical concentration for animal survival because it was similar to the critical concentration suggested by these studies but less than the present concentration in lower Santa Monica - San Pedro Basin.

TABLE VIII-1

Biomass in Different Depth Ranges of Santa Monica-San Pedro Basin

	Lower basin	Lower Upper basin
Depth range, m	740-900	600-740
Volume, m^3	2.9×10^{11}	3.6×10^{11}
Benthic area, m^2	2.5×10^9	0.6×10^9
Midwater fauna		
Number density	$32/10^4\ m^3$	$32/10^4\ m^3$
Total number in volume	9×10^8	1×10^9
Biomass density	*	$10g/10^4\ m^3$
Total biomass in volume	*	$4 \times 10^8 g$
Epibenthic fauna		
Biomass density	0.86 kg/haul (fish only)	32 kg/haul
Total biomass in area	$2 \times 10^8 g$	$2 \times 10^9 g$
Benthic fauna		
Biomass density	$4g/m^2$	$15g/m^2$
Total biomass in area	$10 \times 10^9 g$	$9 \times 10^9 g$
Total biomass in range	$10 \times 10^9 g$	$11 \times 10^9 g$

Note: Animal densities were taken from SCCWRP's report (Attachment) with epibenthic densities calculated assuming that the otter trawl sampled $10^4\ m^2$ per haul (calculated for a net 7.6 m wide, towed for 20 minutes at 2 kts).

*No data, but assumed small compared to benthic fauna.

Sludge discharge at 600 and 800 m would decrease oxygen concentrations below 4 μM for large depth ranges: discharge at 800 m would depopulate the lower Santa Monica-San Pedro Basin, a volume of 2.9×10^{11} m^3 and an area of 2.5×10^9 m^2. Crude estimates for biomass of midwater, epibenthic, and benthic fauna yield an estimate of 10^7 kg in the lower basin (Table VIII-1). The value for epibenthic biomass does not include invertebrates and was judged to be based on insufficient data (Attachment), but it could only be comparable to that for infauna if it were 50 times larger.

If sludge discharge at 600 m were to reduce oxygen concentrations to less than 4 μM from 600 m to bottom, it would affect an additional volume of 3.6×10^{11} m^3 and a benthic area of 0.59×10^9 m^2. This would affect 10^7 kg more organisms than discharge at 800 m. The biomass affected between 600 and 740 m and that between 740 and 900 m are approximately the same despite the greater animal density shallower because of the greater benthic area in the lower region.

Sludge discharge at 400 m would not lower oxygen content below 4 μM but would impact benthic fauna by locally increasing the sedimentation rate. The area over which the sedimentation of organics would double is 120 km^2. The sedimentation model (Section VI), which does not consider particle oxidation, predicts that on the order of one-third of the sludge lands within this area for standard settling velocity.

Planktonic Interactions

Mid-water fauna live by filtering particulate matter out of the water, scavenging, or predation. Sludge disposal might affect these animals by mixing with their normal food to form a deleterious diet, by interfering with the chemical cues that they need to find their food, or by poisoning them with higher trace metal concentrations.

The California State Water Resources Control Board (1978) has used toxicological data for marine organisms to set receiving water standards (Table VIII-2). The model developed in Appendix 2 predicts that discharge at 400, 600, or 800 m will not exceed the established standards for the trace metals studied. To the extent that these standards do encompass toxic effects on mid-water organisms, the increased trace metal concentrations associated with sludge discharge will not harm the mid-water populations.

The maximum particulate sludge concentration for discharge under standard conditions was 6.7×10^{-3} moles-BOD m^{-3} for discharge at 400 m, 6.9×10^{-3} moles-BOD m^{-3} for discharge at 600 m, and 13.3×10^{-3} moles-BOD m^{-3} for discharge at 800 m. These are equivalent to organic carbon concentrations of 80 $\mu g\ \ell^{-1}$, 83 $\mu g\ \ell^{-1}$ and 160 $\mu g\ \ell^{-1}$, respectively, if one mole of BOD is equivalent to one mole of carbon. Holm-Hansen (1972) reported the particulate organic carbon concentration in the San Diego Trough below 300 m at between 5 and 15 $\mu g\ \ell^{-1}$ and Holm-Hansen et al. (1966) reported values in Santa Catalina Basin of about 50 $\mu g\ \ell^{-1}$. Thus, sludge discharge could increase the particulate organic carbon

TABLE VIII-2

Comparison of Predicted Soluble Trace Metal Concentrations With Those From the 1978 Water Quality Control Plan for Ocean Waters of California (State Water Resources Control Board, 1978)

Element	Maximum allowable ambient concentratiion, M (6 month median)	Predicted maximum soluble concontrations, M, for discharge at 400 m	600 m	800 m
Cadmium	2.7×10^{-8}	9.3×10^{-9}	9.3×10^{-9}	9.3×10^{-9}
Chromium	3.9×10^{-8}	8.5×10^{-9}	8.6×10^{-9}	7.1×10^{-9}
Copper	7.8×10^{-8}	7.6×10^{-9}	7.7×10^{-9}	6.6×10^{-9}
Lead	3.9×10^{-8}	8.0×10^{-10}	8.1×10^{-10}	6.8×10^{-10}
Nickel	3.4×10^{-7}	3.5×10^{-8}	3.5×10^{-10}	3.5×10^{-8}
Silver	4.1×10^{-9}	5.2×10^{-10}	5.2×10^{-10}	4.9×10^{-10}
Zinc	3.1×10^{-7}	1.5×10^{-8}	1.5×10^{-8}	1.3×10^{-8}

concentrations by as much as one order of magnitude over background concentrations. What results this would have on zooplankton present are unknown.

Sludge disposal at 400 m would avoid the serious oxygen depletion associated with deeper disposal. It would increase trace metal particulate organic carbon and dissolved organic concentrations. Trace metal concentrations would still be within a range believed to be non-deleterious; particulate carbon would be much greater than background with possible, but unexplored, consequences on planktonic filter feeders; how dissolved organics affect scavenging or other traits of mid-water organisms is a question that can only be posed, but not yet answered.

Major sludge components not examined in this study, known to affect organisms, are the various hydrocarbons and their halogenated derivatives. The magnitude of their concentrations can be calculated if all hydrocarbons stay on particulates and if peak hydrocarbon concentrations are associated with peak particulate concentrations at the same particulate copper hydrocarbon ratio as in the initially discharged sludge. Then, peak chlorinated benzene concentrations for discharge at 400 m would be about 20 $\mu g/m^3$, about 20 parts per trillion. Predicted DDT inputs are one-twentyfifth of this, implying maximum DDT concentrations of about one part per trillion in the water, two parts per million in the particulate phase. This is based on the horizontally well-mixed model.

This analysis has not attempted to predict effects of sludge disposal on species distribution, community structure, diversity, faunal indices, or any of the other measures of an ecological assemblage because the basins are areas for which none of these are presently known. Prediction of ecological changes would involve an understanding of the mechanisms by which organisms interact with sludge. An attempt has been made to calculate the behavior of major sludge components known or suspected important in those mechanisms and to guess the magnitude of the effects. Hopefully, we have helped to define the scale of biological and ecological observations that need to be made before all environmental changes can be properly assessed. The controversy that still rages over the impact of present sludge disposal practices, in areas that have been intensively studied for over a decade, reminds us of the difficulty of doing more.

IX. AVAILABLE OCEAN DISCHARGE ALTERNATIVES

In this chapter, we consider the available alternatives for ocean discharge of sludge. These alternatives will then be narrowed down to four feasible ones. Finally, the expected scenario for each of these in terms of its environmental impact will be discussed. It should be reiterated that throughout this report it is taken as given that sludge will be discharged into the ocean. No attempt is made to compare ocean discharge with other methods, this being the overall task of the LA/OMA project.

Classification of Coastal Receiving Water

In discussing the possible alternatives and their impacts it is useful to categorize the offshore waters in three parts:

a. Lower basin water: the body of water which is within topographic depressions, and below the lowest of the sills surrounding a basin.

b. Upper basin water: those waters which are in layers that are partially enclosed in basin, perhaps with an opening at one end but contained along the sides and at the opposite end by submarine mountain ranges and sills.

c. Shelf water: the water mass which is generally above the submarine mountain ranges so that its lateral flow and circulation are relatively unimpeded by the basin topography.

For the Santa Monica-San Pedro Basin, the principal focus of our study, the approximate depth ranges are as follows:

a. Lower basin waters: below 740 meters

b. Upper basin waters: between 300 meters and 740 meters

c. Shelf waters: above 300 meters

The salient characteristics of these three bodies of water for modeling the disposal and ultimate fate of sludge are summarized as follows:

a. Lower basin water: the dissolved oxygen in the water column is very low (less than 0.3 mg/ℓ); little density stratification (uniform temperature and salinity); principal water exchange caused by dense water inflows over the end sills, which flow down into the basin to lower or bottom depths, thereby causing gradual upward displacement; sediments may be aerobic in the top few centimeters but below that generally anaerobic.

b. Upper basin water: some slight density stratification due to a modest temperature gradient; dissolved oxygen still very low but gradually increasing toward the top of the layer due to downward diffusion. Greater horizontal water exchange with ocean waters than for the lower basin water.

c. Shelf water: the dissolved oxygen now rapidly approaches saturation with decreasing depth; temperature increases more rapidly, horizontal currents believed to be stronger than in basin waters, with significant exchange with the open ocean.

Sludge Characteristics

One property of sludge which is of great importance in determining its overall behavior in the ocean is its overall bulk density when compared with that of the receiving water. The sludge has a bulk density slightly lighter than seawater as it comes from the digester, but it could be thickened somewhat to make it slightly heavier than seawater. When introduced into the ocean it may either rise or sink depending on its density, but because of the density stratification in the water column it will rise or sink only a limited distance (on the order of 50 m) before the resulting sludge-seawater mixture will stop and spread out at the level of neutral density.

If heavier-than seawater sludge were released via a pipeline at the bottom of the ocean, the discharge would tend to spread out on the bottom in the form of a density current. This would result in quite a different impact than if the sludge were lighter than seawater.

Delivery Systems

The delivery systems to be considered are outfalls and barges. Simply put, outfalls introduce the sludge at the sea floor, whereas barges discharge near the surface. Barges could use a pipe hanging down from the barge for a pumped discharge at depth, but the engineering and logistics problems are such that we presume such a hanging pipe would be limited to approximately 100 meters. According to the classification above, such a discharge would still be in the upper shelf waters.

<u>Alternatives</u>

Given three zones of receiving water, two sludge density possibilities, and two types of delivery systems, there are actually 12 alternatives as shown in Table IX-1.

All but four of these can be eliminated relatively quickly on either environmental or economic grounds. Alternative 3 holds no advantage over alternative 1, which is the current practice at Hyperion. Moreover, cost estimates for barge disposal of sludge without first dewatering are on the order of \$43/dry ton (Raksit, 1977) which is substantially higher than outfall discharge. Thus we eliminate alternative 3. Alternatives 7, 8, 11, and 12, involving barge disposal of sludge into the upper and lower basins, respectively, can be eliminated on the basis of engineering feasibility since it would involve lowering a very long (several hundred meters) pipe from the barge. Alternatives 2, and 6, involving outfall discharge of heavier-than-seawater sludge, are judged environmentally unacceptable since the discharge will form a density current on the bottom. Like a submerged jet or plume it will entrain ambient sea water and because of the density stratification it will shortly reach a level of neutral density. After some dynamic overshoot, it will spread laterally. While this may be acceptable on the bottom of the lower basin (alternative 10), the higher benthic biological activity in the upper basin and on the shelf makes alternatives 2 and 6 undesirable. Finally, alternative 9 is undesirable since it would result in rendering the oxygen level in the lower basin too low (see Chapter VII).

TABLE IX-1

Possible Alternatives for Ocean Discharge of Sludge

Alternative	Receiving Water	Sludge Density	Delivery System	Strategy
1	shelf	lighter	outfall	dispersal
2	shelf	heavier	outfall	dispersal
3	shelf	lighter	barge	dispersal
4	shelf	heavier	barge	dispersal
5	upper basin	lighter	outfall	dispersal
6	upper basin	heavier	outfall	dispersal
7	upper basin	lighter	barge	dispersal
8	upper basin	heavier	barge	dispersal
9	lower basin	lighter	outfall	dispersal
10	lower basin	heavier	outfall	containment
11	lower basin	lighter	barge	dispersal
12	lower basin	heavier	barge	containment

Thus, out of the twelve possibilities, only four alternative schemes remain as listed in Table IX-2. Among these, only one (Scheme C) is for disposal with a barge. Also, only one is for disposal into the lower basin (Scheme D). These four schemes will now be discussed in more detail.

TABLE IX-2

Acceptable Possibilities of Ocean Sludge Disposal Schemes

Scheme	Receiving Water	Sludge Density (relative to seawater)	Delivery System	Strategy
A	shelf	lighter	outfall	dispersal
B	upper basin	lighter	outfall	dispersal
C	shelf	heavier	barge	dispersal
D	lower basin	heavier	outfall	containment

Scheme A. Outfall Dispersal of Unthickened Sludge into Shelf Waters

This is effectively the current practice for the City of Los Angeles at Hyperion where sludge is discharged through a seven mile long outfall at a depth of 100 meters. The sludge is lighter than sea water and rises in the form of a buoyant plume. Both measurements and calculations indicate that the plume rises a vertical distance of about 50 meters before spreading out horizontally and diffusing in ocean turbulence. The basic result of this discharge scheme is dispersal of the sludge material over a wide area. Field studies indicate that benthic effects of the discharge extends only over a relatively small area (a few km^2) near the discharge terminus. It is believed that only a few percent of sludge solids remain in the neighborhood of the discharge with the rest being carried away into the Southern California Bight and open ocean. The best way to determine the environmental effects of this scheme is clearly by observation since such a discharge already exists. Several evaluations of this has already been done and will therefore not be repeated. (See Hyperion EIS and SCCWRP Annual Reports). This is also a separate task in the current LA/OMA Study (Task 5.1).

Scheme B. Outfall Dispersal of Unthickened Sludge into Upper Basin Waters.

This discharge scheme involves the use of a pipeline terminating in the upper basin (depth range 300 m to 740 m). The sludge would not be thickened, so that it is lighter than sea water resulting in a buoyant plume rising a distance on the order of 50 meters above the outfall terminus (anywhere from 20 m to 100 m, depending on local ocean currents and the design of a possible diffuser).

One-dimensional analyses presented in Chapter VII show that this scheme would seem to have a few large scale impacts -- in contra-distinction from a similar scheme into the lower basin. It would, however, impact a community whose sensitivity to sewage solids has not been experimentally tested, viz. the mid-water animals. Lack of reported zooplankton kills caused directly by sludge disposal would suggest that this would not be a problem.

Three dimensional sedimentation analyses in Chapter VI indicate that this scheme would result in wide dispersal of sludge solids. The area on the bottom (mostly below the discharge depth) which would have a sedimentation rate higher than the local oxidation rate is on the order of 120 km^2.

Scheme C. Barge Disposal of Thickened Sludge into Shelf Waters

The disposal of sludge from a barge is a technique practiced primarily in the East Coast of the United States. Two methods have been used: either the sludge is discharged from a bottom-opening hopper barge, or it is pumped out through a pipeline suspended beneath or behind the barge.

In the case of pumped discharge, the sludge would be issued in the form of a jet which mixes with the local ocean waters. The diluted sludge can therefore be thought of as being injected into a layer at a depth which depends on discharge rate, sludge characteristics, barge speed and ocean density stratification, as well as the depth of the discharge pipe.

The physical behavior of the sludge released from a bottom-opening hopper barge depends on the characteristics of the sludge. If the sludge were thickened substantially so that there is much cohesion (probably not practicable), it is possible that it would fall for some distance as a coherent mass (much like a lightweight rock). During this period, pieces could ablate from the mass. Alternatively, if the sludge is thickened enough to be heavier than seawater, but still liquid, it would entrain seawater as it falls, much like a thermal rising in the atmosphere. In this event the downward distance travelled would be much smaller due to entrainment. A point of neutral buoyancy would be reached and then the sludge can again be thought of as being injected into a layer in the ocean.

In general, the physical dynamics resulting after the brief initial period following disposal of sludge from barges can still be envisioned as the injection of the diluted sludge into a certain vertical layer in the ocean, but probably nearer the surface than discharge from a submarine pipeline. The only differences are that: (i) the horizontal location of the discharge point can be varied easily, and (ii) the vertical position of the injection depth can be a substantial distance from the bottom. The result is generally expected to be still wide dispersal of the discharged sludge. It is judged advisable to ensure that the discharged sludge reaches neutral buoyancy below the thermocline to minimize surface contamination.

Barge disposal could make the entire Southern California Bight the site for discharge, minimizing cumulative effects. Local effects associated with sludge release include nutrient concentration. Peterson (1974) showed that sewage particulates decreased the euphotic depth close to large marine sewage outfall by 60%. Disposal in offshore waters would likewise decrease the euphotic depth in the sludge patch, but this would be only over a small fraction of the area of the Bight at any time. Similarly, nutrients present in sludge would enhance phytoplankton production locally as has been shown for coastal outfalls by Eppley et al. (1972). Intensity and extent of these effects would depend on the actual disposal practices.

There should not be a severe impact on dissolved oxygen concentrations because of the high background oxygen concentration and the rapid shelf water turnover estimated at 120 days for the entire Southern California Bight. However, large concentrations of potentially toxic particles would be put in the more productive surface zone. Filter feeders there may be susceptible to changes in the phytoplankton. Whether they will be or not is not possible to say because previous work on effects of sewage outfalls has concentrated on coastal benthic animals. Open ocean planktonic animals should be studied.

It is difficult to make a definite biological assessment of sludge disposal by barge in offshore near surface waters because different disposal strategies would cause different effects and because sludge effects on the planktonic community have not been studied.

Scheme D. <u>Outfall Discharge of Thickened Sludge in Lower Basin</u>

All the schemes discussed above (i.e., A, B, and C) result in wide dispersal of the sludge into the receiving water. By contrast, scheme D results in containment of the sludge solids in a relatively small area; for this scheme, the digested sludge is thickened to a bulk density heavier than that of seawater, then discharged through an outfall with the terminus in the lower basin. Following discharge, the sludge would form a density current flowing towards the depressions in the basin, forming a layer. Measures could be taken by designing the discharge terminus to minimize mixing as much as practicable. In this manner, a layer of concentrated sludge would tend to be formed on the bottom of the basin. Benthic biota would certainly be impacted at the great depths.

This alternative is the most difficult to analyze, and the most uncertain in its effects. Principally, we do not have current data near the bottom with which to predict whether the settled sludge particles will stay put or be "blown" around over a larger area. The natural bottom sediments have a median grain size of 15μ, corresponding to a fall velocity of 10^{-2} cm/sec, which is toward the high end of expected sludge particle settling velocities. Unless the sludge particles have significant cohesion, the sedimentary evidence suggests that much of the sludge particles may be subject to resuspension during "strong" events of overturning or seiching. This could lead to serious oxygen depletion as predicted by the basin model for discharge at 800 m. This scheme is presented here as the only possible strategy for containment of the sludge, but further studies are required to assess its environmental impacts. Considering the engineering difficulties of construction to 740 m (2400 ft) or more, and the lack of assurance that the containment would be effective, this alternative is given a low chance of becoming viable.

Recommendation

If it is desired to reduce the environmental effects below those experienced around the present Hyperion sludge outfall at 100 m depth, it is recommended that engineering feasibility analyses, conceptual designs, and further environmental studies (specified in Chapter X) be undertaken and focused on the following alternatives:

(1) Outfall(s) for unthickened sludge with discharge depth of about 300 m (1000 ft); and

(2) Barging of thickened sludge with submerged pumped discharge between 50 m and 100 m below the surface by means of a hanging pipe; a likely fixed location would be near the center of the San Pedro Basin, although a "roving" discharge location should be considered.

Other possibilities are judged less attractive or less feasible.

This research project has been focused primarily on prediction of the environmental effects of possible discharges of digested sludge from submarine outfalls into the deep basins off southern California. If an outfall scheme is favorably considered on the basis of environmental effects, then the next step is to define one (or more) specific engineering projects for feasibility study and conceptual design. Additional field data and research are also needed on topics listed in Chapter X.

Discharge from barges received little emphasis in the scope of work for the study, probably because the cost of barging sludge is unquestionably several times as high as pumping through sludge outfall(s) (Raksit, 1977). If the barging alternative becomes a serious competitor, more environmental analyses as well as engineering feasibility studies should be made for <u>surface-layer</u> discharge far from shore.

Possible Outfalls and Probable Capital Costs

Although a detailed engineering study of possible sludge outfall projects has not been made, it is possible to define the approximate magnitude of outfall project costs on the basis of length of pipes required to reach the recommended depth of 300 m multiplied by the estimated construction cost per unit length. Use of three separate outfalls (one for each discharge agency) is a more feasible plan than combining the sludge flows into only one or two outfalls because the expense of onshore conveyance to common collection points exceeds the savings in outfall costs (both in construction and operation and maintenance). Possible alignments for these outfalls for the three discharge agencies are shown in Figs. IX-1 to IX-3.

The cost of construction of needed outfalls using coated steel pipe of 18 to 24 inch diameters, is estimated to be approximately $750,000 per mile*($140/ft), using offshore pipelaying technology of the oil-and-gas industry, and presuming the availability of a large pipelaying barge in west coast waters. The cost is relatively insensitive to the diameter in the range of 18 to 24 inches.

The approximate lengths needed by the three agencies to reach 300 m (1000 ft depth) and the associated costs for the marine portion (with and without 100% contingency factor) are given in Table IX-3.

*Lowell Johnston, Lowell Johnston & Associates, Suite 612, 5800 East Skelly Drive, Tulsa, Oklahoma 74135, personal communication.

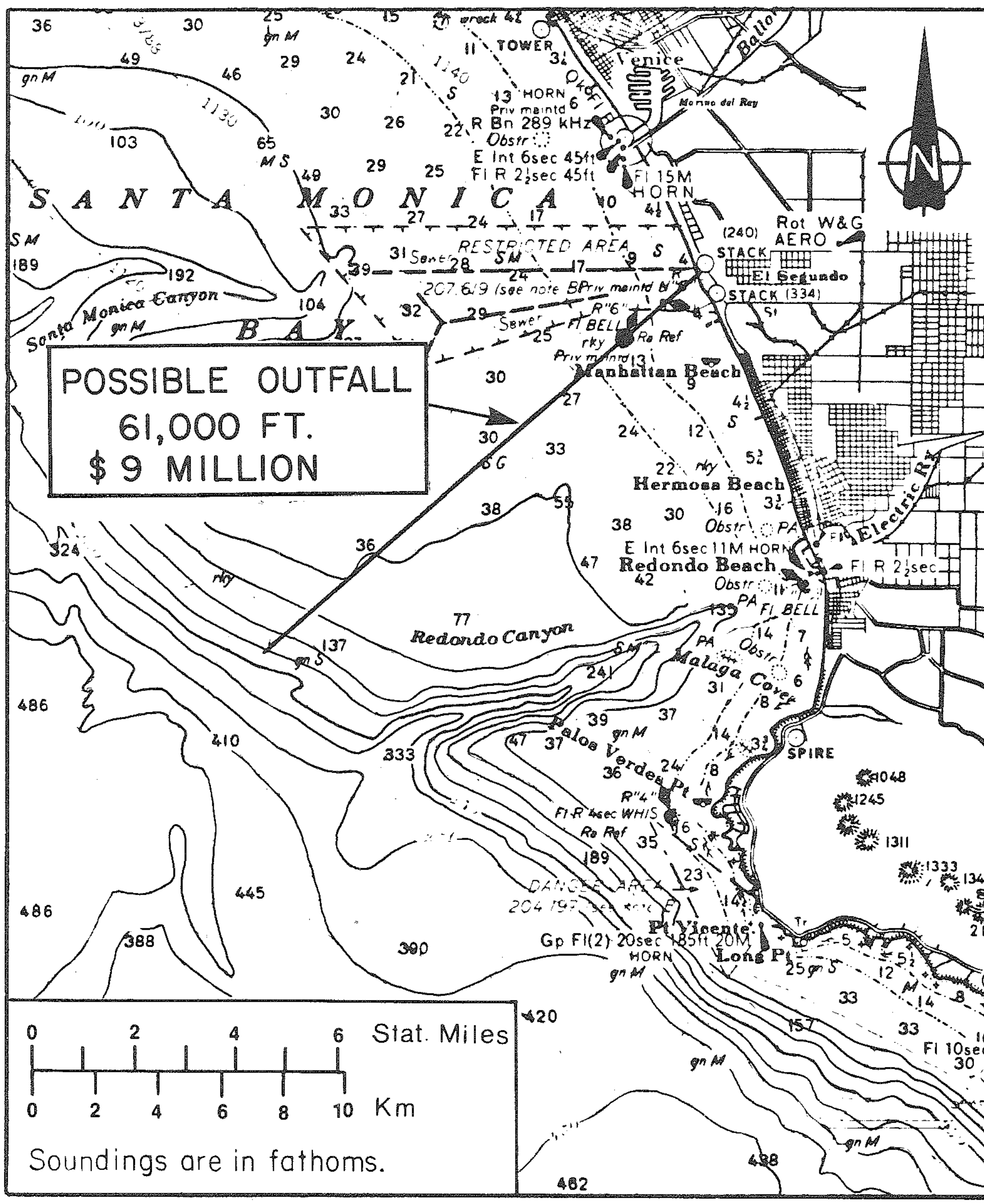


Figure IX-1 Candidate alignment of possible sludge outfall for City of Los Angeles (Hyperion) (after U.S. Coast and Geodetic Survey Chart No. 5101).

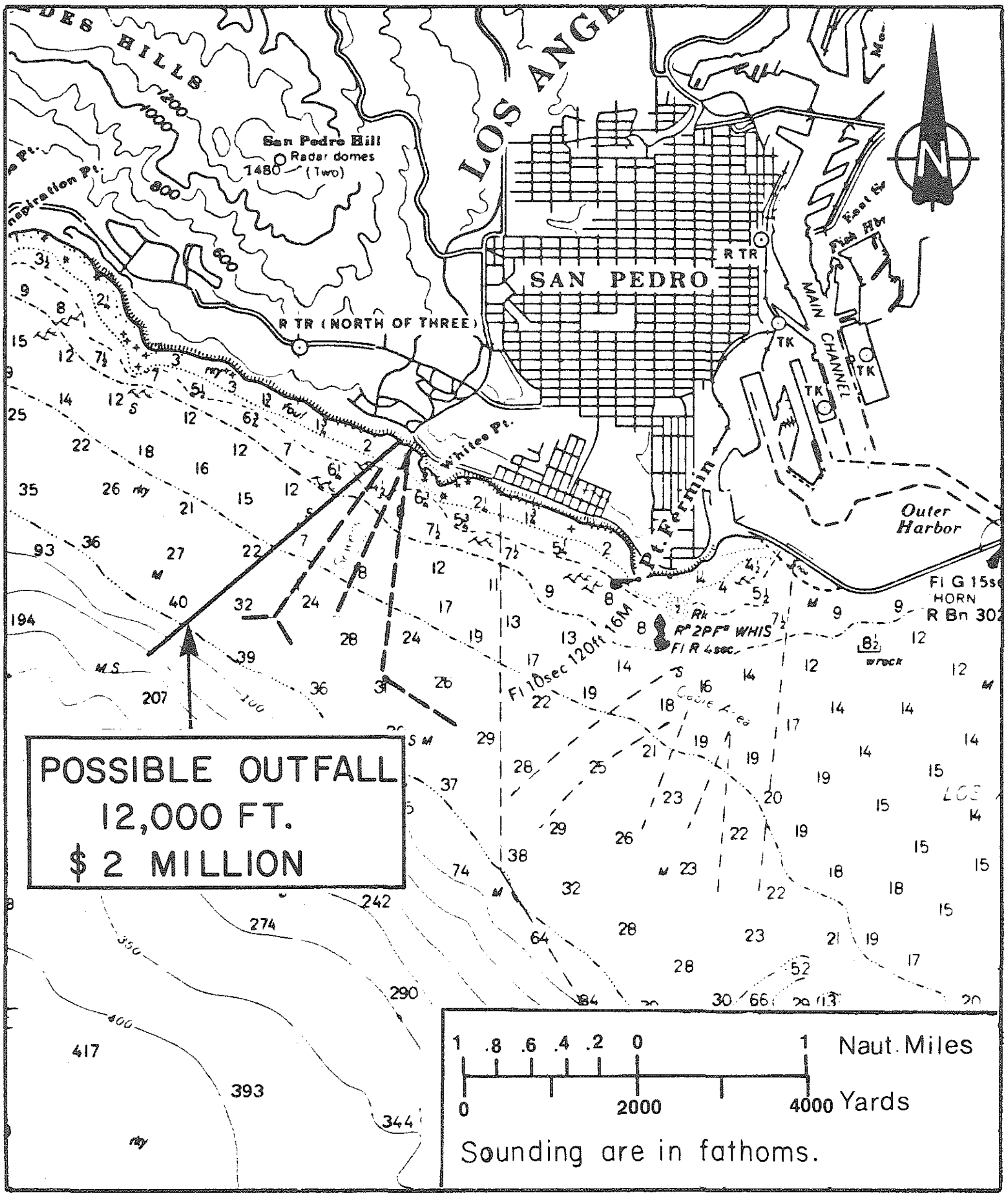


Figure IX-2 Candidate alignment of possible sludge outfall for Los Angeles County Sanitation District (Whites Point) (after U.S. Coast and Geodetic Survey Chart No. 5142).

