LAKE PHOSPHORUS LOADING FROM SEPTIC SYSTEMS BY SEASONALLY PERCHED GROUND WATER, PUGET SOUND REGION, WASHINGTON

By Robert J. Gilliom and Clayton R. Patmont

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Lake Phosphorus Loading from Septic Systems by Seasonally Perched Ground Water, Puget Sound Region, Washington

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ABSTRACT

In a previous study, estimated phosphorus (P) loadings from septic systems to lakes in the Puget Sound region were found to be correlated with old homes around the lakes. In the present study, an assessment was made of the movement of septic-effluent P in seasonally perched ground water near Pine Lake, a typical glacial-till lake in the region. Ground water occurs in soils overlying less permeable glacial till around Pine Lake and many other lakes in the area. Water samples were taken from 15 shallow ($<$ 1.5 meters) wells installed 10-50 meters downgradient from seven septic systems 20 to 40 years old. The equivalent volumetric fraction of each sample consisting of undiluted effluent was estimated from chloride concentration. A Monte Carlo analysis was used to account for the various sources of uncertainty. Although movement of diluted septic effluent to the lake was found to be common, transport of more than 1 percent of effluent P through the soil was probable ($p \geq 0.5$) for only 4 of 26 samples. For only 1 of those 4 samples transport of more than 10 percent of effluent P was probable. The highest probabilities of P movement were associated with two samples from a well that was downgradient from a drainfield located at the base of a hillslope depression where perched ground water concentrates and remains for extended periods. All evidence considered, most P loading to Pine Lake from septic systems appears to come from only a few older systems located in areas where perched ground-water flow and associated saturated soil conditions predominate for extended periods during the winter season.

INTRODUCTION

Eutrophication resulting from nutrient enrichment caused by human activities is a widespread water-quality problem for both urban and rural lakes throughout the United States. The Puget Sound region (fig. 1) contains more than 500 lakes which have a wide range of nutrient levels and land-use settings. The main anthropogenic sources of nutrients for these lakes are nonpoint sources associated with agricultural and residential areas. Though these sources may contribute to loadings of all the major nutrients affecting aquatic plant growth, phosphorus (P) is the limiting and most controllable nutrient in the majority of lakes in the world (Vollenweider, 1968; Schindler and Fee, 1974; Schindler, 1977; Rast and Lee, 1978; and Schindler, 1978) and also in the Puget Sound region (Gilliom and Bortleson, in preparation). The large number of lakes in this region, the

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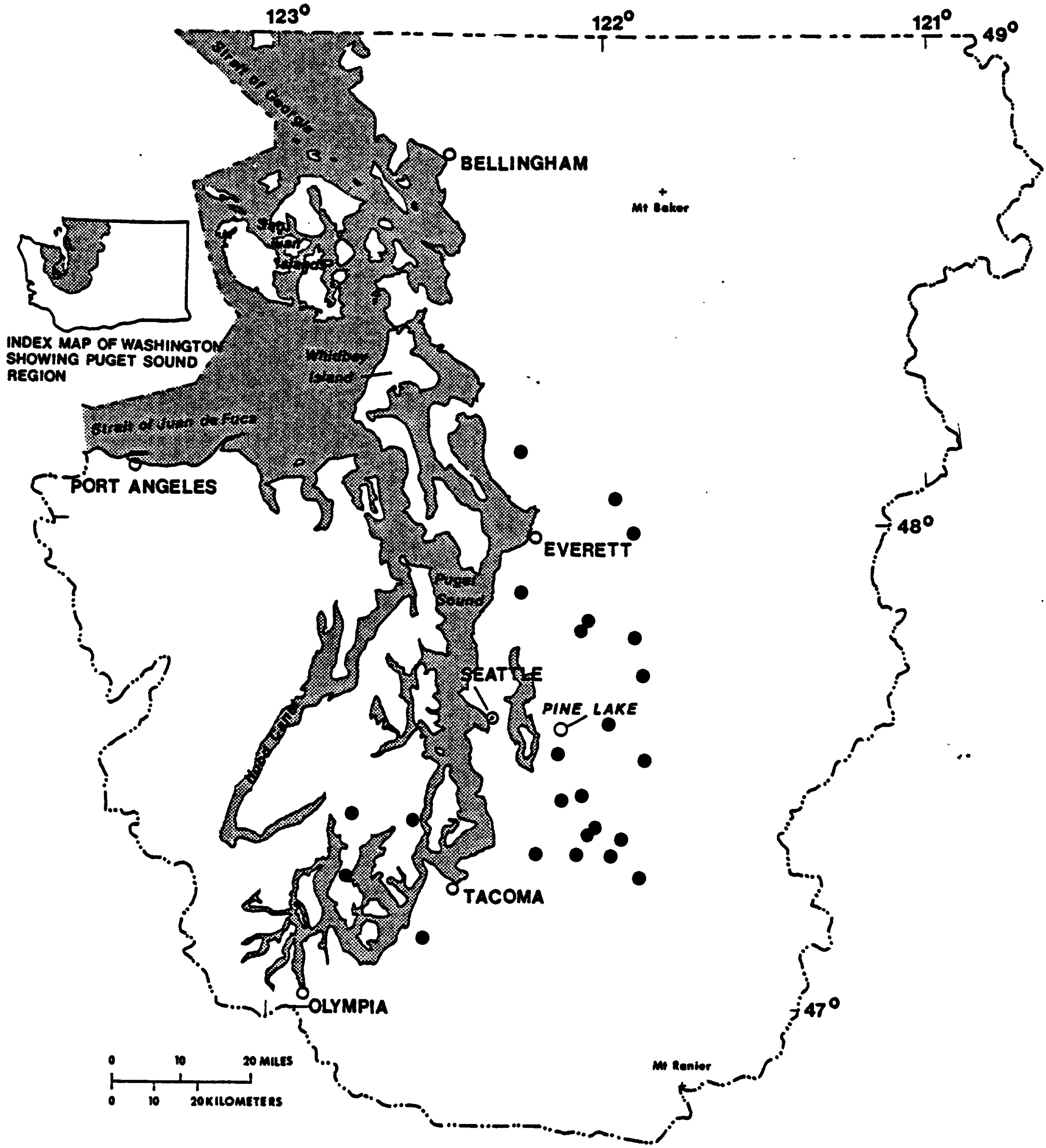

Figure 1.--Location of Puget Sound region and lakes studied.

increasing use and development of the lakes, and the difficulty of assessing and managing nonpoint-source P loadings, make control of eutrophication a pressing and difficult task for local and State agencies.

A potential source of P loading for many lakes is septic-tank and drainfield systems, hereafter referred to as septic systems, located near lakeshores. Septic-system effluent typically contains about 1,000 times the concentration of P in lake waters; 15 mg/L compared to 0.015 mg/L. Past and present development trends favor the establishment of permanent residential development around highly desirable lakeshores long before adjacent rural areas are developed. A substantial and growing number of lakes have been surrounded by near-shore septic systems for many years. Moreover, present policies relating to public sewer extensions tend to favor reliance on septic systems as permanent means of wastewater disposal in outlying areas. Thus, septic systems likely will continue to be possible sources of P for many lakes for the forseeable future.

