WATER RESOURCES RESEARCH, VOL. 28, NO. 3, PAGES 915–938, MARCH 1992

Bacterial Transport in Porous Media: Evaluation of a Model Using Laboratory Observations

GEORGE M. HORNBERGER, AARON L. MILLS, AND JANET S. HERMAN

Department of Environmental Sciences, University of Virginia, Charlottesville

The factors that control the transport of bacteria through porous media are not well understood. The relative importance of the processes of dispersion, of immobilization of bacterial cells by various mechanisms (deposition), and of subsequent release of these trapped cells (entrainment) in describing transport has not been elucidated experimentally. Moreover, the variability of the phenomenological coefficients used to model these processes, given changes in such primary factors as grain size, organism, and ionic strength of the water, is unknown. We report results of fitting solutions of an advection-dispersion equation, modified to account for deposition and entrainment, to breakthrough curves from packed sand columns using two sizes of sand, two ionic strengths of the carrier solution, and two organisms with different sizes. A solution to the advection-dispersion equation including three processes, that is, dispersion, deposition, and entrainment, provides a match to the data that is superior to that achieved by solutions ignoring one of the processes. Fitted values of the coefficient describing deposition vary in a consistent manner with the control variables (organism, grain size, and ionic strength) and are generally within one order of magnitude of those predicted on the basis of theory.

INTRODUCTION

Interest in determining the factors that control the transport of bacteria through geological materials and in deriving a theory suitable for describing the transport has been enhanced in the last decade by concern over pollution of groundwater supplies. The issues include the contamination of groundwater by pathogens (see *Gerba* [1985] for a discussion), the potential for bacterial transport in conjunction with biodegradation of organic contaminants in the subsurface, the potential for discharge (either advertent or inadvertent) of genetically engineered microorganisms into geological media [e.g., *Sayler*, 1986], and the potential role of microorganisms in facilitating the transport of radionuclides in groundwater [e.g., *Champ*, 1986; *West et al.*, 1986].

Despite the importance of gaining an understanding of the movement of bacteria in soils, sediments, and bedrock, available theories are arguably incomplete [*McDowell-Boyer et al.*, 1986; *Elimelech and O'Melia*, 1990], and tests of existing models against laboratory or field data are few. The only approach to modeling transport of bacteria that appears tractable at the present is phenomenological. That is, the transport is described using an advection-dispersion equation modified to account for growth, death, and filtration effects through the incorporation of phenomenological coefficients, with only limited ability to specify the coefficients on theoretical grounds.

A broad-based treatment to quantitate the various processes that affect bacteria in the subsurface is, by necessity, quite complex. We focus our attention on the transport of bacteria by eliminating the complexities that derive from biological processes such as growth, death, and predation. That is, we restrict consideration to bacteria in the resting state (no growth), to time periods for which decay is not observed, and to systems devoid of predators. For the transport of resting bacterial cells the potentially most important processes to include in a transport model are advection, hydrodynamic dispersion, a number of mechanisms that can retain bacteria in a porous medium (hereafter lumped together under the term "deposition"), and the subsequent dislodgement of previously trapped particles (hereafter "entrainment"). Previously published representations for colloid transport include models incorporating (1) advection, deposition, and entrainment but no dispersion [*Rajagopalan and Chu*, 1982]; (2) advection, dispersion, and deposition but no entrainment (A. Dieulin, as cited by *de Marsily* [1986]); and (3) all of the processes mentioned above [*Corapcioglu and Haridas*, 1985]. The first two models were originally put forth as descriptions for transport of inorganic colloids, while the model of Corapcioglu and Haridas was developed specifically for bacterial transport.

The applicability of transport models developed for inorganic colloids to the transport of biocolloids has been examined for bacteriophage by *Bales et al.* [1989, 1991] and for bacteria by *Harvey and Garabedian* [1991]. Recent reviews of the topic are given by *Yates and Yates* [1988] and by *Harvey* [1991].

We present results from a suite of experiments on the transport of bacteria through columns of packed sand. The bacteria were in a resting state, that is, growth/death did not occur during the course of the experiments, so models for colloid transport can be taken to describe the transport process. Analysis of breakthrough curves with respect to the models of *Rajagopalan and Chu* [1982], A. Dieulin (as cited by *de Marsily* [1986]), and *Corapcioglu and Haridas* [1985] indicate that advection, dispersion, deposition, and entrainment are all processes that affect transport in noticeable ways. We find that the coefficient taken to describe deposition varies in a consistent pattern with grain size, organism, and ionic strength of the transporting fluid. Neither the entrainment coefficient nor the dispersion coefficient show any systematic variation with the control variables.

Paper number 91WR02980.
0043-1397/92/91WR-02980$05.00

METHODS

Laboratory Procedures

Data used for fitting the models were taken from the experiments on the breakthrough of bacteria from columns of clean quartz sand described in detail by *Fontes et al.* [1991]. Resting (nongrowing but viable) cells of two strains of bacteria isolated from a shallow freshly augered well were used in the experiments. Strain W6 was a small gram-negative sphere (0.75 μm diameter), and strain W8 was a gram-negative rod (0.75 μm $\times$ 2μm). These organisms had identical surface hydrophobicities, as determined by contact angle measurements; the measured angle was 20°, indicating that the cell surfaces are highly hydrophilic according to the scheme of *Mozes et al.* [1987]. The eluent solution was a dilute artificial groundwater (AGW), a Na^+, Mg^{++}, Ca^{++}, K^+, SO_4^{2-}, HCO_3^-, Cl^-, NO_3^- solution, with an ionic strength of 0.00089 m. A more concentrated solution (10×, ionic strength 0.0089 m) was used for experiments testing the effect of ionic strength on bacterial transport. In this paper the terms "low" and "high" ionic strength refer to the two values of ionic strength that we used. The *p*H of the eluent solution, checked at the entry and the exit of the column, was 6.8.

