Final Report

DEVELOPMENT OF METHODS FOR ESTIMATING THE CHANGES IN MARINE SEDIMENTS AS A RESULT OF THE DISCHARGE OF SEWERED MUNICIPAL WASTEWATERS THROUGH SUBMARINE OUTFALLS

PART II - SEDIMENTATION SIMULATIONS

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ABSTRACT

Time-series of near-bottom current velocities are combined with measurements of resuspension-redeposition fluxes in a simulation model of the resuspension, dispersion, redeposition, and accumulation of sediment particles. This model is used to estimate the dispersion and accumulation of organic material in the sediments surrounding three ocean outfalls discharging treated municipal wastewaters. Predicted and measured concentrations of organic material are compared, and a relationship between the effluent-related flux of this material through the near-bottom waters and changes in the community structure of the benthic infauna is developed.

Measurements of resuspension-redeposition fluxes were carried out using sediment traps. Annual average rates were on the order of 1600 to 5100 mg/cm**2/yr in water depths of 45 to 65m, or more than two orders of magnitude greater than the net accumulation rate of sediments. The sediment trap material had total volatile solids concentrations roughly twice that of the surface (0-2cm) sediments obtained with grab samplers. These characteristics suggest the presence of a thin (< 1mm thick) layer of highly mobile surficial sediments that are not sampled adequately by conventional means. Particles in this layer may dominate sediment transport and dispersion processes, however, and influence the composition and abundance of infauna feeding on suspended solids or the surface of the sediments.

Simulations of a fourth outfall area (White Point), and analysis of sediment core samples from that area, indicate that the accumulation of both effluent material and natural particles in areas influenced by the discharge are substantially greater than predicted by the model, or measured outside the area of influence of the discharge. Changes in the aggregation characteristics of the sediment particles, or in the rate of biologically-induced sediment resuspension, are suggested as a possible reasons for the anomally.

II. BACKGROUND

II.A. Particulate Dispersion and Accumulation in the Near-Bottom Environment

II.A.1. Definition the term "Near-Bottom"

For operational purposes, the dispersion of effluent particles in the ocean can be divided into two sequential processes: (1) the transport, dispersion, and sedimentation of particles from the bulk of the water column and, (2) the resuspension, transport, and redeposition of particles in the immediate vicinity of the sediments.

The simulation of the transport and sedimentation of particles from the the portion of the water column overlying the "near-bottom" layer is discussed in Volume I of this report. This report focuses on the second stage of the process--the transport, dispersion, and accumulation of particles in the near-bottom waters and the sediments.

Measurements of the distribution of resuspended particles in the water column (see Section IV.B.) show that they are primarily confined to the lower 2 to 4 meters in the coastal waters off southern California. Thus the transport and dispersion of resuspended particles will governed by the characteristics of the ocean currents within a few meters of the ocean bottom.

II.A.2. Particle Resuspension

Both physical and biological processes can lead to disturbances of the sediments resulting in the transport of previously stationary sediment particles by ocean currents. Increases in the stress on the bottom resulting from increases in the strength of the currents are one such mechanism. Small-scale fluctuations in the flow, or variations in the surface of the sediments, can also lead to pressure differences that can induce or assist in this transport process.

Stress can be induced by the activities of biota, such as shrimp (Thompson, pers. comm.) and whales (??, 1987). The uptake and subsequent egestion of sediment particles by animals living within an on top of the sediments provide another mechanism.

Following the initial disturbance, the properties of the particle laden water depend on the physical and chemical characteristics of the particles and, to some degree, on the strength of the disturbance. Particles that tend to bind together as the result of physical-chemical forces (such as fine or organically enriched particles) are mixed into a layer of near bottom water. Turbulence in this layer keeps the particles in suspension, hence the term "resuspension" is used to describe this process. The sediments dominated by aggregated particles are termed "cohesive".

Sediments comprised of particles that have negligible inter-particle bonding are termed "non-cohesive". These particles can also be resuspended if the bottom stress is sufficiently large. However, at lower stresses, non-cohesive particles can also be set into motion across the surface of the sediments without being resuspended in the water column. The mass flux of particles associated with this process is termed "bed-load" transport.

In the southern California environment, the sediments in depths comparable with the outfall diffuser depths tend to have a significant fraction of fine particles (e.g. silt and clay) that form these bonds. Effluent particles are also fine, and highly enriched in organic material, so they also tend to form interparticle bonds. Therefore, resuspension processes can be expected to dominate the transport of disturbed sediments, and are the primary focus of this modeling effort. Bed-load transport may, however, be significant in shallower water where the sediments are dominated by larger particles, or in occasional pockets of sandy material in deeper water.

II.A.2.a. Threshold Resuspension Stress

The strength of the inter-particle bonds within cohesive sediments is dependent on the physical-chemical characteristics of the particles, the time the particles have had to form the bonds, and the mass of overlying particles. The latter tend to compact the underlying sediments and assist in bond formation. This bond formation process is "consolidation" of the sediments. Hayer and Mehta (1982) suggest a rough classification of cohesive sediments into four states: (1) a mobile suspension, (2) a stationary suspension, (2) a consolidating bed and, (4) a settled bed. This division primarily reflects the stress required to break these bonds and the rate of resuspension of the particles. Suspensions erode at low stress levels and virtually en mass. Partially consolidated and fully consolidated (settled) beds erode at higher stesses and on an aggregate by aggregate basis.

The stress level at which interparticle bonds are broken and some of the particles are resuspended into the water column is termed the threshold resuspension stress. Since both time and depth in the sediments tend to promote stronger interparticle bonding, the threshold resuspension stress is generally a minimum at the surface and increases with depth within the sediments. A variety of processes with varying time-scales are associated with sediment consolidation, thus a profile of threshold stress within the sediments often yields a layer-like structure (Figure ??).

Once the stress on the surface of the sediments exceeds the threshold resuspension stress, particles will be eroded from the bottom and resuspended into the water column. Studies indicate that the rate of erosion of bottom material is often proportional to the "excess" bottom stress (??, 19??):

$$\frac{dm}{dt} = \frac{e}{t}$$

where:

$\frac{dm}{dt}$ = (dry) mass flux of resuspended sediments per unit area

e = "excess bottom stress"

= b - t

b = bottom stress

t = threshold stress for resuspension

= proportionality factor
(= resuspension rate at unit excess stress)

Thus the mass of sediments placed into resuspension can be estimated (simulated) if the bottom stress, threshold stress, and proportionality factor are known.

For non-cohesive sediments with a small range of particle sizes, the threshold resuspension stress can frequently be adequately estimated from a "Shield's diagram" (??, 19??). This threshold stress will be independent of particle depth, thus once the bottom currents are sufficiently strong to initiate resuspension, the process will continue until the stress on the bottom decreases. The primary difficulties in calculating resuspension rates are relating the bottom stress to the strength of the currents and determining the erosion rate proportionality factor.

For cohesive sediments, the situation is generally complicated by the dependence of the threshold resuspension stress on the state of consolidation of the sediments. For a constant stress level, resuspension of sediment material will cease as soon as the threshold resuspension stress of the re-exposed sediments exceeds the applied stress. Since the dependence of this threshold resuspension stress depends on the previous history of the sediments. both the resuspension and consolidation processes need to be simulated.

II.A.2.b. Current-Induced Bottom Stress

The pressure head between sections of a channel or river can be used to estimate the stress on the bottom. In general, measurements of the ocean currents must be used to estimate this stress in coastal waters. The magnitude of the stress induced on the sediments by these currents depends on the details of momentum transfer within the benthic boundary layer--the portion of the water column adjacent to the sediments in which frictional interaction of the bottom change the properties of the currents. The details of this momentum and energy transfer depend on the temporal variability of the currents and the density stratification of the water column.

Grant and Madsen (198??) discuss the increase in stress associated with the combination of surface gravity waves and slowly varying ocean currents. It was found that the stress associated with the combination of the two processes could differ substantially from the sum of the stresses associated with the two individual sources.

Cacchione (19??) discusses the potential importance of breaking internal waves on the resuspension process in density stratified waters and Winant and Lee (197??) report on the observation of bore-like flows that were attributed to the breaking of these waves. The potential significance of other proceses in determining the structure of the benthic boundary layer and the resuspension still remain to be examined.

Other difficulties exist in relating the strength of ocean currents to the resuspension of sediments. Bedford (19??) describes the results of studies of the micro-scale nature of the stress-turbulence-resuspension relationship. The analysis indicates that a minority of the flow features produce the bulk of the sediment resuspension. These results cast some uncertainity on the validity of stress estimates based on records collected with typical ocean current meters (e.g. averaging of the speeds, spatial averaging by the sensor, etc.), as well a reinforcing the necessity of an adequate description of the details of the benthic boundary layer.

II.A.2.b. Biological Effects on Resuspension Processes

Increases in bottom stress, resulting in the erosion of sediments can also be generated by animals living within the sediments, or moving on or near the sea-sediment interface. ?? (1987) discuss the importance of whale movements in resuspending sediments off the coast of ??. On the other end of the scale, concentrations of resuspended solids reaching ???? mg/l have been generated by the shrimp, Sci...., during laboratory studies (Thompson, pers. comm.).

Bottom dwelling animals can also resuspend sediment particles into the water column by the ingestion of sediment particles and their subsequent egestion into the water column. This process is discussed in more detail in section ??.

Marine biota can also affect the susceptibility of sediment particles to erosion in a variety of other ways. These include modification of the morphology of the bottom, or the formation or distruction of interparticle bonds through the formation of tubes, fecal pellets, algal mats, or burrowing activities (Rhodes, 19??; ???, 19??). In general, quantitative information on these processes is very limited at the present time.

II.A.2.c. Redeposition of Resuspended Particles

The dynamics of the redeposition of resuspended particles also depend on the nature of the particles. For non-cohesive particles, some of the resuspended particles will settle back to the bottom even during periods when the bottom stress is sufficient to cause resuspension (???, 19??). The concentration of resuspended material in the water column thus reflects the relative rates of resuspension and settling.

There is some indication that resuspended cohesive particles are not redeposited on the bottom until the bottom stress falls below the initial stress leading to the resuspension (???, 19??). If the stress on the bottom falls below some even lower value (the threshold redeposition stress), all the resuspended particles will eventually be redeposited on the bottom. Krone (1962) found that the rate of deposition was dependent on the bottom stress:

$$= 1 - b/ d \qquad (b > d)$$

where: d = threshold deposition stress
b = actual stress on the bottom

Partheniades (1965, 1966) subsequently studied the deposition of resuspended particles for stresses that were in excess of the threshold deposition stress, but less than the intial stress initiating the resuspension. For these conditions, he found that although all the resuspended particles were never redeposited, a fraction of the initially resuspended particles did settle to the bottom, resulting in a new concentration of resuspended particles in the water column:

$$F = \frac{Ceq}{Co}$$

where: C = steady-state concentration of resuspended particles at the stress b
Co = initial concentration of resuspended particles (at stress o)

and: o > b > d

One interesting aspect of this study was that the fraction, F, was independent of the initial concentration, Co, and depended only on the flow conditions.

Metha and Parthenidades (1975) investigated the dependence of the equilibrium fraction on the bottom stress for San Francisco Bay mud and kaolinite, and found that it was solely dependent on the factor:

b where: b* = ---
d

s = bottom stress at which the equilibrium fraction -> 0 (i.e. the threshold deposition stress)

The rate of change in the concentration of particles in the water column (and hence the flux of particles setting to the bottom) depends on the settling speed of the particles and their concentration in the water column (and the vertical diffusivity if the settling speeds are small). A number of studies have investigated the aggregation and settling properties of suspensions of cohesive particles (e.g. Krone, 1962; Owen, 1971; Hunt, 1982; Farley and Morel, 1986), and their dependence on particle concentration and the settling environment. In general, the studies yield qualitatively similar, but often quantitatively different, results. For example, the dependence of particle settling speed on (particle mass) concentration is generally found to follow a relationship of the form:

$$\frac{dm}{dt} \quad (C / C^*)^n \qquad (C > C^*)$$

where: C^* = some "critical" (threshold) concentration

Laboratory studies by Hunt (1982) and Farley and Morel (1986) indicate that an appropriate value for the exponent, n, is about 2. However, Owen (1971), using mud resuspended from the river Thames during neap tide and spring tide flows, found that the settling speed (removal rate) roughly followed a quadratic relationship (n=2) for neap tides, but was approximately linear in the concentration (n=1) during spring tides.

Krone (1962) estimated that the concentration, C^*, for the onset of aggregation effects was about 100-700 mg/liter for San Francisco Bay mud, while Farley and Morel (1986) estimate that for clay, C^* is roughly on the order of 1 mg/l.

II.A.2.d. Distribution of Resuspended Particles in the Water Column

For particles with a unique settling speed and a vertical (eddy) diffusivity that is independent of elevation above the bottom, it can readily be shown that the concentration of particles in the water column should follow an exponential distribution of the form:

$$C(z) = C(0) \exp^{-(Vs/Kv) * z}$$

where: $C(z)$ = (dry) mass concentration of particles in the water column at the elevation, z, above the bottom

Vs = settling speed of the particulates

Kv = vertical diffusivity

As noted, however, the settling speeds of resuspended particles may be dependent on the concentration of particles in the water column. Both the settling speed of aggregated particles and the vertical diffusivity may depend on the intensity of turbulence in the near bottom waters. It is difficult to estimate the intensity of turbulence in density stratified waters from conventional current measurements and thus even more difficult to predict or simulate the distribution of resuspended particles in the water column.

II.A.2.d. Biodeposition

The removal of resuspended particulates from the water column and their reincorporation into the sediments may occur as the result of biological processes, as well as from the physical settling of the particles. Benthic infauna often include species that feed on particles suspended in the water column. Thus resuspended particles may be scavenged from the water column and redeposited in the sediments (e.g. as components of fecal pellets)--even during periods when settling of particles is inhibited by bottom stress. Large changes in the abundance and the composition of the infauna have been observed around large ocean outfalls (O'Connor and Mearns, 198??), so biodeposition rates may vary greatly from area to area.

II.A.2.e. Application to the Ocean

All of the physical resuspension and deposition results discussed in the previous sections are based on laboratory studies using flumes and steady flows. These conditions can, at best, be considered as approximations to the ocean environment. For example, the history of the stress on the bottom and the sediment overburden may be complex, resulting in consolidation of the sediments that is not duplicated in the laboratory. Therefore, relationships based on laboratory studies contain considerable uncertainty when applied to the ocean environment.

In general, little is known about the rates of bioresuspension and biodeposition, or the effects of the biota on sediment consolidation. The situation is obviously worse for communities of benthic and epibenthic biota, where synergistic interactions may also be important.

These uncertainties suggest that simulations of the ocean environment will either require that: (1) the values of parameters quantifying represenations of these processes will have to be determined by "fitting" the characteristics of the simulations to the measured values or, (2) direct estimates of appropriate mechanisms (e.g. resuspension rates) will have to be obtained for coastal conditions.

II.B. Outfall Areas

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II.C. Simulation Models

Simulation models of the deposition, resuspension, and transport of particulate material and components of the particulates have been developed for a variety of conditions, including channels and rivers (e.g. Alonso, 1981), lakes (Richardson, 19??), estuaries (e.g. Odd and Owen, 1976; Hayter and Mehta, 1982), the continental shelf (e.g. Smith, 1977; Schubel and Okubo, 1972; Swift, et. al., 1972), and the deep ocean (e.g. McCave and Smith, 1976). In general, the best success has been achieved for non-cohesive sediments in environments where spatial gradients in the properties of the sediments and the flows are small.

Only a small number of attempts have been made to simulate the composition of sediments around ocean outfalls. In southern California waters, these models include those by Chen and Orlob (1971), Hendricks and Young (1974), Hendricks (1978), Orlob, et.al. (19??), and Hendricks (1982). The most comprehensive of these models is described in Hendricks (1982). This model, initially called the BPM model (for bottom processes model) but later referred to as SEDQ (for sediment quality model) was anticipated to provide, with modification, the basis for the simulation efforts during this study. It was originally developed to estimate the effects on the sediments associated with various levels of treatment of the effluent discharged from the Los Angeles County outfall system (White Point).