The objective of this study was to assess the possible causes of septic-system P loading to lakes formed in glacial-till terrain, a common type of lake in the Puget Sound region. Two types of investigations were combined along with inferences from the literature: (1) a previously completed regional evaluation of P loadings that showed a correlation between estimated septic-system P loadings and the presence of old lakeshore homes (Gilliom, 1982), and (2) a field study of lake P loading from old septic systems at Pine Lake, a lake typical of many in the region that are in glacial-till terrain. In this paper, the regional study is summarized and the case study is described in detail. Because glacial till and old septic systems often occur together near lakes in the region, the findings of this study should be valuable throughout the region.

MOVEMENT OF PHOSPHORUS THROUGH SOIL

Soils generally act as extremely efficient filters for removing P from wastewater. Many studies of the movement and retention of P in soils were reviewed and discussed by Jones and Lee (1977) and Sommers and others (1977). Removal of more than 95 percent of P from wastewater is common after passing through a few meters of soil. In acidic soils, such as those typical of the Puget Sound region, most P is probably sorbed by exchangeable and amorphous forms of aluminum and iron (Ballard and Fiskell, 1974). Additional mechanisms are discussed by Stumm and Morgan (1970).

Though efficient retention of wastewater P by soils near the septic drainfield appears to be typical of most systems, the presence of saturated soil conditions in and near a drainfield may lead to reduced P removal (Reneau and Pettry, 1976; Viraraghavan and Warnock, 1976; Shawney and Starr, 1977). Enhanced movement of P under saturated conditions may be caused by (1) low redox potentials, which favor a high equilibrium P concentration in soil solution (Patrick and others, 1973), and (2) more rapid movement of water through the soil, which results in shorter contact times between effluent and soil-particle surfaces. Saturated conditions also restrict the downward movement of effluent through soils near a drainfield, and can sometimes lead to system failure and the surfacing of effluent and transport by overland flow. Other factors that may lead to enhanced movement of P through soil are a coarse soil matrix that permits more rapid flow and has less surface area for sorption than finer textured soil, and saturation of P sorption sites by continued application of wastewater over a long period (Sommers and others, 1977; Dudley and Stephenson, 1973).

REGIONAL EVALUATION OF SEPTIC-SYSTEM PHOSPHOROUS LOADING

The regional assessment of septic-system P loading summarized from Gilliom (1982) played a key role in the present study by narrowing the scope of the Pine Lake study to old systems. In the regional assessment, the relationships between estimated septic-system P loadings and key explanatory variables were investigated.

Environmental Setting

The Puget Sound region has a mild maritime climate characterized by cool, wet winters and warm, fairly dry summers. Average precipitation in the lowland portion of the region ranges from 0.5 to 2.0 m/yr depending on elevation, location relative to rain-shadow effects of the Olympic Mountains, and orographic effects of the Cascade Range. About 80 percent of the precipitation occurs from October through April.

Most lakes in the Puget Sound lowland occupy depressions in glacial till or outwash deposited during the most recent continental glaciation. Soils surrounding the lakes are mainly gravelly sandy loams less than 1 m thick, overlying either till or outwash. Soils in the glacial-till setting are usually characterized by Alderwood soils and soils in outwash settings by Everett soils (Snyder and others, 1973). Both soils are moderately acid, with a pH of 5.1 to 6.0, and typically have a cation exchange capacity less than 20 millequivalents per 100 grams of soil.

The compact, cemented nature of the glacial till underlying Alderwood soils causes unique hydrologic conditions because of its low permeability. Anderson and others (1947) described the till as a mixture of roughly rounded cobbles, gravel, sand, and fine interstitial cementing material that generally conforms to land slopes. They note that the top of the till is generally covered with a fine mat of roots, and, though water percolates through slowly, the soil material just above the till is saturated during periods of winter rains. Because the saturated zone is caused by the abrupt change in permeability between the soil and the till (the till may or may not be variably saturated at different times), the water in the saturated zone has been called perched ground water in this report.

Phosphorous Loading Assessment

Septic-system P loading was estimated for 24 lakes (fig. 1) that had undeveloped, forested drainage basins except for a concentrated ring of single-family dwellings around the lakeshore. All the lakeshore homes use septic systems for wastewater disposal. For each lake, the difference between estimated present-day P loadings and estimated background P loadings was calculated. Present-day loading was estimated from measured lake-water P concentrations for each lake and background loading was estimated from an empirical relationship developed from data for undeveloped lakes in the region. The difference between present-day and background loading is an estimate of residual loading associated with anthropogenic sources. To estimate the amount of residual loading attributable to septic systems, loading by surface runoff from the residential areas, which was estimated from data for four urban lakes, was subtracted from total residual loading.

These estimates of septic-system P loading for the 24 lakes provided the basis for a statistical evaluation of septic-system loadings on a regional scale. Because of the indirect method used to calculate septic-system loading and the inherent variability of such loading, the variance in the sample was large. The mean septic-system loading for the 24 lakes was 5.6 kg/yr with a standard deviation of 14 kg/yr and the median was 3 kg/yr. The variations between lakes were not related to whether a lake was in a glacial-till or outwash setting, and annual precipitation was fairly similar at between 1.0 and 1.5 m for all lakes evaluated. These initial observations led to tests for statistical relationships between the number of dwellings within about 75 m of the lakes in 1970 (data from Bortleson and others, 1976) and estimated loadings from septic systems using linear-regression analysis. No significant correlation was found between the 1970 dwelling counts and septic-system loadings.

The possible relationship between P loading from septic systems and older development was then evaluated. Total numbers of near-shore buildings present around the lakes in 1940, 1950, and 1960 were estimated from U.S. Geological Survey topographic maps. These building counts, which are useful empirical indicators of the number of residences around the lake, were treated as the independent variables in three separate regression tests with estimated loadings. The number of buildings present around a lake in 1940 explained 36 percent of the variance in estimated P loadings (fig. 2); the more buildings present in 1940, the higher the estimated impact. A much poorer, though significant ($\alpha = 0.05$), relationship was found between the number of buildings in 1950 and loading. No significant correlation was found between the number of buildings in 1960 and loading. Multiple-regression relationships based on building counts from more than one year, or including a factor for geologic setting, did not explain more of the variance than 1940 buildings alone.

The overall conclusion from the study was that, on a regional basis, the only significant P loadings from septic systems during 1970-75 were occurring at lakes where substantial lakeshore development had already occurred 20 to 30 years ago. An important question for lake management is whether this relationship between older development and septic-system loadings can be attributed to an inevitable reduction in P treatment efficiency of all septic systems with age, or to a few old systems that were improperly installed or situated. If the efficiency of all systems deteriorates with age, then corrective actions might have to be directed towards eliminating the long-term use of septic systems near lakes. But, if only a few malfunctioning systems contribute P to lakes, then corrective actions may be effectively directed at repairing or replacing those few systems.