The columns used were glass chromatography columns (Kontes) with an internal diameter of 4.8 cm. Autoclaved columns were wet-packed with rounded quartz sand (Unimin Corporation) which had been acid washed in 10% HNO_3, thoroughly rinsed with deionized water, autoclaved, and dried. As used in this paper, "fine" sand was that which passed through a 0.40 mm mesh sieve but not a 0.33 mm sieve; "coarse" sand was that which passed through a 1.14 mm sieve but not a 1.00 mm sieve. A fresh column was packed for each experiment by pouring 400 grams of a single size of dry sand into water standing in the chromatography column. The length of the sand pack in the column was 14 cm. The pore volume was 88 mL.

The downward flow of AGW from a sterile reservoir through the column was regulated by a variable flow peristaltic pump located beyond the column outlet. A shallow standing pool of AGW was maintained above the sand surface to ensure equal distribution of solution across the column at all times. Once a constant flow rate of 88 mL h^{-1} was established, 2 mL of a bacterial suspension containing approximately 10^9 cells mL^{-1} was introduced into the pool at the top of the column. This was accomplished by the use of a valve that changed the source of input to the column from the AGW reservoir to a graduated cylinder containing the bacterial suspension. When exactly 2 mL had been removed from the cylinder, the valve was turned so that inflow to the column was shut off. When the pool just drained to the sand surface, the valve was returned to its original position, and AGW flow resumed. The addition of the bacterial suspension marked "zero time" for the experiments.

Eluent samples were collected from the base of the column in one-fourth pore volume intervals in Pyrex test tubes by use of a fraction collector and analyzed for bacterial concentration using acridine orange direct counts (AODC) [*Hobbie et al.*, 1977]. The funnel-shaped exit into a collection tube of 0.001 m inner diameter and length of approximately 0.5 m was less than 1/16th of a pore volume. Experimental runs were continued until at least three pore volumes of AGW had passed through the columns. Auxiliary experiments indicated that no change in cell numbers, as determined by AODC, occurred during the period of the transport experiments. The percentage of bacterial cells recovered in the eluent from the column depended upon the organism, sand size, and ionic strength of the eluent and ranged from 0.33% for strain W8 in fine-grained sand and high ionic strength solution to 88% for strain W6 in coarse-grained sand and low ionic strength solution.

Mathematical Models

We use a simplified version of the one-dimensional form of the equations proposed by *Corapcioglu and Haridas* [1985], a version that ignores the growth and decay of the bacteria.

$$\partial c/\partial t = \alpha_L (q/n)\ \partial^2 c/\partial x^2 - (q/n)\ \partial c/\partial x - k_c c + k_y s \qquad (1)$$

$$\partial s/\partial t = k_c c - k_y s \qquad (2)$$

where

- c concentration of bacteria suspended in the solution (cells mL^{-1});
- x distance from the surface of the column (cm);
- t time from the initiation of input of bacteria (hours);
- $\alpha_L(q/n) = D$ is the coefficient of hydrodynamic dispersion ($cm^2\ h^{-1}$);
- α_L dispersivity (cm);
- q Darcian velocity (cm h^{-1});
- n fractional porosity;
- k_c deposition coefficient (h^{-1});
- k_y entrainment coefficient (h^{-1});
- s "concentration" of bacteria associated with the solid phase but expressed per volume of pore water (cells mL^{-1}).

(Note that Corapcioglu and Haridas use the term "clogging" for our "deposition" and the term "declogging" for our "entrainment." They also write their equations using σ for the "concentration" of deposited bacteria. Their "σ" is equal to our "s" multiplied by the porosity of the medium and by the volume of a bacterial cell.)

The solutions to these equations that we use are all for semi-infinite columns with zero initial concentrations and a step increase to $c = c_0$ at the surface of the column at $t = 0$. This is appropriate for analyzing the flux concentrations from a breakthrough experiment [*van Genuchten and Parker*, 1984].

The solution presented by *Rajagopalan and Chu* [1982] is for the case where the first term on the right-hand side of (1) is negligible, that is, for $D = 0$. A. Dieulin (as cited by *de Marsily* [1986]) developed a solution for the case when k_y is zero. Finally, *Cameron and Klute* [1977], *Rao et al.* [1979], and *Corapcioglu and Haridas* [1985] give solutions to (1) and (2) without further simplification. (Equations (1) and (2) are identical in form to transport equations for an adsorbing solute when the sorption is kinetically controlled.)

The published solutions are for a continuous (step) input of the colloidal suspension. Our experiments were for pulse inputs of bacteria. The solutions for such a square-wave boundary condition can be obtained using the principle of superposition:

$$c_\varepsilon(x, t) = c(x, t) - c(x, t - \varepsilon) \quad (3)$$

where $c_\varepsilon(x, t)$ is the solution for a pulse input, $c(x, t)$ is the solution for a step input, and ε is the length of the pulse input.

Parameter Estimation

The parameters which are needed to use the transport models and which cannot be measured directly using our experimental setup are α_L, k_c, and k_y. These parameters were estimated by minimizing the sum of squared errors between model-calculated concentrations and measured concentrations. The computer program given by *van Genuchten* [1981] was used to estimate the parameters. This code estimates three dimensionless parameters corresponding to a nondimensional form of equations (1) and (2). These are Pe, the column Peclet number; R, a retardation factor (used for convenience of representation and not as a representation of equilibrium adsorption in this problem; see *van Genuchten* [1981]); and w, a ratio of the time scale for advective transport to the time scale for deposition. The three parameters with which we are concerned are related to the dimensionless parameters by $\alpha_L = L/Pe$ (where L is the length of the column), $k_c = w(q/nL)$, and $k_y = k_c/(1 - R)$.

We report the model efficiency as a normalized measure of the goodness of fit of the model to the data. Model efficiency E is defined as

$$E = 1 - \sum(r_i)^2 \Big/ \sum(c_i - c_{av})^2 \quad (4)$$

where r_i is the ith residual between model prediction and observation, c_i is the ith observed concentration, and c_{av} is the mean of the observed concentrations. A model efficiency of 1 indicates a perfect fit of the model to the data and an efficiency of zero indicates that the model fits the data no better than a horizontal line through the mean concentration.

