

THE IMPORTANCE OF A BENTHIC ECOSYSTEM TO THE REMOVAL OF RADIOACTIVE TRACE ELEMENTS FROM COASTAL WATERS

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(Received 22 September 1988; in final form 23 November 1988)

ABSTRACT

From radiotracer experiments in model ecosystems (MERL tanks), it was established that the first order removal rate constants (λ_w 's) of various radiotracers in shallow coastal water columns are closely related to their distribution ratios between suspended particles and seawater (K_d), the particle flux through the system and to season. The seasonal change in the removal rate constants for the different radionuclides was mainly controlled by the benthic faunal activities, which was responsible for extent and changes of bioturbation and resuspension rates of bottom sediments.

INTRODUCTION

The distribution of a trace substance between the water and larger, filterable particles has been shown to depend, apart from thermodynamic equilibrium constants for all solution and surface site species, on the concentration of the particulate phase due to particle-particle interactions, colloids effects and diffusion limited reactions which lead to slow kinetics of the partitioning (for a review, see (1)).

The fractions of trace elements remaining in the water column as well as their distribution ratios as a function of time have been modeled using observable macroscopic parameters such as particle flux, particle concentration, kinetics of solid-liquid partitioning, transfer velocity for direct sediment uptake, sediment mixing rates in accordance with tracer penetration into sediments (2,3). The purpose of the present study was to investigate in detail how the benthic fauna and bottom sediments affect the removal of trace elements from the water column in different seasons, using the MERL model ecosystems of Narragansett Bay. As we know, the benthic activities are closely related to the macroscopic parameters mentioned above.

The details of the MERL mesocosm tank system are described by Pilson and coworkers (4,5). In short, each MERL tank is 5.5 m high and 1.8 m in diameter, holding 13 m³ of Narragansett Bay Water and about a 30 cm layer of relatively undisturbed surface sediments from the Bay (silty

clay with an intact benthic biological community) at the bottom. The porosity of bottom sediments changes from 0.92 at the surface and decreases linearly to 0.80 at a depth of 3 cm. The water is mixed by a mechanical plunger in a 2 hour on - 4 hour off cycle to mimic the turbulence and rates of sediment resuspension in the Bay. Seawater from the Bay is usually delivered into and out of the tank (through diaphragm pumps) such that the residence time of the water in the tank is similar to that in the Bay (~ 27 days). Alternatively, the tank can be run as a closed (batch) system. To facilitate mass balance, most of the radiotracer experiments were run in a batch mode, including the present work. As previously shown by (5), a batch experiment can continue for at least seven months without appreciable biological divergence from the Bay condition.

In order to test how the seasonal changes in particle flux and bioturbation rate in sediments affect the removal rate of radiotracers, two separate experiments were performed using in each one pair of MERL microcosm tanks. In one experiment, the removal of radiotracers from the MERL tanks with and without bottom sediments was monitored during the winter (January 17 - March 1983; the MERL tanks were designated by MR and MS, respectively) and summer season (June 7 - August 1983; MX and MZ, respectively). The objective was to elucidate the effects of bottom sediments (with normal benthic fauna activities) on the removal of radiotracers from the water column. However, since particles brought in from the Bay and produced in the water column were allowed to settle on the bottom of these "no sediment tanks" during the 1 and 4 weeks, respectively, before the experiments started, these tanks MS and MZ already did have some visible flocs on the bottom (a few millimeters depth) from the start. Therefore, tanks MS and MZ are called here the tanks with sediment veneer. The other experiment consisted of two MERL tanks with bottom sediments but having drastically different sediment resuspension rates during the winter season. The purpose was to study the effect of the sediment resuspension rate alone on the removal of radiotracers from the water column. The water temperature of both tanks was maintained at 4°C (winter condition). One tank (MO) had the normal winter sediment resuspension rate (0.1 - 0.5 mg cm⁻² day⁻¹), but the sediment resuspension rate of the other tank (MQ) was artificially increased to about 9mg cm⁻² day⁻¹ by increasing the stirring rate of the mechanical plunger. The particle flux through the water column was monitored every 1 - 2 days by sediment traps placed about 100 cm above the sediment-water interface.

RADIOTRACER METHODOLOGY

The details of the sampling procedures and the gamma-counting techniques were previously given (3,6,7,8 and references therein). In short, they consist of the following procedures:

The water columns of MERL tanks were spiked on April 15, 1982 (tanks MO, MQ), Jan. 17, 1983 (tanks MR, MS), and June 7, 1983 (tanks MX, MZ) with an acid-stabilized mixture of gamma-emitting radionuclides in ionic form. These isotopes included ²⁰³Ag (II), ¹¹³Sn (IV), ⁵⁹Fe (III), ⁵⁴Mn (II), ⁶⁰Co (II), ⁵¹Cr (III), ⁶⁵Zn (II), ⁹⁵Nb (III), ¹⁰⁹Cd (II) and ¹³⁴Cs (I) nuclides, and ¹⁴¹Ce as inert tracer microspheres (plastic particles of 15 μm diameter).

Samples of water, suspended particles, settling particles (in sediment traps one meter above the bottom), sediments, plankton, benthic fauna and wall material were collected and gamma-counted on a Ge(Li) detector, coupled to a 4096 channel analyzer and a computer. Activities were all normalized to the same geometry (using standards of the same nuclide) and decay-corrected to the beginning of the experiment (3,6,9). Removal rates of radiotracers from the water to the sediments were followed over time.

DESCRIPTION OF THE BENTHIC ECOSYSTEM

Sediments in the MERL tanks were collected from a site north of Conanicut Island on Narragansett Bay using a 0.25 m² box corer (10). They are composed of 18% sand, 60% silt and 23% clay (11).

According to Grassle and coworkers (12), the bioturbating macrofauna at this site and in the MERL Mesocosm are mainly composed of *Mediomastis ambisenta* (a deposit feeding polychaete worm) with an abundance of about 10³ m⁻², *Nucula annulata* (a deposit feeding bivalve) at

about $6 \times 10^3 \text{ m}^{-2}$ and *Ampelisca abdita* (an amphipod) at about $4 \times 10^3 \text{ m}^{-2}$. The meiofauna, which are responsible for some of the particle mixing in the sediments as well, are mainly composed of Nematoda, Herpactoida and Foraminifera (13).