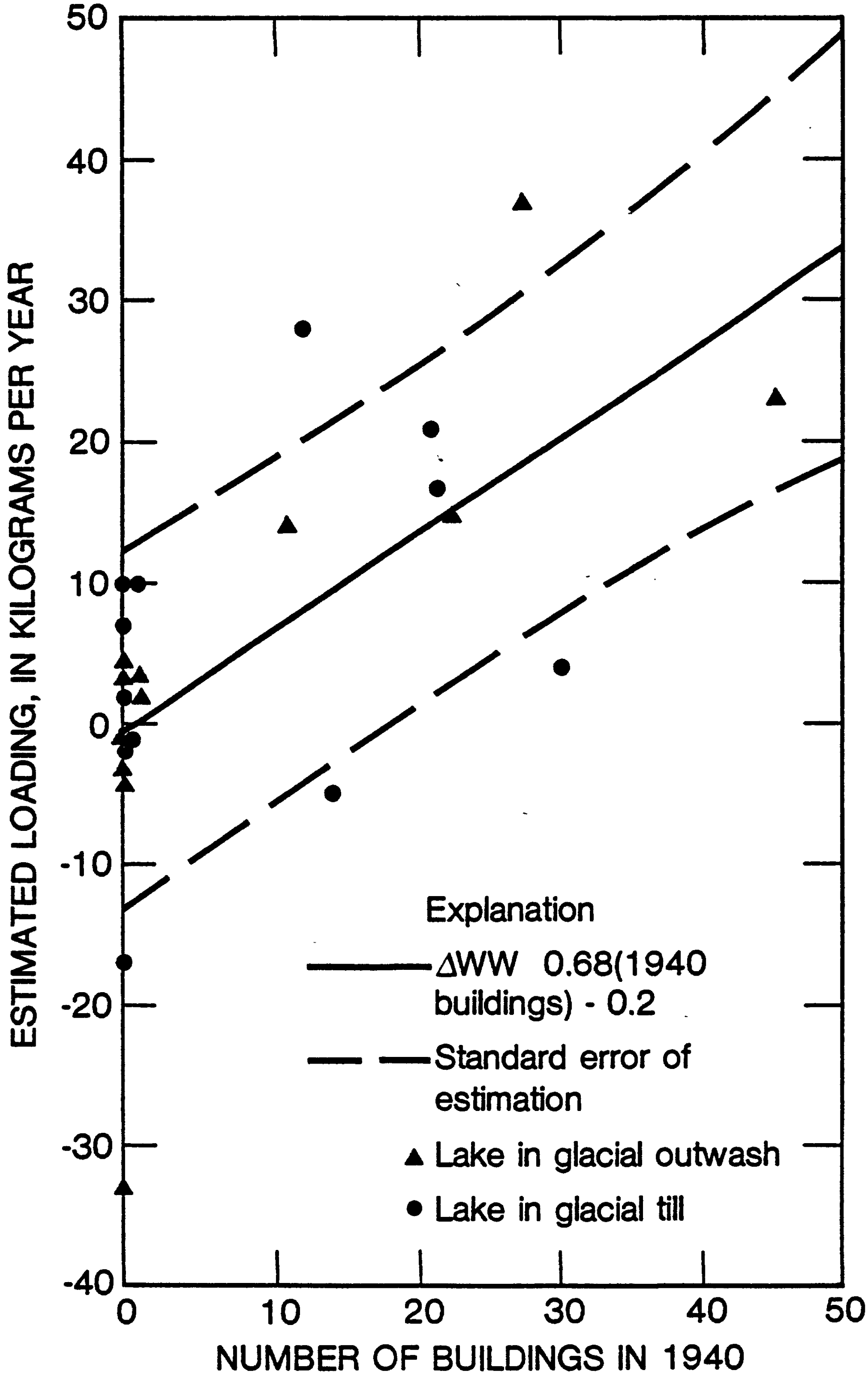

Figure 2.--Relationship between estimated phosphorus loading from near-shore septic systems and numbers of near-shore buildings present in 1940.

PINE LAKE CASE STUDY

The case study of Pine Lake was undertaken to determine how P is moving to lakes from old septic systems in glacial-till terrain. Our specific goals were to determine (1) whether septic effluent is entering Pine Lake in perched ground water flowing laterally through soil overlying the glacial till, (2) whether any P in such effluent is reaching the lake, and (3) whether the movement of P is fairly uniform among most old systems or is mainly occurring at only a few systems, and why.

Characteristics of the Pine Lake Drainage Basin

Pine Lake is a lowland lake formed in glacial till. Its location in the region is shown in figure 1. The lake has an area of 36 ha, a maximum depth of 12 m, and a surface elevation of 119 m above sea level. It is located in a 320 ha basin with rolling terrain averaging 6-15 percent slope. The main water inputs to the lake, estimated by Harper-Owes (1981), are direct precipitation (~ 36%), intermittent inflow streams (~ 28%), the outflow of a 17-hectare marsh (~ 21%), and perched ground water flowing along the till surface (~ 14%). About 83 percent of the drainage basin is covered by Alderwood soils, which were described earlier.

About 300 of the 900 present-day residents in the Pine Lake basin reside within 50 m of the lakeshore (Harper-Owes, 1981). Although the basin population is growing by roughly 25 people annually, lakeshore development has nearly stabilized at a saturation level and all but a few homes are year-round residences. Septic systems within the basin, and especially near the lakeshore, vary substantially in age, distance to the lake, and wastewater loading. There are a sustantial number of homes more than 20 years old around Pine Lake, and most of these use the original septic system installed with the home. Several septic systems are located within 20 m of the lake.

Data Collection

Thirty-three monitoring wells were installed around the shoreline of the lake, with 26 located downslope from 8 septic-system drainfields used throughout the year that ranged from 20 to 40 years old. Five wells were located in three areas known to be free of septic systems and two additional wells were located near a six-year old system. The only well at one of the eight old systems never had enough water to obtain a sample. Locations of the remaining seven old systems, the focus of this study, are shown in figure 3, and the seven sites and wells at which sampling was successful are described in table 1. It became apparent following the start of the study that effluent from one of the systems frequently emerged at the land surface near the drainfield and flowed overland into the lake. This waste stream was also monitored.

Most monitoring wells, which ranged from 41 to 130 cm deep, were installed as near to the lake as possible without risking temporary positive gradients from the lake to the wells when the lake level fluctuated. Some wells, however, had to be located according to property-owner stipulations and were farther from the lake. The bottoms of all wells were located above maximum lake level, which fluctuated 15 cm during February, 1981 (N. P. Dion, oral commun., 1982).

