Sediment Model Verification

Recovering sediment traps

The characteristics of sediments surrounding an ocean outfall can be altered by the accumulation of organically enriched particles from municipal wastewater discharge. The composition and abundance of animals that live in and on the sediments can also be affected. Several numerical models have been developed to relate changes in sediments and bottom-dwelling organisms to the characteristics of wastewater discharge and the receiving environment.

Prior efforts by SCCWRP to model the fates of particles discharged from ocean outfalls focused on transport and sedimentation of discrete effluent particles, and their subsequent resuspension, transport, redeposition, and accumulation in the sediments. Sedimentation patterns predicted by these models correspond reasonably well with observed patterns (e.g., Hendricks 1984, 1987). However, predicted rates of sediment accumulation are less than observed rates.

Settling column measurements on County Sanitation Districts of Los Angeles and County Sanitation Districts of Orange County final effluents in the early 1970s suggested that most of the particle mass was associated with very small, slow-settling particles. Only about 10% of the mass of suspended solids was associated with particles with settling speeds >13 m/day; approximately one-half of the particle mass was associated with settling speeds <0.25 m/day (Myers 1974, Herring and Abati 1978, Hendricks 1983). The slow-settling particles would require two months or more to settle 15 m from a wastefield to the bottom. Fast-settling particles contribute the most to sedimentation predicted by early SCCWRP deposition simulation models—about 90% of the particle mass is predicted to be carried beyond the outfall area before reaching the bottom.

Particles entering the ocean may not remain as individual particles, but may coalesce among themselves or with natural particles to form larger "aggregate" particles with higher settling speeds. If the smaller particles aggregate after discharge, the sedimentation rate in the ocean will be greater than the sedimentation rate predicted from settling column measurements. The aggregation of natural particles has been observed in the ocean and the aggregation of effluent particles is suggested by laboratory and theoretical studies.

As part of a contract from the California State Water Resources Control Board, we examined the ability of two models (DECAL and SED2D) to simulate the characteristics of sediments around ocean outfalls off Point Loma (San Diego), Huntington Beach (Orange County), and the Palos Verdes Peninsula (Los Angeles County) (Hendricks and Eganhouse 1992). The model DECAL was developed by Dr. Kevin Farley of Clemson University and the set of submodels SED2D were developed by Dr. Tareah Hendricks of SCCWRP.

Methods

The modeling study: 1) examined the sensitivity of model predictions to input data and the self-consistency of the predictions, and 2) provided site specific predictions based on the consequences of particle aggregation at the three outfall sites. The DECAL and SED2D models had to be modified and expanded to accomplish this. The modeling study was supported by field and laboratory studies that provided input data for the simulations and characterized the sediments for comparison with model predictions.

The simulation of the wastefield in the water column in DECAL (ODES Tool #61; Tetra Tech 1987) was not representative of the discharge and receiving waters in Southern California (i.e., distinct subsurface wastefield isolated from the bottom by an underlying layer of receiving water). We subcontracted with Dr. Farley to conduct new studies of the aggregation process under receiving water conditions present in Southern California. A generalization of the results for a wastefield of arbitrary thickness is found in Hendricks and Eganhouse (1990).

The most important conclusions of the aggregation process studies by Castro (1990, Farley and Castro 1990) are:

1) differential particle settling was the dominant aggregation mechanism for typical ocean and discharge conditions (i.e., larger, faster settling particles falling through smaller, slower settling particles resulted in collisions and aggregation);

2) the rate of production of aggregate particles was approximately proportional to the square of the concentration of suspended solids (2.3-power) and to the thickness of the wastefield (1.2-power);

3) the settling speed of aggregate particles was approximately proportional to the squares of the suspended solids concentration (1.8-power) and wastefield thickness (1.7-power); and

4) the production of aggregate particles in the layer of receiving water beneath the wastefield could be neglected.

