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ABSTRACT

Two groups of new septic systems in coarse-textured soils overlying shallow ground water were monitored for two years to determine the potential of contamination of individual ground-water supply from the use of phosphate-built (PO_4) or carbonate-built (CO_3) detergents. The distribution of nutrients and chloride in the shallow aquifer were examined to trace contamination from the septic systems.

The data were evaluated statistically, and a stochastic nutrient transport model was compiled to simulate ground-water contamination by nutrients for a five-county region. The stochastic modeling of the data showed that neither detergent caused delivery of total phosphorus to ground water in concentrations above 0.1 mg/l as P. However, total nitrogen was removed more efficiently from systems receiving PO_4 -built than CO_3 -built detergents. The total nitrogen from septic systems reached the ground water in concentrations of 39 and 69 mg/l as N from PO_4 - and CO_3 -built detergent use, respectively. The detergent formula has a substantial effect on ground-water contamination by nitrogen from septic systems.

INTRODUCTION

Protection of ground water is of great importance for two reasons: (1) people depend heavily on ground water for drinking water, and polluted water may cause public health hazards, (2) nutrient-bearing ground water discharging to surface water can contribute to eutrophication of recreational lakes and streams that are important to the tourism economy.

Trends favor establishing permanent residential development around highly desirable lakeshores and in rural areas. Present policies on public sewer extensions favor relying on septic systems as a permanent means of waste-water disposal in outlying areas. In the United States, 17 million or 33% of existing housing units and 25% of new homes rely on septic systems for waterborne waste disposal (Canter and Knox, 1985). In the United

States alone, septic systems serve over 70 million people and discharge to ground water 3.0×10^9 m³/yr of partially treated waste water. Septic tank effluent may pollute ground water with nutrient forms of phosphorus (P) and nitrogen (N), especially in sandy soils where the biochemical and physical processes of household waste-water purification during percolation through soil may be insufficient.

Banning phosphorus from detergents provoked concern by public officials, environmental scientists and engineers, land-use planners, government agencies, and the general public for the effects that the alternative formulations may have on the performance of septic systems and on the levels of nutrients in the leachates reaching ground water in unsewered areas. Where septic systems are used, questions of detergent formulations as they relate to ground-water contamination should be seriously addressed.

Such concerns justified this investigation of the effects of two major laundry detergent types, namely phosphate-built (PO_4) and carbonate-built (CO_3) formulations, to evaluate potential contamination of individual ground-water supplies from upgradient septic tank systems, using test wells along the downflow path of effluent migration from drainfields to home water-supply wells and stochastic modeling of the data. Parameters selected for this study were chloride (Cl), total volatile solids (TVS), volatile suspended solids (VSS), total phosphorus (TP), and total nitrogen (TN).

MATERIALS AND METHODS

Site Selection

Two sets of new and replacement septic systems of approximately the same age were selected in five counties in south-central Wisconsin. The first set comprised eight systems (Sites 1 to 8) receiving wastes from households using PO_4 -built laundry detergent. In the following, these are called PO_4 -systems, their locations PO_4 -sites, and their effluents PO_4 -effluents. In the second set, nine systems (Sites 9 to 17) received wastes from households using CO_3 -built detergent. These are henceforward called CO_3 -systems, their locations CO_3 -

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sites, and their effluents CO₃-effluents. Three different types of septic systems were represented in the study; conventional systems at Sites 4 to 8, 13, 16, and 17; pressurized dosing systems at Sites 3, 9, 11, and 12; and mound systems at Sites 1, 2, 10, 14, and 15. Water meters and other plumbing arrangements were made to measure the water (hydraulic) load to individual septic systems.

Site Description

The soils were described in the field and classified in accordance with the USDA soil taxonomy system (Soil Survey Staff, 1975). Soils at Sites 2, 4, 6, 9, 10, 12 to 14, 16, and 17 were classified as Typic or Aquic Udipsamments. A Typic Udipsamment is an excessively drained, rapidly permeable soil that is formed in the sandy outwash of glacial lake deposits. An Aquic Udipsamment consists of deep, somewhat poorly drained, rapidly permeable soil that is developed in sandy outwash of glacial lake deposits. Sites 3, 5, 7, and 8 have soils that were classified as Hapludalfs; Site 1, Udiaqualf; Site 11, Eutrochrept; and Site 15, Haplaquoll. The soil parent materials at Sites 3 and 8 were loess overlying calcareous drift; Site 5, glaciofluvial sand overlying calcareous drift; Site 7, glaciofluvial sand; Site 1, sandy outwash of glacial lake deposits underlying loess; and Sites 11 and 15, loess.

Wide expanses of glacial lake deposits of former Lake Wisconsin and Lake Baraboo of mid-Wisconsinan age mantle the bedrock in the study area. In small parts of the study area, glaciofluvial deposits comprising sediments laid down in ephemeral fresh-water streams also existed. Geologic maps indicate that the thickness of unconsolidated material varies from site to site: 8 m at Sites 1, 2, 11, 14, and 15; 20 m at Sites 4, 9, 10, 12, 13, 16, and 17; and 40 m at Sites 3, 5 to 8. The water table was within 3 m of the land surface at each site.