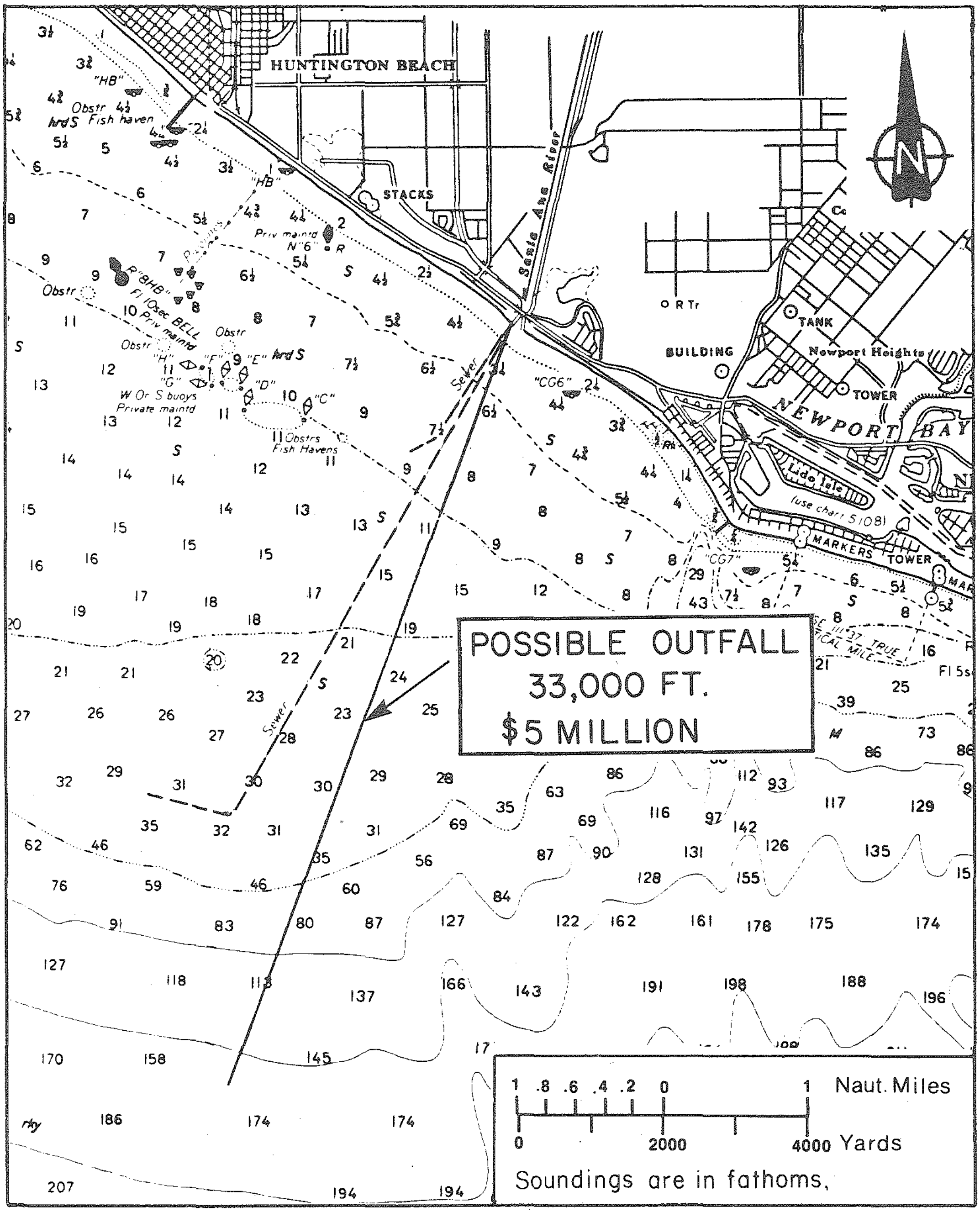


Figure IX-3 Candidate alignment of possible sludge outfall for County Sanitation District of Orange County (after U.S. Coast and Geodetic Survey Chart No. 5142).

TABLE IX-3

Estimated Lengths and Costs for Possible Sludge Outfalls
(Marine Portions Only)

Agency	Length From Shore to 300 m Depth		Estimated Construction Cost ($ Millions, 1979)	
	miles	feet		(with 100% contingency factor)
City of L.A. (Hyperion)	11.5	61,000	9	18
LACSD (Whites Point)	2.3	12,000	2	4
OCSD (off Santa Ana River outlet)	6.3	33,000	5	10
TOTAL	20.1	106,000	16	32

The capital costs given in the table are very reasonable compared with all other options studied by LA/OMA. The operating cost for sludge outfalls consists mainly of pumping, as no additional pretreatment of sludge (such as thickening) is needed. Screening may be necessary to trap any possible oversize solids as is now done at the Hyperion Treatment Plant (City of Los Angeles). Outfall maintenance would also be very small, because scouring velocities will be used.

In summary, the total costs of construction, operation, and maintenance of sludge outfalls are far less than the other options studied by LA/OMA. It would be worthwhile to pursue further field research to resolve the environmental questions enumerated in Chapter X; quite possibly it would be feasible to construct one of the shorter outfalls and use it on a trial basis in conjunction with intensive field observations of the ultimate dispersal of the digested sludge and its biological effects.

X. RECOMMENDATIONS FOR FURTHER STUDY

1. Current and hydrographic data should be collected for at least one year to determine flow patterns and mixing rates within the Santa Monica-San Pedro Basin, to determine exchange rates with Santa Cruz Basin to the north and San Diego Trough to the south and to determine the exchange rate between the Southern California Bight and the open ocean.
2. More information on physical and chemical properties of sludge should be determined. Physical properties include particle settling velocities and effect of coagulation processes on them; chemical properties include sludge BOD and the degradation rates, trace metal release rates, and interplay between oxygen and nitrate consumption rates.
3. Interactions between sludge particulates and mid-water animals should be studied. This should be done at particulate concentrations expected in the basin to test the effect of high particulate carbon and particulate trace metal concentrations. Additional experiments should be performed to test whether sludge would degrade chemosensory functions of mid-water organisms.
4. Distributions and abundances of basin organisms should be determined to provide baseline information on present populations.
5. More detailed modeling of sludge plumes should be attempted using new current data to determine the validity of the horizontally well-mixed model developed here.

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APPENDIX 1
CHEMICAL REACTIONS

I. INTRODUCTION

Introduction of sludge into seawater initiates a series of biologically-mediated reactions as the various oxidants in seawater are reduced by the sludge and subsequently re-oxidized in the water around them. Thermodynamic considerations predict the energetics of the various electron transfer reactions but kinetic and stoichiometric considerations determine their relative importance. Thus, in a closed aqueous system containing organic matter, its oxidation proceeds with reduction of O_2, then of NO_3^-, followed by that of NO_2^-. These will be followed by the reduction of MnO_2, FeOOH and eventually of SO_4^{2-} (Stumm and Morgan 1970). Concentrations of maganese and iron in oceanic waters are approximately 4×10^{-8}M and 2×10^{-7} M, respectively, small compared to oxygen (5 - 30 μM in the basins), nitrate (30 μM), and sulfate (0.028 M). For this reason, metal reduction reactions have been neglected in this study.

Thermodynamically most favored reactions are not always the important ones. Nitrate reduction is energetically less favorable than oxygen reduction until oxygen concentration reaches 10^{-12} M, but nitrate reduction has been reported when oxygen concentrations reach 5×10^{-6} M. An obvious interpretation is that the supply rate to an organism becomes more important than the absolute concentration to an oxidant. Thermodynamic information, then, will be used to determine the ordering of different reduction reactions but must be used in conjuntion with rate data to predict the effect of sludge disposal in oceanic basins. This appendix surveys the available relevant data.

Biochemical oxygen demand (BOD) of a waste water will depend on the source and history of the sample. BOD measurements are usually conducted over a 5-day period using bacteria cultured under conditions to maximize organic matter utilization. Organics are broken down at a rate that follows first order kinetics, where rate of reaction is proportional to amount of substance left. Organic matter unreacted after 5 days is about 33% of what would be consumed after very long times (Sawyer and McCarty, 1978). This, total BOD is the relevant parameter for oxygen demand in ocean disposal. Thus the BOD of interest is 50% greater than the 5-day BOD commonly measured.

Sludge particulates are hodge podge collections that have been removed from various streams in a waste water treatment plant. Much of the carbon will be nonreactive compounds such as cellulose. Myers (1974) found that between 60 and 75 percent of organic carbon in a mixture of primary and secondary effluent from Hyperion treatment plants were refractory in sea water. Fraction of reactive carbon should be lower for particles from a digester than for particles from a primary or advanced primary stream. Refractory material in sludge may or may not have an ecological impact, but the oxygen consumption of reactive material is clearly ecologically important. We have emphasized the fate of the reactive fraction of sludge in this study.

To estimate the BOD of sludge to be discharged into marine basins, we have had to develop a relationship between it and the expected discharge rate for suspended solids. The 5-day BOD of a mixture of primary and secondary sludge discharged through the 7 mile line at Hyperion is 1.9g ℓ^{-1}; its suspended solids content is 7.3g ℓ^{-1} (SCCWRP, 1975). This is equivalent to $8.1\text{x}10^3$ moles 5-day BOD/ton of suspended solids, or $1.2\text{x}10^4$ moles total BOD/ton suspended solids. The mixture discharged at the Joint Water Pollution Control Plant has a 5-day BOD of 213 mg/ℓ, a suspended solids content of 276 mg ℓ^{-1}, which implies a relation of $3.6\text{x}10^4$ moles total BOD/ton suspended solids. We assumed a value of $2\text{x}10^4$ moles BOD/ton when calculating BOD sludge discharged to marine basins.

II. REDUCTION REACTIONS

II-A. AEROBIC SLUDGE STABILIZATION

Myers (1974) established upper and lower limits for the decomposition rate of particles in mixed primary and secondary effluent from the Hyperion treatment plant. The ratio of particulate organic carbon concentration at a given time (t), to the initial concentration is given by f(t). Values of f(t) were fit to the equation:

$$f(t) = f_R + (1-f_R)\, e^{-kt} \qquad (1\text{-}1)$$

where f_R is the fraction of refractory organic carbon and k is a first order rate constant. The parameters in Table 1-1 provide upper and lower limits for the first order rate constant and the fraction of organic carbon refractory under aerobic conditions at 17°C. Values of k range from 0.05 to 0.22 day^{-1}.

TABLE 1-1

Upper and Lower Limits for Parameters of Equation (1) at 17°C

Decay Limit	Approximate F* Initial Rate	Approximate f_R	Estimated k
Upper	0.088 day^{-1}	0.60	0.22 day^{-1}
Lower	0.013 day^{-1}	0.75	0.05 day^{-1}

Muellenhof (1977) observed stabilization rates of anaerobically digested sludge under both aerobic and anaerobic processes in seawater at different hydrostatic pressures. The parameters f_R and k, derived from fitting the data to Eq. 1-1, are shown in Table 1-2. Statistical analysis of values for f_R and k shows that there is a significant difference between their values under aerobic and anaerobic conditions but there is no significant difference between their values at one and at 34 atmospheres.

Muellenhof's (1977) value for the fraction of organic carbon that is not biodegradable, approximately 70%, falls within the range established by Myers (1974) for effluent particulates, and his value for the rate constant is slightly below Myers's lower limit of .05 per day.

*From Myers (1974)

$$F = \text{Initial rate } \left.\frac{d[f(t)]}{dt}\right|_{t=0} = -k(1-f_R)$$

TABLE 1-2

Rate Constants and Fraction of Non-biodegradable Organic Carbon for Muellenhof's Decomposition Experiments

Experimental* Conditions	k (days^{-1})	f_R	Duration of Experiment (days)
Aerobic			
1 atmosphere	0.042	0.689	20
34 atmosphere	0.042	0.699	20
34 atmosphere	0.036	0.692	170
Anaerobic			
1 atmosphere	0.020	0.899	20
34 atmosphere	0.022	0.907	20
34 atmosphere	0.015	0.917	130

*All experiments were run at a temperature of 23°C. From Muellenhof (1977).

Thus, the results of these two authors show satisfactory agreement considering the difference in their experimental conditions and material (effluent particles versus anaerobically digested sludge).

These carbon consumption rates can be compared with oxygen consumption of digested sludge measured by Muellenhof (1974). The laboratory measurements were made on a 2 centimeter thick sludge bed in a tank in which sea water was circulated and in which a dissolved oxygen sensor continuously monitored oxygen concentration. The in situ measurements were made on a twelve meter by sixty meter sludge bed, which ranged from 0 to 1 centimeters thick, and was found at a depth of 15 meters. The ambient temperature of the sea water was 23°C over the several day duration of the measurements. The oxygen uptake measurements were made using two acrylic hemispherical domes, each equipped with a dissolved oxygen sensor and a stirrer. The results of these measurements are reported in Table 1-3. and they are compared with sludge stabilization rates using the expression of Muellenhof (1977) in Table 1-4. Lack of information on system geometry precluded calculations of initial oxygen uptake rates for laboratory experiments.

TABLE 1-3

Oxygen Uptake Rates for Digested Sludge
(from Muellenhof 1974)

	Sludge Description	Initial Rate ($g - O_2/m^2/day$)	Rate at a Later Time ($g - O_2/m^2/day$)
Laboratory Measurement	Corvallis Wastewater Treatment Plant (Oxygen)	2.72	0.98 at t = 53 days
Laboratory Measurement	Nassau County Sewage Treatment Plant Fast Rackway, N.Y.	0.72	0.55 at t = 20 days
In Situ Measurements	Anaerobically digested sludge	2.51	1.68 at t = 2.9 days (70 hrs)
In Situ Measurements	Aerobically digested sludge	3.74	2.0 at t = 2.7 days (65 hrs)

The agreement between measured and calculated oxygen utilization rates indicates that Muellenhof's (1977) rate constant can be used to obtain an estimate of the rate of oxygen uptake by digested sludge.

TABLE 1-4

Comparison of oxygen utilization rates as measured by Muellenhoff (1974) with sludge stabilization rates calculated from the expression of organic matter concentration versus time reported in Muellenhof (1977).

Source of Sludge	Initial Oxygen(1) Utilization Rate	Initial Sludge(2) Stabilization Rate	$\frac{\text{Rate at time} = t}{\text{Rate at time} = 0}$ (3) Measured	Calculated
Anaerobically digested sludge: In situ Measurement	0.025 mole-O_2/day	0.03 mole-C/day	Ratio = 0.67 (at t = 3 days)	Ratio = 0.89
Corvallis Treatment Plant Oregon	-	-	Ratio = 0.36 (at t = 53 days)	Ratio = 0.12
Nassau Co. Treatment Plant	-	-	Ratio = 0.76 (at t = 20 days)	Ratio = 0.45

(1) The measured initial oxygen utilization rate = 2.5 g-O_2/m^3/day. One hemisphere was 76 cm in diameter and the other was 50 cm in diameter. Area covered by 76 cm diameter hemisphere = 0.45 m^2; Area covered by 50 cm diameter hemisphere = 0.20 m^2. Taking 0.3m^2 as an intermediate value, O_2 utilization rate/hemisphere = $(2.5\text{g-}O_2/m^2/\text{day})\ (0.3m^2)\ (\frac{1\ \text{mole}\ O_2}{32\ \text{g-}O_2})$.

(2) The calculated initial sludge stabilization rate [denoted R(t=0)]: $R(t=0)=kC_0=(0.04\text{day}^{-1})(0.3)(10\ \frac{\text{g-C}}{\ell}) = 0.2\text{g-C}/\ell\text{day}$; where 10 $\frac{\text{g-C}}{\ell}$ is the initial concentration of organic carbon, 0.3 of which is biodegradable. Assuming a 1 cm thick sludge bed, the volume of

sludge per hemisphere is about (1 cm) $(.3m^2)(10^4 \frac{cm^3}{m^2})(10^{-3} \frac{\ell}{cm^3}) \approx 3\ell$.
Thus the $R(t=0) = (0.12\text{g-C/ day})(3\ell) = 0.36\text{g-C/day}$ or 0.03moleC/day.

(3) $R(t=0) = -kC_0$, and the rate at a time, t, denoted R(t) is:

$R(t) = kC_0\, e^{-kt}$. Thus $\frac{R(t)}{R(t=0)} = \frac{kC_o\, e^{-kt}}{kC_0} = e^{-kt}$.

II-B. ANAEROBIC SLUDGE STABILIZATION AND SULFATE REDUCTION

Muellenhof's (1977) experimental design for the measurement of the first order rate constant for the process of sludge stabilization and sulfide production under anaerobic conditions are described in Section II-A and his results are reported in Table 2-2. The values for the fraction of organic carbon that is not biodegradable are only approximate because of the relatively short 20 day reaction time; a 130 day experiment established that the fraction is probably close to 0.9. Maximum total dissolved sulfide concentration observed was 16 mM (Muellenhof 1977). The rate constant for anaerobic stabilization of digested sludge is about one-half of the aerobically-obtained rate constant at the same temperature (23°C). The sulfide production rate can be obtained by assuming a stoichiometry for the oxidation of sludge by dissolved sulfate which, as will be discussed below, is probably close to 2 moles of carbon consumed per mole of sulfide produced.

Berner (1974) has discussed the oxidation of organic matter with concomitant sulfide production in anoxic sediments. He modeled the depth distribution of dissolved sulfate using the processes of diffusion, advection and sulfate reduction. The rate of sulfate utilization was assumed proportional to the concentration of organic matter usable by sulfate reducing bacteria, (defined as G_s):

$$\frac{-d[SO_4^{=}]}{dt} = k_s G_s$$

where k_s is a rate constant (note that this expression is similar to those used by Myers, 1974, and Muellenhof, 1977). Values for k_s and G_s estimated by Berner (1974) for three cores are presented in Table 1-5. Values for the rate constant are at least an order of magnitude lower than that measured by Muellenhof (1977). This could be due to, among other factors, differences in the nature of anaerobically digested sewage sludge and the organic matter deposited in sediments derived from natural marine sources, especially with respect to nutrient content. One might expect the higher nutrient content of digested sludge to support a larger population of bacteria than sedimented organic matter, which has undergone degradation in the water column.

II-C. THE EFFECT OF TEMPERATURE ON SLUDGE STABILIZATION RATES

Myers (1974) measured the rate of decomposition of effluent particles in sea water at three temperatures: 35°C, 17°C, and 2°C. The rate constant at 17°C was 0.12 per day, and at 2°C was 0.012 per day. Thus, based on one experimental run for each temperature, a drop in temperature of 15 degrees decreases the rate constant by an order of magnitude. This is a much larger temperature effect than one would expect from a typical biological Q_{10} value of 2, (Lehninger, 1970). For such a Q_{10} the rate should decrease by no more than a factor of three or four for the same drop in temperature. Clearly, Myers (1974) experiment was designed to obtain a semi-quantitative idea of the temperature effect. A more reasonable estimate would be that rates at 23°C are a factor of four or five times greater than the rates at 8°C.

TABLE 1-5

Values for the rate constant and biodegradable organic matter concentration applicable to sulfate reduction from three marine sediment cores (Berner, 1974)

CORE LOCATION	k_s (day^{-1})	G_s
Santa Barbara Basin	6.5×10^{-6}	2.5×10^{-1} mole-C/ℓ
Somes Sound, Maine	4.8×10^{-4}	1.8×10^{-1} mole-C/ℓ (0.8% by weight)
Long Island Sound, Conn.	1.6×10^{-4}	1.3×10^{-1} mole-C/ℓ (.62% by weight)

II-D. REDUCTION OF NITRATE

With the depletion of oxygen, nitrate becomes the dominant oxidizing agent. There is extensive evidence for denitrification in low-oxygen-containing oceanic areas. Fiadeiro and Strickland (1968) suggested that denitrification becomes important when oxygen concentrations are lower than 0.2 ml/ℓ (9 μM). Work by Goering and Cline (1970) suggests that the crucial value is closer to 0.1 ml/ℓ (4.5 μM). The oxygen concentration range of 0.1 - 0.2 ml/ℓ is also the range where midwater crustacean respiration rates start to show a dependence on oxygen concentration (Childress, 1975).

Mass balance calculations discussed in Appendix 2 show that in lower Santa Barbara Basin and lower Santa Monica-San Pedro Basins, nitrate is as important an oxidizer as oxygen, if not more important. Dissolved oxygen concentrations in these regions are 0.1 ml/ℓ (4.5 μM) or less.

II-E. CONCLUSION

Oxidation rates of sludge organic matter will depend on concentrations of organic matter, oxygen, nitrate and sulfate. Because our calculations show that oxygen in the water column could be depleted upon sludge discharge but nitrate would not, we have not considered sulfate as one of the important sludge oxidizers.

We used a rate expression similar to that used to describe competition for an enzyme by two substrates (Neame and Richards, 1972). This is an extension of the Michaelis-Menton equation to two different substances. Such an expression is a more accurate representation than is one where oxygen and nitrate have to have the same pε before nitrate uptake switches on. It is also computationally simpler. The exact expression used and values chosen for constants are in Section III of Appendix 2.

III. THE OXIDATION OF AQUEOUS AMMONIA*

Muellenhof (1977) reports that the range in the ammonia concentration for digested sludge from Bay Park Water Pollution control plant is from 550 to 850 milligrams per liter, and SCCWRP (1975) reports that, for the effluent-sludge mixture discharged from the seven mile pipe from LACSD, the aqueous ammonia concentration is about 300 milligrams per liter. This constitutes a chemical oxygen demand of 1400 milligrams per liter. This constitues a chemical oxygen demand of 1400 milligrams per liter. Nitrifying bacteria, (chemoautotrophs), isolated from the marine environment have been shown to oxidize ammonia at very low concentrations of dissolved oxygen, (Gunderson, 1966).

Carlucci and Strickland (1968) studied the effect of temperature and substrate concentration on the growth constant of bacteria that they had collected from the North Pacific. None of the cultures isolated oxidized ammonia at 5°C over the three month duration of their experiments. On the other hand, they point out that some of the isolates had been collected from waters whose late summer temperature is as low as 9°C, and that a culture isolated from sub-arctic waters oxidized ammonia "very readily" at 12°C after a fifty day lag period. Thus, while quantitative data is lacking on the rate of oxidation of aqueous ammonia at low temperatures and low oxygen concentrations, it is

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*Aqueous ammonia as used here refers to ammonium ion as well as to dissolved ammonia.

probably much slower than that of digested sludge so that the effect of ammonia oxidation on the oxygen concentration is probably small.

IV. THE OXIDATION OF AQUEOUS SULFIDE BY DISSOLVED OXYGEN

Oxidation of aqueous sulfide by oxygen in sea water is a complex process with an as yet unknown mechanism. Chen and Morris (1972a,b) studied the effect of pH, initial sulfide concentration and initial oxygen concentration on the reaction rate at low ionic strength. Cline and Richards (1969) studied the reaction kinetics in sea water. In addition, workers at Woods Hole have investigated the effect of bacteria on the sulfur cycle in the ocean. The investigations of the kinetics of the reaction of aqueous sulfide with dissolved oxygen will be discussed in Section IV-A and biological aspects will be discussed in Section IV-B.

IV-A. THE KINETICS OF THE REACTION OF DISSOLVED OXYGEN WITH AQUEOUS SULFIDE

Chen and Morris (1972a) and Cline and Richards (1969) noted that sulfide oxidation kinetics are complex with an induction period of from .5 to 5 hours. Table 1-6 shows that there are several conceivable products of the reaction, ranging in oxidation state from zero (elemental sulfur) to plus six (sulfate ion).

TABLE 1-6

Possible Pathways for the Reaction of Aqueous Sulfide and Dissolved Oxygen

aHS^-	+	$b\ O_2$	=	products	$Rc \equiv \frac{a}{2b}$
HS^-	+	$2O_2$	=	$SO_4^= + H^+$	0.25
$2HS^-$	+	$3O_2$	=	$2SO_3^= + 2H^+$	0.33
$2HS^-$	+	$2O_2$	=	$S_2O_3^= + H_2O$	0.5
$2HS^-$	+	O_2	=	$S° + 2OH^-$	1.0

(continued on next page)

TABLE 1-6
(continued)

$S°$	+	SO_3^{2-}	=	$S_2O_3^{=}$	
HS^-	+	$SO_3^{=} + 1/2\ O_2$	=	$S_2O_3^{=} + OH^-$	
H_2O	+	$S_2O_3^{=}$	=	$SO_4^{=} + S° + 2H^+$	
HS^-	+	$S°$	=	$S_2^{=} + H^+$	Polysulfide formation
$S_2^{=}$	+	$S°$	=	$S_3^{=}$ etc.	

$nHS^- + \left(\frac{n+5}{2}\right)O_2 + (n-2)\ H^+ = S_nO_6^{2-} + (n-1)H_2O$ generalized reaction for polythionate formation.

In their kinetic studies of the reaction of 25°C, Chen and Morris (1972a) varied the initial sulfide concentration from 50 to 200 μM, the initial oxygen concentration from 160 to 800 μM, and the pH from 6 to 13. They followed the oxygen concentration, the sulfide concentration (both spectrophotometrically and colorimetically), and occasionally determined elemental sulfur, thiosulfate, sulfite, polysulfides and polythionates in the reacted mixture. They expressed their results in terms of the following rate law:

$$-\frac{d[S_T^{2-}]}{dt} = k[S_T^{2-}]^{1.34}\ [O_2]^{0.56}$$

where k is a rate constant and has units of $M^{-0.9}$ $hour^{-1}$. This rate law describes the course of the reaction directly following the induction period. The rate constant is strongly dependent on pH and weakly dependent on the initial concentrations of dissolved oxygen and total sulfide.

The rate constant, k, has maxima at pH's of 8 ($k = 22\ M^{-0.9}\ hour^{-1}$) and 11, minima at pH's of 6 (k=0) and 9 ($k=6M^{-0.9}hour^{-1}$). At a pH of 7, k is about 5 $M^{-0.9}$ $hour^{-1}$. Thus, changes in pH from 8 to either 7 or 9 decrease the rate by a factor of four to five (Chen and Morris, 1972a). The pH affects duration of the induction period and product distribution as well as the rate constant. The induction period is 0.5 hours at pH's of 8 and 11, 6 hours at a pH of 7, and 2 hours at a pH of 9. Thus, the lag time is smallest at the pH values where the rate constant is largest. Maximum amounts of polysulfides are formed at a pH of 8. At pH values above 8.5, thiosulfate is the major product. At neutral and acid pH's the major product is polysulfide when oxygen is in excess, elemental sulfur when it is not (Chen and Morris, 1972a).

Cline and Richards (1969) expressed the results of their sea water experiments in terms of the rate law

$$-\frac{d[O_2]}{dt} = k'[O_2][S_T^{=}],$$

where k' is the apparent rate constant, 1.5×10^{-3} μM^{-1} $hour^{-1}$. The rate constant of Chen and Morris (1972a) for approximately the same conditions is about 20 $M^{-0.9}$ $hour^{-1}$ or 2.0×10^{-5} μM^{-1} $hour^{-1}$. This discrepancy will be discussed in the last section. Cline and Richards also reported an induction period of about one hour.

The product distribution in the presence of an excess of dissolved oxygen indicated that thiosulfate was the major product under their conditions. They stated that at a low concentrations of oxygen, (below 2 or 3 μM), the products tend toward lower oxidation states, but they could not detect elemental sulfur and did not analyze for polysulfides.

Cline and Richards (1969) calculated that the reaction rate should halve for a ten degree drop in temperature by using the Arrhenius activation energy equation. They noted that this agreed with the data of Avrahami and Golding (1968), whose work was done under substantially different experimental conditions (i.e., pH's of 11 to 13, temperatures from 25 to 55°C, and total sulfide and dissolved oxygen concentrations of from 100 to 1000 μM as contrasted to pH's between 7.5 and 7.8, oxygen concentrations of 30 to 240 μM and a temperature of 10°C).

Divalent transition metal ions, (Mn(II), Co(II), Ni(II), Cu(II)) and the alkali earth metals (Ca(II) and Mg(II))increased the rate of the reaction by as much as two orders of magnitude, depending on their concentration and the pH (Chen and Morris, 1972b). Cline and Richards (1969) found that the 5 μM Fe(II) increased the rate slightly under their experimental conditions, (which include an ionic strength of about 0.7). Chen and Morris (1972b) found that Ni(II) had the most pronounced effect, increasing the rate by a factor of ten at a concentration of 10 μM and a pH of 8.65. Mg and Ca at concentrations of 1 mM increased the reaction rate by a factor of five for a pH of 8.6. Both investigations found that the presence of certain organic compounds inhibited the reaction, but only rarely did the presence of an organic compound decrease the rate by more than a factor of two. The most pronounced inhibitory effect was observed with cyanide ion, which decreased the reaction rate by a factor of ten when present at concentrations above 20 mM. The results of these catalysts and inhibition studies indicate that, while metal ions can significantly increase the rate when present at low concentrations, nothing significantly decreases the rate unless present at relatively high concentrations.

IV-B. THE ROLE OF BACTERIA IN THE OXIDATION OF AQUEOUS SULFIDE

Bacteria capable of oxidizing aqueous sulfide, elemental sulfur, and aqueous thiosulfate are present in the open ocean, in coastal waters, in the waters of anoxic basins, and in anoxic sediments, (Tuttle and Jannasch 1972, 1973, 1976).

Tuttle and Jannasch (1972) tested marine bacteria isolates for the ability to oxidize sulfide and thiosulfate. Most strains grew more efficiently on a sulfide substrate than a thiosulfate substrate (only 19% of the isolates oxidized more than 5% of the thiosulfate in the medium and only one strain was able to attack elemental sulfur). Half of the isolates were found to be similar to T. *trautweinii*, and the authors point out that the inclusion of this strain in the thiobacillus species has been "justifiably disputed." This facultative autotrophic species, along with certain other strictly heterotrophic bacteria, oxidizes thiosulfate to polythionates. Whether this metabolic pathway can provide sufficient energy to support autotrophic growth is not certain. However, the authors point out that sufficient energy might be available if high concentrations of thiosulfate are present. The isolates similar to T. *trautweinii* were able to grow in an inorganic medium, which suggests that they are capable of chemotrophic growth.

None of the isolates found by Tuttle and Jannasch (1972) were obligative autotrophes. Several strains oxidized more thiosulfate in the presence of organic substrate than in its absence. The authors found acidophillic thiobacilli only in near shore environments. They concluded by saying that the fact that 30% of their strains grew on sulfide indicates that participation in the process of oxidation of aqueous sulfide to sulfur by organisms could be significant in sulfide turnover in the marine environment. Whether bacterial oxidation of sulfide can compete with chemical oxidation under aerobic conditions is a key question.

Tuttle and Jannasch (1976) measured thiosulfate utilization rates of bacterial isolates under conditions of low temperature and both low and high pressure. They had one strain with an average rate of thiosulfate utilization at 2°C and 5300 meters depth of 1.3 μM day^{-1}. The thiosulfate utilization rate near the sea surface was 266-300 micromolar per day for 22 day experiments with sea water and sea water plus 10 mM potassium nitrate as media. Based on the known metabolic pathways of the axenic cultures used, the authors concluded that tetrathionate must have been the product of the oxidation of thiosulfate.

IV-C. DISCUSSION AND CONCLUSION

Rates of aqueous sulfide oxidation by dissolved oxygen as calculated from the expressions of Cline and Richards (1969) and Chen and Morris (1972a) are compared in Table 1-7 for various concentrations of dissolved oxygen and total sulfide. Also compared are the rates as calculated with the expression of Chen and Morris (1972a) and those calculated with the same rate constant but assuming that the reaction is first order with respect to the concentrations of the reactants (recall that Chen and Morris (1972a) found the reaction to be of an order 1.34 for total sulfide and 0.56 for oxygen). The rates calculated assuming the reaction to be first order with respect to both reactants are smaller than the rates calculated using the orders determined by Chen and Morris (1972a). At very low oxygen concentrations, there is a factor of six difference in the rates, but as the oxygen concentration increases, the rates approach each other.

TABLE 1-7

Comparison of Calculated Sulfide Oxidation Rates
(Initial Reaction Rates)

Initial Reaction Concentration (μM)		Chen and Morris' Rate Law		Cline & Richards Rate Law	
		using their orders(1)	assuming second order overall(2)	@10°C(3)	@25°C(4)
$[O_2]$	$[\Sigma S^=]$				
10	65	0.066	0.011	1.0	2.7
75	65	0.20	0.083	7.3	20.3
250	65	0.40	0.28	24.4	67.5
160	100	0.65	0.32	24	66
50	300	1.5	0.30	22.5	62
300	300	4.1	1.8	135	374
600	300	6.0	3.6	270	728

Calculations:

(1) Rate = $K[O_2]^{.56}\ [\Sigma S^=]^{1.34}$ where $K \simeq 20/M^{0.9}$ -hr @ pH $\simeq$ 8 and 25°C. $[O_2]$ and $[\Sigma S^=]$ expressed in Molar units.

(2) Rate = $K[O_2]\ [\Sigma S^=]$ where $K = 20/M^{0.9}$ -hr, as above, but the rate is assumed to be first order with respect to both reactants.

(3) Rate = $K^1[O_2]\ [\Sigma S^=]$ where $K^1 = 1.5 \times 10^{-3}/\mu M$ -hr @ pH $\simeq$ 7.5 to 7.8, T = 9.8°C.