These results were incorporated into a new version of the DECAL model by Dr. Farley and into a new set of SED2D submodels by Dr. Hendricks. The revised models were used for sensitivity and self-consistency studies, and for site-specific simulations.

A large number of complex processes determine the fate of natural and effluent particles in the ocean (Figure 1). The following processes, which are only a subset of all the processes involved, were represented in the two simulation models:

1) initial dilution (initial concentration of effluent particles in the wastefield),

2) concentration, flux, and production rate of natural particles in the water column,

3) aggregation of particles into larger particles with faster settling speeds,

4) settling of aggregate particles as they are transported by ocean currents,

5) decay of organic material in the water column and in the sediments,

6) mobilization and demobilization of trace constituents on the particles (DECAL),

7) resuspension (DECAL and SED2D), transport, and redeposition (SED2D) of sediment particles, and

8) accumulation rate and concentration of organic material (DECAL and SED2D) and trace constituents (DECAL) in the sediments.

Although the two models had similar goals and generally incorporated representations of the same processes, the assumptions, representations, and approaches for some of the processes were substantially different (e.g., Hendricks and Eganhouse 1992).

Results and Discussion

The sensitivity and self-consistency studies brought out several fundamental problems in assessing the importance of particle aggregation to the fate of particles discharged from outfalls. These uncertainties fall into four categories: 1) assumptions used to develop the aggregation rate and particle settling speed equations, 2) aggregation characteristics of natural suspended solids, 3) decay rates or fluxes of effluent and natural particles in Southern California coastal waters and sediments, and 4) quantitative representation of resuspension, transport, and redeposition of sediment particles. We discuss some of the predicted consequences and implications of particle aggregation for wastewater discharge, and the sensitivity of the predictions to those uncertainties.

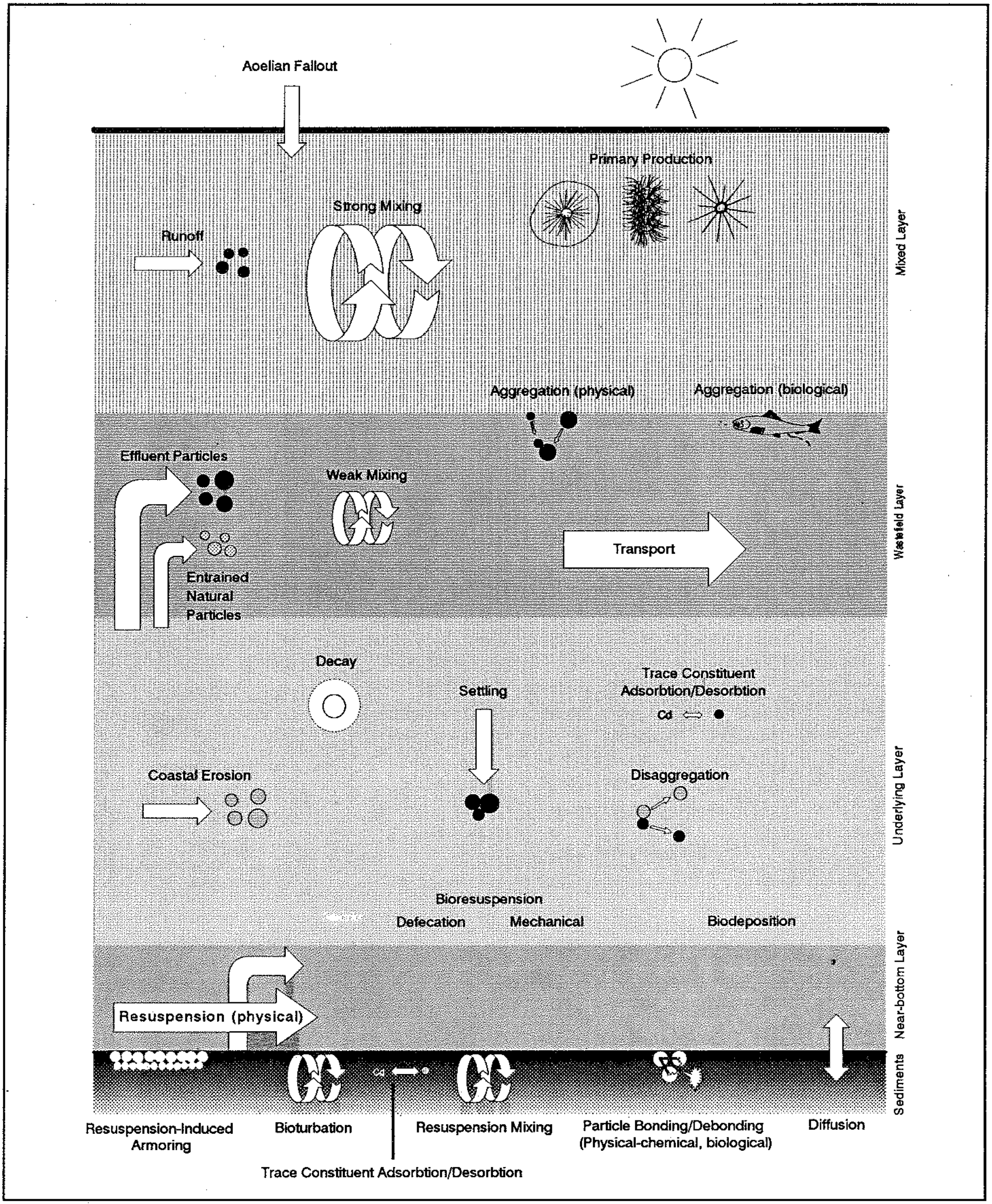
Effects of Natural Suspended Solids in the Ocean