The sum of squared errors response surface may be convoluted in nonlinear parameter estimation problems, with local minima scattered about. In such cases the optimal values of parameters derived from a parameter estimation routine may be strongly conditioned by initial guesses of the parameters. We ran the optimization five times using different values of initial guesses for the parameter values. Convergence to the same solution was obtained in all cases.

Theoretical Values of Parameters

Tien et al. [1979] present a theoretical expression from which values of the deposition coefficient can be calculated. Disregarding the effects of gravitational forces in deposition (an assumption that should be very good for bacterial cells because the density of cells is close to that of water) and also disregarding the effects of straining (an assumption that should also be valid because the bacterial cells are so much smaller than the mineral grains), the value of k_c is given by

$$k_c = [3(1 - n)q][4A_s^{(1/3)}N_{Pe}^{(-2/3)}]/2d_g \quad (5)$$

where

$A_s = 2(1 - p^5)/(2 - 3p + 3p^5 - 2p^6)$;
$N_{Pe} = 3\pi\mu d_p d_g q/(kT)$;
$p = (1 - n)^{(1/3)}$;
d_g grain diameter;
d_p particle diameter;
μ fluid viscosity;
T temperature (°K);
k Boltzmann constant (1.38048×10^{-23} J/K).

RESULTS

The Dieulin solution fits the data from many of our experimental runs quite well, for example, for conditions of the experiment using organism W6, coarser sand, and lower ionic strength (Figure 1*a*). This supports *de Marsily*'s [1986] observation that elaborations beyond Dieulin's solution are unnecessary for describing colloid transport in porous media. If the results are compared for logarithms of concentrations (common for reporting bacterial concentrations), however, a discrepancy between model and observations is readily apparent (Figure 1*b*). It is clear that the effect of entrainment, although small, is required to explain the observations. (Note that the fit of Dieulin's solution to the data was done "by eye", that is, optimal values of the parameters were not sought. The nonoptimal fit suffices to demonstrate that a solution ignoring entrainment is not able to mimic the observed extended tails of the breakthrough curves.)

Similarly, comparison of the observations with the solution of Rajagopalan and Chu suggests that the effects of dispersion, even for these relatively short columns, cannot be ignored (Figure 1*c*). The solution to the unaltered equations (1) and (2) is clearly superior to the others reported here (Figure 1*d*) in the sense that the effects of dispersion and of entrainment are included. Consequently, further results reported below are restricted to the solution of the complete equations.

In many of our experiments we observed (relatively) small concentrations of bacteria in the first or second one-fourth pore volume eluted from the column after injection of the pulse of bacteria (Figure 2). This result, which is inconsistent with a dispersivity value required to fit the observed peak concentrations, is puzzling. Other results from our laboratory argue against explanation of this effect as an artifact of the experimental procedure. Experiments using chloride ion as a tracer in our columns do not show early breakthrough. Samples taken from columns into which no bacteria have been injected show zero concentrations. Consequently, we believe that the observed early breakthrough is real but can offer no definitive explanation for it. (One hypothesis might be a size exclusion effect whereby large cells move rapidly through the column [e.g., *Harvey and Garabedian*, 1991]). Because the early breakthrough is inconsistent with the theory that we are evaluating, however, we discount those data in the parameter estimation; model efficiencies reported below ignore the data for one-fourth and one-half pore volumes.

It should also be noted that a least squares fit to data will give greatest weight to the highest concentrations because the potential for a large residual between a datum and a model-calculated concentration is greatest for these points. In visually comparing figures of model-calculated concentrations with observed concentrations on a logarithmic scale, one must bear in mind that errors that are not very important in their contribution to the sum of squared errors may appear to be "large."

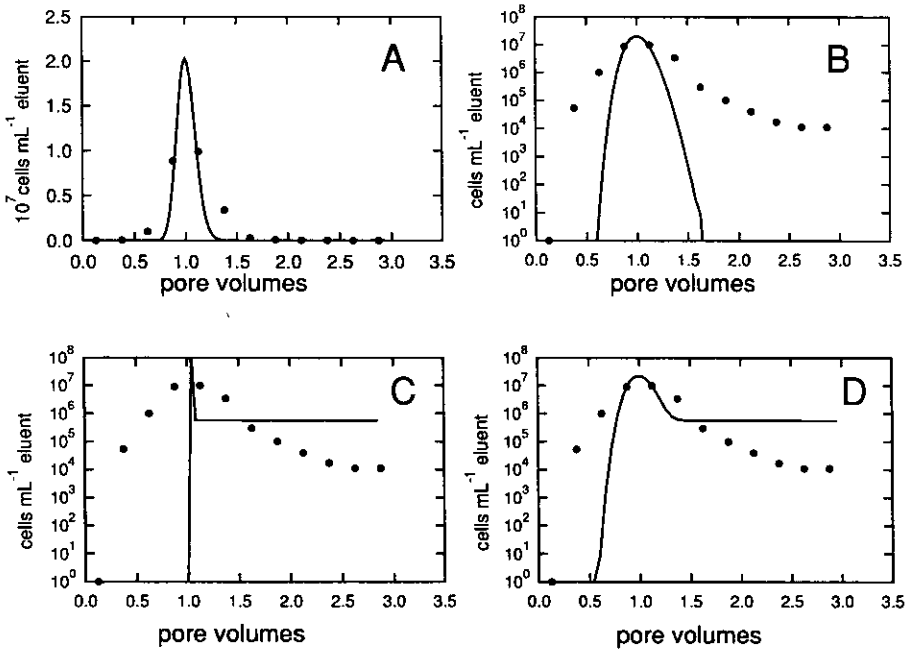

Fig. 1. (*a*) Concentrations as predicted using the solution of A. Dieulin (discussed by *de Marsily* [1986]) and those measured experimentally for organism W6, low ionic strength, and coarse sand. The solid curve is the continuous solution; the solid circles are the measured concentrations from consecutive one-fourth pore volume samples. (*b*) Same as Figure 1*a* but concentrations are plotted on a logarithmic scale. Concentrations less than unity are set equal to one. (*c*) Concentrations as predicted using the solution of *Rajagopalan and Chu* [1982] and those measured experimentally for organism W6, low ionic strength, and coarse sand. Curves and points as in Figure 1*a*. (*d*) Concentrations as predicted using a solution to (1) and (2) and those measured experimentally for organism W6, low ionic strength, and coarse sand. Curves and points as in Figure 1*a*.

