Tereah J. Hendricks

FORCASTING CHANGES IN SEDIMENTS NEAR WATEWATER OUTFALLS

Important questions about the effects of ocean outfall discharges on the nearby bottom can be largely answered by a fitted numerical model, provided the model bears some resemblance to reality. The questions concern the relationship between the material discharged and the physical and chemical nature of the sediments that receive the discharge. Once this relationship is understood, it becomes possible to forecast the effects of various possible changes in the character of the effluent resulting from modifications of the treatment processes.

The Coastal Water Research Project has used the numeri-cal simulation model described here to make such forecasts and has reinforced them with biological forecasts that reach similar conclusions. Although the model in principle can be extended to many coastal areas, most of our work to date has been applied to Los Angeles County Sanitation Districts Whites Point outfall system because data from past studies in that area could be used in the model development.

The model consists of two parts. The first part estimates the longshore position of the effluent wastefield as a function of the time elapsed since the effluent was re-leased into the ocean. This distribution of positions is then combined with information on the settling characteristics of the effluent particulates and the bathymetry in the area to estimate the flux of effluent-related particulates to the ocean bottom. The second part of the model uses the flux of effluent particulates, combined with estimates of the flux of natural particulates and the reworking of the existing sediments by resuspension processes or mixing by benthic biota, to determine the change in thick-ness and composition of outfall-influenced bottom sediments.

FLUX OF EFFLUENT-RELATED PARTICULATES TO OCEAN BOTTOM

The longshore dispersion of effluent and effluent particulates is estimated from a current meter record, under the assumption that the longshore component of the currents measured at that site is representative of the entire out-fall area. The longshore component of measured currents is represented by a Fourier series:

$$v(n\Delta t) = \sum_{j=0}^{N/2} v_j \cos(\omega_j n\Delta t + \phi_j), \quad (1)$$

where

N = the number of current meter measurements during a sampling interval, Δt,

n = 1,2,3,....,N,

v(nΔt) = the longshore component of the current for the nth sample, and

$\omega_j = 2\pi j/N \cdot \Delta t$.

The longshore position, x, of effluent particles at time nAt is the approximately given by

$$x(n\Delta t) = \int_0^{n\Delta t} v(t')dt' \quad (2)$$

$$= \int_0^{n\Delta t} \sum_{j=0}^{N/2} v_j \cos(\omega_j t' + \phi_j)dt'. \quad (3)$$

The difference x[(n + l) Δt] - x(nΔt) determines the distance a particle released at time nΔt will move during the next measurement interval, At. Therefore, by considering all adjacent pairs of position values in the sequence of positions, the model can estimate the probability of effluent particles being a distance x away from the outfall during one sampling interval, Δt--i.e., P(x | Δt). Similarly, the same probability can also be estimated for 2Δt, 3Δt, etc., and used to estimate the conditional probability, P(x | t), i.e., the probability of finding a particle a distance x away from the outfall t hours after its release from the diffuser.

The period of current measurements is generally short compared with the existing (or proposed) period of discharge. Therefore, the probability of a particle moving x distance in t hours given other currents that might also occur has been estimated by assuming that the spectral energy density distribution for a longshore component of the currents is an invariant. This assumption has support from our current measurements off Point Loma (Hendricks 1977). Other possible position sequences are then created from Equation 3 by randomizing the values of the phase angles, ϕj.

It is assumed that the settling particles move with the longshore currents until reaching the bottom. In addition, it is assumed that the mean position of the wastefield in the water column in 30 meters above the bottom. If the fraction of particles that settle from a height of 30 meters in the time interval between t and t + dt is represented by H(t), then the probability of a particle settling at a dis-tance x away from the outfall is given by

$$G(x) = \int_0^{\tau} P(x|t)H(t)dt,$$

where τ is the duration of the discharge. H(t) has been obtained from laboratory measurements of particle settling velocities in effluent and seawater mixtures (Myers 1974; Herring and Abati, this report). Because of increasing un-certainty in the value of $P(x|t)$ with increasing time, and the generally decreasing values of both $P(x|t)$ and H(t) with increasing time, T has been operationally chosen as 120 hours. As reported elsewhere (Hendricks 1975), the long-shore distribution of outfall-related sediments at the Whites Point area has been estimated using Equation 4, and the results have been compared with the field measurements of Myers.

In principal, the cross-shore component of the currents from the original current meter record could also be used at the same time to produce the areal probability, $P(x,y|t)$. If purely random phase angles are used to create an ensemble of possible currents, then it is necessary to assume that the x and y axes are uncorrelated so that

$$P(x,y|t) = P_1(x|t)P2(y|t).$$

In practice, however, we chose not to do this because ob-served drogue movements and movements predicted from a current meter record collected at the same time showed much less correlation in the cross-shore direction than in the longshore direction. A similar lack of correlation in the cross-shore direction was observed in current meter records collected simultaneously at two locations. This lack of correlation indicates that the assumptions used in the model are not well fulfilled in the cross-shore direction.

On occasion, we have estimated the cross-shore distribution of the wastefield by assuming a similarity hypothesis, i.e., that the distribution of particulates (or wastefield concentration) has the same shape at all times (e.g., a normal distribution), but that the characteristic width of this distribution in the longshore direction changes with time.

If $\sigma\gamma(t)$ is chosen to represent the characteristic width at time t (e.g., the square root of the variance for a normal distribution), then, for no net onshore/offshore advection,

$$P(x,y=0|t) = P(x|t) \cdot \frac{\sigma_y(0)}{\sigma_y(t)}.$$

If Q(y,0y) is the chosen similarity distribution, the areal probability is given by

$$P(x,y|t) = P(x|t) \cdot \frac{\sigma_y(0)}{\sigma_y(t)} \cdot Q(y,\sigma_y).$$

As field observations indicate that o (t) should probably not be calculated from a current meter record, we have generally assumed either a normal or a "top hat" distribu-tion and assumed that o,,(t) increases with time, as follows:

$$\sigma_y(t) = \sigma_y(0) + v_D t,$$

or, alternatively (but not equivalently),

$$\sigma_y^2(t) = \sigma_y^2(0) + (v_D t)^2,$$

where v_D) is an "effective diffusion velocity."