(4) Calculated by assuming a factor of two increase in the rate per 10 degree rise in temperature.

Rates calculated using the expression of Cline and Richards (1969) are two orders of magnitude greater than those calculated using the expression of Chen and Morris (1972a). Cline and Richards (1969) performed their experiments in sea water, which contains, among other metal ions, approximately 50 mM magnesium and 10 mM calcium. The sea water no doubt contains trace quantities of the divalent transition metal ions which Chen and Morris (1972b) showed can greatly increase the rate of reaction even when present in micromolar concentrations. The expression of Chen and Morris (1972b) showed can greatly increase the rate of reaction even when present in micromolar concentrations. The expression of Chen and Morris (1972a) yields a lower limit to the rate. Sorokin (1970) estimated sulfide oxidation rate at the interface of oxic and anoxic waters in the Black Sea to be 0.13 μM/hr, a value that agrees well with rates calculated using Chen and Morris' expression.

Bacteria increase the rate of sulfide oxidation. However, Sorokin (1970) suggests that oxidation of aqueous sulfide in the Black Sea proceeds chemically, but that bacteria are probably important in converting the products of chemical oxidation (e.g., sulfur, thiosulfate, etc.) into sulfate.

There is evidence that the major product of chemical sulfide oxidation in sea water is elemental sulfur and/or polysulfides. Cline and Richards (1969) suspected that elemental sulfur was the major product in their experiments. Chen and Morris (1972b) found that the major product in the presence of many of the metal ions that catalyzed the reaction was elemental sulfur. Nelson et al. (1977) found that, for the oxidation of solid ferrous sulfide in sea water by dissolved oxygen, the major product was elemental sulfur. A suite of products was observed in media with lower ionic strengths.

V. PARTICULATE METAL DISSOLUTION RATES

Rohatgi and Chen (1975) measured metal release rates from digested sludge after the sludge had been mixed with sea water, in ratios ranging from 50:1 to 200:1. Their results, recalculated in terms of first-order reaction constants are similar to the sludge oxidation rate of 0.01 d^{-1} used in this study. Cadmium release was faster, at about 0.09 d^{-1}, chromium slower at about 0.003 d^{-1}. They detected no release of iron.

We have assumed in this study that trace metal release rates are the same as sludge oxidation rates for simplicity.

TABLE 1-8

Dissolution Rates, d^{-1}, for Trace Metals*

Metal	50:1 Dilution	100:1 Dilution	200:1 Dilution
Cd	0.076	0.086	0.09
Cu	0.0015	0.0016	0.0027
Cr	0.00058	0.0006	0.0011
Mn	0.011	0.012	0.012
Ni	0.019	0.025	0.029
Pb	0.014	0.012	0.013
Zn	0.0057	0.008	0.025

*Rates were calculated for assumed exponential decrease of particulates using data collected by Rohatgi and Chen (1975). They measured trace metals released from particles in digested Hyperion sludge after five weeks. Sludge was diluted 50:1, 100:1, and 200:1 with filtered sea water.

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APPENDIX 2

EXCHANGE PROCESSES AND ONE-DIMENSIONAL MODELING FOR OFFSHORE BASINS

I. INTRODUCTION

Exchange of sea water from the Southern California Bight with open oceanic waters is limited by the vertical water density structure and by the benthic topography. The alternation of mountains and valleys that dominate Southern California landscape continues for up to 40 km to sea. These mountain ranges isolate waters in the valleys from each other. With horizontal movements limited by valley walls and vertical movement controlled by density stratification, each water mass develops its own characteristics which separates it from the open ocean. Just as the blockage of winds by the mountains ringing the Los Angeles Basin has caused a smog problem, so have the offshore mountains caused the accumulation of low-oxygen conditions in bottom waters.

The extent to which water at a given location is isolated from the open ocean varies considerably. Surface waters can move through the bight with flow interrupted only by the mainland or the offshore islands. Barriers to water movements increase with depth, cutting off communication between Santa Barbara and Santa Monica Basins around 250 m depth, between Santa Cruz Basin and the open ocean at 350 m (Figure II-4). Valley waters at these intermediate depths are trapped in dead end canyons, exchanging horizontally through slow turbulent processes with waters outside. Deeper, in what have been called basins, surrounding valley walls cut off waters from all horizontal communication with the open ocean.

Oxygen is a substance whose concentration is changed by biological processes. Near the surface, dissolved oxygen concentration (DO) is kept at approximately 0.25 moles m^{-3} (5.6 liters m^{-3}) by contact with the atmosphere. Oxygen in deeper waters is depleted by the oxidation of organic matter. Higher oxygen consumption rates in coastal waters leads to depletion of oxygen in valley waters relative to open oceanic waters (Figure II-3). Resulting concentrations are determined by rates of oxygen consumption relative to rates of resupply. (Oxygen concentrations are expressed in a diversity of units that matches the diversity of fields in which it is studied. Their values are 1 mole m^{-3} = 1 mM = 22.4 liters m^{-3} = 22.4 ml $liter^{-1}$ = 32 mg $liter^{-1}$.)

Currents in the surface region of the Southern California Bight are complex, involving the California Current, the Southern California Countercurrent and wind stresses (Jones, 1971). Residence time for surface water in the bight is about three months. The rapid turnover and high oxygen concentrations of these surface waters protect them from major changes induced by sludge disposal.

Bottom water sources have been studied by following water tracers (Emery, 1960). Exchange in these basins is controlled by water at the depth of the lowest gap in the surrounding valley wall. Over this gap, called the sill, flows a variable amount of denser water which sinks to the bottom, bringing more oxygen (Sholkovitz and Gieskes, 1971). This flow can come in a torrent, displacing all the old basin water, or it can come in a relatively continuous trickle, causing a continuous upward flow of more than 0.2 m day^{-1}. There is also a continuous vertical eddy diffusion exchange which allows basin waters to mix with overlying waters. These two processes of vertical advection and eddy diffusion keep basin waters from total isolation.

There have been no studies on exchange rates at intermediate depths. Intermediate waters will exchange with basin waters below and surface waters above through vertical advection and eddy diffusion. They will also exchange laterally down the canyons and through the openings by way of horizontal dispersive and advective processes. These intermediate waters will be called upper basin waters to emphasize their isolation from rapid horizontal exchange processes characteristic of the surface layer; bottom basin waters will be called lower basin waters to distinguish them from the upper basins.

II. ONE-DIMENSIONAL MODELS

Vertical profiles have been taken over a wide area in Santa Barbara Basin (Sholkovitz, 1972) and in Santa Monica and San Pedro Basins (Minard, 1968). Vertical distributions within a basin vary but show no apparent horizontal gradients. Horizontal variations are the result of temporary vertical movements caused by internal waves. Because horizontal gradients are smaller than vertical gradients, we have assumed that waters within a basin are horizontally well mixed, that important processes cause vertical variations and, therefore, that concentration of a substance depends only on the depth.

The concentration of a substance at a given depth can be described in terms of the various processes influencing it. The total amount in a slice dz thick, at a depth z, where the basin cross section is A(z) and the concentration C(z), is A(z)C(z)dz. Changes in this will result from vertical advection, particle settling, eddy diffusion, and various sources and sinks:

$$\frac{\partial(AC)}{\partial t} = \left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{vertical}\\ \text{advection}}} + \left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{particle}\\ \text{settling}}} + \left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{horizontal}\\ \text{exchange}}} + \left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{vertical}\\ \text{eddy}\\ \text{diffusion}}} + \left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{sources,}\\ \text{sinks}}} \qquad (2\text{-}1)$$

Each of these terms can be mathematically described.

Vertical Advection (Upwelling)

Concentration change for an advection process is a function of downward flow velocity, v_z(m d^{-1}), and concentration. Flow velocity is related to mass flow, Q(m^3 d^{-1}); $Q = v_z A$. Because water is conserved, changes in mass flow vertically must involve horizontal water flows. This is expressed by:

$$\frac{\partial Q}{\partial z} = v_{hu} W \qquad (2\text{-}2)$$

where v_{hu}(m d^{-1}) is the horizontal influx velocity at a depth involved in upwelling (positive entering the basin); W(m) is the width of the basin opening at depth z.

Concentration changes will depend on the vertical and horizontal flows:

$$\left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{vertical}\\ \text{advection}}} = \frac{-\partial(QC)}{\partial z} + v_{hu}\ W\ C_u$$

$$= -Q\frac{\partial C}{\partial z} - C\frac{\partial Q}{\partial z} + v_{hu}\ W\ C_u$$

$$= -Q\frac{\partial C}{\partial z} + v_{hu}\ W\ (C_u - C)$$

or

$$\left.\frac{\partial C}{\partial t}\right|_{\substack{\text{vertical}\\ \text{advection}}} = -\ v_z\frac{\partial C}{\partial z} + f_u\ \Delta C \qquad (2\text{-}3)$$

where C_u = concentration in water flowing laterally

$= C$ if $v_{hu} \leq 0$

$= C_{ext}$ if $v_{hu} \geq 0$

C_{ext} = concentration in water outside basin

$\Delta C = C_{ext} - C$

$$f_u\ (d^{-1}) = \frac{v_{hu}\ W}{A} \quad \text{if } v_{hu} \geq 0 \qquad (2\text{-}4)$$

$= 0$ if $v_{hu} < 0$

= upwelling exchange rate

Water flowing into the basin is assumed to flow into a depth where the temperature is the same. Thus, $\Delta T = 0$ and the equation describing temperature changes becomes:

$$\left.\frac{\partial T}{\partial t}\right|_{\substack{\text{vertical}\\ \text{advection}}} = v_z \frac{\partial T}{\partial z} \qquad (2\text{-}5)$$

Particle Settling

The mathematical description of particle settling is similar to that of advection. For constant particle settling velocity, v_s (m d^{-1}),

$$\left.\frac{\partial (AC)}{\partial t}\right|_{\substack{\text{particle}\\ \text{settling}}} = -\frac{\partial}{\partial z}(v_s AC) \qquad (2\text{-}6)$$

and

$$\left.\frac{\partial C}{\partial t}\right|_{\substack{\text{particle}\\ \text{settling}}} = -v_s\left(\frac{\partial C}{\partial z} + C\,\frac{1}{A}\,\frac{dA}{dz}\right)$$

Eddy Diffusion

Communication of basin waters with adjacent waters outside the basin will be described differently than with overlying basin waters. Vertical mixing (when the vertical eddy diffusion coefficient is ε_z ($m^2 d^{-1}$)) is given by

$$\left.\frac{\partial (AC)}{\partial t}\right|_{\substack{\text{vertical}\\ \text{eddy diffusion}}} = \frac{\partial}{\partial z}(\varepsilon_z A \frac{\partial C}{\partial z})$$

$$\left.\frac{\partial C}{\partial t}\right|_{\substack{\text{vertical}\\ \text{eddy diffusion}}} = \varepsilon_z (\frac{\partial^2 C}{\partial z^2} + \frac{\partial C}{\partial z}(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz})) \qquad (2\text{-}7)$$

Horizontal Exchange Processes

Mathematics of horizontal exchange between a basin and its neighbors are similar for eddy diffusion and advection.

Diffusive horizontal exchanges of this layer will depend on the concentration gradient at the openings and the width of the openings:

$$\left.\frac{\partial (AC)}{\partial t}\right|_{\substack{\text{horizontal}\\ \text{eddy diffusion}}} \approx W(z)K\Delta C \qquad (2\text{-}8)$$

where $W(z)$ is the width of the basin openings at $z(m)$; ΔC = concentration outside minus concentration inside basin near the opening; and K is an exchange coefficient.

Horizontal advection moves the same amount of water in as it does out. Net changes will be:

$$\left.\frac{\partial(AC)}{\partial t}\right|_{\substack{\text{horizontal} \\ \text{advection}}} = W\, v_{ha}\, \Delta C \tag{2-9}$$

where v_{ha} (md^{-1}) is the advective velocity.

The two processes can be described together simply as horizontal exchange:

$$\left.\frac{\partial C}{\partial t}\right|_{\substack{\text{horizontal} \\ \text{exchange}}} \equiv \left.\frac{\partial C}{\partial t}\right|_{\substack{\text{horizontal} \\ \text{eddy diffusion}}} + \left.\frac{\partial C}{\partial t}\right|_{\substack{\text{horizontal} \\ \text{advection}}}$$

$$= f_h\, \Delta C$$

$$\text{where} \qquad f_h(d^{-1}) = \frac{WK}{A} + \frac{Wv_{ha}}{A} \tag{2-10}$$

= horizontal exchange rate.

Sources and Sinks

Source and sink terms in the conservation equation (2-1) account for distributed additions or removals of a substance. One such source could be sludge discharge. For example, if B(moles d^{-1}) is the discharge rate of organic carbon, and if this carbon enters in a uniform 10 m layer, the source term g(z) (moles $m^{-1}d^{-1}$) would be B/10 at the depth of the layer and zero elsewhere. Consequently,

$$\left.\frac{\partial C}{\partial t}\right|_{\text{source}} = \frac{g(z)}{A} \tag{2-11}$$

Sinks can be any of the various processes which remove a substance such as reaction with the bottom, radioactive decay, or chemical reactions. Reactions with the bottom will depend on the bottom area in contact with a horizontal layer. That area for a slice dz thick is $-\frac{dA}{dz}\,dz$. Thus, the loss to the volume of water dz thick at depth z caused by particle sedimentation on the bottom is

$$\frac{\partial(AC)dz}{\partial t} = -v_s C\left(-\frac{dA}{dz}\,dz\right)$$

or

$$\left.\frac{\partial C}{\partial t}\right|_{\substack{\text{bottom}\\ \text{sedimentation}}} = +\, v_s C \,\frac{1}{A}\frac{dA}{dz}. \tag{2-12}$$

Similarly, oxygen uptake by the sediments will reduce oxygen concentrations. If $\ell(C,z)$ (moles $m^{-2}d^{-1}$) is the oxygen uptake of the sediment, then

$$\left.\frac{\partial C}{\partial t}\right|_{\text{sediment}} = -\ell(C,z)\,\frac{1}{A}\frac{dA}{dz}. \tag{2-13}$$

For a radioactive substance, a constant fraction is always disappearing. The radioactive decay loss is

$$\left.\frac{\partial C}{\partial t}\right|_{\text{decay}} = -\lambda C \tag{2-14}$$

where λ is the decay rate (d^{-1}).

Chemical reaction would be represented in the same way. If $r(d^{-1})$ is the reaction rate for the disappearance of C, then

$$\left.\frac{\partial C}{\partial t}\right|_{\text{reaction}} = -rC \qquad (2\text{-}15)$$

The Differential Equation

The differential equation for a given substance consists of the sum of all the appropriate terms. Settling and radioactive decay are not important for temperature so the temperature conservation equation would be

$$\frac{\partial T}{\partial t} = \text{upwelling} + \text{vertical eddy diffusion}$$

$$= -v_z \frac{\partial T}{\partial z} + \varepsilon_z \left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial T}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) \qquad (2\text{-}16)$$

For oxygen of concentration ϕ, the equation must include the inputs from outside the basin as well as oxygen sinks.

$$\frac{\partial \phi}{\partial t} = -v_z \frac{\partial \phi}{\partial z} + \varepsilon_z \left(\frac{\partial^2 \phi}{\partial z^2} + \frac{\partial \phi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) + f_u \Delta\phi + f_h \Delta\phi$$

$$- r\psi - \ell \frac{1}{A}\frac{dA}{dz} \qquad (2\text{-}17)$$

where ψ is concentration of sludge particles.

For sludge particles (concentration ψ) settling is also important.

$$\frac{\partial\psi}{\partial t} = -v_z\frac{\partial\psi}{\partial z} + \varepsilon_z\left(\frac{\partial^2\psi}{\partial z^2} + \frac{\partial\psi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right)$$

$$+ (f_u + f_h)\,\Delta\psi - r\psi + \frac{g}{A}$$

$$- v_s\left(\frac{\partial\psi}{\partial z} + \psi\frac{1}{A}\frac{dA}{dz}\right) + v_s\frac{\psi}{A}\frac{dA}{dz} \qquad (2\text{-}18)$$

III. DETERMINING PHYSICAL PROCESS RATES

Understanding of basin chemical dynamics must involve knowledge of the processes that drive them. Such processes include vertical advection-upwelling, horizontal exchange, eddy diffusion and oxygen uptake. Because these rates are not well known, we have had to assume eddy diffusivities and oxygen demands and used these values to infer upwelling and horizontal exchange rates.

E. Sholkovitz (1972) collected hydrographic data in his study of the marine basins of Southern California (Appendix 4). He sampled mostly in the Santa Barbara Basin, but sampled once each in various locations in the Southern California Bight and sampled Santa Monica and San Pedro Basins four times over the course of a year. Other groups that have sampled Santa Monica-San Pedro Basin include the Bureau of Land Management and Minard (1968), but neither of these studies involved periodic resampling. Intercalibration difficulties make it dangerous to draw conclusions using data taken by different investigators. We used Sholkovitz's data to infer mixing rates because they were the most consistent data with a time component.

Chung (1973) tried to measure the eddy diffusivity of lower Santa Barbara Basin using a radioactive tracer released by the sediments. His calculation of the diffusivity ignored the non-flat nature of a basin and, as noted by Lietzke and Lerman (1975), therefore flawed his result. Sarmiento et al. (1976) measured vertical eddy diffusivities in the deep Pacific and Atlantic Oceans. They found a strong relationship between the vertical eddy diffusivity, ε_z, and the density gradient, $\frac{g}{\rho}\frac{\partial\rho}{\partial z}$, where g is the gravitational acceleration and ρ is the potential density. The best fit equation between the two was

$$\varepsilon_z(\mathrm{cm}^2\ \mathrm{sec}^{-1}) = 4\mathrm{x}10^{-6}/[\ \frac{g}{\rho}\ (\frac{\partial\rho}{\partial z})] \qquad (2\text{-}19)$$

where all units are cgs. We have used this relationship to infer the values of ε_z from density profiles calculated from the hydrographic data.

Data taken in the San Pedro Basin and in the Santa Monica Basin during a cruise were treated together. Polynomials in z were fitted to temperature, density, and dissolved oxygen concentration as functions of depth (Figs. 2-1, 2-2, 2-3) for the region between 300 and 750 m and the region between 750 and 900 m. These power fits were used in place of the actual data in subsequent calculations. Thus, the density derivative needed to calculate ε_z came from differentiating the cubic expression fit to the density versus depth profile. The resulting vertical eddy diffusivity as a function depth was also fit to a cubic power series (Fig. 2-4). Basin bottom area was fit to a rational function of depth (Fig. 2-5). The result of all of this curve fitting was that temperature, dissolved oxygen, area, ε_z, and their derivatives were known as functions of depth through the water column.

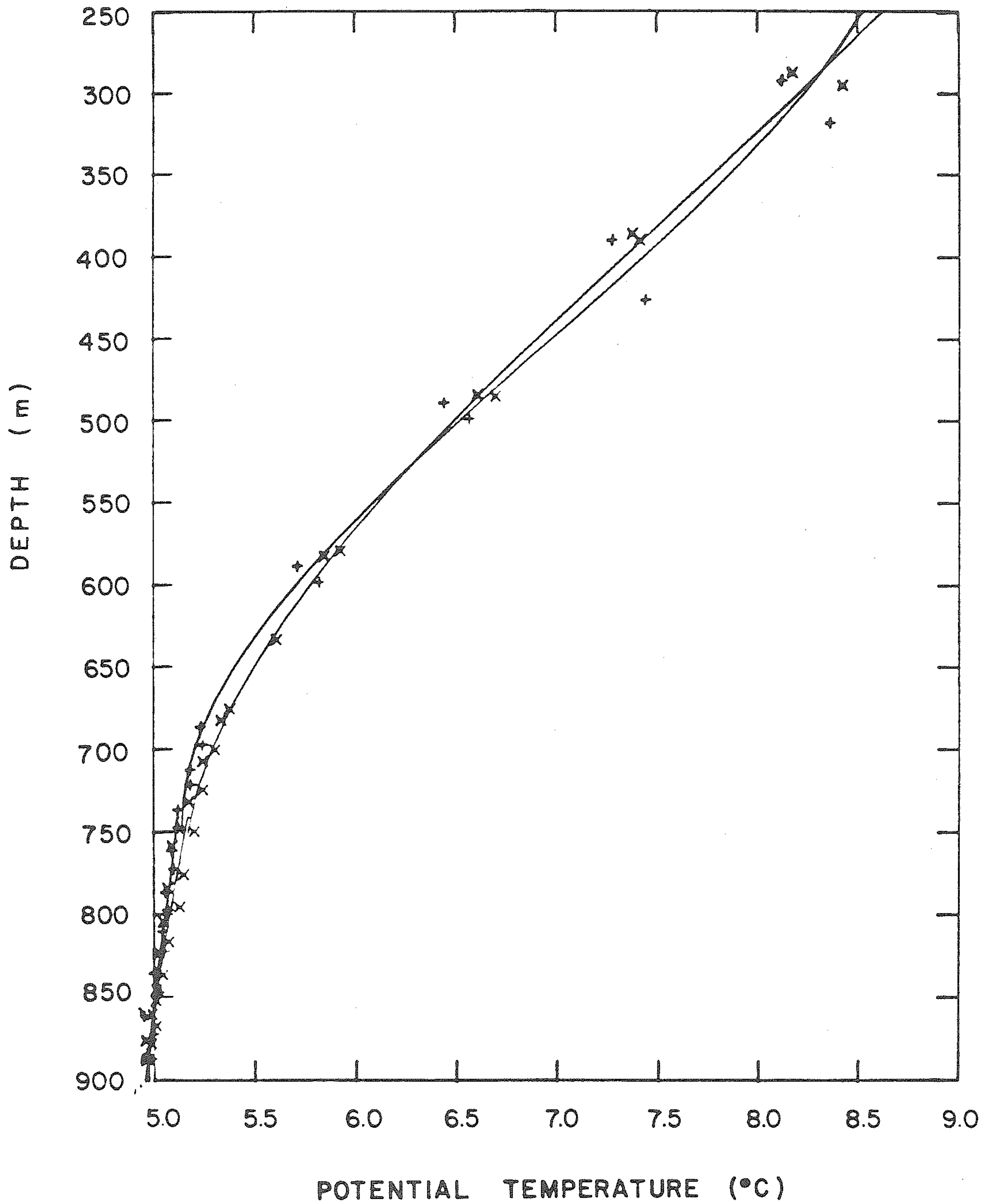

Figure 2-1 Potential temperature as a function of depth in Santa Monica-San Pedro Basin. Lines represent cubic least square fits to data points in two segments: 300-750 m and 740-900 m. + - May 1970, x - November 1970.

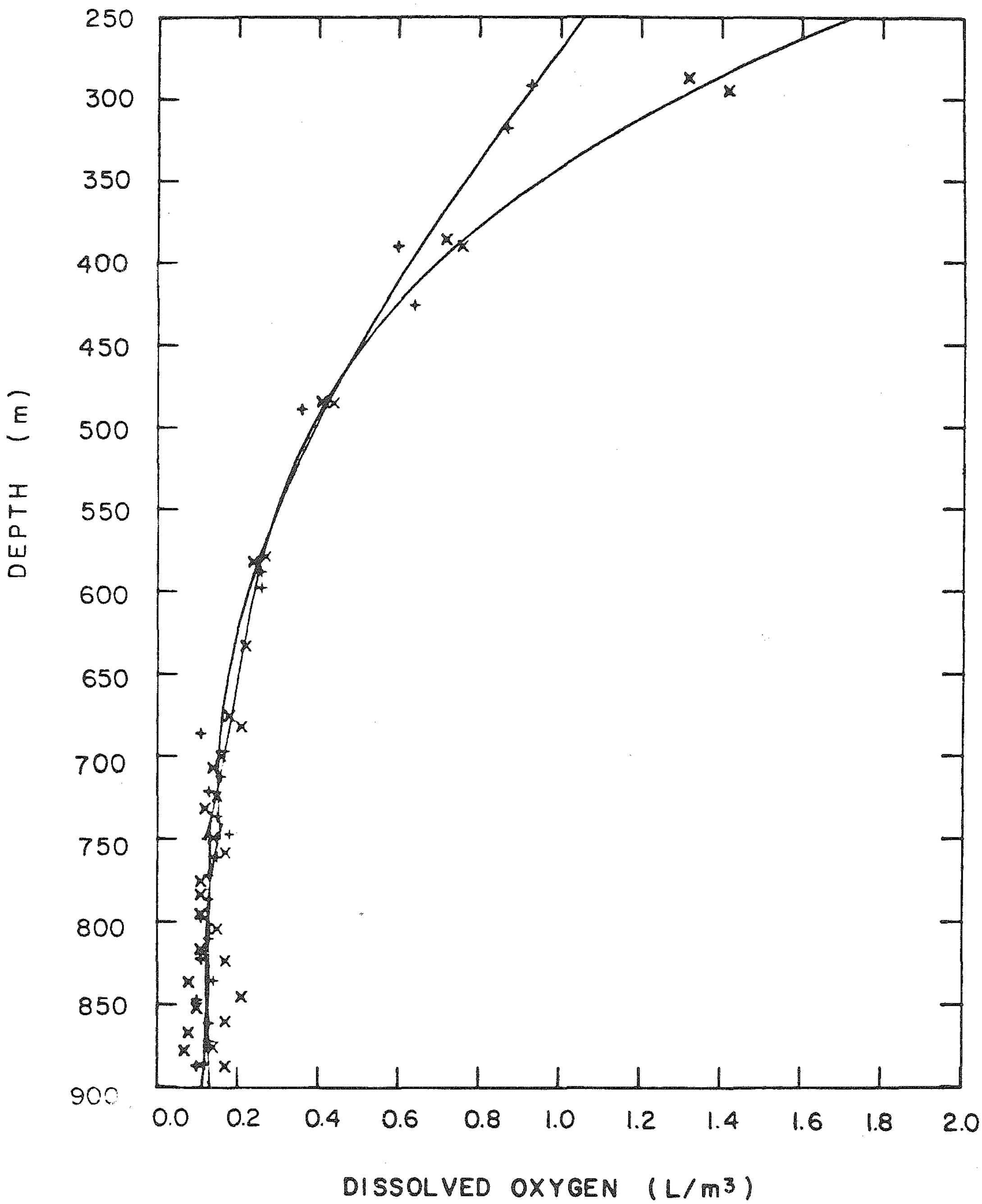

Figure 2-2 Dissolved oxygen concentrations as a function of depth in Santa Monica-San Pedro Basins. Lines represent cubic least squares fits. + - July 1970, x - November 1970.

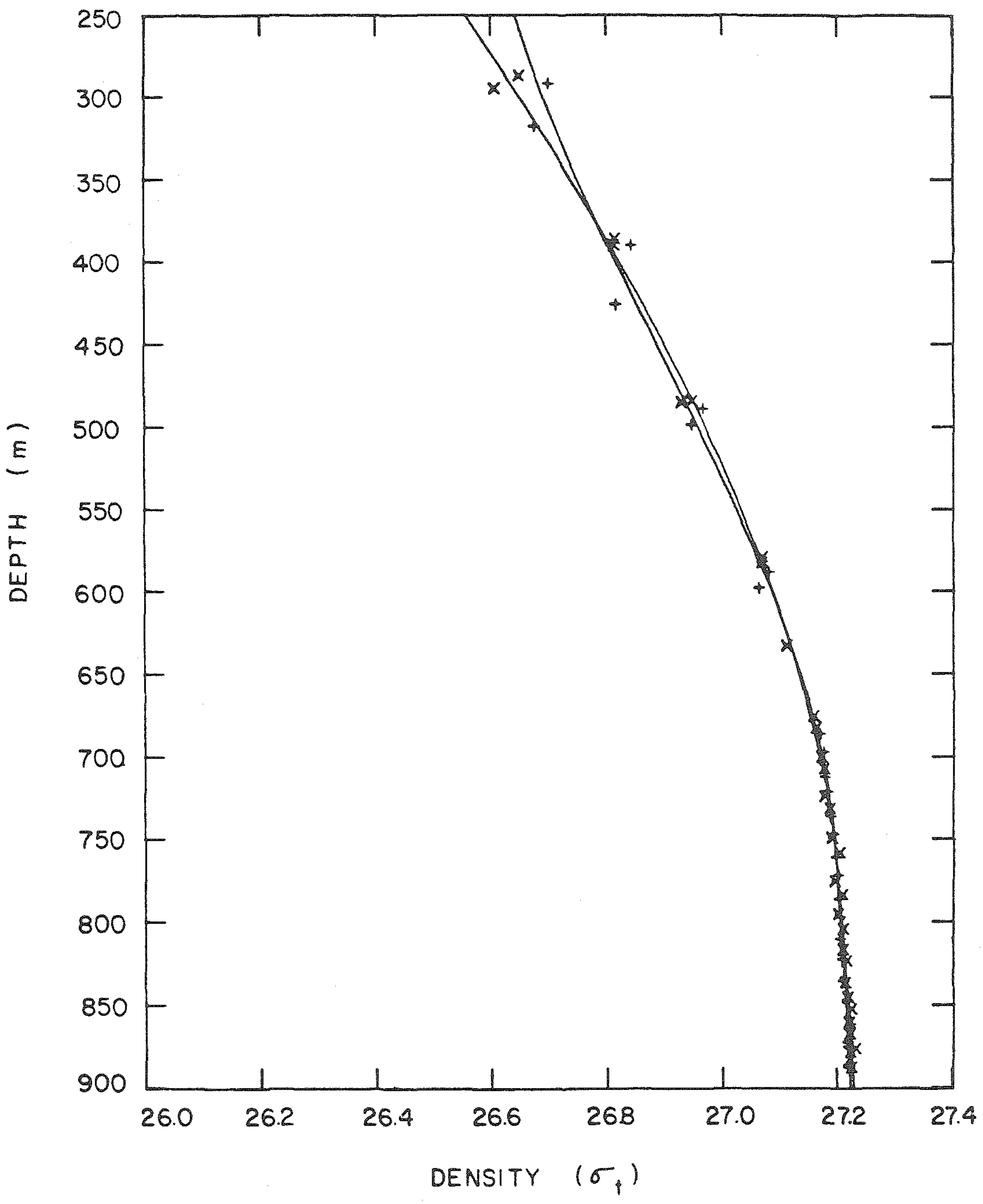

Figure 2-3 Density as a function of depth in Santa Monica-San Pedro Basin. Lines represent cubic least squares fits. + - May 1970, x - November 1970.