II.C.1. Review of the Bottom Processes Model SEDQ (formerly BPM)

II.C.1.a. Overview

SEDQ is a simulation model using statistical methods to describe the properties of the near-bottom processes that affect the composition and distribution of effluent materials in the sediments around an ocean outfall. In this model, the area around the outfall is divided into a set of cells. The composition of the sediments in each cell, and the acccumulation of particulate material, is determined by the relative fluxes of natural and effluent material into, and out of the cell, as well as any changes in composition occurring within the cell.

The flux of effluent related material into each cell from the water column is supplied as input information (e.g. from a sedimentation simulation model such as SEDF2D - see Volume I), and can be varied on an annual basis. The sedimentation rate of natural particulates from the water column is also provided as input, and assumed to be constant in time.

Processes simulated in the model include the resuspension, transport, deposition, and accumulation of particles in the sediments (see Figure ??). The rates of these processes are estimated from measurements of near-bottom currents and the current speeds required to resuspend surface sediments. Other types of information, such as the bioturbation "depth" representing the mixing of sediments by benthic biota and the settling time of the resuspended particulates, appear in the form of parameters that must be estimated from direct measurements, or by comparison of predicted and observed characteristics of the sediments.

II.C.1.c. Resuspension Representation

Resuspension was assumed to be the result of stress induced on the bottom by the near-bottom currents and commenced when this stress exceeded the threshold value. Threshold stress varies with sediment composition and was estimated from in-situ measurements in outfall areas using a portable flow channel. Around southern California outfalls, a significant dependence on the organic content of the sediments was observed (Hendricks, 1978). The dependence on particle grain size was weak, reflecting the generally silty nature of the sediments at typical outfall depths (45-65m). The inverse relationship between threshold resuspension speed and organic content indicated that the threshold resuspension speed, and hence the average flux, of sediments could be modified by the discharge of organically enriched particles from an outfall.

Current meter data recorded at elevations of 1 to 2 meters above the ocean bottom were used to estimate the statistical properties of the bottom stress. It was assumed that a simple scaling factor could be used to transform the current meter speeds into the equivalent speed in the resuspension tunnel.

Resuspension was assumed to commence whenever the bottom stress exceeded the threshold stress. Sediments within the simulation area were assumed to be either cohesive, or non-cohesive, but not both. The amount of material placed into resuspension was dependent on the type of sediments. For cohesive sediments, it was assumed that a constant mass of sediments was placed into resuspension during each resuspension "event". This is equivalent to assuming that the sediments could be represented by a series of layers, each associated with a different state of consolidation, and that the distribution of bottom current speeds was such that only the surface layer (or a constant number of layers) was resuspended during most of the resuspension events. The average total mass placed into resuspension (over an extended period of time) was, therefore, proportional to the fraction of the time that the speed of the near-bottom currents exceeded the threshold resuspension speed.

For non-cohesive sediments, it was assumed that the mass of material placed into resuspension was proportional to the excess bottom stress (see Section ??). This is equivalent to assuming that either: (1) the duration of a resuspension event was constant and shorter than the time required for the equilibrium concentration of particles to be established in the water column or, (2) the resuspension event was of sufficient duration to establish an equilibrium concentration of resuspended particles in the water column, and this concentration was proportional to the excess bottom stress. The latter assumption is equivalent assuming a constant unique settling speed for all the resuspended particulates.

II.C.1.d. Distribution of Resuspended Material in the Water Column

The concentration of resuspended material in the water column was assumed to follow an exponential distribution. The "characteristic thickness", Ho (= Kv/Vs, see Section ??), of the layer of resuspended material was assumed to be either constant, or proportional to the speed of the near-bottom currents at the time of resuspension. The latter is equivalent to assuming that the particle settling speed is constant, but the vertical diffusivity is proportional to the current speed. This "thickness" was assumed to remain the same, independent of the subsequent strength of the near-bottom currents, until all the particles had been redeposited.

II.C.1.e. Transport of Resuspended Material

Resuspended material was assumed to be transported in each of four directions: upcoast, downcoast, onshore, and offshore. The probability of transport in each direction was estimated from the near-bottom current meter records. For each direction of flow, the transport speed was approximated by the average speed of flow in that direction. This approximation assumes that the time between resuspension and redeposition of the sediments was much shorter than the time-scales characterizing the dominant the fluctuations in the near bottom currents--or that the transport could be approximated as a diffusive process characterized by a constant diffusion velocity.

Transport in directions other than the four primary directions requires at least two resuspension events. This is a reasonable approximation provided that resuspension occurs at frequent intervals, or that there are only weak spatial gradients in the threshold resuspension speed of the sediments along at least one of the two principal axes (longshore or cross-shore).

II.C.1.f. Redeposition of Resuspended Material

Resuspended particles were assumed to have either: (1) a constant settling speed, independent of the concentration of resuspended particles or spatial location or, (2) a settling speed that was inversely proportional to the threshold resuspension speed. The latter representaton (not used in the simulations) was intended to reflect the faster settling speeds of coarse, inorganic particles (e.g. sand) versus lighter, more easily resuspended, organically-enriched particles.

Resuspended particles were assumed to settle out from the water column as the particles moved away from the point of resuspension. Since all the resuspended particles were assumed to have the same settling speed, the deposition of particles to the bottom is characterized by a deposition time, Td, or a transport distance, Xd:

$$Td = Kv / (Vs)^2$$

$$Xd = Va * Td$$

where: Va = average near-bottom current speed in the "X" direction

II.C.1.g. Composition and Accumulation of Material in the Surface Sediments

The flux of organic and total material into each cell is equal to the sum of the fluxes associated with sedimentation from the water column and redeposition of sediment particles resuspended in surrounding cells (Figure ??).

Loss of material from the cell is the result of the decay of organic material and resuspension of cell material followed by transport out of the cell. Time scales characterizing the decay of organic material are on the order of days to weeks (Myers, 1974), while characteristic response times of sediment characteristics are on the order of years (see Section ??). Therefore, for simulation purposes it is assumed that fluxes can be approximated by the remaining mass after decay is complete.

The net flux of material into (or out of) cell "i" as the result of resuspension processes is thus:

$$(Sr)i = \sum_{j=1}^{N} [Sji - Sij]$$

where: (Sr)i = net resuspension flux into cell "i"
Sij = mass of material resuspended in cell "i" and deposited in cell "j"
N = all the cells for which Sij or Sji =/ 0

It is assumed that material deposited on the surface of the sediments is rapidly mixed by the benthic biota with sediments remaining in the cell. Mixing is assumed to occur uniformly from the surface to a fixed "depth", and on time-scales that are short compared with the time-scales characterizing changes in the composition of the sediments. Since sediment consolidation is not simulated in the model, sediment depth is expressed in terms of the mass per unit area, Mb, that is mixed by the biota rather than the physical depth (in units of length). The use of this measure of "depth" simplifies calculations since mass fluxes form the basis of the model computations. It also has the characteristic that bioturbation depths (in dimensions of length) will be less in dense sediments (e.g. sand) than in lighter or more porus sediments (such as silt).

This mixing buffers changes in the composition of the sediments. For cells with a net accumulation rate of material, Sn, the characteristic response time, Tb, for the surface sediments is:

$$Tb = Mb/Sn$$

The composition of the surface sediments after a time step, T, is related to both the net flux into the cell and the "bioturbation mass" by the relationship:

$$M(org,new) = (Si(org)* \quad T) + M(org,old)$$

$$M(tot,new) = (Si(tot)* \quad T) + M(tot,old)$$

$$C(new) = \frac{M(org,new)}{M(tot,new)}$$

where: M(org,old) = mass of organic material in the bioturbation layer at the start of the time step
M(tot,old) = corresponding total mass
C(new) = concentration (fraction) of organic mass in the bioturbation layer at the end of the interval

Since there will generally be a net flux of material into, or out of a cell, the particles subject to bioturbation will change in time as older particles are buried by new deposits, or old sediments are reexposed to bioturbation as the result of erosion. This process is simulated in the model by using a "stack" of cells extending from the sea-surface interface downward into the deeper sediments. The uppermost cell represents the bioturbation layer, and is the only sediment cell in the stack affected by the deposition or erosion of material at the sea-sediment interface.

In a depositional area, as material accumulates in the surface cell, it is "pushed" downward into a deeper cell to maintain a roughly constant mass in the surface layer (cell). Conversely, if there is a net erosion of material, the material in deeper cells is moved upward ("popped") to replace the material lost from the upper cell. This stack operation occurs when a mass of material equal to one-half the bioturbation mass has been deposited in, or eroded from, the surface layer.

II.C.1.h. Information Required for a Simulation

Input data required for a simulation includes:

1. The sedimentation rate of natural particulates, and their composition.
2. The sedimentation rates and pattern of effluent particulates (e.g. from a sedimentation flux model such as SEDF2D), and their composition.
3. The refractory fraction of organic material in the effluent particulates.
4. The characteristic deposition time.
5. The relationship between sediment organic content and threshold resuspension speed.
6. The distribution of near-bottom current speeds, the probability of flow in each of the four transport directions, and the average speed of the flow in these directions.
7. A scale factor relating the speeds measured by the current meter(s) to those associated with the threshold resuspension speed measurements.
8. The resuspension mass coefficient.
9. The bioturbation mass (/unit area).
10. The time-history of particle mass emissions from the outfall.

II.C.1.i. Simulation Proceedure

Initially, the simulated sediments are composed of natural particles.

Beginning with the first year of discharge, the fluxes of material into and out of each cell are computed with a simple forward time-stepping. The average annual mass emission rate of effluent suspended solids during the year is used in combination with sedimentation probabilities from the sedimentation flux model SEDF2D (see Volume I) to compute the mass flux of effluent particles from the water column. At each time step, the mass of particles in the surface sediments of each cell is examined and the stack of cells representing the profile of sediments is adjusted, if necessary.

Several time steps are used for each year of simulation in order to : (1) provide for transport of resuspended sediments along directions other than the four primary directions (through the simulation of multiple resuspensions), (2) ensure that the accumulated mass in the surface sediments during a single time step is less than the bioturbation mass and, (3) minimize the computational errors associated with the simple time stepping proceedure.

The effects of each year of discharge are computed in sequence until the simulation for the desired year is completed. The concentration of TVS in the surface sediments is contained in an array, and the stack of cells representing the profile of the sediments for each of the simulation cells is stored in a file that can be examined to determine the time dependent rate of accumulation of particle mass.

II.B.1.j. Previous Simulations

This model has been used to simulate the composition and distribution of the sediments around the White Point and Orange county outfalls (Hendricks, 1983). The model was able to adequately reproduce the distribution and concentration of organic material in the surface sediments around the White Point outfall (see Figure ??). However, the accumulation of effluent-related material in the sediments was predicted to occur about 1 kilometer farther offshore than actually occurred (Figure ??). In addition to the differences in cross-shore distribution, the total mass of effluent material predicted to accumulate in the sediments was only about seventy percent of the actual accumulation. This error is, however, within the uncertainty associated with estimates of the rate and distribution of the initial sedimentation of effluent particles from the water column.

Simulations for the area around the Orange County outfall predicted higher concentrations of organic material than were actually observed in grab samples. However, changes were observed in the Infaunal Index (a measure of benthic invertebrate community structure) around the outfall, and the variational pattern was similar to the predicted distribution of organic material in the surface sediments.

VIII. CONCLUSIONS

VIII.A. Simulation Capability

This study indicates that additional research will be required before it is possible to adequately describe the response of the sediments, and the accompanying biota, to the discharge of organically-enriched effluent particles. However, the model validation tests carried out during the study suggest that the present version of the simulation model SEDR may be suitable for predicting the gross properties of the sediments around outfalls with moderate mass emissions of suspended solids (e.g. < 50,000 m-tons/yr) and relatively inorganic natural sediments (e.g. total volatile solids < 4 percent). It also appears possible to estimate the changes in benthic infaunal community structure for these discharges--although additional simulation comparisons would increase the confidence in these estimates.

VIII.B. Areas Requiring Additional Research

The differences between the White Point area, and the other areas, suggests that the response of the sediments may have some threshold conditions. Exceeding these thresholds appears to result in greatly increased accumulation rates of both effluent and natural particles, and increases in the concentration of effluent particles in the sediments. It was not possible to identify either the appropriate processes, or threshold values, in this study, but the existence of these thresholds could have significant implications for the regulation of discharges, or the siting of ocean outfalls. Areas of research that may provide crucially needed information include: (1) a description of aggregation processes within the surficial sediments, including the aggregation of particles within this layer and their bonding to the permanent sediments and, (2) bioresuspension and biodeposition rates for communities of benthic animals, including the dependence on abundance and composition.

VIII.C. Characteristics of the Sediments and Importance to Environmental Studies and Regulations

The sediment trap studies suggest the presence of a (usually) highly mobile, very thin, surficial layer of sediments overlying the more permanent sediments. The organic content of particles in this layer is generally greater (typically twice as large) as in the "surface" (0-2 cm) sediments obtained with a grab sampler. Infaunal Index changes appear to correlate with the flux of material into, and out of this surficial layer, to a much greater degree than with the concentration of effluent particles in the surface sediments. This suggests that the composition and flux of material in this surficial layer significantly influences the composition of the benthic biota, but it is not sampled by convential sampling techniques. This could have significant implications for laboratory simulations of sediment toxicity or bioaccumulation of trace constituents by benthic and epibenthic biota using sediment samples collected with grab samplers.

V. CHANGES IN THE BENTHIC COMMUNITY STRUCTURE

V.A. Background

V.A.1. Infaunal Index

The Infaunal Index (II) was developed to provide a quantative measure of changes in the community structure of the benthic infauna (see Word, 1978). Selected species are assigned to one of four groups, allegedly on the basis of feeding type although there is some question about the uniqueness of the feeding strategy for many of the species. In these rough terms, the groups correspond to suspension feeders, suspension and surface detritus feeders, surface detritis feeders, and subsurface detritis feeders. Thus the value of the Infaunal Index can be expected to be a function of sediment type (e.g. sand, silt, clay, etc.), the flux of organic material in the epibenthic water, and the accumulation of organic material in the sediments.

V.A.2. Relationship between Infaunal Index and Sediment TVS Concentration in the Coastal Sediments along Southern California

Sediment samples, including the benthic infauna, were collected in water depths of 30 to 100 meters, including outfall areas, along the coast of southern California during 197??. Sediment TVS and the Infaunal Index for the benthic community were measured or calculated for each sediment sample. The set of samples were partitioned into 1 percent increments in TVS concentration, and the average (and standard deviation) of the Infaunal Index for each of these groups was calculated.

Figure ?? shows the resulting relationship. Overall, the Infaunal Index values tend to diminish with increasing concentrations of organic material in the sediment, although there is a large variation of Infaunal Index values within each increment of TVS concentration. The decrease in Infaunal Index accelerates for TVS concentrations in excess of about ?? percent, and for TVS concentrations greater than ?? percent, virtually all the benthic infauna belong to a single group (i.e. II = 0).

V.A.3. Lack of Relationship between Infaunal Index and Sediment TVS Concentrations around the Orange County Outfall

This relationship suggests that it should be possible to estimate the changes in Infaunal Index associated with the discharge of suspended solids from an ocean outfall from the changes in the sediment concentrations of TVS. Figure ?? is a plot of the Infaunal Index for the sediment samples in the vicinity of the Orange County outfall (circles in Figure ??) as a function of the corresponding TVS concentration of the sediments. No significant correlation exists (the best-fit line, although statistically insignificant, actually indicates that II will slightly increase with increasing TVS). This lack of a significant relationship casts doubt on the use of sediment TVS values to estimate Infaunal Index values--in spite of the clear relationship observed along the coastal waters of the entire bight.

V.B. Relationship Between the Flux of Effluent Material and Infaunal Index

V.B.1. Hypothesis

As noted in Section ??, the pattern of change in Infaunal Index around the Orange County outfall bears a strong resemblence to the distribution of accumulation rate. This suggests that some relationship between Infaunal Index and the discharge exists--even if it is not related to sediment TVS.