The value of VQ is chosen on the basis of measurements of the currents, the transverse component of the subpycnocline "eddy diffusion velocity," and the slope of the bottom. Values for the southern California coastal area would be expected to fall within the range of 0.1 to 4 cm/sec, but the precise choice for a particular situation is at the present time more a matter of art than science.

Once we have obtained estimates of the cross-shore distribution of the wastefield, we can estimate the areal deposition of effluent particulates on the bottom:

$$G(x,y) = \int_0^t P(x|t) \frac{\sigma_y(0)}{\sigma_y(t)} Q[y,\sigma_y(t)]H(t)dt. \qquad (5)$$

We have applied the first phase of the model to the Point Loma outfall situation to conservatively estimate (i.e., overestimate) the particulate depositional flux, using a value of 0.4 cm/sec for v_D and assuming a "top hat" distribution of the wastefield in the cross-shore direction. The resultant depositional pattern is shown in Figure 1.

CHANGES IN COMPOSITION AND THICKNESS OF OUTFALL-RELATED BOTTOM SEDIMENTS

Once the flux of effluent particulates to the ocean bottom has been estimated, the second part of the model is used to estimate the fate of the particulates and

the composition of the bottom sediments. In contrast to the previous computations, which are primarily focused on the longshore direction, the second phase is oriented in the cross-shore direction because (1) the concentration gradients of effluent-related particulates are generally much greater in the cross-shore direction than in the longshore direction and (2) limited measurements of the currents within 2 meters of the bottom indicate that, at this depth, the cross-shore component can be comparable to the longshore component. If resuspension of bottom sediments is assumed to be an important process, its principal effects will show in the cross-shore direction, although some changes will also occur in the longshore direction.

Based on this hypothesis, a particular longshore location in the outfall area is divided in the cross-shore direction into a number of cells, as shown in Figure 2. Within each cell, a number of processes are assumed to occur, including (1) the deposition of natural and effluent-related particulates, (2) the occasional resuspension of bottom sediments, with a net offshore flux of part of these resuspended sediments, (3) the deposition of some portion of the resuspended sediments from the inshore cell(s), and (4) the mixing of the newly settled particulates with the earlier sediments by the benthic biota. These processes are schematically illustrated in Figures 2 and 3.

Resuspension is estimated by assuming that the net amount of resuspension over a year-long period is proportional to the fraction of the time that the bottom currents within a particular cell exceed the critical resuspension velocity. This velocity has been estimated from previous Project studies (Hendricks 1976). Bottom currents have been calculated by assuming that they are wave-induced and then using height-period probabilities measured by Pawka et al. (1976) at Torrey Pines Beach.

We have used the second phase of the model to simulate the characteristics of the sediments in the area around the Whites Point outfall system. Rather than choose a somewhat arbitrary value for v_D, to estimate the cross-shore depositional flux, we assumed a normal distribution whose variance would be one of the model parameters to be esti-mated from field measurements. (A small skewness was introduced into the distribution to make a first-order correction for the sloping bottom.)

The numerical relationships used to calculate the cell fluxes and concentrations are listed in Table 1. In addition to the parameter related to the width of the waste-field, there are a number of other unknown parameters in this formulation. These include (1) the fraction, a, of the resuspended material from the inshore cells that settles into the cell under consideration, (2) a parameter, y, related to the amount of sediment resuspended during the course of a year, (3) the amount of sediment mass per unit area, N3*, mixed by the benthic biota, and (4) the fraction, f, of organic carbon lost through bacterial decay. The latter two parameters have been estimated using data for the Whites Point area from Myers (1974).

The values of the remaining three unknown parameters (wastefield width, adjacent cell settling factor, and resuspension factor) have been estimated by computing the concentration and distribution of organic carbon in the surface

sediments along a transect of stations over the Whites Point outfall (Transect 8) and adjusting the values until the observed distribution and concentrations are matched as well as possible. To produce a simulation, the computation starts at the inshore cell (where there is no flux of resuspended sediments from an inshore cell) and steps in the offshore direction. It is assumed in the model that the sediments are pristine at the start of the simulation. Therefore, computations for the Whites Point situation begin with 1937, the year in which discharge was initiated. The processes taken into account in the model (Figures 2 and 3) are such that the time steps for the simulations must be shorter than 1 year. In addition, changes in effluent composition and outfall location are introduced on a yearly basis. The computations continue until the entire period of discharge has been simulated.

After the unknown parameters are fixed, the simulations were repeated for Whites Point Transects 1, 2, 3, 5, and 10, which range from 11 km upcoast to 3.5 km down-coast of the outfall. The predicted organic carbon concentrations in the surface sediments along these transects and Transect 8 are compared with observed values in Figure 4. In spite of the simple nature of the model, there is generally a good correlation between the predicted and observed values--approximately two-thirds of the differences between the predicted and observed concentrations are within 1 percent organic carbon.

Myers (1974) measured the vertical profile of organic carbon concentrations at a station near the Whites Point outfalls (Station 6C). We compared the model-predicted profile with his observed profile (Figure 5) and found that the shape of the profile was reproduced quite well by the model, but that the model only accounted for about 70 percent of the effluent-related organic carbon actually deposited at that site over the 35-year period of discharge.