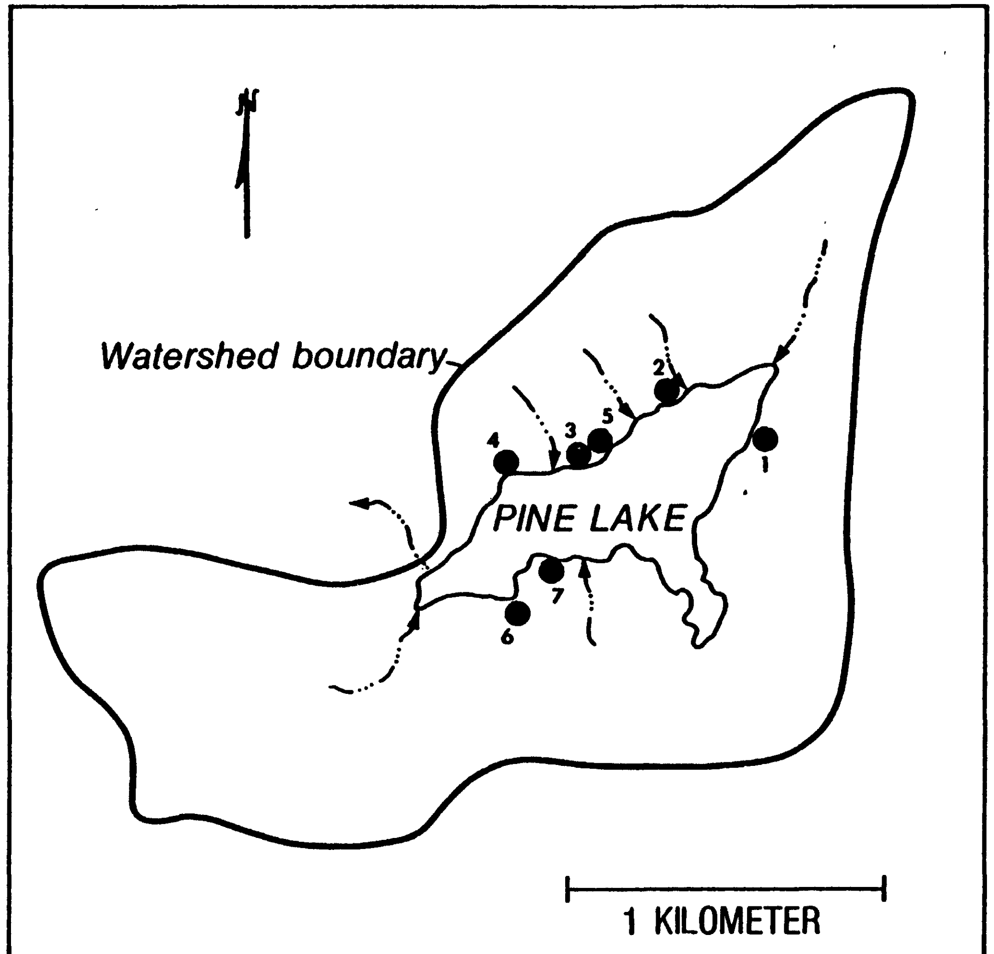

Figure 3.--Pine Lake basin and locations of study sites.

Table 1--Well characteristics and observed water levels.

Site	Approximate land slope in vicinity of wells (percent)	Well	Approximate catchment area (ha)	Distance from lake (m)	Approximate distance from drainfield (m)	Depth of well (cm)	Depth of water in well (cm) 2/13/81	2/17/81	2/25/81
1	5-10	1	0.4	20	10	90	22	32	0
		2	.4	4	30	41	21	23	12
		3	.4	4	30	43	26	24	11
		4	.4	5	30	46	30	30	0
		5	.4	5	30	46	25	23	0
2	0-5	1	1.8	3	10	73	51	49	37
3	5-10	1	.5	4	30	84	76	66	--
4	0-5	1	.4	6	9	120	100	72	63
		2	.4	6	9	82	30	38	32
		3	.4	4	10	96	44	41	37
		4	.4	3	10	130	29	32	27
5	5-10	1	.5	3	30	61	31	30	--
6	10-15	1	.4	5	20	73	--	40	--
		2	.2	9	50	67	--	27	--
7	0-5	1	1.0	20	10	98	30	26	--

Depending on the well, effluent contained in water samples from the wells had travelled 10-50 m, more commonly 10-30 m, laterally through the soil. Most of the water sampled was just about to enter the lake.

All monitoring wells were installed in early January 1981 by digging a 15- to 25-cm-diameter hole with a post-hole shovel through the Alderwood soil and a few centimeters into relatively unweathered glacial till. The wells were lined with 15-cm-diameter PVC pipe with narrow slits to allow water to enter from saturated portions of the soil. The 2- to 5-cm space between the pipe and soil was packed with washed medium sand to prevent clogging. The top several centimeters of this annular space was packed with less-permeable native material. A thin layer of sand was also poured into the base of the well to prevent resuspension of fines introduced during well construction.

Before samples were taken from a well for analysis, the static water level was recorded. The well was then pumped dry and allowed to refill or, alternatively, 2- to 3-casing volumes of water were pumped before sampling. Prior to the first sampling of each well, the volume of water in each well was exchanged at least four times to minimize construction-related contamination. The water was sampled by pumping with a small hand-held pump through Tygon[1/] tubing and a coarse, nylon-screen filter connected to a Pyrex sidearm flask. All apparatus was rinsed before each sampling and periodically acid-washed. Water samples were filtered through a 0.45 μ filter within 12 hours of sampling, acidified with sulfuric acid and frozen prior to analysis.

In February 1981 we collected and analyzed a total of 46 water samples from 29 wells that contained enough water for an adequate sample. Twenty-nine of these samples were collected February 17 shortly after the peak of the water-level rise associated with the 9-day precipitation event that began February 11. The sampling dates are indicated on figure 4 which shows the pattern of precipitation at Pine Lake during February. Samples were analyzed for total dissolved P, chloride (Cl), and total dissolved nitrogen (N). All N and Cl analyses were performed at the U.S. Geological Survey Central Laboratory in Denver. The method for determining Cl was described by Skougstad and others (1979), and total N was analyzed with an Antek Instruments Model 705 Gas Chromategraph/Chemiluminescent Nitrogen Detector. Total dissolved P was determined at the University of Washington, Civil Engineering Laboratory, by the persulfate digestion/molybdenum blue procedure (American Public Health Association and others, 1975). Initial screening of the data for obvious errors resulted in a final sample of 41 observations of Cl, P, and N in ground water collected from 29 different wells.

Analysis of Phosphorus Transport

The transport of effluent-derived P was evaluated in two computational steps:

1. The equivalent volumetric fraction of each sample consisting of undiluted septic effluent was calculated from the Cl concentration in the sample.

2. The movement of P was calculated as the ratio of the measured increase in P above background to the potential increase in P above background if there was no retention by soil. The potential P concentration was

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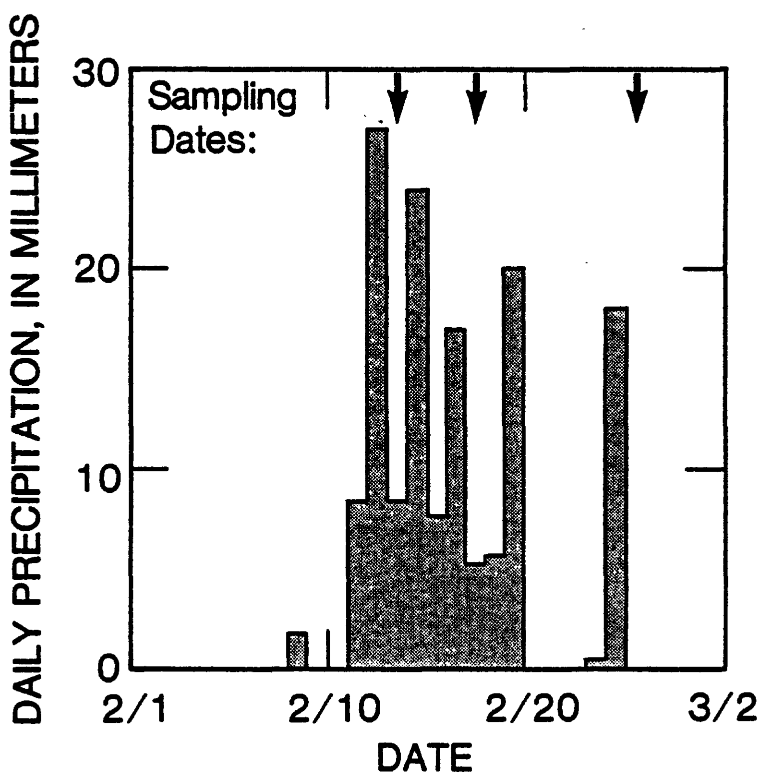

Figure 4.--Sampling dates in relation to February 1981 precipitation at Pine Lake.

was computed from the estimated amount of effluent in the sample, with no reduction in P except by dilution. The difference between potential and measured amounts is attributed to sorption of P as it passes through the soil.

