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PREDICTING SEDIMENT QUALITY AROUND OUTFALLS

The physical and chemical composition of sediments and the abundance and composition of benthic biological communities show some of the greatest changes associated with the discharge of treated municipal wastewaters into open coastal waters. The purpose of developing a numerical simulation model of sediment processes is to obtain a predictive tool which can be used to relate these changes to the characteristics of the discharge and the receiving water environment.

The simulation model discussed here reproduces the surface sediment concentrations of total volatile solids (TVS) around the White Point outfall. The accumulation of outfall-related volatile solids is also adequately calculated, but with some variations that may reflect model deficiencies. At other outfalls the surface sediment volatile solids concentrations are generally overestimated by the model. Surprisingly, the model appears to do a somewhat better job of predicting Infaunal Index values (a measure of the community structure of benthic infauna) for those areas.

Other SCCWRP studies have provided estimates of the rate of sediment resuspension by biological processes and the amount of resuspended material in the water. These have been incorporated into the present model where they play an important role in determining sediment quality near major outfalls.

Some problems remain in obtaining accurate predictions for all types of outfall conditions. In particular, it is difficult to reproduce the rate of accumulation of natural particulates in the sediments in the absence of any discharge; the difficulty may result from the sensitivity of accumulation rates to small changes in the competing processes of resuspension and redeposition, and thus to small errors in current measurements.

BACKGROUND

SCCWRP Model

The purpose of the original simulation model (Hendricks 1978) was to describe the properties of the surface sediments around the White Point outfall(s) and to predict how these properties changed as the mass emission rate of suspended solids was reduced and the treatment processes modified. The processes included in the original and subsequent versions of the model were 1) the sedimentation of natural and effluent particulates from the water column; 2) the biochemical alteration of organic material; 3) the resuspension, transport, and redeposition of sediments; and 4) the net erosion or deposition of material in the sediments. The initial goal of the model was to predict the TVS concentrations in the sediments, since changes in benthic infaunal community structure and concentrations and distributions of trace constitutents in sediments are often well correlated with TVS distributions.

The initial model was fairly successful in prediciting the properties of the surface sediments around the White Point outfall. It could not, however, be reliably used for other outfalls since the relationship between some of the model parameters and the properties of the receiving water environment (e.g. currents, etc.) was not defined. The initial model was also quasi one-dimensional, since the transport of resuspended sediments was limited to the offshore direction. This was an appropriate assumption for White Point, where the sediment field is highly elongated in the alongshore direction and the near-bottom currents have a substantial offshore component. The sedimentation fields around other outfalls are generally not so elongated.

NOAA/SCCWRP Model

The SCCWRP model was substantially modified and refined under a grant from the National Oceanographic and Atmospheric Administration (NOAA). The purpose of this revision was to make a model applicable to a wider variety of receiving water environments.

Both the sedimentation flux and benthic processes submodels were converted from quasi one-dimensional transport representations to two-dimensional forms. In addition, measurements of the midwater and near-bottom currents were collected at three outfall sites (Orange County, White Point, and Encina/Oceanside) to provide input into the model and to supply insight into the characteristics of midwater and near-bottom transport processes. The formulation of the sedimentation flux submodel, and the sedimentation patterns and rates calculated by it for the White Point and Orange County outfalls, are discussed in Hendricks (1982).

The sedimentation flux submodel supplied the distribution and rate of sedimentation of effluent particulates to the second submodel--the benthic processes submodel. The latter considered the various inputs of natural and effluent particulates into each area around the outfall (from sedimentation and resuspension processes), as well as the "decay" of organic material. In the NOAA/SCCWRP model, the parameters in the earlier model were expressed in terms of specific mechanisms or processes instead of as generalized "transport" parameters. As a result, the dependence of these parameters on environmental conditions (and the dimensions of the "cells" used in the simulation model) was clarified (Hendricks 1983). The resuspension process representations used in both the original and the revised models were suitable for cohesive ("sticky" or "clayey") sediments.

The NOAA/SCCWRP model was able to simulate the surface sediment concentrations of TVS around the White Point outfall remarkably well. It was less successful in estimating either the concentrations around other outfalls or the net accumulation of material around the White Point outfall (see the RESULTS section below).

EPA/SCCWRP Model

When the work for NOAA had been completed it was apparent that, although the model had some notable predictive successes, deficiencies still remained. The sediment quality model is presently in the process of modification and refinement as the result of part of a grant from the Environmental Protection Agency (EPA). Representations of bioresuspension and the resuspension of noncohesive sediments have been added to the cohesive sediment representations in the current version of the model.