PREDICTION OF TRACE CONSTITUENT CONCENTRATIONS IN BOTTOM SEDIMENTS

The organic carbon concentration must be computed in the model because the critical resuspension velocity of the sediments is a function of this concentration (Hendricks 1976) . We also made a provision in the model that permits prediction of the concentration of a trace constituent present in the particulates, provided that the constituent meets the following criteria: (1) Any desorption or mobilization of the substance, if it occurs, will be a constant fraction of the initial mass concentration on the particu-lates and (2) the constituent concentration will have a negligible effect on the benthic mixing or resuspension processes.

In particular, we attempted to predict the concentration of DDT in the sediments around the Whites Point outfalls. There was some uncertainty in supplying the model with effluent-particulate concentrations of DDT for years prior to 1971, since these concentrations were not monitored. Therefore, we assumed that the mass flux of DDT observed just prior to the initiation of

source control in 1971 had existed for at least several years prior to that time. In Figure 6, the resulting model-predicted DDT concentrations in the surface sediments in 1972 and 1975 are compared with field measurements taken in those years (Young et al. 1977). In general, the model values for the most contaminated areas are comparable to the actual values for those areas, although the model-predicted concentrations are about 20 to 25 percent higher (about 10 to 15 percent of this difference may be attributable to the fact that simulation and sampling times for each year were slightly different). The reduction in concentration of DDT in the most contaminated surface sediments between 1972 and 1975 is remarkably well predicted by the model. There are, however, substantial differences between model and field values for both concentration and reduction in concentration of DDT at stations more distant from the outfalls.

PREDICTION OF BOTTOM SEDIMENT CHANGES RESULTING FROM MODIFICATIONS IN TREATMENT PROCESS

Based on these encouraging results, we used the model to predict the changes that might occur in the surface sediments off the Whites Point outfalls over the next 20 years or so if the mass flux of particulates were reduced by a modified treatment process. The annual mass flux of particulates for the simulation period is shown in Figure 7, as are the model-predicted corresponding surface concentrations of organic carbon and DDT at a station near the outfall system (Station 7C). Although the sediment concentrations of both DDT and organic carbon decline after treatment modification is Initiated, it is evident that the principal factor affecting the DDT concentrations over the simulation period was the initiation of source control in 1971. Sediment profiles generated by the model indicate that the DDT reduction is predominately due to burial by subsequent sedimentation, and that the substance will still be present in relatively high concentrations below the near-surface sediments.

Let us consider a hypothetical and idealized example of how the model might be used to provide guidance in choosing among several treatment modifications proposed when an alteration in the characteristics of outfall-influenced sediments is desired. Suppose that an outfall system similar to the Whites Point system in design and history of suspended solids emission has been in operation for a sufficiently long period of time to allow the concentrations of constituents found in the effluent particulates to attain their equilibrium values in the sediments. New criteria for concentrations of trace constituents are then adopted, and it is discovered that sediment concentrations of one of the particulate-associated trace constituents exceeds the stipulated level. Three treatment modifications are proposed as possible corrective measures: (1) "source control," in which the trace constituent mass emission rate is reduced to f times the original value, (2) "secondary treatment," in which both trace constituent and suspended solids mass

emission rates are reduced to f times the original values, and (3) "unsettled secondary treatment," in which the trace constituent mass emission rate remains the same but the suspended solids emission rate is increased to 1/f times the original value. The task is to determine which of these processes or combination of processes will most rapidly reduce the trace constituent concentrations in the sediments to an acceptable value.

Model simulations of each of these processes alone were carried out, as were simulations of the combination of source control and secondary treatment. It was found that, for a given emission rate change, f, the various processes have differing levels of effectiveness in reducing the sediment concentrations of the constituent. In addition for equal reductions, the various processes also produce differing rates of decline.

Figure 8 illustrates the reduction factor, R (the ratio of the final equilibrium concentration in the sediments to the initial concentration) as a function of the emission rate change factor, f. The greatest reduction for a given value of f is associated with source control; the least, with secondary treatment. For example, the sediment concentration level produced by using source control to reduce the trace constituent mass emission rate to one-half its original value would be equivalent to the level produced by using secondary treatment to reduce the trace constituent and suspended solids mass emission rates to slightly less than one-third their original values. The combined effect of source control and secondary treatment can be obtained by multiplying the individual concentration reductions (i.e., the f values) associated with the two processes.

Secondary treatment also produced the slowest rate of decline to a given sediment concentration level. Reductions below 0.76 occurred most rapidly with unsettled secondary, but these required emission rate change factors of less than 0.66, which is probably not a very realistic expectation. Source control recovery times were significantly shorter than those associated with secondary treatment. Typically, about 6 to 7 years were required for 90 percent of a given reduction to take place using source control, but on the order of 10 to 12 years were required with secondary treatment. Maximal secondary treatment (i.e., no particulate discharges, or f = 0) yielded a 90 percent recovery time of 14 years.

It should be noted here that, if both source control and secondary treatment are required to produce a desired reduction, the most rapid reduction occurs when source control is used alone at the start of the change and second-ary treatment is added at a later date (the actual time being dependent on the relative reductions associated with each process). If both are initiated simultaneously, recovery occurs at the slower rate associated with secondary treatment.

All of these discussions are, of course, for an idealized and simplified case. It is implicitly assumed that the concentration of the trace constituent on natural particulates is zero; if, in fact, it is not, the non-zero value is subtracted from the sediment concentration, the mass emission rate value is modified to reflect the excess above that associated with the discharge of natural particu-

lates, and the other model procedures described here are carried out unchanged. The predictions then apply to the "excess" concentration. In addition, it is assumed in the model that the particulate organic carbon concentration, the distribution of settling velocities, and the benthic mixing "depth" are not affected by the changes in the treatment. For real cases, changes in these parameters could be examined and readily incorporated into the model. It is also assumed that the organic carbon concentration in the sediments is not a limiting factor. Finally, it is recognized that equal levels of effort expended in each process will generally not result in equal values of f; for example, it is probably easier to achieve an f value of one-third for many ubiquitously distributed trace constituents using secondary treatment rather than source control.

