EPA/440/6-87/007

United States Environmental Protection Agency

Office Of Water (WH-550G)

EPA 440/6-87-007
June 1987

EPA

Septic Tank Siting To Minimize The Contamination Of Ground Water By Microorganisms

Septic Tank Siting to Minimize the Contamination of Ground Water by Microorganisms

Marylynn V. Yates, AAAS Fellow
U.S. Environmental Protection Agency
Office of Ground-Water Protection
Office of Water
Washington, D.C. 20460

June, 1987

FORWARD

This report is one in a series of occasional technical documents prepared by the U. S. Environmental Protection Agency's (EPA) Office of Ground-Water Protection (OGWP). These publications report on miscellaneous scientific topics which may be of interest to State ground-water program managers. The methodologies described in these reports reflect the views of the authors and do not represent EPA policy. These technical documents are intended to assist State decision-makers as well as to contribute to the scientific literature.

This report, Septic Tank Siting to Minimize the Contamination of Ground Water by Microorganisms, is a reference to be used in conjunction with, Septic Systems and Ground-Water Protection, a publication which was directed by a technical panel on septic system management and was organized under the auspices of OGWP.

ACKNOWLEDGMENTS

This report was prepared during the author's tenure as a EPA/American Association for the Advancement of Science (AAAS) Environmental Science and Engineering Fellow during the summer of 1985. Mention of trade names or commercial products does not constitute endorsement or recommendation by the author or EPA.

The views expressed herein are entirely the author's and do not represent official policy of either the EPA or AAAS. I would like to express my appreciation to the staff of the Office of Ground-Water Protection for their support. Special thanks go to Ron Hoffer for his helpful advice and to Norbert Dee for teaching me about environmental rating systems. The considerable efforts of Pat Curlin and Harold Wolf to make this research effort an enjoyable and enlightening experience are gratefully acknowledged. I would also like to thank Scott Yates for several helpful discussions, as well as his constant encouragement and patience.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

SUMMARY

As more and more cases of ground-water contamination are reported, the public has become increasingly aware of the importance of preserving the quality of this limited resource, especially in areas totally dependent on ground-water sources. Over one-half of the waterborne disease outbreaks in the United States are due to the consumption of contaminated ground water. Currently, most of the attention is focused on pollution by organic chemicals, although chemicals are responsible for a relatively small percentage of the reported ground-water-related disease outbreaks. The majority of waterborne disease outbreaks are caused by bacteria and viruses present in domestic sewage. Overflow or seepage of effluent from septic tanks is the most frequently reported source of contamination in these outbreaks. Domestic sewage contains several different types of pathogenic microorganisms, many of which are not inactivated during treatment in the septic tank. In this way, infective microorganisms can be released into the subsurface where they may travel through the soil and reach ground water, posing a potential health hazard to persons consuming the water. Indeed, from 1971 to 1979, overflow or seepage of sewage from septic tanks or cesspools was responsible for 43% of the reported outbreaks and 63% of the reported cases of illness caused by the use of untreated, contaminated ground water.

In the past, minimizing the potential for ground-water contamination has not always been the primary concern when siting and installing septic tanks. Considered individually, septic tank effluent may not seem to pose a large threat to human health. On a nation-wide basis, however, over one trillion gallons of waste are introduced to the subsurface by septic tanks every year, making septic tanks the leading contributor to the total volume of wastewater discharged directly to the subsurface. Therefore, minimizing the potential for contaminants in septic tank effluent to reach potable waters would make a significant contribution towards decreasing the incidence of waterborne disease outbreaks in this country. Currently, there is little guidance available to aid in this effort.

The purpose of this project was to develop a rating system using readily available data which could be used as a tool in septic tank siting to aid in decreasing the potential for the introduction of contaminants, specifically pathogenic microorganisms, to the ground water.

The literature was reviewed to determine what factors are important in influencing the survival and migration of microorganisms in the subsurface environment. Existing environmental rating systems were reviewed to assess their applicability to this project. Appropriate parts of these systems were adapted for use in this system. Several of the factors were not addressed appropriately for microorganisms by the existing systems. Therefore, an extensive literature review was conducted to obtain quantitative information on how these factors affect the fate and transport of microorganisms in the subsurface. Rating

curves for these factors were developed from these empirical data. Eight factors were used in the rating system: depth to water, net recharge, hydraulic conductivity, temperature, soil texture, aquifer medium, application rate, and distance to a point of water use. The factors were ranked in terms of their importance relative to the other factors in influencing the survival and movement of microorganisms through the subsurface. Weights were assigned to each factor, with a weight of 1 signifying the least importance and a weight of 5 signifying the greatest importance. In addition to the weights, which are constant, each factor is assigned a rating based on the conditions found at the particular site being considered. The ratings are determined from graphs which have been provided for each factor. An index, which gives an indication of the relative potential for ground-water contamination by microorganisms present in septic tank effluent, can then be computed by multiplying each factor rating by its associated weight and summing for all factors.

Examples were given to illustrate the use of the system. Suggestions for the interpretation of the index and use of the rating system were made.

PURPOSE

The purpose of this report is to develop a rating system using readily available data which could be used as a tool in septic tank siting to aid in decreasing the potential for the introduction of contaminants, specifically pathogenic microorganisms, to the ground water. The focus of this report will be on evaluating the possibility of microbial contamination, by both bacteria and viruses, because they are responsible for the majority of the illness associated with ground-waterborne disease outbreaks.

Objectives

The specific objectives of this report are:

1) Identify the important factors in the survival and transport of pathogenic microorganisms in the subsurface environment.

2) Assess the availability of the factors identified in 1).

3) Determine the relationship between the factors identified in 1) and the potential of the microorganisms to contaminate the ground water.

4) Rank and/or weight each factor identified in 1) as to its importance in influencing the microorganisms' ability to contaminate the ground water.

5) Using the information obtained from 3) and 4), develop a rating system which will give the user an idea of the relative potential for ground-water contamination by pathogenic microorganisms present in septic tank effluent at the site being considered.

Organization of Report

This report is divided into two main parts. The first part contains background information on the significance of waterborne disease in this country, the role of microorganisms in causing the outbreaks, and the contribution of septic tanks to the problem of ground-water contamination. It also reviews several systems which have been developed to evaluate the impact of various waste disposal practices on the environment.

The second half of the report details the development of a rating system which specifically addresses the potential for microorganisms present in septic tank effluent to migrate through the subsurface, enter the ground water, and travel to points of use such as drinking-water wells. It provides rating curves which can be used to calculate an index which reflects the relative potential for ground-water contamination by microorganisms in septic tank effluent, along with the data used to develop the curves. Examples to illustrate the use of the system are given, and suggestions for the interpretation of results and use of the rating system are made.

BACKGROUND

Ground water supplies over 100 million Americans with their drinking water. In rural areas, there is an even greater dependence on ground water, as 90 to 95% of the drinking water used is ground water (Bitton and Gerba, 1984). The increasing dependence on ground water as a source of potable water has spurred efforts to protect the quality of this limited resource.

Septic tank leachate is the most frequently reported cause of ground water contamination (U.S. Environmental Protection Agency, 1977). In 1970, twenty-nine per cent of the United States' population disposed of their domestic waste through individual on-site disposal systems (U.S. Environmental Protection Agency, 1977). This represents approximately 19.5 million single units, almost 17 million of which are septic tanks or cesspools. About 25% of all new homes being built in the United States have septic tanks to dispose of domestic wastewater (U.S. Environmental Protection Agency, 1980). While the relative percentage of new homes using septic tanks has decreased over the past several years, the total number of septic tanks is increasing at a rate of about one-half million per year (Scalf, Dunlap, and Kreissl, 1977).

It has been estimated that the total volume of waste disposed of via septic tanks is approximately one trillion gallons per year, virtually all of which is disposed in the subsurface (Office of Technology Assessment, 1984). This makes septic tanks the leading contributor to the total volume of wastewater discharged directly to the soils overlying ground water. Figure 1 shows a typical septic tank-soil absorption system and its relationship to the underlying ground water (Canter and Knox, 1984).

Basically, the household waste is transported to the septic tank, where heavy materials or septage are allowed to settle out. After a suitable retention time, which can vary from one to five days, the effluent goes to the soil absorption system, where the majority of the "purification" takes place. The effluent is "purified" as it moves through the soil by attenuation and adsorption of the contaminants onto soil particles. If the system is properly constructed and maintained, the contaminants in the effluent should be reduced to levels that are not harmful to human health. If, however, the system is not maintained properly or the density of systems in an area is so great that the capacity of the soils to treat effluent is exceeded, there is a potential for ground-water contamination by septic tank effluent.

Waterborne Disease Outbreaks

From 1920 to 1983, 1517 outbreaks of waterborne disease affecting 414,935 persons were reported in the United States (Craun, 1986a,b). It is generally believed that the actual

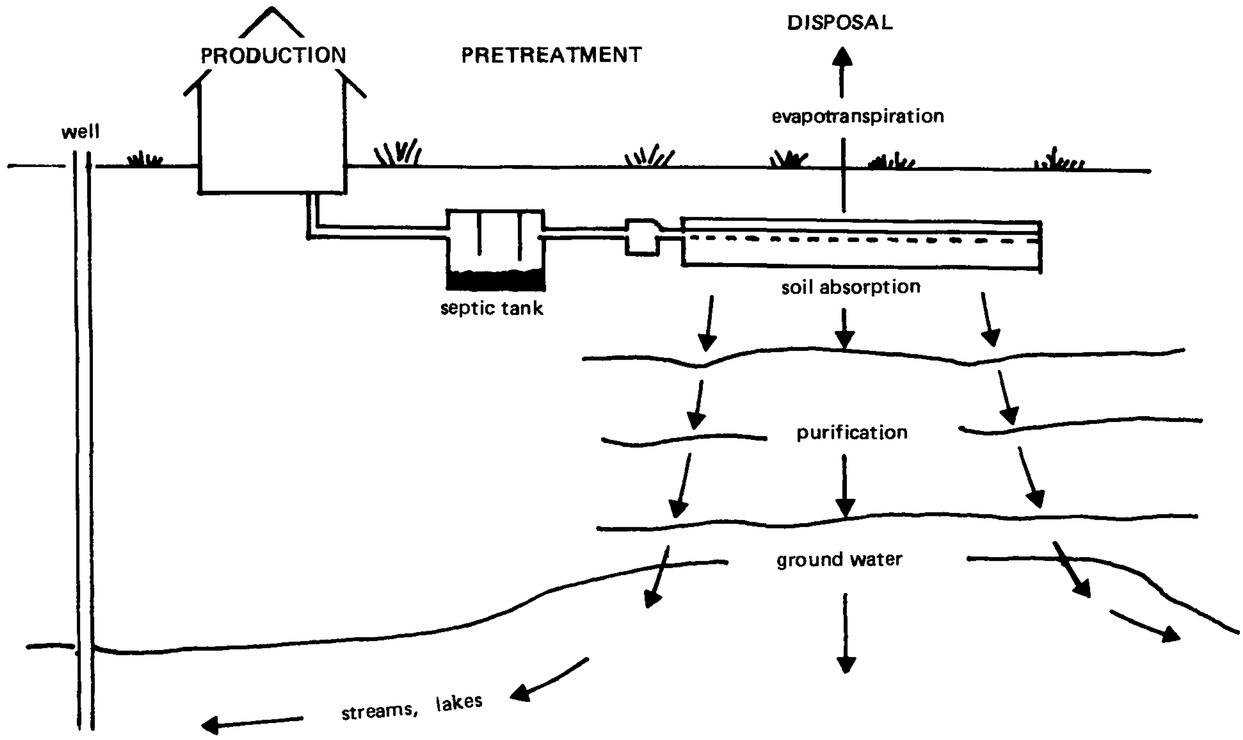

Figure 1. Schematic cross - section through a conventional septic tank - soil disposal system for on-site disposal and treatment of domestic liquid waste (Canter and Knox, 1984).

number of outbreaks is much higher than the number reported, due to the fact that the outbreak may not be recognized as such, that the disease was not serious, or that a very small number of people was involved. This belief is supported by the fact that an improved reporting and surveillance system in one state accounted for 25% of the total number of reported outbreaks from 1976 through 1980 (Lippy and Waltrip, 1984). In cases with suspected viral etiologies, outbreaks are very difficult to document because of the wide range of symptoms which can be manifested in people infected with the same virus.

The reported occurrence of waterborne disease outbreaks in the United States has been increasing since 1966 (Lippy and Waltrip, 1984). This trend is shown in Figure 2, which illustrates the frequency of waterborne disease outbreaks in 5-year increments since 1946. This figure, as well as all analyses based on reported waterborne disease outbreaks must be interpreted with caution. As pointed out earlier, the intensity of surveillance can vary greatly from state to state. In addition, apparent increases in numbers may reflect heightened awareness and better reporting of waterborne outbreaks, especially since 1971 when the current system of reporting was established (Lippy and Waltrip, 1984), rather than an actual increase in the number of outbreaks.

Almost one-half of the outbreaks occurred in non-community systems (a public water system serving at least 25 persons or with 15 service connections but who are not year-round residents), 96% of which use ground water, although many more cases of illness resulted from outbreaks in community systems (those public systems which have at least 15 service connections or provide water to at least 25 people on a year-round basis) (Figure 3). Reported outbreaks in individual systems, which depend primarily on ground-water sources, accounted for only 1% of the cases of illness. This may not accurately reflect the actual number which occur, as outbreaks in individual systems are usually not recognized or reported.

Causative agents were determined in 48% of the outbreaks (Figure 4, Table 1). Only 7.3% were caused by acute chemical poisoning; the vast majority were caused by pathogenic (disease-causing) microorganisms. The remainder (52%) were classified as acute gastrointestinal illness of unknown etiology. It is believed, based on recent retrospective serological studies on the etiology of common-source outbreaks of gastroenteritis, that many of these were caused by viruses such as the Norwalk virus or rotaviruses (Kaplan et al., 1982), for which detection methods have only recently become available (Gerba, 1983). It has been suggested that the Norwalk virus is responsible for approximately 23% of all reported waterborne outbreaks in the United States (Keswick et al., 1985).

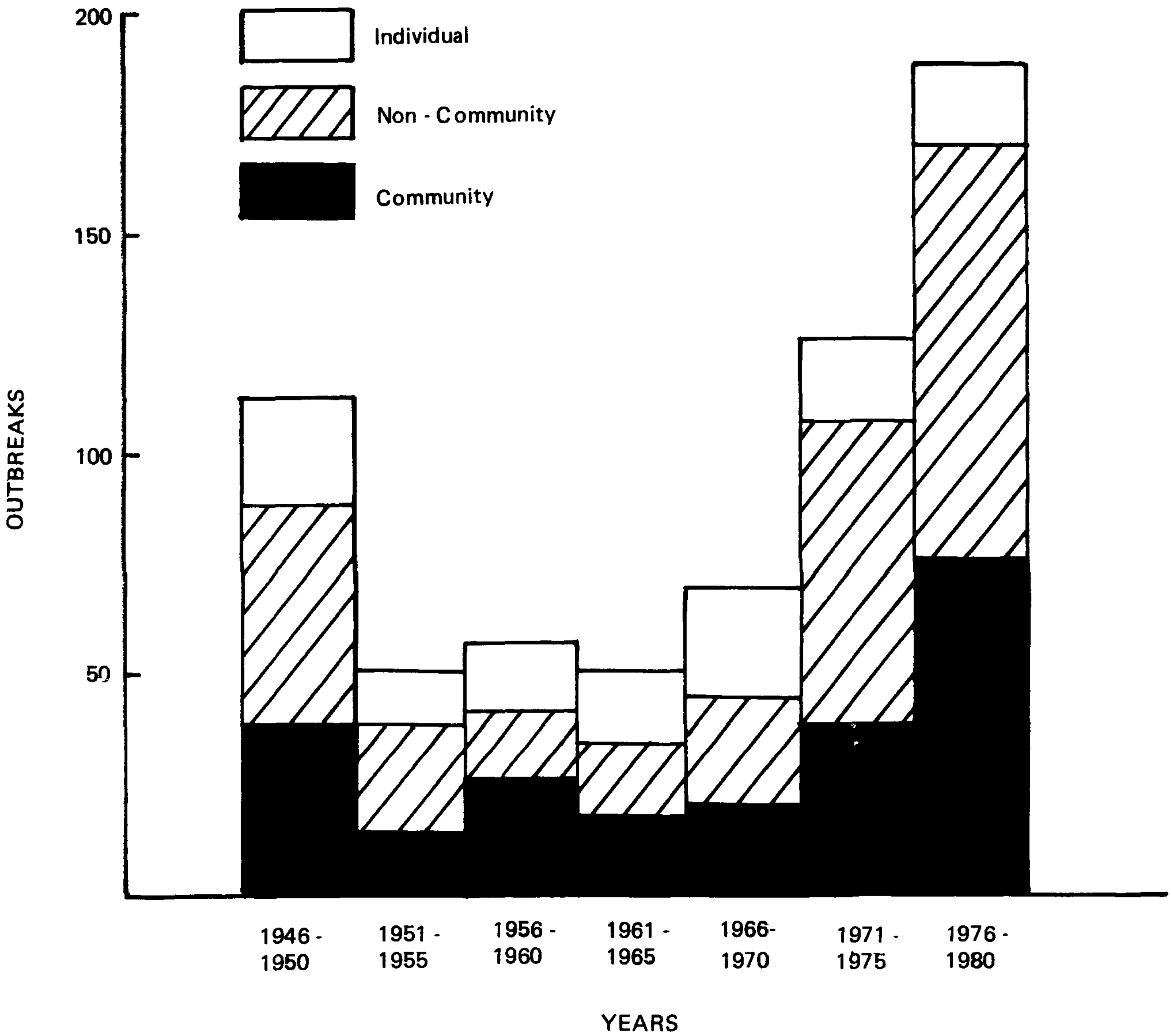

Figure 2. Occurrence of waterborke discease outbreaks by five - year increments (Lippy and Waltrip, 1984).