Sediment TVS values are relatively independent of the accumulation fraction (provided that it is << 1). However, they are dependent on the accumulation rate of effluent particles relative to that of natural particles. Thus variations in accumulation rate will result in corresponding variations in predicted sediment TVS, and the observed changes in Infaunal Index will correlate with the predicted TVS concentrations--but not the measured TVS values.

The accumulation rates are, however, equal to the product of the average mass of effluent particles in the surficial layer of the sediments or, equivalently for small accumulation fractions, to the flux of effluent particles moving through the near-bottom waters in the simulation cell. If it is assumed that the biota are responding to this flux of material (particularily the organic component), rather than the accumulation of effluent particles, then variations will occur around the outfall even if the accumulation fraction is zero and no accumulation occurs, or if the accumulation fraction changes with location.

This process would require that changes in Infaunal Index between outfall areas would be identical if the fluxes of organic material through the cells are the same--even if the accumulation fractions, and hence the accumulation rates, are different.

V.B.2. Test of the Infaunal Index - Effluent Particle Flux Hypothesis

V.B.2.a. Method

This hypothesis was tested using the sediment grab samples collected from the Orange County and San Diego outfall areas. The Encina area was not included in the analysis since Infaunal Index information was not available, and the accumulation rates of effluent particulates were very small and confined to a relatively small area around the outfall.

The simulation cell corresponding to each of the sediment grab samples was determined, and the flux of effluent particles in that cell was computed by dividing the accumulation rate by the accumulation fraction. To reduce natural variability in the samples, the set of measurements were subdivided into groups according to effluent particle flux. The average Infaunal Index for each group was then computed.

A least-squares best fit to the collection of groups was calculated to estimate the Infaunal Index value in the absence of any effluent flux. This "base" value generally changes from area to area and probably reflects differences in the natural environment, or results from inputs into the area from sources other than the outfall discharge. The base values for the Orange County, San Diego, and White Point outfall areas are summarized in Table ?? (the White Point area will be discussed in Section ??). This base value is subtracted from the measured Infaunal Index values to obtain the portion of the variations that are associated with the effluent discharge. The resulting relationship with effluent particle flux in the near-bottom waters is shown in Figure ??. The open circles represent observations from the Orange County area; the solid circles, from the San Diego area.

A least-squares best fit to the points in this figure yields the relationship:

II = - 0.2?? * Fx (r = 0.9?? , p < ??)

where: Fx = flux of effluent particles in the near bottom waters (or surficial sediments) in mg/cm**2/yr

The individual slope values, the correlation coefficients, and the number of points for the two individual areas are summarized in Table ??. These results indicate that changes in Infaunal Index values around these two ocean outfalls are comparable, and that the flux of effluent particles in the epi-benthic waters (or in the surficial sediments) may be a much better indicator of these changes than the accumulation rates of effluent particles (or sediment TVS concentrations). I. INTRODUCTION

I.A. Nature and Relevance

Some of the most evident effects associated with the discharge of treated municipal wastewaters through ocean outfalls are changes in the physical, chemical, and biological characteristics of the sediments and the near bottom waters. These changes primarily result from the sedimentation of organically enriched particles and their accompanying trace constituents. In order to be able to evaluate the suitability of potential discharge sites, estimate the impacts of the proposed discharge, assess the consequences of alternate methods of treatment or disposal, and distinguish between outfall-induced changes and natural variability in this environment, it is necessary to develop an understanding of the processes and mechanisms that determine the fate of effluent particles in the ocean environment.

One tool that can provide a valuable role in achieving this predictive capability is development of computer simulation models. These models use mathematical relationships to quantitatively describe the interaction of the various processes governing the fates of the particles. As such, they play two vital roles.

First of all, they provide a quantitative expression of the conceptual "picture" of the dynamics of these processes. To the extent that the models fail to reproduce observed changes, the differences indicate deficiencies in our understanding of these processes. The nature and magnitude of these deficiencies can suggest changes in our conceptual picture of the environment, generate new hypotheses regarding the controlling mechanisms, and guide the direction of future research. Secondly, to the extent that the models can provide an explaination of a useful fraction of the changes observed around the outfalls, they can be used for predictive and assessment purposes.

I.B. Objective

The objectives of this study are three-fold. The first objective is to determine if, through the used of computer simulation models, a predictive tool can be developed to assess the impacts of ocean discharges on the near-bottom and bottom environment.

The second goal is to identify potential defects in our present conceptual picture of the dynamics of this environment, as manifested by differences between predicted and observed characteristics of the near bottom waters and sediments, and to suggest possible areas of research that might provide increased understanding of this environment.

A third objective was to use the results of the simulations to deduce, if possible, causal relationships that may exist in this environment and, where appropriate, to provide quantitative descriptions of these relationships.

I.C. Scope of the Study

The scope of this study included the development of predictive models describing the initial sedimentation of effluent particles from the water column and the subsequent resuspension, transport, dispersion, and accumulation of these particles in the near bottom waters and sediments. This process was to be accomplished through the modification of existing simulation models through the incorporation of additional process representations into the models, where appropriate, and to improve the orignial representations and computational techniques. In addition, simplified methods of estimating the initial sedimentation of effluent particles from the water column were to be developed.

The validity of the improved models were to be tested by comparing predictions of the characteristics of sediments around various outfall areas with measured values of these parameters.

To carry out these comparisons, some additional information would be required on the characteristics of the ocean environment in the areas to be simulated. These requirements included information on the mid-water and near-bottom currents, and the relationship between current-generated stress on the bottom and the resuspension of sediment particulates.

If these improved models were capable of providing a useful predictive capability, they were to be used to determine if changes in the characteristics of the benthic infauna could be predicted from the characteristics of the effluent, the discharge system, and the ocean environment.

The modeling of the initial sedimentation of particles from the water column is described in Volume I of this report; this volume discusses the subsequent resuspension, transport, dispersion, and accumulation of these particles, and the possible effects these processes may have on the benthic community structure.

During the course of this latter effort, it was necessary to modify the scope of the work. In particular, deficiencies in the bottom processes model became evident during analysis of the simulations. This necessitated the development of a new simulation model of these processes using a different approach. This change in approach, in turn, necessitated changes in the type of supplemental measurements that required for the simulations to be carried out in the discharge areas. In particular, measurements of resuspension-redeposition fluxes, using sediment traps, replaced the bottom stress-resuspension studies that were to be studied with an in-situ resuspension tunnel. NON-TECHNICAL DISCUSSION

Effluent from municipal wastewater treatment plants contains organically enriched particles. Many of the trace constituents of the effluent (e.g. metals and orgnic compounds) are attached to these particles. Following discharge, some of these particles settle to the bottom around the outfall, where they have the potential to alter the physical, chemical, and biological characteristics of the bottom environment.

It is obviously desirable to be able to predict the magnitude and extent of any of these outfall-related changes when assessing the potential impacts of proposed discharges. This predictive capability would also assist in evaluating the results of altered methods of treatment and discharge, or in distinguishing between outfall-related changes and the changes that are part of the normal variability of the ocean environment.

The accumulation of effluent particles in the sediments around the outfall is the end product of the interaction of a complex and generally poorly understood set of physical, chemical, and biological processes. In broad terms, some of the particles settle to the ocean bottom following their release from the outfall. They are then subject to resuspension and subsequent transport and dispersion by the ocean currents. Eventually they become part of the permanent sediments and are "buried" by subsequently deposited particles.

The initial sedimentation of the effluent particles after they are discharged from the outfall is discussed in Volume I of this report. This volume discusses the development of a computer model to simulate the subsequent resuspension, transport, dispersion, and accumulation of these particles in the sediments.

Resuspension of particles can be the result of physical or biological processes. The most familiar mechanism is the physical process in which increases in current speed produce increases in the stress on the particles in the surface sediments, resulting in the resuspension of these particles. It is this process that generally gives rise to the turbid water associated with floods. The details of this process, however, depend to a considerable extent on the characteristics of the particles--for example, their size, density, and chemical composition. The description of the relationship between these characteristics and the rate of resuspension, concentration of resuspended particles in the water column, redeposition of the particles, and resistence to erosion of the sediments is an ongoing area of active research.

The initial effort in this study was to modify an existing model of the dispersion and accumulation of effluent particles associated with resuspension processes so that the calculations would form a more complete representation of the actual mechanisms. This model, "SEDQ", had previously provided acceptable estimates of the surface sediment concentrations of effluent-related organic material around the Los Angeles County outfalls--but it did not reproduce the observed distribution of the accumulation of this material.

Modifications of the representation of physical resuspension proceses, and the incorporation of a biological resuspension process, provided greatly improved simulations and suggested that bioresuspension may provide an important contribution to the total resuspension of bottom sediments in these areas. However, additional defects in the model became evident. The three most significant defects were: (1) the inability to reproduce the observed accumulation rate of sediments in the absence of an outfall discharge, (2) overestimation of the TVS concentrations around other outfalls and, (3) the sensitivity of the sediment accumulation rates to normal uncertainties in the measured speeds of near bottom currents. This lead to the development of an alternative simulation model.

In this new model, information on resuspension-redeposition rates is provided from sediment trap measurements. These consist of vertically oriented tubes, closed at the bottom end, positioned at various depths above the ocean bottom. This direct observational approach eliminates the requirement to simulate the complex processes that generate the resuspension. As a result, the uncertainties in resuspension-redeposition rates are greatly reduced. A side benefit of this approach is that information generated by these sediment trap studies has provided new insight into the details of the surface sediments, with corresponding implications for monitoring the characteristics of the sediments and understanding of the processes occurring at the sea-sediment boundary.

Briefly summarized, the rates of resuspension and redeposition of sediment particles are two orders of magnitude greater than the rate of accumulation in the sediments (and about an order of magnitude greater than the largest sedimentation rate of effluent particles from the water column). These differences in the rates indicate that the particles undergo a large number of resuspensions and redepositons before they become part of the deeper, less mobile sediments. Particles settling from the water column appear to form a surficial layer of sediments with a thickness of only a few tenths of a millimeter (hundredths of an inch). After resuspension, they occupy the lower few meters (1-3m) of the water column. The organic content of the particles in this surficial layer is generally about twice that in the surface sediments (0-2 cm depth) obtained with a grab sampler.

The large number of resuspensions and redepositions suggests that settling effluent particles can be dispersed over a large area by the near bottom ocean currents, while becoming mixed and diluted with natural particles. A new model was developed to describe, in a statistical sense, this dispersion, dilution, and accumulation process using time-series measurements of the ocean currents at an elevation of 2m above the ocean bottom and the pattern and rate of effluent particles from the overlying water column provided by other simulation models (see Volume I).

sediments were carried out for the Orange County (Newport Beach), San Diego (Point Loma), and Encina (Carlsbad) ocean outfalls. The outfall associated increases in organic material were generally predicted to be small and within the variations in the concentrations observed in natural sediments. Thus the simulation results were consistent with observation, but the small increases, relative to natural variability, prevent a precise comparison.

Information on the types of bottom dwelling animals that tend to group together and inhabit the sediments was available for the Orange County and San Diego outfall areas. Significant and nearly identical relationship, were observed between the changes in these groupings and the flow of effluent related organic material through the near bottom waters and surficial sediments at the two sites. These outfall-induced changes were of the same magnitude as normal variations.

Simulations were also carried out for the Los Angeles County (White Point) outfall area. In contrast to the other areas, the predicted concentrations of organic material in the sediments were smaller than measured in grab samples or in sediment cores.

Cores from White Point were used to provide estimates of the accumulation rate of effluent particulates in the permanent sediments. The net accumulation rates estimated from these cores were almost two orders of magnitude greater than predicted by the model. In addition, the accumulation of natural particles during the thirty-one year period of discharge through the deep outfalls was more than an order of magnitude greater than outside the area influenced by the outfall.

The mechanisms leading to the differences between this site and the three other sites are not known at the present time. The most likely candidates are outfall-induced changes in the degree and strength of aggregation of particles in the surficial layer (and between the surficial layer and the permanent sediments), or discharge-related changes in the abundance and types of bottom dwelling animals (resulting in changes in the bioresuspension of surficial sediments). Additional research will be required before these processes can be incorporated into the model without large uncertainties accompanying the results of the simulations.

A significant relationship was again observed between the flow of effluent organic material through the near bottom waters and in the surficial sediments, but the dependence of the change on this flow was different from the other areas. The community structure in regions predicted to be negligibly affected by the discharge also differs substantially from that in the other areas. This may account for at least part of the difference in the community structure-effluent particle flux relationship. Natural variability in the measure of community structure may also contribute.

Additional information on bioresuspension processes, sediment particle aggregation, and benthic community structure will be

Additional information on bioresuspension processes, sediment particle aggregation, and benthic community structure will be required to resolve the differences between the White Point outfall area and the other areas. VI. WHITE POINT OUTFALL AREA - THE ANOMALLY

VI.A. The Simulation Site

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VI.B. SEDR Simulation(s)

VI.B.1. Parameter Selection

Threshold resuspension and redeposition speeds of 8 and 5 cm/sec, respectively, were also selected for the White Point (Palos Verdes) simulations. Emery (1960) has estimated the accumulation rate of natural particles in this area to be about 10 mg/cm**2/yr. However, the station location provided by Emery indicates that the core used for the accumulation analysis was obtained about ?? km downcoast from the mean location of the White Point outfalls, and perhaps in 100m of water (vs. 55-60m water depth at the outfall diffusers).

The annual average resuspension-redeposition flux observed in 52m of water off Palos Verdes was about 4500 mg/cm**2/yr. One month of sampling along a longshore transect indicated that variations in the collection rate are minor over an longshore distance of about 7 kilometers. An accumulation fraction of 0.0022 is required to generate an accumulation rate of natural particles equivalent to 10 mg/cm**2/yr. This is about one-third the accumulation fraction used for the Newport Beach simulations.

VI.C.2. Results

VI.C.2.a. Predicted Accumulation Rates

Figure ?? shows the accumulation pattern and rate of effluent particulates for an annual mass emission rate of 122,000 m-tons of suspended solids. The maximum rate is ?.? mg/cm**2/yr, and is about 1/??? the peak sedimentation rate of effluent particles from the water column (see Hendricks, 1986).

VI.C.2.b. Steady-State TVS Concentrations

The corresponding steady-state TVS concentrations in the surface sediments are shown in Figure ?? (for a mass emission rate of 122,000 m-tons/yr). The peak steady-state concentration of TVS is predicted to occur in the vicinity of the 90-inch (upcoast) outfall and has a value of ??.? percent.

Samples of the surface sediments were collected with a Van Veen grab sampler (1978) and a corer (1981). The locations of these samples, and the corresponding TVS concentrations in the upper 2 cm, are indicated by the solid circles (1978) and crosses (1981) are shown in Figure ??. The peak concentration occurs in the vicinity of the outfall diffusers and has a value of about ?? percent. Examination of the distribution of TVS in the cores (see Appendix ??) indicates that at this station, sediments at a depth in excess of ?? cm (?? gm/cm**2) are representative of the sediments before the discharge commenced. Typical TVS concentrations in these deep sediments are about ?? percent, thus the discharge-induced increase in TVS concentrations is evident both from the spatial distribution in the surface sediments and with sediment depth.

It is interesting, and puzzling, to note that while the predicted TVS concentrations in the surface sediments off Newport Beach (Orange County) and San Diego (Point Loma) tended to be somewhat greater than the measured values, the opposite trend is evident in this White Point simulation.

VI.C.2.c. Transient TVS Concentrations

The mass emissions of suspended solids has varied considerably since the first deep outfall commenced operation in 1956. Initially, annual mass emissions of suspended solids paralleled increases in the flow from the outfall. Beginning in the mid 1970's, improvements in the treatment process have reduced the annual mass emission rate from a peak of about 165,000 m-tons (197??) to the current (1986) level of 78,000 m-tons (Figure ??).

Because of these variations, the "steady-state" concentration of TVS in the surface sediments can be expected to also vary in time, and it is difficult, a priori, to determine what the actual TVS concentration would be in any given year without including the effects of bioturbation and changing emission rate.

The history of suspended solids emissions shown in Figure ?? was used to estimate the (transient) TVS concentration in the surface sediments at the end of 1980 for a bioturbation mass of 500 mg/cm**2. The results are shown in Figure ??. As before, the solid circles and accompanying numbers indicate the measured TVS concentrations in grab samples collected in 1978 and the crosses the values in the cores collected in 1981.