RESULTS AND DISCUSSION

Fig. 1 summarizes for the first experiment the contrast in physical and biochemical parameters (temperature, fluorescence intensity, which is a measure of phytoplankton biomass, suspended particle concentration and the particle flux in sediment traps) for the MERL tanks with sediment column and veneer. The most important parameters appear to be temperature (Fig. 1a) and particle flux in sediment traps (Fig. 1d).

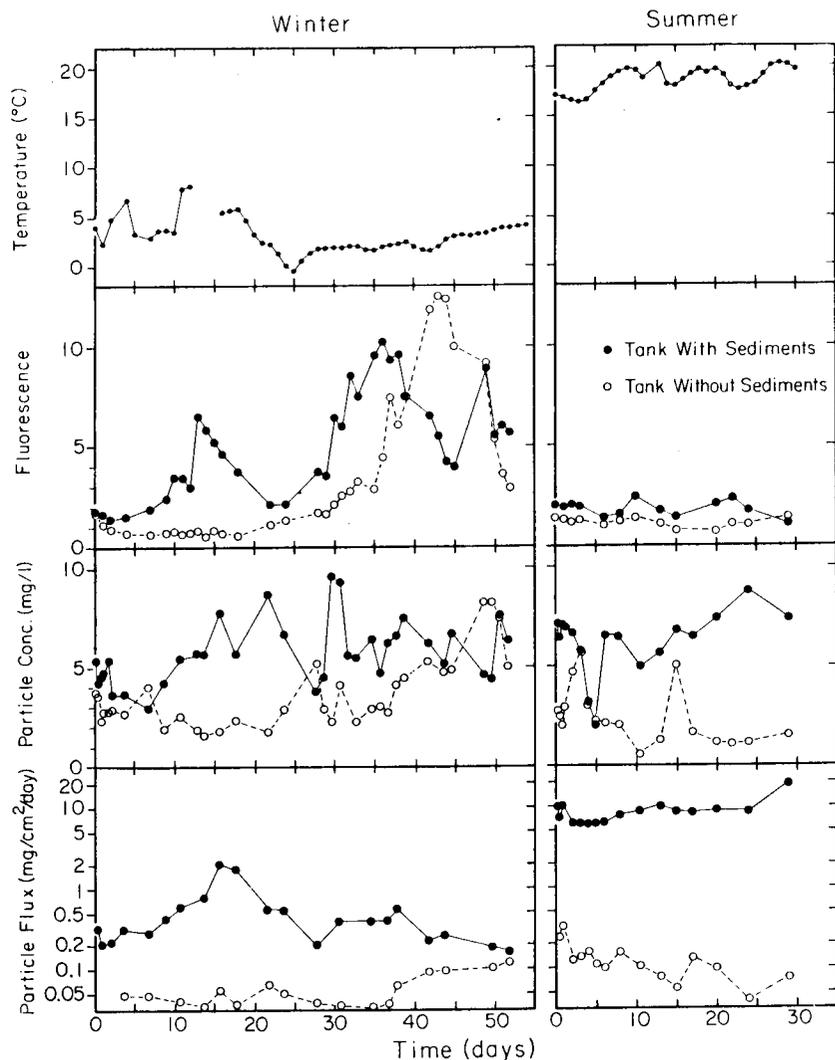


Fig. 1:
The plots of a) temperatures, b) fluorescence intensity (at 360 mu) in arbitrary units, c) suspended particle concentrations and d) the particle fluxes to sediment traps as a function of time (after the addition of radiotracer spikes) in the MERL tanks with and without (but with veneer) sediments.

As expected, the MERL tank with sediments veneer had a much lower particle flux than the tank with bottom sediment column, indicating that most of the particle flux in the latter originated from the resuspension of bottom sediment particles. The temperature and particle flux measured in sediment traps was considerably higher during the summer than the

winter. The high resuspension rate of bottom sediments in the tank with sediments during the summer months was enhanced by intensive benthic fauna activities such as direct ejection of fine particles by benthic fauna and/or reduction of shear stress of surface sediments by intensive bioturbation (14 and references therein). The high fluorescence intensity (at 360 mu) in the tanks during the winter (Fig. 1b) corresponded to high phytoplankton cell concentrations. The low fluorescence intensity during the summer indicates the active grazing of phytoplankton by zooplankton. Interestingly, the particle concentrations in the tanks did not change much with seasons.

The fraction of each radiotracer remaining in the water column decrease more or less exponentially with time as summarized in Fig. 2 (winter) and in Fig. 3 (summer),

i.e.
$$c/c_0 = e^{-\lambda_w t} \tag{1}$$

where C = the concentration of radiotracer (both dissolved and particulate forms) in the water column at time t .

$C_0 = C$ at time zero.

λ_w = removal rate constant (day^{-1})

The radiotracers removed from the water mostly resided in the bottom sediments except that just a few percent of Mn and Co were adsorbed onto the walls of tanks at the end of each experiment.