This report will provide a conceptual view of the various processes that determine the properties of the sediments around ocean outfalls, discuss the results of the NOAA/SCCWRP sediment quality model, and indicate the changes and preliminary results from the evolving EPA/SCCWRP model.

BASIC CONSIDERATIONS: A WHITE POINT EXAMPLE

The concentration and accumulation of TVS around an ocean outfall reflects the relative inputs and losses of total and organic mass within the sediments. For example, the TVS concentration can be calculated from the equation

$$\mathrm{TVS(sed)} = \frac{\mathrm{TVS(eff)} \times \mathrm{F(eff)} + \mathrm{TVS(nat)} \times \mathrm{F(nat)}}{\mathrm{F(eff)} + \mathrm{F(nat)}}$$

where TVS(...) = TVS concentration in the sediments (sed), effluent particulates (eff), or natural particulates (nat)

F(...) = mass flux of effluent or natural particles

providing that the appropriate concentrations and fluxes are known. Let us now use this equation to examine processes that may affect the properties of the sediments around the White Point outfall(s).

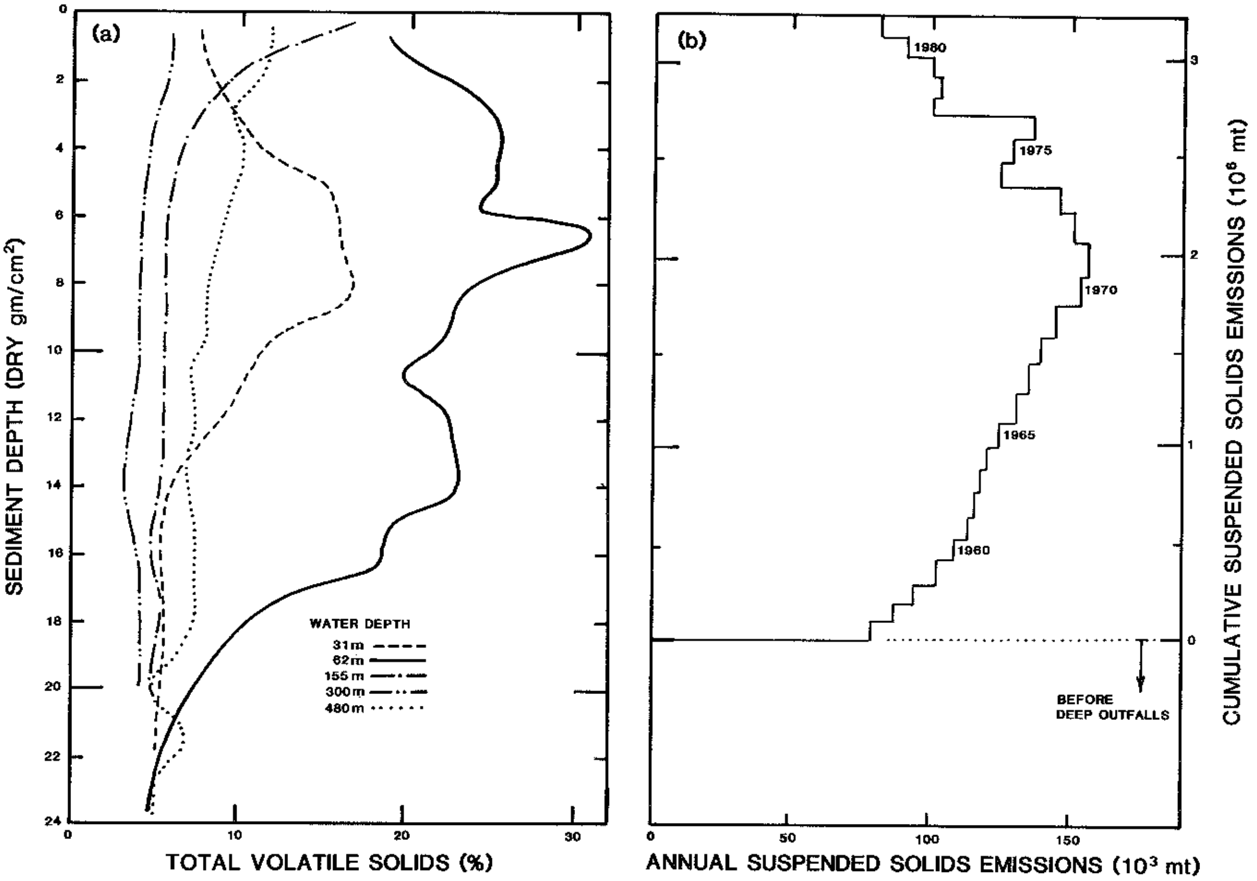

Figure 1. Deep outfall suspended solids history. a) Total volatile solids (TVS) in the sediments along an onshore-offshore transect passing near the east side of the 90-in. outfall (depth in cm is approximately two times the depth in dry gm/sq cm). b) Annual mass emissions of suspended solids. Note how the "profile" of the discharge approximates the profile of TVS in the 60-m (outfall depth) core. Discharges prior to 1956 were in shallower water.