The data from experiments using a pulse input of bacteria are not sufficient to estimate all three model parameters well. The values of w (and hence of k_c) were estimated reasonably well, with standard errors of the parameter estimates generally between 5 and 10% of the parameter values (Table 1). Values of Pe (and hence of α_L) were, in general, not well estimated. Standard errors of the estimates of Pe were often larger than 10% and sometimes close to 25% of the parameter values. Values of R (and hence of k_y) were poorly estimated, with standard errors generally at least 40% of the parameter values.

For runs with low ionic strength solution as the carrier, the model fits were good (Figure 2 and Table 1). The model efficiencies, roughly equivalent to the R^2 of a regression, are all greater than 0.6; in fact, with one exception all efficiencies exceed 0.8. For the higher ionic strength solution the results are not as good. Nevertheless, the efficiencies are all greater than zero and, despite the relatively poorer fits in comparison to the low ionic strength runs, the deposition coefficient again can be estimated with good confidence from the data (Table 1).

The optimal values of the parameter for deposition vary in a consistent pattern with each of the controlled variables, that is, grain size, organism, and ionic strength (Table 1); k_c is larger for organism W8 than for W6, for finer sand than for coarser sand, and (with one exception) for higher ionic strength than for lower ionic strength. The deposition coefficient basically determines the height of the peak of the breakthrough curve and also the total number of bacteria that are released over three pore volumes in our experiments. The observation that k_c varies consistently with the controlled variables accords with our observation that the percentage of bacteria eluted from the base of the column during the various experiments is strongly conditioned by all three of the controlled variables [*Fontes et al.*, 1991].

Values for the deposition coefficients calculated from the theory presented by *Tien et al.* [1979], which does not account for effects of ionic strength, are sometimes reasonably close to the optimized values and, even in the worst cases, are generally within about one order of magnitude (Table 2). Because the theory is for spherical particles, two values for organism W8 are calculated. The first takes the large dimension of the rod (≈2 μm) as the "diameter" of the particle. The second is for the diameter of the sphere having an equivalent volume of a rod of length 2 μm and diameter of 0.75 μm. The theoretical values for W8 are lower than for W6. The fitted values, on the other hand, show consistently higher values for W8 relative to W6.

DISCUSSION

Our results indicate that the model of *Corapcioglu and Haridas* [1985] can successfully describe some of the important characteristics of the transport of bacteria through porous media, at least under certain conditions. The processes of dispersion, deposition, and entrainment must all be retained in the model to mimic the detailed behavior observed.

The process having the largest impact on the breakthrough curve calculated by the model is deposition. This is in accord with the extensive observations on the filtration of colloids in sand beds. The fitted values for the deposition coefficient