The resulting transient TVS concentrations show the same feature as the steady-state concentrations--the predicted values are lower than the observed values.

VI.B.2.d. Comparison of Predicted and Observed Accumulation Rate

Since TVS concentrations in the sediments around the outfall are in excess of the concentrations in the natural sediments, the sediment core data can be used to provide direct estimates of the accumulation rate of effluent particles. The average accumulation rate of effluent particle mass, Se, on the bottom over the 25 year period of discharge is (Hendricks, 1986):

$$Se = \frac{1}{1+Rt} \frac{Mt}{T}$$

where:

$$Rt = \frac{Ce-Cen}{Cen-Cn}$$

Se = average accumulation rate (mg/cm**2/yr)
Mt = total sediment mass with elevated concentrations of TVS (mg/cm**2)
T = period of discharge (25 years)
Ce = TVS concentration of effluent particles (after decay)
Cen = TVS concentration of the mass, Mt
Cn = TVS concentration of natural sediments

Myers' (1974) measurements of the reduction in effluent particle concentration associated with decay indicate that the organic carbon concentration of the refractory fraction after decay will be about 0.6 to 0.8 of the original value. Since there usually is a good correspondence between total organic carbon and total volatile solids, it is assumed that the same reduction applies to TVS values. Thus the TVS concentration of effluent particles is reduced by decay from about 70 percent to about 42 to 56 percent.

The distribution of total volatile solids in the sediments in the core collected between the two outfall diffusers is listed in Appendix ??. Analysis of this core indicates that the average accumulation rate of effluent particles (after decay) ranges from ??? to ??? mg/cm**2/yr, depending on the refractory fraction. These rates are between one and two orders of magnitude greater than the accumulation rate predicted in the SEDR simulations.

The average accumulation rate of natural material, Sn, in the portion of the sediments affected by the discharge is (Hendricks, 1986):

$$Sn = Rt * Se$$

For this same core, the average accumulation rate of natural particles ranges from ??? to ??? mg/cm**2/yr. This flux is also one to two orders of magnitude greater than the rate estimated by

Emery (1960), or in sedimentation studies of the offshore slope and basin (??, pers. comm.).

A similar analysis for the other cores indicates that the accumulation rates of natural and effluent particles are linearly correlated. This relationship is indicated in Figure ??. These accumulation rates are incompatible with the small accumulation fractions used in the simulation of the Orange County, San Diego, and Encina outfalls, as well as the initial simulation carried out for this outfall.

A new simulation was carried out for White Point, assuming an accumulation fraction equal to 0.500 in place of the original value of 0.0022. The resulting accumulation rates of effluent particles are shown in Figure ??, and the accumulation rate of natural particles would be 0.5 * 4100 = 2050 mg/cm**2/yr. The predicted accumulation rate of effluent particles in the region of the two outfall diffusers is now consistent with the measured accumulation rate (i.e. within the range of uncertainty in the estimated sedimentation rate of effluent particles from the water column). However, the predicted accumulation rate of effluent particles (2050 mg/cm**2/yr) is about four times greater than the rate estimated from the core analysis, and hints that the accumulation fraction might be different for the two types of particles.

VI.D. Relationship between the Flux of Effluent Organic Material and Benthic Community Structure

Possible relationships between the flux of effluent material in the epi-benthic waters and surficial sediments, and changes in the community structure were carried out for the White Point simulation area using the same method described in Section V.

Figure ?? shows the resulting dependence of the Infaunal Index on this flux (for an accumulation fraction of 0.0022). As in the Newport Beach and San Diego areas, increases in the flux of organic material result in a reduction in the index. The correlation coefficient is 0.95, indicating a significant relationship at a confidence level of ??.

Figure ?? compares the Infaunal Index and the effluent particle flux for an accumulation fraction of 0.500. The ....

It is noteworthy, however, that the rate of decrease in the Infaunal Index with increased effluent particle flux in the near bottom waters is only about one-third the rate observed at the two other sites..... The reason(s) for this difference are not known at the present time.

One possibility is that the relationship is not linear, but changes with the community structure or the flux rate. Table ?? summarizes the value of the Infaunal Index at each of the three outfall sites for no effluent discharge, as well as the rate of change in the infaunal index per unit flux of effluent particles in the near bottom water. It is evident that the natural benthic communities (in the absence of the discharge) are substantially different among the three areas, with the "no-discharge" value at White Point significantly lower that the other two sites (and almost one-half the Index value at San Diego).

>>>> Benthic Biomass, Filter Feeders, Bioresuspension, Biodeposition, Aggregation <<<<<<<<<

SEDQ

Background

SEDQ is a simulation model using statistical methods to describe the properties of the near-bottom processes that affect the composition and distribution of effluent materials in the sediments around an ocean outfall. In this model, the area around the outfall is divided into a set of cells. The composition of the sediments in each cell, and the acccumulation of particulate material, is determined by the relative fluxes of natural and effluent material into, and out of the cell, as well as any changes in composition occurring within the cell.

Processes incorporated into the previous version of the model included the sedimentation of natural and effluent particles froms the water column, the resuspension and redistribution of sediment material by bottom currents, mixing of the upper layer of the sediments by the benthic biota, and vertical changes in the location of the sea-sediment interface (to reflect the net accumulation or loss of material to or from the sediments).

Resuspension was addressed only in terms of physical processes. The distribution of near-bottom current speeds was used to determine the fraction of the time that resuspension of the bottom sediments occurred. Material resuspended in a simulation cell was transported in each of four directions (upcoast, downcoast, onshore, offshore) according to the relative probabilities of transport in each of these directions.

A fixed mass of material was assumed to be resuspended during each resuspension event. This representation was chosen as an approximation to the situation where a layer of relatively unconsolidated cohesive sediments lies on top of a bed of consolidated material. The resuspension of this consolidated materiala was assumed to be negligible as a result of the increased threshold resuspension speed. Threshold resuspension speeds were related to the organic content of the sediments using in-situ measurements of the resuspension speed (Hendricks, 1978 and Figure ??). As a result, as the composition of the sediments changed during the couse of the simulation, the threshold resuspension speed also changed.

Resuspended material was assumed to be distributed in the water column according to an exponential function:

$$C(z) = C(z=0) * e^{-(z/Ho)}$$

where: C(z) = concentration of suspended solids at the elevation, z.

Ho = "characteristic" resuspension layer thickness

It was further assumed that the ratio between the characteristic thickness of this resuspended mass and the settling speed of the resuspended particles was a constant, resulting in a characteristic settling time:

$$Td = (Ho / Vs)$$

where: Td = "characteristic" deposition time.

Vs = settling speed of the resuspended particles

The deposition of resuspended material into downstream cells is determined by the exponential distribution of suspended mass above the sediments, the characteristic depostion time, and the average current velocity in each of the four downstream directions, and the corresponding probability of flow in each direction.

The "instantaneous" composition of the surface sediments within each cell is determined by the flux rates of organic material into the cell as a result of deposition from the overlying water column and transport of resuspended sediments from surrounding cells, and the flux rate of of material resuspended within the cell into surrounding cells.

$$C(org) = \frac{Sn(o) + Se(o) + Sr(o)}{Sn(t) + Se(t) + Sr(t)} = \frac{Si(org)}{Si(tot)}$$

where: C(org)= concentration of organic material (experessed as a fraction of the total mass)

Sn(o),Sn(t) = fluxes of natural organic and total mass respectively from the water column (sedimentation)

Se(o),Se(t) = corresponding sedimentation fluxes of effluent material

Sr(o),Sr(t) = flux of organic and inorganic material associated with the resuspension and redeposition of sediment material.

S(org),S(tot) = net flux of organic and total mass into the cell

The resuspension associated fluxes can be described in terms of the individual fluxes from cell "j" to cell "i":

$$(Sr)i = [\ Sji - \quad Sij\ ]$$

where:

(Sr)i = net resuspension flux into cell "i"

Sij = mass of material resuspended in cell "i" and deposited in cell "j"

It is assumed that material deposited on the surface of the sediments is rapidly mixed by benthic biota with the previous surface sediments. This mixing process "buffers" the change in composition of the surface sediments. Thus the composition of the surface sediments after an elapsed time, T, is related to both the net flux into the cell and the "bioturbation mass" by the relationship:

$$M(org,new) = (Si(org)* \quad T) + M(org,old)$$

$$M(tot,new) = (Si(tot)* \quad T) + M(tot,old)$$

$$C(new) = \frac{M(org,new)}{M(tot,new)}$$

where:

M(org,old) = mass of organic material in the bioturbation layer at the start of the time step

M(tot,old) = corresponding total mass

C(new) = concentration (fraction) of organic mass in the bioturbation layer at the end of the interval

The distribution of effluent-related material accumulating in the sediments is simulated using a "stack" of cells extending from the sea-surface interface downward into the deeper sediments. The uppermost cell represents the bioturbation layer, and is the only sediment cell in the stack affected by the deposition or erosion of material at the sea-sediment interface.

In a depositional area, as material accumulates in the surface cell, it is "pushed" downward into a deeper cell to maintain a roughly constant mass in the surface layer (cell). Conversely, if there is a net erosion of material, the material in deeper cells is moved upward ("poped") to replace the material lost from the upper cell. This stack operation occurs when a mass of material equal to a bioturbation mass has been deposited in, or eroded from, the surface layer.

A simulation begins with natural sediments throughout the simulation area. The outfall discharge then commences. At each time step, the mass emissions from the outfall is combined with the effluent-related sedimentation pattern to estimate the effluent-related deposition of material into each cell. This flux is combined with the flux of natural particulates from the water column. At the same time, the initial composition of the sediments information is used, in combination with the threshold resuspension speed information and transport properties of the currents, to estimate the redistribution of the surface sediments among the simulation cells as a result of resuspension.

At the end of the time step, the total flux of material into each cell (water column sedimentation, resuspension) and the flux out of each cell (loss of resuspended material to other cells) is combined with the remaining material in the surface sediments to obtain the new composition of the surface sediments. The mass of organic material is also reduced to reflect loss due to "decay" and, if necessary, material is "pushed" or "poped" from the sediment "stack" to maintain roughly a constant mass in the surface sediments (i.e. the bioturbation layer). This procedure is repeated until the desired elapsed time has been simulated.

Input data required for a simulation includes:

1. The sedimentation rate of natural particulates, and their composition.

2. The sedimentation rates and pattern of effluent particulates (e.g. from a sedimentation flux model such as SEDF2D), and their composition.

3. The refractory fraction of organic material in the effluent particulates.

4. The characteristic deposition time.

5. The relationship between sediment organic content and threshold resuspension speed.

6. The distribution of near-bottom current speeds, the probability of flow in each of the four transport directions, and the average speed of the flow in these directions.

7. A scale factor relating the speeds measured by the current meter(s) to those associated with the threshold resuspension speed measurements.

8. The resuspension mass coefficient.

9. The bioturbation mass (/unit area).

10. The time-history of particle mass emissions from the outfall.

The sources of this information for the simulations carried out to date are summarized in Table ??.

Table ??

Source of Input Information

Parameter(s)	Source(s)
Natural sedimentation	Emery (19??)
Outfall sedimentation	Simulations with SEDF2D
Refractory fraction	Myers (1974)
Deposition time	"Fitted" parameter (White Pt.)
Threshold speeds	Hendricks (1978)
Near-bottom currents	Direct measurement (1-2m elev)
Speed scaling factor	Assumed = 1
Resuspension mass	"Fitted" parameter (White Pt.)
Bioturbation mass	Myers(1974), core analysis (DDT)
Mass emissions	Appropriate discharger / SCCWRP

This model was used to simulate the composition and distribution of the sediments around the White Point and Orange county outfalls (Hendricks, 1983). The model was able to reproduce the distribution and concentrations of organic material in the surface sediments around the White Point outfall (see Figure ??). However, the accumulation of effluent-related material in the sediments was predicted to occur about 1 kilometer farther offshore than actually occurred (Figure ??). Simulations for the area around the Orange County outfall predicted higher concentrations of organic material in the sediments around the outfall than were actually observed in grab samples.

Modification of Process Representations in SEDQ

Inclusion of Non-Cohesive Sediments

The inability of the model to reproduce the accumulation of effluent material in the sediments around the White Point outfall suggests that the representation of sediment resuspension used in the model may not adequately describe the actual processes. At the beginning of this study, it was believed that a potentially important defect in the model was the failure to provide for resuspension of both cohesive and non-cohesive sediments.

Effluent particles are characterized by small size and high organic content (total volatile solids 50 percent after decay) promoting inter-particle aggregation and the formation of cohesive sediments. In contrast, in this area natural sediment particles have substantially lower organic content (e.g. 0.7 -> 6 percent) and often include a significant fraction of particles of larger size. Therefore, they are less likely to form cohesive sediments--particularily in shallow water.

Measurements of the near-bottom currents in this area indicate a significant offshore component to the near-bottom flow, suggesting that natural sediments from the area inshore from the outfall-related sedimentation field may be a significant source of "diluting" natural particles in the effluent-associated sedimentation field. Therefore, it is possible that the transport of natural particulates into the outfall-related sedimentation field may be associated with the resuspension of non-cohesive sediments, while the resuspension and transport of material out of the organically-enriched, outfall-associated sedimentation field may be associated with the resuspension of cohesive sediments.

Since non-cohesive particles do not undergo consolidation, their threshold resuspension speed can be expected to be nearly independent of depth within the sediments at the commencement of the resuspension event. Therefore sediment erosion and resuspension can continue as long as the speed of the near-bottom currents is in excess of the threshold resuspension speed. This behavior is at variance with the resuspension representation used in SEDQ (a fixed mass of particles resuspended during each event).

This difference in resuspension characteristics has potentially important consequences for the resuspension simulations. In sediment samples collected around the White Point outfall during 1978 to 1982, the peak concentrations of volatile solids in the surface sediments was about 20 percent. Thus a flux of natural particles (VS = 5 percent) equal to about twice the sedimentation flux of effluent particles must be permanently deposited in order to produce the observed sediment VS concentration.

The estimate of the resuspension mass parameter, Mc (in mass/cm**2/event), used in the simulations is essentially "fixed" by this dilution requirement. However, once this mass is chosen, the resuspension mass flux for the organically enriched sediments is also fixed. Thus the two resuspension and transport rates are intimately connected in the model--even though the actual resuspension processes may be quite different if natural sediments are non-cohesive while the organically enriched sediments are cohesive.

At the beginning of this study, it was anticipated that the discrepancy between the predicted and observed patterns of the accumulation of effluent material around the White Point outfall might be related to the use of a single resuspension representation in the model. In order to examine this hypothesis, the resuspension representation was changed so that the (original) "constant resuspended mass" approximation was retained for organically enriched, cohesive sediments, but for non-cohesive sediments it was assumed that the mass rate of sediment resuspension was proportional to the "excess bottom stress" (??, 197??):

$$\frac{dM}{dt} = Mnc * \frac{(Vb^2 - Vr^2)}{Vr^2}$$

where: Mnc = mass resuspension rate for non-cohesive sediments (mg/cm**2/yr)
Vb = near-bottom current speed
Vr = threshold resuspension speed

The change from non-cohesive to cohesive sediments was assumed to be related to the organic content of the sediments, with the transition point corresponding to the discontinuity in the relationship between threshold resuspension speed and sediment volatile solids at concentration of about 5.8 percent (see Figure ??).

After this change was made in the model, simulations were again carried out for the White Point outfall area. With an appropriate selection of values for the parameters Mc and Mnc, it was possible to reproduce both the observed distribution of volatile solids concentrations in the surface sediments (as in the original version) and the qualitative features of the accumulation pattern. While the distributional pattern of the accumulation of effluent material was now in generally good agreement with observation, the magnitude of the predicted accumulation was still only about 60-70 percent of the observed value. This difference may, however, be related to uIII. SEDQ SIMULATIONS

III.A. Modifications to SEDQ

III.A.1. Resuspension Representation Revisions

The dynamics of the various processes incorporated into SEDQ were reviewed to see if the representations of near-bottom processes, or an alternate set of parameter values, could reduce the discrepancies between the predicted and observed cross-shore accumulations of effluent material in the White Point area and the overestimates of TVS concentrations in Newport Beach and other outfall simulations.

