INTERNATIONAL HYDROLOGICAL PROGRAMME

Groundwater pollution by sanitation on tropical islands

by

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FOREWORD

On many inhabited low coral islands, the groundwater lens is a vital source of freshwater for domestic consumption and for growing food. Lenses are highly vulnerable to salinization by lateral incursion of seawater, and to pollution by contaminants, primarily from human and animal wastes. Such impacts have significant effects on the health and well-being of the local communities.

The International Hydrological Programme of UNESCO commissioned in 1995 two field studies within its Humid Tropics Programme designed to enhance and disseminate understanding of groundwater lens behaviour in selected Pacific islands. These studies were recommended by Member State water resources specialists at the UNESCO-SOPAC-UN Workshop on *Pacific Water Sector Planning, Research and Training*, Honiara, Solomon Islands, 1-8 June 1994. The projects combine both technical and sociocultural investigations and are being implemented in close collaboration with the South Pacific Applied Geoscience Commission (SOPAC). They also form part of the IHP contribution to UNESCO's transdisciplinary project on *Environment and Development in Coastal Regions and Small Islands*.

In preparation for the two studies, and following a recommendation by regional experts, IHP, through UNESCO Office Apia, commissioned literature surveys on each topic. This *Technical Document in Hydrology* by Dr Peter Dillon presents a survey on groundwater pollution. A parallel document will present another survey on atoll groundwater recharge.

In many Pacific villages, each home has its own sanitation. Usually the facilities are inadequate to prevent contamination of the underlying groundwater lens. Where this lens is used as a source of freshwater, there is an obvious risk to health. A better understanding of the movement of the groundwater in the lens, and the behaviour and distribution of the contamination is needed to mitigate this risk.

It should be noted that field work on the study on Lifuka Island, Haapai group, Kingdom of Tonga, commenced in April 1996 and is continuing. The final results will be fully reported in due course.

Abstract

Contamination by sewage can threaten the use of groundwater as a drinking water supply. This is an especially severe problem on small and low-lying tropical islands, where surface water supplies are generally unavailable, and population densities in urbanising areas are increasing ahead of centralised sewerage collection and treatment systems. On such islands soils are usually thin, and aquifers are highly permeable and can only be tapped at shallow depths without drawing in saline water. These factors lead to a high risk of microbiological and nitrate contamination of groundwater which can have serious and recurrent affects on the health of local communities which rely on the groundwater supply.

The objective of this report is to review the scientific foundations for managing this issue with particular reference to small tropical islands. This includes a brief assessment of the extent of groundwater pollution by sanitation systems, the design of sanitation systems, the nature of contaminants in sewage, their fate in the subsurface environment including factors affecting their attenuation, and the methods which have been used to study the movement of sewage contaminants in groundwater. The report concludes with a summary of the options for managing this problem, including criteria for establishing common sewerage systems; well-head protection policy options; siting, design, and maintenance of sanitation systems; monitoring procedures related to objectives; treatment of water supplies; and public education and action programs. These provide a range of measures which can be adapted by local communities to meet their needs for safe water supplies, and give assurance of this, at reasonable costs.

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1. Introduction

On coral islands and coastal areas of other islands, contamination by sewage can threaten the use of groundwater as a drinking water supply. This is especially severe on small and low-lying islands, where surface water supplies are generally unavailable, and population densities in urbanising areas are increasing ahead of centralised sewerage collection and treatment systems. On such islands soils are usually thin, and aquifers are highly permeable and can only be tapped at shallow depths without drawing in saline water. These factors lead to a high risk of microbiological and nitrate contamination of groundwater which can have serious and recurrent affects on the health of local communities which rely on the groundwater supply.

This study was commissioned under the International Hydrological Programme of UNESCO to evaluate the minimum separation distance needed between sanitation and water supply wells on tropical islands. The study was identified as a research need by Falkland (1991) in a comprehensive review of water resources management issues in small islands, and was subsequently recommended for approval by the Intergovernmental Council (Falkland and Stewart, 1995). The study fits under two themes of IHP-V *'Groundwater resources at risk'*, and *'Humid tropics hydrology and water management'*. The study recognises that short and long term measures are required to adequately protect groundwater quality from a range of potential contaminants (including salinity), but focuses on just one issue which is prevalent and consequential, that of preventing contamination by sanitation systems.

The objective of this report is to review the scientific foundations for managing this issue with particular reference to small tropical islands. This includes a brief assessment of the extent of groundwater pollution by sanitation systems, the nature of contaminants, their fate in the subsurface environment including factors affecting their attenuation, and the methods which have been used to study the movement of sewage contaminants in groundwater. The report concludes with a summary of the options for managing this problem, including siting, design, and maintenance of sanitation systems, and techniques to undertake site-specific studies.

2. Extent of Problem

The pollution of groundwater supplies by sanitation systems is a universal problem and is particularly severe for communities on low-lying islands. Sanitation systems are taken to include latrines (or cess pits), septic tanks, and common effluent schemes. Most of the literature on sanitation effects on groundwater quality refers to septic tanks, but is applicable as will be shown later, to latrines and other forms of sanitation. The following cases are evidence of the extent of the problem.

Faecal pollution of groundwater by sewage from septic tanks has caused the closure of water supply wells at Kiritimati, Republic of Kiribati, and Majuro, Marshall Islands (Falkland, 1991, p217). A study of bacterial contamination on Moen, Truk Islands (Miller *et al*, 1993) found that all 13 wells sampled were contaminated with faecal coliforms (ranging from 16 to 360,000 CFU/100mL) however no correlation could be found with the proximity of latrines, or the presence of animals and standing water.

In a karst aquifer on San Salvador Island, Bahamas, Balcerzac *et al*, (1990) found only occasional evidence of contamination by human waste, but very high faecal streptococci levels, indicating recent animal contamination from birds or ruminant animals. Beswick (1985) reported that the density of on-site sewage disposal was creating a groundwater risk for intensively occupied parts of the Cayman Islands.

In Bermuda, Thomson and Foster (1986) reported that infiltration from unsewered sanitation is a major factor in preventing saline intrusion into fresh groundwater from the central lens of a small limestone aquifer which has been intensively developed and monitored. As a consequence concentrations of nitrate in groundwater have risen to 40 mg NO_3-N/L in places. A centralised groundwater mixing, and treatment system enables reticulated water to meet WHO health guidelines.