This general appproach is similar to one used by Kerfoot and Skinner (1981), though they used specific conductance rather than chloride as the effluent tracer.

The movement of effluent N was evaluated in the same way as P, but we have not reported the details in this paper. On the average, about half the N in septic effluent reached the sampling wells.

The transport analysis required estimates of both background and septic-effluent concentrations of Cl and P in addition to measured concentrations for each sample containing effluent. Background concentrations were estimated from a group of uncontaminated samples and applied uniformly to samples from all sites. Effluent concentrations were estimated from published studies and also applied uniformly. Thus, for evaluating an individual sample taken at a particular time at a particular well, there was considerable potential for error in estimating appropriate values for background and effluent concentrations.

To evaluate the effect of these uncertainties on estimates of P transport, we used Monte Carlo simulation. This method of stochastic analysis represents selected variables (background and effluent concentrations in this study) as probability distributions rather than discrete values, and thus the apparent movement of P can be described in probabalistic terms for each sample. This type of description is superior to one based on discrete values, such as means, because the uncertainty in the values of key variables is reflected directly in transport estimates and not left open to the same degree of subjective interpretation.

Transport Model and Monte Carlo Simulation

The equivalent volumetric fraction of each water sample that consisted of undiluted septic effluent (EF) was estimated by equation 1.

$$EF_{ij} = \frac{ClM_i - ClB_j}{ClE_j - ClB_j} \qquad (1)$$

where, for sample 'i' and iteration 'j' in the Monte Carlo simulation, ClM, ClB, and ClE are respectively the measured, background, and effluent chloride concentrations. The values of ClB_j and ClE_j were each randomly chosen from probability distributions of values, which are described shortly.

For all iterations in which EF_{ij} was greater than zero, the movement of effluent P is described by equation 2.

$$FPT_{ij} = \frac{PM_i - PB_j}{EF_{ij}\ (PE_j - PB_j)} \qquad (2)$$

where FPT is the fraction of the potential effluent-derived P transported to the monitoring well, which is equal to the ratio of the observed increase above background concentration to the potential increase. The values of PM, PB, and PE are the measured, background, and effluent concentrations of P. Less than one percent of the generated values of EF_{ij} were zero or negative, indicating a high probability that all samples were taken from plumes of effluent-affected ground water.

Equations 1 and 2 can be combined to yield:

$$FPT_{ij} = \frac{(PM_i - PB_j)\ (ClE_j - ClB_j)}{(ClM_i - ClB_j)\ (PE_j - PB_j)} \tag{3}$$

With estimated probability distributions for background and effluent concentrations of Cl and P, equation 3 can be used to assess the probability distribution of P transport for individual samples and for any combination of samples. Values of FPT were calculated 100 times for each water sample in the Monte Carlo analysis and constrained within limits of actual possible values (0.0 - 1.0). This number of iterations produced a fairly smooth, empirical probability distribution. Values of FPT less than zero were set equal to zero, and values greater than one were set equal to one. Summary statistics and empirical probability distributions were determined for each individual sample and for all samples combined.

Probability Distributions of Background and Effluent Concentrations

The probability distributions of background concentrations of Cl and P were determined from selected samples collected at Pine Lake. Data used were from five sampling wells believed not to be downgradient from septic systems, plus all additional samples in which the Cl concentration was less than 1.5 times the median concentration of samples from the five stations. This criterion resulted in a pool of 15 samples from a total of 14 sampling wells dispersed among 7 sites. These samples represent 'background' water quality, which is defined for our purposes as not influenced by septic systems but not necessarily representative of 'natural' concentrations.

Summary statistics for Cl and P for the background samples are given in table 2. No published data were found on soil-water concentrations of Cl and P for areas similar to the Pine Lake basin. The relatively wide range in background concentrations reported in table 2 is probably due to a combination of factors, including varying mixtures of water that have been in the soil for different periods of time (Pilgrim and others, 1979) and unknown effects of human activities typical of residential areas.

Table 2.--Concentrations of chloride and phosphorus in ground water not contaminated by septic effluent.

constituent	range (mg/L)	mean (mg/L)	coefficient of variation	skewness
Cl	1.8 - 5.3	3.4	0.28	0.35
P	0.007 - 0.071	0.028	0.61	0.97

Both Cl and P have a lowest possible bound of zero and an undefined upper bound, resulting in a tendency toward positive skewness. Such data are often best represented by a log-normal distribution. The full-quantile method described by Stedinger (1980) was used to calculate the third parameter (lower bound) of a three-parameter log-normal distribution for both constituents, but for each the computed lower bound was zero. This indicated that both constituents might best be represented by a two-parameter log-normal distribution (lower bound of zero) fit by the maximum likelihood procedure described by Stedinger (1980). Figure 5 shows these fitted distributions in comparison to measured concentrations. Though the fit for P is not particularly good, other distributions did not fit the data measurably better. The discontinuity in the plotted data for P from 10 to 25 mg/L could not be attributed to differences in such factors as well location or soil variations based on our limited data. The effect of possible errors in the probability distribution for P on the simulation results is relatively small.

The probability distributions of effluent concentrations were more difficult to estimate. Published data are sparse and no data were collected at Pine Lake. Data from five septic systems in Wisconsin (Otis and Boyle, 1976) were used to characterize P concentrations (no Cl data were available for those systems), and data from two other septic systems in different parts of the country were used to characterize the distribution of Cl concentrations. No suitable data were found for characterizing possible variations in septic-effluent quality between regions of the country, but such variation would probably be small compared to system-to-system variability.

Combined data from the five septic systems that were used to characterize effluent P are summarized in table 3. Approximately equal numbers of samples were taken from each system over a 2-year period. The raw data for these septic systems were not available, so a distribution could not be empirically fit. The distribution was approximated by a three-parameter log-normal distribution with a lower bound set at one-half the lowest concentration observed. The lower bound (third parameter) for P, combined with the mean and standard deviation from table 3, uniquely determined the probability distribution for effluent P for use in the simulation. The method of deriving the distribution was that described by Stedinger (1980) as the method of moments (with a predetermined third parameter). For small samples, this approach performs as well as the maximum likelihood approach (Stedinger, 1980).

Table 3.--Concentrations of phosphorus in septic-tank effluent (Otis and Boyle, 1976).

	range (mg/L)	mean (mg/L)	coefficient of variation	number of samples
total P	3.8 - 90	15	0.80	54