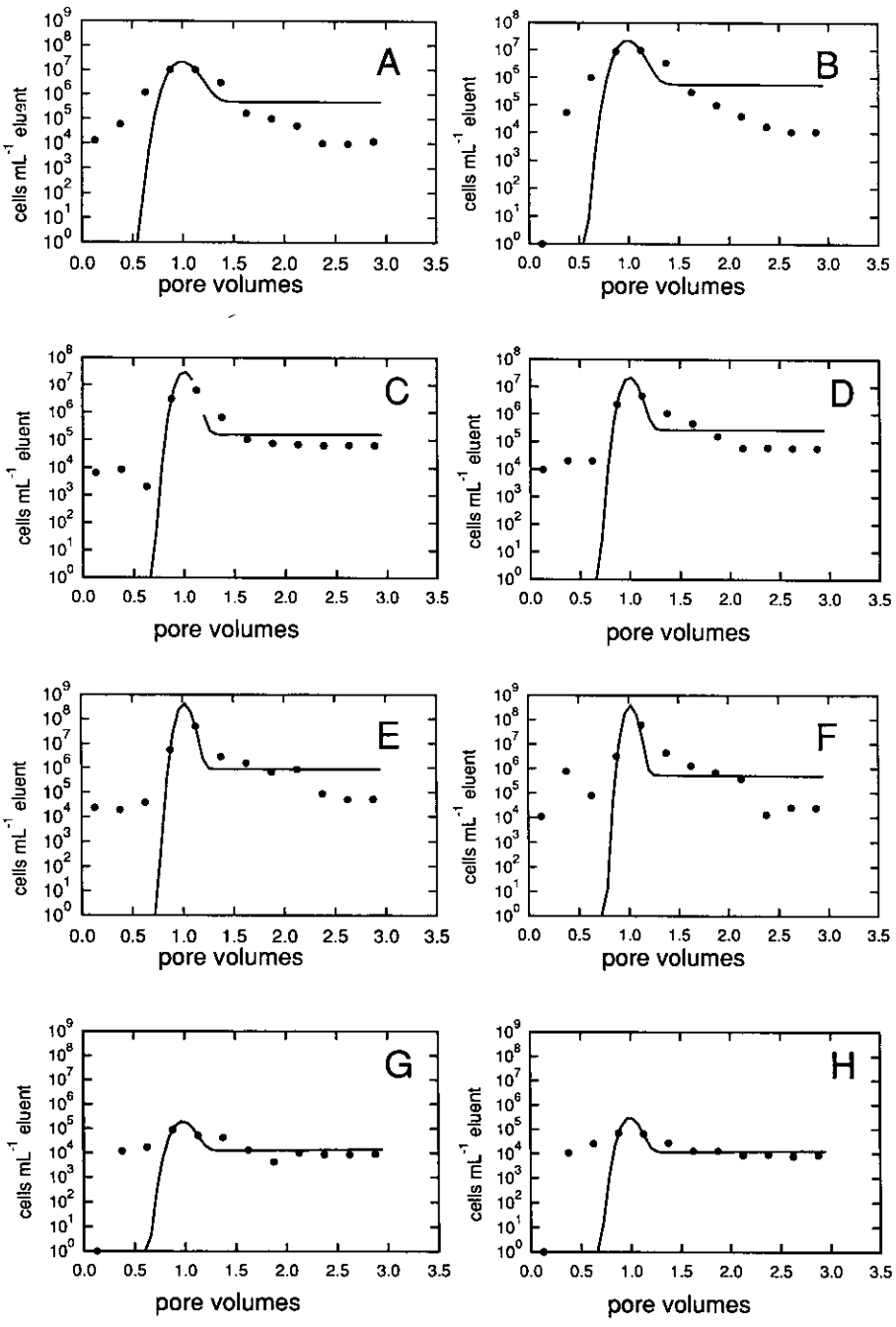

Fig. 2. Concentrations as predicted using a solution to (1) and (2) and those measured experimentally (all runs). The solid curve is the continuous solution; the solid circles are the measured concentrations from consecutive one-fourth pore volume samples. (*a*) W6LC1, (*b*) W6LC2, (*c*) W6LF1, (*d*) W6LF2, (*e*) W6HCl, (*f*) W6HC2, (*g*) W6HF1, (*h*) W6HF2, (*i*) W8LC1, (*j*) W8LC2, (*k*) W8LF1, (*l*) W8LF2, (*m*) W8HCl, (*n*) W8HC2, (*o*) W8HF1, (*p*) W8HF2.

vary in a consistent way with the controlled variables of the experiments. Values of k_c are higher for the finer sand, for the larger organism, and, with one exception, for the higher ionic strength.

In theory, the observed values of k_c should be less than or equal to those calculated from (5). The ratio of the observed value to the calculated value then gives the "sticking efficiency" [e.g., *Elimelich and O'Melia*, 1990]. Our results (Table 2), even taking into account the standard errors of the parameter estimates, suggest that the sticking efficiency in our columns was close to, if not greater than, unity. Values higher than unity would be indicative of a serious problem with the theoretical calculation as applied to bacteria. Even values of close to unity are larger than those previously reported for other biocolloids. *Harvey and Garabedian* [1991] use a value of about 0.01 for the sticking efficiency to model the transport of bacteria through a sandy aquifer on Cape Cod, Massachusetts. *Bales et al.* [1991] report values of sticking efficiencies from about 0.001 to 0.1 for transport of bacteriophage in experimental columns. The disagreement between experimental observation and existing theory suggests that further work is needed to better establish

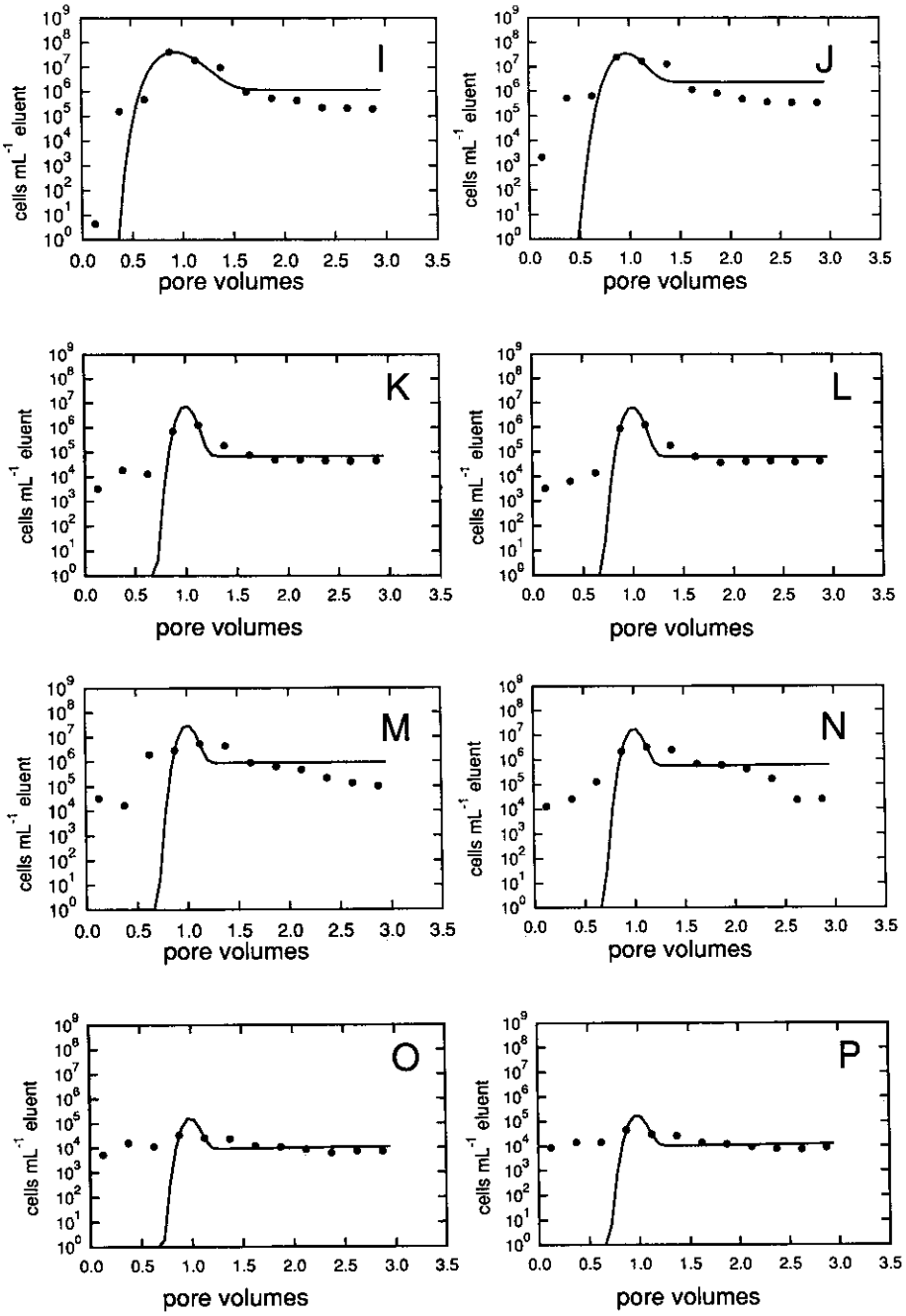

Fig. 2. (continued)

adequate, mechanistic theory as the basis for appropriate description of bacterial transport.