Studies have been undertaken in a series of Atlantic coastal barrier islands of the United States of America, including Sanibel Is, Florida, and Hog Is, Virginia (Bryson, 1988), Figure Eight Is, North Carolina (Andrews, 1988), and Long Is, New York (Nemickas *et al*, 1989) where elevated nitrate concentrations in groundwater occur due to infiltration from septic tanks. Bryson and Nemickas *et al* reported that population pressures have forced the construction of sewerage systems and wastewater treatment plants in order to protect the groundwater which continues to be a source of drinking water. Andrews and Bryson advocated calculating a water and nitrogen balance, to determine the acceptable density of septic tanks, which would not breach drinking water standards in the aquifer.

Population densities of selected small islands are given by Falkland (1991, p206) ranging up to 30,000 p.km^{-2} (Male, Maldives), with many islands having densities exceeding 400 p.km^{-2}. In a number of these islands groundwater contributes the largest percentage of freshwater production Falkland (1991, p208), *eg.* Gran Canaria, Canary Is.,Spain (420 p.km^{-2}, 84%), Oahu, Hawai (640 p.km^{-2}, 87%), and Malta (1080 p.km^{-2}, 67%). These examples indicate there is a need on a large number of islands to evaluate the maximum density of on-site sewage disposal which is compatible with sustaining groundwater as a drinking water resource. It is expected that in many cases this may be a more severe constraint to sustainable development than the limitations on the quantity of freshwater which can be produced.

In the United States, where septic tanks were introduced in 1884, approximately one third of existing housing units and one quarter of all new homes being constructed have septic tanks. There are about 20 million septic tanks, used by 70 million people, discharging 3000 GL of domestic wastewater below ground annually (Canter et al, 1988, p79). Septic tanks are the leading contributor to the total volume of wastewater discharged to the subsurface, and are strongly linked to the incidence of waterborne disease. The consumption of untreated or inadequately treated groundwater is responsible for almost 3,000 reported cases per year of waterborne disease in the United States. Only about 10% of all outbreaks and 3% of illnesses were caused by toxic chemicals. The remainder were due to pathogenic microorganisms. Specific disease-causing agents were not determined for 55% of cases, and most of these are believed to have a viral origin (Table 1, modified from Yates and Yates, 1988).

Note that while almost half of the US population received their drinking water from groundwater supplies (Canter et al, 1988), the proportion of illnesses occurring in waterborne disease outbreaks between 1971 and 1983 from untreated or inadequately treated groundwater was only 32%. This implies that the effectiveness of pathogen attenuation within aquifers was at least as reliable as the treatment given to surface water supplies before reticulation. It is also interesting to note that shigellosis, hepatitis A, and typhoid were more likely to outbreak in untreated groundwater systems than surface water systems, whereas giardiasis, viral gastroenteritis, salmonellosis, and chemical poisoning were more likely to occur in surface water systems.

Table 1. Causes of waterborne disease outbreaks in the United States, 1971-1983 (modified from Yates and Yates, 1988, p 308)

Disease	Outbreaks	Illnesses	% illnesses from untreated or inadequately treated groundwater
gastroenteritis illness, cause unknown	227	60,191	42.7
giardiasis	81	22,721	0.4
chemical poisoning	46	3,743	4.2
shigellosis	31	5,727	86.2
hepatitis A	22	730	67.5
viral gastroenteritis	17	5,734	23.7
salmonellosis	10	2,300	15.3
campylobacter diarrhea	5	4,773	-
typhoid	4	222	100
escherichia coli diarrhea	1	1,000	100
cholera	1	17	-
yersiniosis	1	16	100
Total	446	107,174	
Mean			32.0

3. Sanitation Systems as Contaminant Sources

Design of Sanitation Systems

Sanitation systems are generally designed to suit local conditions. Figure 1 (from Palmer Development Group, 1995) shows system designs ranging from bucket, latrine, and septic tank to toilets supplied by mains water and connected to a sewerage scheme. The amount of water required to operate each system is shown. Aside from the sewered options (which may relocate the problem of disposing nutrient rich wastes back to the environment), liquid and solids are disposed to the soil. In latrines or cess pits, the liquid soaks away through the base and sides of the pit. The pit itself may act like an aerobic-anaerobic digester, depending on the frequency of saturation of the wastes and on latrine design. Variations of latrine designs to accelerate digestion are shown by Feachem et al (1983) including a "Multrum" continuous-composting toilet (Figure 2), and there are some new designs, incorporating hand operated pedals, which, when turned, aerate the digester. Latrines have less liquid waste than septic tanks and any percolating effluent is more concentrated. The pit cover should prevent rainfall or runoff infiltrating through the wastes in the pit, during its operating life and for a long time after closure and relocation of the latrine. It will be shown later that aerobic composting of sludge from latrines and septic tanks may produce pathogen-free soil conditioners.

The septic tank or aqua privy with on-site disposal have separate digester and soakaway components. The digester (tank) provides some storage and settling of wastes, and liquid wastes decant to a tile drainage area. There the wastewater percolates out through perforated pipe laid in one or more trenches in order to distribute the water evenly over an area. See Figure 3 (from Canter *et al.*, 1988). These pipes are generally shallow so that