The model is a relatively simplistic representation of only a few of the processes affecting the fate of particulates in the sediments around an outfall. However, it appears to be a potentially valuable tool in estimating the changes that may occur in these sediments if the character and mass emission rates of effluent particulates are altered by a change in treatment process.

REFERENCES

Hendricks, T.J. 1975. A model of the dispersion of wastewater constituents. In Annual report, 1975, pp. 173-7. Coastal Water Research Project, El Segundo, Calif.

___. 1976. Current velocities required to move sedi ments. In Annual report, 1976, pp. 71-76. Coastal Water Research Project, El Segundo, Calif.

__. 1977. Coastal currents. In Annual report, 1977, pp. 53-62. Coastal Water Research Project, El Segundo, Calif.

Myers, E.P. 1974. The concentration and isotopic composition of carbon in marine sediments affected by a sewage discharge. Ph.D. dissertation, California Institute of Technology, Pasadena.

Pawka, S.S., D.L. Inman, R.L. Lowe, and L. Holmes. 1976. Wave climate at Torrey Pines Beach, California. Tech. Paper No. 76-5, U.S. Army Corps of Engineers, Coastal Engineering Research Center.

Young, D.R., D. KcDermott-Ehrlich, and T.C. Heesen, 1977. Sediments as sources of DDT and PCB. Mavi-ne Pollut. Bull. 8:254-7.

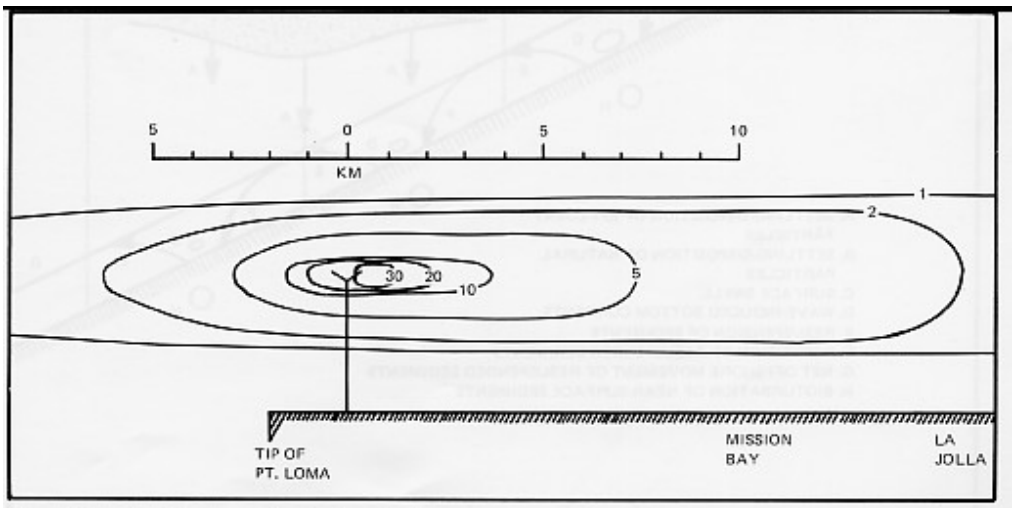

Figure 1. Annual sedimentation flux (mg/sq cm/yr) of effluent suspended solids along an idealized section of the San Diego coastline, given an annual suspended solids emission rate of 20,700 metric tons/yr. The actual line of symmetry for the deposition pattern will follow the 62-meter isobath.

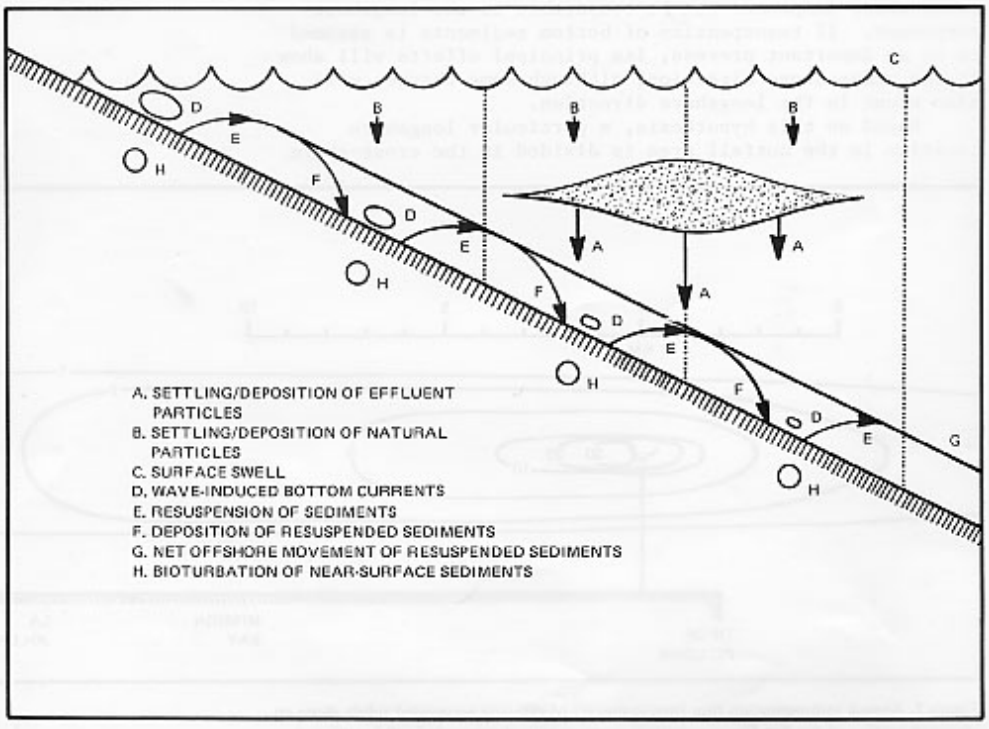

Figure 2. Conceptual approach to the predictive model.