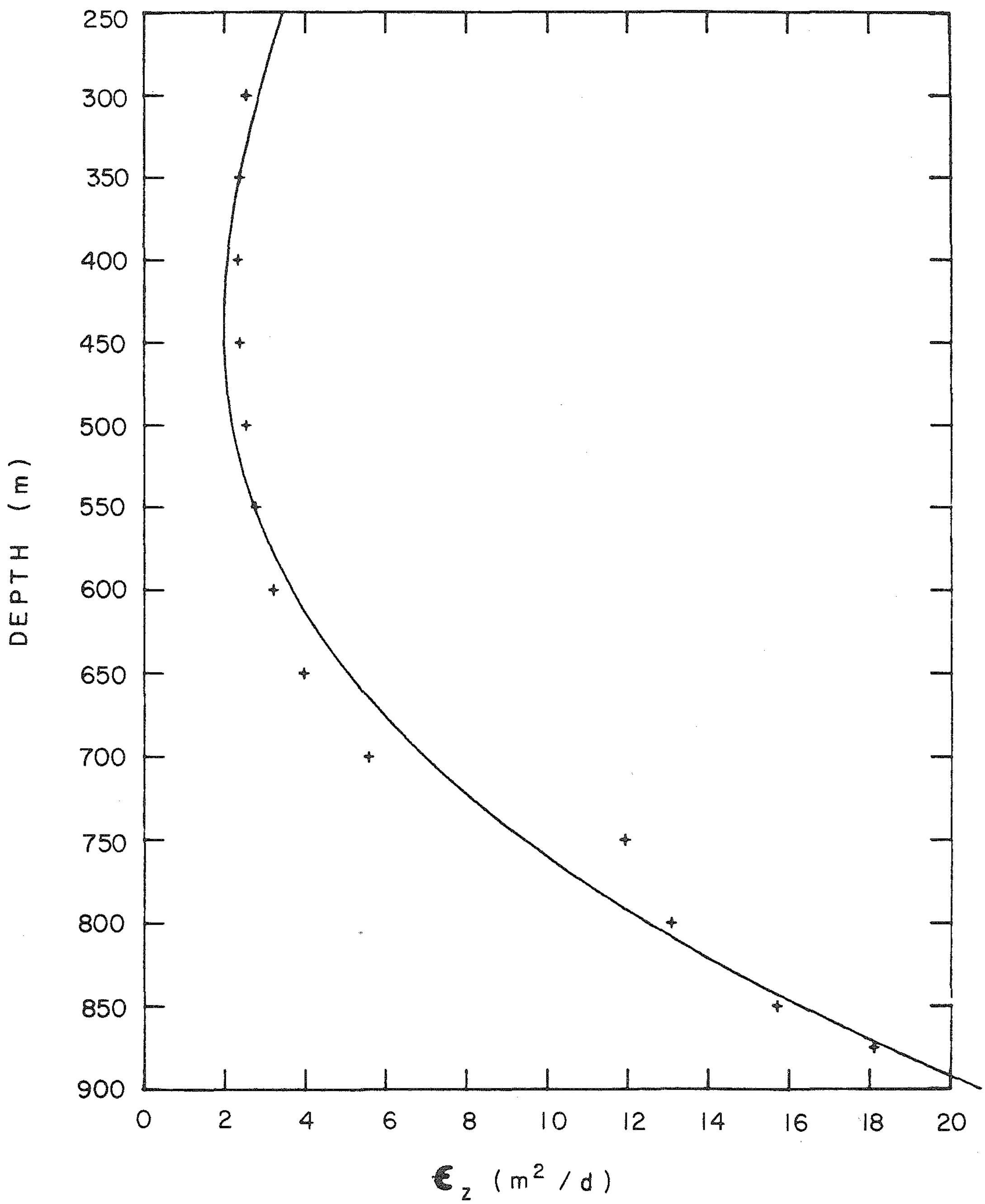

Figure 2-4 Vertical eddy diffusion, ε_Z, as a function of depth in Santa Monica-San Pedro Basin. Points were calculated using density fits for May 1970 and for November 1970 at 50 m intervals and than averaged.

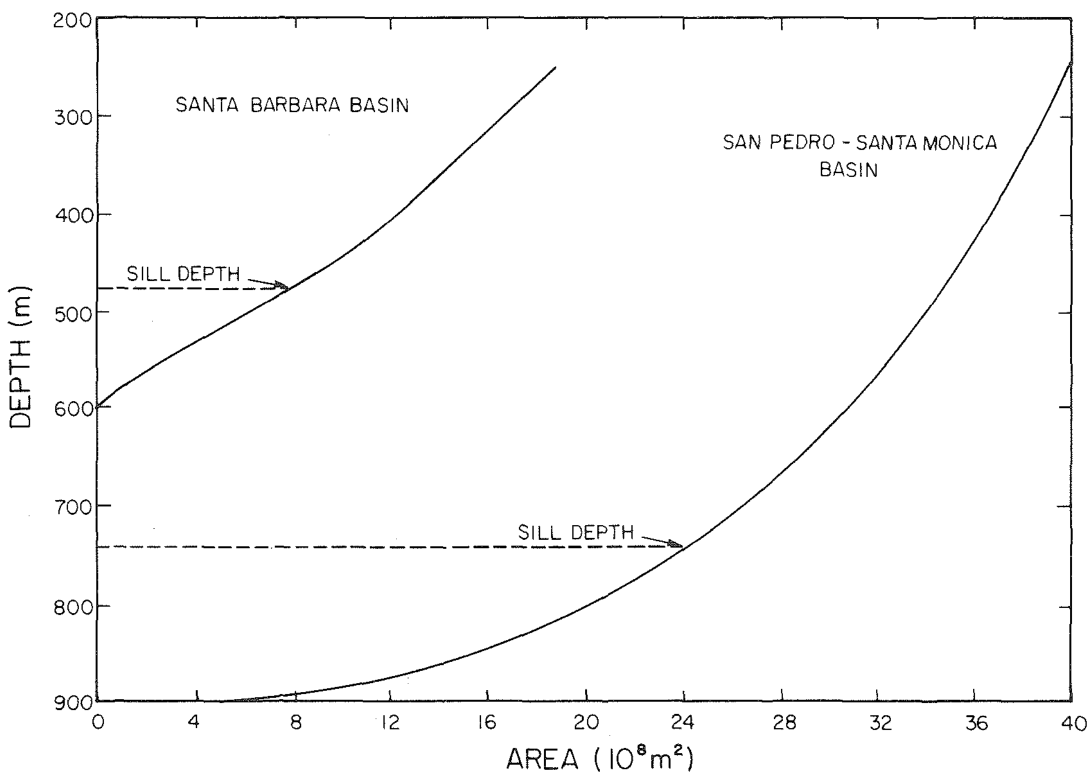

Figure 2-5 Basin area as a function of depth

The equation describing temperature changes in the basin is (from the previous section)

$$\frac{\partial T}{\partial t} = \varepsilon_z\left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial T}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) - v_z\frac{\partial T}{\partial z} \qquad (2\text{-}16)$$

Solved for v_z, this becomes

$$v_z = \left[\varepsilon_z\left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial T}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) - \frac{\partial T}{\partial t}\right] / \frac{\partial T}{\partial z} \qquad (2\text{-}20)$$

The various derivatives can be approximated for two sets of hydrographic data taken period Δt apart. The term $\frac{\partial T}{\partial t}$ was approximated as $\frac{\Delta T}{\Delta t}$, where ΔT is the temperature difference at a given depth for the two different sampling times. Similarly, other terms in equation 2-20 can be approximated by averaging the values given by the power fits for the two different sample sets.

The resulting calculation of the vertical velocity in the upper basin shown in Figure 2-6 for the period of July to November 1970, shows upward flow of water at 400 meters depth at a velocity of about 0.1 m d^{-1}. Near the sill depth, 737 m, water flow is downward and approximately 0.2 m d^{-1}. This downward flow moves heat down with it, driving the upward flow in the lower basin. The vertical velocity values calculated in this way were fit with a power series for later use.

This technique for calculating upwelling velocities does not work well in the lower basin. Errors in the functions used to fit temperature, area, and vertical eddy diffusivity are greater in the lower basin, where area and eddy diffusivity change rapidly. Such

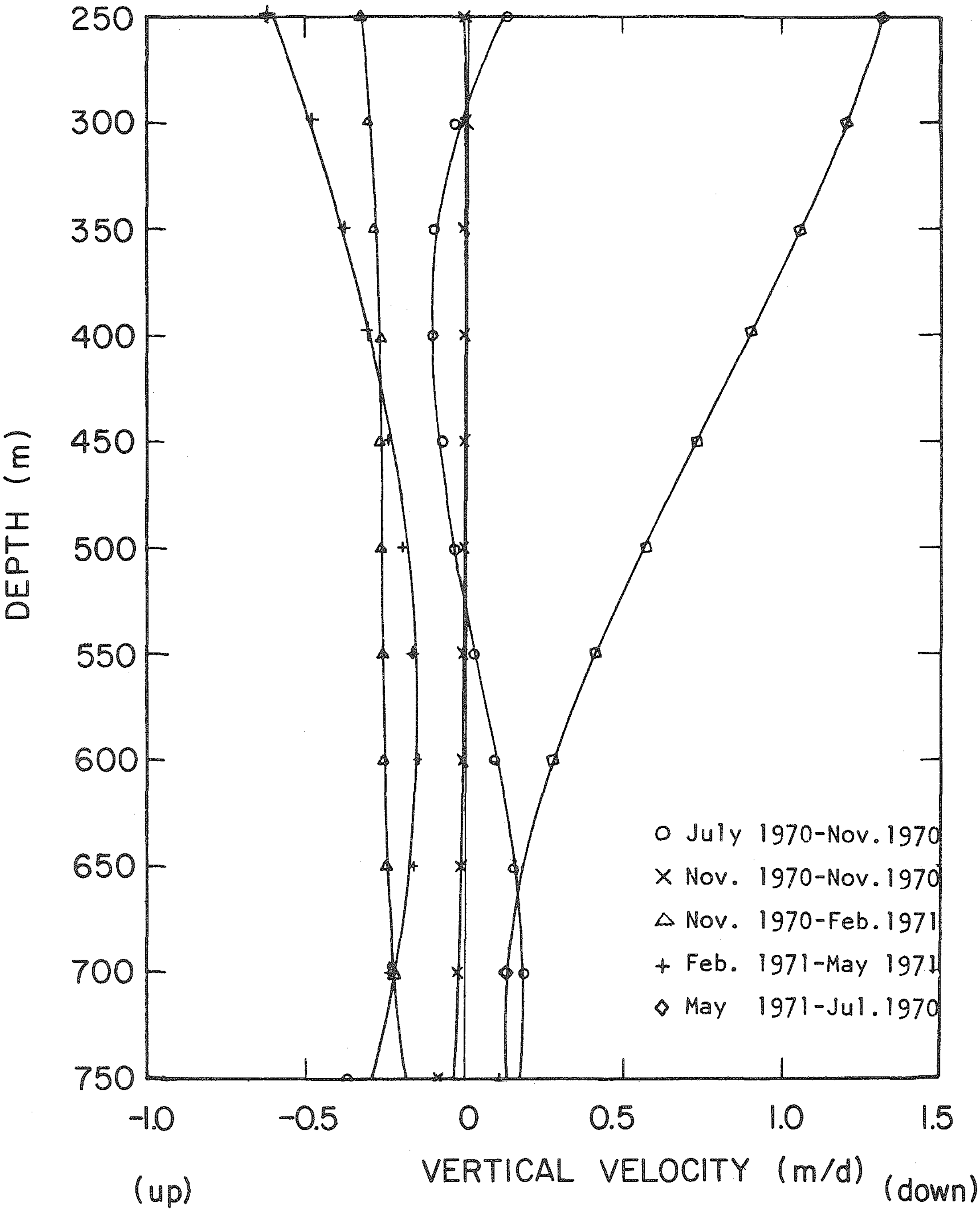

Figure 2-6 Calculated vertical advection in Santa Monica-San Pedro Basin. February-May 1971 represents upwelling. If T profile for July 1971 were the same as that of July 1970, then the May 1971 to July 1970 profile would represent downwelling.

errors are magnified with the use of derivatives. A cruder technique less sensitive to parameter errors can be used to estimate vertical velocities there. Note that total heat flow down at 700 meters must balance that at 800 m if the basin temperature is to remain constant. Heat would flow down by eddy diffusion and advection, at 700 and 800m, and would flow out at the sill depth when the downward flow from the upper basin met the upper flow from the lower basin. The equation describing this is

$$Q_{700}(T_{700} - T_{740}) - \varepsilon_{z,\ 700}\, A_{700}\, \nabla T_{700} = Q_{800}(T_{800} - T_{740}) - \varepsilon_{z,800}\, A_{800}\, \nabla T_{800} \qquad (2\text{-}21)$$

where the numerical subscripts denote the depth at which variable is evaluated. The resulting vertical velocity for the lower basin calculated for data of July-November 1970 is -0.24 m d^{-1} (the negative sign indicates that flow is upward). We have assumed that this velocity is constant with depth in the lower basin.

The equation describing basin oxygen concentration, ϕ, is similar to that for temperature but includes terms describing oxygen added by water coming from the sides--from Santa Cruz basin to the north and the San Diego Trough to the south and terms describing consumption within the basin:

$$\frac{\partial\phi}{\partial t} = \varepsilon_z\left(\frac{\partial^2\phi}{\partial z^2} + \frac{\partial\phi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) - v_z\frac{\partial\phi}{\partial z} + f_u\Delta\phi + f_h\Delta\phi - r\psi - \ell\,\frac{1}{A}\frac{dA}{dz} \qquad (2\text{-}22)$$

With oxygen concentration described by power series fits to the hydrographic data (Fig. 2-2), with v_z and then f_u calculated from the temperature data, the unknowns remaining are the horizontal exchange rate, f_h, external oxygen concentration, ϕ_{ext}, and oxygen consumption

Water column consumption of oxygen is small compared to that by the sediments (see Sect. 2-IV) and will be neglected. Reasonable estimates of sediment demand can be made ; we have assumed maximum sediment oxygen consumption, ℓ_{max}, to be 0.24 liters O_2 m^{-2} d^{-1} and assumed a hyperbolic dependence for oxygen consumption on oxygen concentration

$$\ell = \frac{\phi \ell_{max}}{\phi + \phi_{cr}} \qquad (2\text{-}23)$$

where ϕ_{cr} is 0.15 liters O_2 m^{-3} = 6.7 μM.

Incoming water was assumed to have the oxygen as a function of temperature characteristics of Santa Cruz Basin water sampled on July 1970. This relationship was described with a cubic power fit (Fig. 2-7, 2-8). Because water coming into the basin was assumed to mix with water of the same temperature, temperature in the Santa Monica-San Pedro Basin could be used to determine the incoming oxygen concentration at most depth.

Horizontal exchange rates could thus be calculated

$$f_h = \frac{1}{\Delta\phi}\left\{\frac{\ell}{A}\frac{dA}{dz} + v_z\frac{\partial\phi}{\partial z} - f_u\,\Delta\phi - \varepsilon_z\left(\frac{\partial^2\phi}{\partial z^2} + \frac{\partial\phi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right)\right\} \qquad (2\text{-}24)$$

The calculated f_h values are shown in Figure 2-9 for the period of June-November 1970. Horizontal exchange rates are about $7 \times 10^{-3} d^{-1}$ at 300 m and a third as much near the sill depth.

There is, of course, no horizontal exchange in the lower basin. Thus the oxygen consumption rate there can be determined from previously determined terms. The net amount of oxygen brought into the lower basin is the amount consumed:

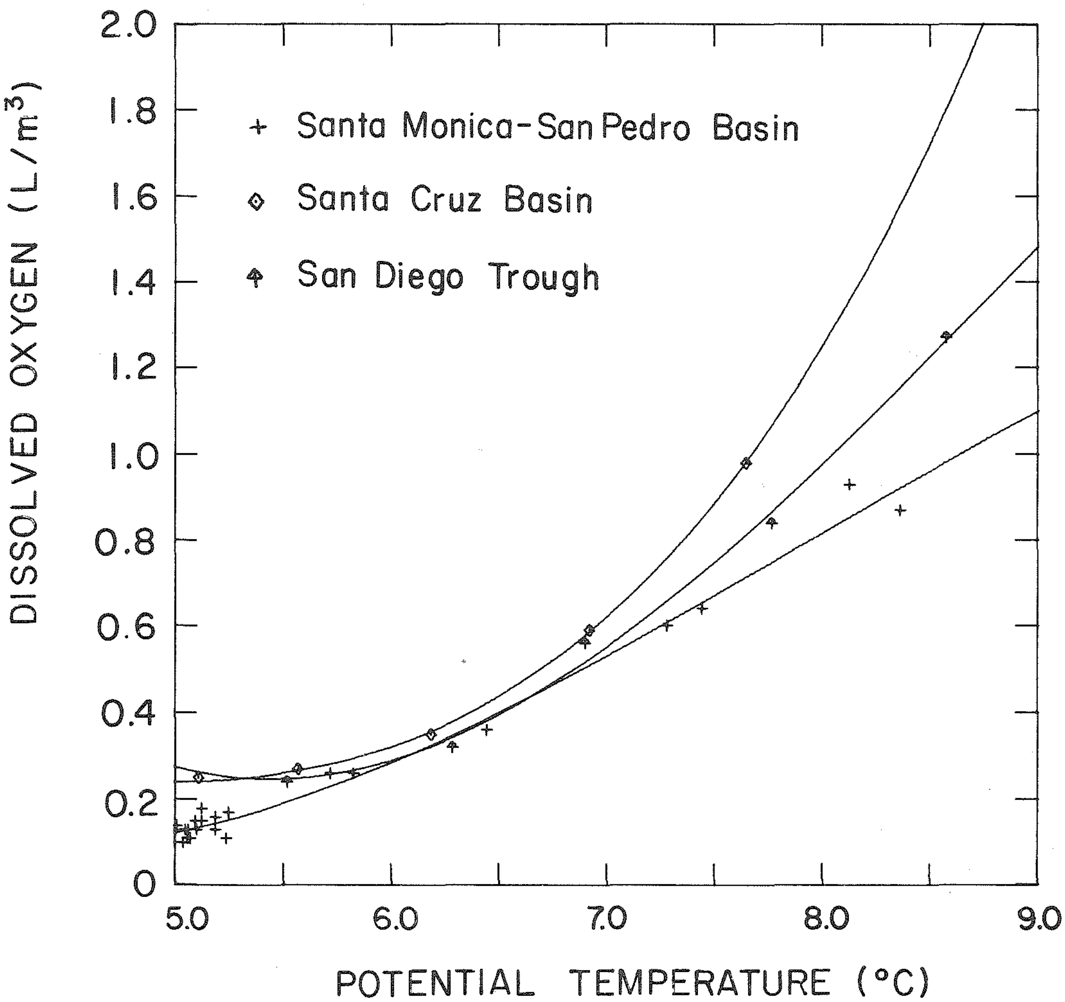

Figure 2-7 Oxygen concentration as a function of potential temperature. July 1970. Lines represent cubic least square fits of oxygen to temperature.

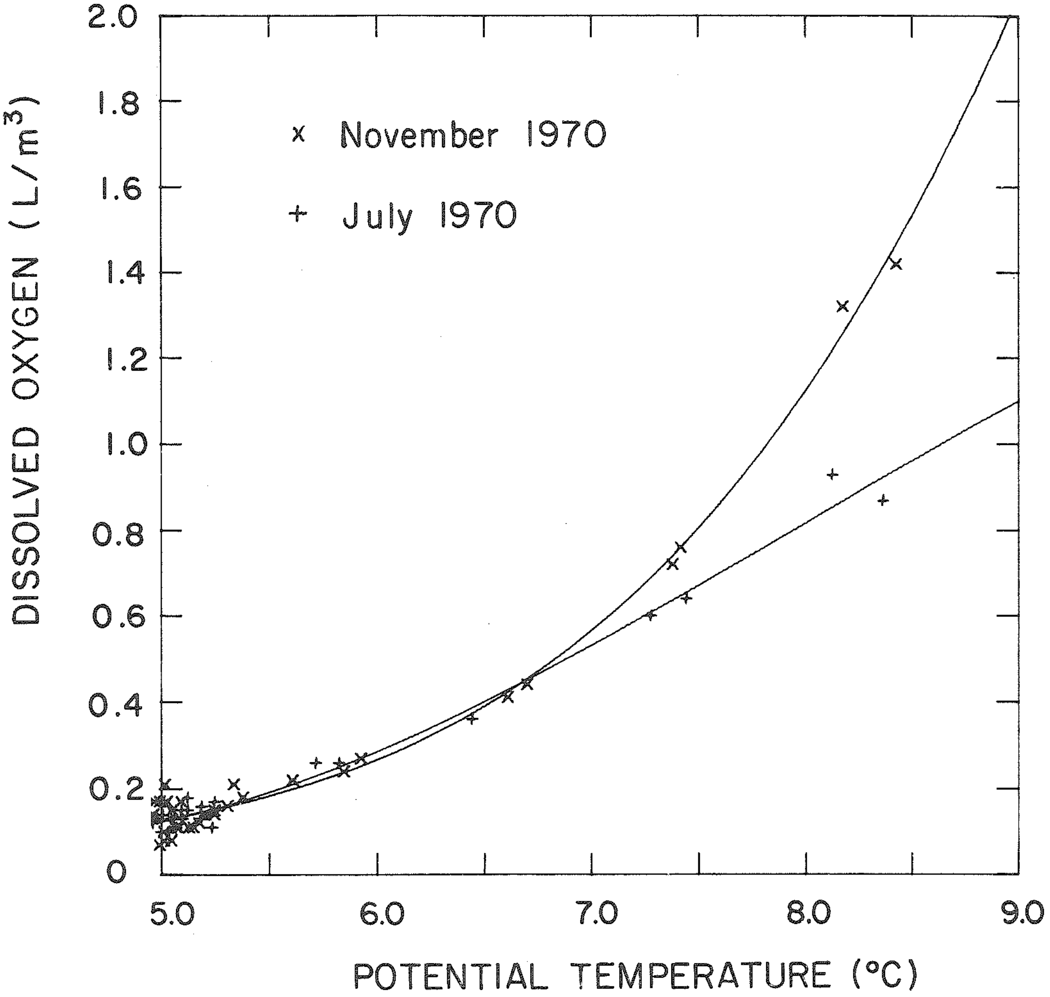

Figure 2-8 Oxygen concentration as a function of potential temperature in Santa Monica-San Pedro Basin. Note the increase in oxygen by November.

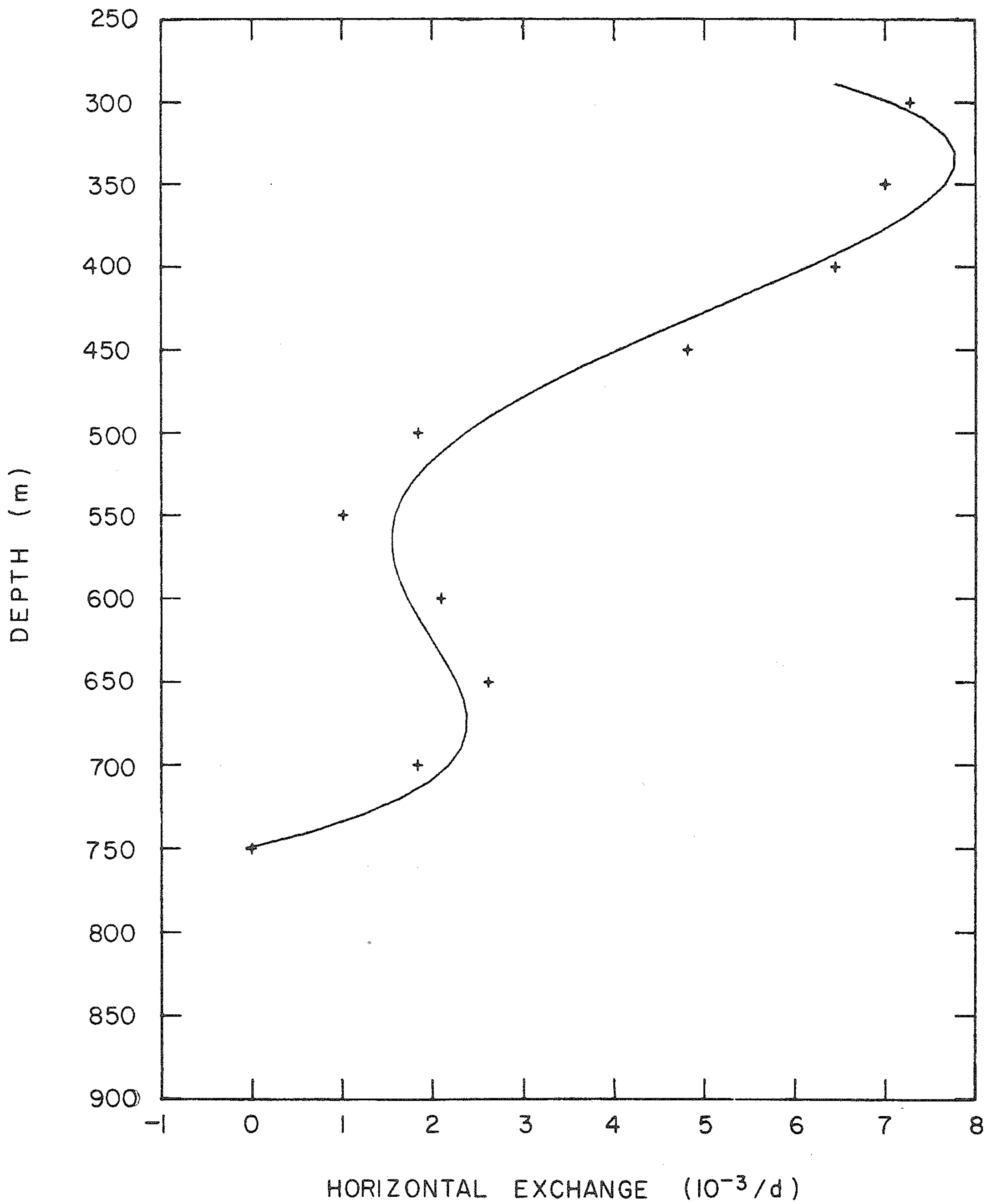

Figure 2-9 Horizontal exchange, f_h, calculated at 500 m intervals for July - November 1970 in the Santa Monica-San Pedro Basin. Line represents a fourth order best fit.

$$\ell = v_z \phi_{800} - \varepsilon_{z,800} \frac{\partial \phi}{\partial z} \phi_{800}$$

$$= 0.38 \ \ell \ m^{-2} d^{-1}$$

$$= 1.7 \text{ mmoles } m^{-2} d^{-1}$$

If sediment oxygen consumption depends on oxygen as in equation 2-23, ℓ_{max} = 85 ml m^{-2} d^{-1} = 3.8 mmoles $m^{-2}d^{-1}$. This is one-third the value assumed for the upper basin.

Nitrate consumption in the lower Santa Monica-San Pedro Basin can be calculated in the same manner. The result is that nitrate consumption, ℓ', is 1.5 mmoles-NO_3 $m^{-2}d^{-1}$. Nitrate taken up by the sediments is being reduced to N_2 (Goldberg, personal communication). As a result, nitrate reduction involves the transfer of 5 electrons, as opposed to the four electrons involved in O_2 reduction. If O_2 and NO_3^- are to be considered as competitors in supplying oxidants, nitrate supply rates should be expressed as oxygen equivalents by multiplying with a factor of 1.25. Thus,

$$\ell' = 1.5 \text{ mmoles-}NO_3 \ m^{-2}d^{-1}$$

$$= 1.9 \text{ mmoles-}O_2 \text{ equivalents } m^{-2}d^{-1}$$

One expression for an inhibition relationship is that for competitive inhibition (Neame and Richards, 1972):

$$\ell = \ell_{max} \frac{\beta}{1+\alpha+\beta} \quad (2\text{-}25a)$$

$$\ell' = \ell_{max} \frac{\alpha}{1+\alpha+\beta} \quad (2\text{-}25b)$$

where

α $= \nu/\nu_{cr}$
β $= \phi/\phi_{cr}$
ν = nitrate concentration
ν_{cr} = half saturation constant for nitrate
ϕ_{cr} = half saturation constant for oxygen
ℓ_{max} = maximum oxidant uptake rate

The values for ℓ, ℓ', ϕ, and ν are known in the lower basin, and ϕ_{cr} can be assumed to be 6.7 mmoles m^{-3}. The results are that

$$\ell_{max} = 5.76 \text{ mmoles-}O_2 \text{ equivalent } m^{-2} d^{-1}$$

and

$$\nu_{cr} = 39 \text{ mmoles } m^{-3}.$$

IV. BASIN CIRCULATION IN THE SANTA MONICA-SAN PEDRO BASIN

Lower basin circulation is driven by water flowing from the San Diego Trough region over the sill at 737 m, sinking into the lower basin. This water displaces the less dense water upwards, causing an upward flowing current of about 0.2 m d^{-1}. At the same time, buoyancy (in the form of warmer, less saline water) is mixed downward from the upper basin. Both the water mixing downward from the upper basin and the water coming over the sill bring oxygen into the basin, replacing that consumed within.

Water leaves the lower basin, either flowing out of the Santa Monica-San Pedro Basin (July-Nov 1970) or continuing to flow upward (as from Nov-Feb 1971 and from Feb-May 1971)(Fig. 2-6). During the July-Nov 1970 period, water from the upper basin also flowed down and out around the sill depth. The result would have been jets carrying about 10^9 $m^3 d^{-1}$ out into the San Diego Trough and the Santa Cruz Basin.

Vertical flow in the upper basin is predominantly upward, with velocities as high as 0.5 m d^{-1}. Flow into the basin to support the upwelling is small below 500 m. This would explain the observation made by Sholkovitz and Gieskes (1971) that water in the Santa Barbara Lower Basin occasionally overturns during upwelling but in Santa Monica-San Pedro Basin does not. The shallow sill at Santa Barbara (475 m) is in the depth zone affected by upwelling but the deeper sill of Santa Monica-San Pedro Basin (737 m) is not. Thus the depth of the Santa Monica-San Pedro sill gives that basin a constancy that the Santa Barbara Basin does not have.

Circulation in the upper Santa Monica-San Pedro Basin was dominated by horizontal exchange with outside waters during the July-November 1970 period (Fig. 2-10). This was inferred from the increase in oxygen in basin waters during that time. Such an increase could only have occurred with the inflow of water richer in oxygen from Santa Cruz Basin and San Diego Trough (Fig. 2-7), at a time when upwelling was relatively small. The fact that oxygen does not increase indefinitely suggests that horizontal exchange is not always this strong. Unfortunately, without continuing sampling of the oxygen content of the source waters, we cannot make the same calculations for the other periods when Sholkovitz sampled Santa Monica-San Pedro Basin.