The bedrock is of Cambrian age overlying the igneous and metamorphic rocks of the Precambrian age. The Cambrian rocks are primarily sandstones of the Elk Mound Group but include some siltstones, shales, and dolomites. They are clean, poorly sorted, fine- to coarse-grained sandstones that are locally well-indurated and cemented by silica and iron oxides. Sedimentary features include ripple marks, cross bedding, and numerous joints.

Detergents

Each homeowner was supplied *ad libitum* with PO₄- or CO₃-built detergent. Both detergents were white, granular, and contained normal sudsing anionic surfactants.

Surfactants comprising 18 and 22% in the PO₄- and CO₃-built detergents were linear alkylbenzene sulfonates (LAS), tallow alcohol sulfates, ethyloctyl sulfates, and sodium sulfosuccinates. Both detergents contained 0.9% polyethylene glycol.

The PO₄-built detergent contained 24% sodium tripolyphosphate, a builder and complexing agent, and 12% sodium silicate (SiO₂:Na₂O = 1.6) as corrosion inhibitor. The CO₃-built detergent contained 20% sodium carbonate (Na₂CO₃), a builder and a precipitating agent, and 20% sodium silicate (SiO₂:Na₂O = 2.4). The PO₄-built detergent also contained carboxymethylcellulose (CMC) as a suspending agent.

Whitening (fluorescent) agents made up 0.130 and 0.175% of the PO₄- and CO₃-built detergent. Perfume and dye were 0.15 and 0.14% in PO₄-built and 0.20 and 0.80% in CO₃-built detergents.

Sodium sulfate (Na₂SO₄), a filler and anti-caking material comprised 37 and 32%, and the remaining portion 6.0 and 4.0% was water for PO₄- and CO₃-built detergents, respectively.

Well Installation and Monitoring Network

The direction of local ground-water movement at each site was determined using a "Dowser" model 10 ground-water flow meter (K-V Associates, Falmouth, MA) by drilling a hole in the saturated zone 1 m below the water table using a 76-mm diameter Soil Conservation Service stainless steel bucket auger (Art's Machine Shop, American Falls, OR). The "Dowser" probe was then inserted immediately below the water level and oriented with an enclosed compass. This probe deploys a transient, radially emanating heat pulse that decays in response to ground-water flow direction. The movement of ground water caused heat conduction in the direction of flow, which was detected by a relative temperature rise between five pairs of diametrically opposed thermistors. The direction of ground-water flow at each site was determined by plotting a vector diagram from the differences in readings of the thermistor pairs, using the setting of the compass needle as reference point. The accuracy of the "Dowser" readings were confirmed by piezometric measurements at some sites.

Monitoring wells were constructed for installation at each site. The well casings were Schedule 40 polyvinyl chloride (PVC) pipe 3.8 cm in internal diameter; the well screens were 30 cm in length and fitted with PVC points, each with four rows of slits 0.15 mm in width, 25 mm long, and spaced 5 mm apart (Timco Mfg., Sauk City, WI). Shallow wells were installed by hand-augering through the

soil to or slightly below the water table using a 76-mm diameter Soil Conservation Service stainless steel bucket auger. Drillings were stored in sequence on a plastic sheet. A steel driving cap was placed in the end of the pipe, and the well was driven to 1 m below the water table using a post driver. Emergent pipe was cut off at the ground surface, and a rubber vacuum pump hose was inserted into the well. Water pumped from the well using a bilge pump and vacuum flask was squirted down the outside of the casing as the drillings from the hole were returned in the reverse order of the sequence in which they had been removed, to settle the sand by wetting and reconstitute the original soil profile. The top 1 m of the drilled hole was sealed with dry, pulverized bentonite clay (Quick-Jell, N. L. Baroid Industries, Houston, TX). After installation, each well was developed by pumping until the withdrawn water contained no visible sediments. The wells were capped with a screw-on top and secured.

Three interceptor wells for ground-water monitoring were placed in the effluent plume downflow in the hydrologic gradient from the drainfields of each septic system. Wells labeled 1 were 30 cm from the edge of the drainfields and those labeled 2 and 3 were downgradient at further intervals of 3 m. Background (control) monitoring wells labeled 4 were 10 m or more upgradient from the edge of the drainfields at each site. Additional wells labeled 5 were located adjacent to the drainfield at Sites 8 (a PO_4 -system) and 10 (a CO_3 -system).

Sampling and Monitoring

At sites with an effluent dosing pump (mounds and pressurized dosing systems), effluent samples were taken through the pump chamber manhole with a bailing device. At conventional systems, a 1-cm diameter Plexiglass tube was cemented into the clean-out plug of the septic tank and inserted into the effluent beyond the outlet baffle within the tank. A Tygon tube was attached to the Plexiglass tube and coiled between samplings in a recessed receptacle in the ground. Samples were withdrawn through these tubes using a manual bilge pump and vacuum flask flushed five times prior to sample collection. All effluent samples were collected at least once a month for a period of two years in 500-ml Nalgene bottles previously washed with acid and distilled water, and rinsed three times with septic tank effluent.