The first of the 60-m outfalls (i.e., the 90-in. (2.3-m) outfall) at White Point was placed in operation in 1956; the second (120-in. outfall), in 1966. In a joint project with Los Angeles County personnel (Joint Water Pollution Control Project (JWPCP)), sediment cores were collected along several transects in this area in 1981. The TVS profiles in the sediments along one of these transects (near the 90-in. outfall) are shown in Figure 1a.

The deep sediments along this (and the other transects) indicate that the concentration of TVS in the natural sediments before the discharges began was about 4-6% (after decay of the organic material). We assumed that TVS(nat) = 4.5% for our calculations. The TVS concentrations in the upper sediments change with depth (time), presumably reflecting the variations in the mass emission rate from the outfall (Figure 1b). The maximum TVS concentration was about 26%; it occurred as about 7 gm/sq cm at 12 cm below the surface and was probably associated with the greater mass emission rate of suspended solids occurring in the early 1970's. By 1981, the maximum concentration had declined to about 19%. We will use a value of TVS(sed) = 26% .

The concentration of TVS in effluent particulates has varied during the course of the discharge, but generally it was about 70%. Myers' (1974) studies indicated that the decay of organic material would result in a concentration of 42-54% after a period of a few weeks to months. Very little decay occurred after that time. We used these latter values for TVS(eff).

The average mass emission rate of suspended solids (see Figure 1b) during the 1956-1981 period was 122,000 mt/year. The peak emission occurred in 1972 and has been variously estimated at 144,000 to 167,000 mt. Assuming a peak emission rate of 157,000 mt, the sedimentation flux submodel calculated that the corresponding sedimentation rate near the 90-in. outfall peaked at about 540 m/sq cm/year in 1972 and averaged about 430 mg/sq cm/year for the simulation period. We assumed that the maximum TVS concentration in the sediment corresponded to the maximum mass emission and set f(eff) = 540 mg/sq cm/year . We can now calculate that the required flux of natural particulates (F(nat)) must be 400-700 mg/sq cm/year (depending on the decay factor used) to generate the observed TVS concentration in the sediments.

Natural particulates constantly settle from the water column. Can they be the source of these "diluting" particulates? Estimates of the sedimentation rate of these particulates in this area (using sediment traps or C14 or PB210 dating) range from 9-103 mg/sq cm/year for the measurements closest to the White Point area--about 40 mg/sq cm/year. Thus, the simple sedimentation of natural particulates from the water column cannot alone account for the observed "dilution" of the effluent particulates.

It can be argued that we have overestimated the effluent-related flux of particulates. We can test our estimate by comparing the calculated and observed accumulation of effluent-related TVS. The accumulation of effluent-related TVS in the sediments was estimated by assuming that concentrations in excess of the natural concentrations were derived from effluent particulate organic material. The excess volatile solids (EVS) in the core collected near the 90-in. outfall indicate that approximately 3100 mg/sq cm of effluent-related TVS had accumulated during the 25-year period, which amounted to an average TVS accumulation rate after decay of about 124 mg/sq cm/year. The model calculated average "effective" TVS accumulation rates of 93 to 150 mg/sq cm/year--which in turn average to approximately 122--for the range of Myers' decay factors. Thus, the effluent accumulation rate determined by the model, in the absence of processes other than decay of organic material, was consistent with the observed accumulation rate.

The question then is "How does one obtain the observed TVS concentration without losing the agreement between modelled and observed TVS rates of accumulation?" There are three possible answers: 1) bioturbation mixes the surface sediments with deeper natural sediments, reducing the TVS concentration; 2) the actual sedimentation rate of effluent-related particulates is 2-3 times greater than the model-determined rate, but less of the organic material is refractory to decay (i.e., 20 to 30% of Myers' estimate); or 3) there are other processes producing a flux of natural particulates, such as the resuspension, transport, and redeposition of sediments from surrounding areas. Let us examine these hypotheses.