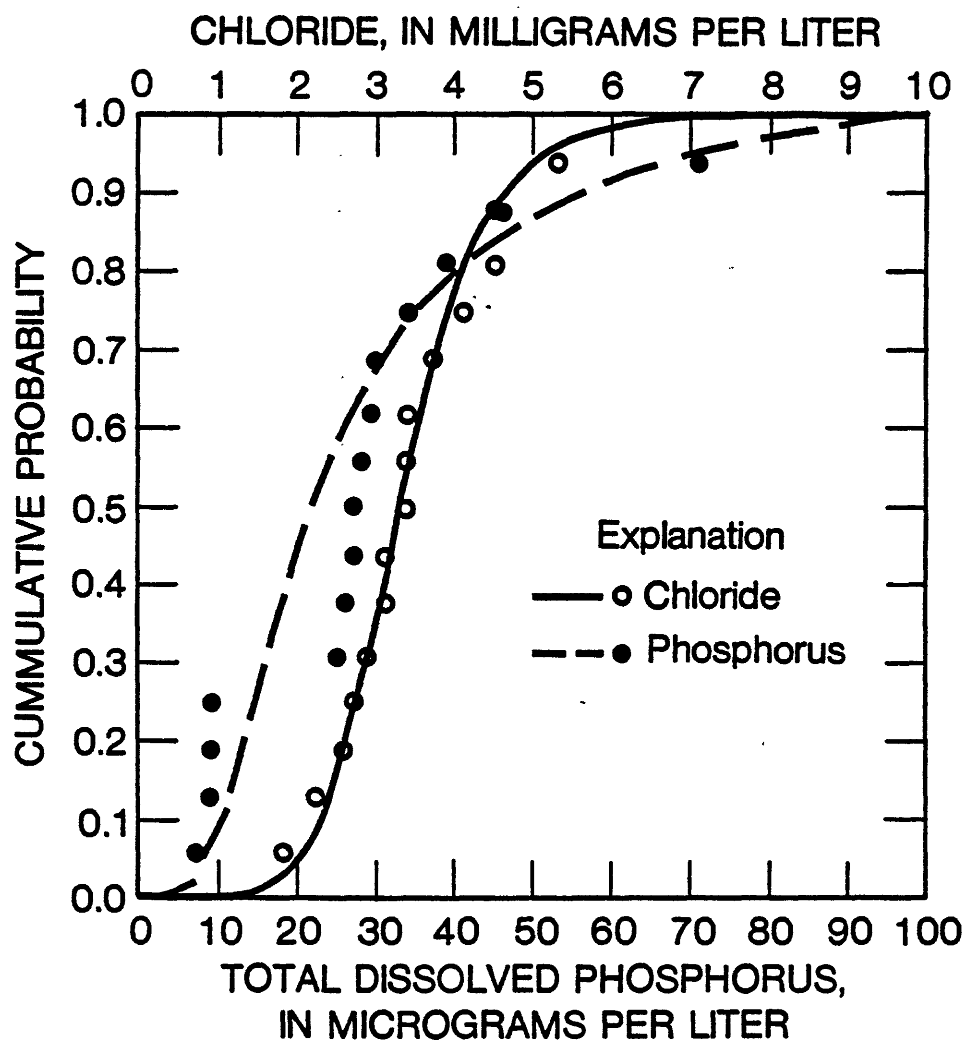

Figure 5.--Background concentrations of chloride and phosphorus and fitted frequency distributions used in Monte Carlo analysis.

Data on effluent Cl concentrations from two studies, representing one septic system each, are given in table 4.

Table 4.--Concentrations of chloride in septic-tank effluent.

study	range (mg/L)	mean (mg/L)	coefficient of variation
Viraraghavan and Warnock (1976)	37-100	53	0.18
Brandes (1978)[a]	30-100	66	--

[a] estimated from flow and concentration data for gray water and black water.

The same general technique used for P was used to approximate a three-parameter log-normal distribution for Cl. The lower bound was computed as half of the lowest concentration measured, the average of the means in table 4 was used, and the coefficient of variation was estimated to be a conservatively high value of 0.50 based on the data from Viraraghavan and Warnock (1976) and by comparison with the variability of other constituents as reported by Otis and Boyle (1976).

Necessary Assumptions and Their Validity

Some key assumptions were required as part of our analysis of P transport:

(1) Effluent Cl moves freely through the soil with no losses by sorption or additions by desorption,

(2) Septic effluent is the only nonbackground source of Cl and P, and

(3) The amount of effluent P that travels unsorbed through the soil to a sampling well, moves through the soil at the same speed as Cl released at the same time.

There is strong evidence that Cl in wastewater will move freely through the soil around Pine Lake. Johnson and others (1979) studied the movement of anions in wastewater through Everett soils, which are fairly similar to Alderwood soils except that they overlie relatively loose outwash rather than glacial till. Johnson and his colleagues found no retention of Cl by Everett soils for wastewater with Cl concentrations between 20 and 30 mg/L. Some types of soils may sorb Cl (Gerhardt and Coleman, 1974; Chan and others 1980), and this possibility should be considered for each different type of soil, but most soils appear to retain little Cl (Hanes, 1971).

There also are probably no serious violations of the assumption that septic effluent is the only nonbackground source of Cl and P. The only potential noneffluent source of Cl might be deicing salt, but freezing conditions are rare in the Pine Lake area and salt is generally not used for this purpose. Lawn fertilizer conceivably could be a source of P, but P applied to the land surface probably would not move through unsaturated soil to the saturated zone in appreciable quantities. Furthermore, 10 of the 15 samples used to evaluate background concentrations of both Cl and P were from lawn areas receiving the same treatments, if any, as the areas downgradient from drainfields. Thus, as noted earlier, 'background' concentrations actually represent concentrations affected by all influences except septic effluent.

The assumption that effluent P that is transported to a sampling well moves at the same speed as effluent Cl released at the same time is the most difficult to assess. This is an important assumption because if unsorbed effluent P moves at a different speed then Cl in ground water, then dilution estimates for P for individual samples based on Cl concentrations would be incorrect. Different net speeds of movement could occur if quantities of P are temporarily sorbed and released sporadically under certain chemical conditions. It is known that release of previously sorbed P may occur under strongly reducing conditions, particularly at a low pH (Patrick and others, 1973). The possibility of such an effect was not evaluated in this study, however, and this assumption should be recognized as an unknown source of uncertainty in the analysis. The potential for violation of the assumption is probably greatest for samples from areas where ground-water flow is intermittent and slow, with periodic anoxic conditions. Where ground water is present for extended periods and flows steadily with a relatively small portion of effluent, the assumption is probably accurate because chemical conditions would tend to be fairly constant.

Response of Perched Ground Water to Precipitation

Water-level data shown in table 1 demonstrate the probable occurrence of saturated lateral flow of ground water through soils surrounding Pine Lake. All nonzero water levels indicate a positive gradient toward the lake and induced flow would follow the least resistant pathway through the permeable soil overlying the till. Actual gradients in the areas of the wells were controlled by local land slopes, which also are indicated in table 1. Water levels generally responded rapidly to precipitation and receded at variable rates. Rates of recession were greatest where some combination of steep land slope, small upslope catchment areas, or unusually permeable till occurred. These general conditions prevailed at site 1, described in table 1. Rates of recession were slower where some combination of slight slope, large catchment area, or particularly impermeable till occurred, such as at sites 2 and 4 described in table 1. This finding is in general agreement with Ahuja and others (1981) who demonstrated that the extent of decrease in "interflow" (saturated lateral flow through soil) due to downward flux of water into the subsoil depends on land slope and the relative conductivity of the subsoil. At Pine Lake, some areas may have water perched above the till for several days or more following the end of a typical storm before water leaves by lateral flow or seeps into the till, while other areas will have none after only 1 or 2 days. Precipitation events are usually closely spaced throughout the winter season in the Puget Sound region; therefore, perched ground water may be present in some till-covered areas in the region continuously for weeks or months.

Movement of Effluent from Septic Systems

The movement of effluent from septic systems to monitoring wells was inferred from chloride concentrations measured in the 26 samples not included in the background group described earlier. These 26 samples were collected from a total of 15 wells; three wells were sampled on three occasions and five were sampled on two occasions. The Monte Carlo simulation showed that, for each of the 26 samples, there is a probability greater than 0.90 that some effluent was present. For all but four samples there is a probability greater than 0.95 that effluent was present. Calculated amounts of effluent in samples (mean values from the Monte Carlo simulation) ranged from 4 to 37 percent by volume and averaged about 11 percent. Computed amounts of effluent in each sample are indicated in table 5.