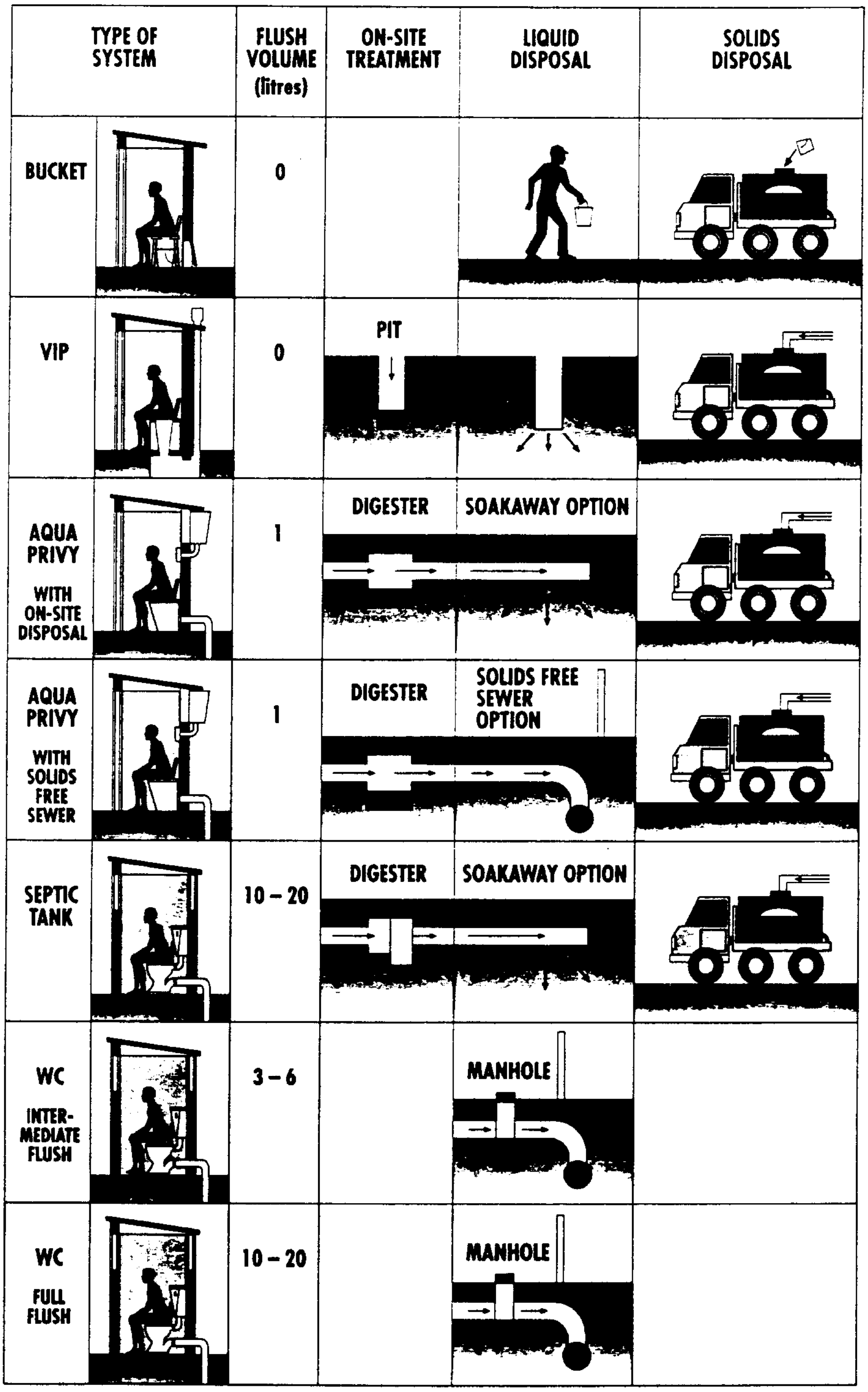

Figure 1. Sanitation system designs (from Palmer Development Group, 1995)

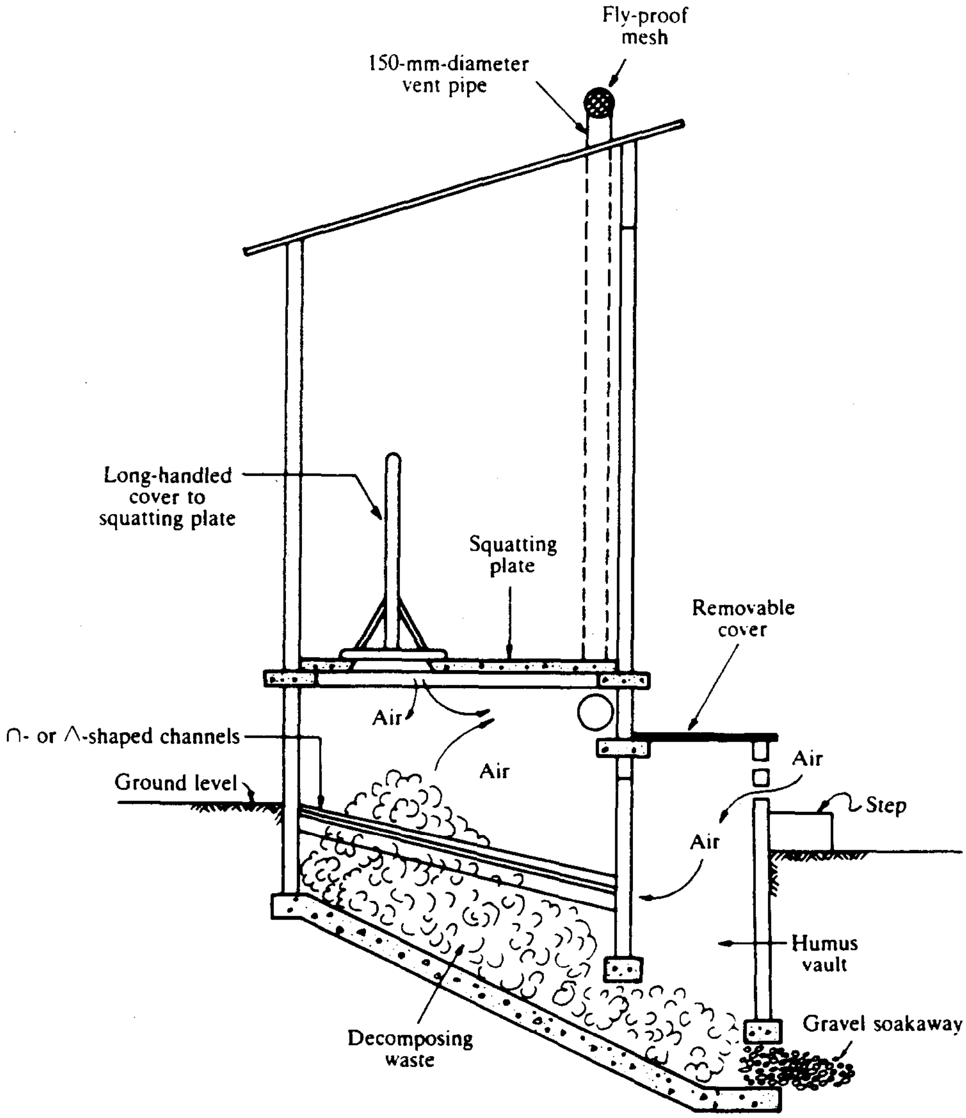

Figure 2. "Multrum" continuous-composting toilet (from Feachem *et al*, 1983)