We found that the deposition coefficient increased with ionic strength. The tenfold change in ionic strength that we used resulted in increases in k_c of approximately twofold for three of the four comparisons (Table 2). (The fitted values of k_c for experiments using organism W6, lower ionic strength, and finer sand were anomolously high when judged by the relationship between the fitted values of k_c and the percent of bacteria retained in the columns after three pore volumes had been eluted as reported by *Fontes et al.* [1991]. This results in the exception to the expected observation of increasing k_c with increasing ionic strength.) Variation of retention with ionic strength has been reported by a number of workers previously [e.g., *Goldschmid et al.*, 1972; *Gerba and Bitton*, 1984; *Sharma et al.*, 1985]. The clean-bed filter model of *Tien et al.* [1979] that we used here does not result in different predictions for differing ionic strengths. We do not have the measurements necessary to determine whether the theories of *Speilman and Friedlander* [1974] or of *Wnek et al.* [1975], which account for changes in surface interactions due to solution composition, would agree with our results. The results of *Elimelich and O'Melia* [1990], however, show large discrepancies between the Spielman-Friedlander theory and observations, using latex beads as particles and glass spheres for the porous medium, over a

TABLE 1. Fitted Parameters (With Standard Errors)

Data Set	*Pe*	*w*	*R*	α_L, cm	k_c, h^{-1}	k_y, h^{-1}	Efficiency
W6LC1*	189 (40.0)	1.52 (0.107)	25.5 (21.1)	0.074	1.50	0.061	0.860
W6LC2	222 (47.0)	1.52 (0.129)	21.9 (17.1)	0.063	1.51	0.072	0.818
W6LF1	481 (19.9)	2.50 (0.047)	197 (97.8)	0.029	2.48	0.013	0.973
W6LF2	488 (45.9)	2.83 (0.113)	108 (53.2)	0.029	2.81	0.026	0.891
W6HC1	817 (51.6)	0.785 (0.083)	38.2 (15.7)	0.017	0.78	0.021	0.983
W6HC2	1016 (141)	0.313 (0.226)	9.14 (11.0)	0.014	0.31	0.038	0.969
W6HF1	268 (83.4)	5.47 (0.362)	96.4 (42.9)	0.052	5.43	0.057	0.786
W6HF2	388 (66.5)	5.14 (0.267)	120 (48.8)	0.036	5.10	0.043	0.838
W8LC1	63.6 (15.5)	2.16 (0.080)	62.8 (20.4)	0.220	2.15	0.035	0.900
W8LC2	135 (82.8)	2.65 (0.213)	62.8 (55.5)	0.104	2.63	0.090	0.622
W8LF1	529 (21.1)	3.88 (0.057)	257 (68.4)	0.026	3.85	0.015	0.973
W8LF2	464 (18.3)	3.97 (0.056)	269 (81.3)	0.030	3.94	0.015	0.974
W8HC1	528 (172)	4.06 (0.477)	87.2 (61.8)	0.026	4.03	0.047	0.388
W8HC2	490 (122)	4.59 (0.393)	104 (59.6)	0.028	4.56	0.044	0.531
W8HF1	456 (104)	7.64 (0.494)	165 (67.9)	0.031	7.58	0.046	0.819
W8HF2	415 (96.3)	7.53 (0.466)	163 (65.3)	0.034	7.48	0.046	0.831

*The experiment is defined by organism (W6 or W8), ionic strength (L, low or H, high), grain size (C, coarse or F, fine) and replicate column (1 or 2).

very wide range in ionic strengths. *Tobiason* [1989] also found discrepancies between model predictions and observed filtration rates for high ionic strengths.

The observed values of k_c also vary systematically with the organism, with higher values associated with W8, the larger organism (Table 2). The theory of *Tien et al.* [1979] is qualitatively in conflict with our observations in the sense that the differences between the coefficients for organisms W6 and W8 do not go in the direction predicted by theory. (The collection efficiency should be at a minimum for a particle size of several micrometers for the conditions of our experiments [e.g., *Harvey*, 1991]). This may be due to the fact that the shape of organism W8 is nonspherical and thereby renders the theory invalid. *Jang et al.* [1983] found that spores of a bacterium were retarded less than were the bacterium itself. Thus their results also indicate that a larger, rod-shaped organism is retained more strongly than a smaller, spherical organism. Alternatively, interactions between the bacterial cells and the mineral surfaces, other than those taken into account by the theory, may be important. *Bitton et al.* [1974] found a smaller percent total retention for an encapsulated organism (approximately 3×4 μm) in a column of sandy soil as compared with an unencapsulated (approximately 1×2.5 μm) organism. The peak concentration in the breakthrough curve for the unencapsulated organism, however, was higher than that for the encapsulated organism. The change in the bacterial surface of the encapsulated organism relative to the surface of the unencapsulated organism, as well as the size differences, very likely played a major role in affecting the response in this case.

TABLE 2. Theoretical and Fitted (Mean of Two Replicates) Values of the Deposition Coefficient

Organism	Grain Size	k_c (Theory)	k_c (fitted) Low Ionic Strength	k_c (fitted) High Ionic Strength
W6	fine	3.07	2.64	5.26
	coarse	0.53	1.50	0.594
W8*	fine	1.66	3.90	7.53
	coarse	0.28	2.39	4.30
W8†	fine	2.27	3.90	7.53
	coarse	0.39	2.39	4.30

*An effective diameter of 2 μm, the long dimension of W8, was used in the calculation of the theoretical k_c.