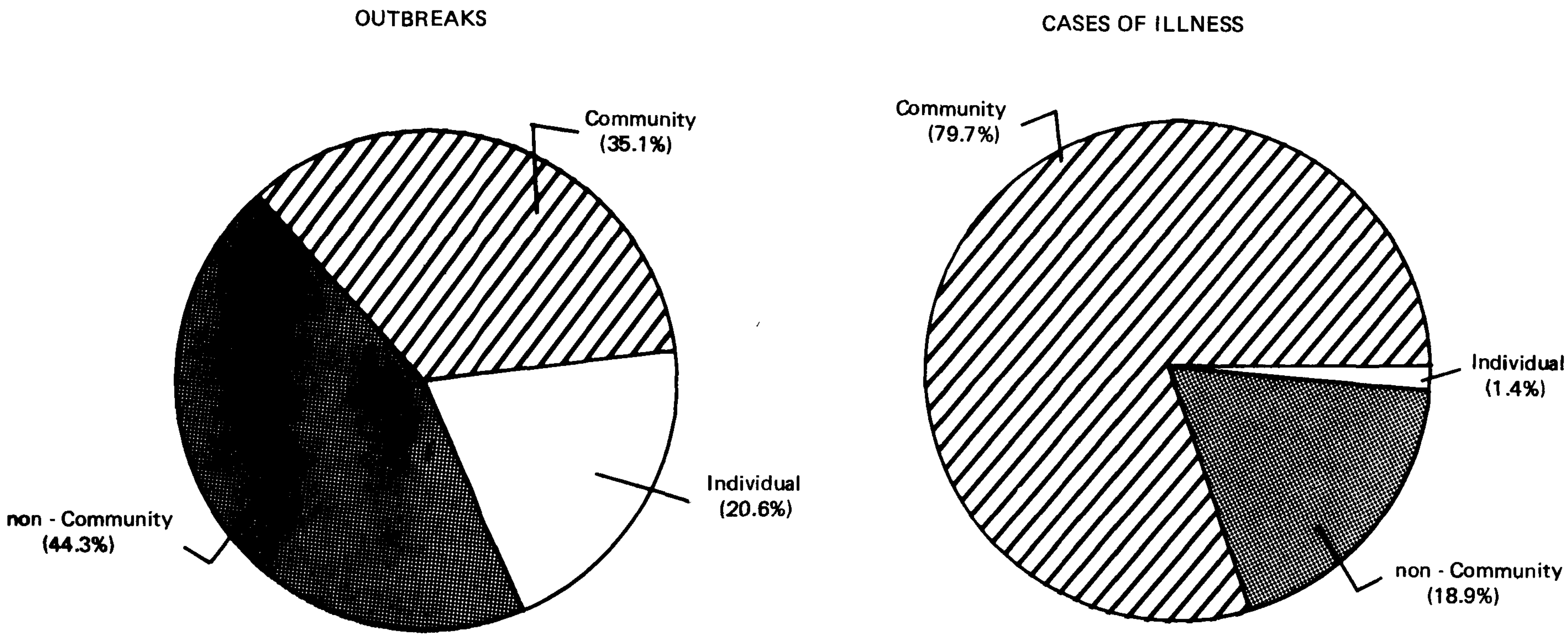

Figure 3. Waterborne disease outbreaks (1946 - 1980) and cases of illness by type of system (Lippy and Waltrip, 1984).

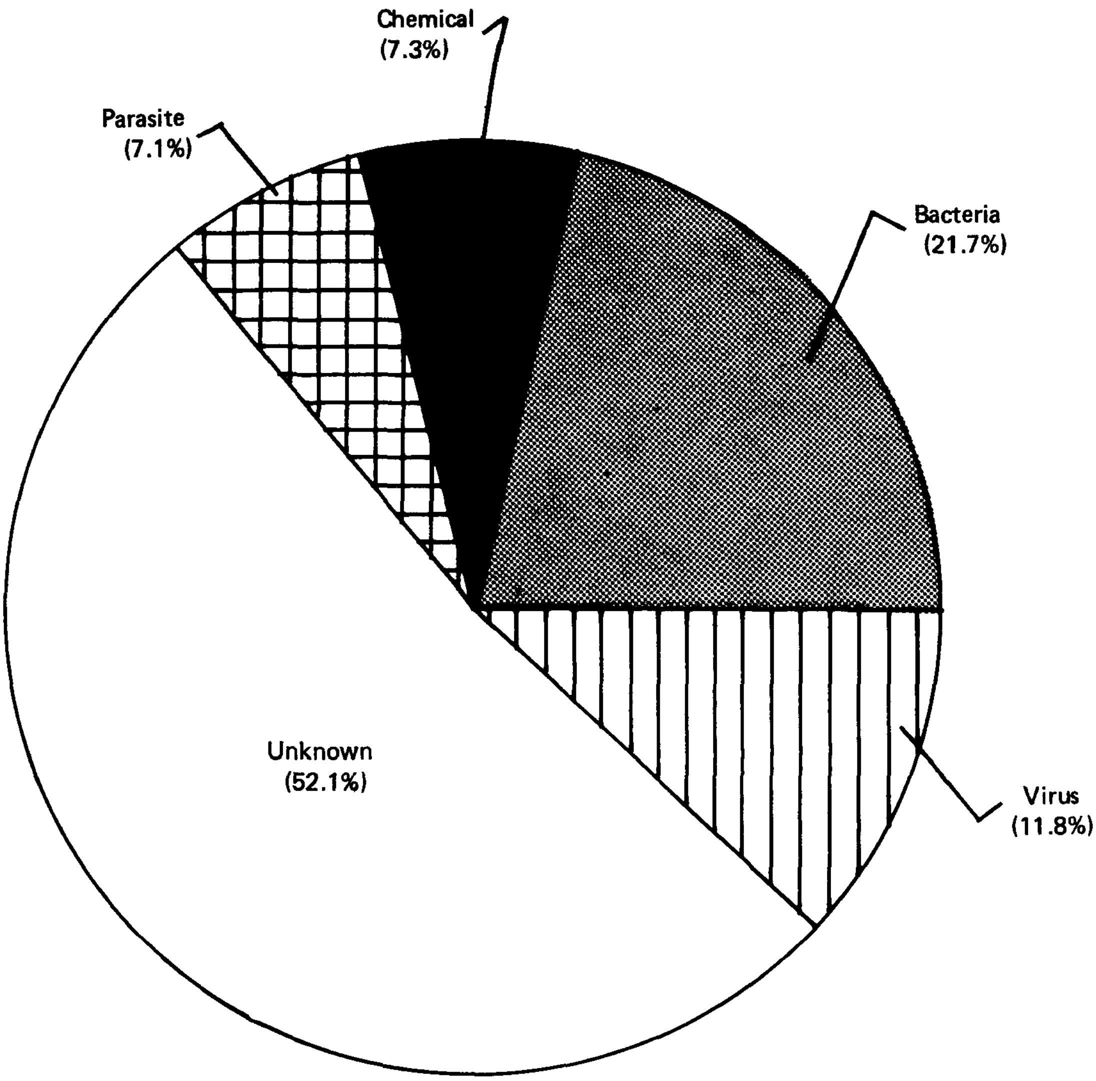

Figure 4. Waterborne disease outbreaks (1946-1980) by causative agent (Lippy and Waltrip, 1984).

Table 1. Causative agents of waterborne disease outbreaks in the United States, 1946-1980 (Lippy and Waltrip, 1984)

Agent	Outbreaks	Cases of Illness
Bacterial		
Campylobacter	2	3800
Pasteurella	2	6
Leptospira	1	9
Escherichia coli	5	1188
Shigella	61	13089
Salmonella	75	18590
Total	146	36682
Viral		
Parvoviruslike	10	3147
Hepatitis A	68	2262
Poliovirus	1	16
Total	79	5425
Parasitic		
Entamoeba	6	79
Giardia	42	19734
Total	48	19813
Chemical		
Inorganic	29	819
Organic	21	2725
Total	49	3616
Unknown	350	84939
Grand total	672	150475

The consumption of untreated or inadequately treated ground water was responsible for over one-half of all the waterborne outbreaks and 45% of all cases of waterborne disease from 1971 to 1979 (Craun, 1984). Overflow or seepage of sewage from septic tanks or cesspools was responsible for 43% of the outbreaks and 63% of the cases of illness caused by the use of untreated, contaminated ground water from 1971-1979 (Table 2). Many septic systems which were installed in the 1960's and designed to function for ten to fifteen years have exceeded their functional life-span and are beginning to contaminate the ground water (Canter and Knox, 1984). Thus, septic tanks represent a significant threat not only to preserving the potability of ground water, but to human health.

Table 2. Source of contamination in waterborne disease outbreaks caused by use of untreated ground water in the United States, 1971-1979 (Craun, 1984)

	Outbreaks	Illness
overflow or seepage of sewage	33	4167
data insufficient to classify	24	934
contaminated springs	9	940
chemical contamination	9	127
contamination through limestone or fissured rock	5	880
contamination by surface runoff	6	396
flooding	2	588
total	88	8032

Microorganisms in the Subsurface

Acute chemical poisoning accounts for a relatively small percentage of the illness caused by the consumption of contaminated ground water, therefore, this report will focus on the microbiological agents of disease. Several microorganisms which have been isolated from domestic sewage, along with the diseases they cause, are listed in Table 3.

Bacteria

Bacteria are microscopic organisms, ranging from approximately 0.2 to 10 μm (1 μm = 10^{-6}m) in length. They are distributed ubiquitously in nature and have a wide variety of nutritional requirements. Many types of harmless bacteria colonize the human intestinal tract, and are routinely shed in the feces. One group of intestinal bacteria, the coliform bacteria, has historically been used as an indication that an environment has been contaminated by human sewage. In addition, pathogenic bacteria, such as *Salmonella* and *Shigella* are present in the feces of infected individuals. Thus, a wide variety of bacteria is introduced into septic tanks. Many of these bacteria can survive and grow in septic tanks, and are present in the liquid portion of the effluent when it moves to the soil absorption field.

As the septic tank effluent percolates through the soil, its bacteriological quality changes depending upon the characteristics of the subsurface environment. One of the most important factors is the pore size of the soil matrix. Many bacteria are large enough to be filtered out as the water moves through the soil pores, thus limiting the depth of penetration. Another limitation on the distances bacteria can travel is the moisture content of the soil; bacteria can move greater distances in saturated soil than in unsaturated soil (Hagedorn, 1984). Bacteria are subject to biological, chemical, and physical inactivation in the soil, as well as death due to lack of nutrients and proper environmental conditions such as inadequate oxygen. These are especially important considerations when the effluent must move great distances to reach an aquifer.

Removal by filtration and inactivation notwithstanding, bacteria can migrate considerable distances in the subsurface given the proper conditions. In fractured rock and coarse-grained soils, bacteria can move quite rapidly. For example, in a sand and gravel aquifer, coliform bacteria have been isolated 100 ft from the source just 35 hours after the sewage was introduced (Hagedorn, 1983). Bacteria can also move considerable distances in the soil; Kudryavtseva (1974) reports that bacteria were transported 1000 m through a weathered limestone aquifer. Model calculations using laboratory data indicate that coliform bacteria can be transported for more than 1 km in loamy sand aquifers and for several km in fissured karstic aquifers (Matthess and Pekdeger, 1981). In addition to traveling through fractured

Table 3. Pathogenic microorganisms in domestic wastewater (Adapted from Kreissl, 1983, Fitzgerald, 1983 and Sobsey, 1983a)

Microorganism	Disease(s) caused
BACTERIA:	
Salmonella species	typhoid, paratyphoid, gastroenteritis
Shigella	bacillary dysentery
Yersinia	gastroenteritis
Mycobacterium	tuberculosis
Leptospira	leptospirosis
Campylobacter jejuni	gastroenteritis
Pathogenic coliforms	gastroenteritis, urinary tract infections
Yersinia enterocolitica	gastroenteritis
Pseudomonas	respiratory and burn infections, diarrhea
Klebsiella	pneumonia, bronchitis
Serratia	respiratory and urinary tract infections, summer diarrhea
VIRUSES:	
polioviruses	poliomyelitis
hepatitis A	infectious hepatitis
echoviruses	respiratory disease, aseptic meningitis, diarrhea, fever
coxsackieviruses	respiratory disease, fever, aseptic meningitis, myocarditis
Norwalk and Norwalk-like viruses	gastroenteritis
rotaviruses	gastroenteritis
adenoviruses	respiratory disease, eye infections

Table 3. Pathogenic microorganisms in domestic wastewater (continued)

Microorganism	Disease(s) caused
PARASITES:	
Entamoeba histolytica	amoebic dysentery
Giardia lamblia	giardiasis ("backpacker's diarrhea")
Balantidium coli	dysentery, gastroenteritis
Ascaris ova	pneumonitis, intestinal and nervous system disorders
Trichuris	chronic gastroenteritis
Enterobius vermicularis	enterobiasis
Cestode ova	chronic gastroenteritis
Coccidia	diarrhea, toxoplasmosis

rock and large pore-sized soils, bacteria have also been detected in ground water 35 ft from the source of contamination after moving through a sandy-clay soil (Caldwell and Parr, 1937).

Viruses

Viruses are ultramicroscopic particles, ranging from approximately 20 to 200 nm (1 nm = 10^{-9} m) in diameter, which are incapable of replication outside of a host cell. The enteric viruses, which are of interest here, are not normally present in the gastrointestinal tract, and are shed only in the feces of infected individuals. Therefore, viruses will only be present in the septic tank system when one or more persons in the contributing household(s) is infected and shedding virus. Most people have at least one virus infection every year, so it is likely that a septic tank system will receive virus-laden wastewater at some time over the course of a year (Sobsey, 1983a). Hain and O'Brien (1979) isolated enteric viruses from all four septic tanks they sampled. In addition, one septic tank which was sampled periodically over a year was positive for enteric viruses on all five occasions.

Virus concentrations may be as high as 10^6 to 10^{10} particles per gram of feces (Tyrrell and Kapikian, 1982). Over 100 different types of enteric viruses capable of infecting humans are excreted in the feces and may be present in domestic sewage (Gerba, Wallis, and Melnick, 1975). In general, viruses are very host-specific, that is, viruses which infect humans cannot infect any other animals (with the exception of a few primates). Therefore the isolation of a human enteric virus from water is proof that the contamination is from a human source.

Because viruses cannot reproduce outside of a living cell, they behave very much like chemical particles in the soil. They do not require any nutrients in order to survive (as bacteria do), but they are susceptible to inactivation by physical means such as high temperature. Due to their small size, viruses are generally not filtered out by soil pores as the septic tank effluent percolates through the soil unless they are aggregated or associated with particulate matter (Sobsey, 1983b). The major mechanism of virus removal in soil is by physical-chemical adsorption onto soil particles, especially clays due to their highly-charged nature. This adsorption is not permanent, however. Viruses can be desorbed by rainfall and migrate further through the subsurface where they can be readsorbed or remain freely suspended in the ground water. This phenomenon was observed by Wellings et al. (1975) at a site at which sewage effluent was being used for irrigation purposes. After a period of heavy rainfall, viruses were detected in ground-water samples which had previously been free of viruses.

Viruses can travel considerable distances in the subsurface; depths as great as 67 m (220 ft) and horizontal migrations as far as 400 m (1310 ft) have been reported (Keswick and Gerba, 1980).

Protozoa

Protozoa are single-celled organisms, generally considerably larger in size than bacteria and viruses (as large as 100 m). Due to their large size, they are removed fairly efficiently during passage through sand, with a 99.3 to 99.9% removal rate reported for *Giardia* cysts (Logsdon et al., 1984). Although there have been a few reported outbreaks of waterborne disease caused by protozoa, especially *Giardia lamblia*, associated with the consumption of contaminated ground water (Craun, 1986a), parasitic diseases of humans are a minor problem in the United States (Fitzgerald, 1983). For this reason, and because very little quantitative information on the survival and transport of protozoa in the subsurface is available, these organisms will not be considered in the remainder of this document.

Movement of Microorganisms from Septic Tank Systems

There have been relatively few studies which have actually followed the movement of bacteria and viruses from septic tanks to ground water. The most comprehensive study on this subject was performed as a part of the Small Scale Waste Management Project at the University of Wisconsin-Madison (Stramer, 1984). Four septic tank systems were used for the experiments.

The first system consisted of a modified conventional septic tank serving a family of six. Poliovirus was introduced in a single inoculum of 10^{11} particles via the inlet baffle of the septic tank. Twelve days after the introduction of the viruses, 220 virus particles/ml were detected in a well located 53 m (175 ft) away. It was calculated that the viruses moved at a rate of 4.5 m (14.6 ft)/day. Detection of only 220 particles/ml may seem relatively insignificant when 10^{11} particles were originally introduced; however, only one virus particle may be required to cause disease (Westwood and Sattar, 1976), so the presence of any viruses in water poses a potential health hazard.

The second system was a septic system located on a lakeshore which received intermittent use, mainly on the weekends. Stools containing poliovirus (10^7 particles) were introduced into the septic tank through the inlet baffle. Eight days later, poliovirus was isolated from ground-water wells located 12.3 m (40.5 ft) and 20.6 m (67.5 ft) from the septic tank. One week later, viruses were detected in greater quantities from these wells; in addition, viruses were detected in a well 28.8 m (94.5 ft) from the septic tank. On days 43 and 71 after the virus was introduced, poliovirus was isolated from the lake water (46.2 m from the septic tank), and from the lake sediment on day 109. It was determined that the poliovirus moved at approximately the same rate as the ground water.

The third system was a newly installed septic tank which served a household of two adults. Viruses were introduced by flushing poliovirus-containing stools down the toilet in the house. Thirteen days later, polioviruses were detected in a well located 9.1 m (30 ft) from the vent pipe in the drainfield. Samples from this well continued to be positive for viruses for 131 days.

In addition to monitoring the presence of viruses in the ground-water wells, the number of indicator bacteria (total coliforms, fecal coliforms, and fecal streptococci) was also determined. This was done in an effort to correlate the presence of viruses (a costly and time-consuming analysis) with the presence of indicator bacteria (a simple, quick, and relatively inexpensive analysis) which are routinely used as an indication of fecal contamination of water. No correlation could be found between the presence of indicator bacteria and the detection of viruses: on some occasions, bacteria were present when no viruses were detected; on other occasions, viruses were isolated in the absence of bacteria.

The fourth system was a septic tank-mound system serving a family of four. Poliovirus was, again, introduced by flushing virus-containing stools down the toilet in the house. Viruses were recovered only in one well, located 1 m from the point of wastewater application in the mound, on days 105 and 119. The number of total coliform bacteria decreased from 10^4 on day 56 to less than 0.1 on days 70 to 147. Thus, again, the presence of indicator bacteria did not correlate with the presence of viruses in the ground-water samples. These findings corroborate those of several other investigators that the absence of indicator bacteria does not guarantee freedom from viral contamination.

Another study on the movement of viruses from a septic tank to a ground-water well was done in New Mexico, on the floodplain of the Rio Grande River (Hain and O'Brien, 1979). Poliovirus was found to survive longer than 20 days in the septic tank, and could be recovered from soil cores in the drainfields 7 days after it was introduced. These investigators also isolated viruses from ground-water samples taken from 4.6 m (15 ft)-deep wells located 3.4 m (11 ft) from the septic tank discharge pipe.

In a study in Texas, enteric viruses were isolated from a well 25 m (82 ft) distant from a septic tank system (Wang et al., 1981). Vaughn et al. (1983) monitored the movement of viruses from septic tanks through a sandy sole-source aquifer on Long Island, New York. Viruses were detected in wells as far as 65 m (213 ft) from the source of sewage.