Hypothesis 1

The effluent particulates are diluted by bioturbation with deeper natural particulates. Estimates of the mass of sediments "mixed" by benthic biota, combined with the fluxes of effluent and natural particulates estimated above, suggest that the response time for sediments to changes in the effluent-related input should be fewer than 5 years. This is supported by the subsurface distribution of TVS concentrations, which roughly follows the history of mass emission rates (see Figure 1). Therefore, bioturbation cannot account for the observed TVS concentrations.

Hypothesis 2

Greater decay reduces the concentration of TVS in effluent particulates. It is possible that the model could have underestimated the sedimentation rate of effluent particulates because of difficulties in obtaining accurate estimates of the mass distribution of particulate settling speeds using laboratory measurements. However, it seems unlikely that estimates of both the sedimentation rate and the fraction of the organic material essentially refractory to decay would have been in error by a factor of 3-4. The correspondence between the deep sediment concentrations and the mass emission rates also argues against substantial additional decay.

Hypothesis 3

Resuspension of sediments supplies the flux of "diluting" particulates. Mitchell and Schafer* placed sedimentation traps in the area off Newport Beach, California, in water depths ranging from 30 to 180 m. The traps were mounted on stands with their horizontal opening about 1 m above the sediments. The measured "sedimentation" rates varied from 860 to 3600 mg/sq cm/year, generally decreasing with increasing water depth. These rates, much greater than the sedimentation of natural or effluent particulates in that area, suggested the settling of sediment particulates resuspended from the surrounding areas. The observations, combined with our in situ measurements of the threshold speeds required to resuspend sediments (Hendricks 1976), motivated us to include resuspension processes into our models.

MODEL RESULTS

NOAA/SCCWRP Model

Appropriate values for the parameters used in the benthic processes submodel were estimated by comparing the calculated and observed distributions of surface sediment TVS concentrations along an onshore-offshore transect extending through the 90-in. White Point outfall. The model was then used to calculate the surface sediment TVS (Figure 2) concentrations in the entire White Point simulation area. The results are shown by the concentration contours in Figure 2a. For comparison purposes, the concentrations measured in the surface sediments of the cores (1981) are shown, along with the values from

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*Personal communication. 1982. Charles T. Mitchell, Marine Biological Consultants, Inc., Coasta Mesa, Calif., and Henry A. Schafer, Associate Environmental Specialist, SCCWRP.