†An effective diameter of 1.19 μm, the diameter of a sphere with a volume equivalent to that of W8, was used in the calculation of the theorectical k_c.

Sorption of bacteria to various mineral surfaces is controlled, to at least some extent, by surface electrochemical interactions [e.g., *Scholl et al.*, 1991]. When considered as a rapid process that effectively instantaneously partitions solute between an aqueous and a sorbed state, adsorption is understood to delay the breakthrough of a solute as well as to decrease peak concentrations. In all of our experiments (see also the results of *Bitton et al.* [1974] and of *Wollum and Cassel* [1978]), however, there is exceedingly strong retention of bacteria within the column but little or no retardation of the breakthrough in time. Thus the increase in "adsorption" of bacteria with increasing ionic strength is more akin to increasing efficiency of a sedimentation mechanism than it is to a classic adsorption response. If one is to retain the terminology associated with adsorption models, it appears that adsorption of bacteria in the columns is kinetically controlled rather than instantaneous. Thus the use of equilibrium adsorption models in conjunction with bacterial transport, such as the linear adsorption isotherm used by *Peterson and Ward* [1989] and by *Mills et al.* [1991], may not be fully adequate for describing transport of bacteria.

The entrainment parameter is clearly the least important to achieving fits of model to data when the sum of squared errors is the measure of fit. This is consistent with our observation that the solution of A. Dieulin (as cited by *de Marsily* [1986]), which neglects entrainment, fits our data very well except for the long "tail" of the breakthrough curve following cessation of the input. The entrainment effect is clearly a "second-order" effect and could safely be ignored in many cases. For example, in the case of migration of radionuclides away from a geological repository via attachment to colloids, the situation discussed by *de Marsily* [1986] and by *Avogadro and de Marsily* [1984], the source might be considered to have a relatively constant strength, and the small effects of entrainment may be completely negligible. On the other hand, there may well be cases where

small numbers of bacteria may be transported long after the "source" is eliminated. Furthermore, if bacteria in even small numbers are transported to a region of an aquifer where conditions for growth are favorable, large population densities may be achieved. In such cases (e.g., persistence of an organism released as a pulse to groundwater), the entrainment term in the transport equation may be important in quantitative forecasts of behavior. Experiments in our laboratory, in which eluent was collected for seven pore volumes after a pulse injection of bacteria, show that the tail of the breakthrough curve persists well beyond the three pore volumes reported here [*Scholl et al.*, 1991]. *Wollum and Cassel* [1978] collected samples for 36 pore volumes in a pulse injection column experiment and found that bacteria were still being eluted from the column in small numbers even in the last sample. Thus the entrainment phenomenon is not merely an "extended dispersion."

Variation of k_y with particle size (i.e., with organism) is not obvious from our data. The theory of *Rajagopalan and Chu* [1982] predicts that k_y should vary as the square of the particle diameter. For organisms W6 and W8 this gives an expected difference of about a factor of seven between the two organisms. Our data do not support a variation of this magnitude.

Although the model results are generally encouraging in that model calculations agree with observations reasonably well, there are clearly serious gaps in our knowledge of what controls the values of the phenomenological coefficients. The situation is even worse when one considers that the ultimate aim is to apply the models in the field. Even for the "simple" behavior of a conservative tracer, modeling in the field may be difficult. For example, we know that it is inappropriate to extrapolate dispersivities from the laboratory to the field. Rather, the current thinking is that a stochastic description of the spatiotemporal variation of the material properties must be obtained. This may be the direction that will be appropriate for describing the parameters controlling bacterial transport in porous media as well, but first a great deal more work must be done to elucidate the factors that exercise control over the transport and to refine abilities to quantitatively relate measurable factors to the phenomenological coefficients of a transport model.

Acknowledgments. The work reported here was supported by the Subsurface Science Program of the U.S. Department of Energy through grant DE-FG05-89ER0842. The modeling work was completed while the senior author (GMH) was a visiting scientist with the U.S. Geological Survey in Menlo Park and a visiting professor in the Department of Applied Earth Sciences, Stanford University. We thank James Saiers and David Fontes for carrying out the laboratory work. Rien van Genuchten graciously provided a copy of his parameter estimation code. We are grateful for the comprehensive comments on an earlier draft of this manuscript provided by Roger Bales, James Hunt, and an anonymous reviewer. Perry McCarty also made useful suggestions for revising the manuscript.

REFERENCES

Avogadro, A., and G. de Marsily, The role of colloids in nuclear waste disposal, in *Scientific Basis for Nuclear Waste Management VII, Mater. Res. Soc. Symp. Proc.*, vol. 26, edited by G. L. McVay, pp. 495–505, North-Holland, Amsterdam, 1984.

Bales, R. C., C. P. Gerba, G. H. Grondin, and S. L. Jensen, Bacteriophage transport in sandy soil and fractured tuff, *Appl. Environ. Microbiol.*, *55*, 2061–2067, 1989.

Bales, R. C., S. R. Hinkle, T. W. Kroeger, and K. Stocking, Bacteriophage adsorption during transport through porous media: Chemical perturbations and reversibility, *Environ. Sci. Technol.*, *25*, 2088–2095, 1991.

Bitton, G., N. Lahav, and Y. Henis, Movement and retention of Klebsiella Aerogenes in soil columns, *Plant Soil*, *40*, 373–380, 1974.

Cameron, D. A., and A. Klute, Convective-dispersive solute transport with a combined equilibrium and kinetic adsorption model, *Water Resour. Res.*, *13*, 183–188, 1977.

Champ, D. R., Microbial mediation of radionuclide transport, paper presented at Chapman Conference on Microbial Processes in the Transport, Fate, and In Situ Treatment of Subsurface Contaminants, AGU, Snowbird, Utah, Oct. 1–3, 1986.

Corapcioglu, M. Y., and A. Haridas, Microbial transport in soils and groundwater: A numerical model, *Adv. Water Resour.*, *8*, 188–200, 1985.

de Marsily, G., *Quantitative Hydrogeology*, Academic, San Diego, Calif., 1986.