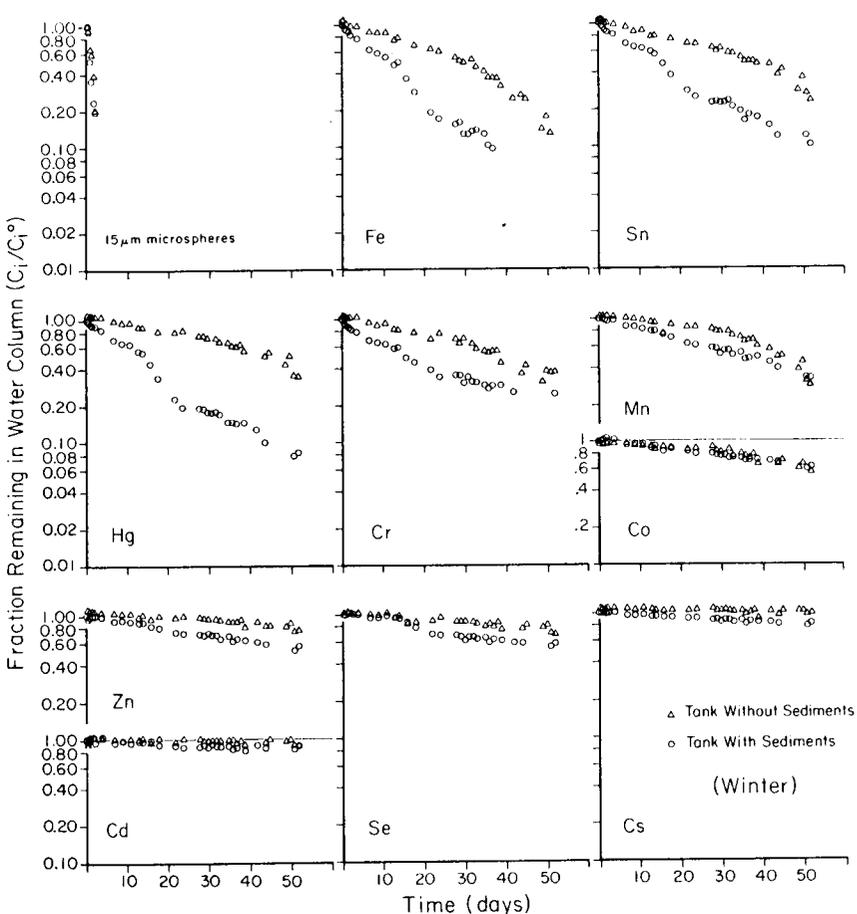


Fig. 2: The plots of the concentrations of various radiotracers (C_i) relative to their initial concentrations (C_0) in the MERL tanks with (MR) and without (but with veneer) sediment columns (MS) as a function of time during the winter season.

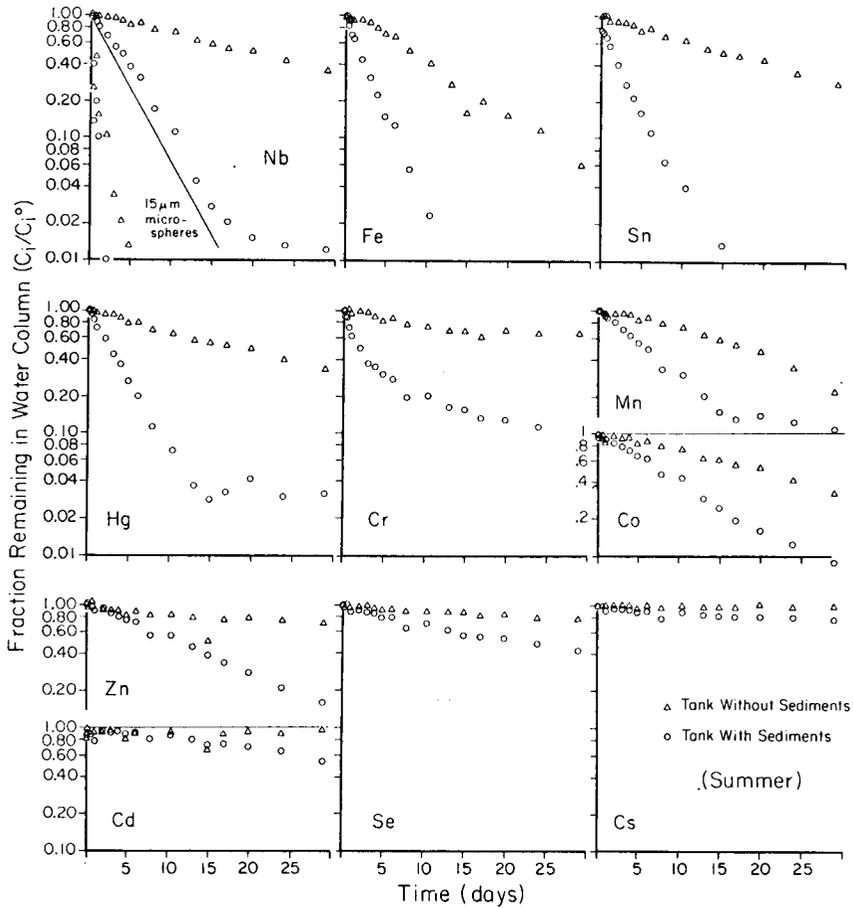


Fig. 3: The same plots as in Figure 2 but for the summer season.

The half removal times (t_w = the time span for radiotracer activity in the water column to be reduced exponentially to one half of the original activity = $0.693/\lambda_w$) of radiotracers was estimated from the slopes of straight line segments in Figures 2 and 3 are summarized in Table 1.

For individual radiotracers, the half removal time (t_w) is much shorter in the tanks with a sediment column than with sediment veneer, and in summer than in winter, corresponding to the overall change in the particle fluxes as measured by the sediment traps (Fig. 1d).

The activities of radiotracers on the suspended particles from the water column and on the deposited materials in sediment traps were also measured. Therefore, the partition or distribution ratios of radiotracers (K_d = activity of filtered particles per gram (dry) or sediment trap materials activity per cm^3 of filtered solution = X_p/C_1) were calculated and are shown in Fig. 4 (winter) and in Fig. 5 (summer) as a function of time.

Table 1. Half removal time (t_w in days) of radiotracers from the water column of MERL tanks during winter and summer seasons.