Water samples were collected periodically (usually monthly and for two years) from each monitoring well. Before sampling, water was pumped from each monitoring well using the bilge

pump and another acid-washed vacuum flask until a clear sample could be obtained or at least until three to five times the volume of the well had been removed. This assured that the sample came from the ground water and not from stagnant water in the well. Water samples (approximately 400 ml) were collected in new 500-ml Nalgene bottles washed with acid and distilled water, and rinsed three times with water from the well. Wells were always sampled in the sequence 4, 3, 2, 1, and 5.

Each effluent and water sample was chilled in ice in an insulated picnic cooler during transport to the laboratory, where it was refrigerated at 4°C for immediate analysis or frozen for later analysis.

After completion of the study, samples were collected from the ambient soil and clogging mat that formed naturally at the gravel-soil interface under the drainfield to examine whether PO_4 - or CO_3 -systems seemed more prone to failure by biological clogging. These samples were taken at three locations under each drainfield using a cased auger designed to drill through the gravel (Harkin *et al.*, 1979).

Analytical Methods

All effluent and ground-water samples were analyzed for Cl, TP, and TN. Effluent samples also were analyzed for TVS and VSS.

Chloride was determined by potentiometric titration on a model 4-2000 Buchler-Cotlove chloridometer (Cotlove *et al.*, 1958), TP by persulfate digestion with final determination by ascorbic acid (APHA *et al.*, 1980), and TN by a modified Kjeldahl method (Bremner, 1965). Solids were analyzed by gravimetric methods (APHA *et al.*, 1980). Triplicate determinations of organic carbon contents in ambient soils and clogging mats were made on composites of three samples from each site using a Leco induction furnace (Tabatabai and Bremner, 1970).

DATA ANALYSIS

The data for Cl, TP, and TN were pooled for effluent and ground-water samples from wells 1 to 5 at PO_4 - and CO_3 -sites. Summary statistics were conducted on these pools to establish the nature of the data.

The raw data exhibited means equal to or greater than medians, high coefficients of variation, and statistically significant positive coefficients of skewness and kurtosis and therefore positively skewed data populations. The Shapiro-Wilk test of normality was conducted on the raw data (Shapiro and Wilk, 1965); the test is very powerful—especial-

ly for small numbers of samples ($n \leq 30$) such as the concentrations for wells 5. In this test, the normalities were not confirmed at a significance level of $p = 0.05$, and the raw data came from populations other than normal.

It was inappropriate to draw conclusions on nutrient transport from simple statistical parameters such as means or medians which represent only normal distributions because the data batches were not from normal distributions, not equal in size, exhibited wide range in concentrations, and have high standard deviations. To accommodate all these uncertainties, statistical and transport models were essential to describe the complexity of movement of nutrients from septic systems and to adequately meet the objectives of the investigation. These models are described in the following sections:

A. Median-Polish Analysis

Median-polish statistical analyses (Tukey, 1977; Velleman and Hoaglin, 1981) were used to fit additive models for two-way tables. Each table involved three components—the row factor, column factor, and response. The row factor was the individual sites, the column factor was the sampling locations (effluent and/or wells 1 to 4), and the response was the nutrient concentrations.

The median-polish technique sweeps out information from the data table and places it in a common value term, a set of column effects, a set of row effects, and residuals through several stages approaching best fit. The sum of the common value, column effect, row effect, and residual is equal to the actual data value. The common value serves as a standard against which to measure trends. The effect values help to quantify any substantial variation of individual sites with sampling locations.

Data from Sites 3 and 13, however, had to be excluded from the median-polish analyses. A well 3 could not be installed at Site 3 because the subsoil (glacial till) had too many cobbles. Soon after installation, well 3 at Site 13 was found to be located in the privy pit of an old homestead house and was not subsequently sampled.

Two-way analysis of variance, i.e., ANOVA, uses the same additive model as the median-polish method, but it fits this model by finding row and column means using least-squares regression. On the other hand, the median-polish method fits medians using resistant line and iterative calculations. One major reason for use of medians in finding the additive fit, however, is to protect the results from being distorted by extraordinary values (outliers) and to show where true differences exist.

The median-polish technique is sensitive at $p = 0.05$. This level is reasonable for field research involving soil systems. Lower values are rarely obtained in work with soils, even in the laboratory, because of the innate variability in the properties of the medium.

B. Nutrient Transport Analysis

The transport analysis of nutrients involved three procedures: (1) the data sets were treated as populations represented by fitting natural log-normal distributions; (2) stochastic (random) values were generated from the moments of the fitted distributions using Monte Carlo simulations; and (3) the transport model was computed with the stochastic values.

Curve Fitting Procedure and Probability Distributions

Because of the complexity of processes occurring in septic systems, it is reasonable to suggest that the processes causing differences in the data were multiplicative rather than additive. Therefore, it was advantageous to transfer skewed distributions of the data into natural log-normal forms since many statistical conclusions are based on normal distributions.