The movement of indicator bacteria from a septic tile was followed by Viraraghavan (1978). Although the concentration of bacteria decreased with increasing distance from the tile, high numbers (10^2 to 10^4) of bacteria were found 15-25 m away. Reneau and Pettry (1975) found that total coliform bacteria were capable of traveling at least 28 m from a septic tank drainfield located in a fine loamy soil. Escherichia coli were isolated from samples taken 20 m from the drainfield in a study conducted by Rahe et al (1979).

From the results of these studies, it is apparent that pathogenic microorganisms in domestic wastewater can survive in septic tanks, migrate through the leach field, reach ground water and travel towards points of use (wells). Many of these studies were conducted in areas with shallow ground-water tables. However, data on the movement of viruses and bacteria from sites of land application of wastewater indicate that considerable migration distances are possible (Keswick and Gerba, 1980). It would seem reasonable to assume that the same could be expected in septic tank leach fields. Indeed, reports of waterborne disease caused by contamination of ground water with septic tank effluent support this assumption.

Septic Tanks and Waterborne Disease

There have been several waterborne disease outbreaks attributable to the contamination of ground water with septic tank effluent. Approximately 1200 people in a town of 6500 developed acute gastroenteritis, probably due to *Shigella sonnei*, in a two-month period (Craun, 1981). An epidemiological study showed that illness was associated with the consumption of tap water. Further investigation revealed that one of the community's two wells had high levels of coliform bacteria. The source of contamination was found, using a dye tracer, to be a church septic tank located approximately 45.7 m (150 ft) from the well. A breakdown in the city's chlorinator had resulted in the distribution of 1 million gallons of contaminated water to the community, causing the large outbreak.

An outbreak of 98 cases of hepatitis A (infectious hepatitis) in Arkansas was traced to the use of commercial pellet ice (Craun, 1979). The water used to make the ice, as well as the ice itself, was found to be heavily contaminated with coliform bacteria. A dye study traced the contamination to a septic tank leach field serving a home occupied by persons who had recently had infectious hepatitis.

Another outbreak of hepatitis A resulted from the contamination of a 3.4 m (11 ft)- to 30.5 m (100 ft)-deep aquifer overlain by fissured bedrock (Vogt, 1961). The drinking-water well of the first reported case was located 1.8 m (6 ft) from the septic tank. Two other wells were located 3 m (10 ft) away. Four weeks later, 16 individuals from the three households served by these wells became ill within a 3-day period. The outbreak was preceeded by a period of snowmelt and heavy rainfall, possibly resulting in virus-contaminated effluent being carried to the drinking-water aquifer.

In 1972, five cases of typhoid occurred in a residential area in Washington as a result of persons consuming contaminated, untreated ground water from a private well (McGinnis and DeWalle, 1983). An epidemiological investigation revealed that a typhoid carrier lived in the area. When a dye was flushed through the septic system of his home, it was detected 36 hours later in several wells in the area, including the ill family's well, which was located 64 m (210 ft) away (Craun, 1979). *Salmonella typhi*, the causative agent of typhoid, was isolated from the well water, and from stool specimens from the patients and the carrier.

A Norwalk-like agent was responsible for over 400 cases of gastroenteritis at a resort camp in Colorado (Craun, 1984). Over one-half of the persons visiting the camp developed diarrhea at the camp or within one week of leaving it. It was found (using dye tracers) that the camp tap water was contaminated with effluent from a septic tank located 15.2 m (50 ft) above the spring supplying the camp.

An echovirus was isolated from a 12.2 m (40 ft)-deep well during an outbreak of gastrointestinal illness in Florida (Wellings et al., 1975). The well was located 30.5 m (100 ft) from a solid waste field in the middle of an area bordered by septic tanks. The virus was isolated from sewage, well water, and stools of individuals living in the camp. In addition, six weeks later, an outbreak of 15 cases of hepatitis A occurred in the same camp.

A correlation between the isolation of coliforms from water and the presence of septic tank systems has been observed in the absence of any reported waterborne outbreaks of disease. In a survey conducted in the State of Alaska, Hickey and Duncan (1966) found a correlation between the rate of coliform contamination in private wells and the use of individual septic tank systems.

Sandhu et al. (1979) made a similar observation: bacterial populations, and especially *E. coli*, were significantly correlated with the distance between the water supply service and the septic tank.

Evaluating the Potential for Ground-Water Contamination by Waste-Disposal Practices

The facts that septic tanks contribute a large volume of waste to the subsurface every year, are the most frequently reported sources of ground-water contamination, are responsible for 43% of the disease outbreaks in which consumption of contaminated, untreated ground water was the cause of the disease, and that the majority of the outbreaks are caused by pathogenic microorganisms demonstrate the magnitude of the role of septic tanks in waterborne disease in the United States.

Several approaches could be taken to decrease ground-water contamination, and the resulting potential public health problems, by septic tank effluent. One approach, probably the most simplistic, would be to prohibit the use of septic tanks altogether. This is unlikely to occur, as septic tanks are the only economically feasible means of domestic wastewater disposal in many rural areas. Another approach would be to require monitoring of the ground water beneath a septic tank system to ensure that the water met certain water quality standards. This option is also unlikely because of the high costs associated with establishing and administering a program which would affect approximately 20 million homeowners. Disinfection of well water is another approach which could be taken to protect the health of the consumer; this may meet with some resistance due to the associated expense.

A more feasible way to decrease the potential for microbiological contamination of ground water by septic tanks would be to carefully evaluate proposed sites for septic tank installation. Most states have laws which regulate septic tank placement in terms of distance to sources of potable water, minimum lot sizes, and/or minimum soil percolation rates. However, in many cases, these regulations have not been adequate to prevent ground-water contamination and waterborne disease outbreaks. One reason for this is that, many times, the laws are imposed over a state-wide area and therefore do not allow for local variations in hydrogeologic conditions. Another reason is that, in the past, septic tank systems were designed to ensure that the effluent would percolate efficiently through the soil, and little, if any consideration was given to the possibility of ground-water contamination.

Over the past 20 years, several systems have been developed which enable one to evaluate the potential for ground-water contamination by various waste disposal practices. These systems provide a methodical means of evaluating a potential site in such a way that it can be compared directly with another site. The end product of such a system is usually a number which reflects the degree of the impact of the waste disposal practice on the environment.

In many of these systems, environmental quality is defined as a value between 0 and 1 (or any other convenient range), where 0 denotes very good quality and 1 denotes very poor quality. The measurements of each of the variables of interest are converted to a quality scale using a functional relationship curve (Dee et al., 1978). For example, one variable of interest in determining water quality is the number of total coliform bacteria in the water. It may be decided that very good quality, a 0, should correspond to the U.S. Environmental Protection Agency primary drinking water standard, which in this case is less than one total coliform per 100 ml of water. Any number greater than one would receive a rating higher than 0. The numerical value of the rating would reflect how much worse the measured number of coliforms is than the standard. The construction of the functional relationship curve is one of the most difficult parts of developing a rating system. Generally, the relationship can be defined based on theory; the relationship must then be validated using empirical data (Dee et al., 1978).

LeGrand System

One of the earliest systems is one developed by LeGrand (1964). The LeGrand system is based on characterizing a site in terms of five environmental factors including depth to water, distance to a point of water use, ground-water gradient, soil permeability, and sorption. A description of these factors and their associated values can be found in Table 4 (see next page). In the LeGrand system, a numerical rating is obtained for each of the five variables using a rating chart. The five ratings are then added to produce a number which can be related to the contamination potential of the site (Table 5).

Table 5. Contamination potential of waste disposal site predicted using the LeGrand system (LeGrand, 1964)

Total Point Value	Contamination Potential
0-4	imminent
4-8	probable or possible
8-12	possible, but not likely
12-25	very improbable
25-35	impossible

This system was intended to be used for contaminants that attenuate or decrease in potency in time or by oxidation, chemical or physical sorption, and dilution through dispersion. Contaminants such as sewage, detergents, viruses, and radioactive wastes are considered to be appropriate for this system. It was not intended to be used in the evaluation of sites for mixed wastes (such as refuse dumps and sanitary landfills) if the critical consideration is the movement of chemical wastes that attenuate slowly.

Surface Impoundment Assessment System

The surface impoundment assessment (SIA) system (U.S. Environmental Protection Agency, 1983) is a modification of a later method developed by LeGrand (1983). The purpose of the SIA is to provide an estimation of the ground-water contamination potential of impoundments at a minimum cost. It is intended to enable one to prioritize sites in order that sites with high contamination potentials can be identified. Then, more costly

Table 4. Factors used in LeGrand system for evaluation of contamination potential of waste disposal sites (LeGrand, 1964)

Factor Name	Description	Value
water table	Distance from base of disposal unit to the average position of the highest water table	0 (0 ft) - 10 (1000 ft)
sorption	Extent to which contaminant is retained on the earth material by chemical and physical sorption	0 (coarse gravel) - 6 (clay) for 2-media sites: 0 (fractured rock) - 4 (clay)
permeability	Flow of water through soil pores, joints, and fractures	0 (coarse gravel)- 3 (clayey sand)- 1 (clay)
water table gradient	Direction and rate of flow of ground water	0 (60% gradient in an unfavorable direction)- 7 (60% gradient in a favorable direction)
distance to point of use	Distance between source of contamination and point of water use	0 (0 ft) - 11 (10 miles) for 2-media sites: 0 (< 50 ft) - 10 (10 miles)
thickness	Thickness of porous granular materials below the disposal point	for 2-media sites: 0 (≤ 12 ft) - 6 (100 ft)

and time-consuming investigations into the actual contamination at these sites can be undertaken.

The SIA system evaluates an impoundment site in terms of two factors: the ground-water contamination potential itself, and the relative magnitude of potential endangerment to current users of underground drinking water sources. A description of the factors used in the SIA system can be found in Table 6 (see next page). The use of this system does not require precise data, as it is only meant to be used as a first-round approximation of the relative ground-water contamination potential of a site.

Environmental Impact Evaluation System

Another system for evaluating the environmental impact of hazardous waste disposal in land was developed by Pavoni et al. (1972). In addition to considering the susceptibility of ground water to contamination, a term is included for airborne pollution.

This system involves the separate rating of the hazardous waste of concern and the landfill site. In evaluating the waste, the factors were weighted in the following manner:

1) Those factors which directly indicated impairment to humans, animals, or plants were assigned a first degree priority and a maximum value of 40 units each.

2) Those factors which directly indicated persistence in the ecosystem were assigned a second degree priority and a maximum value of 24 units each.

3) Those factors which directly indicated mobility in landfill ecosystems were assigned a third degree priority and a maximum value of 16 units each.

A description of the factors and their associated range of values can be found in Table 7 (see page 22). The total waste ranking is then correlated with the hazardousness of the waste (Table 8).

Table 8. Hazardousness of waste predicted using the system of Pavoni et al. (1972)

Rank	Hazardousness
0 - 30	non-hazardous
31 - 60	slightly hazardous
61 - 80	moderately hazardous
>80	hazardous

Table 6. Factors used in the surface impoundment assessment method (U.S. Environmental Protection Agency, 1983)

Factor Name	Description	Value
unsaturated zone	Based on the combined rating of the thickness of the unsaturated zone and the earth material (both consolidated and unconsolidated) in the unsaturated zone	0 - 9
ground-water availability	The ability of the aquifer to transmit ground water. Based on the permeability and saturated thickness of the aquifer	0 - 6
ground-water quality	A determinant of the ultimate usefulness of the ground water. Based on whether or not it is a current drinking water source and the total dissolved solids concentration	0 - 5
waste hazard potential	Potential for causing harm to human health. Contaminant sources are ranked using the Standard Industrial Classification (SIC) numbers. Contaminant types are classified based on USEPA publication 670-2-75-024	0 - 9
potential endangerment to a water supply	Based on the distance from the impoundment to a ground or surface water source of drinking water and the anticipated flow direction of the waste plume	1 - 9

Table 7. Factors used in the environmental impact evaluation system (Pavoni et al., 1972)

Factor Name	Description	Value
Waste Evaluation		
Human toxicity	Measure of the ability of a substance to produce injury once it reaches a susceptible site in or on the body. Uses Sax toxicity rating	0 (no toxicity) - 39 (severe toxicity)
Ground-water toxicity	Minimum concentration of a substance that would cause damage or injury to humans, animals, or plants	0 (non-toxic) - 42 (very toxic)
Disease transmission potential	Defined as the sum of 3 factors: Subgroup I - mode of disease contraction Subgroup II - pathogen life state Subgroup III - pathogen's ability to survive in various environments	0 (low) - 105 (high)
Biological persistence	Biodegradability of a compound, based on ratio of biochemical oxygen demand (BOD) to the theoretical oxygen demand (TOD)	0 (optimal conditions) - 16 (highly hazardous)
Waste mobility	The ease with which the substance can move in a landfill. Based on absorption, solubility, and net charge of the substance	Solids: 0 (low) - 16 (high) Liquids: 10 (low) - 16 (high)

Table 7. Factors used in the environmental impact evaluation system (continued)

Factor Name	Description	Value
Site evaluation		
Soil parameters		
Infiltration potential	The amount of water which may enter the top surface of the cover soil divided by the amount of water necessary within the cover soil to produce a full passage of moisture from the top of the layer to the bottom of the layer and out into the contained refuse. Based on the field capacity of the soil and the thickness of the cover soil layer.	.02 (low) - 20 (high)
Bottom leakage potential	Potential hazard for a waste to travel through a bottom soil from the bottom of the refuse cell through the containing soil layer and into a ground-water flow system. Based on the permeability of the bottom soil layer and its thickness	.02 (low) - 20 (high)
Absorptive capacity	Potential for absorption of a material on the minerals present in the soil. Based on the cation exchange capacity and the organic content of the soil	0 (high) - 16 (low)

Table 7. Factors used in the environmental impact evaluation system (continued)

Factor Name	Description	Value
Ground-water parameters		
Filtering capacity	Ability of the soil to remove solid particles traveling downward in a fluid suspension. Based on average particle diameter	0 (high) - 16 (low)
Organic content	Based on biochemical oxygen demand (BOD) of ground water	0 (low) - 10 (high)
Buffering capacity	Calculated using the smallest number of milliequivalents of either an acid or base required to displace the original ground-water pH below 4.5 or above 8.5	0 (strong buffer) - 10 (weak buffer)
Potential travel distance		0 (<500 ft) - 5 (>50 miles)
Ground-water velocity	The speed with which a hazardous material may spread into the environment. Calculated using the permeability and the gradient	0 (low) - 20 (high)
Air parameters		
Prevailing wind direction	Based on the angle of wind direction in relation to the location of the population and the number of people in the population	0 (low) - 5 (high)
Population factor	The number of people who could be affected adversely by escaping hazardous materials	0 (low) - 7 (high)

The factors used in evaluating the landfill site were weighted using the following estimate:

1) The factors which would immediately affect a waste transmission were assigned a first degree priority and a maximum value of 20 units each.

2) The factors which would affect a waste transmission once it was in contact with water were assigned second degree priority and a maximum value of 15 units each.

3) The factors which represented the present condition of receiving ground water were assigned third priority and a maximum value of 10 units each.

4) The factors which represented factors outside the immediate disposal site were assigned fourth priority and a maximum value of 5 units each.

These factors and their associated values are also described in Table 7. The landfill site ranking is found by adding the values for the above-mentioned factors. The rank may vary between approximately 0 and 110; the lower the rank, the better the landfill for hazardous waste disposal.

The hazardous waste rating and the landfill site rating provide relative indications of the potential threat to the environment and the feasibility of disposing of hazardous waste at the site, respectively.

Waste - Soil-Site Interaction Matrix

Phillips et al. (1977) developed a method for assessing the environmental impact of land disposal of industrial wastes. This system involves ranking the waste of concern, ranking the soil site, and calculating the final score by means of a matrix which combines the waste factor scores (rows) and soil-site scores (columns). The rationale behind using a matrix is that soil-site properties modify waste characteristics, therefore it is appropriate to multiply waste properties by soil-site properties. A description of the factors used in this system is found in Table 9. The total waste - soil-site score can range from a minimum of 45 (best) to a maximum of 4830 (worst). Although the authors stress that experience in using the scores is required before they can be applied to predicting the suitability of a waste-site combination, they do provide a means for classifying sites (Table 10).

DRASTIC

The final system to be described in this selective review is DRASTIC (Aller et al., 1985). This system was created to enable one to systematically evaluate the ground-water pollution potential of any hydrogeologic setting anywhere in the United States

Table 9. Factors used in the soil-waste interaction matrix (Phillips et al., 1977)

Factor Name	Description	Value
Waste factors		
Effects group		
Human toxicity	Based on toxicity ranks compiled by Sax	0 - 10
Ground-water toxicity	Minimum concentration of the waste which would cause injury or damage to humans, animals or plants	0 (non-toxic) - 10 (very toxic)
Disease transmission potential	Evaluated according to three disease transmission properties of the waste: mode of disease contraction, pathogen life state, and ability of the pathogen to survive	0 (no effect) - 10 (maximum effect)
Behavioral group		
Chemical persistence	Based on the decay of the toxic components of the waste, expressed as a pseudo-first order rate constant	1 (very unstable toxic component) - 5 (very stable toxic component)
Biological persistence	Biodegradability of the waste measured as a ratio of the biochemical oxygen demand (BOD) to the total oxygen demand (TOD)	0 (very biodegradable) - 4 (unbiodegradable)
Sorption	The amount of waste which will sorb to the soil versus the total concentration of the waste	1 (very strong sorption) - 10 (no sorption)

Table 9. Factors used in the soil-waste interaction matrix (continued)

Factor Name	Description	Value
Viscosity	An indication of the time scale for flow of the waste towards the water table	1 (very viscous) - 5 (viscosity of water)
Solubility	A measure of the miscibility of the waste in water	1 (low solubility) - 5 (very soluble)
Acidity/ basicity	Reflects the ability of the waste to solubilize or precipitate metals, allowing their transmission as well as undesirability of very acid or very alkaline substances	0 (no effect) - 5 (maximum effect)
Waste application rate	Reflects the ability of a soil site to attenuate the waste based on the sorption parameter for the site, the volumetric rate factor, and the concentration of the waste	1 (low volumetric application rate of a low concentration waste having high sorptive properties) - 10 (high volumetric application rate of a high concentration waste to a site having a low sorptive capacity)
Soil-site factors		
Soil group		
Permeability	Normalizes LeGrand's values	2.5 (low permeability) - 10 (maximum permeability)

Table 9. Factors used in the soil-waste interaction matrix (continued)

Factor Name	Description	Value
Sorption	Normalizes LeGrand's values	1 (high sorption) - 10 (low sorption)
Hydrology group		
Water table	The fluctuating boundary free water level. Normalizes LeGrand's values	1 (deep water table) - 10 (shallow water table)
Gradient	Normalizes LeGrand's values	1 (gradient away from water use) - 10 (gradient towards point point of water use)
Infiltration	The tendency of water to enter the surface of a waste disposal site	1 (minimum infiltration) - 10 (maximum infiltration)
Site group		
Distance	Normalizes LeGrand's values	1 (large separation distance) - 10 (small separation distance)
Thickness of porous layer	Normalizes LeGrand's values	1 (100 ft of depth) - 10 (10 ft of depth)

Table 10. Acceptability of waste - soil-site interaction scores as determined using the matrix of Phillips et al. (1977)

	Acceptable					Unacceptable				
Class	1	2	3	4	5	6	7	8	9	10
waste - soil-site point score	45-100	100-200	200-300	300-400	400-500	500-750	750-1000	1000-1500	1500-2500	>2500

using existing information. It is intended to evaluate the relative vulnerability of an area to ground-water contamination from various sources.