Water flowing into the lower basin comes from the San Diego Trough area. Water coming into the upper Santa Monica-San Pedro Basin can come

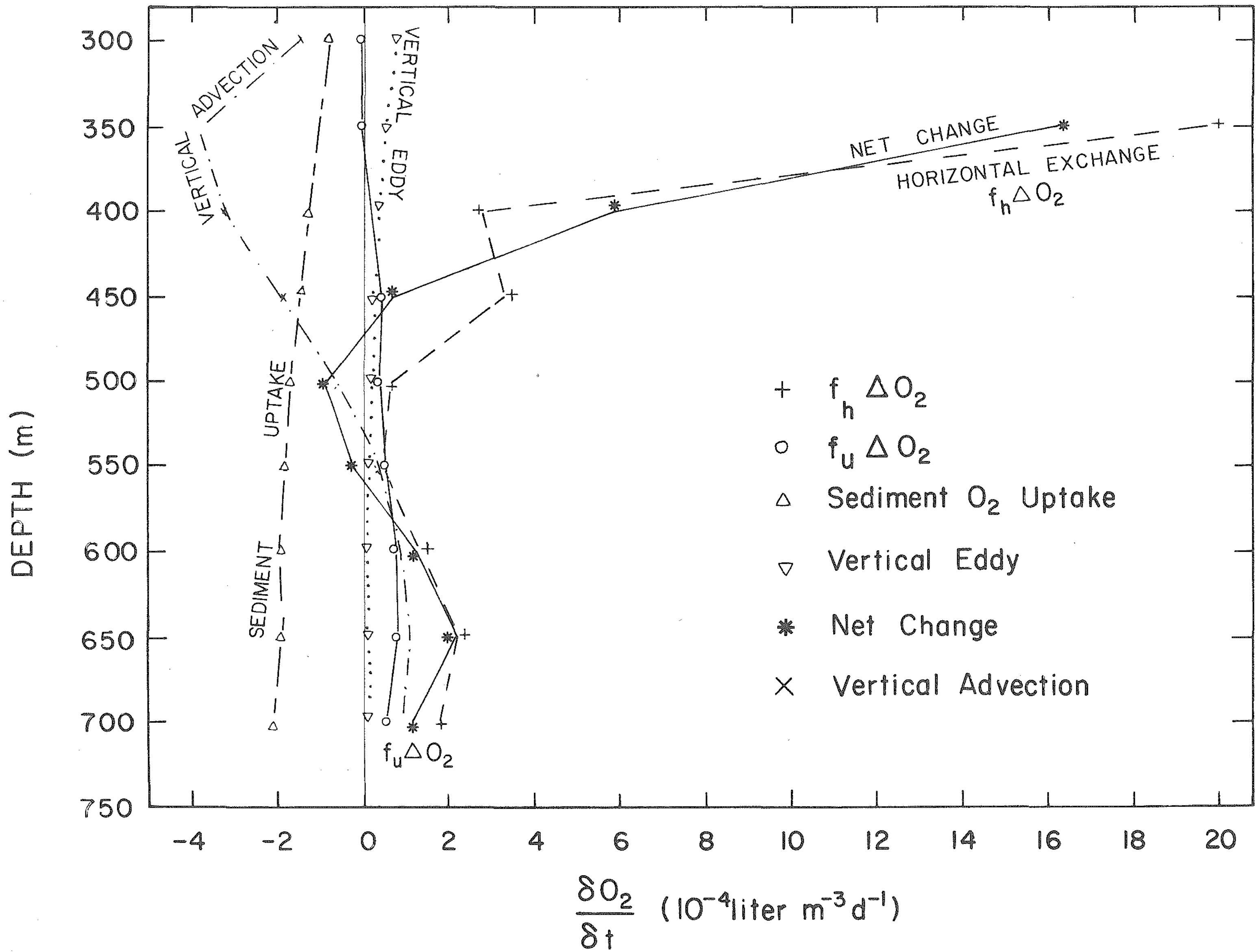

Figure 2-10 Oxygen sources and sinks in Santa-Monica-San Pedro Basin, July-November 1970.

from there or from Santa Cruz Basin. The T-S characteristics of waters from these basins show that Santa Monica-San Pedro Basin water is intermediate to the other two (Fig. 2-11). In July 1970, water in Santa Monica-San Pedro Basin below a depth of 450 m was similar to that of Santa Cruz while that above 450 m was similar to that of San Diego. This suggests that flow and exchange into Santa Monica-San Pedro Basin was predominantly from the north below 450 m and from the south above it. By November 1970 (Fig. 2-12), the T-S curve showed no shifts to the waters of the north or the south. This would result from vertical mixing within the basin and horizontal mixing with waters outside the basin. The influx of northern waters below 400 m and southern waters above reoccurred May 1971 (Fig. 2-13). The evidence of influx of northern waters in May and July but not in November or February suggests that during upwelling months, May to July, there is a massive influx of water from the Santa Cruz Basin into the deeper parts of upper Santa Monica-San Pedro Basin. This water could also move south into the San Diego Trough, establishing a north-south current through the basin. During other times of the year the mixing is more evenly divided between the north and the south, suggesting less current flow and more horizontal mixing.

V. THE MODEL

Our model to study effects of sludge disposal in Santa Monica-San Pedro Basin calculates concentrations and fates of: (a) particulate sludge containing reducing organic matter and selected trace metals, (b) oceanic dissolved oxygen and nitrate, and (c) dissolved trace metals

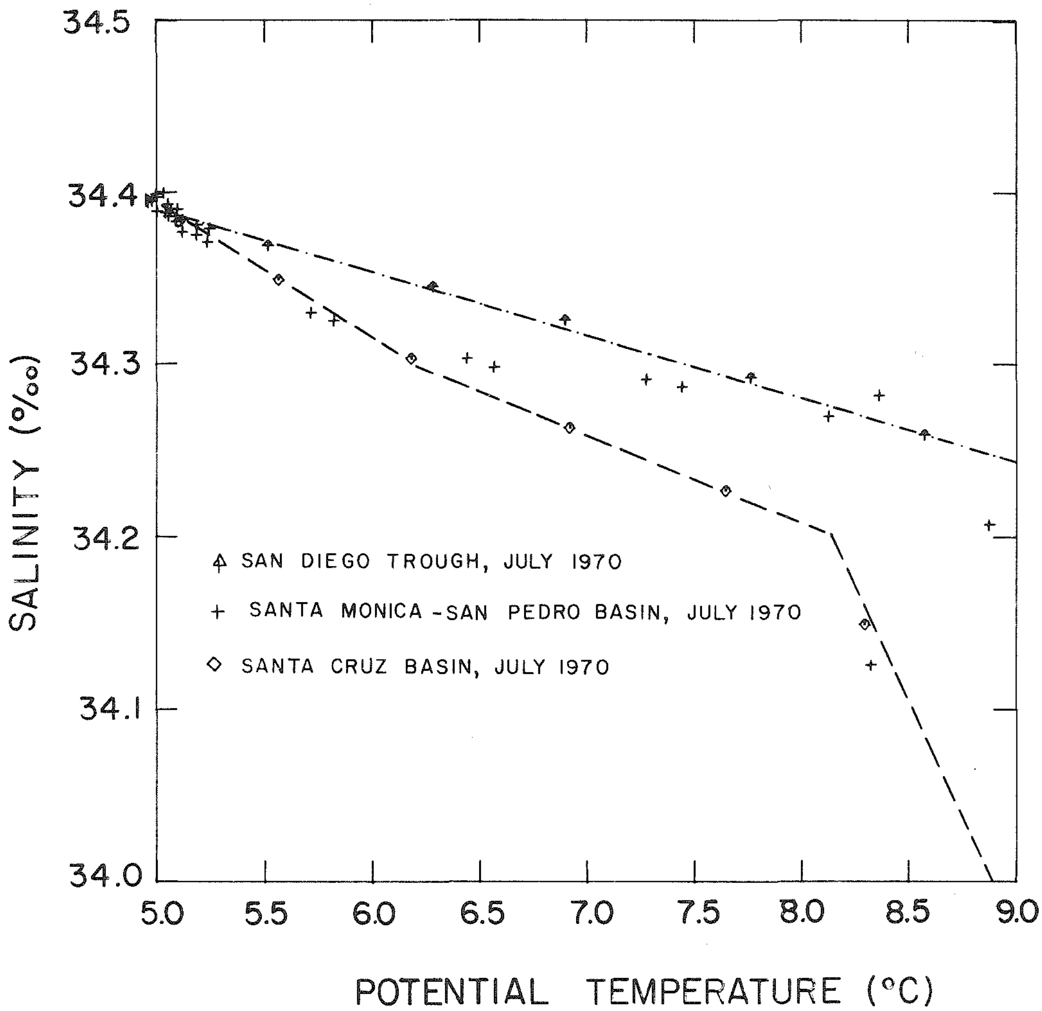

Figure 2-11 Temperature - Salinity plots, July 1970. Lines were hand fit to accentuate basin differences. Solid line is the fit for Santa Monica-San Pedro Basin, November 1970.

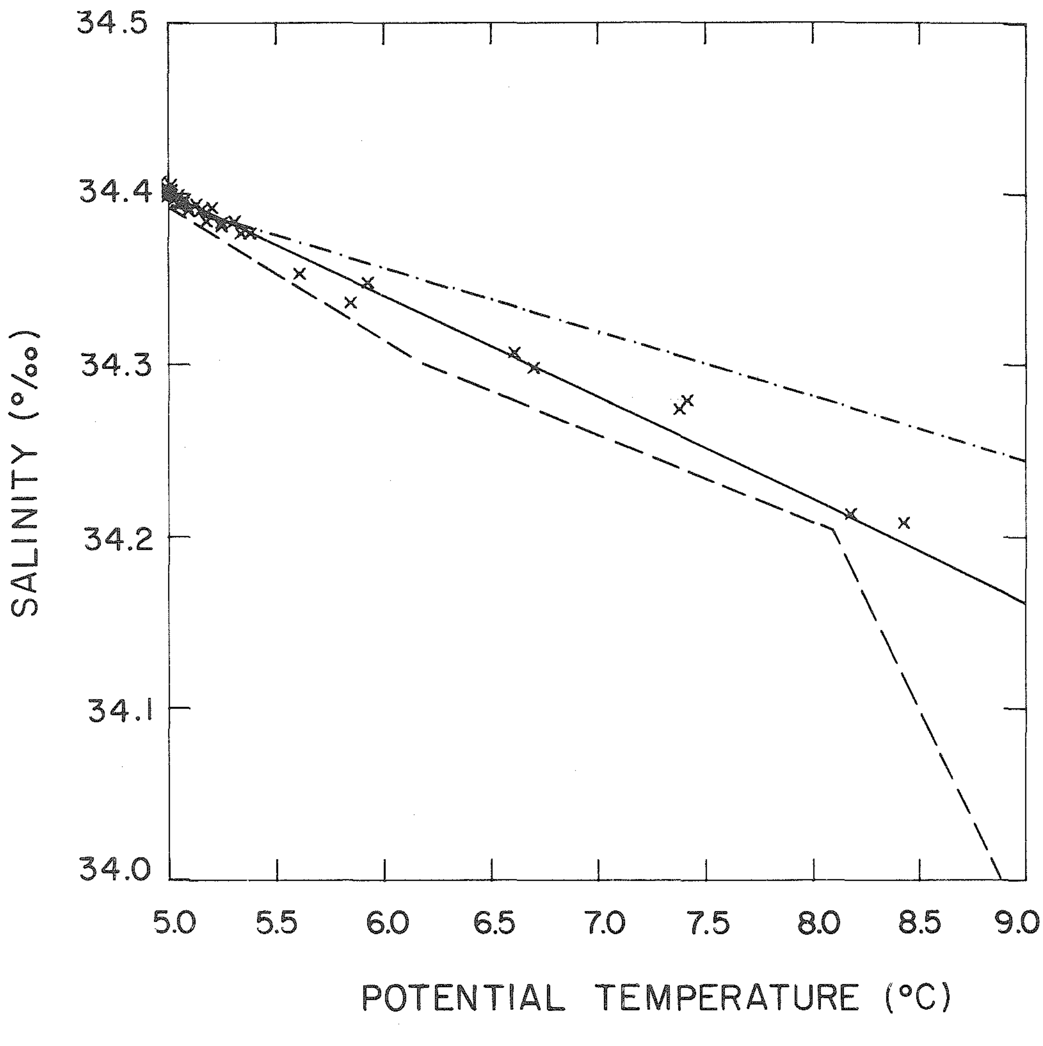

Figure 2-12 T-S Plot, November 1970, Santa Monica-San Pedro Basin. Solid line was hand fit to points. Dashed line is the hand fit for Santa Cruz Basin for July 1970; dot-dash line is the hand fit for San Diego Trough, July 1970 (see Fig. 2-10).

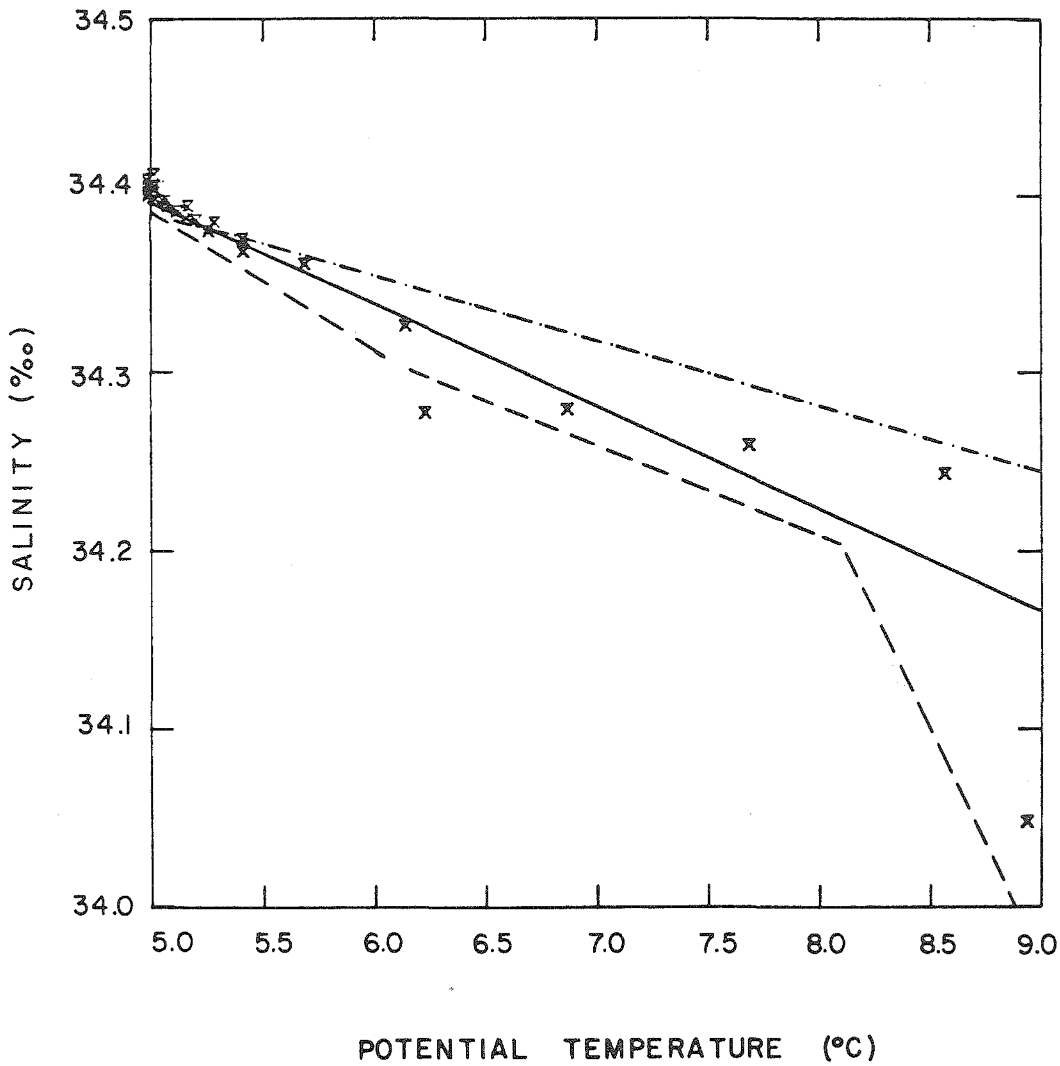

Figure 2-13 T-S plot, May 1971, Santa Monica-San Pedro Basin. Solid line is the hand fit for Santa Monica-San Pedro for November 1970; dashed line is the hand fit for Santa Cruz Basin, July 1970; dot-dash line is the hand fit for San Diego Trough, July 1970 (see Figs. 2-10, 2-11).

with both dissolved and oceanic sources. We consider the various substances to be at steady state. Concentrations are determined by physical and chemical processes discussed earlier in this appendix. Solution of differential equations describing the interactions is done numerically with a finite difference scheme.

The nonlinear, coupled differential equations used to describe concentrations of oxygen (ϕ), nitrate (ν), particulate organic matter (ψ), and oxidized organic matter (μ) are:

$$0 = -v_z \frac{\partial\phi}{\partial z} + \varepsilon_z \left(\frac{\partial^2\phi}{\partial z^2} + \frac{\partial\phi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) + (f_u + f_h)\phi\psi - \ell\frac{1}{A}\frac{dA}{dz} - r\psi \qquad (2\text{-}26a)$$

$$0 = -v_z \frac{\partial\nu}{\partial z} + \varepsilon_z \left(\frac{\partial^2\nu}{\partial z^2} + \frac{\partial\nu}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) + (f_u + f_h)\Delta\nu - 0.8\ell'\frac{1}{A}\frac{dA}{dz} - 0.8\, r'\psi \qquad (2\text{-}26b)$$

$$0 = -v_z \frac{\partial\psi}{\partial z} + \varepsilon_z \left(\frac{\partial^2\psi}{\partial z^2} + \frac{\partial\psi}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) + (f_u + f_h)\Delta\psi - v_s\frac{\partial\psi}{\partial z} - (r + r')\psi + \frac{g}{A} \qquad (2\text{-}26c)$$

$$0 = -v_z \frac{\partial\mu}{\partial z} + \varepsilon_z \left(\frac{\partial^2\mu}{\partial z^2} + \frac{\partial\mu}{\partial z}\left(\frac{1}{A}\frac{dA}{dz} + \frac{1}{\varepsilon_z}\frac{d\varepsilon_z}{dz}\right)\right) + (f_u + f_h)\Delta\mu + (r+r')\psi \qquad (2\text{-}26d)$$

where: f_u, f_h ε_z, v_z, A, g, are defined in section II of this appendix, and

ℓ	=	oxygen demand of sediments, moles $m^{-2}d^{-1}$
ℓ'	=	nitrate demand of sediments, moles $m^{-2}d^{-1}$
r	=	oxygen consumption rate of suspended sludge, particles d^{-1}
r'	=	nitrate consumption rate of suspended sludge, particles d^{-1}
$\Delta\nu$	=	$\nu - \nu_{ext}$
ν_{ext}	=	nitrate concentration of water entering basins at depth z
$\Delta\mu$	=	$\mu - \mu_{ext}$
μ_{ext}	=	concentration of organic matter entering basin at depth z

Values for f_u, f_h, ε_z, v_z, and A are functions only of depth. Values at any depth were calculated using the power series fits derived in the previous section (Figs. 2-4, 2-6, 2-9; Table 2-1).

Sludge input, g, is triangular, centered in the middle of a 10 meter band. If B is the sludge input rate, moles-oxygen equivalent d^{-1}, and z_{in} is the nominal input depth, then

$$
\begin{aligned}
g &= 0 && \text{if } z \le z_{in} \\
&= B(z-z_{in})/5 && \text{if } z_{in} \le z \le z_{in} + 5 \\
&= B(10-(z-z_{in}))/5 && \text{if } z_{in} + 5 \le z \le z_{in} + 10. \\
&= 0 && \text{if } z_{in} + 10. \le z
\end{aligned}
$$

The forms and values of r, r', ℓ, and ℓ' depend on which oxidation mechanisms are being considered. The three alternatives considered here involve oxygen utilization by sediments and sludge particles with no nitrate utilization, with nitrate utilization only by the sediments, or with nitrate utilization by sludge particles and sediments. The standard practice will be nitrate uptake by the sediments only.

TABLE 2-1

Standard Values of Parameters Expressed as Functions of Depth, Z(m)

A = basin area, m^2

$$= 10^6 \times (37.8957 - 1.51256\text{E-}2*Z - 1.11949\text{E-}4*Z^2 + 0.126566\text{E-}6*Z^3 - 3.93305\text{E-}11*Z^4)/(1 - 1.07884\text{E-}3*Z)$$

ν_{ext} = entering nitrate concentration, moles m^{-3}

$$= 1.050184\text{E-}2 + 8.870298\text{E-}5*Z - 7.899890\text{E-}8*Z^2 + 1.853268\text{E-}11*Z^3$$

ϕ_{ext} = entering oxygen concentration, moles m^{-3}

$$= 5.800599 - 2.180700\text{E-}2*Z + 2.832816\text{E-}5*Z^2 - 1.219102\text{E-}8*Z^3$$

ε_z = vertical eddy diffusivity, $m^2 d^{-1}$

$$= 6.308810 - 5.426779\text{E-}3*Z - 4.257471\text{E-}5*Z^2 + 7.383693\text{E-}8*Z^3$$

v_z = vertical advective velocity, $m\ d^{-1}$

$$= 1.531712 - 9.940010\text{E-}3*Z + 1.897540\text{E-}5*Z^2 - 1.069165\text{E-}8*Z^3 \quad \text{if } Z \le 740 \text{ m}$$

$$= -0.24 \quad \text{if } Z > 740 \text{ m}$$

f_h = horizontal exchange rate, d^{-1}

$$= -1.898462\text{E-}1 + 1.723385\text{E-}3*Z - 5.383155\text{E-}6*Z^2 + 7.103985\text{E-}9*Z^3 - 3.387205\text{E-}12*Z^4$$

$$\text{if } Z \le 740 \text{ m}$$

$$= 0 \quad \text{if } Z > 740 \text{ m}$$

Upper boundary was 300 m, lower boundary 900 m. Boundary conditions at 300 m were determined by assuming that surface water circulation sets the various concentration values. The more complex situation at the bottom boundary layer was handled differently for oxygen and nitrate than for the particulate and oxidized organics. Because water entering Santa Monica-San Pedro Basin from surrounding basins was assumed to have neither particulate nor oxidized organic matter, their concentrations were set to zero at 900 m. Sediment utilization of oxygen and nitrate is a function of their concentrations and has to be included in the bottom boundary condition formulations. If the flux away from the bottom equals the flux from water flowing over the sill into the basin minus the flux to the sediments, then the bottom condition oxygen is

$$\varepsilon_z(900\mathrm{m}) \left.\frac{\partial\phi}{\partial z}\right|_{900\mathrm{m}} - v_z(900\mathrm{m})\phi(900\mathrm{m}) = -v_z(900\mathrm{m})\phi_{ext}(900\mathrm{m}) - \ell(\phi(900\mathrm{m})) \tag{2-27a}$$

and for nitrate

$$\varepsilon_z(900\mathrm{m}) \left.\frac{\partial\nu}{\partial z}\right|_{900\mathrm{m}} - v_z(900\mathrm{m})\nu(900\mathrm{m}) = -v_z(900\mathrm{m})\nu_{ext}(900\mathrm{m}) - \ell'(\nu(900\mathrm{m})) \tag{2-27b}$$

where ℓ, ℓ' are defined in Table 2-2.

Trace metal release from sludge particulates was assumed to be at the same rate as particulate oxidation. Therefore, particulate trace metal concentrations are proportional to particulate sludge concentrations and dissolved metal concentration increases are proportional to oxidized organic concentrations, with proportionality factors being the same as those of pre-discharge sludge.

TABLE 2-2

Standard Oxidation Reaction Rates Used in Model

	No Nitrate Use	Nitrate Use by Sediments	Nitrate Use by Sediments and Sludge
Sludge degradation rates (d^{-1}) for oxygen, r	$r_{max} \frac{\beta}{1+\beta}$	$r_{max} \frac{\beta}{1+\beta}$	$r_{max} \frac{\beta}{1+\alpha+\beta}$
for nitrate, r'	0.	0.	$r_{max} \frac{\alpha}{1+\alpha+\beta}$
Sediment uptake rates (moles-O_2 equivalents $m^{-2}d^{-1}$) for oxygen, ℓ	$\ell_m \frac{\beta}{1+\beta}$	$\ell_n \frac{\beta}{1+\alpha+\beta}$	$\ell_n \frac{\beta}{1+\alpha+\beta}$
for nitrate, ℓ'	0.	$\ell_n \frac{\alpha}{1+\alpha+\beta}$	$\ell_n \frac{\alpha}{1+\alpha+\beta}$

where $\alpha = \nu/\nu_{cr}$

$\beta = \phi/\phi_{cr}$

ν_{cr} = half-saturation concentration of nitrate
= 39 mmoles m^{-3} = 39μM

ϕ_{cr} = half-saturation concentration of oxygen
= 6.7 mmoles m^{-3} = 6.7μM

ℓ_m = maximum sediment oxidant uptake without nitrate uptake
= 10.7 mmoles m^{-2} d^{-1} = 10.7 μM $Z \leq 740$ M
= 3.8 mmoles m^{-2} d^{-1} = 3.8 μM $Z > 740$ M

ℓ_n = maximum sediment oxidant uptake with nitrate and oxygen uptake
= 14.2 mmoles m^{-2} d^{-1} = 14.2μM $Z \leq 740$ M
= 5.8 mmoles m^{-2} d^{-1} = 5.8 μM $Z > 740$ M

r_{max} = maximum rate of sludge particle degradation
= 0.01 d^{-1}

Standard values for all remaining constants used in the model are shown in Table 2-3.

We solved the differential equations describing the linked behaviors of sludge, oxygen, and nitrate numerically, using a finite difference scheme incorporating Newton's method to handle the nonlinear interactions. The program package, PASVA3, was developed and described by V. Pereyra (Pereyra,1965, Lentini and Pereyra,1977).

Oxygen and nitrate concentration profiles calculated for no sludge discharge with nitrate uptake by the sediments are similar to observed profiles (Figures 2-14, 2-15). Because horizontal exchange rates were determined to account for oxygen concentrations, the fit to the oxygen profile is not surprising; the fit for nitrate, with the only extra parameters being ν_{cr} and ν_{ext} is satisfying.

Sludge discharge at 400 m without nitrate sludge oxidation results in a small decrease in oxygen concentration between 400 and 500 m (Figure 2-16). Oxidizable particulate sludge is predominantly within 100 meters of the discharge depth (Figure 2-17). Importance of oxidation in confining the sludge to such a narrow depth range is shown by comparison with sludge profile if there were no oxidation (Figure 2-18). Concentration decreases in the latter case are by horizontal exchange with other basins. This figure is the same as that of non-oxidizable sludge particulate matter to within a constant factor. This inert sludge will be ignored in the rest of this report because of its non-interacting nature.

TABLE 2-3

Standard Input Values for Basin Model

Substance	Sludge Input (moles d^{-1})	External Basin Concentration (moles m^{-3})	
BOD	2.0×10^{7}	0.	
Cd	9.75×10^{2}	$9. \times 10^{-6}$	(1)
Cr	2.82×10^{4}	9.6×10^{-7}	(2)
Cu	2.10×10^{4}	2.0×10^{-6}	(3)
Pb	2.5×10^{3}	1.3×10^{-7}	(2)
Ni	5.0×10^{3}	3.4×10^{-5}	(4)
Ag	5.6×10^{2}	3.7×10^{-7}	(2)
Zn	3.7×10^{4}	$5. \times 10^{-6}$	(5)

$\psi(300m)$ = particulate organic concentration at 300m (upper boundary)
= 0

$\nu(300m)$ = nitrate concentration at 300m
= 30 mmoles m^{-3} = 30μM

$\phi(300m)$ = dissolved oxygen concentration at 300m
= 62 mmoles m^{-3} = 62μM

$\mu(300m)$ = oxidized oragnic matter concentration at 300m
= 0

v_s = settling velocity of particulate organic
= 0.78 m d^{-1}

(1) from Boyle, Sclater, and Edmond, 1976.
(2) from Morgan and Sibley, 1975.
(3) from Boyle, Sclater, and Edmond, 1977.
(4) from Sclater, Boyle, and Edmond, 1976.
(5) from Bruland, Knauer, and Martin, 1978.

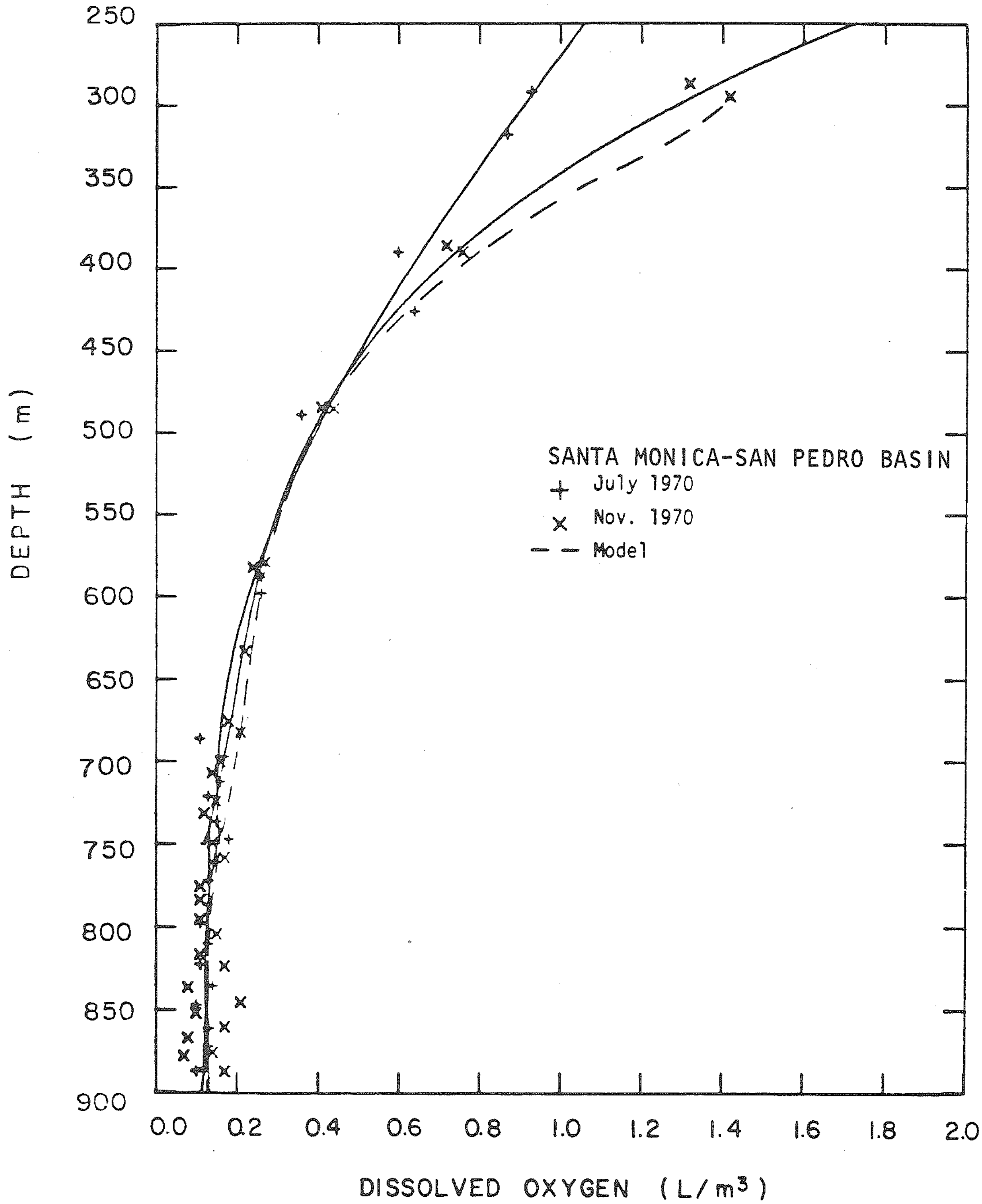

Figure 2-14 Dissolved oxygen concentrations in Santa Monica-San Pedro Basin. Dashed line represents results of model calculation with no sludge input.