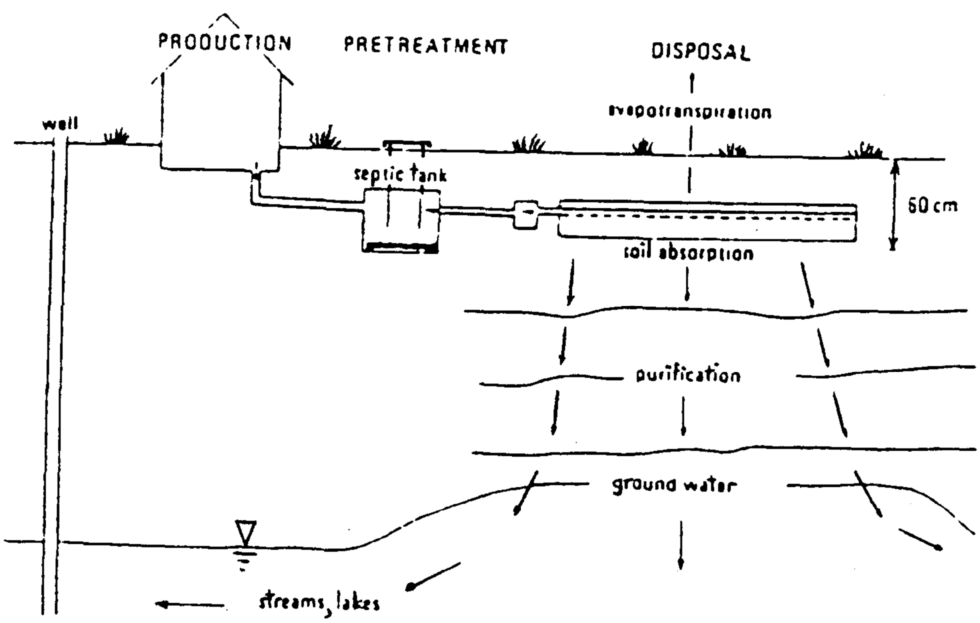

Figure 3. Fate of effluent from a septic tank system in relation to groundwater (from Canter *et al.*, 1988)

the water and nutrients may be taken up by plants, and to maximise the depth of the unsaturated zone beneath the pipe. The attenuation rate of contaminants tends to be higher in this zone, and movement of water is slower than where soils are saturated. Septic tanks require maintenance, such as sludge removal, in order to retain their capacity to treat effluent and to prevent the perforated pipes from clogging, and the tank overflowing.

Most of the literature on sanitation effects on groundwater quality refers to septic tanks, but this information may also be applied to latrines, taking account of some differences as follows. For the same waste loadings, such as mass of nutrients or number of microorganisms, these constituents are much more concentrated in latrines but the volume is smaller. The liquid waste residence time before discharge into the soil is reduced and the actual hydraulic loading through the soakaway area may be smaller than or greater than that for a septic tank or aqua privy, depending on the quantity of water used for flushing, and the effective area of tile drainage.

Septic tanks are preferred to latrines because wastes are stored longer before release, and residence time is important for attenuation of thermophylic microorganisms. Wastes are also less concentrated so less reliance is placed on aquifer mixing processes to dilute concentrations to acceptable levels. Finally and possibly most importantly, septic tanks release water to the soil profile at a higher elevation than is practical for a latrine, allowing a greater thickness of the unsaturated zone through which infiltration occurs, and therefore a higher degree of contaminant attenuation before the wastewater reaches the watertable. Hence the effects of latrines on groundwater quality are expected to be greater than the effects of septic tanks which are extensively reported in scientific literature (eg Table 2). The literature review did not reveal quantitative studies on the impacts of latrines on groundwater, although qualitative evidence is available (eg Rao, 1977).

Table 2
Some examples of septic tanks as causes of waterborne disease
(from Yates and Yates, 1988)

Disease	*No.of cases*	*Source of contamination*
Gastroenteritis	1200	septic tank 45m from city well
	400	septic tank 15m above spring
	n.a.	septic tank 30m from 12m deep well
Hepatitis A	98	septic tank near water supply for commercial ice pellet operation
	17	septic tank 2m from 30m deep well
Typhoid	5	septic tank 65m from well

Mass and Composition of Human Wastes

Feachem *et al* (1983) documented the mass, and chemical composition of faeces and urine, and the microbial composition of faeces for adult populations in various countries, including developing countries. This information which is summarised below, enables wastes to be characterised, and the potential for pollution from sanitation systems to be assessed. In general, human wastes contain large numbers of enteric microorganisms, have high concentrations of nutrients, and a high oxygen demand, all of which may have an adverse impact on groundwater quality. Such wastes may contain other inorganic and organic species which distinguish affected groundwater.

Table 3 (from Feachem *et al*, 1983, p7) provides estimates which are considered representative of population classes, of the masses of faeces and urine produced daily and the biochemical oxygen demand at five days (BOD_5) of this daily load. There is considerable variability within classes, and the figures should be used as indicative only. The inorganic constituents of faeces and urine are given in Table 4 (from Feachem et al, 1983). Note that the carbon to nitrogen ratio is about 8 for faeces and less than 1 for urine. In general composting systems require C/N of 20 to 30, so an additional source of carbon is needed for effective composting. Human wastes may also contain heavy metals and other inorganic substances (sodium, potassium, calcium, magnesium, chloride, and sulfate) (Canter et al, 1988, p80). These will vary with diet. Typical oxygen demand and nutrient loadings per capita and by domestic wastewater source are given for the United States in the 1970's by Table 5 (from Feachem et al, 1983). These give an indication of the changes in loadings to sanitation facilities if other household waste streams are also captured.

Types of pathogenic organisms excreted in faeces are documented by Feachem et al, (1983). The diseases associated with bacterial pathogens in faeces are listed in Table 6, and the number of bacterial microflora present in faeces by national diet are listed in Table 7. These microbial numbers should only be considered as indicators of likely composition for any given community. Tables 8, 9, and 10 list viral, protozoal, and helminthic pathogens excreted in faeces. Table 11 is an attempt to summarise this information on the possible output of selected pathogens in the faeces and sewage of a hypothetical tropical community of 50,000 in a developing country. This takes into account the assumed prevalence of infection of several diseases in the country, and gives the projections in numbers of each pathogen per litre in sewage. It appears that most probable numbers of bacteria, viruses, and protozoa are of the order of 10^6 organisms/100mL, with helminth numbers at least an order of magnitude lower. Treatment and dilution would need to substantially reduce pathogen numbers in order for water having contact with these wastes to meet WHO drinking water guidelines.