The concentrations of Cl, TP, and TN in wells and effluent samples were best represented by natural log-normal distribution fitted by combining the maximum likelihood procedure for the two-parameter distribution with a technique which provides a reasonable estimate of the third parameter (Gilbert, 1987; Stedinger, 1980):

$$\hat{a} = (1/n) \sum_{i=1}^n \ln(x_i - \hat{c}) \quad (1)$$

$$\hat{b} = \left\{ (1/n) \sum_{i=1}^n [\ln(x_i - \hat{c}) - \hat{a}]^2 \right\}^{1/2} \quad (2)$$

where \hat{a} , \hat{b} , and \hat{c} were, respectively, the biased estimates of the population mean, population standard deviation, and the third parameter (lower boundary or the threshold of the distribution). The third parameter of Cl, TP, and TN concentrations for samples from wells was set at zero and for effluent samples at one-half of the lowest observed concentration. This setting of the third parameter was reasonable for the data accumulated and also provided the best observed fit. The maximum likelihood method was generally best for fitting log-normal distributions. However, Stedinger (1980) also found this method robust and that it performed well even when observations obeyed

other than log-normal distribution. The probabilities or frequencies were generated using the California formula of Viessman *et al.* (1972).

In comparison to measured levels, the fitted distributions were very good—individual natural log-normal distributions could not be rejected at $p = 0.05$ using the Kolmogorov-Smirnov goodness-of-fit test (Steel and Torrie, 1980); therefore, the data fit the natural log-normal distribution well. The effects of possible errors in the probability distributions for the various constituents on the fitted results were small and validated use of the fitted values with the nutrient transport analysis.

Stochastic Analysis and Nutrient Transport Model

The transport of nutrient M (here TP and TN) from a septic tank to ground water was evaluated in the following computational steps:

1. The volumetric fraction of effluent ($E_{i,j}$) in each ground-water plume sample (samples from wells 1 to 3 and 5) and iteration j in the Monte Carlo stochastic simulation (Wonnacott and Wonnacott, 1977) was estimated by equation (3) using Cl as a conservative tracer:

$$E_{i,j} = \frac{Cl_{i,j} - Cl_{b,j}}{Cl_{e,j} - Cl_{b,j}} \quad (3)$$

where Cl_i , Cl_b , and Cl_e were, respectively, the concentrations of Cl in plume, background (well 4), and effluent samples. This step showed the probability of having effluent present in the ground water at wells located downgradient from the drainfields.

2. For all iterations in which $E_{i,j}$ was > 0 , the nutrient transport from the septic tank to ground water was described as the percentage ratio of the actual increase in nutrient above background to the increase in nutrient above background if there was no retention by soil. Mathematically,

$$\% MT = \frac{M_{i,j} - M_{b,j}}{E_{i,j}(M_{e,j} - M_{b,j})} \times 100 \quad (4)$$

where % MT was the percentage of nutrient transported; and $M_{i,j}$, $M_{b,j}$, and $M_{e,j}$ were the concentrations of nutrient M in plume, background, and effluent samples and iteration j in a Monte Carlo simulation. The E factor in equation (4), the amount of effluent intercepted in each ground-water sample as judged from the Cl dilution according to equation (3), mitigated the uncertainty regarding the actual sampling location in the plume versus the true plume center since each well point did not necessarily intercept the center of the

plume. The values of % MT in equation (4) were calculated 150 times in the Monte Carlo analysis and constrained within limits of actual possible values from 0 to 100%. This number of iterations produced a fairly smooth empirical probability distribution.

The general approach is similar to the one used by Kerfoot and Skinner (1981) and by Gilliom and Patmont (1983), although the former used electrical conductivity rather than Cl as the effluent tracer and the latter worked with very limited data and applied background and effluent concentrations from a variety of published studies. The present approach used a large original data base from numerous comparable sites under field conditions.

The Monte Carlo simulation evaluated the effect of uncertainties (included in the wide range found for plume, background, and effluent concentrations of Cl and nutrients) on estimates of nutrient transport by standardizing all the data sets for better comparison. The stochastic analysis method represented the selected variables of plume, background, and effluent concentrations of Cl and nutrient as probability distributions rather than discrete values, and thus the apparent movement of nutrients from the septic systems to ground water were best described in probabilistic terms. Such a description is more representative of large areas, e.g., the five-county area where the sites were located, and is superior to the one based on discrete values.

Assumptions Made in the Nutrient Transport Model

The main assumptions used in the nutrient transport model and the likelihood of their validity are:

1. Chloride is a conservative tracer; i.e., it moves freely through the soil without retention or transformation so that any change in Cl concentration is due solely to dilution and dispersion. The validity of this assumption was established by Johnson *et al.* (1979) who found no retention of Cl by soils similar to those in south-central Wisconsin.