Thus, diluted effluent was found to move substantial distances (10-50 m) in perched ground water above the glacial till. This demonstrates both the movement of effluent and the lateral movement of the ground water. Such widespread occurrences of detectable effluent plumes down-gradient from drainfields also were found by Kerfoot and Skinner (1981) at Crystal Lake in Michigan, a lake surrounded by both glacial outwash and till terrain.

Transport of Phosphorus

The degree of movement of effluent-derived P in perched ground water is best inferred from the simulation results for individual water samples and monitoring wells. The simulation results define a probability distribution of the fraction of effluent P passing through the soil in the water contained in each sample collected.

Results of the Monte Carlo simulation are summarized in table 5. Example simulation results for two samples are shown in figure 6. For 15 samples there is a probability greater than 0.50 that some effluent P was being transported, but for only 4 samples is there a probability greater than 0.50 that more than 1 percent of effluent P had been transported to the monitoring well. For one of these four samples there is a 0.78 probability that more than 10 percent of the P in the effluent reached the well. The results indicate that, though the passage of a very small fraction (less than one percent) of the P originally contained in effluent entering the lake was probably common during the times at which samples were collected, the passage of more than one percent was relatively rare.

As was expected from a review of previous studies, P movement through the soil appears to be greatest where saturated conditions prevail for extended periods of time over the entire transport pathway. In humid temperate areas like the Puget Sound region, especially in shallow soils overlying less permeable material, subsurface water concentrates in hillslope depressions and remains the longest at the base of depressions (Anderson and Burt, 1978). The monitoring well that most clearly indicates substantial transport of P in perched ground water, well 1 at site 2, is about 10 m downgradient from a septic system located at the base of a hillslope depression with a large upslope catchment area (table 1). This septic system was also the one mentioned earlier from which effluent emerged at the land surface near the drainfield and flowed into the lake in a small waste stream about 10 m long. The P concentration in the waste stream averaged about 3 mg/L and ranged from 2.4 - 3.5 mg/L for the three sampling dates in February 1981. As shown in table 1, perched ground water was present throughout the

Table 5.--Observed chloride and phosphorus concentrations, estimated amounts of effluent, and probabilities of phosphorus transport for each sample.

Site	Well	Sample	Chloride (mg/L)	Phosphorus (mg/L)	Amount of effluent (percent)	Probability of transport FPT>0.00	FPT>0.01	FPT>0.10
1	1	1	7.6	0.026	9	.65	.27	.01
		2	5.3	.056	4	.90	.85	.33
	2	1	6.6	.019	7	.46	.17	.01
		2	5.8	.024	5	.61	.27	.03
		3	7.5	.039	9	.80	.57	.04
	3	1	9.0	.025	12	.64	.23	.00
		2	5.1	.017	4	.36	.20	.01
		3	6.0	.017	6	.35	.15	.01
	4	1	6.5	.005	7	.01	.00	.00
	5	1	8.7	.010	12	.10	.00	.00
2	1	1	9.4	.324	13	.99	.99	.78
		2	7.1	.088	8	.97	.87	.35
3	1	1	13	.031	21	.66	.27	.01
		2	16	.035	28	.70	.19	.00
4	1	1	5.2	.010	4	.13	.02	.00
		2	5.1	.011	4	.15	.02	.00
		3	5.2	.015	4	.25	.14	.00
	2	1	6.9	.016	8	.52	.10	.00
	3	1	11	.023	17	.59	.10	.00
		2	13	.017	21	.35	.03	.00
	4	1	19	.032	35	.67	.10	.00
		2	20	.015	37	.26	.01	.00
5	1	1	8.1	.020	10	.51	.10	.00
6	1	1	6.5	.013	7	.19	.03	.00
	2	1	5.8	.025	5	.60	.30	.03
7	1	1	5.6	.023	5	.55	.30	.02

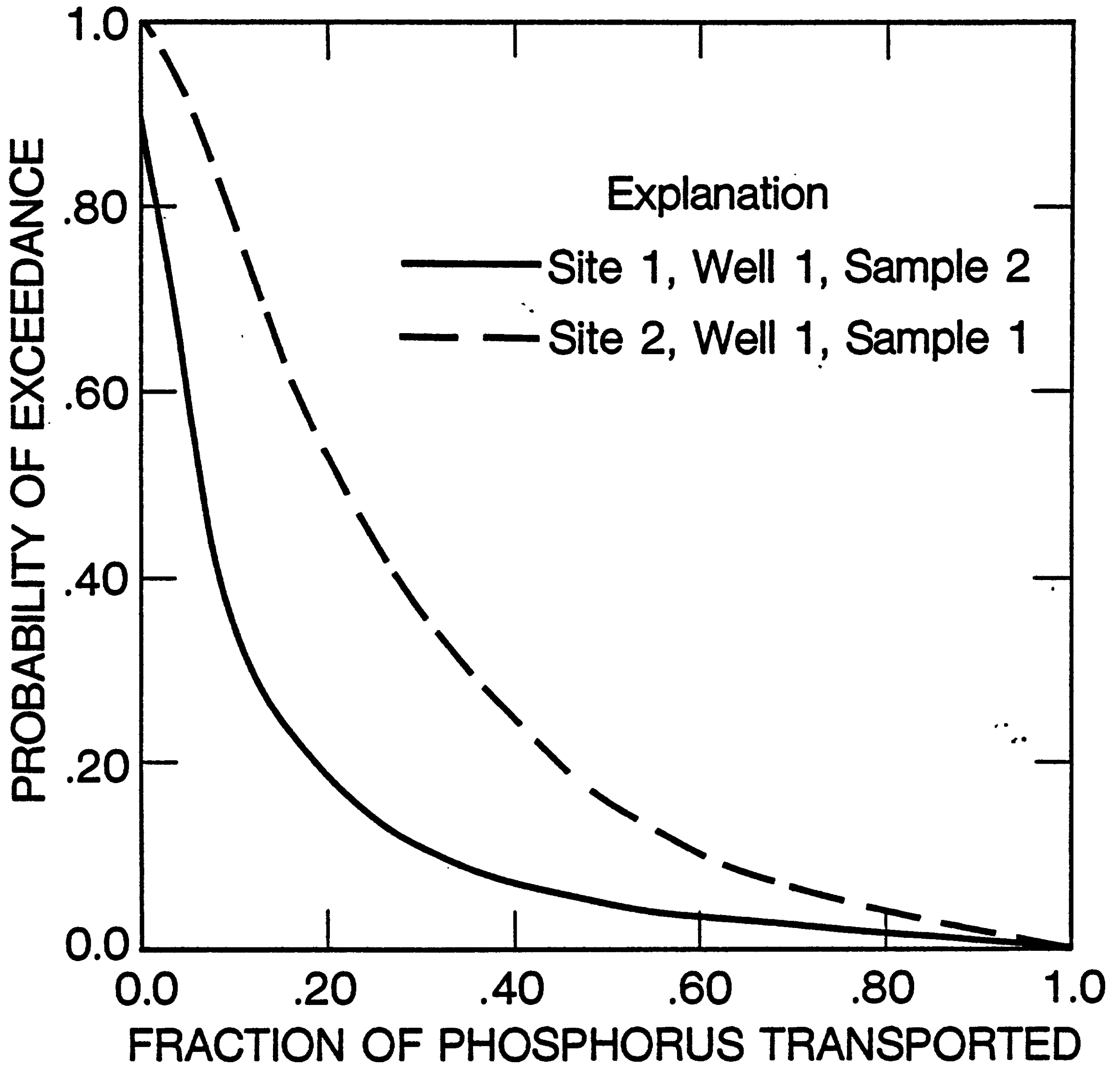

Figure 6.--Probability of phosphorus transport for two samples.

sampling period at site 2. There was only a slight slope between the drainfield and the well so that saturated conditions probably prevailed within the drainfield area and between the drainfield and the well described. Site 4, in table 1, appears similar to site 2, but no substantial P movement was observed. This may have been due to a steep (10-15%) slope between the drainfield and the wells which prevented the occurrence of extended periods of saturated conditions in soil between the drainfield and the wells.