Isotope	Winter		Summer	
	with sediment column (MR)	with sediment veneer (MS)	with sediment column (MX)	with sediment veneer (MZ)
Micro-sphere	0.75	1.1	0.24	0.62
$^{59}\text{Fe(III)}$	11.0	28.5	1.8	10.1
$^{113}\text{Sn(IV)}$	14.1	37.5	1.9	15.9
$^{203}\text{Hg(II)}$	12.2	51.4	2.5	15.8
$^{51}\text{Cr(III)}$	19.7	45.1	2.5	20.3
$^{54}\text{Mn(II)}$	34.4	58.7	5.7	31.4
$^{60}\text{Co(II)}$	69.5	127	9.6	31.8
$^{65}\text{Zn(II)}$	59.3	151	11.8	60.7
$^{109}\text{Cd(II)}$	170	360	27	326
$^{75}\text{Se(IV)}$	48	93	17.6	39.1
$^{134}\text{Cs(I)}$	157	2000	43.6	519
$^{95}\text{Nb(III)}$	--	--	3.5	20.2

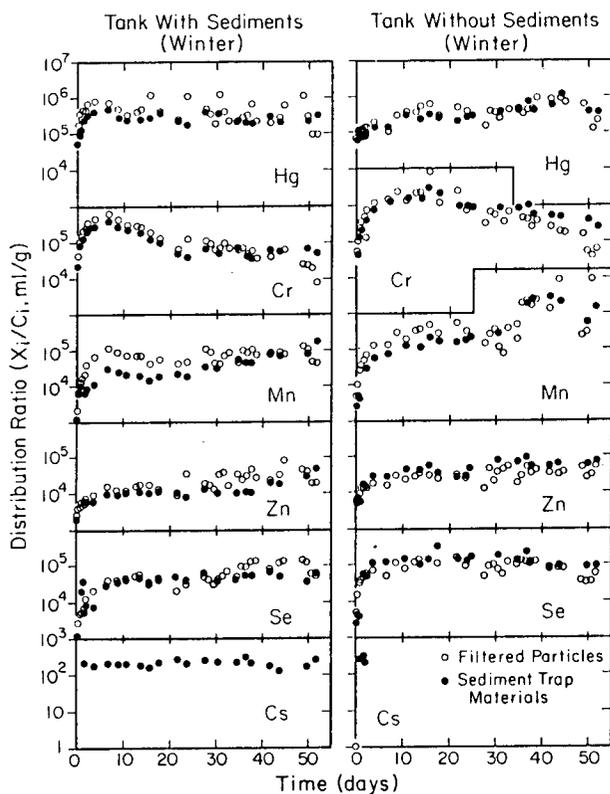


Fig. 4: The distribution ratios of various radiotracers between filtered water and sediment trap materials or filtered particles in the MERL tanks with (MR) and without (but with veneer) sediments (MS) as a function of time during the winter season.

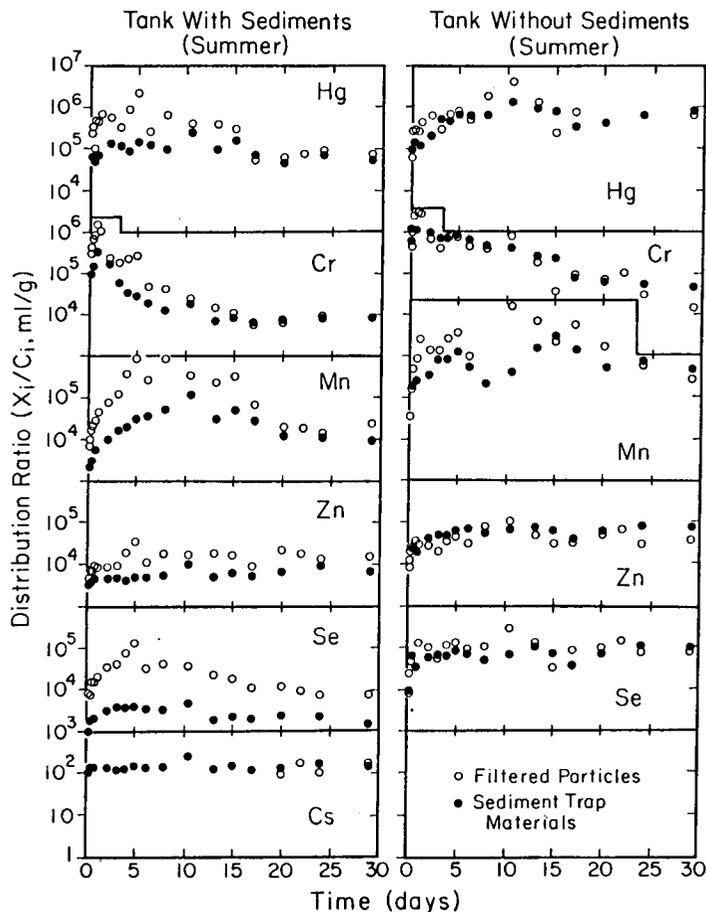


Fig. 5: The distribution ratios in the MERL tanks with (MX) and without (but with veneer) sediments (MZ) during the summer season

In general, the K_d 's obtained for the filtered particles and for the sediment trap materials in tanks with sediment veneer are the same within the experimental uncertainty indicating a same source for these two materials (mostly organic particles with some inorganic fine particles). For tanks with sediment column, the K_d 's obtained for the filtered particles tend to be initially higher than those for the sediment trap materials, resulting either from the fact that the former contain more of fine organic particles than the latter, or from removal rate control by coagulation kinetics (2), leading to higher K_d values for the fine particulate matter with longer residence times.

During the winter, the K_d 's for ^{203}Hg (as well as ^{113}Sn and ^{59}Fe , not shown in Fig. 4), ^{65}Zn (as well as ^{109}Cd) and ^{75}Se increased with time and reached fairly constant values within 5 to 10 days, indicating the attainment of kinetic equilibria after that time. The K_d for ^{51}Cr increased initially, then decreased with time, indicating the oxidation of the less soluble Cr(III) to the more soluble Cr(IV) (8). The K_d for ^{54}Mn (as well as ^{60}Co , not shown) increased with time, indicating gradual oxidation of soluble Mn(II) to less soluble Mn(IV). The K_d for ^{134}Cs reached a constant value within a day's time. The summer experiments also gave similar results, except that the decrease of K_d for ^{51}Cr with time was much more drastic, and the K_d for ^{54}Mn increased with time initially then decreased again for the tank with sediment column, probably indicating partial reduction of Mn(IV) back to Mn(II) in the sediments and subsequent release to the water (8,3). Except for redox sensitive trace metals like ^{54}Mn , ^{60}Co (not shown, but similar to ^{54}Mn) and ^{51}Cr , the K_d 's for the other radiotracers

remained at quite constant values over more than 30 days (except for the first few days) which is surprising for a dynamic system such as the MERL tanks.