The factors used in DRASTIC, along with their ranges of values, can be found in Table 11. Each of the 7 factors used in this system has been weighted to reflect its importance relative to the other factors. The weights were derived by a committee of experts using a Delphi (consensus) approach (Dee et al., 1973). Separate weights were assigned to the factors for use in evaluating agricultural sites. The DRASTIC index is computed by multiplying each rating by its weight and summing. The index allows one to identify areas which are more likely to be susceptible to ground-water contamination relative to other areas. The higher the DRASTIC index, the greater the potential for ground-water pollution.

DEVELOPMENT OF A SYSTEM TO EVALUATE THE POTENTIAL FOR MICROBIOLOGICAL CONTAMINATION OF GROUND WATER

None of these rating systems has been developed to deal specifically with the problem of microbial contamination of ground water. The waste evaluation proposed by Pavoni et al. (1972) considers the disease transmission potential as one of the factors. This factor is also used in the soil-waste interaction matrix of Phillips et al. (1977), although it is given less weight. However, this is meant to be a measure of the probability of disease transmission when pathogens come in contact with a host, rather than a measure of the likelihood that pathogens in the waste can be transported to the ground water where they pose a health hazard.

This system has been developed to address the specific problem of ground-water contamination by microorganisms present in septic tank effluent. A large part of the system is based on empirical data gathered from reports of experiments performed on and field observations of the movement and persistence of microorganisms in the subsurface environment.

The Rating System

This rating system has been structured in the same manner as DRASTIC. Eight factors have been identified as important in controlling the survival and/or movement of microorganisms in the subsurface. The factors have been ranked in terms of their importance relative to one another using information available in the literature and professional judgement. Weights, ranging from 1 (least important) to 5 (most important), were assigned to each factor based on this ranking. These factors and their weights are shown in Table 12 (see page 33). A functional relationship curve has been provided for each of the factors. The curves were obtained from other systems or developed from empirical data on the effect of that factor on microorganisms in the

Table 11. Factors used in DRASTIC system for evaluating ground-water pollution potential (Aller et al. 1985)

Factor name	Description	Values
depth to water	Either the depth to the water surface in an unconfined aquifer or the top of the aquifer where the aquifer is confined	5 (>100 ft) - 50 (0-5 ft)
net recharge	The amount of water per unit area of land which penetrates the ground surface and reaches the water table	4 (0-2 inches)- 36 (> 10 inches)
aquifer media	The consolidated or unconsolidated medium which serves as an aquifer (a medium which will yield sufficient quantities of water for use)	3 (massive shale) - 30(karst limestone)
soil media	The uppermost portions of the vadose zone characterized by significant biological activity (the upper weathered zone, $\leq$ 3 ft)	2 (non-aggregated or nonshrinking clay) - 20 (thin or absent)
topography	The slope and slope variability of the land surface	1 (>18%) - 10 (0-2%)
impact of vadose zone	The zone above the water table which is unsaturated. For a confined aquifer, it includes both the vadose zone and any saturated zones which overlie the aquifer	5 (silt/clay) - 50 (karst limestone)
hydraulic conductivity	The ability of the aquifer materials to transmit water, which controls the rate at which ground water will flow under a given hydraulic gradient	3 (<100 gpd/ft^2) - 30 (>2000 gpd/ft^2)

subsurface. Each factor has been assigned a rating which varies from 0 (or 1) to 10, with 0 signifying the least negative impact and 10 the most negative impact on the environment. An indication of the potential for the contamination of the ground water by microorganisms is obtained by multiplying each factor rating by its assigned weight and summing for all factors. A complete explanation of how to compute the rating index, including examples, is given in a later section. Each factor, and the rationale for using it, will now be discussed in detail.

Depth to Water

The ratings and ranges for depth to water are the same as those used in the DRASTIC system (Table 13). A graph of the ranges and ratings is shown in Figure 5. Depth to water is defined as the distance from the base of the system to the top of the maximum seasonal elevation of the ground water (U.S.EPA, 1980). The depth to water is important because it determines the depth of material through which the microorganisms must travel in order to reach the water table. This is also an indication of the amount of material available to aid in removal of the microorganisms.

In this system, depth to water has also been considered in determining ratings for the soil texture. This will be discussed further in a subsequent section.

Net Recharge

The ratings and ranges for net recharge are the same as those proposed in the DRASTIC system (Table 14, see page 36). Figure 6 shows a graph of the ratings and ranges for net recharge. Net recharge as defined by Aller et al. (1985) is the amount of water (mainly from precipitation) per unit area of land which penetrates the ground surface and reaches the water table on a yearly basis. Recharge water is important in that it can transport contaminants through the soil. Caldwell (1938a) found that coliforms moved less than 0.3 m from a latrine under normal conditions. However, if water was added to the soil, either artificially or in the form of rainfall, the coliforms could be isolated 1.8 m away.

Several investigators have shown that viruses which were absorbed onto soil particles could be desorbed by decreasing the ionic strength of the fluid in the matrix. This has been observed using laboratory soil columns flooded with distilled water to simulate rainfall (Gerba and Lance, 1978; Landry et al., 1979, 1980; Lance et al., 1976; DuBoise et al., 1976; Sobsey et al., 1980). However, the ability of rainfall to desorb viruses depends on the soil type: viruses are more readily desorbed from sandy soils than from clay soils (Gerba and Bitton, 1984).

The ability of rainfall to desorb viruses and translocate them to the ground water has also been observed in a field study

Table 12. Factors and weights used in system to evaluate potential for microbiological contamination of ground water

Factor	Weight
Depth to water (DTW)	5
Net recharge (R)	2
Hydraulic conductivity (K)	3
Temperature (T)	2
Soil texture (S)	5
Aquifer medium (A)	3
Application rate (AR)	4
Distance to well (D)	5

Table 13. Ranges and ratings for depth to water (adapted from Aller et al., 1985)

Depth to Water

Range (ft)	Rating
0 - 5	10
5 - 10	9
10 - 30	7
30 - 50	5
50 - 75	3
75 - 100	2
> 100	1

Weight = 5

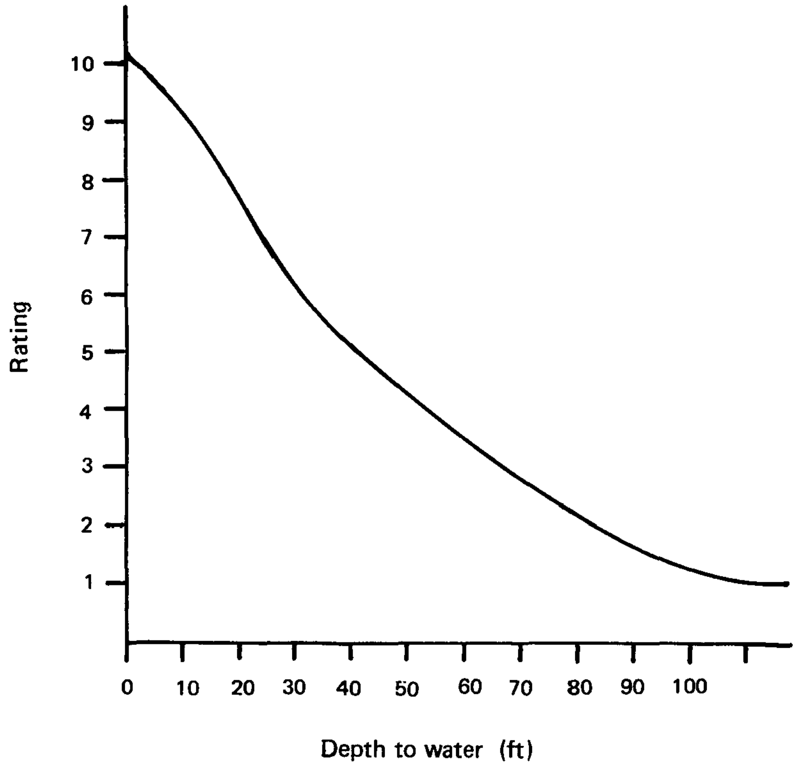

Figure 5. Graph of ranges and ratings for depth to water (Aller et al., 1985).

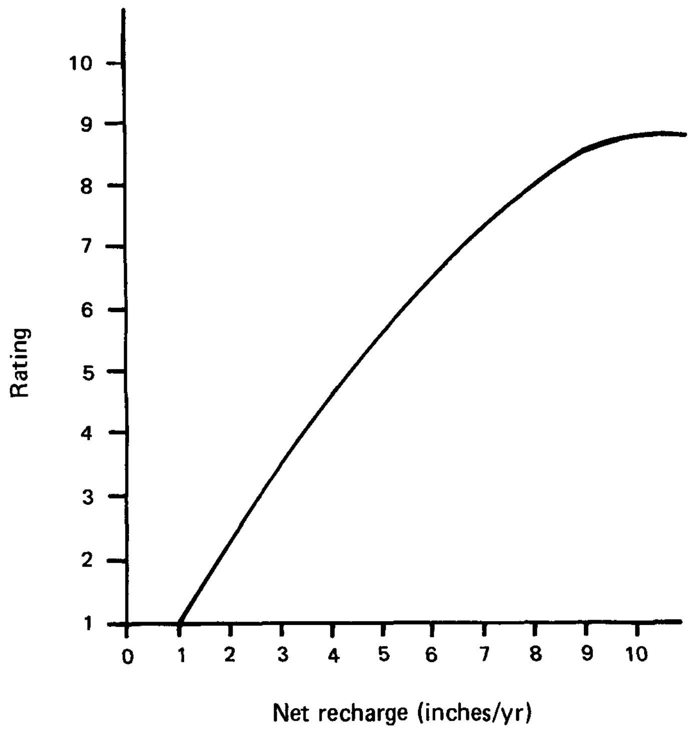

Figure 6. Graph of ranges and ratings for net recharge (Aller et al., 1985).

(Wellings et al., 1974). No viruses were detected in wells at a waste application site until after a period of heavy rainfall.

Hydraulic Conductivity

The ranges and ratings for hydraulic conductivity have been taken from the DRASTIC system (Table 15). A graph of the ratings as a function of the hydraulic conductivity of the aquifer is shown in Figure 7. Hydraulic conductivity is a measure of the ability of the aquifer medium to transmit water. This, in conjunction with the hydraulic gradient, controls the rate at which the ground water flows, which in turn controls the rate at which contaminants can be transported through the aquifer.

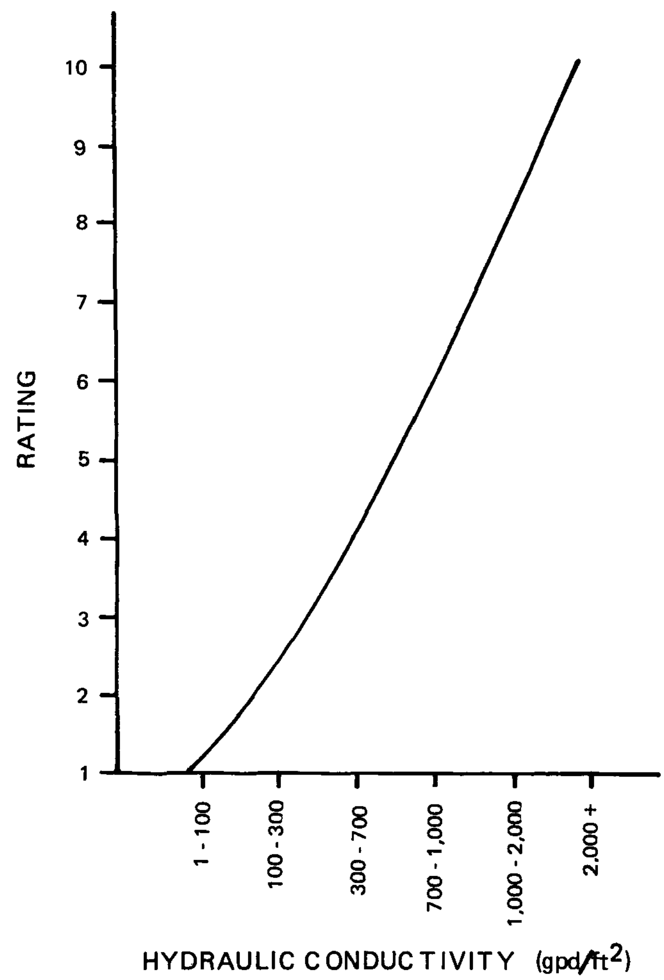

Figure 7. Graph of ranges and ratings for hydraulic conductivity (Aller et al., 1985).

Table 14. Ranges and ratings for net recharge (Aller et al., 1985)

Net Recharge

Range (inches/year)	Rating
0 - 2	1
2 - 4	3
4 - 7	6
7 - 10	8
>10	9

Weight = 2

Table 15. Ranges and ratings for hydraulic conductivity (Aller et al., 1985)

Hydraulic Conductivity

Range(gpd/ft^2)	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
>2000	10

Weight = 3

Microorganisms have been found to move at the same rate as the ground water (Stramer, 1984). In addition, several investigators have used microorganisms as tracers to determine the rate of ground-water flow in an area (Martin and Thomas, 1974; Pyle et al., 1979; Sinton, 1979, 1980; Pyle and Thorpe, 1981; Gerba, 1984; Wimpinny et al., 1972).

Temperature

Temperature is the only environmental factor which has been found to have a consistent effect on the length of time viruses can remain infective in all types of water studied (Sattar, 1981), as well as in different types of soil (Hurst et al., 1980). As the temperature increases, the rate of virus inactivation increases. Indeed, temperature is probably the most detrimental factor affecting virus persistence in the subsurface (Bitton, 1978). Therefore, it was felt that temperature should be included in the rating system.

The data used to develop the ranges and ratings for temperature (Appendix 1) were taken from experiments on poliovirus, echovirus, and bacteriophage MS-2 persistence in ground water. Statistical analysis has shown that there is no significant difference in the inactivation rates of these viruses (Yates et al., 1985). Data on bacteria were not used because enteric viruses, in general, have been found to persist for longer periods of time than bacteria in ground water under the same conditions (Bitton et al., 1983; Keswick et al., 1982). In addition, data on virus persistence in ground water were available over a wide range of temperatures (3 - 30.5°C).

Mean virus inactivation rates $\lfloor -\log_{10}$ (number of viruses)/day$\rfloor$, y, were analyzed as a function of temperature, x, using linear regression. As expected, inactivation rate was highly correlated with temperature ($r = 0.85$). This relationship can be described by the equation:

$$y = 0.4554x - 0.12372$$

and is depicted graphically in Figure A1. These data were converted into the ranges and ratings in Table 16, which are shown graphically in Figure 8.

Soil Texture

The texture of soil through which the septic tank effluent must percolate as it moves from the absorption system to the water table is a very important factor in evaluating the potential for ground-water contamination by microorganisms. There are two major mechanisms whereby microorganisms can be removed as they are transported through the subsurface: filtration and adsorption.

Table 16. Ranges and ratings for temperature

Temperature	
Range (°C)	Rating
< 5	10
5 - 10	9
10 - 12.5	7
12.5 - 17	5
17 - 20	4
20 - 25	2
25 - 30	1
> 30	1

Weight = 2

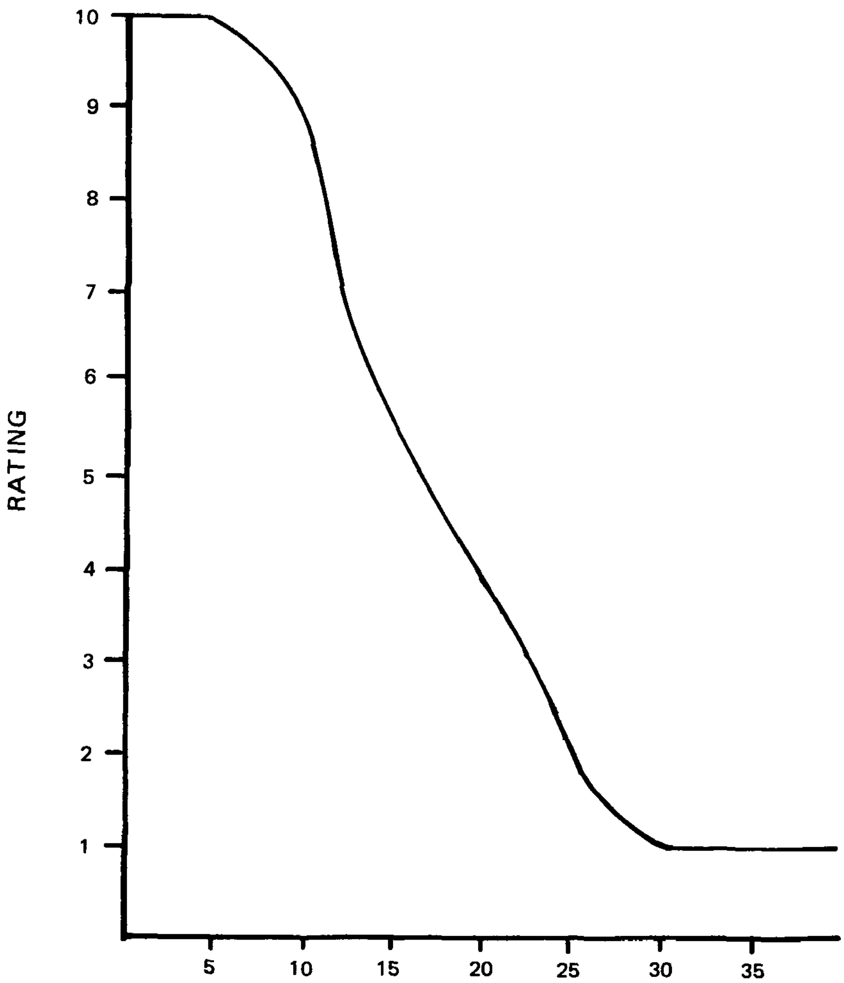

Figure 8. Graph of ranges and ratings for temperature.