Natural and effluent particles can aggregate in the simulations generated by DECAL and SED2D. The aggregation of phytoplankton cells produced in the surface waters above the wastefield can generate particles that settle into the wastefield. Natural suspended solids entrained into the wastefield during initial dilution are another source of particles.

Both models included sedimentation of aggregate phytoplankton cells from the overlying water. The DECAL simulations assumed that the concentration of natural suspended solids in the layer of receiving water beneath the wastefield (i.e., entrainment

Figure 1

Processes that determine the fate of natural and wastewater effluent particles in the ocean.



region during initial dilution) was negligible (Farley and Castro 1990). The SED2D simulations used measurements of natural suspended solids in the water column as the concentration of natural suspended solids entrained into the wastefield. Concentrations measured off White Point, Dana Point (Myers 1974), Encinitas (Kinnetic Laboratories, Inc. 1989), and San Diego (Point Loma Laboratory, City of San Diego, unpublished data) were about 2 mg/L at representative entrainment depths.

The two models estimated initial dilution and the initial concentration of suspended solids in the water column by different methods. Dilutions predicted by SED2D simulations were substantially greater than those predicted by DECAL simulations. For example, SED2D simulations for the Point Loma outfall (San Diego) predicted an average initial dilution of 281:1, while DECAL predicted an initial dilution of 116:1. If we assume an initial dilution of 150:1 and an effluent suspended solids concentration of 70 mg/L (1988 effluent), the initial concentration of effluent suspended solids in the wastefield will be about 0.5 mg/L, or about 25% of the initial concentration of natural suspended solids in the wastefield.

If all natural particles can aggregate, their predominance in wastefield total suspended solids has important consequences for wastewater discharge. In the presence of effluent-natural and natural-natural particle aggregation in our example above, 80% of the mass of wastefield particles that settled to the bottom were natural particles and 20% were effluent particles. Analyses of sediment cores collected in 1981 at 60 m near the outfalls on the Palos Verdes Shelf (Stull *et al.* 1986) provide support for aggregation of wastefield and natural particles. The background natural flux was about 200 mg/cm^2/yr, and each unit mass of effluent particles that accumulated in the sediments was accompanied by approximately one unit mass of natural particles over and above the background flux (Figure 2).