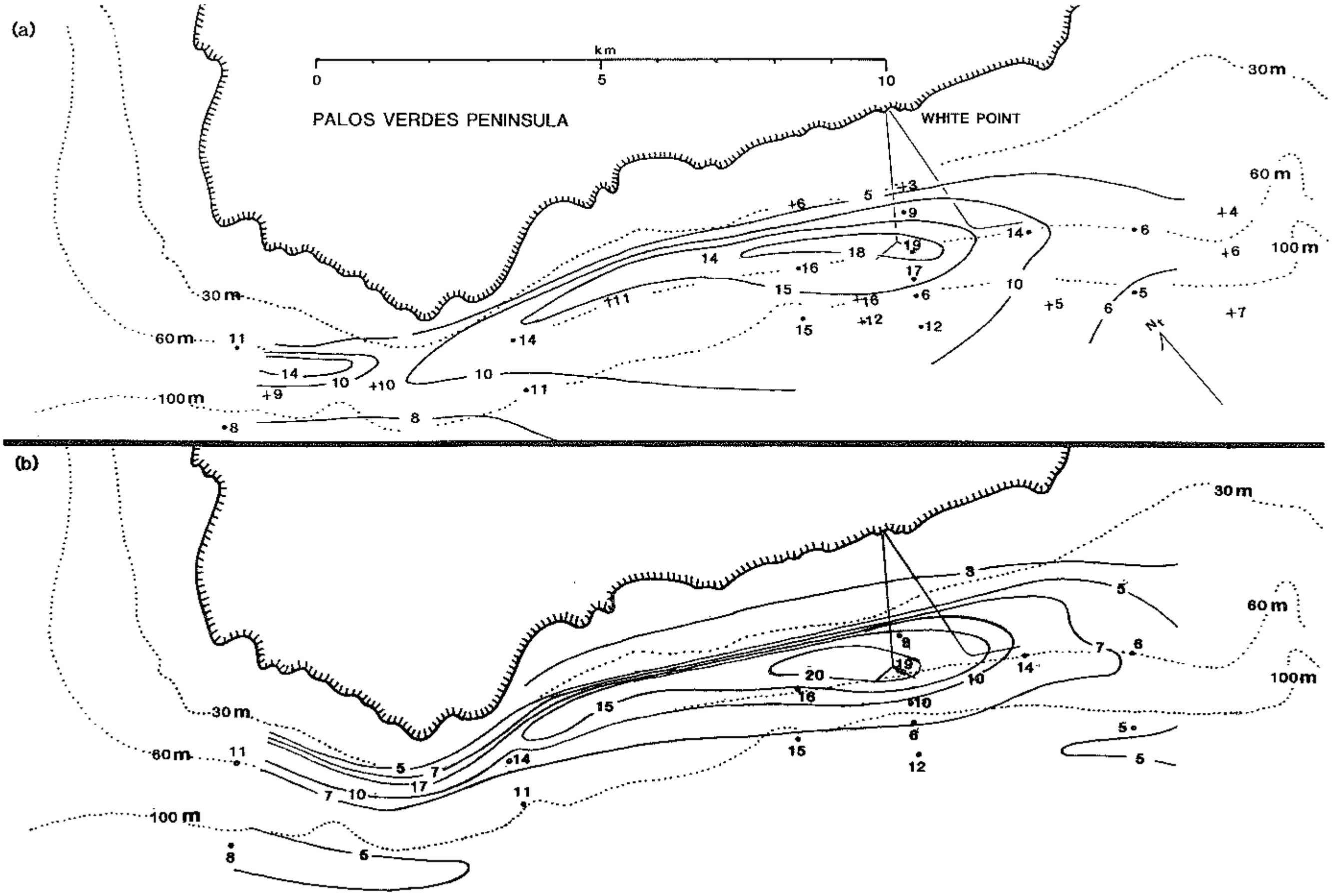

Figure 2. White Point surface sediment TVS, 1981. (a) Contours indicate the TVS concentrations (percent) at the end of 1981 calculated by the NOAA/SCCWRP sediment quality model (physical resuspension). Core values measured in 1981 are indicated by the values associated with dots; 1978 grab sample values, by crosses. (b) Contours show TVS concentrations calculated by a subset of the EPA/SCCWRP model (bioresuspension only) for the end of 1981.

grab samples collected in 1978. In general, there is quite good agreement between the calculated and observed distributions.

The calculated and measured EVS accumulations were compared along a transect passing through the 90-in. outfall, where five cores were available. Unfortunately a "slumping" or "mass flow" of the upper sediments appears to have occurred on the uppermost portion of the slope offshore from the outfall (see Figure 1a); we assumed, therefore, that the ratio of accumulated EVS offshore from the 90-in. outfall would have the same ratio to the accumulation at the 60-m depth (outfall diffuser depth) as was observed along two of the other (upcoast) transects. The calculated and "observed" accumulations, shown in Figure 3, have distributions similarily shaped, but the calculated accumulation is about 25% less than the observed. The biggest