The data in Figure 2 to Figure 5 can be fitted by the numerical model of Nyffeler et al. (2). Their model takes into account measured rates of the slow uptake (adsorption + coagulation) - release (desorption + disaggregation) kinetics, sediment resuspension, in situ particle production in the water column, bioturbation of sediments, etc. For example, Fig. 6 gives good model fits (solid lines) to the observed concentrations and K_d 's as a function of time for ^{113}Sn from the first experiments. ^{113}Sn was chosen here as an example of an easily hydrolysable cation which has a high K_d -value. The model calculations, which used the observed time-dependent particle concentration (C_p) and particle flux (S_{in}) as input parameters as shown in Fig. 1, serve to illustrate the importance of sorption kinetics in the scavenging process.

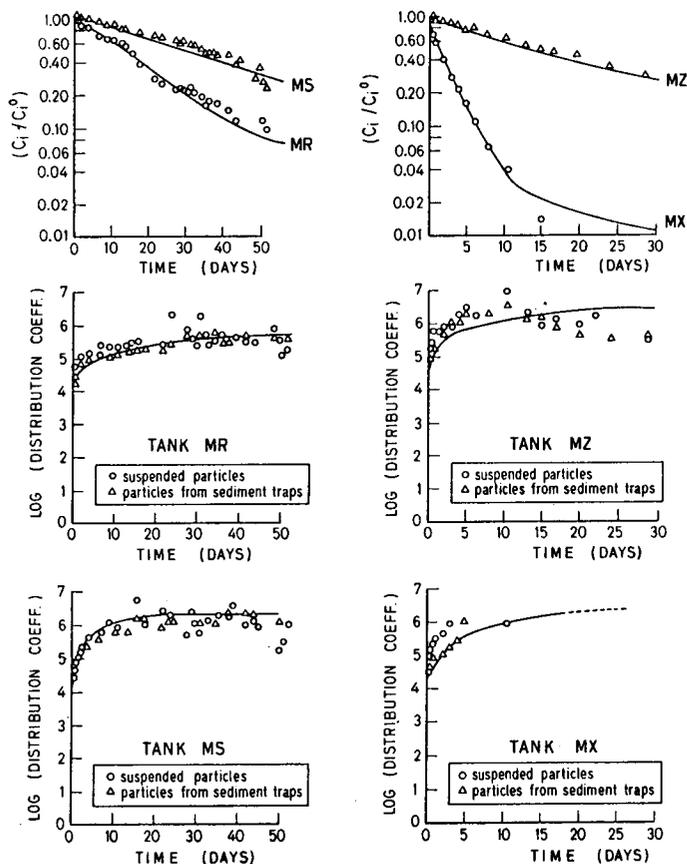


Fig. 6: The fits of the numerical kinetic transport model for model ecosystems (2) to the concentration and distribution ratio data as a function of time for ^{113}Sn in the MERL tanks with (MR, MX) and without (but with veneer) sediment columns (MS, MZ) during winter and summer seasons, respectively.

The in situ particle production rates were assumed to be around $0.04 \text{ mg cm}^{-2} \text{ day}^{-1}$ in all cases, similar to measured values of primary production. The bioturbation rates for tanks with sediment columns were taken to be $3 \times 10^{-8} \text{ cm}^2 \text{ sec}^{-1}$ in winter and $5 \times 10^{-7} \text{ cm}^2 \text{ sec}^{-1}$ in summer (3,9). The kinetic constants for adsorption (k_1) and desorption (k_{-1}) taken were $10^5 \text{ cm}^3 \text{ g}^{-1} \text{ day}^{-1}$ and 0.05 day^{-1} , respectively, (i.e., $k_1 k_{-1}^{-1} = 2 \times 10^6 \text{ cm}^3 \text{ g}^{-1}$) in all cases except for the tank MR of the winter experiment, where somewhat lower values for $k_1 (= 2 \times 10^4 \text{ cm}^3 \text{ g}^{-1} \text{ day}^{-1})$ and $k_{-1} (= 0.01 \text{ day}^{-1})$ but the same $k_1 k_{-1}^{-1}$ were used. These values are within the range of experimental values (2,15). They all yield lower effective $K_d(t)$ -values during the early part of the experiment than the equilibrium values given in Table 2, in agreement with the experimental values (Fig. 6). Since the errors in some of the input parameters were

sufficiently great (i.e. up to +/- factor of two), no rigorous attempt was made to optimize for best fits to the data. Different ideal combinations of parameters can result in similar model curves (2).

Finally, the most interesting observation is that the K_d 's of radiotracers in each tank are inversely correlated to t_w 's of radiotracers as summarized in Fig. 7 (K_d 's are taken from Table 2 at 15 days after spike additions, and t_w 's from Table 1. ^{51}Cr data are not plotted in Fig. 7 because K_d for Cr was affected by the oxidation of Cr (III) to Cr (VI) as mentioned earlier).

Table 2. Distribution Ratios (K_d in $\text{cm}^3 \text{g}^{-1}$) of radiotracers between sediment trap materials and tank waters 15 days after spike additions.