The magnitude of the background flux, and the ratio between the additional flux of natural particles and effluent particles, depend on assumptions about the effects of bioturbation on the distribution of effluent particles in the core horizon influenced by effluent discharge. Background fluxes ranged from about 100 to 300 mg/cm^2/yr in limiting cases, and the ratio of natural flux to effluent flux ranged between 1 and 3. A background natural flux of 200 mg/cm^2/yr is 7 to 20 times greater than published estimates for natural particle accumulation in this region (Emery 1960, Schwalbach and Gorsline 1985).

We examined the predicted change in peak sedimentation of wastefield particulates if treatment removed all suspended solids from the effluent. The initial concentration of total suspended solids in the San Diego wastefield example would decrease from 2.5 mg/L (2.0 mg/L natural + 0.5 mg/L effluent) to 2.0 mg/L. For discharges into Southern California coastal waters, the peak sedimentation rate of wastefield suspended solids on the bottom varies roughly with the square of the initial wastefield concentration (Hendricks and Eganhouse 1990). Total removal of suspended solids from the San Diego effluent (i.e., discharge of distilled water) only reduced the peak sedimentation rate near the outfall diffuser by about one-third. The remaining flux of natural particles from the wastefield was predicted, however, to remain roughly an order-of-magnitude greater than the flux of natural particles in the absence of the discharge.

Why did the model predict such a large enhancement of the sedimentation rate of natural particles in the presence of a particle-free discharge? One possibility is that most of the natural particle mass was associated with particles that did not aggregate. The concentration associated with this mass should not be included in the particle aggregation computations. However, we do not know if cohesive and non-cohesive natural particles exist, or what partitioning may occur. An alternate explanation is that enhanced vertical mixing within the wastefield increased the flux of particles.

Vertical Mixing within the Wastefield

The development of the aggregation equations assumed that all size classes of aggregate particles were uniformly distributed throughout a fully mixed wastefield. Particles undergoing aggregation by settling through the wastefield could be recycled to the top of the wastefield by mixing, allowing them to fall through the wastefield many times. During each fall, they could collide with smaller, slower settling particles, thus increasing aggregate particle mass and settling speed. As particle settling speed increased, the likelihood of the particle settling from the wastefield increased. Ultimately, the settling speed of aggregate particles became so large that turbulence could not carry them upward in the wastefield and they settled to the bottom. In the absence of discharge, the reduced turbulence in the water column did not permit vertical recycling of large, fast-settling particles, so the rate of particle production and settling speed decreased.

We assumed that the 2 mg/L ambient concentration of natural particles in the water column was the steady-state condition in the absence of discharge. The flux of aggregate phytoplankton cells settling from the surface layer into the "wastefield" region of the water column matched the loss of particles from the wastefield region due to aggregation and sedimentation. We did not assume that the wastefield region was fully mixed. Instead, we estimated the thickness of the mixing layer in the aggregation equations that would produce the steady-state.

The results depended on the rate of production of phytoplankton mass in the surface layer. We used 600 mg/m^2/day as the typical production rate, and 2400 mg/m^2/day as the maximum production rate, for Southern California coastal waters (Tetra Tech 1987). The "effective" mixing layer thickness for the aggregation equations was 0.4 m for the typical rate and 1.9 m for the maximum rate. These values are an order of magnitude smaller than normal wastefield thickness (15-30 m). Because aggregate particle production rate varied as the 1.2-power of wastefield thickness (i.e., effective mixing layer thickness) and particle settling speeds varied as the 1.7-power, greatly enhanced production rates and increased settling speeds were predicted in the presence of discharge.