Concentrations of at least one relatively conservative substance in wastewater need to be substantially different to that in groundwater if such substances are to be used as tracers of the effects of septic tanks. Commonly nitrate is used as an indicator of contamination by wastewater. In anaerobic aquifers, or close to the source, ammonium may be a better tracer of wastewater, and in areas where fertilizer usage is intense, bicarbonate or other species may make better indicators of pollution by human wastes.

4. Subsurface Attenuation of Contaminants

Substances which are present in excreta in sanitation systems, leach to the groundwater, and are transported in it, can have several adverse effects on tropical islands. Firstly they may contaminate shallow drinking water supplies, often the sole source of supply, leading to the spread of disease. Secondly they may impair other beneficial uses of the resource, including the support of any ecosystems which are fed by groundwater (*eg.* nutrients discharging into a stream, estuary or lagoon, thereby assisting eutrophication).

Numerous studies have been undertaken to determine the fate of microorganisms and nutrients beneath and nearby septic tank discharge areas. These studies were summarised in Yates and Yates (1988) and Crane and Moore (1984), who identified the factors affecting the fate of bacteria and viruses in the subsurface environment (Tables 12 and 13). These include; temperature, microbial activity, moisture content, hydraulic conductivity, organic matter content, and pH of the soil, and on the type of bacterium or virus type.

Table 4. Chemical composition of human faeces and urine (from Feachem *et al*, 1983)

Constituent	Approximate composition (percent of dry weight) Feces	Urine
Calcium (CaO)	4.5	4.5–6.0
Carbon	44–55	11–17
Nitrogen	5.0–7.0	15–19
Organic matter	88–97	65–85
Phosphorus (P_2O_5)	3.0–5.4	2.5–5.0
Potassium (K_2O)	1.0–2.5	3.0–4.5

Table 5. Pollution loads of wastewater sampled from various plumbing fixtures in the U.S.A. (milligrams per capita daily) (from Feachem *et al*, 1983)

Wastewater source	Biochemical oxygen demand (BOD)		Chemical oxygen demand		NO_3–N		NH_3–N		PO_4	
	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent
Bathroom sink	1,860	4	3,250	2	2	3	9	0.3	386	3
Bathtub	6,180	13	9,080	8	12	16	43	1	30	0.3
Kitchen sink	9,200	19	18,800	16	8	10	74	2	173	2
Laundry machine	7,900	16	20,300	17	35	49	316	10	4,790	40
Toilet	23,540	48	67,780	57	16	22	2,782	87	6,473	55
Total	48,690	100	119,410	100	73	100	3,224	100[a]	11,862	100[a]

Table 6. Bacterial pathogens excreted in faeces (from Feachem *et al*, 1983)

Bacterium	Disease	Can symptomless infection occur?	Reservoir
Campylobacter fetus ssp. *jejuni*	Diarrhea	Yes	Animals and man
Pathogenic *Escherichia coli*[a]	Diarrhea	Yes	Man[b]
Salmonella			
S. typhi	Typhoid fever	Yes	Man
S. paratyphi	Paratyphoid fever	Yes	Man
Other salmonellae	Food poisoning and other salmonelloses	Yes	Animals and man
Shigella spp.	Bacillary dysentery	Yes	Man
Vibrio			
V. cholerae	Cholera	Yes	Man
Other vibrios	Diarrhea	Yes	Man
Yersinia enterocolitica	Diarrhea and septicemia	Yes	Animals and man[c]

a. Includes enterotoxigenic, enteroinvasive, and enteropathogenic *E. coli*.

b. Although many animals are infected by pathogenic *E. coli*, each serotype is more or less specific to a particular animal host.

c. Of the 30 or more serotypes identified so far, a number seem to be associated with particular animal species. There is at present insufficient epidemiological and serological evidence to say whether distinct serotypes are specific to primates.

Table 7. Bacterial microflora of human faeces by national diet (from Feachem *et al*, 1983)

		Number of bacteria in feces (mean log₁₀ per gram)						
National diet	*Country*	*Entero-bacteria*[a,b]	*Enterococci*[b]	*Lactobacilli*	*Clostridia*	*Bacteroides*	*Bifido-bacteria*	*Eubacteria*
Largely carbo-hydrate	Guatemala	8.7	7.9	9.0	9.3	10.3	9.4	ND
	Hong Kong	7.0	5.8	6.1	4.7	9.8	9.1	8.5
	India	7.9	7.3	7.6	5.7	9.2	9.6	9.5
	Japan	9.4	8.1	7.4	5.6	9.4	9.7	9.6
	Nigeria	8.3	8.0	ND	5.9	7.3	10.0	ND
	Sudan	6.7	7.7	6.4	4.9	7.8	8.5	ND
	Uganda	8.0	7.0	7.2	5.1	8.2	9.4	9.3
Mixed Western	Denmark	7.0	6.8	6.4	6.3	9.8	9.9	9.3
	England	7.9	5.8	6.5	5.7	9.8	9.9	9.3
	Finland	7.0	7.8	8.0	6.2	9.7	9.7	9.5
	Scotland	7.6	5.3	7.7	5.6	9.8	9.9	9.3
	United States	7.4	5.9	6.5	5.4	9.7	9.9	9.3

ND. No data.

Sources: England, India, Japan, Scotland, United States, Uganda (Drasar 1974); Denmark, Finland (International Agency for Research on Cancer 1977); Hong Kong (Crowther and others 1976); Nigeria, Sudan (Draser, personal communication); Guatemala (Mata, Carrillo and Villatoro 1969).

a. This group mainly contains *Escherichia coli.*

b. These two groups are the most commonly used fecal indicator bacteria.

Table 8. Viral pathogens excreted in faeces (from Feachem *et al*, 1983)

Virus	*Disease*	*Can symptomless infections occur?*	*Reservoir*
Adenoviruses	Numerous conditions	Yes	Man
Enteroviruses			
Polioviruses	Poliomyelitis, paralysis and other conditions	Yes	Man
Echoviruses	Numerous conditions	Yes	Man
Coxsackie viruses	Numerous conditions	Yes	Man
Hepatitis A virus	Infectious hepatitis	Yes	Man
Reoviruses	Numerous conditions	Yes	Man and animals
Rotaviruses, Norwalk agent and other viruses	Diarrhea	Yes	Probably man

Table 9. Protozoal pathogens excreted in faeces (from Feachem *et al*, 1983)

Protozoon	*Disease*	*Can symptomless infections occur?*	*Reservoir*

Table 10. Helminthic pathogens excreted in faeces (from Feachem *et al*, 1983)