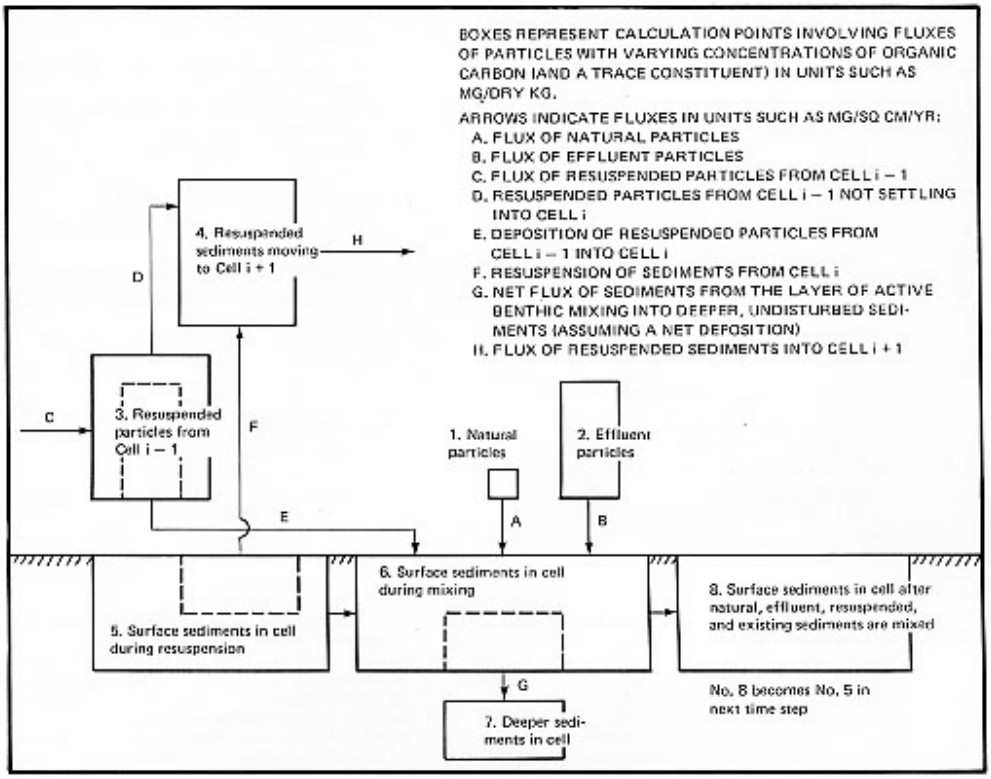

Figure 3. Processes within a cell considered in the model as affecting sediment concentrations of organic carbon (and a trace constituent, if desired).

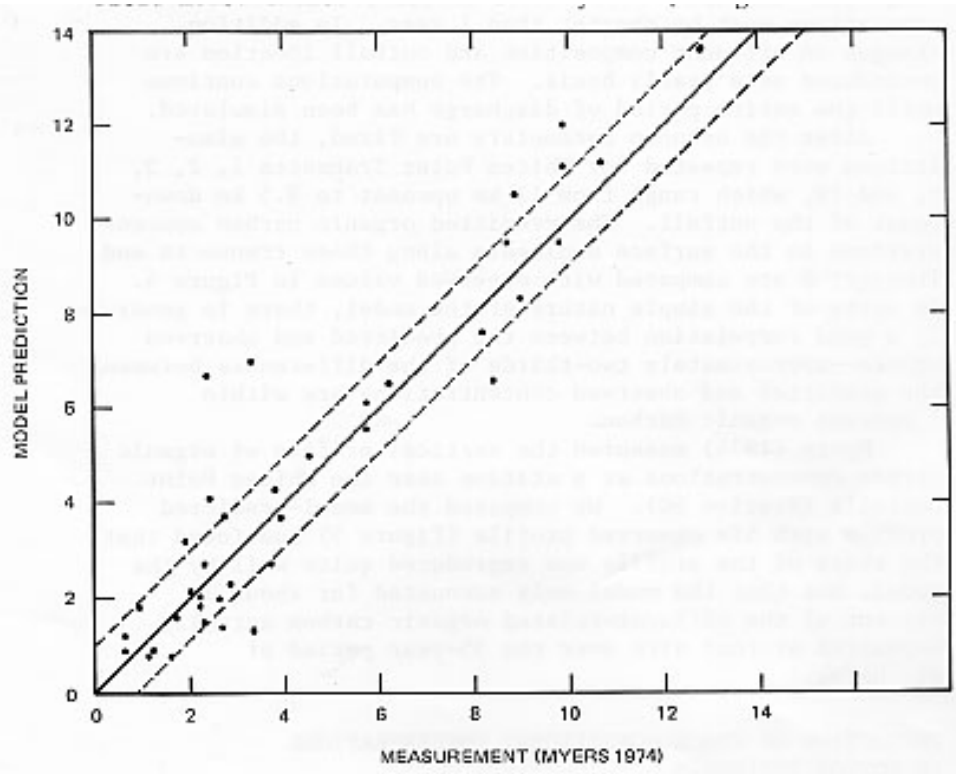

Figure 4. Comparison of predicted and measured percentages of organic carbon in surface sediments (upper 1 cm) at stations between 3.5 km downcoast and 11.5 km upcoast of the Whites Point outfalls. Each point indicates the predicted and measured values for a particular station; the dotted lines mark the boundaries of a deviation of ±1 percent.