Isotope	Winter		Summer	
	with sediment (MR)	without sediment (MS)	with sediment (MX)	without sediment (MZ)
^{59}Fe	1.7E6*	1.0E7	--	1.0E7
^{113}Sn	5.0E5	1.5E6	--	1.7E6
^{203}Hg	3.3E5	4.0E5	1.6E5	8.0E5
^{51}Cr	1.0E5	2.5E6	8.0E3	2.3E5
^{54}Mn	3.2E4	2.7E5	5.1E4	1.0E6
^{60}Co	4.6E3	3.7E4	7.9E3	2.4E5
^{65}Zn	1.0E4	5.0E4	6.3E3	6.0E4
^{109}Cd	7.3E2	9.0E3	1.3E3	--
^{75}Se	4.6E4	1.0E5	2.2E3	1.0E5
^{134}Cs	2.3E2	(2.3E2)	1.5E2	(1.5E2)
^{95}Nb	--	--	1.8E5	2.0E5

* $E_x = 10^x$

We can visualize that the change of the total activity of a radiotracer in the water column with unit area in the MERL tank is controlled by :

1) adsorption of radiotracer onto suspended particles followed by gravitational settling, 2) resuspension of settled particles which have been diluted with underlying uncontaminated sediments by bioturbation and for physical mixing, and 3) adsorption at water-sediment interface through diffusional processes. Quantitatively

$$H \frac{dC}{dt} = - S_{in} \cdot X_p + S_{out} \cdot X_{m^0} - D(X_p - X_{m^0}) / (\Delta z \cdot K_d) \quad (2)$$

where

H = height of the water column in the MERL tank - 500 cm

S_{in} = particle flux through the water column as measured by sediment trap.
($\text{g cm}^{-2} \text{day}^{-1}$)

S_{out} = resuspension rate of bottom sediments $\sim S_{in}$

X_p = the concentration of a radiotracer in sediment trap materials or suspended particles (dpm g^{-1})

X_{m^0} = The concentration of a radiotracer in bottom sediments at the water - sediment interface (dpm g^{-1})

D = molecular diffusion coefficient (cm² day⁻¹)

Δz = stagnant boundary film or diffusive sublayer, thickness (cm)

K_d = distribution ratio = X_p/C_l = X_p/[C - X_pC_p]

C_p = the concentration of suspended particles (g cm⁻³)

(X_p - X_m⁰)/(K_d · Δz) = the concentration gradient across the stagnant boundary layer.

In addition one obtains by mass balance :

$$HC^0 = HC + h(1 - \phi) \cdot \rho \cdot X_m^0 \quad (3)$$

where

C⁰, C = total concentration of radiotracer (dpm cm⁻³ solution) in water column at time zero and time t, respectively

C_l = concentration of tracer in dissolved form at time t

h = the hypothetical mean penetration depth of a radiotracer in the sediments (at time t), defined as equal to $\int_0^\infty X_m \Delta z / X_m^0$

ρ = solid phase density (~2.5 g cm⁻³)

φ = porosity (~0.9 cm³ water (cm³ wet sediments)⁻¹)

X_m = the concentration of radiotracer in the bottom sediments at a depth of z (dpm g⁻¹)

Solving equations 1 to 3, one obtains

$$K_d/(1 + K_d \cdot C_p) = (e^{\lambda_w t} - 1)H/[(1 - \phi) \cdot \rho \cdot h] + \lambda_w \cdot H/[S_{in} + D/(K_d \cdot \Delta z)] \quad (4)$$

The above equation (4) is applicable only in the period when the concentration of any considered radiotracer in the water column decreases exponentially. In this example, the time t in equation (4) cannot be greater than 15 days for Fe, Sn, Nb and Hg in summer tanks with sediment columns.

If $D/(K_d \cdot \Delta z) < S_{in}$ or $K_d > D/(S_{in} \cdot \Delta z)$, then the $D/(K_d \cdot \Delta z)$ term in equation (4) can be ignored, i.e. the removal rate of a radiotracer at the water-sediment interface will be relatively small as compared to the removal rate by settling particles.

Therefore, according to equation (4) without the $D/(K_d \cdot \Delta z)$ term, K_d's should be roughly proportional to λ_w's or inversely related to t_w's, when other physical parameters (C_p, S_{in}, H, φ, ρ, t and h) are constant in the same tank. For example, the D's for most of divalent and trivalent cations are in the order of ~0.5 cm²/day (15); Δz in the MERL tank is in order of 0.1 cm (16); and S_{in} for the tank MS (with sediment veneer) is about 5 x 10⁻⁵ g/cm²/d; thus the D/(S_{in} · Δz) term is about 10⁵ cm³/g for the tank MS. Except for Cd and Cs, the K_d's for most of radiotracers are about 10⁵ cm³/g or greater in the tank MS. Therefore, the removal of these radiotracers (excluding Cd and Cs) from the water column is mainly by the settling particle flux. Similarly, the D/(S_{in} · Δz) term is about 0.5 x 10³ cm³/g for tank MX (with sediment column in summer). Therefore, except Cs and Cd, the rest of radiotracers (K_d's > 10³ cm³/g) were again removed mainly by the flux of settling particles in the tank MX. The solid curves in Fig. 7. represent a relationship between K_d (at t = 15 days) and t_w using a modified equation similar to equation (4) but excluding the term for direct sediment uptake, therefore valid only for particle-reactive elements. The values taken for various parameters are given in the same figure. The C_p and S_{in} values at t = 15 days were read off for Fig. 1, and h-values at t = 15 days were calculated from the modified equation (4), using mainly K_d and t_w data for

^{59}Fe . The radiotracers Cs, Cd and sometimes Co and Zn (low K_d 's) are not expected to fall on the theoretical curves for ^{59}Fe as shown in Fig. 7, because the removal of these radiotracers were dominated by the uptake at the water-sediment interface through diffusional, and/or advective processes. Thus their mean penetration depth in sediments (h) should be much higher than those for ^{59}Fe and other particle reactive radiotracers (i.e. those with high K_d values).

For example, the values for h , calculated from modified equation (4) for Cs at $t = 15$ days are about 3.1 cm (assuming porosity $\phi = 0.8$) in summer and about 0.76 cm in winter for the tank with sediment column. The high h value (3.1 cm) during the summer may indicate active advective exchange of pore water by benthic macrofauna at the water-sediment interface.

During the summer, the Mn data points fall to the right of the theoretical curves in Fig. 7, indicating slower removal than expected from its K_d value measured in the water column. One possible explanation is that actual K_d 's for Mn in the bottom sediments should be lower than those in the water column due to the partial reduction of Mn (IV) to Mn (II) in the sediments (3).

The relationship between half removal times and K_d values depicted in Fig. 7, for these ecosystems with close benthic pelagic coupling is quite impressive and extends over different seasons and extent of benthic-pelagic coupling (i.e., tanks with sediment column or only vencers).