The assumption that complete vertical mixing occurred within the wastefield may be inappropriate. Temperature, salinity, dissolved oxygen, and light transmissivity are generally not uniform between the upper and lower boundaries within wastefields (Hendricks and Harding 1974, Hendricks 1977, 1987, Thompson 1992). Laboratory studies of vertical mixing for conditions analogous to wastewater discharge into a stratified water column indicate a rapid dissipation of vertical turbulence (Lin and Pao 1979). Stratification in these studies, however, was greater than in the ocean.

We also compared the density structure within the wastefield to the structure in the surrounding ambient water. Despite uncertainties introduced by internal waves and tides, density gradients existed within the wastefield that may be comparable to the density gradient in the ambient water. This suggests that using the full thickness of the wastefield in the aggregation equations may substantially overestimate the rate of aggregate particle production and their settling speeds.

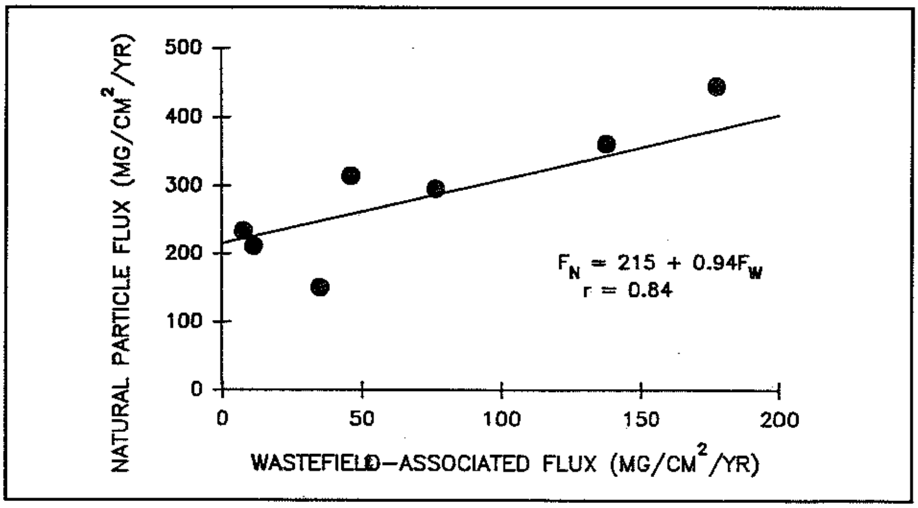
The effective mixing layer thickness in the absence of discharge provides a lower bound for the effective mixing layer thickness within a wastefield. Simulations based on this assumption predicted a substantial increase in the time between particle discharge from the outfall and particle arrival on the sediments (from about one hour to about six days; Hendricks and Eganhouse 1992). The reduced production rate of aggregate particles, and the dispersion of settling particles by currents during longer water column residence times, greatly reduced the sedimentation flux to the bottom. It also minimized or eliminated the normal local enhancement of sedimentation rate near outfalls.

Sediment Resuspension

Once particles settle to the bottom, they can be mixed with sediments, buried, and resuspended; the organic material can decay; and trace constituents can be mobilized. Both models pro-

Figure 2

The relation between natural particle flux (F_N) and wastefield particle flux (F_W) estimated from sediment cores collected at 60 m from the Palos Verdes Shelf in 1981.



vided only primitive representations of these processes. The processes were combined into two first-order rate equations in DECAL (one for organic material and one for a trace constituent). Under steady-state conditions, the rate of loss (or gain) of these processes was proportional to the mass of organic material (or trace constituent) deposited on the sediment surface. The magnitude of this parameter was determined either by choosing a value that minimized the difference between the predicted and observed sediment characteristics, or a value estimated from previous simulations for similar ocean environments.