2. Septic tank effluent is the only nonbackground source of Cl and nutrient. No serious violations of this assumption were found at any site. The only conceivable noneffluent sources of Cl, TP, and TN are deicing salt and lawn fertilizer, but the background samples were from wells in lawn areas receiving the same treatments, if any, as the areas downgradient from drainfields. Thus,

"background" concentrations represent concentrations affected by all influences except septic systems.

3. Unassimilated or unsorted TP, TN, and Cl released from a septic tank and transported to any sampling well move at equal rates through the soil. This assumption is necessary to estimate nutrient dilution in individual samples based on Cl concentrations, but the assumption is difficult to assess in natural systems. Therefore, it is recognized as an unknown source of uncertainty in the analysis. However, the uncertainties were mitigated by the curve fittings and the Monte Carlo simulation analyses; the curve fittings and random simulations were essential components of the transport model.

RESULTS AND DISCUSSION

Statistical Summaries

Summary statistics for Cl, TP, and TN concentrations in septic tank effluents and ground-water wells from the PO₄- and CO₃-systems are presented in Tables 1 and 2. These tables describe the nature of the raw data sets.

The relatively wide range in concentrations was probably due to such factors as different amounts of diluting water (e.g., percolating rain water) in the soil at different periods of time (Pilgrim *et al.*, 1979) and changing patterns of human activity (e.g., use of fertilizers, nearby agricultural management practices, etc.). The TN medians in Table 2 (CO₃-systems) are consistently larger than those in Table 1 (PO₄-systems) by factors of 1.2, 1.2, 1.4, 1.1, and 1.1 for plume wells 5, 1, 2, 3, and effluent, respectively. However, conclusions on the transport of nutrients from the statistical summaries of the raw data cannot be made due to the large variability in the data that are not from normal distributions. To adequately quantify transport of nutrients from septic systems to ground water, modeling was necessary to obtain valid conclusions.

Effluent Transport

The movement of effluent from septic systems to plume wells was inferred from Cl concentrations. The stochastic analyses of Cl transport, i.e., the

Table 1. Summary Concentrations (mg/l) of Cl, TN, and TP in Septic Tank Effluents, Plume Ground Water (Wells 5, and 1 to 3), and Background (Well 4) Samples for PO₄-Systems

Parameter	n	m	\bar{x}/m	Min	Max	COV	g ₁	g ₂
<i>Effluent</i>								
Cl	117	75	2.6	16	830	1.0	1.1 ^c	0.33
TP	170	13	1.0	4.7	39	0.37	1.3 ^c	4.6 ^b
TN	170	63	1.2	10	130	0.39	0.56 ^c	-0.90
<i>Well No. 5</i>								
Cl	27	300	1.0	6.0	910	0.82	0.49	-0.74
TP	30	0.06	8.8	<0.10	2.3	1.5	1.3 ^b	-0.08
TN	30	28	0.80	0.70	40	0.56	-0.66	-1.11
<i>Well No. 1</i>								
Cl	143	42	1.2	0.50	290	1.0	2.6 ^c	8.9 ^b
TP	147	0.01	3.0	<0.10	0.21	1.1	2.4 ^c	6.9 ^b
TN	148	20	1.4	0.20	110	0.99	0.95 ^c	0.15
<i>Well No. 2</i>								
Cl	151	18	3.6	<0.50	560	1.9	2.4 ^c	4.7 ^b
TP	151	0.02	1.0	<0.10	0.14	0.87	2.2 ^c	7.7 ^b
TN	152	8.1	2.7	0.10	120	1.2	1.4 ^c	1.5 ^b
<i>Well No. 3</i>								
Cl	123	21	2.8	0.06	330	1.6	1.8 ^c	1.8 ^b
TP	125	0.01	2.0	<0.10	0.20	0.88	1.9 ^c	5.5 ^b
TN	125	6.9	2.5	<0.10	170	1.5	2.7 ^c	9.2 ^b
<i>Well No. 4</i>								
Cl	121	5.3	1.3	<0.50	30	0.97	1.1 ^c	0.37
TP	121	0.01	3.0	<0.10	0.20	1.2	1.9 ^c	3.7 ^b
TN	124	1.1	2.0	0.10	23	1.4	3.9 ^c	19 ^b

n = number of samples; \bar{x}/m = mean to median ratios; Min and Max = minimum and maximum values;

COV, g₁, and g₂ = coefficients of variation, skewness, and kurtosis. These abbreviations are used throughout the tables.

a, b, and c show significance at p = 0.05, 0.01, and <<0.01, respectively.