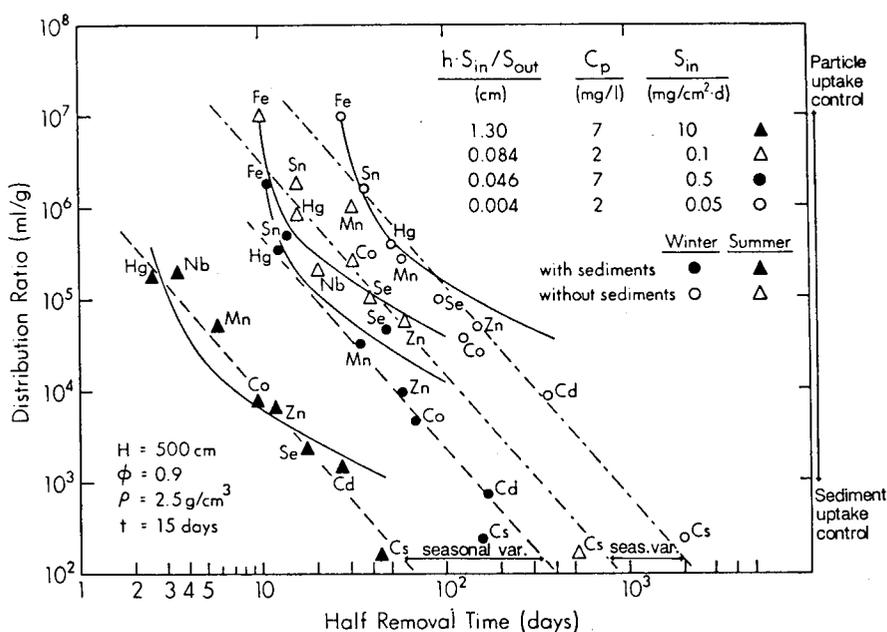


Fig. 7: The plot of the half removal times and the distribution ratio (K_d) at time ~ 15 days for various radiotracers in the MERL tanks with (MR, MX) sediment column and vincer (MS, MZ) during winter and summer seasons, respectively. The solid curve represents the equation (4) without the term for direct sediment uptake (using the parameters in the upper-right hand corner), thus applying only to particle-reactive elements. Dashed curves are drawn in as correlation lines only.

The effective slope of the various log K_d vs log t_w correlation lines is, however, not -1 as would be expected from the modified equation (4) for the region with only particle uptake control, but about -3.5, probably due to a combination of non-linear effects which were not considered in the derivation of equation 4. These might have been caused by

- 1) slow sorption kinetics, affecting mostly high- K_d elements (2,17),

- 2) direct sediment uptake by diffusion, affecting mostly low K_d elements (2,16),
- 3) direct sediment uptake by advection (18), equally affecting all dissolved elements which adsorb in sediments,
- 4) differences between K_d values of suspended particles and surface sediments, affecting mostly elements with intermediate K_d values (e.g., Mn, as described above, see ref. 3).

In short, the half removal times of radiotracers in a MERL tank water column become inversely related to their distribution ratios by the coupling of a number of mechanisms: uptake by particles, resuspension and mixing of bottom sediments, active pore-water exchange by benthic macrofauna in the summer and predominantly diffusive exchange across the sediment water interface in the winter (2, 3, 9). Furthermore, it is interesting to notice that the mean residence times of elements in the ocean as a whole are by definition also inversely related to their average concentrations in oceanic pelagic clays divided by those in seawater (19). For an individual radiotracer, the seasonal change in its half removal time in the tank with sediments is mainly controlled by benthic fauna activity, which enhances the removal of a radiotracer during the summer season by facilitating resuspension of bottom sediments by a factor of 20 and enhancing the mixing rate and the mean penetration depth (h) of settled particles with underlying uncontaminated sediment particles by a factor of about 28 (Table in Fig. 7).

Table 3. Half removal times (t_w in days) of radiotracers from the water column of the MERL tanks with normal (MO) and high (MQ) sediment resuspension rates.

	^{59}Fe	^{113}Sn	^{203}Hg	^{51}Cr	^{54}Mn
MO	4.4	5.0	5.4	8.5	11
MQ	4.0	3.6	5.0	4.5	15

	^{60}Co	^{65}Zn	^{109}Cd	^{75}Se	^{134}Cs
MO	26	38	130	170	130
MQ	35	27	--	--	110

The importance of benthic fauna activity, especially the bottom sediment mixing, on the removal of radiotracers from the water column is reinforced by the results from the second spring experiment, which was carried out under conditions of low bioturbation conditions. The half removal times of various radiotracers from the MERL tanks with different sediment resuspension rates are summarized in Table 3. Other results from this experiment are discussed elsewhere (3). The interesting observation is that t_w 's-value for radiotracers in the two tanks during winter-spring conditions are very similar (they differ by no more than 40%) even though the sediment resuspension rates differ by more than one order of magnitude. Obviously, an increase in sediment resuspension rate alone without a corresponding increase in the sediment mixing rate by bioturbation does not significantly enhance the removal of radiotracers from the water column and their accumulation into sediments. The importance of bioturbation rate on the accumulation of ^{234}Th and $^{239,240}\text{Pu}$ in near shore sediments was previously demonstrated (20,21,22).

CONCLUSIONS

The half removal times, t_w , of different radiotracers from the water columns of MERL tanks with bottom sediments are inversely related to their distribution ratios, K_d 's, between settling particles and solution. The high removal rates of the radiotracers in the tanks with bottom sediments during the summer season resulted from the high benthic faunal activities which enhanced 1) the particle fluxes through the water column by resuspension of bottom sediments and 2) the mixing rates and thus the penetration depths of the settled particles with underlying uncontaminated sediments. Artificially increasing sediment resuspension rates alone does not greatly increase removal rates of radiotracers.

ACKNOWLEDGEMENTS

We thank the staff of MERL for its steady cooperation and help, especially C. Oviatt, C. Hunt and J. Frithsen, and B. Schwertfeger (EAWAG) for typing the manuscript. The work reported here was supported by grants to Lamont-Doherty Geological Observatory of Columbia University, by the U.S. National Science Foundation (Grant OCE 81-11953) and National Oceanographic and Atmospheric Administration (Grant NARAD 00016) and the Environmental Protection Agency (#806072020). The paper was finalized while Yuan-Hui Li was at University of Hawaii and Peter H. Santschi at the Swiss Inst. for Water Resources and Water Pollution Control (EAWAG), 8600 Dübendorf, Switzerland.