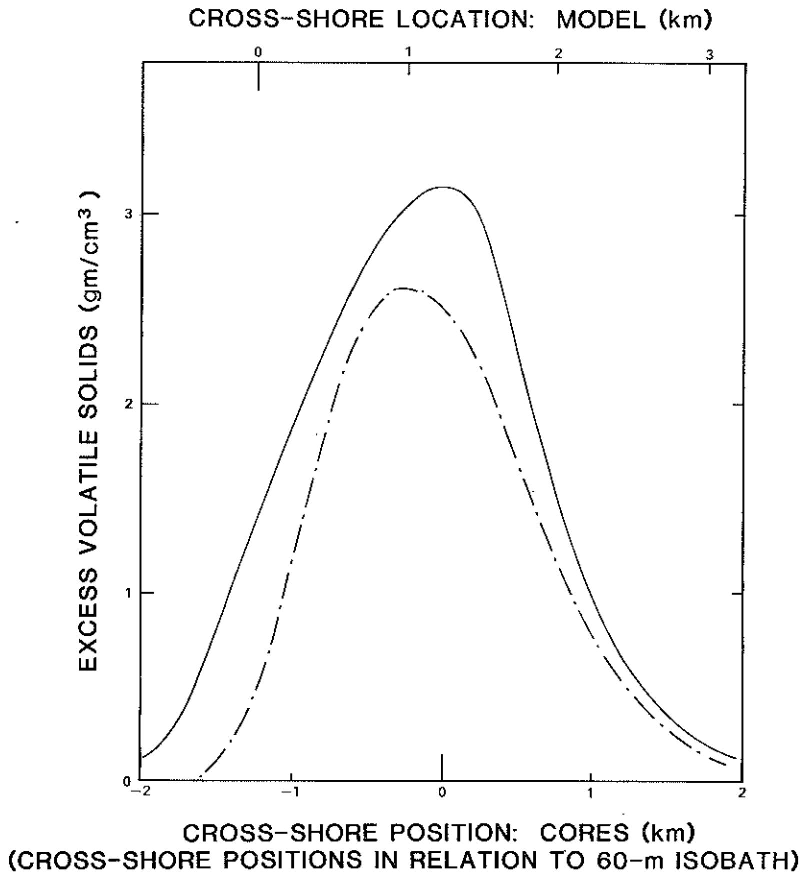

Figure 3. Model-calculated versus expected distribution of excess volatile solids (EVS). The dashed line indicates the cross-shore distribution of accumulated EVS along Transect 8 as calculated by the model. The solid line indicates the expected profile using upcoast transects to correct for the effects of an apparent mass flow along the outer part of Transect 8. The calculated total mass is about 70% of the expected mass (or about 80-85% of the observed excess mass). Note the approximate 1.2-km offshore shift in the location of the profile calculated by the model in relation to the observed profile.

difference is that the calculated accumulation occurs about 1.3 km farther offshore than the measured accumulation.

We also attempted to predict the surface sediment concentrations of TVS at the Orange County (40,000 mt/year, 56 m of water, predominantly primary treatment), Encina (1,600 mt/year, 37 m, primary), and Oceanside (268 mt/year, 33 m, secondary) outfalls. The calculated TVS concentrations were substantially higher than the observed values at both the Orange County and Encina outfalls, but lower than the observed values at the Oceanside outfall. The measured Oceanside TVS concentrations were surprisingly higher than the values observed at the Encina outfall (8 km downcoast), although the latter (in 1982) discharged about 5-6 times the mass of solids.