Bacteria are removed largely by filtration, that is, they are trapped in soil pores as the water passes through the matrix. Therefore, bacteria are removed to a greater degree in soils with small pores than in coarser-textured soils such as sands and gravels. Viruses, especially if they are solids-associated, may also be removed by filtration, although this mechanism of virus removal is probably of minor importance (Sobsey, 1983b).

The major mechanism of virus removal in soils is by adsorption. Viruses are adsorbed more effectively by fine-textured soils than coarser soils, due to the high sorptive capacity of the clay fraction of the soil. Several investigators have studied the adsorption of viruses to different textures of soils (Burge and Enkiri, 1978; Gerba et al., 1980, 1981; Goyal and Gerba, 1979; Moore et al., 1981; and Sobsey et al., 1980). Although the extent of adsorption varies among different viruses, it is generally agreed that virus adsorption increases with increasing clay content. Bacteria are also removed in soil by adsorption to clay particles (Gerba and Bitton, 1984).

In order to develop ratings based on soil texture, data on the extent of vertical movement of microorganisms in soil were accumulated. Some of the data were obtained from column studies conducted in the laboratory, others from field studies. These data, compiled in Appendix 2, were plotted to determine the influence of soil texture on the distance that a microorganism was observed to travel in that soil (Figure A2). Soil texture is plotted as a function of decreasing particle size from fractured rock to fine sand, and as a function of increasing clay content from fine sand to clay. Table 17 provides information on the clay content of a soil as it relates to the soil texture class.

The data were analyzed using linear regression, and a high correlation ($r = -0.83$) was found to exist between soil texture, x, and the $\log_{10}$ (distance) of movement, y. The relationship can be expressed by the equation:

$$y = -0.28928x + 1.7967$$

Once the importance of soil texture in limiting microbial movement was verified, ratings had to be developed to reflect this. It was felt that soil texture in itself was not as important as soil texture in relation to the depth to water. In other words, if the site has a shallow water table, and the soil has a clayey texture, the potential for ground-water contamination is much less than if the soil were a coarse gravel. Also, the importance of the depth to water in a clay soil is less than the importance of depth to water in a sandy soil. The rating scheme developed reflects this two-tiered approach (Table 18). To determine the rating for soil texture from the graph (Figure 9), one first determines the soil texture, interpolating if the exact texture is not on the x-axis, with the aid of Table 17. The rating is read by projecting a line from the soil texture to the line closest to the

Table 17. Soil hydrologic properties by soil texture (Dean et al., 1984)

Texture Class	Ranges of Textural Properties (%)		
	Sand	Silt	Clay
sand	85-100	0-15	0-10
loamy sand	70-90	0-30	0-15
sandy loamy	45-85	0-50	0-20
silt loam	0-50	50-100	0-28
loam	25-50	28-50	8-28
sandy clay loam	45-80	0-28	20-35
silty clay loam	0-20	40-73	28-40
clay loam	20-45	15-55	28-50
sandy clay	45-65	0-20	40-60
clay	0-45	0-40	40-100

Table 18. Ranges and ratings for soil type

Soil Type	Rating Depth to Water 45 m	9 m	1.1 m
fractured rock	10	10	10
coarse gravel	9	10	10
coarse sand	8	10	10
fine sand	7	10	10
sandy loam	6	8.6	10
loam	5.2	7.4	10
sandy clay loam	4.2	6.1	10
clay loam	3.1	4.4	7.7
sandy clay	2.5	3.6	6.2
clay	1	1.4	2.5

Weight = 5

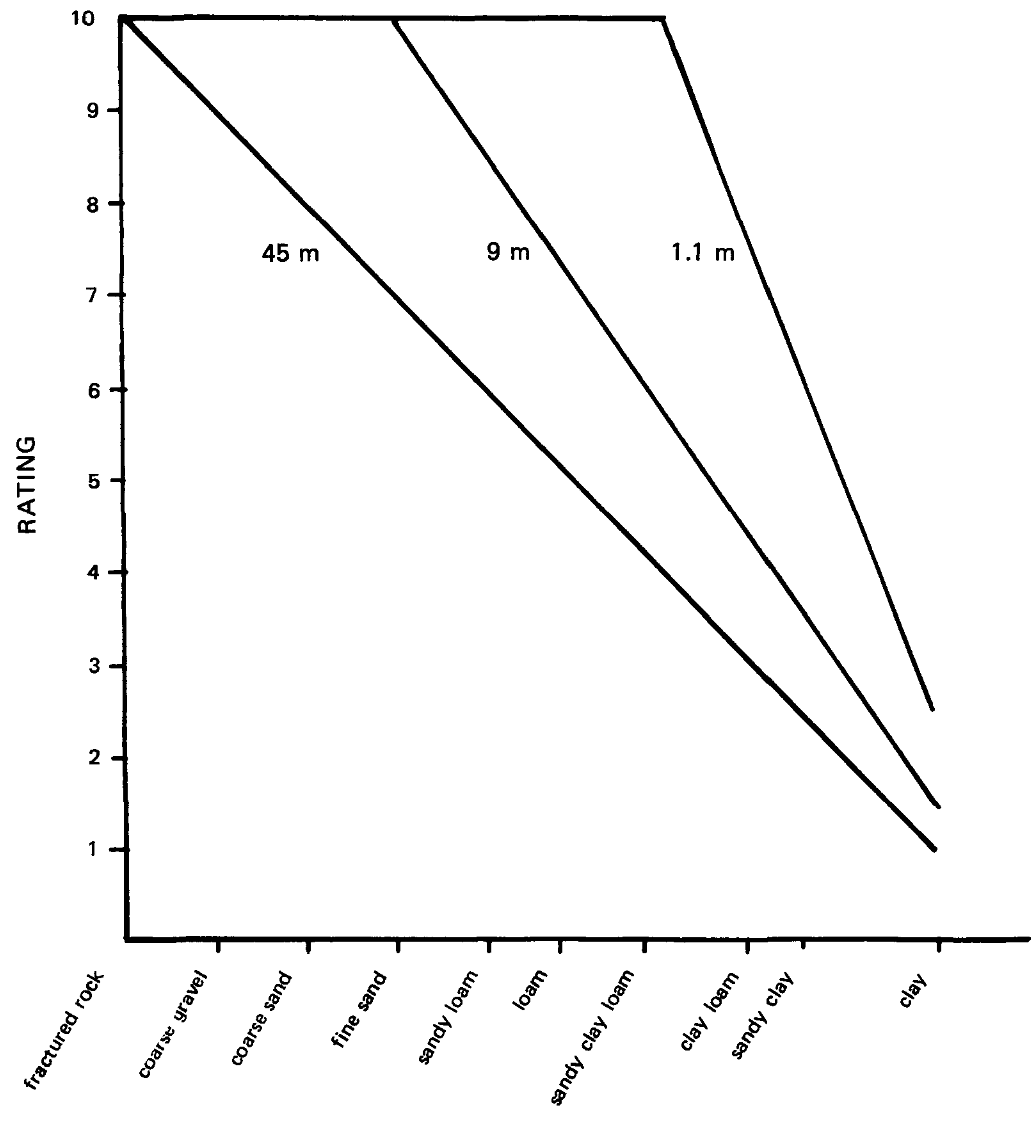

Figure 9. Graph of ranges and ratings for texture.

depth to water at the particular site (using interpolation as necessary), and then projecting the line from that point to the rating axis (y-axis).

Aquifer Medium

The aquifer medium is the material through which the effluent moves after it has traveled through the unsaturated zone (soil) and when it enters the ground water (saturated zone or aquifer). The same argument as was put forth in the development of ratings for soil texture was used in determining ratings for the aquifer medium (in terms of mechanisms of removal of microorganisms in soil and the importance of soil texture in that process).

A graph of the horizontal distance of microbial movement as a function of aquifer medium is shown in Figure A3. The data used to develop this graph are contained in Appendix 3. It was felt that the data could best be described by a shallow curve rather than a straight line.

In an analogous fashion to the system for determining the soil texture rating, the aquifer medium rating is also based on a two-tiered approach (Table 19). In this case, the horizontal distance from the septic tank site to a point of water use (such as a drinking-water well) was considered in rating the aquifer material. The graph to determine the aquifer material rating (Figure 10) is used in the same way as that for the soil texture rating: a line is projected up from the aquifer medium to the line corresponding to the distance (down gradient) to the nearest drinking water well. This point is then projected across to the y-axis to obtain the rating.

Application rate

The rate at which the effluent is applied to the soil is important in that the lower the application rate, the longer the time available for adsorption and retention of the microorganisms by soil particles. The results of a study by Wang et al. (1981) led the authors to suggest that the rate at which the water is applied to the soil may be the most important factor in predicting the potential for virus movement into the ground water. The effect of changing the application rate on the degree of virus removal has been the subject of a few studies (Grigor'eva and Goncharuk, 1966; Lance and Gerba, 1980; Robeck et al., 1962; Vaughn et al., 1981; and Wang et al., 1981).

Data on the effect of application rate on the degree of removal of microorganisms in the percolating effluent were obtained by surveying the published literature (Appendix 4). The application rate, x, was found to be highly correlated ($r = 0.88$) with the degree of removal of microorganisms, y. This relationship, shown in Figure A4, can be expressed by using the equation:

$$y = -0.53763x - 0.59602$$

Table 19. Ranges and ratings for aquifer medium

	Rating		
	Distance to Point of Use		
Soil type	200 m	20 m	2 m
fractured rock	10	10	10
coarse gravel	10	10	10
coarse sand	8.9	10	10
fine sand	7.8	10	10
sandy loam	6.7	8.6	10
loam	5.8	7.4	10
sandy clay loam	4.7	6	8.4
clay loam	3.4	4.4	6.2
sandy clay	2.8	3.6	5
clay	1.1	1.4	2

Weight = 3

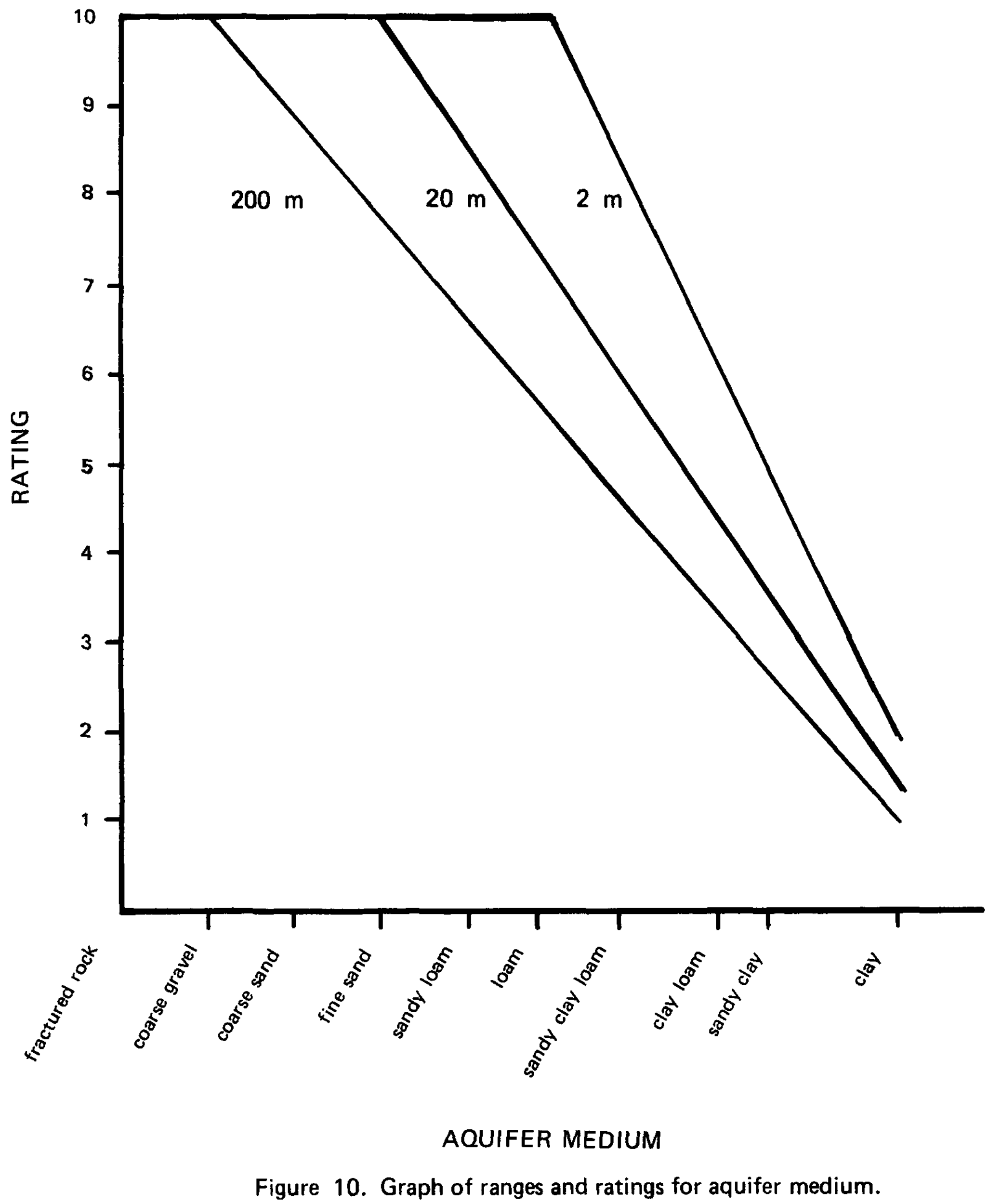

Figure 10. Graph of ranges and ratings for aquifer medium.

The ranges and ratings for effluent application rate are shown in Table 20. In order to determine the rating from the graph (Figure 11), the application rate must first be converted to the log form.

Distance to Point of Use

The ranges and ratings for the separation distance between the point of effluent introduction and a point of water use (such as a drinking-water well) have been taken from LeGrand (1964). His chart has been adapted to table and graph form, in order to be consistent with this system (Table 21, Figure 12). In addition, the ratings have been reversed so that higher numbers reflect a greater hazard than lower numbers. To use the graph, the distance in meters must be converted to the log form before reading the rating.

Computation of the Rating Index

After ratings have been obtained for all eight factors, the index is then computed by using the equation:

$$\text{Index} = 5DTW + 2R + 3K + 2T + 5S + 3A + 4R + 5D$$

The higher the index, the higher the potential for microorganisms to survive and be transported to the underlying ground water. The index may range from 0 to 290. Following are two examples to illustrate the use of the system.

Example 1:

Factor	Value	Rating
Depth to water table	50 ft (16.4 m)	4
Net recharge	5 inches/yr	5.5
Hydraulic conductivity	900 gpd/ft^2	8
Temperature	14°C	6.1
Soil texture	sandy loam	7.5
Aquifer medium	sand	10
Application rate	15 cm/day (log = 1.2)	2.5
Distance	100 m (log = 2)	2.8

$$\text{Index} = 4(5) + 5.5(2) + 8(3) + 6.1(2) + 7.5(5) + 10(3) + 2.5(4) + 2.8(5)$$

$$= 158.7$$

Table 20. Ranges and ratings for effluent application rate

Application rate	
Range (cm/day)	Rating
< 5	1
5 - 13	2
13 - 45	3
45 - 100	4
100 - 360	5
360 - 920	7
920 - 2000	9
2000 - 3300	10

Weight = 4

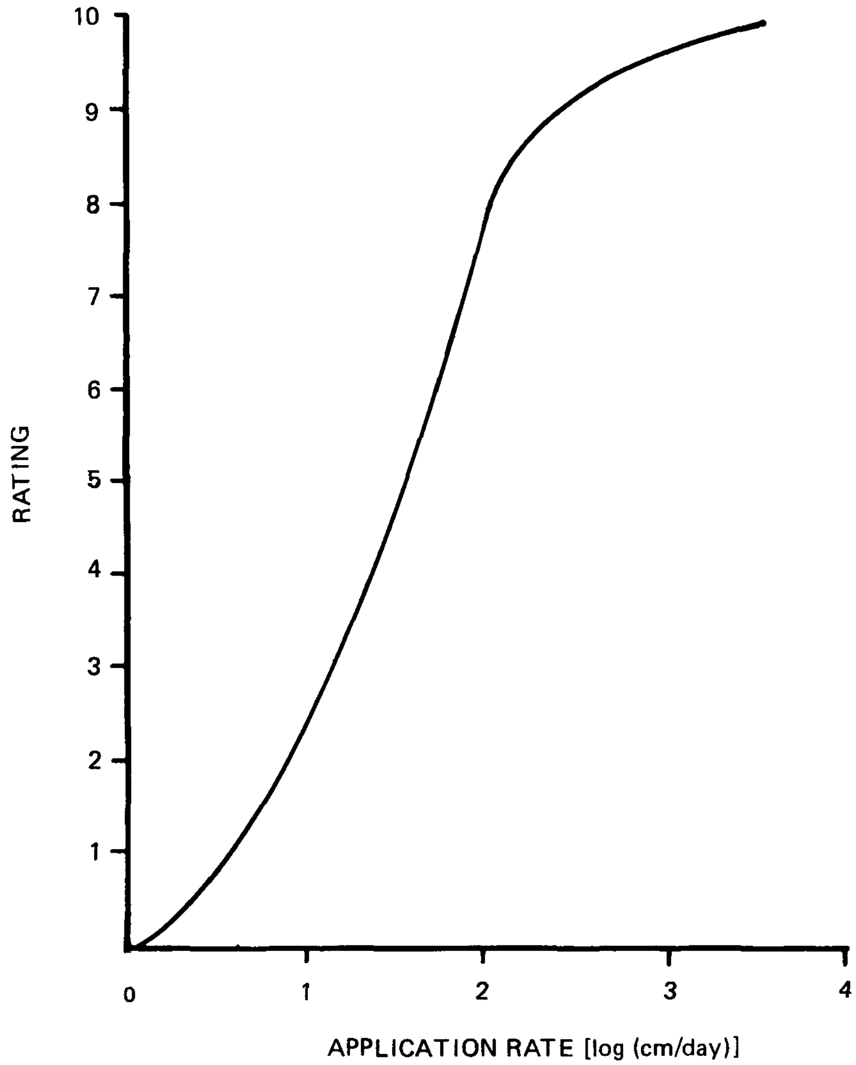

Figure 11. Graph of ranges and ratings for application rate.