Elimelech, M., and C. R. O'Melia, Kinetics of deposition of colloidal particles in porous media, *Environ. Sci. Technol.*, *24*, 1528–1536, 1990.

Fontes, D., A. L. Mills, G. M. Hornberger, and J. S. Herman, Physical and chemical factors influencing transport of microorganisms through porous media, *Appl. Environ. Microbiol.*, *57*, 2473–2481, 1991.

Gerba, C. P., Microbial contamination of the subsurface, in *Ground Water Quality*, edited by C. H. Ward, W. Giger, and P. L. McCarty, pp. 53–67, John Wiley, New York, 1985.

Gerba, C. P., and G. Bitton, Microbial pollutants: Their survival and transport pattern to groundwater, *Groundwater Pollut. Microbiol.* 1984, 65–88, 1984.

Goldschmid, J., D. Zohan, Y. Argaman, and Y. Kott, Effect of dissolved salts on the filtration of coliform bacteria in sand dunes, in *Advances in Water Pollution Research*, edited by S. H. Jenkins, pp. 147–155, Pergamon, New York, 1972.

Harvey, R. W., Parameters involved in modeling movement of bacteria in groundwater, in *Modeling the Environmental Fate of Microorganisms*, edited by C. J. Hurst, pp. 89–114, American Society for Mirobiology, Washington, D. C., 1991.

Harvey, R. W., and S. P. Garabedian, Use of colloid filtration theory in modeling movement of bacteria through a contaminated sandy aquifer, *Environ. Sci. Technol.*, *25*, 178–185, 1991.

Hobbie, J. E., R. J. Daley, and S. Jasper, Use of nucleopore filters for counting bacteria by fluorescence microscopy, *Appl. Environ. Microbiol.*, *33*, 1225–1228, 1977.

Jang, L.-K., P. W. Chang, J. E. Findley, and T. F. Yen, Selection of bacteria with favorable transport properties through porous rock for the application of microbial-enhanced oil recovery, *Appl. Environ. Microbiol.*, *46*, 1066–1072, 1983.

McDowell-Boyer, L. M., J. R. Hunt, and N. Sitar, Particle transport through porous media, *Water Resour. Res.*, *22*, 1901–1921, 1986.

Mills, W. B., S. Liu, and F. K. Fong, Literature review and model (COMET) for colloid/metals transport in porous media, *Ground Water*, *29*, 199–208, 1991.

Mozes, N., F. Marchal, M. P. Hermesse, J. L. Van Haecht, L. Reuliaux, A. J. Leonard, and P. G. Rouxhet, Immobilazation of microorganisms by adhesion: Interplay of electrostatic and nonelectrostatic interactions, *Biotechnol. Bioeng.*, *30*, 439–450, 1987.

Peterson, T. G., and R. C. Ward, Development of a bacterial transport model for coarse soils, *Water Resour. Bull.*, *25*, 349–357, 1989.

Rajagopalan, R., and R. Q. Chu, Dynamics of adsorption of colloidal particles in packed beds, *J. Colloid Interface Sci.*, *86*, 299–317, 1982.

Rao, P. S. C., J. M. Davidson, R. E. Jessup, and H. M. Selim, Evaluation of conceptual models for describing non-equilibrium adsorption-desorption of pesticide during steady flow in soils, *Soil Sci. Soc. Am. J.*, *43*, 22–28, 1979.

Sayler, G. S., Fate of genetically engineered organisms in groundwater, paper presented at Chapman Conference on Microbial Processes in the Transport, Fate, and In Situ Treatment of Subsurface Contaminants, AGU, Snowbird, Utah, Oct. 1–3, 1986.

Scholl, M., A. L. Mills, J. S. Herman, and G. M. Hornberger, The influence of mineralogy and solution chemistry on attachment of bacteria to representative aquifer materials, *J. Contaminant Hydrol.*, *6*, 321–336, 1991.

Sharma, M. M., Y. I. Chang, and T. F. Yen, Reversible and irreversible surface charge modification of bacteria for facilitating transport through porous media, *Colloids Surf.*, *16*, 193–206, 1985.

Spielman, L. A., and S. K. Friedlander, Role of the electrical double layer in particle deposition by convective diffusion, *J. Colloid Interface Sci.*, *46*, 22–31, 1974.

Tien, C., R. M. Turian, and H. Pandse, Simulation of the dynamics of deep bed filters, *AIChE J.*, *25*, 385–395, 1979.

Tobiason, J. E., Chemical effects on the deposition of non-Brownian particles, *Colloids Surf.*, *39*, 53–77, 1989.

van Genuchten, M. T., Non-equilibrium transport parameters from miscible displacement experiments, *Res. Rep. 119*, 88 pp., U.S. Salinity Lab., Riverside, Calif., 1981.

van Genuchten, M. T., and J. C. Parker, Boundary conditions for displacement experiments through short laboratory soil columns, *Soil Sci. Soc. Am. J.*, *48*, 703–708, 1984.

West, J. M., H. A. Grogan, I. G. McKinley, and E. J. Rowe, Microbial processes influencing the geological containment of intermediate level radioactive waste, paper presented at Chapman Conference on Microbial Processes in the Transport, Fate, and In Situ Treatment of Subsurface Contaminants, AGU, Snowbird, Utah, Oct. 1–3, 1986.

Wnek, W. J., D. Gidaspow, and D. T. Wasan, The role of colloid chemistry in modeling deep bed liquid filtration, *Chem. Eng. Sci.*, *30*, 1035–1047, 1975.

Wollum, A. G., II, and D. K. Cassel, Transport of microorganisms in sand columns, *Soil Sci. Soc. Am. J.*, *42*, 72–76, 1978.

Yates, M. V., and S. R. Yates, Modeling microbial fate in the subsurface environment, *CRC Crit. Rev. Environ. Control*, *17*, 307–344, 1988.

J. S. Herman, G. M. Hornberger, and A. L. Mills, Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903.

(Received January 4, 1991;
revised November 12, 1991;
accepted November 26, 1991.)