Since the initial sedimentation of effluent particles from the water column has a cross-shore maximum roughly along the 55-60m isobath (see Volume I), the offshore maximum in the accumulation of effluent particles predicted by the model must be the result of resuspension and transport processes. Therefore, any changes that reduce the offshore flux of resuspended particles will reduce the differences between the predicted and observed accumulations.

III.A.2. Resuspension and Offshore Transport Fluxes

One way to reduce this flux is to reduce the resuspended mass parameter (i.e. the average mass resuspended during each resuspension event). A second method is to reduce the transport time for the resuspended particles by increasing the settling speed of the resuspended particles or reducing the vertical diffusivity in the near bottom waters. Both of these options, however, will also reduce the flux of resuspended natural particles into the region of significant effluent particle sedimentation, resulting in an increase in the concentration of TVS in the sediments.

The original values for the resuspension mass parameter and the resuspension transport time were selected so that the predicted surface sediment concentrations of TVS would be be consistent with the observed values along a cross-shore transect near the outfall (Transect 7 - see Figure ??). Therefore, reductions in the magnitude of these parameters to reduce the offshore transport of effluent particles would generate discrepancies between the observed and predicted concentrations of TVS in the surface sediments. This could be compensated by a reduction in the fraction of refractory organic material in effluent particulates, but this would magnify the differnece between the predicted and observed accumulation of effluent particles and contradict the results of the Myers (1974) study.

Several other possibilities also exist. For example, there are substantial differences between effluent and natural particles. If these differences result in different flux rates for the two types of particles (e.g. through different resuspension mechanisms or particle settling speeds), the offshore flux of effluent particles could be reduced without altering the diluting flux of natural particles.

II.A.2.a. Changes in the Representation of Current Induced Resuspension

Since the net movement of the near bottom waters includes an offshore component, the primary source of natural particles mixing with and diluting the sedimenting effluent particles is from sediments in water depths of less than 55-60 meters. In general, these sediments have lower TVS concentrations and larger grain sizes. Therefore, inshore particles are more likely to be non-cohesive. In that case, it would be inappropriate to use a representation for cohesive particles to simulate their resuspension.

An examination of the threshold resuspension speed observed in the in-situ resuspension tunnel studies (Hendricks, 1978) suggests a change in the relationship between threshold resuspension speed and sediment organic content at a TVS concentration of about five and one-half percent (see Figure ??). For TVS concentrations above this value, the threshold resuspension speed decreases much more rapidly with increasing organic content than for lower values. This suggests that some change in the resuspension process may accompany this change in sediment concentration.

In order to evaluate the implications of this hypothesis, it was assumed that sediments with TVS values lower than 5.6 percent were non-cohesive, while sediments with higher organic contents were cohesive. With this distinction between sediment type, the resuspension representation used for cohesive sediments remained the same as in previous simulations (a fixed mass of sediments was resuspended each time the speed of the near bottom currents exceeded the threshold resuspension speed). For non-cohesive sediments, it was assumed that whenever the near bottom current speed exceeded the threshold resuspension speed, a mass of sediments proportional to the excess bottom stress associated with the resuspension was resuspended into the water column (see Section ??).

Two flux parameters now describe the resuspension process, the mass resuspended during each resuspension event (cohesive sediments) and the mass per unit excess bottom stress (non-cohesive sediments).

III.A.2.a.i. Simulations with Cohesive and Non-Cohesive Sediments

Simulations were carried out with this revised representation of the resuspension dynamics. In the previous simulations, the concentration of TVS in the surface sediments, and the cross-shore distribution of this concentration (across a single transect), were used to select appropriate values for the resuspension mass and the transport time parameters. The additional resuspension representation introduced a third parameter. Therefore, the accumulation of organic material, as well as the TVS concentrations in the surface sediments and their cross-shore distribution (again along a single transect) were used to estimate the three parameter values.

By an appropriate selection of these parameters, it was possible to essentially reproduce the original surface sediment concentrations of TVS, but with a maximum accumulation of effluent particles close to the 60m isobath. As before, the accumulation rates of effluent particles in the simulation area were less than the rates estimated from sediment cores, but this discrepancy is most likely associated with the estimation of effluent particle sedimentation from the water column (see Volume I).

III.A.2.b. Bioresuspension

As discussed in Section ??, animals living adjacent to, or within the sediments may also resuspend sediment material. The rate of resuspension can be expected to depend on the abundance and type of animals. If the sedimentation of effluent particles produces changes in the abundance or community structure of the benthic biota, a difference in resuspension rates may develop between areas impacted by the discharge and the surrounding areas. In particular, if the rate of resuspension is reduced as the flux of effluent particles increases, the resuspension and transport of particles from this area will be reduced while the flux of natural particles into the area will be maintained. Therefore, this bioresuspension process has the characteristics required to minimize the offshore transport and accumulation of effluent particles, while providing the required dilution of these particles along the 60m isobath.

Dr. Bruce Thompson, of SCCWRP, has been studing the population dynamics of the benthic worm, Pectinaria californesis. Ingestion-egestion rates were measured as part of the study, and the average egestion rate per animal was found to be about ??? mg/animal. The abundance of this worm on the nearshore shelf and slope of southern California has also been studied for various habitats. This abundance information (Thompson, pers. comm.) is shown in Figure ?? as a function of the TVS concentration of the sediments. The resulting egestion rates, expressed now in terms of mg/cm**2/yr are also shown. For TVS concentrations representative of natural sediments (e.g. ?? - ?? percent), the egestion rate is on the order of ??? mg/cm**2/yr. At a TVS concentration of 20 percent (e.g. near the White Point outfall diffusers), the egestion rate is reduced to about ???, or about one-?? of the rate in areas unaffected by the discharge.

Obviously the total bioresuspension rate depends on the abundance and type of all the benthic biota inhabiting the sediments. In the absence of equivalent information on other animals, it was decided to see if the TVS concentration dependent egestion flux from this single worm could account for the distribution of effluent particles in the sediments around the White Point outfall.

It was assumed that the entire mass of egested particles were placed into resuspension. Since this worm is commonly called the "ice cream cone" worm because of the mound of particles that build up around its burrow, this assumption clearly results in an overestimation of the effective resuspension rate. However, this overestimation compensates, to some degree, that the resuspension rate used in the simulation was for only this one species of worm. With these assumptions, the resuspension flux was predetermined, and no corresponding parameter "fitting" process was used for the simulations. The value of the transport time parameter was selected to be the same as estimated from the previous simulations with current-induced resuspension.

III.A.2.b.i. Bioresuspension Simulations

Figure ?? shows the distribution of TVS concentrations in the surface sediments around the White Point outfall for a simulation with bioresuspension, but no current-induced resuspension. Although there are some differences between the results for bioresuspension and for current-induced resuspension (Figure ??), the concentrations and patterns are remarkably similar. This similarity suggests that bioresuspension processes may play an important role in determining the fate of effluent particles in the sediments.

III.A.3. Remaining Model Deficiencies

The representations used in the model for either current-induced resuspension (both cohesive and non-cohesive sediments) or bioresuspension reasonably reproduce the surface sediment concentrations of TVS and the overall accumulation of effluent particulates. Although not tested, it is likely that a combination of the two processes could produce the same result.

An examination of the details of the predicted TVS concentrations and accumulation distribution around the White Point outfall, combined with and simulations carried out for other outfall areas, suggest that at least three problem areas remain with this simulation model:

1. Simulations of outfall areas other than White Point predict surface sediment TVS concentrations that are significantly in excess of measured values.

2. For current-induced resuspension in the absence of effluent discharge, the predicted accumulation rate of natural particles is greatly in excess of the actual accumulation rate.

3. The small-scale (cell-to-cell) features of the cross-shore distribution of sediment accumulation are highly sensitive to the normal uncertainites that accompany estimates of the net cross-shore component of the near-bottom currents obtained from current meter records.

For resuspensions resulting from current-induced stress on the sediments, the predicted TVS concentratons in the surface sediments can be reduced to values comparable with measured concentrations by increases in the resuspension rate parameter for non-cohesive sediments. However, this increase would increase the discrepancy between the predicted and actual accumulation rate of natural particulates in the absence of a discharge, and generally would increase the sensitivity of the small-scale variations in the cross-shore accumulations to uncertainties in the current measurements. A changing resuspension mass would also imply that the resuspension mass and resuspension rate parameters can vary from area-to-area.

III.A.4. Drawbacks to SEDQ as a Simulation Tool

Simulations carried out for different outfall areas indicate that the the resuspension parameters (resuspension mass, resuspension rate, transport time) may change from area to area. Since suitable values for these quantities are difficult to obtain by direct measurement (and were estimated from the distributions and accumulation of effluent material around operating outfalls), it would be difficult to apply the model to proposed (versus operational) outfall discharges.

In areas with sediment or oceanographic characeristics that differ from those in the coastal waters of southern California, it might also be necessary to make direct measurements of the threshold resuspension speeds and some adjustment of the speed scaling factor (i.e. the conversion from the current speed measured at some elevation above the sediments to the corresponding speed of the flow in the resuspension tunnel).

In addition, the role of bioresuspension is uncertain. Laboratory studies have provided estimates of the egestion rate of sediment material into the water column by a single worm, but the efficiency of this process is unknown. An extension of this preliminary representation of bioresuspenion to include the entire benthic (and epi-benthic) biota (and their abundance in various environments) would require a formidable effort.

Even with more detailed and extensive information on both physical resuspension and bioresuspension, the problem of natural particle accumulation rates and the sensitivity of the cross-shore distributions of total accumulation remain. Obviously with sufficient new and additional information, and appropriate changes in the representations of the appropriate processes and the computational scheme used in the model, these deficiencies could ultimately be corrected. What is not clear, however, is what resemblance the "final" form of the model would have to the present version.

Because of these problems and the requirement for extensive information on the physical, chemical, and biological characteristics of the ocean environment in the region around the outfall, SEDQ does not appear to be an appropriate simulation model for regulatory purposes (e.g. 301-h Applications). IV.C. The Resuspension, Transport, and Accumulation Model SEDR

IV.C.1. Basic Description

SEDR is a simulation model of the resuspension and dispersion of effluent particles from the time they are initially deposited on the sea-sediment interface until they are incorporated into the permanent sediments. Output from the model consists of the spatial distribution and accumulation rates of effluent particles within the bounds of the inner grid of the sedimentation flux model SEDF2D. Utility programs provide for the calculation of steady-state or transient TVS concentrations in the surface of the "permanent" sediments.

Information used in the model includes sedimentation flux rates (supplied by the simulation model SEDF2D), time-series of near-bottom currents (from current measurements), rates of resuspension and redepositon of surficial sediment material (provided by near-bottom sediment traps), the net accumulation rate of natural particles in the sediments in the absence of the outfall discharge and, if available, information on suitable threshold resuspension and deposition speeds for particles in the surficial layer of the sediments.

The calculation proceeds in four stages. In the first stage, the time-series of current measurements is used in combination with sediment threshold resuspension and redeposition speeds to estimate, in a statistical sense, the dispersion and deposition of particles following a single resuspension event.

The second stage utilizes this information to estimate the dispersion of particles for a large number of resuspensions. Following each resuspension, a small fraction of the particles in the surface layer are "deposited" into the "permanent" sediments, while the remainder are available for resuspension during the next event. The output from this stage represents the accumulation pattern of particles into the permanent sediments originating from a single point of resuspension.

In the third stage, each cell within the inner grid of the sedimentation flux simulation model SEDF2D is treated as a source of resuspended particles. The mass of effluent particles "available" for resuspension is the flux of these particles settling from the water column. The output from this stage is the spatial distribution and flux of effluent particles into the permanent sediments.

The fourth, and final stage, uses the accumulation fluxes of natural and effluent particles (and their corresponding TVS concentrations) to estimate the steady-state, or transient, distribution and concentration of TVS in the permanent sediments. The transient concentrations, which span the period between the time the discharge first commences and when steady-state conditions are achieved, are the result of bioturbation or temporally changing mass emissions of suspended solids.

This computational scheme assumes that the resuspension and redeposition characteristics (e.g. threshold resuspension and redepositon speeds) and the transport probability from the layer of surficial sediments into the permanent sediments are independent of the mass of particles in the surficial layer, or their chemical characteristics. The latter is equivalent to assuming that the equilibrium TVS concentration in the permanent sediments is the same as in the surficial sediments.

IV.C.2. Procedure

IV.C.2.a. Single Resuspension Dispersion (ARRAY)

To estimate the statistical dispersion of particles after a single resuspension event, the dispersion of particles is simulated for a point source at the center of a rectangular grid of cells. The dimensions of the cells forming the grid are the same as those of the inner grid in SEDF2D, however, the number of cells along each axis is twice the number used in the SEDF2D grid (actually 2N-1). After a unit mass of particles are resuspended from the center of this grid, their subsequent movement is computed from the current meter record until the particles are redeposited.

The simulation begins with the first observation in the current meter record. If the observed speed is less than the threshold resuspension speed of the particles in the surficial sediments (Ur), no resuspension occurs during that time interval. The second current meter observation is examined next. Again, if the current speed is less than the threshold value, no resuspension occurs and the next current meter observation is tested. This proceedure continues until an observation indicates that the speed of the currents exceeds the threshold value. "Mass resuspension" (see Section ??) is assumed to occur, and all the sediment material available in the surficial layer is assumed to be resuspended.

The next current meter observation is then examined to see if the current speed has fallen below the threshold deposition speed (Ud, with $Ud < Ur$). If the speed remains in excess of the threshold value, deposition is assumed to be inhibited and transport continues. Laboratory observations suggest that some deposition may occur when the current speed falls below the original resuspension speed, but above the threshold redeposition speed (see Section ??). This process is not included in the present version of the model, and deposition only occurs when the current speed falls below the threshold value.

In the simulations carried out in this report, it is assumed that the time required for redeposition is less than the current meter sampling interval (45 minutes). For a characteristic thickness for the resuspended material of 2 meters, this is equivalent to assuming that the settling speed of the resuspended particles exceeds 0.07 cm/sec. A longer settling time, and correspondingly slower particle settling speed, would generally provide greater dispersion of the particles, so the present simulations should err toward an overestimate of the accumulation rates of effluent particles and the corresponding sediment concentrations of TVS.

Once the particles are deposited, subsequent current meter observations continue to be examined to see if another resuspension occurs. When this happens, the transport and location of deposition for that resuspension "event" is also computed. Proceeding in this manner through the entire current meter record provides an estimate of the statistical dispersion of resuspended particles following a single resuspension event.

Two utility programs are used to carry out this simulation, "TRANS" and "ARRAY". The format of the files containing the current meter data used by these programs is identical to the format required by the sedimentation flux model SEDF2D.

Frequently, as in this study, the threshold resuspension and deposition speeds are not known for the surficial layer of sediments. The sensitivity of various "descriptors" of the resuspension-redeposition process, such as the average number of resuspensions per day, the mean motion and variance of the dispersion pattern for a single resuspension, and the transport and dispersion per day, can be examined as a function of the two threshold speeds using the utility program "URUD".

IV.C.2.b. Subsequent Resuspensions of Material from a Point Source (DISPER)

Comparison of resuspension-redeposition rates observed with near-bottom sediment traps with the net accumulation rate of sediments suggests that most of the particles deposited at the completion of a resuspension-redeposition event will again be resuspended during the next event, with only a small fraction remaining behind to be incorporated into the "permanent" sediments. The utility program "DISPER" computes the dispersion of particles within the surficial layer and their eventual accumulation into the permanent sediments. This calculation is made for a single cell of surficial sediment material (at the center of the grid). Input required for this stage of the simulation is the single resuspension dispersion pattern calculated with ARRAY, and the fraction of the deposited material that is incorporated into the permanent sediments.

Since only a small fraction of the surfical sediments are lost to the permanent sediments following each redeposition, a large number of resuspensions must be simulated to determine the ultimate distribution of the material. At the end of the first resuspension of surficial sediment material, the simulation grid cells contain (in a statistical sense) the distribution of mass as calculated by ARRAY. A fraction of this material is deposited in the permanent sediments, with the remainder available for the next resuspension. During this second resuspension, all the cells receiving resuspended material from the first resuspension serve as sources for the next resuspension event.