Table 21. Ranges and ratings used for separation distance between septic tank and point of water use (Adapted from LeGrand, 1964)

Distance

Range m	Range ft	Rating
0 - 15	0 - 50	10
15 - 23	50 - 75	9
23 - 30	75 - 100	8
30 - 38	100 - 125	7
38 - 46	125 - 150	6
46 - 61	150 - 200	5
61 - 91	200 - 300	4
91 - 152	300 - 500	3
152 - 305	500 - 1000	2
>305	>1000	1

Weight = 5

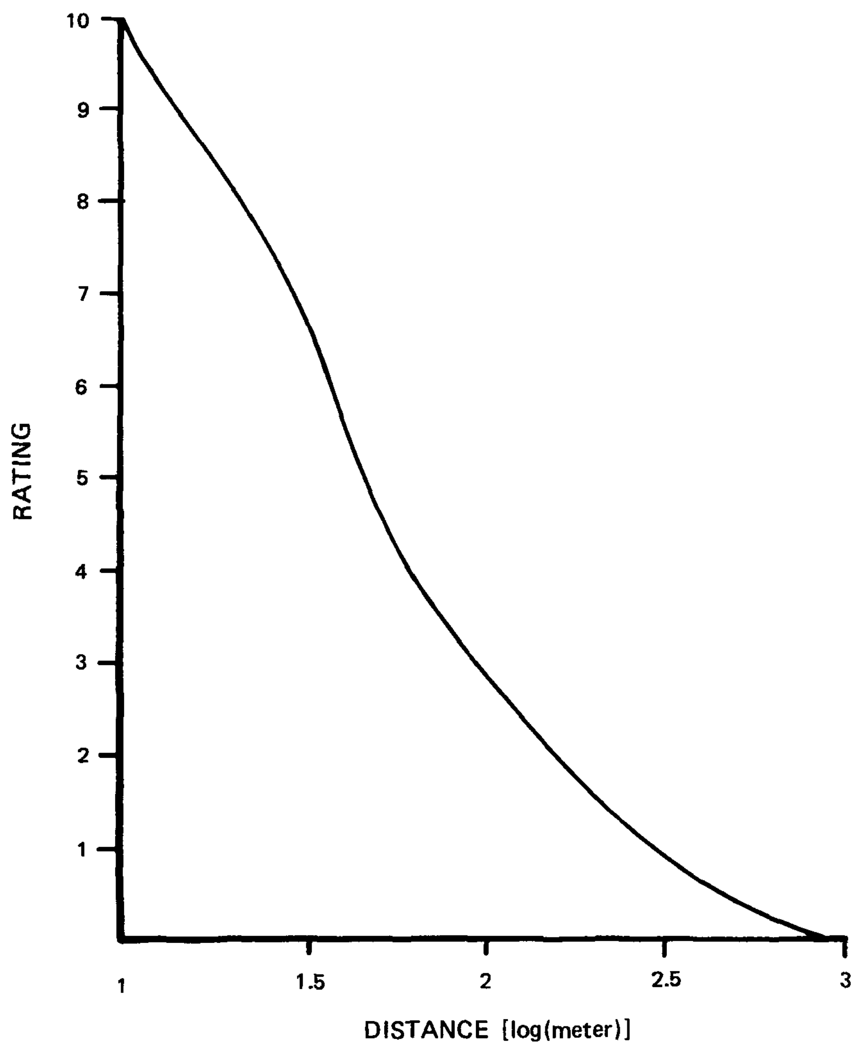

Figure 12. Graph of ranges and ratings for distance between septic tank and point of water use (LeGrand, 1964).

Example 2:

Factor	Value	Rating
Depth to water table	3 ft (1 m)	10
Net recharge	3 inches/yr	3.3
Hydraulic conductivity	2000 gpd/ft^2	10
Temperature	10°C	9
Soil texture	sand	10
Aquifer medium	fractured rock	10
Application rate	120 cm/day (log = 2)	8.4
Distance	50 m (log = 1.7)	4.4

$$\text{Index} = 10(5) + 3.3(2) + 10(3) + 9(2) + 10(5) + 10(3) + 8.4(4) + 4.4(5)$$
$$= 240.2$$

At many sites, there may be several soil layers underlying the soil absorption field through which the effluent must travel before it reaches the ground water. Under such circumstances, it will be necessary to use professional judgement in order to obtain the rating. For example, if the soil profile consists of layers of coarse sands and clays, some intermediate rating will have to be used. If the profile is primarily coarse sand with a few thin clay layers, it may be appropriate to use the ratings for a sandy loam, as the clay will not affect the movement of the microorganisms to any great extent. If the clay comprises a substantial proportion of the profile, then the rating for a sandy clay would be more appropriate to use.

Interpretation of Results

The system is intended to be used as a guide in evaluating a septic tank site in terms of its susceptibility to ground-water contamination by pathogenic microorganisms. Although quantitative data have been used to help derive the ranges and ratings, professional judgement and observations were used to create the system. Therefore, the index should not be used as a substitute for a detailed site investigation and professional judgement. Conditions and circumstances at the individual site as well as common sense need to be considered in addition to the index.

The index provides a relative indication of the potential for ground-water contamination by microorganisms. A site with a higher index is more likely to have contamination problems than one with a lower rating. If a definitive interpretation of the index for a particular site is desired, it is suggested that the following scale may be used as a guide:

0 - 75	not very probable
75-150	possible
150-225	probable
>225	very probable

Using the scale to interpret the result of the two examples cited, site 1 would be considered possible to probable, whereas site 2 would be a very probable.

Sources of Information

The information needed to determine the ratings for the eight environmental factors can be obtained from a number of sources. The U.S. and state geological surveys can provide information on the depth to water table, hydraulic conductivity, aquifer medium, and net recharge. Soil texture information can be obtained from the U.S. Department of Agriculture - Soil Conservation Service, or from a soil survey done on the site. City or local water utilities have information on depth to water, water temperature, and locations of nearby water supply wells. Other sources of information include local universities and associated agricultural extension services, state departments of natural resources and environmental protection, and the Army Corps of Engineers.

Use of System

It is anticipated that the rating system could be used in two different ways:

1) The system could be used to evaluate a region in order to delineate areas which are most susceptible to ground-water contamination by microorganisms in septic tank effluent as an aid in community planning. Using the results of the rating system, a decision could be made to allow septic tanks only in certain areas of the community where the potential impacts on ground-water quality and human health are minimal.

2) The second use for this system would be when someone desires to install a septic tank at a certain location. The calculated rating could be used as an aid in septic tank installation. For example, if the index was above a

certain cut-off, indicating that the potential for contamination was unacceptably high, the size of the adsorption field could be increased to decrease the potential. Again, it should be emphasized that this system should not be used as a substitute for a detailed site investigation.

The USEPA's ground-water classification system or State classification system could be used in conjunction with the rating as an additional input in the siting process. For example, a higher rating (higher contamination potential) might be more acceptable if Class II ground water would be impacted as opposed to Class I ground water.

Validation of the System

Once a rating system such as this has been developed, the next step is to verify that the results will closely approximate what happens in the environment. One way to do this would be to perform a retrospective study on sites where waterborne disease outbreaks have occurred and determine whether the rating system would have predicted that ground-water contamination was likely. It should also be tested at several field sites and be compared with the judgement of professionals to see how well the two correspond.

The system should also be validated using sensitivity analysis. The index is calculated based on the shapes of the functional relationship curves as well as on the weights which have been assigned to each of the eight environmental factors. A sensitivity analysis will indicate to which of the curves and weights the index is most sensitive. In othe5 words, it will indicate whether the calculated index would be changed appreciably if the shape of a functional relationship curve were altered slightly or a weight were changed by one unit in either direction.

APPENDICES

AND

REFERENCES

Appendix 1. Data used to determine temperature ranges and ratings

Reference	Temperature (°C)	Decay Rate ($-log_{10}$/day)
Yates, 1985	20	0.15
"	"	0.11
"	"	0.12
"	"	0.069
"	"	0.086
"	23	0.16
"	"	0.10
"	"	0.13
"	"	0.13
"	24.5	0.20
"	"	0.14
"	"	0.18
"	"	0.17
"	"	0.16
"	"	0.20
"	"	0.21
"	"	0.11
"	"	0.15
"	"	0.16
"	"	0.15
"	26	0.16
"	"	0.20
"	"	0.17
"	"	0.23
"	"	0.11
"	"	0.33
"	"	0.25
"	"	0.27
"	"	0.11
"	"	0.18
"	"	0.21
"	"	0.16
"	"	0.29
"	27	0.40
"	"	0.43
"	"	0.15
"	"	0.48
"	"	0.21
"	"	0.22
"	"	0.17
"	"	0.16
"	"	0.18
"	"	0.20
"	"	0.18

Appendix 1. Data used to determine temperature ranges and ratings (continued)

Reference	Temperature (°C)	Decay Rate ($-log_{10}$/day)
Yates, 1985	27	0.23
"	"	0.21
"	"	0.46
"	"	0.17
"	"	0.29
"	"	0.58
"	28.25	0.25
"	"	0.34
"	"	0.22
"	"	0.19
"	"	0.26
"	"	0.16
"	"	0.22
"	"	0.19
"	30.5	0.64
"	"	0.21
"	"	0.22
"	"	0.29
"	"	0.46
"	"	0.23
"	"	0.28
"	"	0.71
"	"	0.31
"	"	0.36
"	"	0.29
"	"	0.23
"	"	0.39
Yates, 1984	30	0.58
"	"	0.64
"	26	0.21
"	"	0.42
"	"	0.28
"	"	0.23
"	"	0.28
"	"	0.25
"	"	0.27
"	"	0.29
"	"	0.36
"	"	0.27
"	"	0.29
"	"	0.32
"	"	0.32
"	"	0.40

Appendix 1. Data used to determine temperature ranges and ratings (continued)

Reference	Temperature (°C)	Decay Rate ($-\log_{10}$/day)
Yates, 1984	26	0.44
"	"	0.32
"	"	1.10
"	30	0.42
"	"	0.63
"	27	0.65
"	25	0.20
"	27	0.31
"	25	0.39
"	"	0.65
"	"	0.54
"	"	0.13
"	"	0.19
"	27	0.11
"	25	0.28
"	"	0.31
"	30	1.87
"	27	0.14
"	25	0.25
"	"	0.34
"	"	0.21
"	"	0.25
"	27	0.13
"	4	0.020
"	12	0.093
"	23	0.24
"	4	0.064
"	12	0.16
"	23	0.58
"	4	0.014
"	12	0.030
"	23	0.019
"	4	0.012
"	12	0.095
"	23	0.26
"	4	0.025
"	12	0.040
"	23	0.33
"	12	0.034
"	"	0.037
"	13	0.077
"	"	0.11

Appendix 1. Data used to determine temperature ranges and ratings (continued)

References	Temperature (°C)	Decay Rate ($-log_{10}$/day)
Yates, 1984	18	0.082
"	17	0.075
Keswick et al., 1982	3-15*	0.19
"	"	0.21
Bitton et al., 1983	22	0.046
	"	

*Not used in regression analysis, included for completeness.

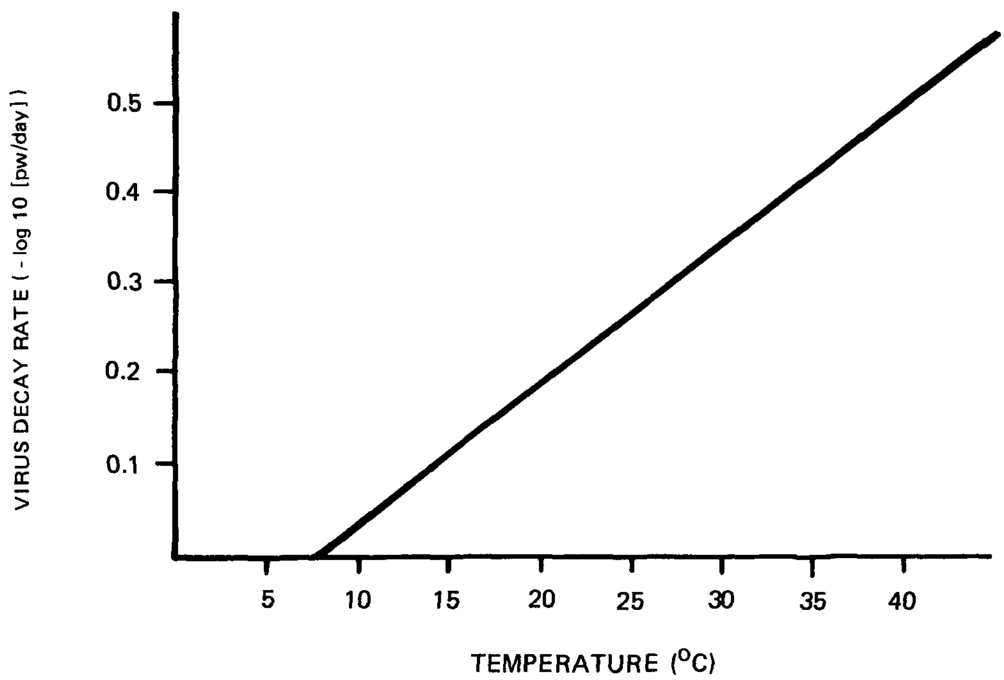

Figure A1. Virus decay rate as a function of temperature.

Appendix 2. Data used to determine soil texture ranges and ratings

Reference	Vertical Distance (m)	Soil Texture	Microorganism
Wellings et al., 1975	3	sandy clay	viruses
Wellings et al., 1974	3-6	sand	viruses
Vaughn and Landry, 1977	22.8	sand	coxsackievirus-B3
Schaub and Sorber, 1977	29	silty sand & gravel	f2 phage
Koerner and Haws, 1979	16.8	sand & coarse gravel	viruses
Reneau and Pettry, 1975	2	sandy clay loam	coliforms
"	4.3	"	"
"	0.64	sandy loam	"
Lance and Gerba, 1980	1.60	loamy sand	poliovirus
Rahe et al., 1979	0.33	silty clay loam	*E. coli*
"	1	"	"
Kudryavtseva, 1972	4	fine sand	coliforms
Malin and Snellgrove, 1958	0.91	stone clay & sand	coliforms
"	0.61	stone and clay	"
"	0.3	firm clay	"

Appendix 2. Data used to determine soil texture ranges and ratings (continued)

Reference	Vertical Distance (m)	Soil Texture	Microorganism
Vaughn et al., 1978	11.3	coarse sand & fine gravel	echovirus
"	6.1	"	"
Brown et al., 1978	1.2	sandy clay	bacteriophage
"	0.85	sandy clay & clay	fecal coliforms
Weaver, 1983	0.10	clay	*Salmonella enteriditis*
Anan'ev and Demin, 1971	10 - 12	loam & sandy loam, sand & gravel	coliforms
Warrick and Muegge, 1930	0.3	fine sand	*E. coli*
Caldwell, 1937	4	fine & coarse sand	*E. coli*
Caldwell and Parr, 1937	1.5	sand & sandy clay	*E. coli*
Caldwell, 1938a	0.15	fine & medium sand	*E. coli*
Fournelle et al, 1957	0.15	sandy - gravel	*Streptococcus zymogenes*
Lefler and Kott, 1974	0.2	sand	poliovirus
Vaughn et al, 1978	10.6	coarse sand & fine gravel	poliovirus

Appendix 2. Data used to determine soil texture ranges and ratings (continued)

Reference	Vertical Distance (m)	Soil Texture	Microorganism
Vaughn and Landry, 1977	6.1	sand	poliovirus
"	2.4	"	"
"	6.4	"	"
"	9.1	"	"
Aulenbach, 1979	45.7	sand	bacteriophage
Keswick and Gerba, 1980	18.3	fine loamy sand over gravel	coxsackievirus-B3
Vaughn et al., 1981	7.62	coarse sand and fine gravel	poliovirus
Butler et al., 1954	4	fine sandy loam over fine sand	total coliforms
Gerba and Lance, 1978	0.4	loamy sand	virus

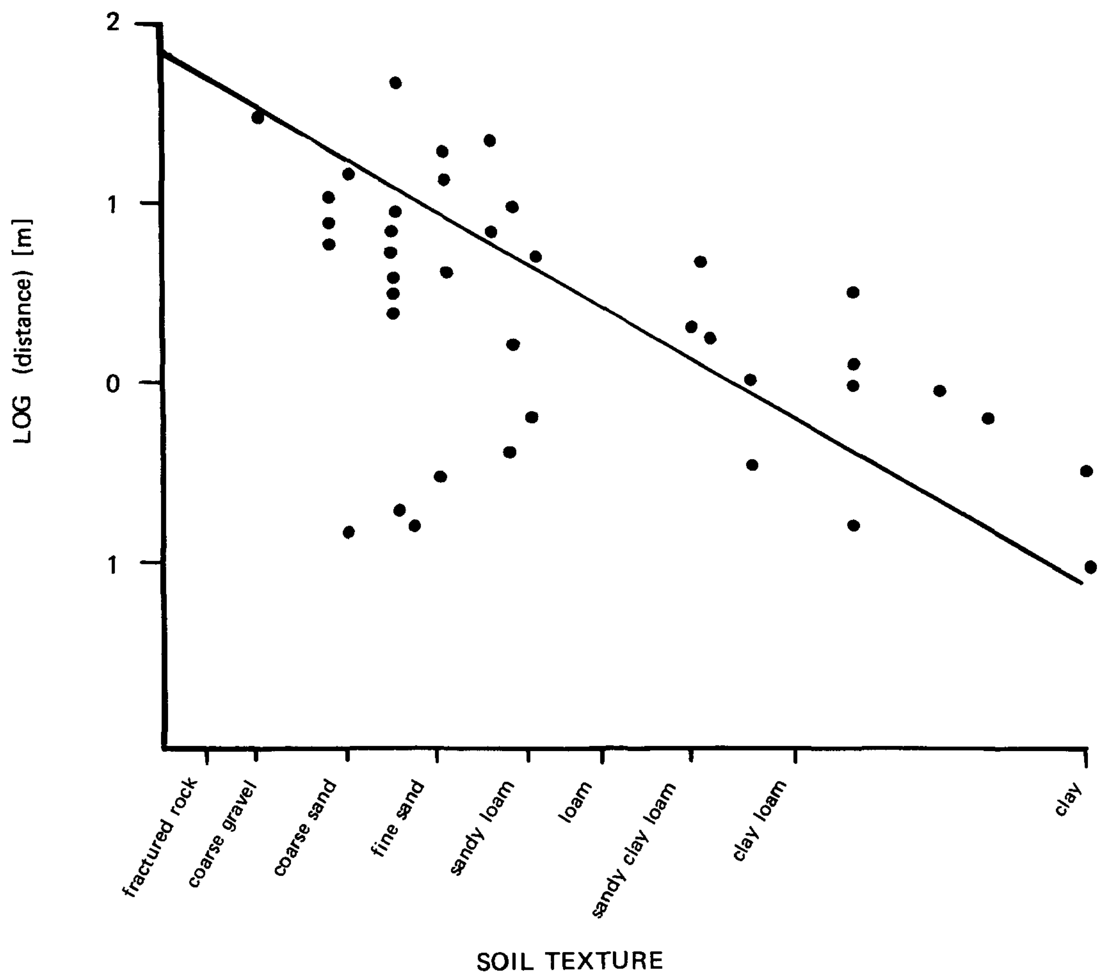

Figure A2. Vertical movement of microorganisms as a function of soil texture.