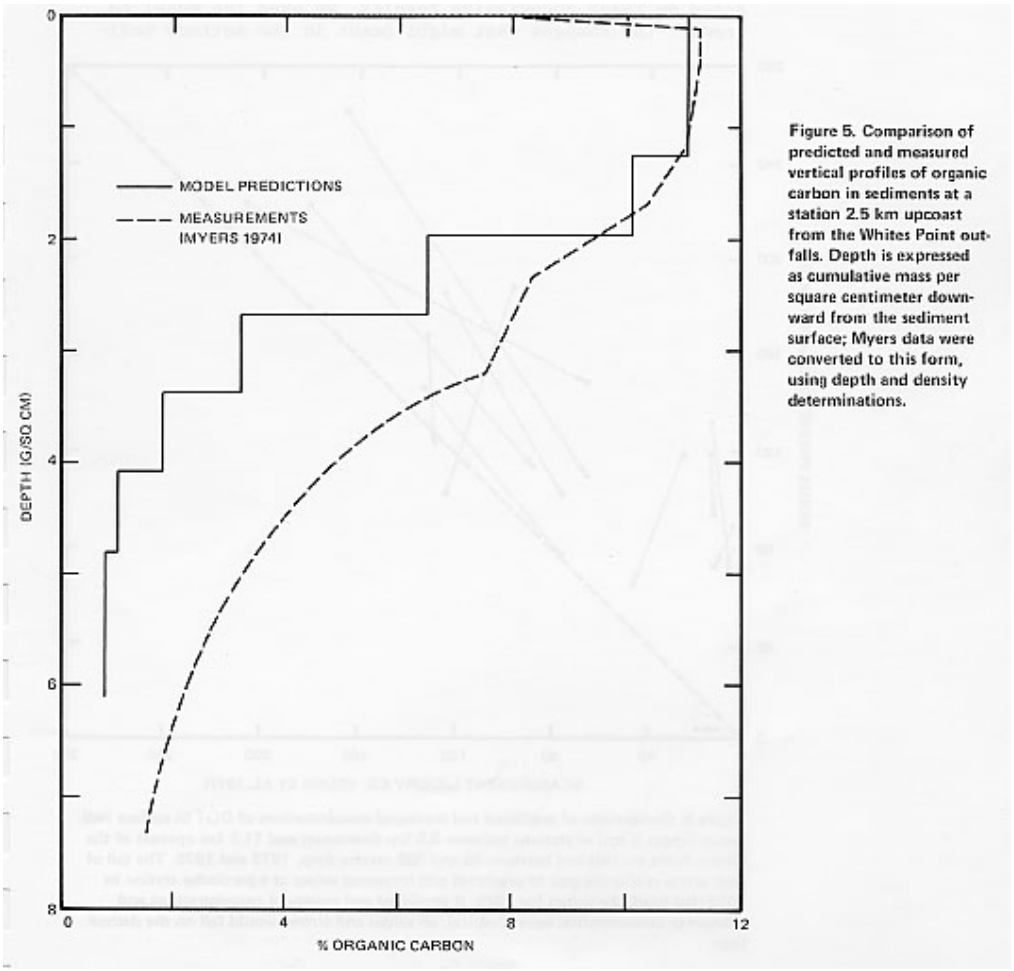

Figure 5. Comparison of predicted and measured vertical profiles of organic carbon in sediments at a station 2.5 km upcoast from the Whites Point outfalls. Depth is expressed as cumulative mass per square centimeter downward from the sediment surface; Myers data were converted to this form, using depth and density determinations.