The subsequent fluxes and dispersion of this material are obtained by combining the mass of material available for resuspension from the first event with the single resuspension dispersion distribution calculated with ARRAY (after shifting the latter so that the center of this grid corresponds to the center of the source cell). This deposition-resuspension sequence continues until all the original resuspended material has been deposited in the permanent sediments, or the remaining material has "moved" out of the simulation grid.

For a typical simulation in this report, the number of resuspensions required is on the order of 25 (most of the resuspended material is transported out of the simulation grid). Within a few resuspension events, virtually all of the simulation grid cells become "source" cells of resuspended material. Since a typical simulation grid consists of an array of 31 by 31 cells, the deposition associated with 961 source cells must be computed for each resuspension. Assuming that each source cell results in a deposit in five percent of the grid cells, the total number of transfers computed in a single simulation is on the order of one million (e.g. 961 x 961/20 x 25). As might be expected, this stage of the simulation requires the bulk of the total computation effort.

The output from DISPER is a matrix (e.g. 31 x31 elements) containing the transfer probabilities for particles initially in the surficial sediments at the center of the grid to the permanent sediments associated with each cell in the grid.

IV.C.2.c. Transfer of Sedimenting Effluent Particles into Permanent Sediments (SEDR)

The program SEDR uses the transfer matrix generated by DISPER to redisperse the effluent material settling from the water column through the simulation area, resulting in the accumulation of this material in the permanent sediments. The grid used in this phase of the simulation is the same as the inner grid used in the SEDF2D simulations for the area.

The mass of surficial sediment material available for resuspension in each cell is equal to the effluent-related sedimentation rate. By an appropriate "shifting" of the center of the matrix produced by DISPER (so that the center of the array corresponds to the center of each sedimentation flux grid grid cell, the dispersion and accumulation of effluent material in the permanent sediments can be readily computed.

Since this calculation need only be carried out once, it typically requires only about 1/25 the computation time required by DISPER. The output from this model is a matrix whose elements correspond to the fraction of a unit discharged mass that is subsequently is incorporated into the permanent sediments in each of the grid cells. The actual sedimentation rate can be obtained from the annual mass emission rate of suspended solids using the utility program SCOMB.

IV.C.2.d. Steady-State Sediment TVS Concentrations (SSTVS)

In the absence of bioturbation (and mobilization or decay of material), the composition of the permanent sediments is determined by the relative accumulation rates of natural and effluent materials (and the concentrations of the materials on their respective particles):

$$Cs = \frac{Cn * Sn + Ce * Se}{Sn + Se}$$

where:
- Sn = sedimentation rate of natural particulates
- Se = sedimentation rate of effluent particulates
- Ce = concentration of material in natural particulates
- Cs = concentration in the permanent sediments

In the case of mobilization or decay, the concentrations and fluxes must be adjusted to reflect this loss of material. For example, the TVS of effluent particles is generally on the order of 70 percent. Within a few weeks, the decay of organic material is nearly complete, resulting in a new concentration that is about 70 percent of the original concentration (Myers, 1974). Thus the "effective" effluent concentration is about 50 percent (.7 x .7). The "effective" effluent-related sedimentation rate is also reduced to about 80 percent of the original rate (e.g. new organic mass + inorganic mass = 0.7 x 0.7 + 0.3 = 0.79). Analogous calculations can be used for other constituents of the effluent particles.

This TVS calculation is carried out for each cell in the simulation grid using the utility program "SSTVS".

IV.C.2.e. Transient TVS Concentrations (TRANSTVS)

When bioturbation is present, there will be a period of time before the concentration of TVS in the surface sediments reaches its equilibrium (steady-state) value since the accumulating material will be mixed with underlying sediments. For a constant sedimentation rate, the "response time" required to approach steady-state conditions is equal to the mass (per unit area) of sediments that are mixed by the benthic biota (Mb), divided by the sedimentation rate from the water column (Section ??). The rate of change in the TVS concentration in the surface sediments if given by:

$$\frac{dC}{dt} = (C^* - C)\ \frac{1}{Mb}\ \frac{dM}{dt}$$

where: C = TVS concentration in the bioturbation layer
C* = TVS concentration in the sedimenting particles (= steady-state concentration)

Mb = Bioturbation mass (e.g. mg/cm**2)

$\frac{dM}{dt}$ = Sedimentation rate (e.g. mg/cm**2/yr)

This has the solution:

$$\frac{C^* - C}{C^* - Co} = e^{-(t/Tr)}$$

where: Co = TVS concentration at time t=0

Tr = Characteristic response time
= Mb / (dm/dt)

For example, for a bioturbation mass of 500 mg/cm**2 (typically a sediment depth of 5-7 cm), the response time for the sedimentation rate of natural particles (at 10 mg/cm**2/yr) is about 50 years.

The program "TRANSTVS" uses this relationship to calculate the expected concentration of TVS in the permanent surface sediments (e.g. the bioturbation layer) at a selected time after the commencement of discharge. It uses the sedimentation probabilities for each (SEDF2D inner grid) cell computed with SEDR and the time-history of suspended solids annual mass emissions. A temporally varying annual mass emission rate is approximated as a series of annual steps, as illustrated in Figure ??. Since the sedimentation rate, and hence the response time, varies from cell to cell, the transient TVS concentration is computed for each cell. The output is an array of surface sediment TVS values. IV.D. Simulations of Surface Sediment TVS Concentrations

IV.D.1. Newport Beach

IV.D.1.a. The Accumulation Fraction

Table ?? (Section ??) summarizes the resuspension-redeposition fluxes measured in each of the simulation areas. The annual average rate at Newport Beach during 1985 and 1986 was about 1600 mg/cm**2/yr. The ratio of the net accumulation rate of particles in the permanent sediments to this resuspension-redeposition flux is the average fraction of the material in the surficial sediment layer that is transferred to the permanent sediments during each resuspension event.

Unfortunately, the average accumulation rate of natural particulates in this area is not known. As noted in Section ??, Emery (1960) estimated that the accumulation rate on the outer edge of the shelf off Palos Verdes (?? km upcoast) was about 10 mg/cm**2/yr. Assuming that this accumulation rate is also representative of the area off Newport Beach, the accumulation fraction is estimated to be about 0.0063 (i.e. 10 / 1610). This value was used for the Orange County outfall simulations.

IV.D.1.b. Threshold Resuspension and Redeposition Speeds

IV.D.1.b.i. Dependence of Dispersion Characteristics on the Threshold Speeds

The threshold resuspension and redeposition speeds for particulates in the surficial sediment layer are not known at the present time. Obviously if the current speed rarely exceeds the threshold resuspension speed, or falls below the threshold deposition speed, only a few resuspension events will occur during the data record.

Figures ??a and ??b illustrate the dependence of the average number of resuspensions per day as a function of these two speeds during the summer and winter respectively. These estimates are based on approximately 5 months of near-bottom (2m elevation) current meter measurements collected in the summer, and 3 months collected during the winter, in the vicinity of the Orange County outfall. The maximum average number of resuspensions per day during the summer is about 4, and is associated with threshold resuspension and deposition speeds of about 7.5 cm/sec and 6.5 cm/sec, respectively. The maximum number of daily resuspensions during the winter is about the same, and is associated with approximately the same threshold speeds.

Resuspension events are expected to occur less frequently than once a day for a threshold resuspension speed in excess of about 13 cm/sec, or a threshold deposition speed of less than 1 cm/sec.

Approximately ?? percent of the observations have speeds between these two values.

Figures ??a,b show the average daily "longshore" transport of resuspended material (number of resuspensions per day times the average transport per resuspension) as a function of the two threshold speeds. For the summer period, the maximum longshore transport is weak, with a net daily downcoast movement of about 0.3 kilometers, for a threshold resuspension speed of 10 cm/sec, and a threshold redeposition speed of 3 cm/sec. For the winter period, the longshore transport is much stronger, with a maximum value of about 1.9 km/day (again for threshold speeds of 10 and 3 cm/sec). During the winter, the transport is only weakly dependent on the selection of threshold depositon speed, but it diminishes significantly for threshold resuspension speeds in excess of 14 cm/sec.

Figures ??a,b show the average daily "cross-shore" transport of resuspended material. For the summer period, the maximum cross-shore transport is about 0.9 km/day (in the offshore direction) at threshold speeds of 7 and 6 cm/sec. In the winter, the cross-shore movement is stronger, with a maximum daily offshore displacement of about 1.7 km associated with threshold speeds of about 5 and 4 cm/sec.

IV.D.1.b.ii. Threshold Speeds Selected for the Simulations

The threshold resuspension and redeposition speeds for the Orange County outfall simulations were selected somewhat arbitrarily to be 8 cm/sec and 5 cm/sec, respectively. The annual average number of resuspensions per day associated with this selection is 2.9. The average longshore transport during the summer is downcoast at 0.03 km/day; during the winter, it is upcoast at about 1.8 km/day. The average cross-shore movement is offshore during the summer at about 0.9 km/day; during the winter, it is offshore at about 1.6 km/day.

IV.D.1.b.iii. Sensitivity to the Selection of Threshold Speeds

The program DISPER computes the accumulation of surficial sediment material initially resuspended from a point source. This dispersion-accumulation pattern is represented by an array of probability elements. Figure ?? shows the dependence of the maximum element in this array as a function of threshold resuspension and redeposition speeds. Figure ?? shows the corresponding threshold speed dependence of the fraction of resuspended material the subsequently accumulates in the permanent sediments within the entire simulation grid. Both of these quantities tend to increase as the threshold speeds ???. Based on the variation of these two measures of accumulation in the permanent sediments, the error in the estimated accumulation rates based on the selection of 8 and 5 cm/sec is about + ?? percent for a 50 percent change in the threshold speeds.

IV.D.1.c. Effluent and Natural Particulate TVS Concentrations

In general, there is a trend toward increasing TVS concentrations in the natural sediments with increasing distance offshore (or water depth). However, for simulation purposes, the concentration of TVS in the natural sediments is assumed to be 2.1 percent.

Effluent particles are highly enriched in organic material, with typical TVS concentrations on the order of 70 percent. We have assumed that decay of organic material reduces this concentration to about 70 percent of the original value (Myers, 1974), or about 49 percent. This reduction is accompanied by a 21 percent loss of total particle mass.

IV.D.1.d. Effluent Annual Mass Emission Rates

The annual mass emissions of suspended solids since the deep outfall commenced operation (in 1971) is shown in Figure ??. A mass emissions of 33,000 metric-tons of suspended solids per year is typical, and used to illustrate the simulations.

IV.D.1.e. Simulation Results

IV.D.1.e.i. Effluent Particle Accumulation Rates

Figure ?? shows the accumulation rate of effluent-related particulates in the vicinity of the Orange County outfall for a mass emissions rate of 33,000 m-tons/year. The peak accumulation rate of outfall particles is predicted to be about 1.4 mg/cm**2/yr (before decay). This is about two orders of magnitude less than the peak sedimentation rate of effluent particles from the water column (about 100 mg/cm**2/yr - Hendricks, 1986).

The difference between the sedimentation rates from the water column and the accumulation rate into the permanent sediments reflects the resuspension and transport (upcoast and offshore) of effluent particles in the surficial layer of sediments.

IV.D.1.e.ii. Steady-State TVS Concentrations

Figure ?? shows the predicted equilibrium (steady-state) concentration of TVS in the surface (permanent) sediments for an annual mass emission rate of 33,000 m-tons/year of suspended solids. The peak steady-state TVS concentration occurs in the vicinity of the outfall diffuser and is on the order of 7 percent).

IV.D.1.e.iii. Transient TVS Concentrations

Myers (1974) estimated that the effective depth of bioturbation is on the order of 5 cm. For typical surface sediment densities, this corresponds to a bioturbation mass of about 500 - 1000 mg/cm**2. Since the total accumulation rate of sediments in the simulation area is on the order of 10-11 mg/cm**2/yr, the time required between the beginning of the discharge and the attainment of steady-state TVS concentrations in the sediments can be expected to be on the order of 45 years, or more.

The program TRANSTVS is used to compute the TVS concentrations in the sediments as a function of the duration of the discharge. Figure ?? shows the predicted concentrations at the end of 1981 for an annual mass emssion rate of 33,000 m-tons, beginning in 1971. The pattern of TVS values is essentially the same as the steady-state TVS concentration pattern, but the peak concentration is reduced to about 2.9 percent. The transient values are essentially equal to the background concentration plus about ?? percent of the difference between the steady-state and the background concentration.

IV.D.1.e. Comparison with Measured TVS Concentrations in the Surface Sediments

The solid circles accompanied by numbers in Figure ?? represent the locations were samples were collected with a Van Veen grab sampler in 1978. The crosses indicate the locations of grab samples collected in 1981. The numbers adjacent to each mark indicate the measured surface sediment (0-2 cm) concentration of TVS. In general, the predicted increases are greater than the observed concentrations (in the vicinity of the 55m isobath). In fact, no significant discharge-related increases in TVS concentration can be discerned.
Measured concentrations in the immediate vicinity of the outfall (i.e. < 100m from the diffuser), however, tend to be greater than the predicted values. This difference results from computing the average concentration in each cell (0.5 sq. km. in this simulation), thus eliminating the gradients that can occur within a cell.

IV.D.1.f. Sensitivity of the Simulations to Parameter Values

As noted previously, the appropriate values for the accumulation fraction and the threshold resuspension and deposition speeds are not known. The sensitivity of the simulation results to changes in these parameters can be examined by carrying out simulations for other values.

Figures ??a,b show the sensitivity of the cross-shore and longshore distributions (through the transects with the highest peak accumulation rate) to variations in the accumulation fraction (e.g. 0.0063 in the previous simulation). The shapes of the distributions are nearly independent of moderate changes in the accumulation fraction, and the accumulation rate is nearly proportional to the accumulation fraction.

A doubling of the accumulation fraction will result in roughly a doubling of the accumulation rate of effluent particles. At the same time, however, the accumulation rate of natural particles will also double. Thus the steady-state concentration of TVS in the surface sediments will be nearly the same--although the transient concentrations will approach the steady-state values at approximately double the original rate.

Figures ??a and ??b show the dependence of the maximum accumulation probability on the choice of threshold resuspension and deposition speeds, respectively. For ??? changes in these speeds, the accumulation probabilities change to about ?? to ?? percent of the original probability (8 and 5 cm/sec). Table ?? compares the peak steady-state and transient (1981) TVS concentrations in the sediments associated with the the original, a doubling, and a halving of the predicted effluent accumulation rate. These changes are 2 to 3 times greater than have likely occurred, based on the variations indicated in Figures ??a,b.

Table ??

Dependence of Sediment TVS Concentrations on Effluent Particle Accumulation Rate (Newport Beach)

Maximum Accumulation Rate (mg/cm**2/yr)	Maximum Steady-State TVS (percent)	Maximum Transient TVS (percent)
0.7	4.6	2.77
1.4	6.9	3.42
2.8	10.8	4.71

The differences between the maximum transient TVS concentration and the measured values in the same area are relatively small compared with the variability between sediment samples. Thus it is difficult to select between these two accumulation rates--although the lower rate is in better agreement with the average measured value. It seems unlikely, however, that the TVS concentration of 4.7 percent associated with an effluent particle accumulation rate of 2.8 mg/cm**2/yr would be observable. Thus threshold resuspension and deposition speeds are unlikely to be lower than the values selected for the simulation.

Since sediment TVS values near the outfall (but outside the 100m distance) are virtually indistinguishable from the concentration in natural sediments, it is not possible to use this data to make direct estimates of the accumulation of effluent particles.

The differences among the predicted steady-state TVS concentrations are sufficiently large so that a clear distincition should be possible between the three accumulation rates. However, additional elapsed time and additional sediment samples may be required to provide a clear distincition.

IV.D.2. Encina Simulations

IV.D.2.a. Parameter Values

Many of the same simulation difficulties that were encountered in the simulations of the Orange County outfall area also exist at Encina--the accumulation rate of natural particulates and the threshold resuspension and redeposition speeds are unknown.