Appendix 3. Data used to determine aquifer medium ranges and ratings

Reference	Horizontal Distance (m)	Aquifer Medium	Microorganism
Wellings et al., 1975	7-38	sand	viruses
Vaughn and Landry, 1977	408	sand	coxsackievirus-B3
Schaub and Sorber, 1977	183	silty sand & gravel	f2 phage
Koerner and Haws, 1979	250	sand	viruses
Reneau and Pettry, 1975	6.1	sandy clay loam	coliforms
"	13.5	"	"
"	28	"	"
Viraraghavan, 1978	15.25	sandy clay	bacteria
Allen and Morrison, 1973	29	fractured rock	Bacillus stearothermophilus
Hagedorn et al., 1978	3	silt loam	E. coli
"	5	"	Streptococcus faecalis
"	1.5	silty clay loam	E. coli
"	0.5	"	Streptococcus faecalis

Appendix 3. Data used to determine aquifer medium ranges and ratings (continued)

Reference	Horizontal Distance (m)	Aquifer Medium	Microorganism
Rahe et al., 1979	15	silty clay loam	*E. coli*
Martin and Thomas, 1974	510	boulder clay	bacteriophage
"	570	sandstone	"
Bouwer et al., 1974	9.1	fine loamy sand and gravel	fecal coliforms
Sinton, 1980	920	stony silt loam	bacteria
Martin and Noonan, 1977	900	stony silt loam	fecal coliforms
Marti et al., 1979	90	alluvial gravel	bacteria
Kudryavtseva, 1972	850	pebbles	coliforms
"	1000	weathered limestone	"
"	2	fine sand	"
Ditthorn and Luersson, 1909	21	medium to coarse sand	bacteria
Dappert, 1932	457	fine sand	bacteria
Brown et al., 1979	0.85	clay	bacteriophage
"	1.2	sandy clay	fecal coliforms

Appendix 3. Data used to determine aquifer medium ranges and ratings (continued)

Reference	Horizontal Distance (m)	Aquifer Medium	Microorganism
Green and Cliver, 1974	0.6	medium sand	poliovirus
Kingston, 1943	457	limestone	*Salmonella typhi*
Pyle and Thorpe, 1981	125	medium sandy gravel	*E. coli*
"	50	fine sandy gravel with cobbles	*E. coli*
Vaughn et al., 1978	3	coarse sand and fine gravel	echovirus
"	45.7	"	echovirus
Anan'ev and Demin, 1971	850	sand-gravel	coliforms
Wesner and Baier, 1970	30.5	fine to coarse sand	bacteria
Randall, 1970	55	coarse sand and gravel	coliforms
Young, 1973	6.1	fine to medium sand	bacteria
Stiles and Crohurst, 1923	19.8	fine sand	*E. coli*
Warrick and Muegge, 1930	70.7	fine sand	*E. coli*
Caldwell, 1937	24.4	fine & coarse sand	*E. coli*
Caldwell and Parr, 1937	10.7	sand & sandy clay	*E. coli*

Appendix 3. Data used to determine aquifer medium ranges and ratings (continued)

Reference	Horizontal Distance (m)	Aquifer Medium	Microorganism
Caldwell, 1938b	15.5	fine & medium sand	*Clostridium welchii*
Caldwell, 1938b	3.1	fine & medium sand	*E. coli*
Butler et al., 1954	1.2	fine sandy loam	coliforms
McGauhey and Krone, 1954	30	pea gravel & sand	bacteria
Baars, 1957	3.1	sand	*E. coli*
Fournelle, 1957	15.2	sandy-gravel	*Streptococcus zymogenes*
McMichael and McKee, 1965	2.4	fine to medium sand	fecal coliforms
Merrell, 1967	457	coarse gravels	bacteria
Aulenbach, 1979	400	sand	coliphage
Fletcher and Myers, 1974	1600	karst	coliphage T4

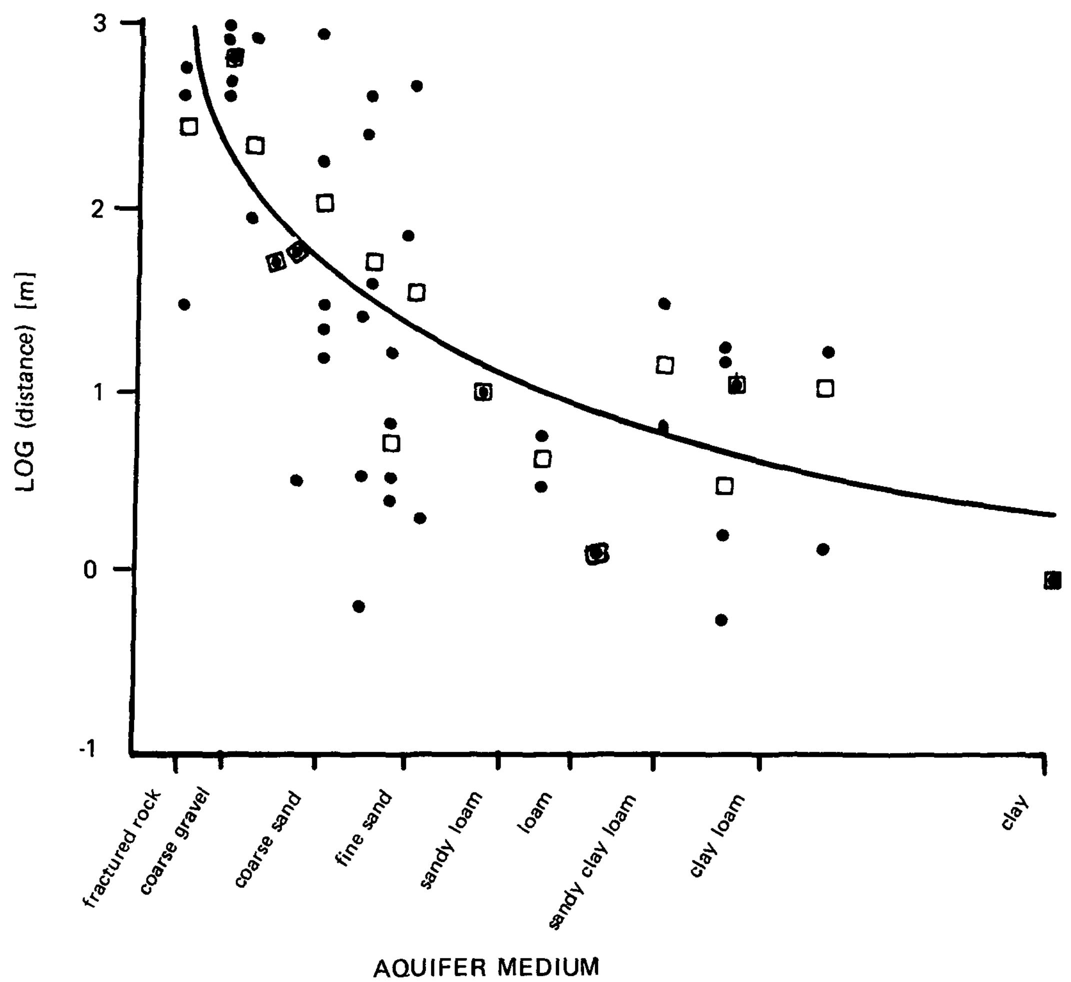

Figure A3. Horizontal movement of microorganisms as a function of the aquifer medium.

Appendix 4. Data used to determine application rate ranges and ratings

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Drewry and Eliasson, 1968	loam	66	7.97×10^{-2}	T2 phage
"	sandy clay loam	70	4.37×10^{-2}	"
"	loam	50	5.41×10^{-2}	"
"	clay loam	18	$>7.86 \times 10^{-2}$	"
"	sandy loam	53	$>7.32 \times 10^{-2}$	"
"	loam	57	8.18×10^{-2}	T1 phage
"	sandy clay loam	62	6.42×10^{-2}	"
"	loam	32	8.06×10^{-2}	"
"	sandy loam	62	8.21×10^{-2}	"
Young and Burbank, 1973	low humic latasol	559	$>6.93 \times 10^{-1}$	T4 phage
"	"	571	$>6.93 \times 10^{-1}$	"
"	cinder	144000	1.26×10^{-2}	"
"	low humic latasol	559	1.65×10^{-1}	poliovirus-2
"	"	571	1.65×10^{-1}	"

Appendix 4. Data used to determine application rate ranges and ratings (continued)

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Young and Burbank, 1973	cinder	144000	$4.9x10^{-3}$	poliovirus-2
Lance and Gerba, 1980	coarse sand	60	$1.56x10^{-2}$	poliovirus-1
"	"	120	$7.11x10^{-3}$	"
"	"	240	$5.47x10^{-3}$	"
"	"	400	$9.08x10^{-3}$	"
"	"	1200	$8.09x10^{-3}$	"
Robeck et al., 1962	unsaturated sand	86	$4.10x10^{-2}$	poliovirus-1
"	"	17	$7.35x10^{-2}$	"
"	coarse sand	11745	$1.81x10^{-3}$	"
"	"	5872	$1.41x10^{-3}$	"
"	"	367	$1.08x10^{-2}$	"
"	"	184	$>8.48x10^{-3}$	"
"	"	46	$>2.63x10^{-2}$	"

Appendix 4. Data used to determine application rate ranges and ratings (continued)

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Robeck et al., 1962	coarse sand	92	$2.07x10^{-2}$	"
"	fine sand	11745	$6.18x10^{-3}$	"
"	"	5872	$1.96x10^{-3}$	"
"	"	367	$5.93x10^{-3}$	"
"	"	184	$8.67x10^{-3}$	"
"	"	46	$2.63x10^{-2}$	"
"	"	92	$6.80x10^{-3}$	"
Lefler and Kott, 1974	sand	115	$1.26x10^{-2}$	poliovirus
"	"	229	$6.83x10^{-3}$	"
Lance et al., 1976	loamy sand	55	$2.78x10^{-2}$	poliovirus
"	"	15	$2.90x10^{-2}$	"
Wang et al., 1981	sand	76	$2.70x10^{-2}$	echovirus-1
"	"	88	$2.60x10^{-2}$	"

Appendix 4. Data used to determine application rate ranges and ratings (continued)

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Wang et al., 1981	sand	118	$2.20x10^{-2}$	"
"	"	222	$1.90x10^{-2}$	"
"	"	282	$7.00x10^{-3}$	"
"	sandy loam	33	$4.00x10^{-2}$	poliovirus-1
"	sand	75	$2.70x10^{-2}$	"
"	"	153	$2.00x10^{-2}$	"
"	"	194	$1.90x10^{-2}$	"
"	"	204	$1.60x10^{-2}$	"
"	"	314	$9.00x10^{-3}$	"
"	"	1352	$7.00x10^{-3}$	"
Vaughn et al., 1981	fine gravel and coarse sand	1800 -2400	$4.41x10^{-3}$	poliovirus-2
"	"	144	$7.87x10^{-3}$	"
"	"	24	$8.92x10^{-3}$	"
"	"	12	$1.22x10^{-2}$	"

Appendix 4. Data used to determine application rate ranges and ratings (continued)

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Berg et al., 1968	sand	13214	3.90×10^{-2}	poliovirus-1
Butler et al., 1954	fine sandy loam	9	$>6.99 \times 10^{-2}$	total coliforms
"	sandy loam	6	$>6.99 \times 10^{-2}$	"
"	"	9	$>6.99 \times 10^{-2}$	"
"	"	9	4.00×10^{-2}	"
"	sand	3	5.10×10^{-2}	"
Kreissl, 1983	medium sand	5	1.59×10^{-1}	poliovirus
"	"	50	4.83×10^{-2}	"
Sobsey et al., 1980	sand	1	1.70×10^{-1}	poliovirus
"	"	1	2.52×10^{-1}	"
"	organic	1	1.82×10^{-1}	"
"	sandy clay loam	1	4.40×10^{-1}	"
"	sand	1	4.40×10^{-1}	fecal coliforms

Appendix 4. Data used to determine application rate ranges and ratings (continued)

Reference	Soil Texture	Application rate (cm/day)	Removal (log_{10}/cm)	Microorganism
Sobsey et al., 1980	sand	1	$4.30x10^{-1}$	fecal coliforms
"	organic	1	$5.00x10^{-1}$	"
"	sandy clay loam	1	$5.70x10^{-1}$	"

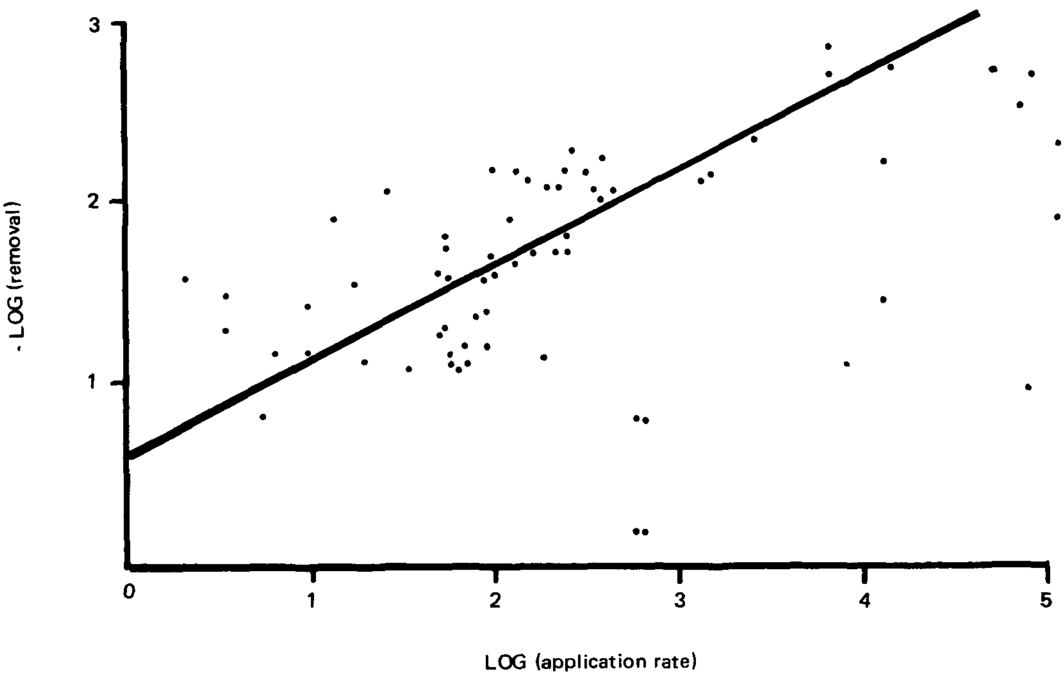

Figure A4. Removal of microorganisms as a function of the application rate of the effluent.

REFERENCES

Allen, M.J. and S.M. Morrison. 1973. Bacterial movement through fractured bedrock. Ground Water 11:6-10.

Aller, L., T. Bennett, J.H. Lehr, and R.J. Petty. 1985. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. U.S. Environmental Protection Agency pub. no. EPA-600/2-85-018.

Anan'ev, N.I. and N.D. Demin. 1971. On the spread of pollutants in subsurface waters. Hyg. and Sanit. 36:292-294.

Aulenbach, D.B. 1979. Long term recharge of trickling filter effluent into sand. U.S. Environmental Protection Agency pub. no. EPA-600/2-79-068.

Baars, J.K. 1957. Travel of pollution, and purification en route, in sandy soils. Bull. World Health Org. 16:727-747.

Berg, G., R.B. Dean, and D.R. Dahling. 1968. Removal of poliovirus-1 from secondary effluents by lime flocculation and rapid sand filtration. J. Amer. Water Works Assoc. 60:193-198.

Bitton, G. 1978. Survival of enteric viruses. In: Water Pollution Microbiology, vol. 2. R. Mitchell (ed.) John Wiley & Sons, New York.

Bitton, G., S.R. Farrah, R.H. Ruskin, J. Butner, and Y.J. Chou. 1983. Survival of pathogenic and indicator organisms in ground water. Ground Water 21: 405-410.

Bitton, G. and C.P. Gerba. 1984. Groundwater pollution microbiology: the emerging issue. In: Groundwater Pollution Microbiology. G. Bitton and C.P. Gerba (eds.) John Wiley & Sons, New York.

Bouwer, H., J.C. Lance, and M.S. Riggs. 1974. High-rate land treatment. II: Water quality and economic aspects of Flushing Meadows project. J. Water Poll. Contr. Fed. 46:844-859.

Brown, K.W., J.F. Slowey, and H.W. Wolf. 1978. The movement of salts, nutrients, fecal coliform, and virus below septic leach fields in three soils. In: Proceedings of the Second National Home Sewage Treatment Symposium, 1977. American Society of Agricultural Engineers.

Brown, K.W., H.W. Wolf, K.C. Donnelly, and J.F. Slowey. 1979. The movement of fecal coliforms and coliphages below septic lines. J. Environ. Qual. 8:121-125.

Burge, W.D. and N.K. Enkiri. 1978. Virus adsorption by five soils. J. Environ. Qual. 7:73-76.

Butler, R.G., G.T. Orlob, and P.H. McGauhey. 1954. Underground movement of bacterial and chemical pollutants. J. Amer. Water Works Assoc. 46:97-111.

Caldwell, E.L. 1937. Pollution flow from pit latrines when an impervious stratum closely underlies the flow. J. Infect. Dis. 61:270-288.

Caldwell, E.L. 1938a. Studies of subsoil pollution in relation to possible contamination of the ground water from human excreta deposited in experimental latrines. J. Infect. Dis. 62:272-292.

Caldwell, E.L. 1938b. Pollution flow from a pit latrine when permeable soils of considerable depth exist below the pit. J. Infect. Dis. 62:225-258.

Caldwell, E.L. and L.W. Parr. 1937. Ground water pollution and the bored hole latrine. J. Infect. Dis. 61: 148-183.

Canter, L. and R.C. Knox. 1984. Evaluation of septic tank system effects on ground water quality. U.S. Environmental Protection Agency pub. no. EPA-600/2-84-107.

Craun, G.F. 1979. Waterborne disease - a status report emphasizing outbreaks in groundwater systems. Ground Water 17:183-191.

Craun, G.F. 1981. Outbreaks of waterborne disease in the United States: 1971-1978. J. Amer. Water Works Assoc. 73:360-369.

Craun, G.F. 1984. Health aspects of groundwater pollution. In: Groundwater Pollution Microbiology. G. Bitton and C.P. Gerba (eds.) John Wiley & Sons, New York.