Helminth	*Common name*	*Disease*	*Transmission*	*Distribution*
Ancylostoma duodenale	Hookworm	Hookworm	Man → soil → man	Mainly in warm wet climates
Ascaris lumbricoides	Round worm	Ascariasis	Man → soil → man	Worldwide
Clonorchis sinensis	Chinese liver fluke	Clonorchiasis	Man or animal → aquatic snail → fish → man	Southeast Asia
Diphyllobothrium latum	Fish tapeworm	Diphyllobothriasis	Man or animal → copepod → fish → man	Widely distributed foci, mainly temperate regions
Enterobius vermicularis	Pinworm	Enterobiasis	Man → man	Worldwide
Fasciola hepatica	Sheep liver fluke	Fascioliasis	Sheep → aquatic snail → aquatic vegetation → man	Worldwide in sheep- and cattle-raising areas
Fasciolopsis buski	Giant intestinal fluke	Fasciolopsiasis	Man or pig → aquatic snail → aquatic vegetation → man	Southeast Asia, mainly China
Gastrodiscoides hominis	n.a.	Gastrodiscoidiasis	Pig → aquatic snail → aquatic vegetation → man	India, Bangladesh, Vietnam, Philippines
Heterophyes heterophyes	n.a.	Heterophyiasis	Dog or cat → brackish-water snail → brackish-water fish → man	Middle East, southern Europe, Asia
Hymenolepis nana	Dwarf tapeworm	Hymenolepiasis	Man or rodent → man	Worldwide
Metagonimus yokogawai	n.a.	Metagonimiasis	Dog or cat → aquatic snail → freshwater fish → man	East Asia, Siberia (USSR)
Necator americanus	Hookworm	Hookworm	Man → soil → man	Mainly in warm wet climates
Opisthorchis felineus	Cat liver fluke	Opisthorchiasis	Cat or man → aquatic snail → fish → man	USSR, Thailand
O. viverrini	n.a.			
Paragonimus westermani	Lung fluke	Paragonimiasis	Pig, man, dog, cat or other animal → aquatic snail → crab or cray-	Southeast Asia, scattered foci in Africa and South America

Table 11. Possible output of selected pathogens in the faeces and sewage of a tropical community of 50,000 in a developing country (from Feachem *et al,* 1983)

Pathogen	*Prevalence of infection in country (percent)*[a]	*Average number of organisms per gram of feces*[b]	*Total excreted daily per infected person*[c]	*Total excreted daily by town*	*Concentration per liter in town sewage*[b]
Viruses					
Enteroviruses[d]	5	10^{6}	10^{8}	2.5×10^{11}	5,000
Bacteria					
Pathogenic *E. coli*[e]	?	10^{8}	10^{10}	?	?
Salmonella spp.	7	10^{6}	10^{8}	3.5×10^{11}	7,000
Shigella spp.	7	10^{6}	10^{8}	3.5×10^{11}	7,000
Vibrio cholerae	1	10^{6}	10^{8}	5×10^{10}	1,000
Protozoa					
Entamoeba histolytica	30	15×10^{4}	15×10^{6}	2.25×10^{11}	4,500
Helminths					
Ascaris lumbricoides	60	10^{4}[f]	10^{6}	3×10^{10}	600
Hookworms[g]	40	800[f]	8×10^{4}	1.6×10^{9}	32
Schistosoma mansoni	25	40[f]	4×10^{3}	5×10^{7}	1
Taenia saginata	1	10^{4}	10^{6}	5×10^{8}	10
Trichuris trichiura	60	2×10^{3}[f]	2×10^{5}	6×10^{9}	120

? Uncertain.

Note: This table is hypothetical, and the data are not taken from any actual, single town. For each pathogen, however, the figures are reasonable and congruous with those found in the literature. The concentrations derived for each pathogen in sewage are in line with higher figures in the literature, but it is unlikely that all these infections at such relatively high prevalences would occur in any one community.

a. The prevalences given in this column refer to infection and *not* to morbidity.

b. It must be recognized that the pathogens listed have different abilities to survive outside the host and that the concentrations of some of them will rapidly decline after the feces have been passed. The concentrations of pathogens per liter in the sewage of the town were calculated by assuming that 100 liters of sewage are produced daily per capita and that 90 percent of the pathogens do not enter the sewers or are inactivated in the first few minutes after the excretion.

c. To calculate this figure it is necessary to estimate a mean fecal weight for those people infected. This must necessarily be the roughest of estimates because of the age-specific fecal weights and the age distribution of infected people in the community. It was assumed that people over 15 years old excrete 150 grams daily and that people under 15 excrete, on average, 75 grams daily. It was also assumed that two-thirds of all infected people are under 15. This gives a mean fecal weight for infected individuals of 100 grams.

d. Includes polio-, echo-, and coxsackieviruses.

e. Includes enterotoxigenic, enteroinvasive, and enteropathogenic *E. coli.*

f. The distribution of egg output from people infected by these helminths is extremely skewed; a few people excrete very high egg concentrations.

g. *Ancylostoma duodenale* and *Necator americanus.*

Considering these factors in relation to tropical islands, it would seem that high temperatures which tend to reduce bacterial and viral survival times, assist with the attenuation of these organisms. However most other factors indicate that groundwater protection may be difficult. In many tropical islands soils are moist for long periods due to high rainfall, which also enhances migration through the unsaturated zone. On low-lying islands the thickness of the unsaturated zone is limited, and migration increases under saturated conditions.

Soils on sand and coral islands are generally coarse textured, due to the high-energy of depositional environments, and have low clay and organic matter contents. This means infiltration rates are high, and the capacity for organisms to be filtered or adsorbed is low. In such soils the organic matter within the sewage, may ultimately provide adsorption sites for microorganisms. Biofilms which grow in the vicinity of septic tank pipe perforations and latrine pits, may be highly significant for attenuation of the transport of pathogens.

In summary almost all of the features of climate, soils, and lithology of tropical sand and coral islands, create conditions which favour the extended survival and subsurface transport of enteric bacteria and viruses. An exception is the prevalence of high temperatures, which accelerate attenuation of these microorganisms in the subsurface.

Islands with greater relief, such as islands of volcanic origin may be more capable of attenuating contaminants and protecting groundwater quality, due to deeper unsaturated zones, and the presence of clay and higher concentrations of organic matter in the soils.