The same threshold resuspension and redeposition speeds were chosen for the Encina simulation as for the Orange County simulations (8 and 5 cm/sec, respectively). The annual average resuspension/redeposition flux at the outfall depth was about 3100 mg/cm**2/yr (winter/summer, 1986), and is about twice the flux observed at Orange County. For an annual accumulation rate of natural particles of 10 mg/cm**2/yr, this would require an accumulation fraction of 0.0032. On the other hand, if the accumulation fraction is the same as at Newport Beach, the accumulation rate of natural particles would be 19.7 mg/cm**2/yr.

A natural accumulation rate of 10 mg/cm**2/yr (and an associated accumulation fraction of 0.0032) was selected for the simulations. This selection will maximize the effect of the the effluent discharge on the sediment TVS concentrations.

IV.D.2.b. Results

Figure ?? shows the accumulation rate of effluent particles in the sediments around the outfall for an annual mass emission rate of 1,700 m-tons of suspended solids. The peak accumulation rate is about 0.?? mg/cm**2/yr, and is about 1/?? the sedimentation rate of effluent particles from the water column (see Hendricks, 1986).

The steady-state concentration of surface sediment TVS associated with this accumulation rate is shown in Figure ??. As before, the solid circles and accompanying numbers indicate measured TVS values (using grab samples collected in 1982). The steady-state TVS concentrations show only a very minor increase in the immediate vicinity of the outfall, and these differences are within the spatial variability and the experimental error associated with the set of measurements. Since the steady-state concentrations are so similar to the background TVS concentrations, no transient estimates were calculated.

IV.D.3. San Diego Simulations

IV.D.3.a. Parameter Selection

Threshold resuspension and redeposition speeds for the simulations of the San Diego (Point Loma) outfall area were also 8 and 5 cm/sec, respectively. As at the other two sites, it was assumed that the accumulation rate of natural particles in the simulation area was 10 mg/cm**2/yr. The average resuspension-redeposition flux measured at depths comparable to the outfall diffuser depth (e.g. 62-65m) was about 5800 mg/cm**2/yr, requiring that the accumulation fraction equal 0.0017. If the same accumulation fraction were used as for the Newport Beach simulations, the accumulation rate for natural particles would be 32.5 mg/cm**2/yr.

IV.D.3.b. Results

Figure ?? shows the predicted accumulation rate of effluent particles in the sediments around the San Diego outfall. The maximum rate is ?? mg/cm**2/yr, and is about 1/??? the predicted rate of sedimentation of effluent particles from the water column (Hendricks, 1986). Figure ?? shows the steady-state TVS concentration in the surface sediments, and Figure ?? shows the transient concentrations predicted for 1978. The solid circles and accompanying numbers indicate the location and TVS values measured in sediment samples collected in the same year with a grab sampler.

.... Continue ...... VII. SUMMARY

The physical and chemical characteristics of the sediments, and the abundance and composition of the biota that live within and on the sediments, can be affected by the accumulation of organically rich effluent particles from an ocean outfall, or the flux of these particles through the near bottom waters. The prediction of the physical transport of the particles in the water column and near-bottom waters, and their deposition and accumulation in the sediments, is a basic step in aquiring the ability to predict the magnitude and extent of these changes for new outfall, changes in the method of treatment, or in time.

Volume I of this report addresses the problem of estimating initial sedimentation of effluent particle discharged from an ocean outfall. The work reported in this volume develops methods for estimating the subsequent resuspension of sediment particles, transport by the near bottom currents, redeposition, and their ultimate accumulation in the deeper sediments.

Initially, changes in the representation of these near-bottom processes were made to an existing model (SEDQ) in order to mitigate differences that had been found between the predicted and observed cross-shore distributions of effluent particle in the region around the two outfalls operated by Los Angeles County (White Point). The principal modification was to provide separate resuspension representations for cohesive and non-cohesive sediment particles. With this change, the discrepancy between the predicted and observed cross-shore accumulations of effluent material was significantly reduced. At the same time, the predicted concentration of organic material within the sediments was comparable with the observed values.

However, the model was incapable of reproducing the accumulation rate of natural particles in the absence of any discharge--predicted flux rates were more than an order of magnitude greater than the observed accumulation rate of natural particles. This discrepancy cast doubt on application of the model to areas with small mass emissions (relative to White Point), and led to consideration of alternative sediment resuspension mechanisms.

One of these mechanisms is the resuspension of sediment particles by the physical movements of animals living in the surface sediments, or in the water just above the sediments. The uptake and egestion of particles by these animals constitutes another source of resuspension. The potential importance of bioresuspension processes was examined by simulating the characteritics of the sediments around the White Point outfall for the bioresuspension associated with the benthic worm, Pectinaria californesis, in the absence of current-induced resuspension. Bioresuspension rates were estimated from laboratory studies carried out by other investigators at SCCWRP, and abundance measurements in the coastal waters of southern California.

The results of this simulation showed that the distribution of effluent-related organic material in the sediments around the outfall could be approximately reproduced using only this single, crude estimate of bioresuspension. At the same time, discrepancies between the predicted and actual accumulation rate of natural particles in the absence of the discharge were reduced. Nevertheless, other problems developed with the model simulations--principally the sensitivity of the cross-shore particle accumulation rates to small errors in measurements of the near-bottom currents, and the inability to reproduce the characteristics of the sediments at other outfall sites. These problems lead to the development of a new simulation model (SEDR).

The new model uses direct estimates of the resuspension-redeposition fluxes of effluent particles instead of trying to predict the rates from measurements of the near-bottom currents, sediment consolidation characteristics, and bioresuspension rates. Sediment traps are used to provide the direct estimates. Moorings containing traps were placed in the vicinity of the Orange County, Los Angeles County, City of San Diego, and Encina outfalls during both winter and summer seasons. Usually three traps were used on each mooring, at elevations of 0.5, 2, and 5 meters above the ocean bottom.

Annually averaged resuspension-redeposition rates (in 45 - 65 meters of water) varied from about 1600 mg/cm**2/yr (Orange County) to 5800 mg/cm**2/yr (San Diego). These rates are much higher than estimates of the accumulation rate of natural particles (10 - 30 mg/cm**2/yr), and suggest that the particles on the surface of the sediments are highly mobile and undergo a large number of resuspensions and redepositions (e.g. >100) before becoming part of the permanent sediments. Assuming that somewhere between 1 and 4 resuspensions take place per day (based on near-bottom current meter data), the average thickness of this surficial layer of particles is less than 1 millimeter.

The new model uses these flux estimates, in combination with time-series measurements of the near-bottom currents and the accumulation rate of natural particles, to estimate the accumulation rate and distribution of effluent particles, and the time-dependent and steady-state concentration of organic material in the sediments.

Simulations were carried out for the Encina, San Diego, and Newport Beach outfall sites. Effluent-associated increases in the concentration of organic material were predicted to be small--a consequence of the large number of resuspensions before becoming part of the permanet sediments and the large flux of natural particles in the near bottom waters. Observed increases around these outfalls ranged from indetectable to small. Natural variability prevented precise comparison, but the predicted and observed values appear to be comparable. There is an indication that the predicted increases may be greater than the observed.

Virtually no increase in organic content of the sediments was measured at the Orange County outfall site. Nevertheless, changes are observed in the community structure of the benthic infauna. It was hypothesized that this community structure may respond to the increase in flux of organic material through the near-bottom waters as a result of the effluent discharge. This hypothesis was tested using Infaunal Index information for the San Diego and Newport Beach outfall areas (no values were available for the Encina site). It was found that the Infaunal Index value for the benthic infauna population decreased with increased flux of organic material through the near-bottom waters according to the relationship:

$$II = -0.204 * Fe \qquad (r = 0.92, \quad p < ??)$$

where; II = effluent-related change in Infaunal Index
Fe = resuspension-redeposition flux of effluent particles (in mg/cm**2/yr, from SEDR)

This model was also used to simulate the sediments around the White Point outfalls. In contrast to the other areas, the predicted increases in organic content of the sediments were less than the measured increases. In addition, the measured accumulation rates of both effluent and natural particles were more than an order of magnitude greater than predicted, or measured away from the influence of the outfall. These differences are reduced if the resuspension fraction (i.e. 1 - accumulation fraction) is reduced from nearly 100 percent to somewhere in the range of 0 to 70 percent. It also appears that this fraction is dependent on the effluent particle sedimentation rate (or effluent particle flux in the near-bottom waters) and may be different for natural and effluent particles. Possible mechanisms include particle aggregation, or changes in the abundance and composition of the benthic biota with associated changes in the bioresuspension and biodeposition rates. IV.B. Sediment Trap Studies

IV.B.1. Method

IV.B.1.a. Strategy

Apparent sediemntation rates were measured with sediment traps at a number of outfall locations (Encina, San Diego, Newport Beach, and White Point) for periods ranging from ?? to ?? months. Measurements were carried out at one, or more, moorings at each site (typically at the discharge depth and roughly one-half the discharge depth). Each mooring consisted of a taut-line mooring and usually with three sediment traps positioned at elevations of 0.5, 2.0, and 5.0 meters above the bottom. A small float at the surface facilitated recovery of the mooring (see Figure ??).

The assumption that the measured "sedimentation" rates were associated with resuspension (or at least with a particle enriched layer of near-bottom water) could be tested by comparing the fluxes measured at each of the three elevations. This information could also be used to estimate the distribution of material in the near-bottom waters and extrapolate the data to obtain an estimate of the flux at the sea-sediment interface.

IV.B.1.b. Sediment Trap Design

The sediment traps consist of a ?? cm (?? inch) long plastic tube 10 cm (4 inch) in diameter. A second tube (the collection chamber) was connected to the bottom of the primary (sedimentation) tube. A funnel forms a partition between the two tubes (see Figure ??). The traps were taped to the taut line mooring (?? cm diameter polypropylene line) with the lip of the sedimentation tube at the selected elevation above the bottom.

The mooring was anchored to the bottom with a ?? kg (?? pound) block of concrete. A float with ?? kg (?? lb) of buoyancy was positioned ?? meters above the upper float to minimize any "leaning" of the mooring in the vicinity of the sediment traps. A single lobster float (2.7 kg buoyancy) at the surface marked the location of the trap for recovery and servicing of the traps.

IV.B.1.c. Analysis

Material collected in each trap was transferred to a jar and refrigerated (with ice) for transport back to the laboratory. The trap was also rinsed, and the rinse water included in the sample. If any macroscopic biota were present, they were removed from the sample.

Samples with a collected mass of less than about 20 gm of material were filtered using a pre-weighed ?? glass-fiber filter. The filter and collected material were dryed at 90 degrees Celsius and weighed. The dry mass of collected material was approximated as the difference between the total weight of the filter and material, and the tare weight of the filter. The filter was not rinsed with fresh water prior to weighing so the salt content of the sea water retained in the filter contributes slightly to the apparent collection rate. Based on a limited set of wet wt. versus dry wt. measurements, this omission leads to a overestimate of the sedimentation rate by about 4 to 8 percent.

The samplès were then heated at 500 degrees Celsius for a period of one hour to drive off the volatile solids, then cooled and reweighed. The difference between the original and final dry weights yields the "total volatile solids" contents of the sample. No correction was made for the apparent volatile solids content of sea salt. The error associated with this effect is also generally small (typically about a 15 percent of the salt weight).

IV.B.1.d. Calibration and Variability

The collection efficiencies of the traps, and inter-trap variability, was examined by comparing the fluxes from three moorings containing sediment traps at an elevation of 1 meter and a single mooring containing a bottom mounted "Soutar" sediment trap (also at an elevation of 1m) in 55m of water off Newport Beach, CA. In addition, collections were made at the "normal" elevations of 0.5, 2.0, and 5.0 meters at a nearby (fifth) mooring.

For the individual SCCWRP sedimentation traps at the 1 meter elevation, the coefficient of variation in the flux rate was about 0.23. The average flux for the three traps at the 1 meter elevation differed by about 5.8 percent from the flux estimated at the 1 meter elevation using the data obtained from the traps at elevations of 0.5, 2.0, and 5.0 meters.

Comparison of the sedimentation rates into Santa Barbara Basin measured by Soutar type traps with the accumulation rates obtained from examination of the varved cores indicates that the two methods yield comparable results (Soutar, et. al., 19??)-- although longer sediment trap deployments for this comparison would be desirable to include seasonal variability, if any.

The average flux for the three SCCWRP traps at an elevation of 1 meter was 1493 mg/cm**2/yr. There is some uncertainty in the selection of the appropriate collection area for the Soutar trap because there is a small "lip" that extends horizontally outward from the top edge of the trap. Neglecting this area, the collection efficiency of the SCCWRP traps, relative to the Soutar trap, was about 0.83. Including the area associated with one "edge" of the rectangular Soutar trap (e.g. the edge "upstream" from the collection void) resulted in a collection efficiency ratio of 1.12. Thus the SCCWRP and Soutar sediment traps appear to have comparable collection efficiencies (i.e. 1.00 + 0.17).

The sediment traps are not "poisoned" to minimize the decay of organic material since poisoning may also result in the "deposition" of animals that migrate into the trap. To examine the effects of poisoning, or the lack of poisoning, a pair of sediment traps were deployed (at an elevation of 5m) in the vicinity of the Encina outfall. One trap was poisoned with formalin, the second trap unpoisoned. After 38 days, the traps were recovered and the contents analyzed for total mass and TVS concentrations. The total dry mass recovered from the poisoned trap was 10.8 gm; that from the unpoisoned trap, 10.5 gm. The TVS concentration for the contents of the poisoned trap was 5.8 percent; while the contents of the unpoisoned trap had a TVS of 6.4 percent. These results suggest that the results of the sediment trap measurements are not significantly dependent on whether or not the traps are poisoned.

IV.B.2. Results and Discussion

IV.B.2.a. Newport Beach (Orange County outfall area)

Figure ?? shows the sedimentation fluxes observed in water depths of 30 and 55m approximately ?? km upcoast from the Orange County outfall for the period from ?? 1985 until ?? 1986. The sedimentaton fluxes are relatively independent of season, with a mean value of ?? + ?? mg/cm**2/yr ar a depth of 55m, and ?? + ?? mg/cm**2/yr at the 30m depth.

In general, the dependence of the sedimentation flux on elevation above the bottom follows a exponential relationship of the form:

$$F(z) = F(0)\, e^{-(Z/Zo)}$$

with correlation coefficients on the order of 0.??? (+ 0.???) and a "characteristic thickness", Zo, equal to about ?.? (+ ?.?) meters. There is a slight indication that some fractionation of the particles occurs within this layer since the ratio of the characteristic thickness of organic material is about ?.?? (+ ?.??) that for the total mass.

Total volatile solids concentrations at the 30m depth range from a low of ?? to a high of ?? percent, with a mean value of ?? + ?? percent. In 55m of water, the lowest TVS was ?? percent, and the high and mean values were ?? and ?? percent, respectively. These values can be compared with surface sediment TVS concentrations in this area which range from ?? percent (30m) to about 2.1 percent (55m). The higher concentrations of organic material collected within the traps suggest that: (1) the material collected within the traps is "newer" and hence the "decay" of organic material has not been completed, (2) the organic material tends to be deposited and resuspended, without incorporation into the "permanent" sediments to a greater degree than does the inorganic material or, (3) there is a fractionation of the settling particles by the dynamics of the sediment trap.

The flux into the sediment traps represents the accumulation of material over a number of resuspension "events". Particles on the ocean bottom may be resuspended, deposited, then resuspended again as the strength of the currents againincreases. However, once resuspended material is deposited in the trap it will remain there. Unfortunately, the number of resuspension events that have occurred during each of the sediment trap deployments is not known. Figure ?? illustrates the average number of resuspensions per day if it is assumed that: (1) resuspension is the result of bottom stress by fluid motions, (2) resuspension does not occur until the speed of the currents 2 meters above the bottom exceeds some threshold speed, Ur, and, (3) deposition does not occur until the current speed falls below some threshold value, Ud (it is assumed that for the time scales involved, resuspension and depositon occur "instantaneously"). This figure for the resuspension frequency is estimated from current meter data collected 2m above the bottom by initiating a resuspension event when the current speed exceeds the threshold resuspension speed, Ur; completion of the resuspension event occurs when the speed falls below Ud. The next event occurs when the speed again exceeds Ur. The total number of resuspension events obtained in this manner from the current meter record, combined with the duration of the record, yields the average number of resuspensions/day as a function of Ur and Ud.