Craun, G.F. 1986a. Statistics of waterborne outbreaks in the U.S. (1920-1980). In: Waterborne disease in the United States. G.F. Craun (ed.) CRC Press, Florida.

Craun, G.F. 1986b. Recent statistics of waterborne disease outbreaks (1981-1983). In: Waterborne disease in the United States. G.F. Craun (ed.) CRC Press, Florida.

Dappert, A.F. 1932. Tracing the travel and changes in composition of underground pollution. Water Works and Sewerage 79:265-274.

Dean, J.D., P.P. Jowise, and A.S. Donigan, Jr. 1984. Leaching evaluation of agricultural chemicals (LEACH) handbook. U.S. Environmental Protection Agency pub. no. EPA-600/3-84-068.

Dee, N., J. Baker, N. Drobny, K. Duke, I. Whitman, and D. Fahringer. 1973. An environmental evaluation system for water resource planning. Wat. Res. Research 9:523-535.

Dee, N., T. Breese, K. Duke, G. Stacey, and S. Pomeroy. 1978. Literature review to identify rationale for developing functional relationship between environmental parameters and environmental quality. Final report to U.S. Army Corps of Engineers.

Ditthorn, F. and A. Luersson. 1909. Experiments on the passage of bacteria through soil. Engr. Record 60: 642.

Drewry, W.A. and R. Eliassen. 1968. Virus movement in groundwater. J. Water Poll. Contr. Fed. 40:R257-R271.

Duboise, S.M., B.E. Moore, and B.P. Sagik. 1976. Poliovirus survival and movement in a sandy forest soil. Appl. Environ. Microbiol. 31:536-543.

Fitzgerald, P.R. 1983. Pathogens in wastewaters: transport and fate of parasites. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017.

Fletcher, M.W. and R.L. Myers. 1974. Ground water tracing in karst terrain using phage T-4. Abstr. Ann. Mtg. Amer. Soc. Microbiol., p. 52.

Fournelle, H.J., E.K. Day, and W.B. Page. 1957. Experimental ground water pollution at Anchorage, Alaska. Pub. Health Rept. 72:203-209.

Gerba, C.P. 1983. Virus survival and transport in groundwater. Dev. Indust. Microbiol. 24:247-251.

Gerba, C.P. 1984. Microorganisms as groundwater tracers. In: Groundwater Pollution Microbiology. G. Bitton and C.P. Gerba (eds.) John Wiley & Sons, New York.

Gerba, C.P. and G. Bitton. 1984. Microbial pollutants: their survival and transport pattern to groundwater. In: Groundwater Pollution Microbiology. G. Bitton and C.P. Gerba (eds.) John Wiley & Sons, New York.

Gerba, C.P., S.M. Goyal, I. Cech, and G.F. Bogdan. 1981. Quantitative assessment of the adsorptive behavior of viruses to soils. Environ. Sci. Technol. 15: 940-944.

Gerba, C.P., S.M. Goyal, C.J. Hurst, and R.L. LaBelle. 1980. Type and strain dependence of enterovirus adsorption to activated sludge, soils, and estuarine sediments. Water Res. 14:1197-1198.

Gerba, C.P. and J.C. Lance. 1978. Poliovirus removal from primary and secondary sewage effluent by soil filtration. Appl. Environ. Microbiol. 36:247-251.

Gerba, C.P., C. Wallis, and J.L. Melnick. 1975. Fate of wastewater bacteria and viruses in soil. J. Irrig. Drain. Div., Am. Soc. Civ. Eng. 101:157-174.

Goyal, S.M. and C.P. Gerba. 1979. Comparative adsorption of human enteroviruses, simian rotavirus, and selected bacteriophages to soils. Appl. Environ. Microbiol. 38:241-247.

Green, K.M. and D.O. Cliver. 1974. Removal of virus from septic tank effluent by sand columns. In: Home Sewage Disposal. Proceedings of the National Home Sewage Disposal Symposium. ASAE, St. Joseph, Michigan. pp. 137-144.

Grigor'eva, L.B. and E.I. Goncharuk. 1966. Elimination of viruses from sewage in experimental underground filtration. Hyg. Sanit. 31:158-163.

Grigor'eva, L.V., G.I. Korchak, V.I. Bondarenko, and T.V. Bei. 1968. Sanitary characteristics (virological and bacteriological) of sewage, sludge, and soil in suburbs of Kiev. Hyg. Sanit. 33:360-365.

Hagedorn, C. 1983. Transport and fate: bacterial pathogens in ground water. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017. pp. 153-173.

Hagedorn, C. 1984. Microbiological aspects of groundwater pollution due to septic tanks. In: Groundwater Pollution Microbiology. G. Bitton and C.P. Gerba (eds.) John Wiley & Sons, New York.

Hagedorn, C., D.T. Hansen, and G.H. Simonson. 1978. Survival and movement of fecal indicator bacteria in soil under conditions of saturated flow. J. Environ. Qual. 7: 55-59.

Hain, K.E. and R.T. O'Brien. 1979. The survival of enteric viruses in septic tanks and septic tank drainfields. New Mexico Water Resources Research Institute, Rept. 108, Las Cruces, New Mexico.

Hickey, J.L.S. and D.L. Duncan. 1966. Performance of single family septic systems in Alaska. J. Water Poll. Contr. Fed. 38:1298-1309.

Hurst, C.J., C.P. Gerba and I. Cech. 1980. Effects of environmental variables and soil characteristics on virus survival in soil. Appl. Environ. Microbiol. 40:1067-1079.

Kaplan, J.E., G.W. Gary, R.C. Baron, N. Singh, L.B. Schonberger, R. Feldman, and H.B. Greenberg. 1982. Epidemiology of Norwalk gastroenteritis and the role of Norwalk virus in outbreaks of acute nonbacterial gastroenteritis. Ann. Internal Med. 96:756-761.

Keswick, B.H. and C.P. Gerba. 1980. Viruses in groundwater. Environ. Sci. Technol. 14:1290-1297.

Keswick, B.H., C.P. Gerba, S.L. Secor, and I. Cech. 1982. Survival of enteric viruses and indicator bacteria in groundwater. J. Environ. Sci. Health A17: 903-912.

Keswick, B.H., T.K. Satterwhite, P.C. Johnson, H.L. DuPont, S.L. Secor, J.A. Bitsura, G.W. Gary, and J.C. Hoff. 1985. Inactivation of Norwalk virus in drinking water by chlorine. Appl. Environ. Microbiol. 50:261-264.

Kingston, S.P. 1943. Contamination of water supplies in limestone formation. J. Amer. Water Works Assoc. 35:1450-1456.

Koerner, E.L. and D.A. Haws. 1979. Long-term effects of land application of domestic wastewater: Vineland, New Jersey, rapid infiltration site. U.S. Environmental Protection Agency pub. no. EPA-600/2-79-072.

Kreissl, J.F. 1983. Current practices - subsurface disposal. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017. pp. 27-54.

Kudryavtseva, B.M. 1972. An experimental approach to the establishment of zones of hygienic protection of underground water sources on the basis of sanitary-bacteriological indices. J. Hyg. Epid. Microbiol. Immunol. 16:503-511.

Lance, J.C., and C.P. Gerba. 1980. Poliovirus movement during high rate land filtration of sewage water. J. Environ. Qual. 9:31-34.

Lance, J.C., C.P. Gerba, and J.L. Melnick. 1976. Virus movement in soil columns flooded with secondary sewage effluent. Appl. Environ. Microbiol. 32:520-526.

Landry, E.F., J.M. Vaughn, and W.F. Penello. 1980. Poliovirus retention in 75-cm soil cores after sewage and rain-water application. Appl. Environ. Microbiol. 40: 1032-1038.

Landry, E.F., J.M. Vaughn, M.Z. Thomas, and C.A. Beckwith. 1979. Adsorption of enteroviruses to soil cores and their subsequent elution by artificial rainwater. Appl. Environ. Microbiol. 38:680-687.

Lefler, E. and Y. Kott. 1974. Virus retention and survival in sand. In: Virus Survival in Water and Wastewater Systems J.F. Malina and B.P. Sagik (eds.) Center for Research in Water Resources, Austin, TX. pp. 84-91.

LeGrand, H.E. 1964. System for evaluation of contamination potential of some waste disposal sites. J. Amer. Water Works Assoc. 56:959-974.

LeGrand, H.E. 1983. A standardized system for evaluating waste-disposal sites. National Water Well Association, Worthington, Ohio.

Lippy, E.C. and S.C. Waltrip. 1984. Waterborne disease outbreaks - 1946-1980: A thirty-five year perspective. J. Amer. Water Works Assoc. 76:60-67.

Logsdon, G.S., F.B. DeWalle, and D.W. Hendricks. 1984. Filtration as a barrier to passage of cysts in drinking water. In: Giardia and Giardiasis Biology, Pathogenesis, and Epidemiology. S.L. Erlandsen and E.A. Meyer (eds.) Plenum Press, New York.

Malin, A. and J. Snellgrove. 1958. The examination of sewage effluent and affected soils. Lab. Pract. 7:219-223.

Marti, F., G.D. Valle, V. Krech, R.A. Gees, and E. Baumgartner. 1979. Tracing tests in ground-water with dyes, bacteria, and viruses. Alimenta 18:135-145.

Martin, G.N. and M.J. Noonan. 1977. Effects of domestic wastewater disposal by land irrigation on groundwater quality of central Canterbury plains. Water and Soil Technical Publication no. 7, Water and Soil Division, Ministry of Work and Development, Wellington, N.Z.

Martin, R. and A. Thomas. 1974. An example of the use of bacteriophage as a ground water tracer. J. Hydr. 23:73-78.

Matthess, G. and A. Pekdeger. 1981. Concepts of a survival and transport model of pathogenic bacteria and viruses in groundwater. International Symp. on Qual. of Groundwater, Amsterdam, the Netherlands.

McGauhey, P.H. and R.B. Krone. 1954. Report on the investigation of travel of pollution. 1954. State Water Pollution Control Board, pub. no. 11. State of California.

McGinnis, J.A. and F. DeWalle. 1983. The movement of typhoid organisms in saturated, permeable soil. J. Amer. Water Works Assoc. 75:266-271.

McMichael, F.C. and J.E. McKee. 1965. Wastewater reclamation at Whittier Narrows. State Water Quality Control Board, pub. no. 33. State of California.

Merrell, J.C. Jr. 1967. The Santee recreation project, Santee, California, final report. Water Poll. Res. Series Pub. No. WP-20-7. Fed. Water Poll. Contr. Admin. Cincinnati, OH.

Moore, R.S., D.H. Taylor, L.S. Sturman, M.M. Reddy, and G.W. Fuhs. 1981. Poliovirus adsorption by 34 minerals and soils. Appl. Environ. Microbiol. 42:963-975.

Office of Technology Assessment. 1984. Protecting the nation's ground water from contamination. U.S. Congress, Washington, D.C. OTA-O-233.

Pavoni, J.L., D.J. Hagerty, and R.E. Lee. 1972. Environmental impact evaluation of hazardous waste disposal in land. Water Res. Bull. 8:1091-1107.

Phillips, C.R., J.S. Nathwani, and H. Mooij. 1977. Development of a soil-waste interaction matrix for assessing land disposal of industrial wastes. Water Res. 11: 859-868.

Pyle, B.H., L.W. Sinton, M.J. Noonan, and J.F. McNabb. 1979. The movement of microorganisms in groundwater. Presented at the New Zealand Institution of Engineers Technical Group on Groundwater Symposium, Victoria University, Wellington, 13 Feb 1979.

Pyle, B.H. and H.R. Thorpe. 1981. Evaluation of the potential for microbiological contamination of an aquifer using a bacterial tracer. Proceedings of the Groundwater Pollution Conference, Perth, W. Australia. 19-23 Feb 1979. Australian Water Resources Council. Australian Government Publication Service, Canberra, pp. 213-224.

Rahe, T.M., C. Hagedorn, and E.L. McCoy. 1979. A comparison of fluorescein dye and antibiotic-resistant Escherichia coli as indicators of pollution in groundwater. Water, Air, and Soil Pollution 11:93-103.

Randall, A.D. 1970. Movement of bacteria from a river to a municipal well - a case history. J. Amer. Water Works Assoc. 62:716-720.

Reneau, R.B. and D.E. Pettry. 1975. Movement of coliform bacteria from septic tank effluent through selected coastal plain soils of Virginia. J. Environ. Qual. 4:41-44.

Robeck, G.G., N.A. Clarke, and K.A. Dostal. 1962. Effectiveness of water treatment processes in virus removal. J. Amer. Water Works Assoc. 54:1275-1290.

Sandhu, S.S., W.J. Warren, and P. Nelson. 1979. Magnitude of pollution indicator organisms in rural potable water. Appl. Environ. Microbiol. 37:744-749.

Sattar, S.A. 1981. Virus survival in receiving waters. In: Viruses and Wastewater Treatment. M. Goddard and M. Butler (eds.) Pergamon Press, New York.

Scalf, M.R., W.J. Dunlap, and J.F. Kreissl. 1977. Environmental effects of septic tank systems. U.S. Environmental Protection Agency pub. no. EPA-600/3-77-096.

Schaub, S.A. and C.A. Sorber. 1977. Virus and bacteria removal from wastewater by rapid infiltration through soil. Appl. Environ. Microbiol. 33:609-619.

Sinton, L.W. 1979. The use of bacteria as tracers of groundwater movement. In: The quality and movement of groundwater in alluvial aquifers of New Zealand. M.J. Noonan (ed.) Dept. Agric. Microbiol. Tech. pub. no. 2, Lincoln College Press. Canterbury, New Zealand, pp. 93-103.

Sinton, L.W. 1980. Investigations into the use of the bacterial species Bacillus stearothermophilus and Escherichia coli (H_2S positive) as tracers of ground water movement. Water and Soil Technical Publication no. 17. Water & Soil Division, Ministry of Works and Development, Wellington, NZ.

Sobsey, M.D. 1983a. Research needs - virology considerations in soil absorption of wastewater. In: Proceedings from a Workshop on Research Needs Pertaining to Soil Absorption of Wastewater. National Science Foundation, Washington, D.C.

Sobsey, M.D. 1983b. Transport and fate of viruses in soils. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017, pp. 174-213.

Sobsey, M.D., C.H. Dean, M.E. Knuckles, and R.A. Wagner. 1980. Interactions and survival of enteric viruses in soil materials. Appl. Environ. Microbiol. 40:92-101.

Stiles, C.W. and H.R. Crohurst. 1923. Principles underlying the movement of B. coli in groundwater with the resultant pollution of wells. Pub. Health Rept. 38:1350-1353.

Stramer, S.L. 1984. Fates of poliovirus and enteric indicator bacteria during treatment in a septic tank system including septage disinfection. Ph.D. dissertation, University of Wisconsin, Madison, Wisconsin.

Tyrrell, D.A. and A.Z. Kapikian. 1982. Virus Infections of the Gastrointestinal Tract. Marcel Dekker, Inc., New York.

U.S. Environmental Protection Agency. 1977. The Report to Congress. Waste disposal practices and their effects on ground water. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency. 1980. Design Manual. Onsite Wastewater Treatment and Disposal Systems. U.S. Environmental Protection Agency pub. no. EPA-625/1-80-012.

U.S. Environmental Protection Agency. 1983. Surface Impoundment Assessment National Report. U.S. Environmental Protection Agency pub. no. EPA-570/9-84-002.

Vaughn, J.M. and E.F. Landry. 1977. Data report: an assessment of the occurrence of human viruses in Long Island aquatic systems. Department of Energy and Environment, Brookhaven National Laboratory, Upton, N.Y.

Vaughn, J.M., E.F. Landry, L.J. Baranosky, C.A. Beckwith, M.C. Dahl, and N.C. Delihas. 1978. Survey of human virus occurrence in wastewater-recharged groundwater on Long Island. Appl. Environ. Microbiol. 36: 47-51.

Vaughn, J.M., E.F. Landry, C.A. Beckwith, and M.Z. Thomas. 1981. Virus removal during groundwater recharge: effects of infiltration rate on adsorption of poliovirus to soil. Appl. Environ. Microbiol. 41: 139-147.

Vaughn, J.M., E.F. Landry, and M.Z. Thomas. 1983. The lateral movement of indigenous enteroviruses in a sandy sole-source aquifer. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017.

Viraraghavan, T. 1978. Travel of microorganisms from a septic tile. Water, Air, and Soil Pollution 9:355-362.

Vogt, J. 1961. Infectious hepatitis epidemic at Posen, Michigan. J. Amer. Water Works Assoc. 53:1238-1242.

Wang, D.S., C.P. Gerba, and J.C. Lance. 1981. Effect of soil permeability on virus removal through soil columns. Appl. Environ. Microbiol. 42:83-88.

Warrick, L.F. and O.J. Muegge. 1930. Safeguarding Wisconsin's water supplies. J. Amer. Water Works Assoc. 22: 516-526

Weaver, R.W. 1983. Transport and fate - bacterial pathogens in soil. In: Microbial Health Considerations of Soil Disposal of Domestic Wastewaters. U.S. Environmental Protection Agency pub. no. EPA-600/9-83-017. pp. 123-152.

Wellings, F.M., A.L. Lewis, and C.W. Mountain. 1974. Virus survival following wastewater spray irrigation of sandy soils. In: Virus Survival in Water and Wastewater Systems. J.F. Malina and B.P. Sagik (eds.), Center for Research in Water Resources, Austin, TX pp. 253-260.

Wellings, F.M., A.L. Lewis, C.W. Mountain, and L.V. Pierce. 1975. Demonstration of virus in groundwater after effluent discharge onto soil. Appl. Microbiol. 29:751-757.

Wesner, G.M. and D.C. Baier. 1970. Injection of reclaimed wastewater into confined aquifers. J. Amer. Water Works Assoc. 62:203-210.

Westwood, J.C.N. and S.A. Sattar. 1976. The minimal infective dose. In: Viruses in Water. Berg, Bodily, Lennette, Melnick, and Metcalf (eds.) American Public Health Association, Washington, D.C.

Wimpenny, J.W.T., N. Cotton, and M. Statham. 1972. Microbes as tracers of water movement. Water Res. 6:731-739.

Yates, M.V. 1984. Virus persistence in ground water. Ph.D. dissertation. The University of Arizona, Tucson, Arizona.

Yates, M.V. 1985. Unpublished data.

Yates, M.V., C.P. Gerba, and L.M. Kelley. 1985. Virus persistence in groundwater. Appl. Environ. Microbiol. 49:778-781.

Young, R.H.F. 1973. Effects on ground water. J. Water Poll. Contr. Fed. 46:1296-1301.

Young, R.H.F. and N.C. Burbank, Jr. 1973. Virus removal in Hawaiian soils. J. Amer. Water Works Assoc. 65: 598-604.