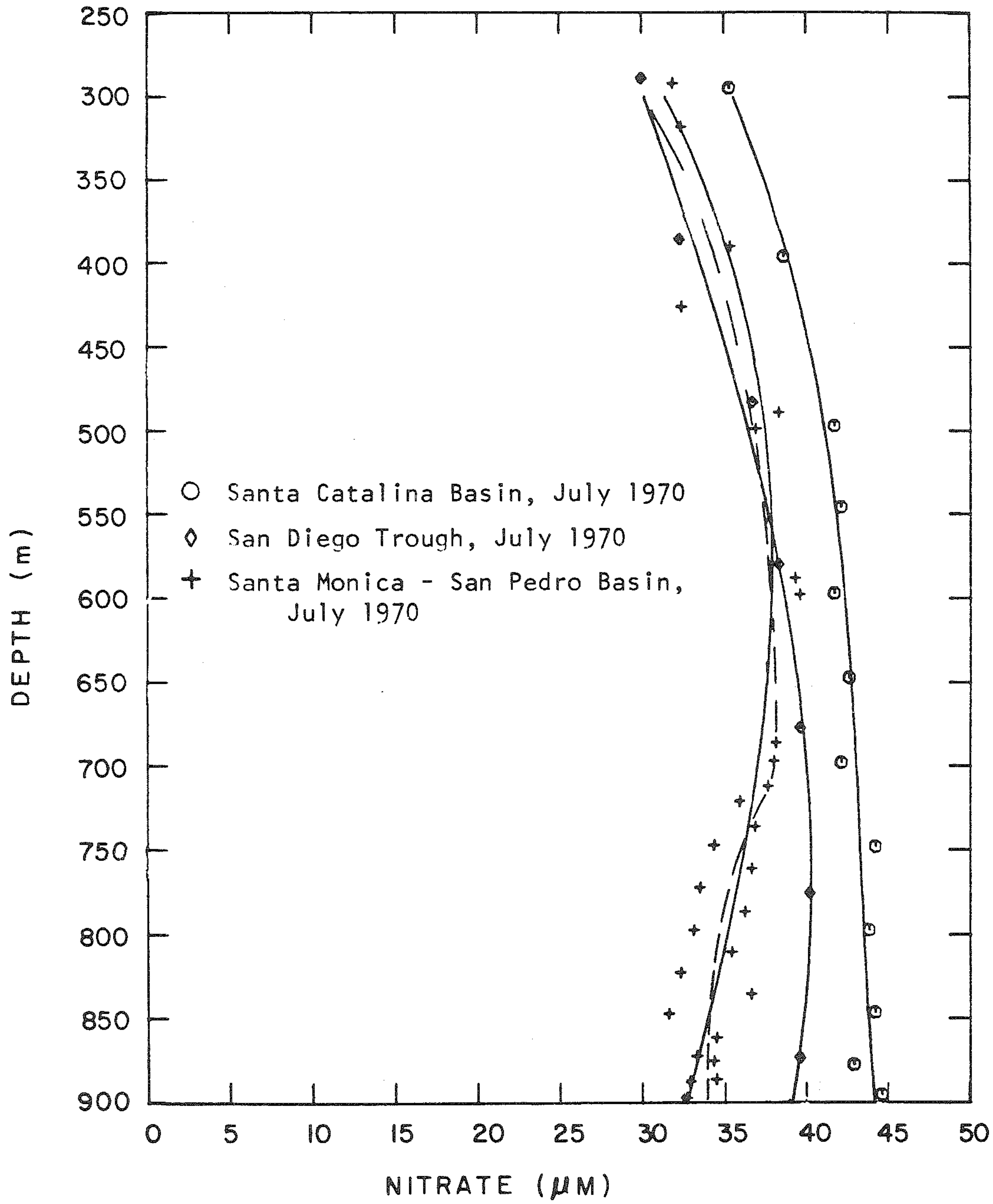

Figure 2-15 Nitrate concentration in various offshore basins. Dashed line represents model values for no sludge input.

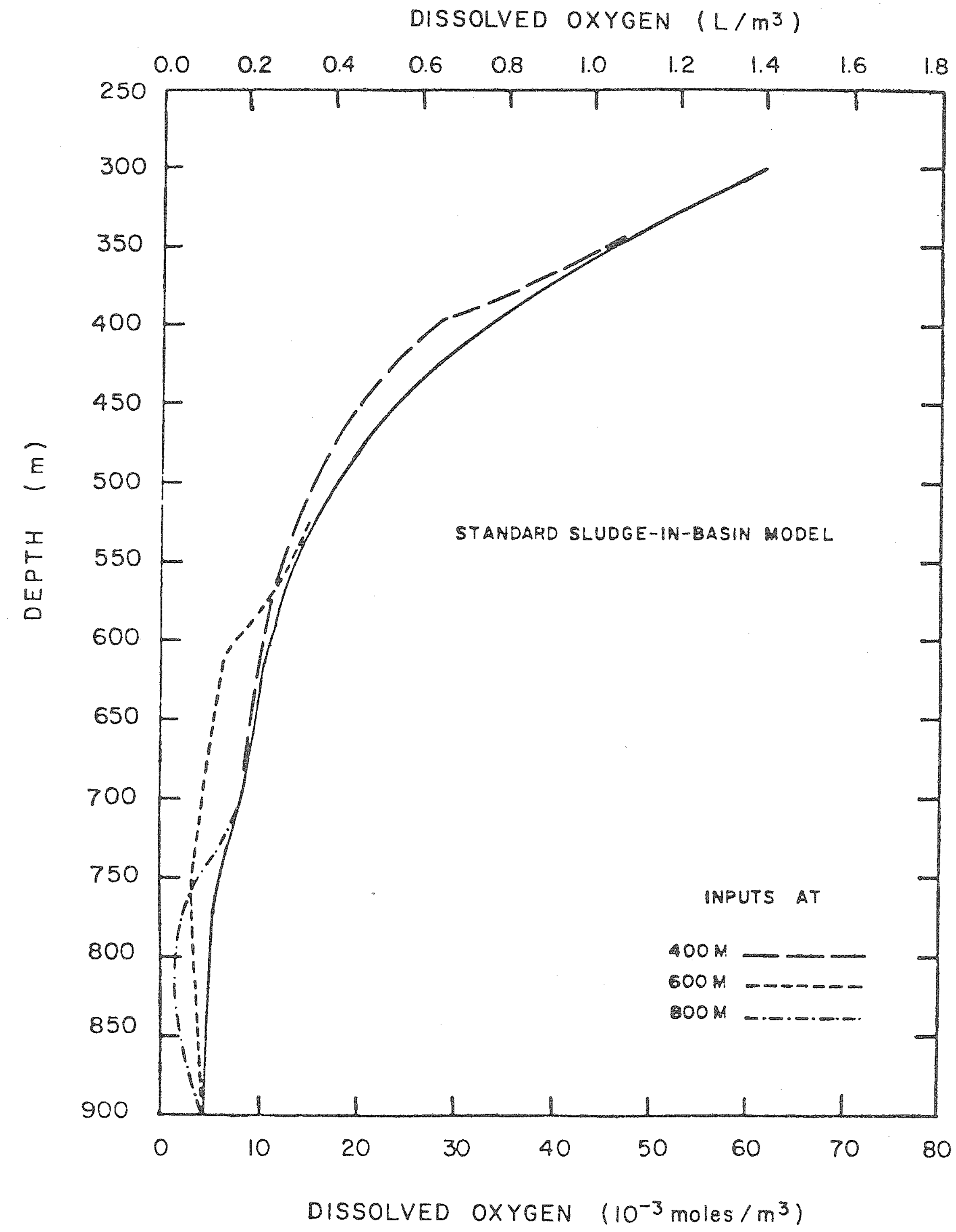

Figure 2-16 Dissolved oxygen concentration in Santa Monica-San Pedro Basin for standard conditions, only oxygen reaction with sludge particles. Sludge inputs are to 400, 600, 800 m. Solid line represents no discharge condition.

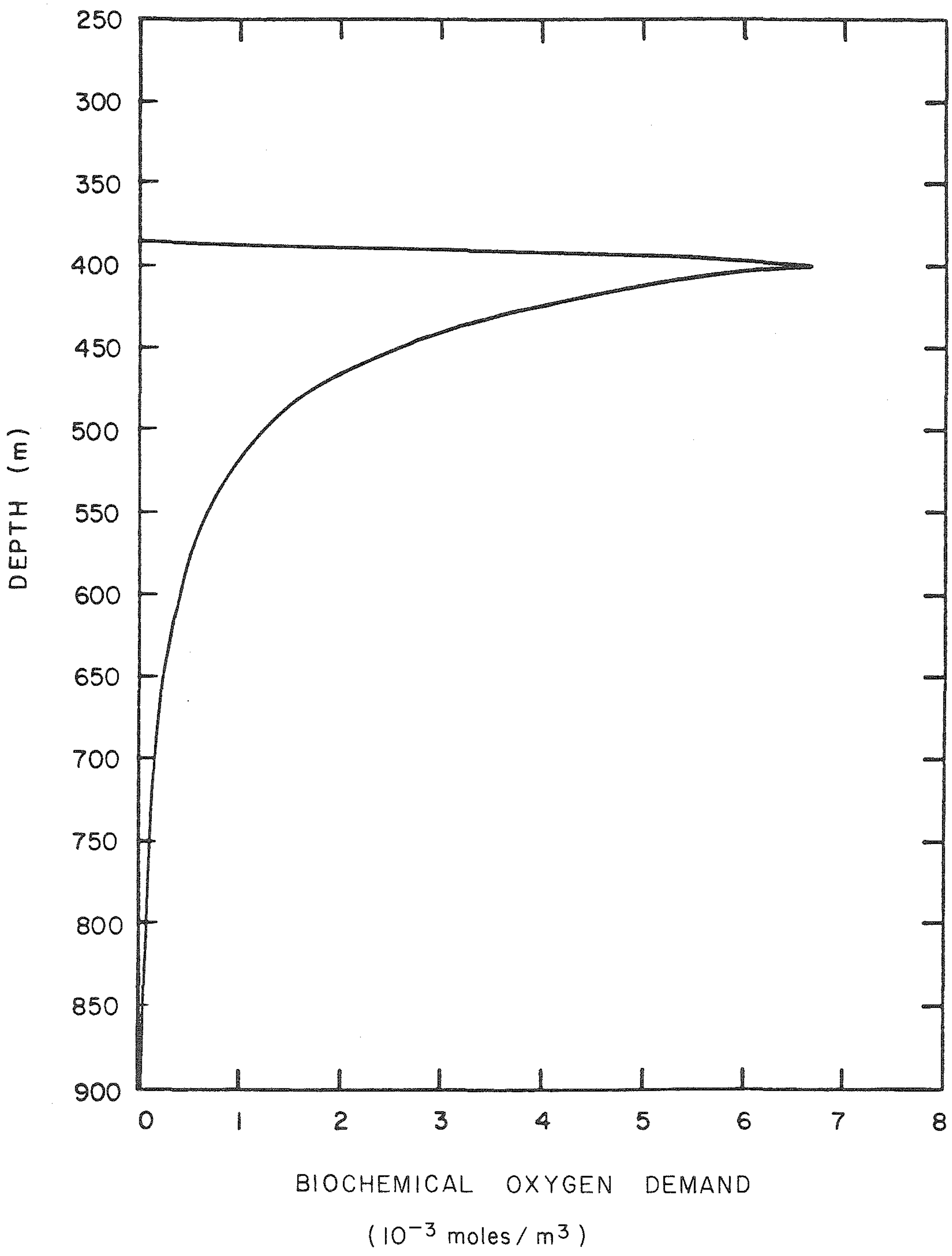

Figure 2-17 Concentration of particulate sludge (oxygen-demanding fraction) in Santa Monica-San Pedro for discharge at 400 m under standard conditions.

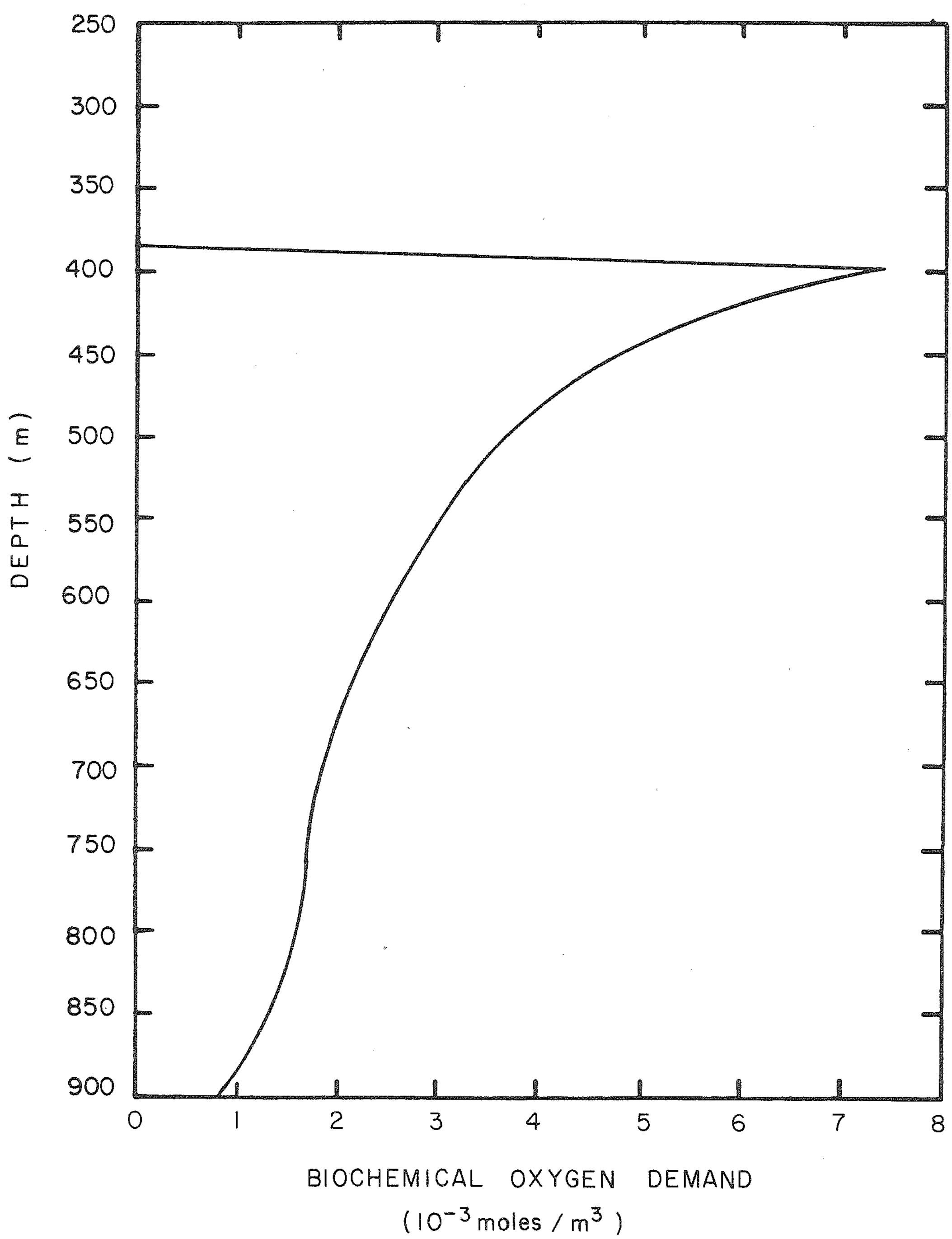

Figure 2-18 Concentration of particulate sludge in Santa Monica-San Pedro Basin for discharge at 400 m with no decomposition.

Sludge input also increases trace metal concentrations. Particulate trace metal distributions are the same as those of the particulate organic matter (Figure 2-17), although absolute concentrations are different. Dissolved trace metal concentrations are not as sharp as particulates (Figure 2-19). Maximum concentration of the dissolved trace metal copper would be three and a half times the background concentration for the case considered.

This model ignores increased sediment respiration caused by increased organic matter sedimentation. Calculation of maximum increases using the sludge particulate distributions in Figure 2-17 shows that this is reasonable. The maximum sedimentation rate is the maximum particle concentration, 7×10^{-3} moles-BOD m^{-3}, times the settling velocity, 0.7 m d^{-1}, which is a value of 5×10^{-3} moles BOD $m^{-2}d^{-1}$. Were this all to be oxidized in the sediments, it would increase the background oxygen demand of 10×10^{-3} moles-O_2 $m^{-2}d^{-1}$ by 50%. Incomplete oxidation of this organic matter would decrease this value. Furthermore, the rapid decrease in particulate concentration with depth would limit this large a change in sediment oxygen demand to a small area. Therefore, the omission of increased sediment oxygen demand is a reasonable approximation for a basin model. However, in local areas around an outfall this might not be true (see Section VI).

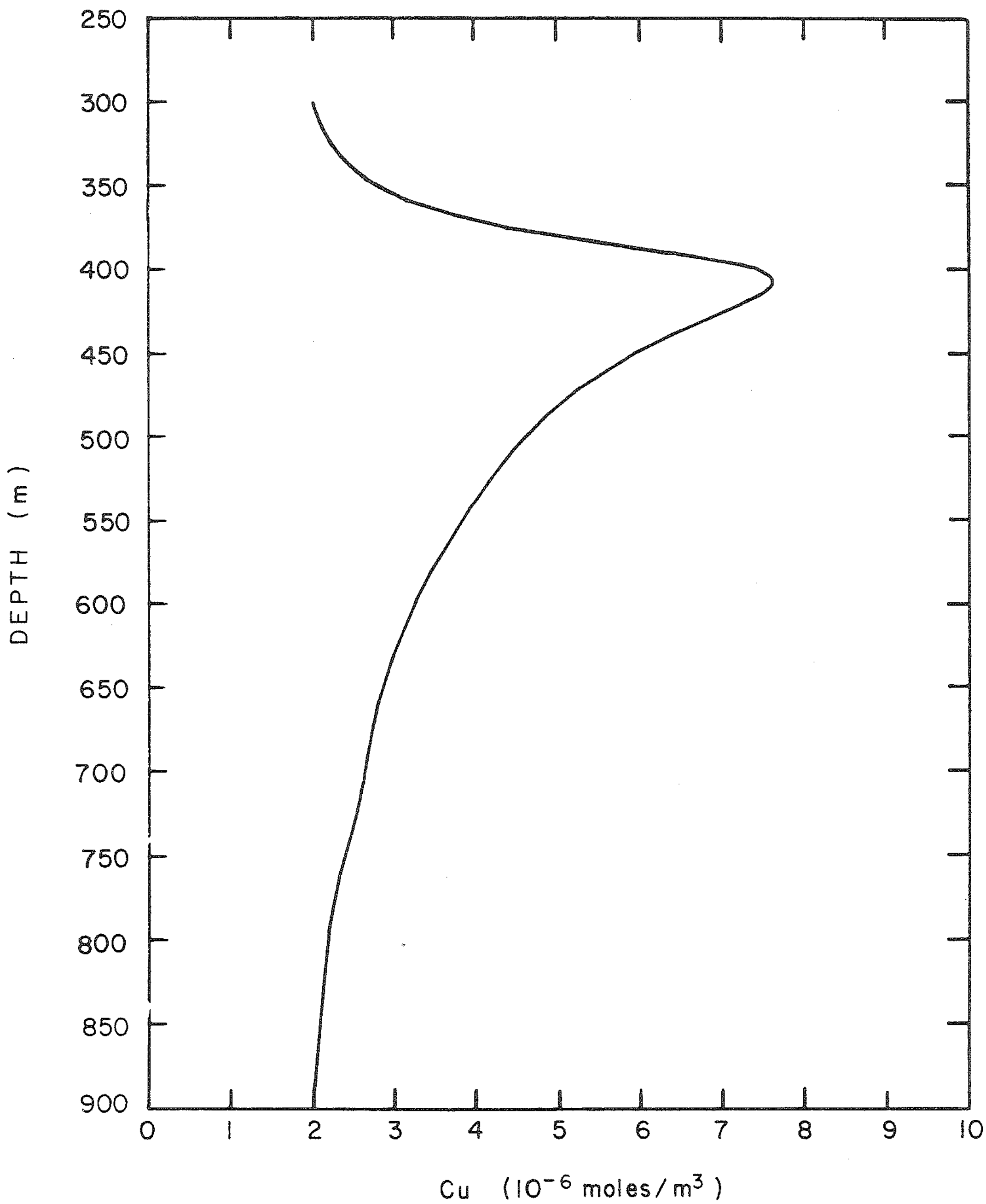

Figure 2-19 Dissolved copper concentration for sludge discharge at 400 m under standard conditions.

VI. REFERENCES FOR APPENDIX 2

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APPENDIX 3

REGIONAL WASTEWATER SOLIDS MANAGEMENT PROGRAM
LOS **A**NGELES/**O**RANGE COUNTY **M**ETROPOLITAN **A**REA
WRITE: **LA/OMA** PROJECT, P.O. BOX 4998, WHITTIER, CA. 90607 TEL: (213) 699-7411

April 5, 1978

Prof. Norman Brooks
California Institute of Technology
1201 East California Blvd.
Pasadena, California 91125

MASS EMISSION DATA FOR SLUDGE METALS AND TRACE ORGANICS

Enclosed are the mass emission data for sludge metals and trace organics as required for analysis of the effects of ocean disposal alternatives for sludge according to Contract No. 2290. Please note that there are two sets of projections for the year 2000; one involving the case of secondary treatment for total plant flow (full secondary), and the other assuming secondary treatment for partial plant flow to meet projected requirements for marine secondary treatment.

We will shortly send you another set of projected data which will reflect the impact of proposed EPA pretreatment guidelines on sludge metals and trace organics.

If you have any questions, please call Sagar Raksit.

Bill Davis

Bill Davis
Project Manager

BD:SKR:mar

Enclosures:

TABLE 3-1

PROJECTED SLUDGE LOADS FOR

THE LA/OMA AGENCY PLANTS FOR THE YEAR 2000

	JWPCP		HYPERION		OCSD	
	Primary	WAS	Primary	WAS	Primary	WAS
1. Full Secondary Treatment						
a. Secondary Flow, MGD	275		400		280	
b. Raw Sludge Quantity, Dry Tons/Day	530	175	320	220	260	180
2. Marine Secondary Treatment						
a. Assumed Secondary Flow, MGD	200		200		121	
b. Raw Sludge Quantity, Dry Tons/Day	530	128	320	112	260	78

TABLE 3-2

MEASURED AND PROJECTED SLUDGE METAL AND TRACE ORGANICS CONCENTRATIONS
FULL SECONDARY TREATMENT

	HTP, CLA			JWPCP, LACSD			OCSD		
	Plant Input	1976 Digested Primary	2000 Digested Prim & WAS	Plant Input	1976 Digested Primary	2000 Digested Prim & WAS	Plant Input	1976 Digested Primary	2000 Digested Prim & WAS
Sludge Quantity, (dry tons/day)		170	370+		249	475+		98	300+
TRACE METALS (lbs/day)									
As	30	10	15	--	--	--	--		--
Hg	9	3	8	5	3	4	--		--
Ag	100	30	80	49	24	39	20	13	16
Cd	103	45	91	84	36	74	84	30	74
Ni	575	124	207	950	227	342	284	77	102
Pb	167	57	130	924	603	721	388	183	303
Cr	1250	401	1113	1920	1022	1709	466	148	415
Cu	1216	577	1070	1150	625	1012	979	468	862
Zn	1500	725	1200	3870	2077	3096	1304	612	1043
TRACE ORGANICS (lbs/day)									
DDT's	0.26	0.23	0.23	6	4.5	5.4	0.15	0.03	0.09
PCB's	2.1	0.65	1.40	7	4.0	6	6.8	1.18	2.76
TICH	2.4	0.75	1.60	13	8.8	12	7.0	1.20	2.85
Chlorinated Benzene	51.0	22.00	47.00	80	--	67	43.5	--	32

HTP - Hyperion Treatment Plant (City of Los Angeles)
JWPCP - Joint Water Pollution Control Plant (LACSD)
OCSD - Orange County Sanitation Districts

+ - Based on projected primary and WAS productions in year 2000 and estimated volatiles destruction during anaerobic digestion. Effect of process sidestreams not included.

TABLE 3-2 (Continued)

ASSUMPTIONS

1. Removal Efficiencies are as per RWQCB, LA Region, NPDES Permit for JWPCP, #CA 0053813, June 1977, and are shown below:

Constituents	Removal Effluent %
TRACE METALS	
As	49
Hg	83
Ag	80
Cd	88
Ni	36
Pb	78
Cr	89
Cu	88
Zn	80
TRACE ORGANICS	
DDT's	77
PCB's	66
TICH	66
Chlorinated Benzene	92

2. MER values for the year 1976 were obtained by multiplying the respective sludge quantities by measured metal concentrations.

3. MER values for the year 2000 (full secondary) was determined by multiplying the plant inputs for various constituents by their respective removal efficiencies.

4. The respective plant inputs for various constituents for 1976 were obtained from the following sources:

   a. Hyperion: 1976 inputs from Dept. of Public Works, "1976 Averages, Chemical Analysis of Sewage," Trace Organics inputs were back calculated from effluent concentrations using SCCWRP data.

   b. JWPCP: 1976 inputs assumed; N. Ackerman, "Conc. and Mass Flow Rates of Trace Constituents in the JOS System, 1971-76," August 1977.

   c. OCSD: 1976 inputs, "1976 Annual Report to the RWQCB, Santa Ana Region," Jan. 1978, Trace Organics inputs and MER's in sludge back calculated from 1976 sludge conc.

5. The plant inputs for the year 2000 have been assumed to remain the same as those for the year 1976.

TABLE 3-3

PROJECTED SLUDGE METAL AND TRACE ORGANICS EMISSIONS
IN THE YEAR 2000
FOR MARINE SECONDARY TREATMENT
(in LBS/DAY)

	HYPERION			JWPCP			OCSD		
	Plant	MER in Sludge		Plant	MER in Sludge		Plant	MER in Sludge	
Trace Metals	Input	Primary	WAS	Input	Primary	WAS	Input	Primary	WAS
As	30	10	2.5	NA	--	--	--	--	--
Hg	9	3	2.5	5	3	0.7	--	--	--
Ag	100	30	25	49	24	11	20	13	1.3
Cd	103	45	23	84	36	28	84	30	19
Ni	575	124	42	950	227	84	284	77	11
Pb	167	57	37	924	603	36	388	183	52
Cr	1250	401	356	1920	1022	500	466	148	115
Cu	1216	577	247	1150	625	281	979	468	170
Zn	1500	725	238	3870	2077	741	1304	612	186
Trace Organics									
DDT's	0.26	0.23	0	6	4.5	0.65	0.15	0.03	0.03
PCB's	2.1	0.65	0.38	7	4.0	1.5	6.8	1.18	0.68
TICH	2.4	0.75	0.43	13	9.0	2.2	7.0	1.20	0.71
Chlorinated Benzene	51	22.00	13.00	80	22.61	32.05	43.5	9.6	9.8
Digested Prim & WAS, dtpd*		285			440			225	

*Based on projected primary and WAS productions in year 2000 and estimated volatiles destruction during anaerobic digestion. Effect of process sidestreams not included.

**MERs are estimated as follows:

a. MER_{prim}: same as for 1976 MER

b. MER digested WAS = $(MER_{2000\text{-full secondary}} - MER_{Prim}) \times \frac{\text{Marine Secondary Flow}}{\text{Full Secondary Flow}}$

APPENDIX 4

DATA BASES

The data used in this study were collected by E. Sholkovitz and J. Gieskes. The complete set will be published as a CALCOFI (California Cooperative Oceanic Fisheries Investigation) data report in 1978 or 1979. Data used in this study were obtained from Joris Gieskes of the Scripps Institution of Oceanography, La Jolla, California, and are reproduced with his permission (Tables 4-1 to 4-10).

An intensive spatial survey of Santa Monica-San Pedro Basin hydrography was performed by the FWPCA (Federal Water Pollution Control Administration) in 1968. Data can be obtained from David R. Minard, Region IX, United States Environmental Protection Agency, 100 California St., San Francisco, California, 94111.

The Bureau of Land Management has supported a survey of the entire Southern California Bight. These data can be obtained from Science Applications, Incorporated, 1200 Prospect St., P.O. Box 235, La Jolla, California, 92038.