The relative constancy of the flux rates observed in the traps suggests that resuspension occurs relatively frequently. Therefore, it seems likely that the two threshold speeds, Ur and Ud, do not lie near the high and low ends of the speed distribution. For intermediate speeds (e.g. 3 < Ur: Ud < 10 cm/sec), the number of resuspensions is generally in the range of 2 to 4 resuspensions per day, or roughly 700 to 1500 resuspensions per year.

The average sedimentation rate at the 55m depth in the region of the Orange County outfall is about 1600 mg/cm**2/yr. In combination with the estimate of 700 to 1500 resuspensions per year, this suggests that on the order of 1 to 2 mg/cm**2 (dry mass) of particles are resuspended from the surface of the sediments during each event. Assuming that these surficial sediments are on the order of 90 to 95 percent water and that the density of the (dry) particles is on the order of 1.5 gm/cm**3, the average thickness of the particles prior to resuspension is on the order of 0.07 to 0.3 mm (0.003 to 0.01 inches). Assuming an average resuspended mass of 1-2 mg/cm**2 , and an average characteristic thickness of the resuspended material in the water column of 2 meters, the average concentration of suspended solids in the near-bottom water is on the order of 0.5 to 1 mg/liter.

These estimates suggest that: (1) it is likely that the surficial sediments that are predominantly involved in resuspension events are either: (1) "blown away" during the emplacement phase of the resuspension tunnel (see Section ??) or, (2) virtually unobservable in those studies. The apparent "thinness" of this surficial layer, and the consistently higher TVS concentrations observed in the sediment trap material, versus the "surface" sediment concentrations obtained from cores suggests that samples from the latter may not be representative of the surficial sediments.

Thus measurements of threshold resuspension speeds collected with the SCCWRP in-situ resuspension tunnel may not provide an adequate description of the threshold resuspension speeds for the particles actually involved in the bulk of the the resuspension and redistribution processes. This casts doubt on the validity of the resuspension representations used in the sediment quality simulation model, SEDQ (see Section ??)--although they may be representative of the threshold speeds associated with episodic events causing erosion of the deeper sediments during periods of extreme bottom stress. In a similar manner, surface (upper 2 cm) sediment samples collected with typical coring devices may not provide information on the composition of the particles scavenged by suspension or surface deposit feeders (or in contact with epi-benthic biota).

IV.B.2.b. Palos Verdes (White Point - Los Angeles County outfall area)

Figure ?? shows the seasonal dependence of the sedimentation flux observed off Palos Verdes in 30 and 52m of water. In contrast to the Orange County area, there appears to be a significant seasonal dependence, with peak fluxes in the winter (at 52m) on the order of 10,000 mg/cm**2/yr, and typical fluxes during the summer on the order of ?? mg/cm**2/yr. At the 30m depth, the fluxes are slightly higher in the winter, and lower in the summer, relative to the observations in 52m of water. The average flux for all the observations (at a depth of 52m) is about 4100 mg/cm**2/yr, or approximately 2.5 times greater than observed at a similar depth (55m) off Newport Beach.

At Newport Beach, the TVS concentrations of the material collected in the traps is relatively indpendent of season. Off Palos Verdes, a seasonal dependence is again suggested (see Figure ??) with the lowest TVS concentrations observed in the winter, and the highest concentrations occurring in the spring and early summer. At a depth of 52m, the average TVS concentration is about 12 percent, or about 2 times greater than observed in the sediment traps at Orange County and also in the natural sediments below the influence of the outfall discharge at White Point (see Appendix ??).

Figure ?? shows the estimated average number of resuspensions per day as a function of the threshold resuspension and deposition speeds (based on 2 months of near-bottom current measurements during the summer). On the order of 2 to 6 resuspensions are estimated to occur each day for "mid-range" values of the two threshold speeds, resulting in surficial sediment masses availble for resuspension that are on the order of ?? to ?? mg/cm**2. The average characteristic thickness of the particle-laden near-bottom water following a resuspension event is about ?.? (+ ?.?) meters, suggesting suspended solids concentrations on the order of ?? to ?? mg/l.

As noted earlier, Emery (1960) estimated that the accumulation rate of natural particulates on the outer portion of the nearshore shelf off Palos Verdes was on the order of 9-10 mg/cm**2/yr. Since the average sedimentation flux at the sea-sediment interface in 52m of water is on the order of 4100 mg/cm**2/yr, this suggests that, on the average, only about 0.2 percent of the mass deposited following a resuspension event is not resuspended during the next resuspension event. Thus the average particle in the surficial sediments can be expected to undergo about 500 resuspensions and depositions before it is finally incorporated into the "permanent" sediments. At three resuspensions/day, the residence time of a particle in the surficial sediments or epi-benthic water would be on the order of 5-6 months.

IV.B.2.c. Carlsbad (Encina outfall area)

Table ?? summarizes the sedimentation fluxes measured off Carlsbad, CA. Again a seasonal pattern is suggested in the measurements collected in a water depth of 46m, with an average flux in the winter of ???? mg/cm**2/yr, and a flux of ???? mg/cm**2/yr observed during the single month of observations during the summer.

On February 1-2, and again on Feb 15-16, of 1986, long-period, large-amplitude swell generated from North Pacific storms swept into the coastal area. Measurements of the energy spectra associated with these two periods at Del Mar, CA (?? km south of the study area) and Oceanside, CA (?? km north of the study area) indicated that the total energy and dominant periods associated with the two swells were comparable (???. 198??). A small reduction in energy reaching the coast may have occurred in the Oceanside area during the February 1-2 swell (probably from a "shadowing" effect of the offshore islands).

The fluxes of material into the sediment traps in 25m of water during these two periods of high surf were, however, drastically different. One deployment spanned the period from January 9 to February 10 (32 days). The lower trap (0.5m elev.) collected a total dry mass of 20.0002 gm during this period, resulting in an sedimentation rate (on an annual basis) of 3845 mg/cm**2/yr at the sea-sediment interfâce. The characteristic thichness (Zo) of the resuspended sediments in the water column was 1.6 meters, and the TVS concentration of the material was 5.2 percent.

The next deployment was from February 10 to February 27 and included the swell on February 15-16. During this 17 day period, the lower trap (0.5m elevation) collected 184.90 gm of material, for an annualized sedimentation flux at the sea-sediment interface of about 105,000 mg/cm**2/yr, or about 27 times greater than measured during the first deployment--even though the first period included the February 1-2 swell. Assuming that this increase in flux was associated with the Feb. 15-16 swell, the effective sedimentation rate during the 12 hour period of maximum wave energy was probably on the order of 3.5 million mg/cm**2/yr. In spite of the apparent increase in stress on the bottom, and accompanying energy dissipation, the characteristic thickness of the layer of resuspended particles in the water column was only 0.7 meters, or less than half the value during the previous deployment. The TVS concentration of the sediment material also declined from the previous value 5.2 percent to 1.4 percent, the sediment material appeared to have a greater percentage of the larger grain sizes, and iron pyrite flakes were visible.

The number of resuspensions that occurred during the period of the swell are unknown. Assuming a lower bound of 1 resuspension, the deposited material would correspond to about 2.1 gm/cm**2, or a thickness of about 0.9 cm for particles with a density on the order of 2.5 gm/cm**3 (e.g. sand).

It should be noted that this mooring was only recovered after the mooring line parted between the anchor and the lower sediment trap during the recovery operation. This suggests that: (1) greater deposition occurred and the anchor was "sanded in", (2) substantial bed-load transport occurred (not sampled by the sediment traps) or, (3) eddies around the anchor resulted in local erosion, "burying" the anchor. The occurrence of any of these processes casts some doubt on the validity of the sediment trap measurements as a reliable estimate of the extent of sediment movement during these conditions--although both the sediment trap results and the difficulties in recovering the mooring suggest that the mass of distrubed sediments was large.

The data is also insufficient to determine why anomalously large fluxes of particles were observed during the Feb. 15-16 swell, but not during the Feb. 1-2 swell. The two most likely reasons are: (1) the erosion of "permanent" (i.e. not "surficial") sediments requires a large bottom stress and this threshold stress was not exceeded on Feb. 1-2 due to "shadowing" of the swell by offshore islands and, (2) resuspension of bottom material in shallow water occurred during the first swell, but redeposition occurred before it was carried out to the 25m isobath. The second swell resuspended this material and transported it the rest of the way to the sediment trap mooring.

Unfortunately, sediment trap moorings in 46m of water at Encina and in a water depth of 55m off Newport Beach were lost during the February 15-16 swell, so the offshore extent of the enhanced resuspension and transport could not be determined.

These exceptionally high flux rates, and the apparent sensitivity of the transport, indicate that for southern California coastal waters, it may be difficult to simulate the sediments in water depths of 25 meters, or less. In view of these large fluxes, however, substantial effluent-related increases in organic content of the sediments are unlikely--except on a transient basis.

IV.B.2.d. Point Loma (City of San Diego outfall)

Table ?? sumarizes the results of sediment trap measurements in various depths of water off Point Loma during the winter (Nov-Jan) of 1986-7. Also included are observations at three depths (each approximately 1 month in duration) during the summer of 1985. Comparison of the fluxes during the summer and winter at the moorings in 30-35m of water suggests that enhanced resuspension and deposition occurs during the winter. However, comparison of the fluxes as a function of depth for both the summer and the winter observations suggests that resuspension and deposition is suppressed in shallow water, hence the observatons at 30m and 35m may not be directly comparable. One possible explaination for these reduced fluxes in shallow water is that the bottom is rocky in that area, limiting the amount of material available for resuspension.

Table ?? also indicates that resuspension/sedimentation fluxes are still significant in 77m of water (?? km offshore), with an average rate of 1832 mg/cm**2/yr. Even ?? km offshore in 100m of water, the average value was 522 mg/cm**2/yr.

<<< compare with Newport Beach using offshore distance >>>

IV.B.3. Conclusions - Sediment Trap Studies

Measurements of resuspension-redeposition fluxes near the sea-sediment interface at a variety of locations and water depths along the coast of southern California indicate that the fluxes are typically between two to three orders of magnitude greater than published estimates of the net accumulation rate of sediments on the nearshore shelf. This suggests that only a small fraction (less than 1 percent) of the material deposited after a resuspension event is "incorporated" into the "permanent" sediments and not resuspended during the next event.

The average number of resuspension events occurring each day is not known. If threshold resuspension and deposition speeds for the particles are chosen that avoid the extreme ends of the speed distribution for near-bottom currents (1 to 2 m elevation), analysis of current meter time series suggests that the reoccurrance interval for these events may be on the order of 4 to 24 hours. If so, the mass of material resuspended in each event is confined to a very thin (a fraction of a millimeter thick) surficial layer on the surface of the sediments.

The material collected in the sediment traps typically has a TVS concentration that is approximately twice the concentration measured in the "surface" (0-2 cm depth) sediments collected with conventional sediment sampling devices. This disparity introduces some question into the suitability of using sediment samples collected with these samplers for laboratory based resuspension studies, or for exposure (or growth) studies of benthic animals that are surface detritis or suspension feeders.

Typical "thicknesses" of the layer of near-bottom water that is laden with resuspended particles are on the order of 1 to 3 meters. Measurements of current velocities at similar elevations (1-2m) generally show a net speed that is on the order of 1 to 3 cm/sec. If only a small fraction of the deposited surficial sediments are incorporated into the permanent sediments during each resuspension-deposition event, the "average" particle will undergo a large number of resuspensions (e.g. 100-500) before it is no longer subject to resuspension and dispersion. Therefore, unless the number of resuspensions per day is very large, a typical particle will be transported a large distance from its initial point of sedimentation from the water column before it actually becomes part of the "permanent" sediments.

This means that: (1) effluent particles are likely to be dispersed over a much larger area than suggested by simulations of the initial sedimentation pattern and, (2) large fluxes of natural particles will also be carred through the area definining the outfall-related (initial) sedimentation field. Both processes will have the effect of providing additional dilution of the outfall particulates with natural particulates, reducing the intensity of impact of effluent particle sedimentation, but spreading it over a larger area.

Comparisons of the seasonal dependence of the fluxes as a function of offshore distance and water depth at Palos Verdes and Newport Beach suggests that enhanced resuspension in winter is more closely correlated with offshore distance than it is with water depth, although a definitive conclusion cannot be made without a comparison of the sea/swell spectral energy characteristics during the sampling periods. IV. A NEW SIMULATION MODEL OF BOTTOM TRANSPSORT PROCESSES (SEDR)

IV.A. An Overview

In view of the difficulties experienced with SEDQ, it was decided to adopt a different approach to the simulation of bottom transport processes. The objectives of the new simulation technique were:

1. Provide resuspension, transport, and deposition representations that maximize the use of direct measurements and minimize the number of parameters that need to be estimated or fitted.

2. Direct measurements are to be obtained using as simple and inexpensive methods as possible.

3. The predicted accumulation of natural particles in the absence of an outfall discharge should match measured rates.

As discussed in Sections ?? (Background) and ?? (SEDQ), the resuspension of sediment particles from the ocean bottom represents the complex interaction of physical, chemical, and biological processes. Quantitative descriptions of many of these processes--particularily those relating to biological processes--are lacking at the present time. Even in the physical/chemical domain, adequate descriptions of the details of the dynamics of resuspension and sediment consolidation are subjects of active research and debate at the present time.

Most simulation models of sediment transport and accumulation assume that biological influences on the resuspension of sediments are negligible and that the dynamics of physical processes can be described from current measurements, an idealized structure for the benthic boundary layer, and measurements of the consolidation of sediments in a laboratory environment.

Since ocean sediments often contain large benthic populations (often with increases in biomass and/or changes in composition around the outfall diffuser--Mearns and O'Connor, 198??), the neglect of biological effects on resuspension is questionable. In addition, the physical-chemical characteristics of effluent particles differ substantially from natural particles, greatly increasing the amount of resuspension and consolidation information that must be obtained from laboratory simulations of the ocean environment. Finally, there are always questions about how well the laboratory environment can be made to simulate the conditions in the ocean (e.g. stress history, etc.). In order to bypass these difficulties, it was decided to obtain direct estimates of resuspension fluxes using sediment traps.

Measurements carried out in the vicinity of the Orange County outfall in 197?? using sediment traps positioned 1 meter obove the bottom yielded resuspension-redeposition rates that ranged from about ??? to ??? mg/cm**2/yr in water depths ranging from ?? to ??? meters. These rates are one to two orders of magnitude greater than the accumulation rate of natural particles on the nearshore shelf about ?? kilometers farther upcoast (Emery, 1960). They are also an order of magnitude greater than the peak sedimentation rate of effluent particles in the immediate vicinity of the outfall diffuser (Hendricks, 19??, 1986). These high rates, therefore indicate that the traps were collecting material resuspended from the ocean bottom, and thus could be used to obtain direct estimates of the resuspension-redeposition rates. Sediment traps have also been used to study sediment resuspension and measure fluxes in deep ocean environments (e.g. in the HEBBL and STRESS studies).

This approach essentially consolidates all the uncertainties about the dynamics of the various sources of sediment resuspension into a single question: How well do sediment traps measure resuspension-redeposition fluxes?

Ongoing and previous studies of sediment accumulations in southern California coastal waters have compared the measured rates (based on radioactive tracers) with the rates estimated from traps positioned well above the ocean bottom. Generally there has been good agreement between the two methods (??, ??; ??, pers. comm.). These measurements were made over the nearshore slope and within nearshore basins, so there is some uncertainty about how similar they are to the near-bottom environment on the nearshore shelf. However, limited data suggests that current speeds (a factor potentially affecting trap collection efficiencies) in the two environments are not drastically different. Therefore, an intercalibration between our traps and the type of traps used in these studies would yield some information about our trap collection efficiency.

The flux measurements provided by the sediment trap studies are a key element of the new simulation model. Many elements of the simulation approach were guided by the resuspension characteristics observed during the studies. Therefore, it is appropriate that the experimental design of the sediment trap study, the construction of the traps, intercalibration, and the results of the study be discussed before describing the new simulation model.