Table 2. Summary Concentrations (mg/l) of Cl, TN, and TP in Septic Tank Effluents, Plume Ground Water (Wells 5, and 1 to 3), and Background (Well 4) Samples for CO₃-Systems

Parameter	n	m	\bar{x}/m	Min	Max	COV	g_1	g_2
<i>Effluent</i>								
Cl	124	54	1.0	1.0	110	0.39	0.05 ^c	-0.01
TP	187	7.0	1.1	2.8	30	0.45	3.0 ^c	14 ^b
TN	186	72	1.0	37	140	0.32	0.73 ^c	0.09
<i>Well No. 5</i>								
Cl	26	43	1.0	0.30	78	0.61	-0.17	-1.4
TP	26	0.01	2.0	<0.10	0.10	1.3	1.8 ^b	2.6
TN	26	35	1.1	1.3	78	0.55	0.06	-0.43
<i>Well No. 1</i>								
Cl	165	28	1.0	<0.50	76	0.73	0.26	-0.74
TP	170	0.02	1.0	<0.10	0.20	0.92	2.3 ^c	9.2 ^b
TN	172	24	1.1	0.20	110	0.76	0.90 ^c	1.0 ^a
<i>Well No. 2</i>								
Cl	151	17	1.2	<0.50	77	0.99	0.97 ^c	0.03 ^b
TP	152	0.01	3.0	<0.10	0.20	0.78	1.6 ^c	2.6 ^b
TN	154	11	1.7	0.60	75	0.99	1.1 ^c	0.00 ^b
<i>Well No. 3</i>								
Cl	141	3.1	4.2	<0.50	75	0.78	1.9 ^c	2.9 ^b
TP	142	0.01	3.0	<0.10	0.10	0.72	1.7 ^c	2.0 ^b
TN	143	7.8	1.8	0.30	68	1.2	1.4 ^c	0.62 ^a
<i>Well No. 4</i>								
Cl	153	5.3	2.7	<0.50	120	1.5	2.4 ^c	5.8 ^b
TP	154	0.03	8.7	<0.10	2.3	2.3	2.2 ^c	3.3 ^b
TN	153	2.4	4.0	0.10	65	1.5	2.1 ^c	3.7 ^b

solutions to equation (3) for the combined plume wells at the PO₄- and CO₃-sites are shown in Table 3.

Table 3 shows that the calculated amounts of effluent in combined samples from the plumes at the PO₄- and CO₃-sites averaged 39 and 45%. The closeness of the Cl transport values between the PO₄- and CO₃-sites indicate that the plumes at these sites were intercepted by the wells similarly.

Phosphorus

To examine the potential for TP to reach ground water from septic systems, two-way analyses by median-polish were performed. The best-fitted models are reported in Table 4 for the PO₄-, CO₃-, and combined septic systems.

Table 3. Percentage of Septic Tank Effluent Intercepted (% E_{i,j}) for the Combined Plume Wells at PO₄- and CO₃-Sites Calculated Using Equation (3)

Sites	n	\bar{x}	90% Confidence interval	m
PO ₄	595	39	38-40	37
CO ₃	444	45	35-54	21

Table 4. Median-Polish Analyses of TP (mg/l) as Tracer of Pollution Plumes from 15 Septic Systems

Location/site	PO ₄ -systems	CO ₃ -systems	Combined systems
<i>Column effects</i>			
Effluent	12	7.0	9.5
Well 1	0.000	0.000	0.000
Well 2	0.000	0.000	0.000
Well 3	0.000	0.000	0.000
Well 4	0.000	0.004	0.000
<i>Row effects</i>			
1	0.02		0.02
2	0.00		0.00
4	0.00		0.00
5	0.00		0.00
6	0.01		0.01
7	0.03		0.03
8	0.00		0.00
9		0.00	0.00
10		0.01	0.01
11		0.06	0.06
12		0.00	0.00
14		0.02	0.00
15		0.00	0.00
16		0.00	0.01
17		0.00	0.00
Common value	0.01	0.01	0.01

Sites 1, 7, 11, and 14 showed relatively high TP row effects in excess of the common value; the septic systems at these sites transported some P to ground water (Table 4). However, the TP column effects for plume wells at all sites were equal to or less than the TP column effects for the background wells. Therefore, no difference was found with respect to ground-water contamination by TP regardless of whether the septic systems received waste water from PO₄-built or CO₃-built detergent use.

Transport of Phosphorus

Statistical summaries and probability distributions of the percent TP transported to all plume wells combined for PO₄- and CO₃-systems are shown in Table 5.

There was a 10% probability that more than 1% of the TP in the effluent reached ground water from PO₄-systems versus none from CO₃-systems, and there was a 50% probability that neither detergent caused delivery of any TP to ground water (Table 5). The mean TP transported from both systems, however, was <1%, i.e., <0.1 mg/l. The desired goal for the prevention of plant nuisances in streams or other flowing waters not discharging directly to lakes or impoundments is 0.1 mg/l TP (U.S. EPA, 1986). There was no probability that more than 4.4 and 2.5% of the TP in the effluent reached ground water from PO₄- and CO₃-systems, respectively. These estimates indicated that the TP intercepted in plume samples from septic systems was never more than 0.6 and 0.2 mg/l when PO₄-built and CO₃-built detergent was in use and is below the recommended TP level of 1.0 mg/l for effluent discharges to surface water from sewage treatment plants (Harrington-Hughes, 1978).

Total Nitrogen

Best-fitted median-polish analyses using TN concentrations for each system as the response, sampling location as the column factor, and site as the row factor are presented in Table 6.