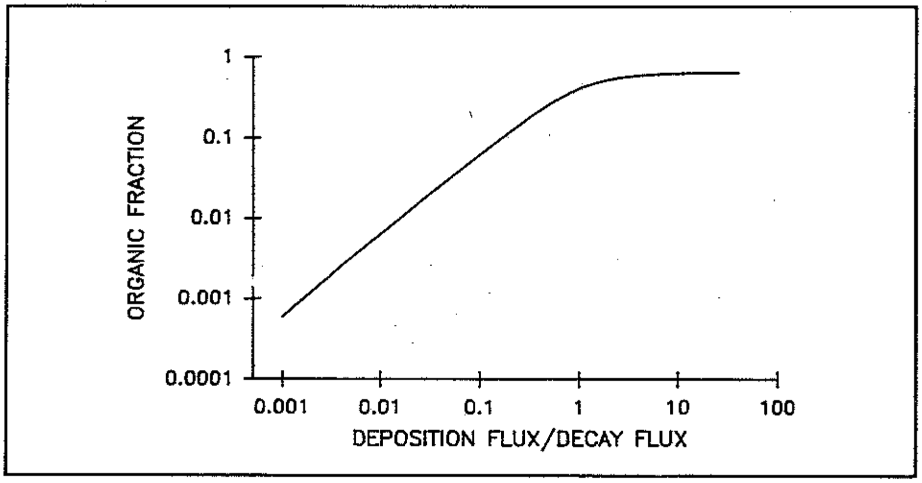
The SED2D simulations used a different representation for sediment decay processes and did not simulate trace constituent concentrations. The simulations estimated fluxes of material into and out of the sediments as a result of resuspension, transport by near-bottom currents, and redeposition. Observations with sediment traps deployed off Southern California at 0.5, 2.0, 5.0 m above the bottom formed the conceptual framework of the resuspension submodels.

The material collected in sediment traps is primarily resuspended sediments (Hendricks and Eganhouse 1992, unpublished data). Most of the resuspended material is found within 3 m of the bottom and is transported out of the immediate area by near-bottom ocean currents (Hendricks 1987). In the absence of discharge, fluxes of resuspended sediments into the sediment traps are one to two orders of magnitude greater than the rate of accumulation of particle mass in the sediments (SCCWRP 1986, 1987, Hendricks 1987, Hendricks and Eganhouse 1992).

Knowledge of the ocean conditions leading to sediment resuspension and redeposition are required to conduct SED2D simulations of sediment resuspension, transport, and redeposition. These conditions are not well known for the three test sites. However, studies by Washburn *et al.* (1991) near the outfalls on the Palos Verdes Shelf provide some empirical data.

Figure 3

The relation between the organic content of sediments and the ratio of the deposition flux to the limiting decay flux for particles with an initial organic fraction of 0.65 and inorganic fraction of 0.35.



Resuspension begins at current speeds of about 10 cm/sec and no material is resuspended at current speeds of a few cm/sec. (Resuspension also occurs under the combined stress of waves and currents.) We used a threshold resuspension speed of 9 cm/sec and a threshold deposition speed of 4.5 cm/sec for the simulations.

The other required piece of information for SED2D is the average number of resuspensions a particle undergoes before it is buried in the sediments. In the absence of wastewater discharge, this is approximately equal to the deposition flux of mass into a near-bottom sediment trap divided by the accumulation flux of mass into the sediments (approximately 10 to 100 resuspensions). However, changes in the composition of the sediments associated with wastewater discharge, or alterations of the sediments by benthic and epibenthic biota, may affect this number in a way that cannot now be determined *a priori*. For example, SED2D simulations suggested that the average number of resuspensions was lower in the area affected by the Los Angeles County discharge than in the other two test areas. (This could explain the high rate of accumulation of natural particles estimated from the Palos Verdes Shelf cores.)