If the 15 wells sampled were representative of the distribution of hydrologic conditions around Pine Lake, then findings for all the wells could be combined to yield a single probability distribution describing P transport from older systems by shallow ground water. The results are biased towards wet periods and areas, however, because samples were collected when and where water was present. Some wells installed were never sampled. Therefore, our results describe an upper possible limit on the true distribution of P transport occurring during the study period. This distribution is shown in figure 7. Data from each monitoring well were given equal statistical weight. As determined from this distribution, the upper limit on the average fraction of effluent P transported by perched shallow ground water from 20-40-year-old systems to the lake was about three percent. This fraction is only of the portion of septic effluent that reaches the lake by flow of perched ground water. Because we did not determine how much effluent reaches the lake, the mass transport of P to the lake from septic systems cannot be calculated.

CONCLUSIONS

A regional analysis of septic-system P loading (Gilliom, 1982) and the case study of Pine Lake indicate that loadings of P to some lakes in the Puget Sound region are attributable to septic systems. The regional analysis indicated that most such loading was coming from old septic systems. The Pine Lake study showed that effluent from each of the old septic systems that were studied was reaching the lake in perched ground water flowing through soil overlying less permeable glacial till. However, movement of more than 1 percent of effluent P to the lake was found to be rare. The loading of P to the lake by old septic systems is probably associated with only a few of the old systems that are located in areas where soils are persistently saturated during the winter season. These wet areas tend to be located in or near hillslope depressions, particularly at the base of a depression where perched ground water is present the longest. Septic systems in these wet areas may contribute P to a lake by both shallow ground water flowing into the lake and the surfacing of septic effluent and subsequent movement to the lake by overland flow.

The probable relationship between septic-system P loading and the occurrence of persistently saturated soils indicates a possible explanation in addition to system age for the empirical relationship between old septic systems in the region and P loading. The relationship may be at least partly caused by the location of more old systems in seasonally wet areas compared to newer systems. This could have occurred because regulation and enforcement of construction practices for septic systems were less stringent in the 1940's and 1950's than in recent years. The joint occurrence of older systems and location in wet areas probably results in the greatest septic-system loadings to lakes. However, even new systems might add P to a lake if they were improperly located in areas where soils are persistently saturated.

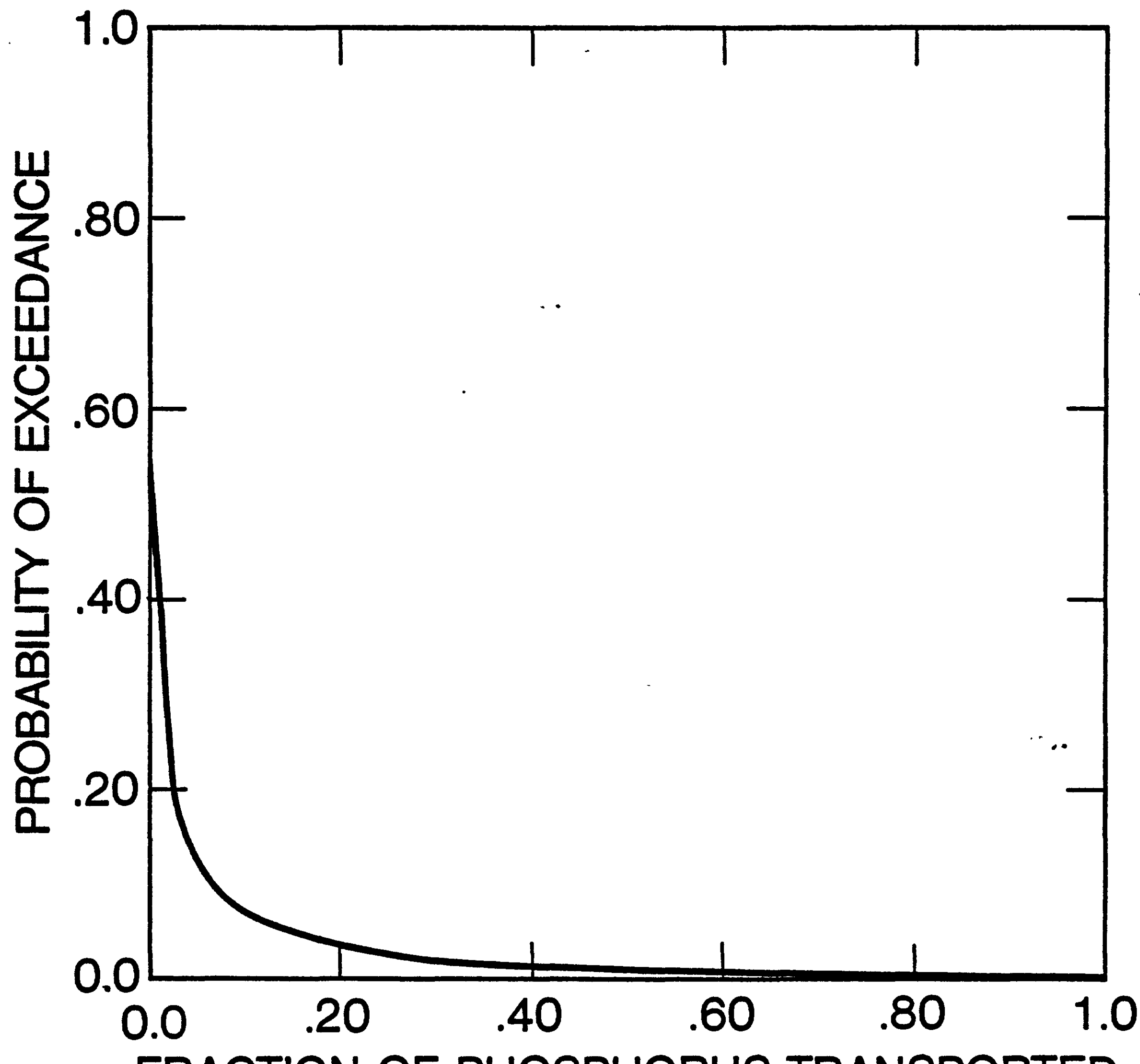

Figure 7.--Probability of phosphorus transport indicated by all samples combined.

A question that remains unanswered is whether P-treatment efficiency of soils, even at sites that are suitable for septic systems, deteriorates with time. No long-term or detailed studies of very old septic systems have been published to our knowledge. This type of study is needed to help aid planning for future wastewater disposal around lakes.

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