Data in Table 6 reveal that the TN concentrations in plume wells were higher than background,

Table 6. Median-Polish Analyses of TN (mg/l) as Tracer of Pollution Plumes from 15 Septic Systems

Location/site	PO ₄ -systems ^a	CO ₃ -systems	Combined systems
<i>Column effects</i>			
Effluent	1.2	49	45
Well 1	0.1	3.5	2.7
Well 2	0.0	0.0	0.0
Well 3	-0.5	-0.5	-0.3
Well 4	-2.6	-5.9	-6.7
<i>Row effects</i>			
1	-0.3		-1.0
2	0.3		20
4	-0.1		-2.2
5	0.0		4.4
6	1.2		50
7	0.5		20
8	-3.1		-7.9
9		-3.2	-1.3
10		0.5	0.0
11		0.5	0.2
12		19	20
14		30	30
15		-0.5	0.0
16		-6.7	-7.1
17		-5.7	-3.4
Common value	2.9	8.5	8.8

^aPower of re-expression is natural logarithm for the PO₄-systems.

and TN in ground water decreased with distance from the drainfield (column effects for TN in wells decreased with distance from the drainfield). No TN row effect exceeded the common value for PO₄-sites but did for Sites 12 and 14 among the CO₃-sites. The average row effects of TN concentrations were 1.3 mg/l for PO₄-systems versus 4.2 mg/l for CO₃-systems (2.9 mg/l higher or an increase by more than two times with CO₃-built detergent use); this indicates that considerably more TN reaches ground water when phosphate-free detergent is used.

Transport of Total Nitrogen

Table 7 depicts simulations as statistical summaries and probability distributions of trans-

Table 5. Transport of TP (% MT) to Plume Wells from PO₄- and CO₃-Systems Calculated Using Equation (4)

Systems	n	\bar{x}	90% Confidence interval	Probability (%)				
				m	0	5	10	50
PO ₄	595	0.52	0.35-0.70	0.13	4.4	1.9	1.3	0.00
CO ₃	444	0.05	0.02-0.08	0.00	2.5	0.36	0.00	0.00

Table 7. Transport of TN (% MT) to Plume Wells from PO₄- and CO₃-Systems Calculated Using Equation (4)

Systems	n	\bar{x}	90% Confidence interval	Probability (%)				
				m	17	50	80	100
PO ₄	595	54	51-57	45	100	46	15	0.0
CO ₃	444	94	92-96	100	100	100	93	28

Table 8. Summary Statistics of TVS and VSS Loadings (kg/yr) of Septic Tank Effluent and C Content (%) of the Clogging Mats at PO₄- and CO₃-Sites

Parameter ^a	PO ₄ -sites					CO ₃ -sites				
	n	\bar{x}	m	Min	Max	n	\bar{x}	m	Min	Max
TVS	170	426	427	65	2970	187	384	334	28	1818
VSS	170	100	86	2.7	1514	187	84	70	1.7	502
C	21	0.67	0.39	0.18	2.4	24	0.27	0.21	0.01	0.68

^aThe C content values are from three determinations on samples from three boreholes at the clogging mat in each septic system drainfield and the background soil, and represent the difference between the C content in the clogging mats and background soils.

ported TN at plume wells combined for PO₄- and CO₃-systems.

There was an 80% probability that more than 46% of TN in the effluent reached ground water from PO₄-systems versus 93% from CO₃-systems (Table 7). The intercepted mean TN in plume samples were 54 and 94% from PO₄- and CO₃-systems; this corresponds to TN concentrations of 39 and 69 mg/l as N reaching the ground water from septic systems with PO₄- and CO₃-built detergent use.

The use of PO₄-built detergent caused substantially lower concentrations of TN in the leachates from septic systems apparently due to higher efficiency of TN removal by denitrification in the clogging mat or soil. The greater amount of P reaching soil from PO₄-built detergent use in the households (mean TP concentrations in effluents were 13 mg/l from PO₄-systems vs. 7.7 mg/l from CO₃-systems; Tables 1 and 2, respectively) may have stimulated the prolific growth of denitrifying bacteria accumulating polyphosphate and poly-β-hydroxybutyrate simultaneously by "luxury consumption" (Nicholls and Osborn, 1979). A direct relationship between denitrification and P application and uptake by denitrifying bacteria has been reported in fertilizer-amended soils (Minami and Fukushima, 1983; Stepanov and Umarov, 1984) and in waste waters (Mycielski *et al.*, 1982). Nitrogen losses due to denitrification occurred with large P applications of 47 mg P/kg soil (Stepanov and Umarov, 1984). Nitrous oxide evolved from ammonium-treated soils increased from 1.2- to 4.2-fold with the application of 5.7 mg P/10 g soil for 12 days of incubation (Minami and Fukushima, 1983). Highest denitrification efficiency and increased biomass occurred with high P uptake in waste water with P concentrations of 15 to 50 mg/l (Mycielski *et al.*, 1982).