We used sensitivity simulations to examine the ratio between the peak sedimentation flux of wastefield particles to the bottom and the net deposition of wastefield particles in sediments at that location after resuspension. As used herein, "sedimentation" is the initial deposition of particles from the water column; "deposition" is the deposition of particles after resuspension. This ratio was approximately inversely proportional to the average number of resuspensions experienced by a particle—provided that the number of resuspensions was in excess of about 10. Estimates of the peak accumulation rate of sediments were sensitive to errors in estimates of the average number of resuspensions of sedimenting particles. Sensitivity varies away from the area of peak sedimentation, where effects of the deposition of sediments resuspended from adjacent areas are more important.

Other simulations suggested that the average distance a resuspended particle traveled before redeposition was sensitive to threshold resuspension and redeposition speeds. Changes in transport distance had only minor effects on peak deposition rates around outfalls, but influenced deposition fluxes in areas on the fringes of wastefield sedimentation. Uncertainties in the effects of sediment resuspension in areas most heavily impacted by discharge were more sensitive to the average number of resuspensions and less sensitive to the threshold speed.

Decay of Organic Material

The discussion so far has implicitly assumed that particle mass is inert. If the particle contains labile organic material, loss due to decay can affect the initial deposition flux to the bottom, the rate of accumulation of particle mass in the sediments, and sediment composition. Approximately 70% of effluent particle mass is organic material (Hendricks and Eganhouse 1992); effects of decay may alter particle fate predictions. We examined the sensitivity of the results to uncertainties in the decay rate of organic material in the water column and in the sediments.

The decay of organic material as a particle settles through the water column reduces the organic content, total mass, and deposition flux of material to surface sediments. Loss of mass reduces particle settling speed, increases residence time in the water column, and magnifies the effects of decay. The decay of organic material has the potential to produce large changes in particle composition and sedimentation fluxes if settling time becomes comparable to, or greater than, the characteristic decay time (inverse of the decay rate). Unfortunately, the decay rate of organic material in the ocean is not well known. Estimates based on treatment plant observations are about 0.1/day (Tetra Tech 1987). Laboratory and *in situ* studies suggest 0.52/day (Myers 1974). Simulations were carried out for values of 0.1 and 0.52/day.

Collecting sediment trap material

When the decay rate was reduced from 0.52 to 0.1/day in DECAL, the predicted peak fluxes of total suspended solids to the sediments increased by about two (Los Angeles County) to four (Orange County). The effects were smaller in the SED2D simulations for two reasons. First, entrainment of natural suspended solids during initial dilution increased the wastefield concentration and particle settling speeds, thus reducing residence time in the water column. Second, particles consist of inorganic as well as organic material, so all of the particle mass was not subject to decay and the change in particle settling speed was less than in similar DECAL simulations.

Decay can continue after particles settle to the ocean bottom. In the SED2D model, decay was assumed to be confined to a layer of surface sediments. Hence there is a limit to the rate of loss of organic material (per unit area)—even if the sediments consist entirely of organic matter. For sediments with reduced concentrations of organic material, the rate of loss was correspondingly reduced below the limiting value. The decay flux can determine the rate of accumulation of mass in sediments, the organic content of sediments, and the rate at which sediment composition changes in response to changes in treatment method or changes in the ocean environment. No estimates of the "limiting" decay flux were available for sediments at the three test sites. Estimates from offshore basins and other geographical areas vary over several orders of magnitude.