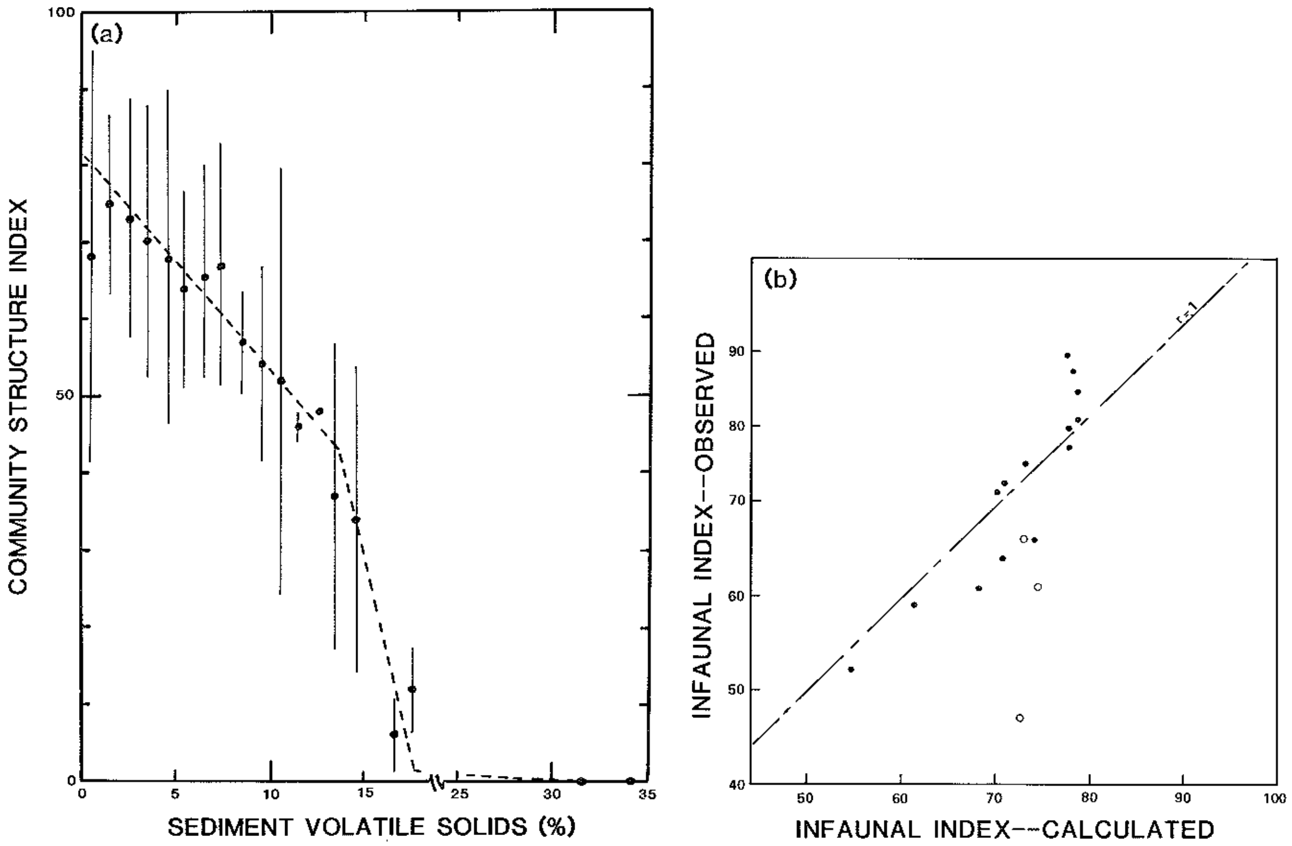

Figure 4. Infaunal Index changes. (a) The decline in the community structure index (Infaunal Index) is shown as a function of sediment volatile solids. Note that the index decreases at a more rapid rate for sediment volatile solids in excess of about 13% (based on data in Bascom et al. 1978). (b) Comparison of observed and model-calculated Infaunal Index values for Newport Beach. Although there is considerable scatter, there is a greater correlation between the calculated and observed Infaunal Index values than between the calculated and observed volatile solids concentrations.

The Infaunal Index has been used as a measure of the structure of benthic infaunal communities (Word 1978). Since the index was found to be relatively well correlated with the concentration of TVS in sediments (Figure 4a) (Bascom 1978), this relationship can be used to predict changes in community structure. When the index-TVS correlation was used to estimate the distribution of Infaunal Index values around the Orange County outfall (Figure 4b), however, we found better agreement between calculated and observed infaunal distributions than between calculated and observed TVS concentrations. This finding suggests that a) infauna are sensitive to the flow of organic material through their environment and b) this material tends to accumulate in the White Point area but not around the present Orange County outfall.

EPA/SCCWRP Model

Two Types of Sediment Resuspension by Physical Processes. The accumulation of EVS in the White Point area was not well calculated by the NOAA/SCCWRP model. This failure may have resulted from using a single representation for all the resuspension that takes place within the simulation area. While the organically enriched sediments around the outfall are likely to be cohesive, the inshore natural sediments, which are the primary source of "diluting" natural sediments, are more likely to be noncohesive. Thus, if the resuspension parameters in the model were varied to supply the required flux of undifferentiated natural particulates, the effluent particulate resuspension had to increase as well. This increased resuspension could force the model to show accumulation of effluent particulates offshore. One of our first tasks under the EPA grant was to incorporate separate representations for the two types of sediments. Following this separation, we found that the previous agreement between calculated and observed surface sediment TVS concentrations could be maintained while "returning" the area of calculated effluent particle accumulation to the depth of the outfall diffuser. This procedure decreased offshore transport in the model by reducing the rate of resuspension and transport of cohesive sediment.

Bioresuspension: A Third Type of Resuspension. Dr. Bruce Thompson's group at SCCWRP measured the egestion rates of particulates by individual *Pectinaria californiensis* (a tube worm) under laboratory conditions corresponding to the upper portion of the slope (a 350-m depth). These animals efficiently resuspended sediment particulates by injecting egested material upward into the water column some 12 mm above a 5-mm cone every 9 min (see Figure 5). The bioresuspension rates associated with the slope populations were substantially lower than the rates associated with physically induced resuspension in the NOAA/SCCWRP model, thus bioresuspension was not included in that model; the revised model, however, gives lower offshore resuspension rates, so bioresuspension could have increased importance.

Because the abundance of *Pectinaria* was found to be greater on the shelf than on the slope and densities varied among "normal," "changed," and "degraded" areas (Bascom et al. 1978; Thompson 1982), representative population densities were compared with sediment TVS concentrations for each type of area to obtain the TVS bioresuspension rates shown in Figure 5. This relationship was incorporated into the EPA/SCCWRP sediment quality model and simulations carried out for the White Point material using the decay factors estimated by Myers. No physically induced resuspension was incorporated into these simulations. The results (using the average of Myers' range of decay values) are shown in Figure 2b. For Myers' upper and lower bounds for decay, the calculated concentrations differed from the measured values near the