A higher energy source was also provided to the bacteria in the soil by effluents from PO₄-systems compared to CO₃-systems (Table 8). Table

8 shows that the amount of carbon (C) in the clogging mat averaged 2.5 times more at PO₄-sites than at CO₃-sites. The TVS and VSS loadings—indicators of organic content—also are higher from PO₄-effluents than CO₃-effluents. The high C content at PO₄-sites may be detrimental to the longevity of septic systems by reducing the infiltrative rate of septic tank effluent into the soil because C is considered the prime agent responsible for clogging of soil infiltrative surfaces in the drainfields of septic systems (Kristiansen, 1981; Thomas *et al.*, 1966). However, organic C produced from septic tank effluent is readily degraded, and denitrification decreases N in the liquid-soil system (Magdoff *et al.*, 1974; Magdoff and Keeney, 1975). The high organic C content is therefore beneficial to the performance of septic systems because it reduces N loadings to ground water by enhancing denitrification and N loss to the atmosphere. PO₄-built detergent use increases septic tank effluent and drainfield soil C content and decreases the N level in the intercepted plumes in ground water.

Detergent manufacturers are responding to U.S. demographic changes, consumer preferences, and geographic restrictions on builder use by introducing new product formulations, and their watchword is convenience. To reduce the P content of municipal sewage, voluntary and statutory restrictions have been introduced to limit the use of sodium tripolyphosphate builder (STPP) in detergents (Taylor, 1980). Detergent phosphates are banned in seven U.S. states and 27 cities; limited to an amount in grams per wash in three more states, four counties, and 12 cities; and banned or restricted by law in six countries, with voluntary restrictions honored in four more countries (Stinson, 1987). The principal organic contenders for replacement of STPP used are trisodium nitrilotriacetic acid (Na₃NTA), sodium citrate, sodium carboxymethyltartronate (CMT), and sodium carboxymethyloxysuccinate (CMOS). The inorganic builder zeolite A has been used as a partial substi-

tute for STPP along with sodium carbonate.

Na₃ NTA, a soluble and effective chelating agent, is used in Finland, Sweden, Switzerland, the Netherlands, Norway, and Canada but is not used in Japan and the U.S.A. because it was voluntarily discontinued by the detergent industry following what were later shown to be erroneous safety testing results (Stinson, 1987). Zeolite A, which softens water by ion exchange, is widely used in Japan and the U.S.A. Sodium citrate has candidacy for use in liquid detergents, but is expensive and has weak sequestrancy for calcium and magnesium. CMT has biodegradability and acclimatization problems under anaerobic conditions; CMOS has more complexing power than citrate but has problems of acclimatization in sewage treatment plants (Barth *et al.*, 1979; Lamberti, 1977).

The impact of these alternative formulations on ground-water quality in unsewered areas is not known. The present investigation has shown that use of CO₃-built detergent in households served by septic systems influences septic system performance and exacerbates N leachate to ground water. Septic system leachate has implications for human health and environmental hazard and is a serious concern because it occurs in locations where ground water is being withdrawn for drinking water. Consequently, effects of other detergent formulations should be deliberated. For example, Zeolite A-built detergent may enhance clogging of septic system drainfield infiltrative surfaces, thereby influencing performance and reducing system longevity. Zeolite A is framework aluminosilicate that softens wash water by exchanging sodium for hardness cations in solution. Sodium-saturated Zeolite A swells in water and may infiltrate into and clog soil pores, physically impeding effluent percolation and causing waste water to surface or back up in the house, resulting in system failure. It may also shrink as the ionic strength of waste water or soil solution increases causing cracks in the clogging mat, an increase in the infiltration of waste water through soil, and a possible enhancement of ground-water pollution.

CONCLUSIONS

Statistical analyses and stochastic transport modeling of a large, two-year data base from two groups of septic systems receiving detergents of two types led to the following conclusions:

- The TP transported to ground water from septic systems does not exceed a mean of 1% or <0.1 mg/l for sites using PO₄-built and CO₃-built detergents, the level EPA recommends to control

eutrophication at points where waters are not discharging directly to lakes and streams. Therefore, neither detergent type contributes to ground-water pollution by P, and properly functioning septic systems are not a source of P to ground water, are not a biological nuisance, and do not contribute to lake eutrophication. Other investigators (Fetter, 1977; Reneau and Pettry, 1976; Sawhney and Hill, 1975; Tofflemire and Chen, 1977) have observed similar results with regard to P removal from waste water by sandy soils in laboratory and field experiments. The present investigation quantifies TP transport from septic systems in the field and shows it to be negligible.

- Septic systems are sources of N to ground water, and the detergent formulation substantially influences the operation of septic systems in this respect. The PO₄-built detergent improves the efficiency of N removal during effluent percolation through septic system drainfields and reduces the N level in the intercepted plumes without any significant effect on the P concentrations of ground water. The CO₃-built detergent use causes TN level in the intercepted plumes to increase by 77%, compared to PO₄-built detergent use. Further research is recommended to test other formulations presently on the market and those being manufactured for future use.

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