TABLE 4-1

Oceanographic profile data for Santa Cruz Basin, July 13, 1970 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 7 OP BASIN	7	130770	3339.00	11931.40	1901	NO. SAMP=35	SANTA CRUZ BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		18.40	18.40	33.583	6.01	24.110	*****	*****	*****
25.		10.87	10.87	33.617	4.56	25.744	*****	*****	*****
50.		9.59	9.58	33.811	3.28	26.114	*****	*****	*****
100.		8.98	8.97	33.972	2.70	26.339	*****	*****	*****
201.		8.32	8.30	34.149	1.68	26.582	*****	*****	*****
300.		7.68	7.65	34.227	0.98	26.740	*****	*****	*****
399.		6.96	6.92	34.263	0.59	26.871	*****	*****	*****
498.		6.23	6.18	34.303	0.35	27.000	*****	*****	*****
596.		5.62	5.57	34.349	0.27	27.114	*****	*****	*****
695.		5.17	5.11	34.383	0.25	27.195	*****	*****	*****
744.		4.86	4.80	34.411	0.23	27.254	*****	*****	*****
794.		4.70	4.63	34.419	0.24	27.278	*****	*****	*****
844.		4.55	4.48	34.438	0.24	27.310	*****	*****	*****
894.		4.42	4.35	34.449	0.24	27.333	*****	*****	*****
944.		4.34	4.26	34.453	0.25	27.346	*****	*****	*****
994.		4.27	4.19	34.461	0.26	27.360	*****	*****	*****
1045.		4.24	4.15	34.463	0.27	27.365	*****	*****	*****
1091.		4.19	4.10	34.465	0.26	27.372	*****	*****	*****
1138.		4.19	4.10	34.465	0.26	27.373	*****	*****	*****
1185.		4.18	4.08	34.465	0.27	27.374	*****	*****	*****
1233.		4.17	4.07	34.460	0.28	27.372	*****	*****	*****
1280.		4.16	4.05	34.463	0.26	27.376	*****	*****	*****
1327.		4.15	4.04	34.462	0.26	27.376	*****	*****	*****
1375.		4.16	4.05	34.462	0.28	27.376	*****	*****	*****
1423.		4.17	4.05	34.461	0.27	27.374	*****	*****	*****
1471.		4.16	4.04	34.462	0.27	27.377	*****	*****	*****
1519.		4.17	4.04	34.460	0.27	27.375	*****	*****	*****
1567.		4.18	4.05	34.461	0.17	27.375	*****	*****	*****
1617.		4.18	4.04	34.457	0.25	27.372	*****	*****	*****
1665.		4.17	4.03	34.465	0.21	27.380	*****	*****	*****
1714.		4.18	4.03	34.465	0.21	27.379	*****	*****	*****
1763.		4.18	4.03	34.454	0.26	27.371	*****	*****	*****
1813.		4.18	4.02	34.461	0.30	27.377	*****	*****	*****
1862.		4.21	4.05	34.467	0.25	27.379	*****	*****	*****
1893.		4.19	4.02	******	0.30	******	*****	*****	*****

TABLE 4-2

Oceanographic profile data for Santa Monica Basin, July 14, 1970
(by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR CATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 7 OP BASIN	8	140770	3345.80	11848.20	900	NO. SAMP=17	SANTA MONICA

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		19.80	19.80	33.611	5.94	23.777	0.8	*****	*****
101.		9.30	9.29	33.865	3.15	26.205	29.4	*****	23.0
200.		8.35	8.33	34.125	1.87	26.558	45.9	*****	30.1
318.		8.40	8.36	34.282	0.87	26.676	55.6	*****	32.4
426.		7.49	7.45	34.287	0.64	26.816	63.3	*****	32.4
499.		6.62	6.57	34.298	*****	26.945	75.2	*****	36.9
598.		5.88	5.83	34.325	0.26	27.063	88.3	*****	39.6
697.		5.31	5.25	34.379	0.17	27.176	106.3	*****	38.0
721.		5.25	5.19	34.381	0.13	27.185	109.5	*****	35.9
747.		5.19	5.13	34.384	0.18	27.194	111.7	*****	34.3
772.		5.17	5.10	34.390	0.13	27.202	113.9	*****	33.5
797.		5.14	5.07	34.390	0.11	27.206	116.0	*****	33.1
822.		5.13	5.06	34.393	0.11	27.209	117.1	*****	32.3
847.		5.11	5.04	34.400	0.10	27.217	117.1	*****	31.6
872.		5.08	5.00	34.397	0.13	27.219	117.1	*****	33.3
887.		5.08	5.00	34.399	0.10	27.221	117.1	*****	32.9
897.		4.06	3.99	34.397	0.10	27.330	117.1	*****	32.7

TABLE 4-3

Oceanographic profile data for San Pedro Basin, July 16, 1970 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 7 OP BASIN	9	160770	3331.60	11824.00	890	NO. SAMP=18	SAN PEDRO BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
1.		18.56	18.56	33.540	5.96	24.038	1.2	*****	*****
49.		10.65	10.64	33.547	4.46	25.729	14.2	*****	13.7
98.		9.35	9.34	33.828	3.30	26.168	27.5	*****	22.3
195.		8.90	8.88	34.207	1.55	26.537	43.3	*****	28.3
292.		8.16	8.13	34.270	0.93	26.702	53.6	*****	31.9
390.		7.32	7.28	34.291	0.60	26.843	64.6	*****	35.4
489.		6.49	6.44	34.303	0.36	26.966	75.6	*****	38.3
588.		5.77	5.72	34.330	0.26	27.081	87.0	*****	39.3
686.		5.30	5.24	34.371	0.11	27.171	100.1	*****	38.1
712.		5.25	5.19	34.375	0.16	27.179	101.2	*****	37.6
736.		5.19	5.13	34.377	0.15	27.189	103.4	*****	36.8
761.		5.16	5.09	34.383	0.15	27.197	105.0	*****	36.6
786.		5.13	5.06	34.386	0.13	27.203	106.6	*****	36.2
810.		5.12	5.05	34.388	0.13	27.206	107.2	*****	35.4
835.		5.08	5.01	34.389	0.14	27.212	107.7	*****	36.6
861.		5.03	4.96	34.395	0.13	27.223	111.0	*****	34.5
875.		5.06	4.98	34.395	0.13	27.220	112.0	*****	34.3
886.		5.04	4.96	34.394	0.12	27.221	112.0	*****	34.5

TABLE 4-4

Oceanographic profile data for San Diego Trough, July 26, 1970
(by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 7 CP BASIN	13	260770	32.32	117.46	1230	NO. SAMP=18	SAN DIEGO TROUGH

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		19.44	19.44	33.591	5.65	23.854	1.9	*****	*****
19.		14.22	14.22	33.496	5.99	25.001	5.3	*****	0.9
38.		11.15	11.14	33.574	4.48	25.660	13.6	*****	14.7
57.		10.38	10.37	33.684	3.78	25.882	19.3	*****	19.4
95.		9.66	9.65	33.946	2.85	26.209	29.4	*****	23.1
144.		9.30	9.28	34.086	2.38	26.378	35.4	*****	26.1
192.		9.12	9.10	34.193	1.80	26.491	40.8	*****	28.6
289.		8.61	8.58	34.259	1.27	26.625	47.9	*****	30.0
386.		7.81	7.77	34.292	0.84	26.773	58.3	*****	32.3
483.		6.95	6.90	34.325	0.56	26.922	70.3	*****	36.7
580.		6.34	6.28	34.345	0.32	27.020	75.5	*****	38.3
677.		5.58	5.52	34.369	0.24	27.136	90.4	*****	39.6
775.		4.97	4.90	34.409	0.30	27.240	100.2	*****	40.2
873.		4.61	4.54	34.428	0.37	27.296	106.8	*****	39.6
970.		4.29	4.21	34.450	0.49	27.349	112.8	*****	39.0
1068.		3.91	3.83	34.487	0.52	27.418	120.4	*****	37.2
1166.		3.60	3.51	34.519	0.66	27.475	128.0	*****	38.6
1205.		3.47	3.38	34.523	0.72	27.491	129.2	*****	38.4

TABLE 4-5

Oceanographic profile data for Santa Monica Basin, November 8, 1970 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 8 SBNOV 70	7	81170	33.46	118.48	890	NO. SAMP=18	S MONICA BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		16.46	16.46	33.523	5.87	24.528	14.8	0.49	*****
97.		10.06	10.05	33.718	3.69	25.964	17.3	1.46	*****
198.		9.08	9.06	34.085	2.25	26.414	31.0	2.31	23.7
295.		8.46	8.43	34.208	1.42	26.608	39.8	2.58	26.9
390.		7.46	7.42	34.279	0.76	26.813	52.2	3.07	30.8
485.		6.75	6.70	34.298	0.44	26.928	61.1	3.34	32.7
579.		5.98	5.93	34.348	0.27	27.069	74.0	3.47	33.5
675.		5.44	5.38	34.377	0.18	27.159	84.7	3.65	33.2
700.		5.37	5.31	34.384	0.16	27.173	87.3	3.75	32.2
724.		5.31	5.25	34.383	0.15	27.179	87.9	3.76	31.2
749.		5.27	5.20	34.392	0.14	27.191	89.9	3.80	30.5
775.		5.22	5.15	34.390	0.11	27.196	91.7	3.90	28.9
795.		5.20	5.13	34.394	0.11	27.202	92.8	3.91	28.1
816.		5.15	5.08	34.397	0.11	27.210	94.8	3.88	26.9
836.		5.12	5.05	34.399	0.08	27.215	97.8	3.95	25.6
852.		5.09	5.02	34.405	0.10	27.224	99.8	4.00	24.8
867.		5.09	5.01	34.402	0.08	27.222	102.8	4.04	22.6
878.		5.07	4.99	34.401	0.07	27.223	102.7	4.07	21.4

TABLE 4-6

Oceanographic profile data for San Pedro Basin, November 9, 1970 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 8 SBNOV 70	8	91170	33.32	118.24	900	NO. SAMP=20	S PEDRO

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		16.79	16.79	33.567	5.94	24.485	1.9	0.59	*****
36.		12.36	12.35	33.429	5.00	25.323	6.8	0.94	4.9
87.		10.40	10.39	33.662	3.69	25.862	15.8	1.51	11.5
187.		9.21	9.19	34.106	2.20	26.409	31.7	2.26	18.2
287.		8.21	8.18	34.213	1.32	26.650	45.3	2.66	21.5
386.		7.42	7.38	34.274	0.72	26.815	54.4	3.09	22.7
484.		6.66	6.61	34.307	0.41	26.947	64.9	3.36	25.9
582.		5.90	5.85	34.336	0.24	27.069	82.3	3.62	26.6
633.		5.67	5.61	34.353	0.22	27.112	87.0	3.75	26.3
682.		5.40	5.34	34.377	0.21	27.164	91.6	3.73	26.1
707.		5.31	5.25	34.381	0.14	27.178	94.2	4.08	24.8
731.		5.24	5.18	34.384	0.12	27.188	96.2	3.87	23.7
758.		5.16	5.09	34.390	0.17	27.203	94.1	3.92	25.6
783.		5.14	5.07	34.395	0.11	27.209	100.1	3.97	22.9
804.		5.12	5.05	34.393	0.15	27.210	98.0	3.84	23.1
823.		5.10	5.03	34.397	0.17	27.216	97.9	3.61	25.4
845.		5.09	5.02	34.399	0.21	27.219	97.8	3.66	26.2
860.		5.07	5.00	34.398	0.17	27.221	98.8	3.62	25.3
876.		5.04	4.96	34.407	0.14	27.231	102.8	3.63	24.3
887.		5.05	4.97	34.401	0.17	27.226	102.7	3.65	24.4

TABLE 4-7

Oceanographic profile data for San Pedro Basin, February 3, 1971 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 9 SBFEB-71	1	30271	33.32	118.24	878	NO. SAMP=20	S PEDRO BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		13.20	13.20	33.360	6.02	25.104	*****	*****	*****
50.		11.26	11.25	33.493	4.31	25.578	19.1	*****	*****
100.		10.08	10.07	33.728	3.68	25.969	*****	*****	*****
199.		8.95	8.93	34.127	2.27	26.467	43.4	*****	*****
300.		7.97	7.94	34.244	1.16	26.710	*****	*****	*****
401.		7.15	7.11	34.291	0.63	26.867	68.8	*****	*****
501.		6.31	6.26	34.324	0.40	27.007	*****	*****	*****
602.		5.67	5.62	34.361	0.26	27.117	93.0	*****	*****
651.		5.46	5.40	34.376	0.22	27.155	*****	*****	*****
677.		5.42	5.36	34.377	0.21	27.161	100.1	*****	*****
702.		5.30	5.24	34.385	0.20	27.182	*****	*****	*****
728.		5.25	5.19	34.388	0.22	27.190	103.6	*****	*****
752.		5.19	5.13	34.395	0.20	27.203	*****	*****	*****
778.		5.16	5.09	34.400	0.19	27.211	97.6	*****	*****
802.		5.12	5.05	34.400	0.18	27.216	*****	*****	*****
828.		5.11	5.04	34.402	0.19	27.219	104.5	*****	*****
853.		5.10	5.03	34.402	0.17	27.220	108.1	*****	*****
863.		5.09	5.01	34.405	0.19	27.224	103.8	*****	39.2
878.		5.07	4.99	34.405	0.18	27.226	108.2	*****	35.6
894.		5.06	4.98	34.405	0.18	27.228	113.1	*****	34.8

TABLE 4-8

Oceanographic profile data for Santa Monica Basin, February 3, 1971 (by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 9 SBFEB-71	2	30271	33.46	118.49	885	NO. SAMP=20	S MONICA BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
0.		13.14	13.14	33.391	6.35	25.140	*****	*****	*****
50.		10.71	10.70	33.875	4.48	25.973	22.7	*****	*****
100.		9.70	9.69	******	3.09	******	*****	*****	*****
201.		8.73	8.71	34.103	2.02	26.483	42.2	*****	*****
301.		8.02	7.99	34.232	1.14	26.694	*****	*****	*****
401.		7.33	7.29	34.264	0.69	26.820	67.1	*****	*****
500.		6.25	6.20	34.337	0.36	27.025	*****	*****	*****
602.		5.75	5.70	34.367	0.27	27.112	86.5	*****	*****
652.		5.48	5.42	34.386	0.22	27.161	*****	*****	*****
678.		5.38	5.32	34.394	0.21	27.179	96.5	*****	*****
704.		5.26	5.20	34.388	0.20	27.189	*****	*****	*****
729.		5.23	5.17	34.388	0.17	27.193	95.7	*****	*****
754.		5.19	5.13	34.400	0.14	27.207	*****	*****	*****
780.		5.16	5.09	34.396	0.14	27.208	107.4	*****	*****
805.		5.14	5.07	34.399	0.13	27.213	*****	*****	*****
829.		5.12	5.05	34.406	0.18	27.221	98.5	*****	*****
854.		5.12	5.05	34.403	0.16	27.219	109.4	*****	*****
865.		5.12	5.04	34.391	0.19	27.209	108.7	*****	*****
880.		5.09	5.01	34.400	0.14	27.220	110.1	*****	*****
895.		5.08	5.00	34.404	0.10	27.225	112.0	*****	*****

TABLE 4-9

Oceanographic profile data for San Pedro Basin, May 4, 1971
(by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 11 SPMAY-71	1	40571	33.31	118.14	880	NO. SAMP=16	S PEDRO BASIN-QUESTIONABLES

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
2.		14.02	14.02	33.530	*****	25.068	8.4	*****	0.5
75.		9.34	9.33	33.819	*****	26.162	33.0	*****	21.0
500.		6.28	6.23	34.277	0.39	26.973	72.9	*****	33.2
595.		5.74	5.69	34.361	0.31	27.109	86.6	*****	37.6
642.		5.47	5.41	34.375	0.26	27.152	96.6	*****	39.9
666.		5.35	5.29	34.385	0.27	27.176	89.8	*****	37.7
681.		5.28	5.22	******	*****	******	*****	*****	*****
703.		5.23	5.17	34.394	0.19	27.197	101.6	*****	38.5
730.		5.14	5.08	34.397	0.19	27.210	104.5	*****	37.8
755.		5.12	5.05	34.402	0.22	27.217	95.0	*****	34.0
779.		5.11	5.04	34.405	0.17	27.221	104.5	*****	37.5
805.		5.09	5.02	34.405	0.26	27.223	103.4	*****	36.5
830.		5.09	5.02	34.399	0.18	27.219	99.7	*****	34.1
840.		5.09	5.02	34.412	0.16	27.229	107.9	*****	37.8
855.		5.06	4.99	34.409	0.16	27.230	100.4	*****	34.0
871.		5.06	4.98	34.409	0.15	27.231	108.8	*****	36.5

TABLE 4-10

Oceanographic profile data for Santa Monica Basin, May 8, 1971
(by Sholkovitz and Gieskes, SIO).

CRUISE	STATION	DAY-MO-YR DATE	LAT. N	LONG. W	BOTTOM DEPTH(M)		
CR# 11 SPMAY-71	2	80571	33.45	118.48	875	NO. SAMP=18	S MONICA BASIN

DEPTH(M)	DEP-SILL	TEMP(C)	POT. TEMP.	SAL	OXYGEN(ML/L)	SIGMA T	SI	P	NO3
7.		12.93	12.93	33.583	6.45	25.330	13.8	*****	2.5
54.		9.60	9.59	33.854	2.95	26.146	30.7	*****	17.5
100.		8.95	8.94	34.048	2.66	26.404	43.3	*****	25.8
195.		8.59	8.57	34.243	1.38	26.614	54.6	*****	30.6
296.		7.72	7.69	34.259	0.95	26.759	60.6	*****	31.5
402.		6.91	6.87	34.279	*****	26.890	69.9	*****	34.2
509.		6.19	6.14	34.326	0.30	27.024	77.5	*****	36.3
613.		5.47	5.42	34.368	0.19	27.147	95.0	*****	37.8
664.		5.32	5.26	34.380	0.16	27.175	90.6	*****	33.4
689.		5.27	5.21	34.386	0.16	27.186	105.2	*****	37.8
714.		5.24	5.18	34.389	0.16	27.192	91.6	*****	31.7
740.		5.19	5.13	34.391	0.18	27.200	106.9	*****	37.6
764.		5.15	5.08	34.394	0.12	27.207	105.8	*****	34.0
788.		5.13	5.06	34.397	0.15	27.212	102.4	*****	32.4
811.		*****	*****	34.399	0.07	******	107.8	*****	31.4
834.		5.06	4.99	34.400	0.14	27.223	109.9	*****	31.1
856.		5.05	4.98	34.404	0.14	27.228	107.8	*****	28.6
865.		5.07	4.99	34.405	0.11	27.226	106.3	*****	29.0

APPENDIX 5

SCOPE OF WORK (From EQL-LA/OMA Contract, August 24, 1977)

Objective of this study is to explore environmental effects of variations of existing ocean disposal practices for digested sewage sludge resulting from:

(a) full secondary treatment, and
(b) marine secondary treatment

SCOPE OF WORK

A. The purpose of LA/OMA Task 5.2 is to assess the environmental effects of variations in present methods for ocean disposal of treated sewage sludge. The presence of low oxygen basins not far offshore is a feature of the Southern California Bight which should be explored as a possible sludge disposal site. With regard to the low oxygen basins, particular questions to be investigated include:

1. Mechanisms and rates of water exchange between oceanic and basin waters.
2. Present rates of oxygen supply and utilization in low oxygen basins.
3. Chemical and geological composition of basin floors.
4. Comparison of natural organic deposition rate with that of sewage solids.
5. Fate of sludge particles discharged in ocean basins.
6. Projected oxygen, sulfide and selected trace metal concentrations upon addition of sewage sludge.
7. Fate of oxygen deficiency, sulfides and trace metals in water discharged from basins.
8. Effects of sludge discharge on benthic and planktonic animals, both in the basins and in surrounding waters.

B. Similar questions should be posed and answered about the effect of extending sludge discharge into waters of various depths greater than 100 m (present depth of Hyperion discharge) up to 900 m in the deep basins. A comparison will be made of the predicted effects of discharge at various depths.

C. Only a small amount of field work (to be a separate contract by SCCWRP) is anticipated at this stage of investigation because of limited time and funds. The most urgent need is for current data which is non-existent in the literature; however, some additional biological work will also be undertaken by SCCWRP. As part of this task, a program of needed additional pre-design field studies will be delineated if this system appears feasible. Determination of the feasibility will be determined jointly by LA/OMA Project and EQL.

D. The Report of findings will include a discussion and evaluation of risks and uncertainties.

TIME SCHEDULE AND REPORTS

A one-year period is required, with submittal of an interim progress report by December 20, 1977, and a final report by June 30, 1978.

COORDINATION WITH SCCWRP

Since the results of field work by SCCWRP will be needed as soon as possible, arrangements will be made for transfer of SCCWRP data to this project just as soon as each segment of data becomes available. SCCWRP's final data report will be in final report of the Environmental Quality Laboratory of the INSTITUTE (EQL) as an appendix. (It will be SCCWRP's responsibility to provide to EQL reproducible masters ready for printing.)

Furthermore, EQL's interim report will be sent to SCCWRP (as well as other agencies) for review and comment. All suggestions will be carefully considered, and any revisions will be made on the final report at the discretion of the EQL principal investigators. EQL will provide LA/OMA Project with copies of the comments and suggestions received.

KEY PERSONNEL

Key personnel to be assigned to the contract and the estimated allocation of revenues are shown in Table 1.

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91109

ENVIRONMENTAL QUALITY LABORATORY

29 March 1979

APPENDIX 6

Memorandum to: Bill Davis

From: N. H. Brooks, G. Jackson, R. C. Y. Koh and J. J. Morgan

Subject: Implications of latest revision of discharge rates on our conclusions in report entitled "Assessment of Alternative Ocean Sludge Disposal Practices."

We have compared the latest revision of discharge rates by Mingin Lo provided by you with the previous rates which we used to estimate effects of sludge discharge into the Santa Monica-San Pedro Basin. Overall, we do not see any revision to be necessary regarding our conclusions. Basically, the total quantities of sludge discharged remained the same while most of the heavy metals discharged are smaller than previously.

As illustrations of how the entries in some of our tables would be altered by using the new emission rates, we attach herewith two tables with added columns alongside the old values. It is clear that the change is relatively minor.

RCYK:dp

Attachments

TABLE V-4

Comparison of Lower Santa Monica-San Pedro Basin Sedimentation with Projected Sludge Discharge

Substance	(A) Lower SM-SP Basin Flux[1]	(B) Projected Sludge Discharge Full Secondary Treatment (old)	(B')[4] Projected Sludge Discharge Full Secondary Treatment (new)	B/A (old)	(B/A)'[4] (new)	(C) Projected Sludge Discharge: Marine Secondary Treatment	C/A
Organic C (BOD 10^9 moles - O_2/yr)	2.6[2]	9.2		3.5		7.7	3.0
Heavy Metals (tone/yr)							
Cd	--[3]	40.	13.	--		30.	--
Cr	130.	537.	81.	4.	0.6	422.	3.
Cu	56.	488.	259.	9.	4.6	393.	7.
Pb	36.	192.	88.	5.	2.4	161.	4.
Hg	--[3]	> 2.2		--		> 1.8	--
Ni	37.	108.	105.	3.	2.8	93.	3.
Ag	3.	22.	39.	7.	12.8	17.	6.
Zn	123.	886.	572.	7.	4.7	760.	6.

1. From Table IV-1, total present fluxes including anthropogenic.

2. Assuming complete oxidation of all C.

3. No estimate available.

4. Estimates from Table 5-1, Technical Memo 103a, LA/OMA 1979. These are total toxicant inputs to LA/OMA agencies, assuming EPA pretreatment regulation, year 2,000.

TABLE VIII-2

Comparison of predicted soluble trace metal concentrations with those from the 1978 Water Quality Control Plan for Ocean Waters of California (State Water Resources Control Board, 1978)

Element	Maximum allowable ambient concentration, M (6 month median)	Predicted maximum soluble concentrations, M, for discharge at (New) A	(old) 400 m	600 m	800 m
Cadmium	2.7×10^{-8}	9.1×10^{-9}	9.3×10^{-9}	9.3×10^{-9}	9.3×10^{-9}
Chromium	3.9×10^{-8}	2.1×10^{-9}	8.5×10^{-9}	8.6×10^{-9}	7.1×10^{-9}
Copper	7.8×10^{-8}	5.0×10^{-9}	7.6×10^{-9}	7.7×10^{-9}	6.6×10^{-9}
Lead	3.9×10^{-8}	4.6×10^{-10}	8.9×10^{-10}	8.1×10^{-10}	6.8×10^{-10}
Nickel	3.4×10^{-7}	3.5×10^{-8}	3.5×10^{-8}	3.5×10^{-8}	3.5×10^{-8}
Silver	4.1×10^{-9}	6.3×10^{-10}	5.2×10^{-10}	5.2×10^{-10}	4.9×10^{-10}
Zinc	3.1×10^{-7}	1.1×10^{-8}	1.5×10^{-8}	1.5×10^{-8}	1.3×10^{-8}

A. Predicted maximum soluble concentrations, M, for discharge at 400 m using amended predicted discharge in Table 5-1, Technical Memo 103a, LA/OMA 1979.

BIOLOGICAL CONDITIONS IN SANTA MONICA AND SAN PEDRO BASINS

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Submitted to:

Regional Wastewater Solids Management Program
P.O. Box 4998
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In partial fulfillment of Contract 2291

28 April 1978

CONTENTS

BIOLOGICAL CONDITIONS IN SANTA MONICA AND SAN PEDRO BASINS

BACKGROUND AND SUMMARY

A variety of marine fish and invertebrates inhabit the bottom and near bottom waters of the coastal basins. Most of the species are restricted to these deeper cold dark waters and are rare on the mainland shelf; however, some, in large numbers, undergo daily vertical migrations toward the surface and back; these and others which do not migrate are forage and food for large near-surface predatory fishes and shellfish such as yellowtail tuna, albacore, rockfish, squid, marine mammals, and marine birds.

While some information is known about deepwater species and their general distribution, very little is known about their overall abundance and specific abundances in the San Pedro/Santa Monica Basin area.

The major purpose of this project is to better define the abundance of mid-water and bottom animals in the basins. To accomplish this, we split tasks into several categories. First, Dr. Bruce Belman, an expert on deepsea animals, was retained to summarize what is known about the abundances of fish and invertebrates that live in the water column over our two coastal basins, i.e., midwater mesopelagic organisms that live between about 200 and 900 meters.

Next, we undertook our own survey of the bottom itself using trawls, grabs and a 35 mm baited camera to sample some eight locations at depths between 525 and 915 m.

Finally, we re-examined existing literature and data from previous surveys to identify organisms not included in the above categories and to compare the abundance and diversity of basin fauna with that of the shallower shelf.

Our investigation confirmed that a large variety of fishes, crustaceans and echinoderms live in the basins and above the basin floor. In general we believe that marine life in the bottom of the basins is about one half to one-tenth as abundant as on the mainland shelf but is composed of species unique to the depths sampled. The water column (midwater) fauna is even less abundant when compared with epipelagic fauna (near the surface), 10-1000 times so. All major phyla (polychaetes, molluscs, echinoderms, and crustaceans) are represented at all but the deepest depth sampled (915 m in Santa Monica Basin) although the variety and abundance of sponges, copepods, euphausids, annelids, and echinoderms is reduced below sill depth (750 m). Below this depth fishes, mysids, and decapods (shrimp) are in low abundance but do dominate the fauna.

The bottom of the basins is presently littered with natural debris (fish bones, scales, shells and tubes of invertebrates, undecomposed algae, brush, and wood) human trash (beer cans, tin foil, paper, plastic) and material of undetermined origin (tar globs). Much of this basin debris is in a surprisingly well preserved state.

MIDWATER FAUNA

Belman (1977) reveiwed available published and unpublished records of fishes and invertebrates which inhabit the midwater (100 - 800 meters) of Santa Monica Basin (deepest depth 950 m) and San Pedro Basin (deepest depth 845 m). While a good deal of collecting has been done in San Pedro Basin, only a few well documented samples are available to characterize Santa Monica Basin. However, Belman believes the faunal composition is quite similar in these two areas.

Methods and Past Sampling

In our coastal area, midwater fauna has been sampled directly by towing small mesh trawls astern of a research vessel. Trawls used in local waters include "6-foot" and "10-foot" Tucker trawls (3.5 m^2 and 9.6 m^2 open mouth area) fitted with 0.5 mm plankton nets in the cod-end or with a 10-ft Isaacs-Kidd Midwater Trawl (IKMT 9.6 m^2 open mouth area). Both open and closing nets have been used, but only data from the closing nets are useful for confirming depth ranges of midwater organisms. The nets are usually towed at 3.5 knots for from 30 min to many hours, retrieved and the catch preserved in formalin and returned to laboratories for storage, sorting, and identification. Very few of these samples have been completely sorted, identified, or analyzed.

Nearly all available midwater trawl data has been collected by investigators using USC's Velero IV.

The only specific records located for Santa Monica Basin were reports on three midwater trawls taken in 1962 using a continuously open IKMT (Los Angeles County Museum of Natural History, LACMNH). San Pedro Basin midwater fauna was reported by Ebling et al. (1970) and in unpublished student reports directed by Dr. Richard Piper, USC.

Results

Species. Of the two basins, San Pedro Basin is best documented in terms of kinds of midwater species. From various data sources Belman concluded the most common fish include lantern fish (Myctophidae), light fishes (Gonostomatidae), deepsea smelts (Bathylagidae), and tube shoulders (Searsidae, Table 1). Identified invertebrates are dominated by olophoroid, pasaphaeid, and sergestid shrimp, copepods, and euphausids(Table 1).

Ebling et al. (1970) also listed 12 fishes and 12 invertebrates that were most common in 36 IKMT samples taken at all depths in San Pedro Basin, 1960-64. As shown in Table 2, at least four faunal zones could be distinguished (< 200 m, 200 - 500 m, 500 - 700 m, and below 700 m). Included in Ebling's groups are several cephalopods, a large mysid (Gnathophausia ingens) and several shrimp.

Seven of the fishes cited in Table 1 plus an additional species (Stenobrachius leucopsaurus) were common to all of the only three trawls in Santa Monica Basin documented by Belman (depth range 631 to 852 m, February-March 1962). Belman did not report information on invertebrates.

Apparently most of the fishes found at depth in San Pedro and Santa Monica Basins are also common to other more distant basins (which have been studied in even greater detail). Rainwater (1975) lists 56 species of fish for Santa Catalina Basin, with 27 species considered common (occur in 95% or more of the collections). Six of the seven most common species there are also the most common species in San Pedro and Santa Monica Basins.

Table 1. Most Commonly Captured Midwater Oraganisms - San Pedro Basin Area

Fishes

1.	*Leuroglossus stilbius stilbius*	(Bathylagidae)
2.	*Cyclothone acclinidens*	(Gonostomatidae)
3.	*Cyclothone signata*	(Gonostomatidae)
4.	*Holtbyrnia melanocephala*	(Searsiidae)
5.	*Lampanyctus ritteri*	(Myctophidae)
6.	*Triphoturus mexicanus*	(Myctophidae)
7.	*Stenobrachius leucopsarus*	(Myctophidae)

Decapod Crustaceans

1.	*Hymenodora frontalis*	(Olophoridae)
2.	*Pasiphaea emarginata*	(Pasiphaeidae)
3.	*Sergestes similis*	(Sergestidae)

Copepods

1. *Calanus* sp.
2. *Eucalanus* sp.

Euphausiids

1. *Euphausia pacificia*
2. *Nematoscelis difficilus*

Table 2. Most common midwater species from San Pedro Basin. Adapted from Ebling et al. 1970.

Upper Mesopelagic (above 200 m)	
Fishes:	
Cyclothone signata	Gonostomatidae
Triphoturus mexicanus	Myctophidae
Diogenichthys atlanticus	Myctophidae
Diaphus theta	Myctophidae
Invertebrates:	
Sergestes similis	Decapod shrimp
Sergestes edwardsii	Decapod shrimp
Abraliopsis hoylei	Cephalopod
Histioteuthis heteropsis	Cephalopod
Middle Mesopelagic (200 - 500 m)	
Fishes:	
Leuroglossus stilbius stilbius	Bathylagidae
Stomias atriventer	Stomiatidae
Lampanyctus ritteri	Myctophidae
Invertebrates:	
Pasiphaea chacei	Decapod shrimp
Galiteuthis phyllura	Cephalopod
Lower Mesopelagic (500 - 700 m)	
Fishes:	
Holtbyrnia melanocephala	Searsiidae
Sternoptyx diaphana	Sternoptychidae
Melamphaes lugubris	Melamphaidae
Invertebrates:	
Gennadus propinquis	Decapod shrimp
Sergestes phorcus	Decapod shrimp
Gnathophausia ingens	Mysid shrimp
Chiroteuthis sp.	Cephalopod
Bathypelagic (Below 700 m)	
Fishes:	
Cyclothone acclinidens	Gonostomatidae
Melanostigma pammelas	Zooarcidae
Invertebrates:	
Pasiphaea emarginata	Decapod shrimp
Hymenodora frontalis	Decapod shrimp

Best and Smith (1965) list 27 species of fish from the Santa Barbara Basin and in deep water off San Luis Obispo Bay, at least 17 of these are common to the Santa Monica-San Pedro Basins.

Abundance and Biomass. Using data provided by Piper, Belman calculated numbers of various organisms per unit volume sampled in 7 San Pedro Basin midwater trawls. Our summary of these data indicate catches from 0 to 600 meters were numerically dominated by copepods; chaetognaths were second in abundance at 0 to 200 meters and euphausids at 200 to 600 meters (Table 3). By comparison, fish and decapods (shrimp) were low in abundance (0-600 m) but increased in importance at depths greater than 600 m where chaetognaths, copepods and euphausids were absent (Table 3). Overall, catches ranged from 32 to 7,700 animals per 10,000 cu m sampled. Densities of small animals in surface water (less than 100 m deep) may reach a maximum of 650,000/10,000 m^3 or 1 to 2 orders of magnitude higher.

In Santa Monica Basin, Belman summarized catch statistics on the eight species of midwater fish most common in three midwater trawls taken at depths ranging to 852 m in 1962. These catches ranged from 25 to 150 fish per 10,000 cu m.

There does not seem to be great depth differences in total biomass of midwater fauna (in the range 50 to 600 m) in San Pedro Basin; again using data from R.E. Piper, Belman reports volumes ranging from 7 to 16 g per 10,000 cu m. Belman suggests that between-sample variation is too high to determine significant depth differences within this range.

Table 3. Summary of median abundances (no. per 10^4 m^3) of midwater organisms from seven midwater trawls in the San Pedro Basin, 1973 and 1974. Based on unpublished student reports, courtesy of Dr. R.E. Pieper, University of Southern California. Adapted from data presented in report from Dr. Bruce Belman to SCCWRP. Also, included are rough estimates of the densities of certain groups in CalCOFI plankton tows (0 to 140 m maximum).