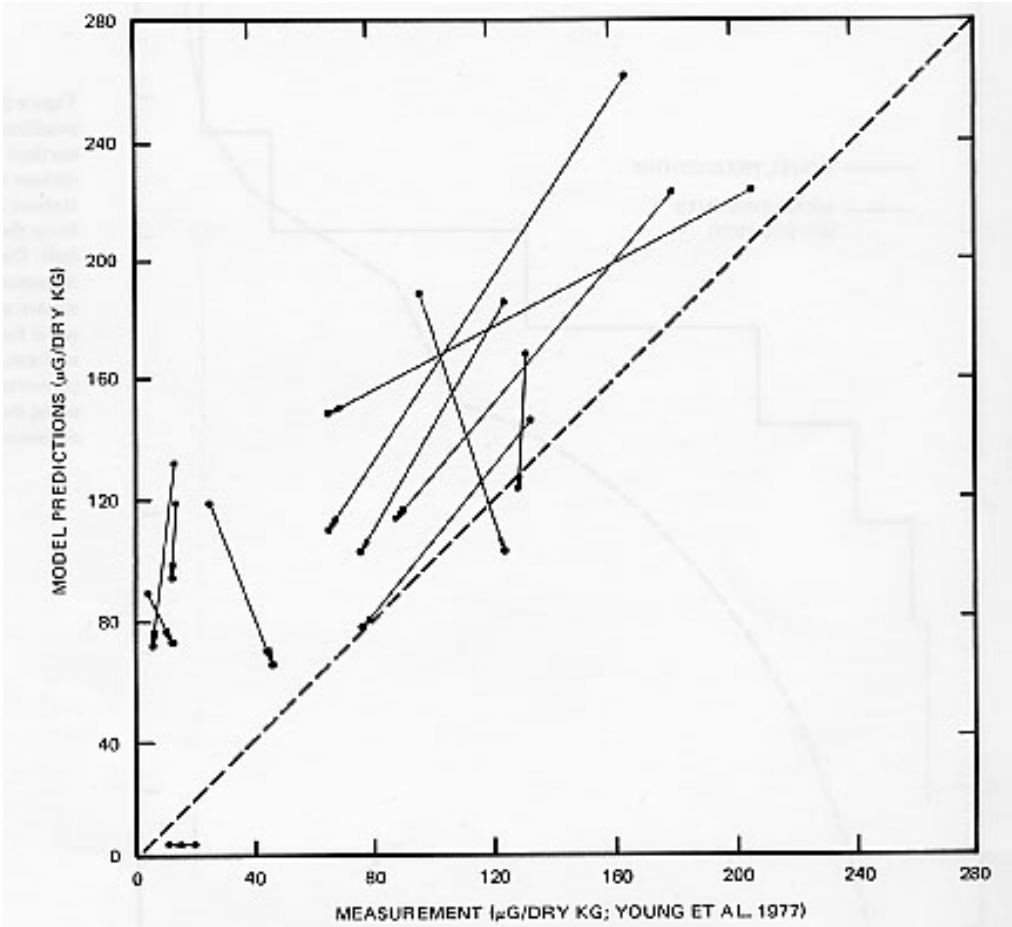

Figure 6. Comparison of predicted and measured concentrations of DDT in surface sediments (upper 5 cm) at stations between 3.5 km downcoast and 11.5 km upcoast of the Whites Point outfalls and between 30 and 300 meters deep, 1972 and 1975. The tail of each arrow marks the pair of predicted and measured values at a particular station in 1972; the head, the values for 1975. If predicted and measured concentrations and changes in concentration were identical, all values and arrows would fall on the dashed line.

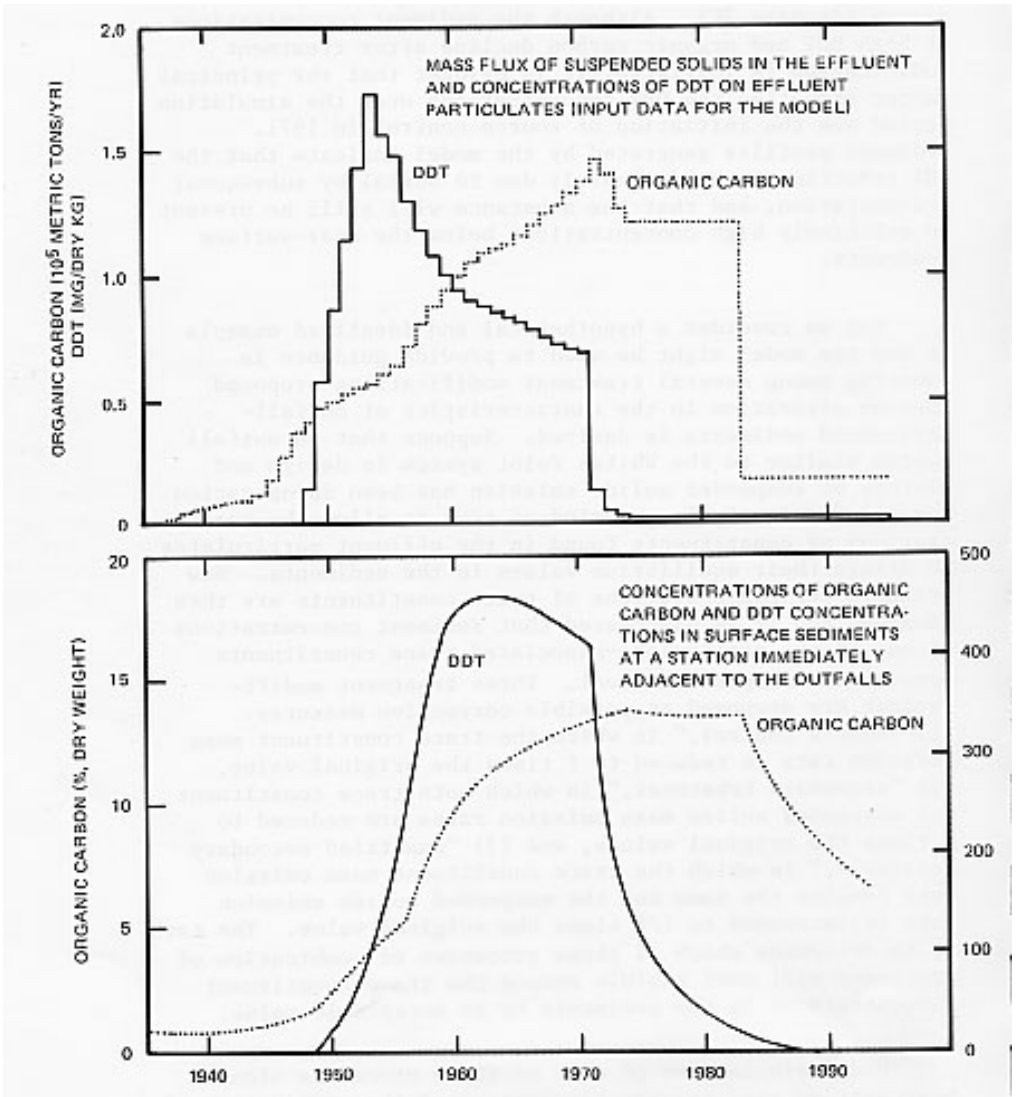

Figure 7. Prediction of the effect of altered effluent composition on the surface sediments in the Whites Point outfall area, 1935 to 1995. The break in the organic carbon concentration curve between 1956 and 1957 reflects the changeover from the short (shallow) outfall to the longer (90-inch) outfall.