REFERENCES

1. Honeyman, B.D., and P.H. Santschi. 1988. Critical review: Metals in aquatic systems. Predicting their scavenging residence times from laboratory data remains a challenge. *Environ. Sci. Technol.*, 22, 862-871.
2. Nyffeler, U.P., P.H. Santschi and Y.H. Li. 1986. The relevance of sorption kinetics to modelling of sediment-water interactions in natural waters. *Limnol. Oceanogr.* 31, 277-292
3. Santschi, P.H., P. O'Hara, M. Amdurer, D. Adler, Y.H. Li, and P. Doering. 1987. Relative mobility of radioactive trace elements across the sediment-water interface of the MERL model ecosystem of Narragansett Bay. *J. Mar. Res.* 45, 1007-1048.
4. Pilson, M.E., C.A. Oviatt, G.A. Vargo and S.L. Vargo. 1979. Replicability of MERL microcosms Initial observation. In "Advances in Marine Environmental Research." F.S. Jadoff (ed.), Proc. of a Symposium, June 1977, U.S. EPA.
5. Pilson, M.E., C.A. Oviatt and S.W. Nixon. 1980. Annual nutrient cycles in a marine microcosm. In "Microcosms in Ecological Research" , J.P. Giesy (ed.), DOE Symposium Series, Augusta, GA., Nov. 8-10, CONF 781101, NTIS, 753-778.
6. Santschi, P.H., D. Adler and M. Amdurer. 1983. The fate of particles and particle-reactive trace metals in sea water. In "Trace Metals in Sea Water", C.S. Wong, E. Boyle, K. Bruland, J.D. Burton and E.D. Goldberg (eds), Plenum Press, 537-562.
7. Adler, M. 1981. Tracer studies in marine microcosms: Transport processes near the sediment-water interface. Ph. D. thesis, Columbia University, N.Y., 346pp.
8. Amdurer, M. 1983. Chemical speciation and cycling of trace elements in estuaries: Radiotracer studies in marine microcosms. Ph. D. thesis, Columbia University, New York, 477 pp.
9. Santschi, P.H., Y.H. Li, D.M. Adler, M. Amdurer, J. Bell and U.P. Nyffeler. 1983. The relative mobility of natural (Th, Pb and Po) and fallout (Pu, Am, Cs) radionuclides in the coastal marine environment: results from model ecosystems (MERL) and Narragansett Bay. *Geochim. Cosmochim. Acta* 47, 201-210.
10. Hunt, C.D., and D.L. Smith. 1983. Remobilization of metals from polluted marine sediments. *Can. J. Fish. Aquat. Science* 40, suppl. 2, 132-142.
11. Oviatt, C.A., E.Q. Pilson, S.W. Nixon, J.B. Frithsen, D.T. Rudnick, J.R. Kelleg, J.F. Grassle, and J.P. Grassle. 1984. Recovery of a polluted estuarine system: a mesocosm experiment. *Mar. Ecol. Progr. Ser.* 16, 203-217.

12. Grassle, J.F., J.P. Grassle, L.S. Brown-Leger, R.F. Petreccal, and N.J. Copley. 1985. Subtidal macro-benthos of Narragansett Bay. Field and mesocosm studies of the effects of eutrophication and organic input on benthic populations. In: Gray, J.S. and Christiansen, M.E., (eds.), *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms*. John Wiley and Sons, Ltd, pp. 421-433.
13. Rudnick, D.T., R. Elengren, and J.B. Frithsen. 1985. Meiofaunal prominence and benthic seasonality in a coastal marine ecosystem. *Oecologia (Berlin)* 67, 157-168.
14. Rhoads, D.C., and L.F. Boyer. 1982. The effects of marine benthos on physical properties of sediments: a successional perspective in "Animal-sediment Relations". P.L. McCall, and M.S. Tevesz (eds.), Chapter 1, 3-43.
15. Li, Y.-H., and S. Gregory. 1974. Diffusion of ions in sea water and in deep-sea sediments. *Geochim. Cosmochim. Acta* 38, 703-714.
16. Santschi, P.H., P. Bower, U.P. Nyffeler, A. Azevedo and W.S. Broecker. 1983. Estimates of the resistance to chemical transport posed by the deep-sea boundary layer. *Limnol. Oceanogr.* 28, 899-912.
17. Nyffeler, U.P., P.H. Santschi, and Y.H. Li. 1984. A kinetic approach to describe trace element distribution between particles and solution in natural aquatic systems. *Geochim. Cosmochim. Acta* 48, 1513-1522.
18. McCaffrey, R.J., A.C. Myers, E. Davey, G. Morrison, M. Bender, N. Luedtke, D. Cullen, P. Froelich and G. Klinkhammer. 1980. The relation between pore water chemistry and benthic fluxes of nutrients and manganese in Narragansett Bay, Rhode Island. *Limnol. Oceanogr.* 25, 31-44.
19. Li, Y.H. 1982. A brief discussion on the mean oceanic residence time of elements. *Geochim. Cosmochim. Acta* 46, 2671-2675.
20. Aller, R.C., L.K. Benninger and J.K. Cochran. 1980. Tracking particle associated processes in nearshore environments by use of $^{234}\text{Th}/^{238}\text{U}$ disequilibrium. *Earth Planet. Sci. Lett.* 47, 161-175.
21. Aller, R.C. 1982. The effects of macrobenthos on chemical properties of marine sediment and overlying water. In "Animal-sediment Relations", P.L. McCall and M.S. Tevesz (eds.), Plenum Press. Chapter 2, 53-96.
22. Santschi, P.H., Y.H. Li, J. Bell, R.T. Trier and K. Kawtaluk. 1980. Pu in coastal marine environments. *Earth Planet. Sci. Lett.* 51, 248-265.