Where water application rates temporarily exceed the hydraulic conductivity of soils, such as during intense rainstorms, or where septic tanks may overflow, solutes are readily leached by preferential flow in sandy soils. This may result in high concentrations of nitrogen and pathogens reaching groundwater more quickly than would be estimated using normal estimation methods for infiltration rates. Therefore maintenance of the septic tank should be undertaken periodically to prevent clogging of perforated pipe, and consequent saturated conditions developing in surrounding soil. This is likely to be an ongoing problem at pit latrines.

Transport within the aquifer depends on the velocity of groundwater movement and on the nature of the aquifer. In general coral or limestone aquifers have hydraulic properties which are very heterogeneous. Where there is karst, or variably cemented limestone and sand deposits, typical of reef environments, solution features and preferential flow paths may occur which can result in extremely rapid transport of contaminants over very long distances. Malard *et al* (1994) reported a study of faecal bacteria in a limestone aquifer adjacent to a sewage-polluted river in Southern France where large differences in bacterial concentrations were attributed to whether or not wells were connected to macropores intersecting the river bed. On a small fractured rock island (Jersey) Robins (1994) reported the importance of fracture patterns in determining pollutant concentrations.

A series of cases where the maximum reported travel distance of bacteria and viruses in the subsurface studies are summarised by Crane and Moore (1984) and Yates and Yates (1988). These results are repeated here in Tables 14, 15 and 16. Although survival time provides the most useful measure, in most cases only travel distance was reported. The longest survival time recorded was 27 weeks for Bacillus coli which travelled 20 metres from a sewage trench intersecting groundwater (Table 14). There are at least 5 cases where bacteria have been recorded to travel in excess of 800 metres, in gravel or limestone aquifers (Table 15). The longest distance reported for a microorganism is 1600 metres for a coliphage in a karst aquifer (Table 16). In a recent study by Paul et al (1995) indicators of pollution by sewage (faecal coliforms, Clostridium perfringens, and enterococci) were found in the Key Largo Limestone aquifer of Florida, on shore and in two of five shallow nearshore

Table 12. Factors influencing bacterial fate in the subsurface (from Yates and Yates, 1988)

Factor	Influence on: Survival	Influence on: Migration
Temperature	Bacteria survive longer at low temperatures	
Microbial activity	Increased survival time in sterile soil	
Moisture content	Greater survival time in moist soils and during times of high rainfall	Generally, migration increases under saturated flow conditions
pH	Increased survival time in alkaline soils (pH > 5) than in acid soils	Low pH enhances bacterial retention
Salt species and concentration		Generally, increasing the concentration of ionic salts and increasing cation valences enhance bacterial adsorption
Soil properties		Greater bacterial migration in coarse-textured soils; bacteria are retained by the clay fraction of soil
Bacterium type	Different bacteria vary in their susceptibility to inactivation by physical, chemical, and biological factors	Filtration and adsorption are affected by the physical and chemical characteristics of the bacterium
Organic matter	Increased survival and possible regrowth when sufficient amounts of organic matter are present	The accumulation of organic matter can aid in the filtration process
Hydraulic conditions		Generally, bacterial migration increases with increasing hydraulic loads and flow rates

Table 13. Factors influencing virus fate in the subsurface (from Yates and Yates, 1988)

Factor	Influence on: Survival	Influence on: Migration
Temperature	Viruses survive longer at lower temperatures	Unknown
Microbial activity	Some viruses are inactivated more readily in the presence of certain microorganisms; however, adsorption to the surface of bacteria can be protective	Unknown
Moisture content	Some viruses persist longer in moist soils than dry soils	Generally, virus migration increases under saturated flow conditions
pH	Most enteric viruses are stable over a pH range of 3 to 9; survival may be prolonged at near-neutral pH values	Generally, low pH favors virus adsorption and high pH results in virus desorption from soil particles
Salt species and concentration	Some viruses are protected from inactivation by certain cations; the reverse is also true	Generally, increasing the concentration of ionic salts and increasing cation valencies enhance virus adsorption
Virus association with soil	In many cases, survival is prolonged by adsorption to soil; however, the opposite has also been observed	Virus movement through the soil is slowed or prevented by association with soil
Virus aggregation	Enhances survival	Retards movement
Soil properties	Effects on survival are probably related to the degree of virus adsorption	Greater virus migration in coarse-textured soils; there is a high degree of virus retention by the clay fraction of soil
Virus type	Different virus types vary in their susceptibility to inactivation by physical, chemical, and biological factors	Virus adsorption to soils is probably related to physicochemical differences in virus capsid surfaces
Organic matter	Presence of organic matter may protect viruses from inactivation; others have found that it may reversibly retard virus infectivity	Soluble organic matter competes with viruses for adsorption sites on soil particles
Hydraulic conditions	Unknown	Generally, virus migration increases with increasing hydraulic loads and flow rates

Table 14. A summary of studies of bacterial transport through soils (from Crane and Moore, 1984)

Nature of pollution	Organisms	Medium	Measured distance travels	Time of travel
Sewage trenches intersecting groundwater	*Bacillus coli*	Fine sand	19.8 m (65 ft)	27 wks
Sewage trenches intersecting groundwater	Coliforms	–	70.7 m (232 ft)	–
Sewage in pit latrine intersecting groundwater	*Bacillus coli*	Fine and coarse sand	24.4 m (80 ft)	–
Sewage in pit latrine intersecting groundwater	*Bacillus coli*	Sand and sandy clay	10.7 m (35 ft)	8 wks
Sewage in pit latrine intersecting groundwater	*Bacillus coli*	Fine and medium sand	3.1 m (10 ft)	–
Primary and treated sewage in infiltration basins	Coliforms	Fine sandy loam	0.6–4 m (2–13 ft)	–
Diluted primary sewage injected subsurface	Coliforms	Aquifer	30 m (98 ft)	33 hrs
Canal water in infiltration basins	*Escherichia coli*	Sand dunes	3.1 m (10 ft)	–
Subsurface injection	Enterococci	–	15 m (44 ft)	–
Secondary sewage in infiltration basins	Coliforms	Sandy gravels	0.9 m (3 ft)	–
Tertiary treated wastewater in percolation beds	Fecal coliforms and fecal streptococci	Coarse gravels	457.2 m (1500 ft)	15 da
Primary sewage injected subsurface	Coliforms	Sand and pea gravel aquifer	30.5 m (100 ft)	35 hr
Secondary sewage injected subsurface	Fecal coliforms	Fine to coarse sand aquifer	30.5 m (100 ft)	–
Tertiary treated wastewater in percolation beds	Coliforms	Sand and gravel	830 m (2723 ft)	–
Inoculated water and diluted sewage injected subsurface	*Bacillus stearothermophilis*	Crystalline bedrock	28.7 m (94 ft)	24–30 hr
Tertiary treated wastewater in infiltration basins	Coliforms	Fine to medium sand	6.1 m (20 ft)	–
Secondary sewage in infiltration basins	Fecal coliforms	Fine loamy sand to gravel	9.1 m (30 ft)	–
Primary sewage in infiltration basins	Fecal streptococci	Silty sand and gravel	183 m (600 ft)	–
Secondary sewage effluent in infiltration basin	Fecal coliforms and fecal streptococci	Fine loamy sand	9 m (29 ft)	–
Septic tank tile effluent	Total coliforms Fecal coliforms	Fine loamy soil Fine loamy soil	6.1 m (20 ft) 13.5 m (46 ft)	– –
Inoculated effluent in tile line	*E. coli*	Silty clay loam	20 m (64 ft)	5 hr