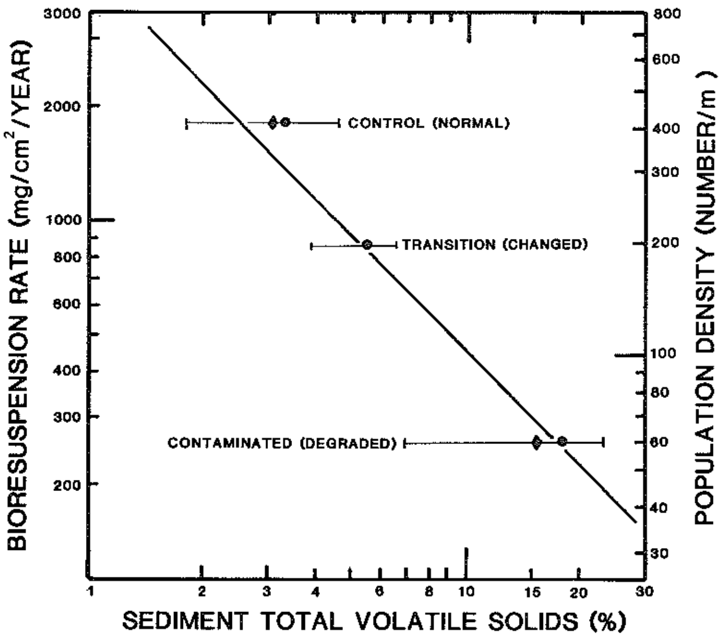

Figure 5. Bioresuspension rate dependence on sediment TVS population densities of *Pectinaria californiensis* and the associated biosuspension rates of sediment material, are shown for three types of sediments. The average TVS values corresponding to each "class" of sediment are indicated by circles (Bascom 1978a) and diamonds (Thompson 1982; Word and Mearns 1978).

90-in. outfall by about 20%. The EVS accumulations occurred slightly inshore from the observed maxima, suggesting that some physical resuspension (or additional bioresuspension) of particulates around the outfall was required.

These results indicate that bioresuspension is probably an important process in determining the characteristics of the sediments around the major outfalls. Bioresuspension is likely to play a lesser role in shallower water, where the physical resuspension associated with surface gravity waves becomes increasingly important.

Effect of Bioresuspension on Orange County Sediments. The rate of bioresuspension decreased with increasing TVS concentrations (Figure 5). Therefore, the lower concentrations of TVS in the natural sediments around the Orange County outfall (about 2% TVS) compared with those around the White Point outfalls (4-5% natural TVS) should produce increased bioresuspension. This difference could account for at least part of the difference between the measured and the NOAA/SCCWRP-calculated values, which only considered physically induced resuspension.

FUTURE MODIFICATIONS/IMPROVEMENTS

Accumulation Rates

In its present form, the EPA/SCCWRP model does not accurately simulate the rate of accumulation of mass in the natural sediments in the absence of any discharge; this is a necessary capability if reliable predictions are to be made for small discharges. In addition, the simulated accumulation rates along a cross-shore transect in the White Point area show the superposition of some anomalous "hills" and "valleys" on the basic distribution. Both of these problems appear to be associated in part with the use of measured currents to estimate the near-bottom transport of resuspended particulates. Both the Mitchell-Schafer sediment trap studies and the model computations indicate that the fluxes of resuspended material moving above the sediments were large relative to the net accumulation rates, which means that small errors in the transport calculations can lead to large errors in the accumulation rate of natural particulates.

For example, from the sediment traps, we estimated that the resuspension, transport, and redeposition rates for a typical area were about 2000 mg/sq cm/year. But if the transport rates estimated from the measured currents contained some inaccuracies, the transport out of one of the simulation cells could have been underestimated by 10%, and the transport into the cell by the corresponding amount. As a result of these relatively small errors, the calculated net accumulation rate increased to 440 mg/sq cm/year (400 + 40), or more than 1000% greater than the observed rate (40 mg/sq cm/year). We calculated the deviations from "continuity" (the conservation of water mass) resulting from the use of measured currents, and found that these deviations showed a strong resemblance to the "hills" and "valleys" in the calculated accumulation rates. Techniques are presently being developed to reduce current meter-associated sources of error.

At least two other processes may need incorporation into the model. These are 1) the presence of an unconsolidated, easily resuspended, thin layer of particulate mass on the surface of the "sediments" and 2) the possible aggregation of organic and fine inorganic particulates in the waters immediately above the sediments.

Tests of the model predictions with observations will be made at the San Elijo, Hyperion, and Ventura outfalls as well as the outfalls at White Point, Orange County, Encina, and Oceanside. Since these discharges cover a wide variety of mass emission rates, diffuser depths, and degrees of treatment, eventually we expect to have a generally applicable model of sediment quality.

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