Depth Range (m)	No. Samples	Total No. Animals	Chaetognaths	Copepods	Euphausids	Decapods	Fish
0-200	(2)	7,700	2,000 (26%)	5,000 (65%)	500 (6.4%)	113 (1.5%)	30 (0.4%)
200-400	(1)	4,700	210 (4.5%)	3,000 (65%)	1,300 (28%)	7 (0.2%)	130 (2.8%)
400-600	(3)	3,400	90 (2.6%)	2,200 (64%)	800 (23%)	20 (0.6%)	45 (1.3%)
600-800	(1)	32	-0-	-0-	-0-	25 (78%)	5 (15.6%
Estimates from CalCOFI Surface Tows							
	(0-100)	10,000-650,000	NA	10,000-650,000	0-500,000	NA	10-100,000 (Eggs and larvae)

Based on scan of data in CalCOFI atlases.

BOTTOMFISH, EPIBENTHIC AND BENTHIC FAUNA

Methods

During the period 4 October to 1 December 1977, Project staff sampled bottom fish and invertebrate populations at eight locations in the San Pedro/Santa Monica Basin area (Figure 1 and Table 4). Locations sampled ranged in depth from 525 to 915 meters. At each location we took a bottom trawl, a bottom grab sample, samples of temperature, salinity, and dissolved oxygen. In addition, a 35 mm baited camera was used to photograph the bottom and marine life at three of the locations. A summary of specific sampling conditions is shown in Table 3.

Trawling was conducted with a 7.6 m (25 ft) Willis Otter Trawl constructed with 3.8 cm (1-1/2 inch) stretch mesh bag and fitted with a 1.3 m (1/2 inch) cod-end to retain small organisms. (Bascom, 1977). Trawling on bottom was conducted at 2 to 2.5 knots for about 20 minutes. During towing operation, which generally took two to three hours, ship location was continually tracked using a LORAN C receiver (accurate to $\pm$ 50 ft.). Upon retrieval, contents of the net were sorted and either identified and counted or preserved and returned to the laboratory for measurement. Fishes were measured to the nearest 0.5 cm, weighed and examined for external signs of disease and parasites.

Relatively undisturbed bottom samples were taken at each site using a 0.1 m^2 (surface area) chain rigged Van Veen grab (Word, 1977). Penetration depth, sediment type, color and odor were recorded and the contents washed through 2.5, 1, and 0.5 mm screens. Retained material was fixed in formalin and returned

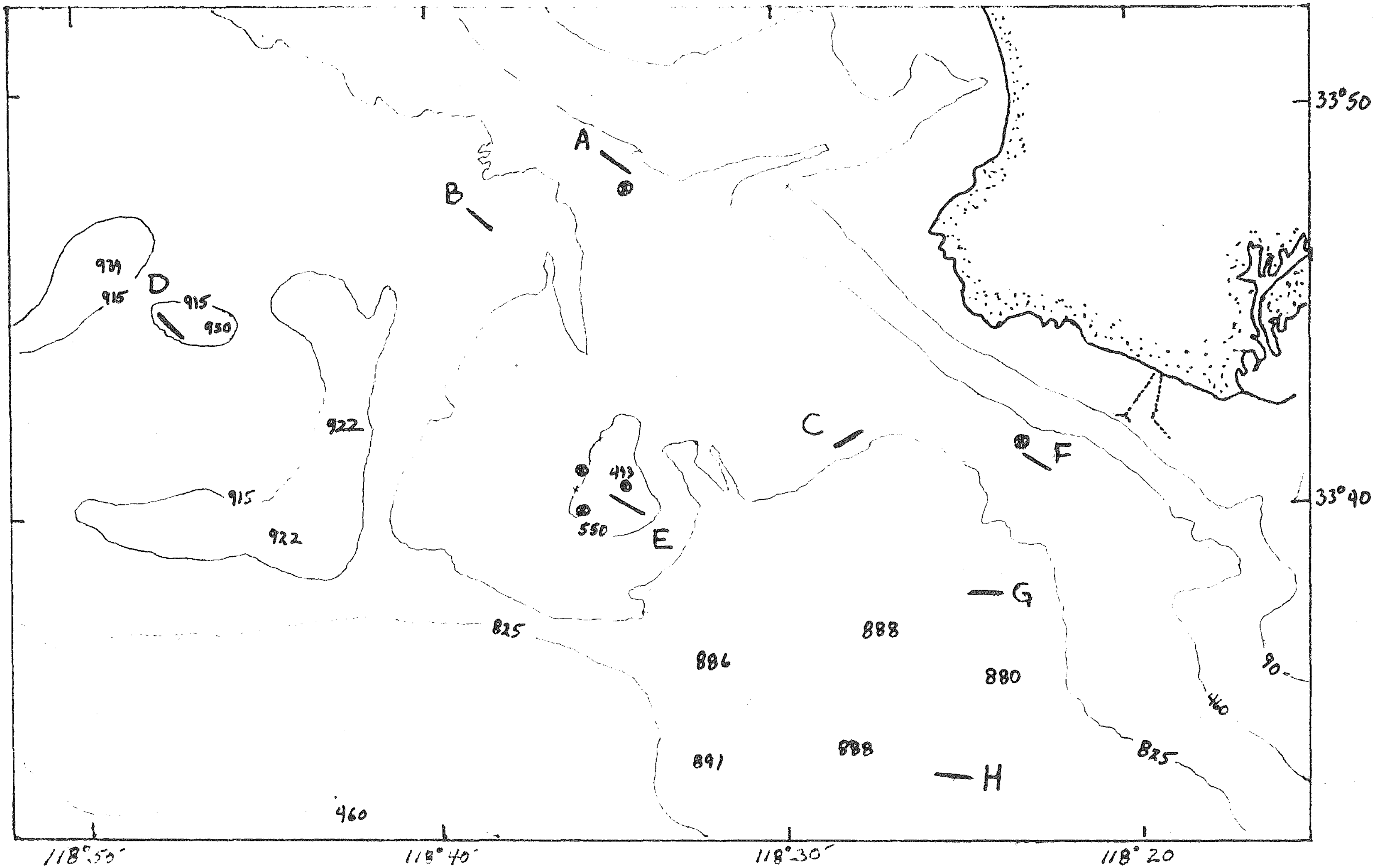

Figure 1. Locations of SCCWRP - LA/OMA Trawl and Grab Stations (lines) and 35 mm baited camera stations in the Santa Monica - San Pedro Basin area. Depths in meters.

Table 4. Station Locations and Sampling Events for SCCWRP/LA OMA Basin Survey, 7 Sept. - 1 Dec., 1977

Station	Depth m	Date	Latitude N	Longitude W	Trawl Time on Bottom	Duration	Direction	Grab Time on Deck	Camera Time in	Camera Dura- tion	Camera Inter- val min.	Vessel
A[2]	549	4 Oct.	34°48'25"	118°34'45"	10:27	20	090°	10:09	-	-	-	Marine Surveyor
	621	8 Sept.	34°47'35"	118°34'00"		-	-	-	08:57	04:42	3.4	Marine Surveyor
B	823	8 Nov.	33°47'00"	118°38'30"	10:12	20	080°	11:42	-	-	-	Van Tuna
C	715	8 Nov.	33°41'30"	118°28'10"	14:32	20	115°	16:30	-	-	-	Van Tuna
D	915	24 Oct.	33°44'18"	118°47'42"	11:45	20	090°	-	-	-	-	Van Tuna
			33°44'24"	118°46'06"	-	-	-	13:40	-	-	-	Van Tuna
E	549	11 Oct.	33°40'00"	118°34'00"	10:01	20	295°	11:29+ 11:55	-	-	-	Marine Surveyor
	523	1 Dec.	33°40'30"	118°34'30"	-	-	-	-	09:10	01:15	1.7	Marine Surveyor
	525	1 Dec.	33°40'00"	118°35'50"	-	-	-	-	10:20	01:02	1.7	Marine Surveyor
	530	1 Dec.	33°40'55"	118°35'55"	-	-	-	-	11:45	01:05	1.7	Marine Surveyor
F	641	6 Oct.	33°40'35"	118°22'35"	10:34	25	270°	12:01	-	-	-	Marine Surveyor
	600	7 Sept.	33°41'20"	118°23'00"	-	-	-	-	10:29	04:30	3.4	Marine Surveyor
G	878	7 Nov.	33°34'24"	118°26'18"	13:56	20	075°	16:01	-	-	-	Van Tuna
H	860	7 Nov.			09:39	25	090°	11:59	-	-	-	Van Tuna

to the laboratory for preservation in alcohol and later sorting and identifications. In the laboratory, animals retained by the 2 and 1 mm mesh were identified to the nearest possible taxon, counted and wet weight determined for major taxa (phyla).

A 35 mm camera, encased in an aluminum housing, mounted in a weighted aluminum frame and fitted with an automatic timer, was used to photograph conditions in the water column and on the bottom. Fresh bait (consisting of squid and catfood) was used to attract animals at each of the three locations. At stations A and F, the camera was set to take photographs at approximately 3.4 minute intervals and was left on each station for about 4.5 hours. At station E, where we lost trawl gear, photos were taken at about 1.7 minute intervals and the camera left at three different depths for approximately one hour each (total time in water about 4 hours).

All sampling was done during daylight hours. No problems were encountered except at station E, where, as noted above, rocks virtually destroyed an otter trawl. However, a variety of invertebrates and one fish were snagged and they were recorded and used in this analysis.

Results

Visual conditions and bottom debris. The bottom of these two basins, particularly San Pedro, appears to be littered with partially decomposed natural and artificial debris. For example, at station H the net and cod end contained green blades of giant kelp (*Macrocystis pyrifera*) red and blue rusty metal paint chips, sea grass (Phyllospadix), hair balls, parchment worm tubes, lead or tin foil, insect wings, cellophane, an abalone shell, steel beer cans, pieces of algae holdfasts and intact spines, jaws, vertebrae, and whole spinal columns, from a variety or large and small fishes. At station H, large two-to-eight inch pads of tar (200 lbs) were collected. Chemical analysis indicated the tar represented well-weathered oil.

This kind of material was not apparent in slides taken at the two sites in Santa Monica Basin or on the top of the rise off Palos Verdes. Photographs indicated a muddy soft bottom with large boulders and rocks at the rise off Palos Verdes. Water was exceptional clear at all three sites.

At no location sampled were we able to detect an odor of hydrogen sulfide in the sediments sampled by the grabs. We were however,able to detect an odor of petroleum at Stations G and H.

Trawl Caught Species. A total of 82 taxa of fishes and invertebrates, comprising over 7,243 individuals, were taken in the eight trawls. There were 683 fish representing 19 species and 13 families and over 6,560 invertebrates representing 63 taxa and seven phyla (appendix I). Overall catch statistics are summarized in Table 5.

The most abundant and common fish were the longspine thornyhead (*Sebastolobus altivelis*, 451 specimens occurring at 7 of the stations) and the California rattail (*Nezumia stelgidolepis*, 71 specimen occurring at 4 of the stations). The next most abundant and common fishes were shortspine thornyhead (*Sebastolobus*

Table 5. Catch statistics for fishes and invertebrates captured at 8 ottertrawl stations in the San Pedro - Santa Monica Basin Area, Fall 1977.

Station	Depth m	Trawl Time min	Fish #Ind.	Fish # Sp.	Biomass kg	Invertebrates #Ind.	Invertebrates #Sp.	Bio-mass kg	No. Specimens Echino-derms	No. Specimens Crusta-cea	No. Specimens Other
A[2]	549	20	140	7	31.6	1,072	14	8.3	837	204	31
E	549	20	1	1	NM	43	13	NM	38	0	5
F	641	20	138	7	39.2	952	15	4.2	722	103	127
C	715	20	203	9	4.8	4,279	13	10.0	18	913	4,348
B	823	20	28	4	0.1	153	10	1.0	0	150	3
G	878	25	151	8	2.95	703	13	NM	1 Frag.	387	315
H	860	25	18	5	0.4	81	7	NM	0	37	44
D	915	20	1	1	NM	7	7	NM	5	2	0
Total or Cumm. No.			680	20	79.05	7.290	66	23.5	1,621	1,796	4,873
Medians			83	6	3.9	428	13	6.3	22	127	38
(n)			8	8	6	8	8	4	8	8	8

NM = Not measured; all other biomass estimates partial alascansus), sablefish (Anoplopoma fimbria) and brown cat sharks (Apisturus brunneus). Dover sole (Microstomus pacificus), common in shallower waters, were captured at two stations. The bottom trawls also collected a few specimens of various midwater fishes including lanternfish (Lampanyctus mexicanus, Stenobrachius leucopsaurus and unidentified myctophids), blackbelly dragonfish (Stomias atriventer) and a midwater eelpout (Melanostigma pammelas).

While numerous invertebrates were captured, few species were common to most trawl sites and large catches of single species occurred at only one or two sites. Keeping this fact in mind, the most abundant species were a small snail (Mitrella permodesta, over 3,000 individuals, primarily at station C), a brachyuran crab (Munidopsis hystrix, primarily at station C and B), a heart urchin (Brissopsis pacificus, 528 specimens, almost all at station A), the shrimp Spirontocaris sica, the starfish Myxoderma sp., and the sea cucumber, Pannychea mosleyi. These last three species were abundant at two or three of the eight sites.

Most of the species are unique to the depth range sampled (550 - 915 meters) and to somewhat shallower waters. A few do occur occasionally in trawls on the mainland shelf (to 200 m); these include sablefish, dover sole, hagfish, and shortspine thornyhead, the clam Macoma carlottensis, the pelagic red crab (Pleuroncodes planipes), the hydrozoan Dromalia alexandri, and the sea star Rathbunaster californicus.

Extremely large accumulations of empty tubes of the shallower water inhabitant Spiochaetopterus (polychaete) together

Table 6. Summary statistics for infauna collected in single grab at eight stations in Santa Monica - San Pedro Basins, 7 September to 1 December 1977.

Station	A	E	F	C	B	H	G	D
Depth (m)	549	549	641	715	823	860	878	915
No. Species	8	16	15	12	4	2	6	3
Density, $\#/m^2$	140	430	400	620	40	40	240	30
Biomass g/m^2								
All taxa	7.8	4.7	34.0	15.1	3.7	3.4	8.4	0.5
Polychaetes	3.08	1.36	2.95	6.44	0.06	2.59	0	0.46
Mollusca	2.16	0.05	17.4	5.24	1.61	0	8.35	0
Arthropoda	0.26	0.16	0.18	2.97	1.89	0.67	0	0
Echino-demata	0.19	3.12	0.33	0.49	0	0.15	0	0
Misc.	2.15	0	13.2	0	0.18	0	0	0
Shannon Weaver Diversity	1.910	2.405	2.254	1.725	1.609	0.950	1.669	1.099

Overall Summary	$\bar{x}$	$\pm$ SD	$\pm S_{\bar{x}}$
No. Species/Sample	8.25	5.47	1.93
$No./m^2$	243	220	77.9
Biomass g/m^2	9.70	10.76	3.80
Polychaeta	2.12	2.16	0.76
Mollusca	4.35	6.04	2.14
Arthropoda	0.77	1.08	0.38
Echinodemata	0.54	1.06	0.37
Miscellaneous	1.94	4.61	1.36
Shannon-Weaver Diversity	1.703	0.505	0.178

with live snails (Mitrella permodesta) occurred at several basin sites at the lower edge of the rapid slope off Palos Verdes (Station F and G). This indicates that coastal shelf debris not only falls into basin depths but also accumulates in certain areas.

No fish showed signs of fin erosion, tumors or other signs of external diseases.

Results of Benthic Grabs. A total of 50 species of invertebrates were identified from the eight grab samples (Appendix II). Polychaetes were the most diverse group with 24 species. There were also seven species of arthropods, six echinoderms, five molluscs, four coelenterates and 4 miscellaneous phyla (Nemertea, Nematoda, Chaetognatha). The number of species per 0.1 sq m sample varied from 16 to 2. The number of individuals varied from 600 to 30 per sq m while biomass ranged from 0.5 to 34.3 g/m^2 and Shannon-Weaver diversity from 0.95 to 2.4 (Table 6).

In general the number of species, individuals, the weight of the animals, and diversity, were all less below sill depths than above sill depth (737 m; Table 7).

Our results compare closely with those of Hartmann and Barnard (1958) who took 33 benthic samples below sill depth in the San Pedro Basin between 1952 and 1954. Average density calculated from these samples was 83.5 animals per m^2 (compared to our mean of 87.5). Our average biomass was slightly lower (4.0 compared to 9.2 g/m^2).

Table 7. Comparison of benthic infaunal characteristics above and below sill depth (737 m). ($\pm$ 1 SE $\bar{x}$, n = 4).

	Above Sill	Below Sill
No. Species/Sample	12.8 $\pm$ 1.80	3.75 $\pm$ 0.85
Density, #/m^2	397 $\pm$ 99	87.5 $\pm$ 50.9
Biomass g/m^2	15.4 $\pm$ 6.6	4.0 $\pm$ 1.6
Shannon Weaver Diversity	2.074 $\pm$ 0.155	1.332 $\pm$ 0.180

Results of Baited-Camera Observations. A 35-mm baited camera was lowered at five separate stations at three sites in the Santa Monica-San Pedro Basins area between 7 September and 1 December 1977 (Stations A, E, and F, see Table 4). A total of 201 on-bottom photos were taken at these sites and examined in the laboratory.

Five species of fish and some ten kinds of large invertebrates were observed in the slides. Pacific hagfish and sablefish were common and abundant at all locations. Rattails, shortspine thornyheads, and Dover sole were seen only at the rise separating Santa Monica and San Pedro Basins (Station E, 523 to 530 m).

A variety of not-readily-identifiable brittle stars and starfish were observed (one or two species per station); one or more species of shrimp were also seen at the deeper sites (Stations F and A) and at Station F (600 m off Palos Verdes). The slides revealed hundreds of small gastropods scattered over the bottom and eventually, on the bait (probably *Mitrella permodesta*).

Compared to the trawls,the camera recorded fewer species. However, the photographs did indicate that hagfish may be much more common and abundant in the basins than indicated by their low abundance in otter trawls. This difference in abundance may be explained by the copious mucous secretion of the hagfish and their extreme agility possibly allowing easy escape through the mesh openings in the trawl nets.

The bottom at all locations was a dark green or brown silt which was easily suspended by the apparently active hagfish and sablefish. Suspended material appeared to either settle rapidly or drift out of the field of view between consecutive photographs (3.4 min at Stations A and F, 1.7 min at Station E). Mainly, however, the water at all sites was exceptionally clear with horizontal visibility greater than 8-10 meters (edge of strobe light pattern).

DISCUSSION AND CONCLUSIONS

Bottom Fish and Benthic Life

The biological sampling conducted by SCCWRP during this program was designed to add to an existing data base that is increasing only very slowly. While much more work needs to be done for a proper quantitative assessment, there are, nevertheless, some important general trends that have been confirmed.

First, the water column, bottom and bottom sediments of San Pedro and Santa Monica Basins are not devoid of marine life. At the deepest depth sampled (915 m) there were few live organisms taken, but there were some (one fish and seven species of invertebrates in the trawl and three invertebrates yielding a biomass of 0.5 g/m^2 in the grab).

Second, while the fauna is lower in abundance and diversity below sill depth (737 m) than above, there appears to be no great sudden drop or faunal discontinuity at sill depth but rather a gradual decline in abundances of most organisms. This lack of sudden drop reflected in the last two columns of Table 8, suggests there are no significant physical or chemical discontinuities

Table 8. General changes in bottomfish and invertebrate fauna with depth in the mainland shelf, slope and plain of Santa Monica - San Pedro Basins.

Depth	60 m	300 m[2]	Above Sill 550-715 m[3]	Below Sill 823-915m[3]	915 m[3]
No. Samples	44	3	4	4	1
Epibenthic Fauna					
Fish					
No/Haul	232[1]	250	121	50	1
Species/Haul	14[1]	7	4	4.5	1
Invertebrates					
No/Haul	369[1]	300	1,500	84	7
Species/Haul	12[1]	14	14	8	7
Infauna					
No/m[2]	2,500[4]	-	397	88	3
No.Species/ Sample	60-70[4]	-	12.8	3.8	3
Biomass g/m[2]	40-150[4]	-	15.4	4.0	0.5

1 - For epibenthic fauna, 60 meter trawl survey, Word, Mearns, and Allen, 1977, 10 minute hauls.

2 - Deepwater sampling conducted 1976-77, in Allen and Mearns, 1977, and Word and Mearns, 1977. 20 minute hauls.

3 - Data collected for this report; 20 minute trawl hauls.

4 - General values 20-200 meters, SCCWRP data.

here as well.

When the entire depth range of the mainland shelf, slope, and basins are considered, as in Table 8, there are some discontinuities in abundance or number of species. For example, previous sampling (Word and Mearns, 1977, and Allen and Mearns, 1977) indicates that epibenthic invertebrate abundance and biomass actually increases from 20 to 450 meters and then declines with depth. In most coastal areas at this depth (450 m) irregular sea urchins (such as _Brissaster_, _Brissopsis_, _Spatangus_) form extremely dense beds and are the major contributors to high invertebrate biomass. Off Palos Verdes, however, this echinoderm fauna is depleted at least to a depth of about 600 meters (Word and Mearns, 1977).

In our basin surveys, an average of 85 fish of 5 species and over 800 invertebrates of 11 species were captured per 20 minute trawl. On the shelf, at a depth of 60 meters, 10 minutes hauls average about 230 fish or 14 species and 370 invertebrates of 12 species (Table 8). Thus the abundance and variety of fishes on the coastal shelf is about twice that encountered in our basin trawls. This trend is consistent with our previous report (Allen and Mearns, 1977), which also suggested that fish abundance, and variety begins its decrease with depth between 200 and 300 m. That report also indicated that peak biomass of bottom fish occurs at between 200 and 400 meters, maximum fish size occurs at 460 meters and diversity remains relatively unchanged from 20 to 610 meters.

The infauna reflects the depth-related trends seen in the trawl-caught epibenthic fauna at depths greater than 450 m. As indicated at the bottom of Table 8, the infauna appears to gradually decrease from an average Of 2500 animals/m^2 at 60 m to an average of 88 below sill depth. Number of species and biomass follow this trend. More importantly, however are changes in community composition and occurrences of unitque organisms or their remains. For example, beyond the urchin dominated community at 450 m the basins appear to be fringed with dense concentrations of polychaete tubes, most of them empty. In fact Hartman and Barnard described this association of empty Phyllochaetopterus as "depauperate". However, we know it contains a variety of other living invertebrates (e.g., dense concentrations of a small snail, Mitrella permodesta).

Midwater Fauna

Our review of the midwater fauna is cursory, at best; the data examined do confirm the trend of a general decrease in density and biomass of midwater organisms with depth. There are several reasons why the midwater fauna data base is weak. First, while numerous samples have been collected and archived by several institutions, very few of the samples have been completely analyzed. Second, very few samples have been taken inthe areas of interest, namely Santa Monica and San Pedro Basins below about 500 meters. Third, those samples that have been taken have generally excluded quantitative information on nearly 25 families of fishes known to contain large species (over 18 inches; in some cases nearly five feet in length); many of these fishes have been taken, albeit rarely, by other methods (Fitch and Lavenberg, 1968).

As a consequence, estimates of total fish or decapod population sizes in the basins should not be extrapolated from existing catch data.

RECOMMENDATIONS

If nearshore basins are to be considered for direct discharge of wastes, some important additional data needs to be gathered.

A specific objective requiring new data is to determine population sizes and movements of midwater and benthic fish and shrimp populations in the lower half of the water column overlying the basins. To minimize additional ship-time costs, this should include additional effort in completely analyzing existing samples at local universities and museums.

Another objective would be to determine whether or not ecologically important midwater or benthic organisms would be displaced by slight changes in water quality (such as dissolved oxygen or turbidity). This may require careful laboratory studies and use of new methods for remotely monitoring movements of midwater organisms (acoustics).

The floor of the basins, especially adjacent to shipping lanes, already harbor a large amount of natural and human-origin debris. This"background" of material and its rate of decomposition, will need to be better documented prior to using these basins for any other purpose.

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BIOLOGICAL CONDITIONS IN SANTA MONICA
AND SAN PEDRO BASINS

APPENDICIES

28 APRIL 1978

SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT
1500 E. IMPERIAL HIGHWAY
EL SEGUNDO, CA 90245

Appendix I. List of fishes collected by otter trawl at 8 stations in the San Pedro - Santa Monica Basin region, 7 September to 1 December 1977.

SPECIES	STATION A	B	C	D	E	F	G	H
Myxinidae								
<u>Eptatretus deani</u>			5				11	
Black hagfish								
Scyliorhinidae								
<u>Apristurus brunneus</u>		1	14		1		4	
Brown cat shark								
<u>Parmaturus xaniurus</u>						1		
Filetail cat shark								
Congridae								
?<u>Gnathophis catalinensis</u>						4		
Catalina conger								
Sternoptychidae								
<u>Argyropelecus sladeni</u>								1
Stomiatidae								
<u>Stomias atriventer</u>	1	4						
S. sp. Blackbelly dragonfish								
Alepocephalida								
?<u>Alepocephalida</u> UI			4					
<u>Alepocephalus</u> sp.							2	
Myctophidae								
<u>Lampanyctus mexicanus</u>								
Mexican lampfish								
Myctophid, UI		4						
<u>Stenobrachius leucopsarus</u>			5				1	1
Zoarcidae								
<u>Melanostigma pammelas</u>			1					1
Midwater eelpout								
Macrouridae								
<u>Coelorhynchus scaphophis</u>			1				4	1
<u>Nezumia stelgidolepis</u>	1	21				5	44	
California rat tail								
Scorpaenidae								
<u>Sebastolobus alascanus</u>	18					8	11	
Shortspine Thornyhead								
<u>Sebastolobus altivelis</u>	102	19	151	1		90	74	14
Longspine Thornyhead								

SPECIES	STATION A	B	C	D	E	F	G	H
Anoplopomatidae								
Anoplopoma fimbria	13		1			17		
Sablefish								
Cyclopteridae								
Careproctus melanurus	1							
Blacktail snailfish								
Pleuronectidae								
Microstomus pacificus	4					13		
Dover sole								

Appendix II. List of invertebrates collected by otter trawl at 8 stations in the San Pedro - Santa Monica Basin region, 7 September - 1 December, 1977.

SPECIES	STATION A	B	C	D	E	F	G	H
Porifera								
? Hexaatinellidae					P			
Porifera UI			32				44+	
Cnidaria								
Hydrozoa								
Dromalia alexandri	12					103		
Anthozoa								
Lip			141				30	
Medusae UI								
Atolla sp.				1				
Melinnexis moorei (Polychaete)	3							
Pennatula phosphorea			107		1	39	4	
Stachyptilum ? *superba*			10			10		
Umbelulla sp.	2				1	2		
Annelida								
Polychaeta								
Echiura UI						3		
Glycera sp.						1		
Amphicteis mucronata	1							
Aphrodita sp.						8		
Maldanid UI								
Spiophanes sp. A						14		
Scale worm UI						1	1	
Phyllochaetopterus tubes							P	
Mollusca								
Aplacophora								
Solenogaster UI					1			
Gastropoda								
Prosobranchia								
Bathybembix bairdii	13					14		
Mitrella permodesta		P	2958				226	44
Mitrella sp.								
Opisthobranchia								
Tritoniidae UI						2		
Corolla spectabilis		P		P				
Pelecypoda								
Calytogena elongata		2					4	
Macoma carlottensis			100					
Macoma sp.								
Pectin UI							5	
Cephalopoda								
Gonatus onyx		1						

SPECIES	STATION A	B	C	D	E	F	G	H
Arthropoda								
Crustacea								
Mysidacea								
Boreomysis sp.				P				
Eucopeia sp.								1
Gnathophausia ingens				P				
Mysid UI								
Natantia								
Hymenodora frontalis		9		P			1	4
Pasiphaea emarginata		3	26					2
Pasiphaea pacifica		2						
Pasiphaea sp.							1	
Sergestes indeta	2							
Sergestes similis		6						
Sergestes sp.				P			1	6
Spirontocaris sica	100		232			101	170	6
Spirontocaris sp.	95							
Spirontocaris snyderi	1							
Anomura								
Callianassa goniophthalma						1		
Munida *quadrispina*		10						
Munidopsis hystrix		130	655			30	214	18
Pleuroncodes planipes				1				
Brachyura								
Chlorilia longipes	6				2	1		
Echinodermata								
Asteroidea								
Asteroid UI								
Asteronyx longifissus			3			122		
? *Crossaster* sp.						2		
Rathbunaster californicus					2			
Pectinaster agassizi evoplus					1			
Echinodea								
Brissopsis pacificus	525					3		
Ophiuroidea								
Myxoderma sp.	193				4	245		
Ophiacantha spp.			12					
Ophiacantha rachophora					13			
Ophiomusium sp.						52		
Ophiomusium jolliensis					14			
Ophiopholis sp.			1					
Ophiopholis longispina			2		1			
Ophioscolex corynetes	6					16		
Ophiuroid frag UI							1	

SPECIES	A	B	C	D	E	F	G	H
Echinodermata (cont.)								
Holothuroidea								
Caudina sp.					2			
Pannychea mosleyi	113				1	282		
Chordata								
Ascidiacea								
Ascidian UI								

Appendix III. Species-station matrix of Benthic Infauna from eight sites in San Pedro and Santa Monica Basins, 1977.

	STATION							
Coelenterates	A	B	C	D	E	F	G	H
Sea pen, UI		1						
Isoedwardsia sp.								
Hydroidea, UI					1			
Pennatula phsophorea						1		
Chaetognatha			1					
Echinoderms								
Asteriidae, UI			1					
Myxoderma sp. (arm frog)						1		
Ophiuroidea, UI (juv.)			1					
Ophiomusium sp. (juv.)			2					
Ophiuroidea, UI (? Ophiopholis)					1			
Apodous holothiuroidea, UI						3		
Polychaetes								
Haploscoloplus elongatus	1							
Notomastus sp.	4				1	2		
Orbiniidae (frags)	P							
Spiophanes sp. A			5	1		1	2	
Phyllochaetopterus limicolus			11		1		10	
Serpulidae, UI (frog & damaged)			1					
Mediomastus californiensis				1				
Flabelligeridae, UI (pieces)				1				
Lunbrineris sp.					1			
Maldanidae, UI (head frogs)					7			
Petaloproctus ornatus					17			
Maldane sp.					1			
Samytha sp.					1			
Terebellidae, UI					1			
Typosyllis ? aciculata					3			
Glycera capitata					1	1		
? Laena sp.					1			
Harmothoe ? forcipulata						1		
Pherusa neopapillata						4		
Prionospio sp.						2		
Ampharetinae, UI						1		
Lysippe annectens						1		
Harmothoe sp.						3		
Spiondae larvae							1	

Mollusca	A	B	C	D	E	F	G	H
Pelecypoda								
Calypogena elongata	2							
Modiolus sp.	1							
Axinopsida serricata					1			
Paramya sp.						4		
Gastropods								
Mitrella permodesta		1	4			14	7	
Arthropods								
Ampelisca sp.	1							
Galtheidae, UI		1				P		
Bathycopeia			1					
Copepoda, UI			30				3	
Conchoecinae			1					
Amphipod, UI					1			
Hymenodora								1
Nemertea, UI	1	1			4			
Cerebratulus	3							
Nematoda			4					