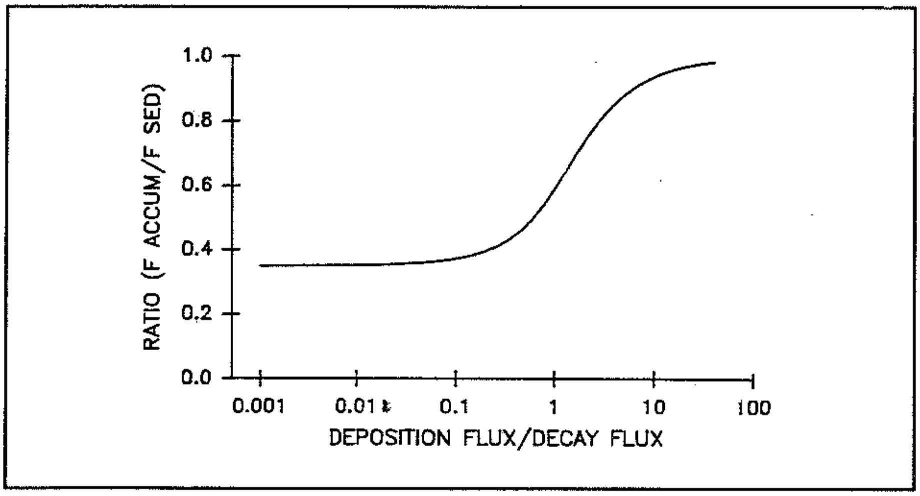
The organic content of sediments was related to the ratio of the deposition flux to the limiting decay flux (Figure 3). Once the deposition flux exceeded the limiting decay flux ($F_{depos}/F_{decay} > 1$), the composition of the sediments became nearly the same as the settling particles (because particles only spent a short time in the sediment layer where decay occurred). At lower deposition rates however, the organic fraction of the sediments was proportional to the deposition flux.

The material remaining after decay contributed to the accumulation of particle mass in the sediments and to sediment burial. The ratio of accumulation flux to deposition flux was less than unity ($F_{accum}/F_{depos} < 1$) and depended on the ratio of the deposition flux to the limiting decay flux (Figure 4). For deposition fluxes that were ten or more times the limiting decay flux ($F_{depos}/F_{decay} > 10$), the accumulation flux was virtually equal to the deposition flux (because little decay occurred before the particles were buried below the decay layer). Conversely, if the limiting decay flux was ten or more times greater than the deposition flux ($F_{depos}/F_{decay} < 0.1$), nearly all of the organic material was lost to decay and accumulation was due primarily to particle inorganic material. At intermediate deposition fluxes, the ratio between accumulation flux and deposition flux varied between these limits. Our best estimate for the decay flux was 180 mg/cm^2/yr, so the region of variability in the accumulation-deposition flux ratio corresponded to deposition fluxes of 18 to 1800 mg/cm^2/yr. This roughly corresponds to the range of accumulation rates (natural + effluent) estimated from cores taken on the Palos Verdes Shelf (Figure 2).

Large uncertainties in estimates of deposition flux were due to uncertainties in: 1) the contribution of natural particles to the aggregation process, 2) the effective mixing layer thickness for particle aggregation, 3) the rate of loss of organic material in the water column due to decay, and 4) the average number of resuspensions of a particle settling to the bottom. Similarly, the limiting decay flux of organic material in the sediments is unknown. These uncertainties magnify the potential for error in estimates of the composition of sediments and their rate of accumulation (i.e., burial).

Figure 4

The relation between the ratio of accumulation flux to deposition flux and the ratio of deposition flux to the limiting decay flux for particles with an initial organic fraction of 0.65 and inorganic fraction of 0.35.



Conclusion

There are substantial uncertainties in the predictions of the fates of wastewater effluent particles based on the DECAL and SED2D simulation models. Both models predicted areas of high rates of sedimentation near outfalls that were surrounded by areas of lower rates of sedimentation. The models predicted an increase in sedimentation of natural particles as a result of a discharge lacking particulate matter.

Uncertainties in the predictions arise from: 1) questions about the validity of aggregation equation assumptions, 2) lack of data on vertical mixing within the wastefield, 3) lack of knowledge about the aggregation characteristics of natural suspended solids, 4) poor understanding of sediment resuspension processes, and 5) lack of estimates of the decay rate of organic material in the water column and sediments. Until these uncertainties are addressed, it will be difficult to assess the validity of the predictions of the two models and the process representations contained in them. However, the models provide qualitative insight into the dynamics of the interaction of a wastefield and natural waters and the localized effects on sedimentation from the discharge of wastewater effluent. ■

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