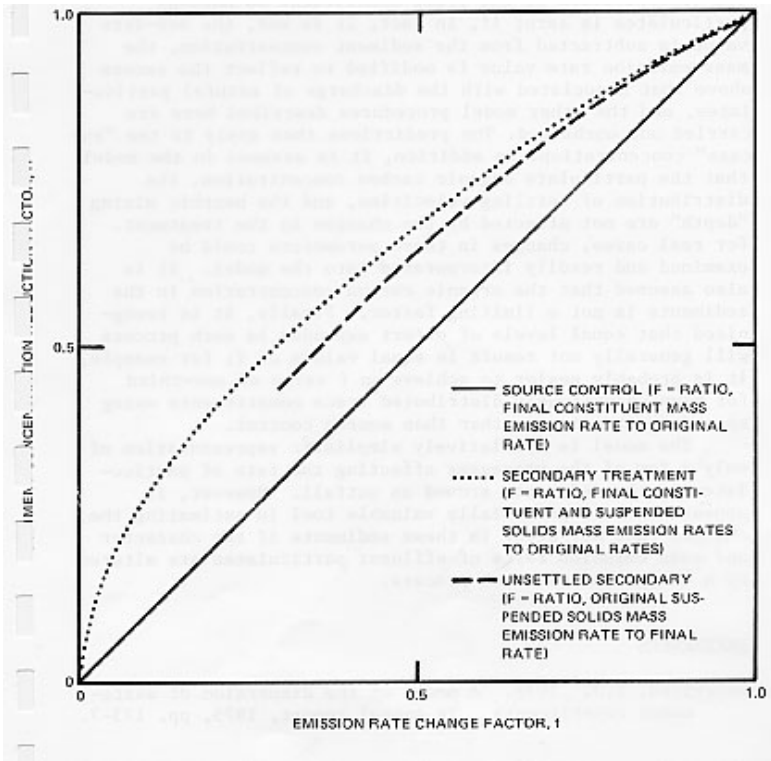

Figure 8. Change in sediment trace constituent concentration as a function of degree and type of treatment modification. A value of zero indicates complete absence of constituent or discharge; a value of 1 means no change in constituent concentration or discharge.

Table 1. Model equations.

DEPOSITION AND RESUSPENSION RATES

J_n = natural deposition rate of particulates
= 9 mg/sq cm/yr

J_i^e = effluent-related particulate deposition rate
$= g_i D$

D = longshore settling rate (mg/cm/yr) obtained from Phase 1 of the model

g_i = cross-shore distribution of settling of effluent particulates (obtained from fitting a normal distribution — 1/cm)

J_i^2 = annual rate of net resuspension in cell i of sediments from cell i
$= \gamma P_i(v_i^*)$

γ = resuspension constant (600 mg/sq cm/yr)

P_i = probability of bottom currents in cell i exceeding v_i^*

v_i^* = critical resuspension velocity for sediments in cell i
$= (22 \text{ cm/sec})/\sqrt{S_i}$

S_i = percent organic carbon concentration of surface sediment in cell i

J^1_{i+1} = flux of resuspended sediments moving from cell i to cell i + 1
$= J_i^2 + (1 - a)J^1_{i-1}$
$= \sum_{n=1}^{i-1} (1 - a)^{n-i} J^2_{i-n}$

a = fraction of resuspended material from inshore cell that settles in cell i

$J_i^{1'}$ = flux of resuspended material from cell i − 1 that settles into cell i
$= aJ_i^1$

CONCENTRATIONS

S_i^1 = concentration of surface sediments (i.e., those subject to bioturbation) after deposition and resuspension

$$= \frac{(S_n \cdot J_n + S_e \cdot J_i^e + S_i^+ aJ_i^1) \cdot \Delta T + S_i M_i}{(J_n + J_i^e + aJ_i^1) \cdot \Delta T + M_i}$$

S_e = effective concentration on effluent particle
$= fS_e^0$

S_e^0 = concentration on effluent particulates

f = decay (or mobilization) factor

S_n = natural particulate concentration

S_i = surface sediment concentration before deposition

ΔT = length of time step

M_i = mass in surface sediment cell before deposition

S_i^+ = concentration on resuspended particulates passed from cell i to cell i + 1

$$= \left[\sum_{n=1}^{i-1} (1 - a)^{n-1} S_{i-n} J_{i-n}^2\right] \Big/ J_i^1$$

MASS SUBJECT TO BIOTURBATION[a]

M_i = Mass in surface cell after resuspension
$= M_i^0 - J_i^2 \cdot \Delta T + \sigma_1 M_0$

M_i^0 = mass before resuspension

$\sigma_1 = 0$ if $M_0 \le M_i \le 2M_0$
$= 1$ if $M_i < M_0$ (see footnote b)

M_0 = reference mass
= 700 mg/sq cm
$= (2/3) \cdot M_0^*$

M_0^* = average bioturbation mass density (mg/sq cm)

M_i'' = mass in surface cell after deposition
$= (J_n + J_e + aJ_i^1) \cdot \Delta T + M_i - \sigma_2 M_0$

$\sigma_2 = 0$ if $M_0 \le M_i'' < 2M_0$
$= 1$ if $M_i'' > 2M_0$ (see footnote c)

$M_i^0 = M_i''$ (for next time step)

---

a. The sediment profile within each cross-shore cell is characterized by a set of "profile cells," with the upper cell (the "surface sediments") having a mass per square centimeter between M_0 and $2M_0$. All the deeper cells contain the mass density, M_0. The "racheting" nature of the computations is used to eliminate "pseudodiffusion" in the model during calculation of the erosion or deposition of sediments. This is achieved at the expense of introducing a small amount of transient inaccuracy in the concentration in the surface sediment cell. The latter error could readily be controlled, if necessary, by reducing the profile cell masses with bioturbation affectir several cells.

b. If $\sigma = 1$, the properties of each sediment profile cell are assigned to the cell above it. The concentration in the surface cell becomes $S_i = (S_i M_i^0 + S_b M_0)/(M_i^0 + M_0)$, where S_b is the previous concentration in the cell below the surface cell.

c. If $\sigma_2 = 1$, the properties of each sediment profile cell are assigned to the cell below it. The top two cells now have the same concentration.