[a] Table adapted from Hagedorn and McCoy, 1979 with several additions.

Table 15. Migration of bacteria in the subsurface (from Yates and Yates, 1988)

Microorganism	Medium	Maximum distance traveled (m) Vertical	Horizontal
Bacillus stearothermophilus	Fractured rock		29
Bacteria	Fine sand		457
	Medium to coarse sand		21
	Alluvial gravel		90
	Pea gravel + sand		30
	Coarse gravels		457
	Gravel		920
	Sandy clay		15.25
	Fine to coarse sand		30.5
	Fine to medium sand		6.1
Clostridium welchii	Fine + medium sand		15.5
Coliforms	Loam + sandy loam		
	Sand + gravel	10 — 12	850
	Fine sandy loam	4	1.2
	Fine sand	4	2
	Pebbles		850
	Weathered limestone		1000
	Stony clay + sand	0.91	
	Stone + clay	0.61	
	Firm clay	0.3	
	Coarse sand + gravel		55
	Sandy clay loam	2	6.1
	Sandy clay loam	4.3	13.5
	Sandy loam	0.64	28
Escherichia coli	Sand		3.1
	Fine + coarse sand	4	24.4
	Fine + medium sand	0.15	
	Fine + medium sand		3.1
	Sand + sandy clay	1.5	10.7
	Silt loam		3
	Silty clay loam		1.5
	Medium sandy gravel		125
	Fine sandy gravel with cobbles		50
	Silty clay loam	1	15
	Fine sand		19.8
	Fine sand	0.3	70.7
Fecal coliforms	Fine loamy sand + gravel		9.1
	Stony silt loam		900
	Fine to medium sand		2.4
	Gravel with sand + clay		9
	Saturated gravels		42
	Sandy clay + clay	0.85	
	Sandy clay	1.2	
Salmonella enteriditis	Clay	0.1	
S. typhi	Limestone		457
Streptococcus faecalis	Silty clay loam		0.5
	Silt loam		5
Strep. zymogenes	Sandy gravel	0.15	15.2

Table 16. Migration of viruses in the subsurface (from Yates and Yates, 1988)

Microorganism	Medium	Maximum distance traveled (m) Vertical	Horizontal
Bacteriophage	Sand	45.7	400
	Sandy clay	1.2	
	Clay	0.85	
	Boulder clay		510
	Sandstone		570
Coliphage f2	Silty sand	29	183
Coliphage T4	Karst		1600
Coxsackievirus B3	Fine loamy sand	18.3	
	Sand	22.8	408
Echovirus	Coarse sand + fine gravel	11.3	45.7
Enterovirus	Sandy loam	3.5	14.5
Poliovirus	Loamy sand	0.4	
	Medium sand		0.6
	Loamy sand	1.6	
	Sand	0.2	
	Silt loam		46.2
	Medium to fine sand		9
	Loamy medium sand		6
	Sand	9.1	
	Coarse sand + fine gravel	10.6	3.0
	Coarse sand + fine gravel	7.62	
Viruses	Sand	6	
	Sandy clay	3	
	Sand	38	
	Sand + coarse gravel	16.8	250

wells (less than 3km from the shore). Wells further from shore showed little sign of contamination.

For small tropical islands such travel distances would be a major concern as it may not be possible to protect water supplies. This is especially so for low-lying islands where the drawdown cone surrounding water supply wells may be very significant with respect to the otherwise very gentle hydraulic gradients within aquifers.

Rates of attenuation of microorganisms have been studied in the field, laboratory, and slow sand filters at water treatment plants, by a variety of techniques. Yates and Yates (1988) reported rates of removal for viruses, bacteriophages, and bacteria for different soil types and rates of application in water. The table of results gives removal rates ranging from 1.2×10^{-3} to 6×10^{-1} $\log_{10}$ number of organisms per centimetre of soil. That is one $\log_{10}$ removal occurs over 1.7cm to 8m. Rates of application varied from 1 cm/day to 12 m/day and the highest removal rates were recorded for the lowest application rates. These results do not allow conclusions on the relative survival of microorganisms or contrasts between soil types. They reflect that there are several removal processes occurring concurrently, notably filtration and die-off.

In the biologically active unsaturated zone, die-off rates are considered to be higher than in groundwater (consistent with the effect of moisture content, Tables 12 and 13), and therefore increasing the residence time of pathogens in the unsaturated zone is thought to be a valuable groundwater protection strategy. This has implications for siting and design of septic tanks, as reported by Cogger *et al* (1988). They found that the effect of doubling the depth to water table beneath a septic tank leach field (from 30 to 60cm) in fine sand on a coastal barrier island had a much more significant effect on faecal coliform numbers, redox potential, and nitrogen speciation in groundwater, than reducing the rate of infiltration from 16 to 1 cm/day. The water table effect reduced most probable numbers of faecal coliforms per litre from 25,000 to 60, and allowed almost complete nitrification. Phosphorus movement however was related to pore water velocity.

Pavelic *et al* (1996) summarised the times recorded by a number of researchers for one log removal of viruses, bacteriophage, and bacteria in groundwater, again with a variety of techniques (Table 17). Removal times ranged from 0.7 to 33 days with typical values in the vicinity of 3 to 10 days. For a pathogen present in wastewater at a concentration of say 10^4 organisms per litre (after Table 11), it would take four times the log removal time reported in Table 17 to reduce this number to 1 organism per litre, without accounting for dilution. In Europe well-head protection zones, in which human and animal wastes and other potentially polluting activities are excluded, are generally defined as the zone in which contaminants in recharge could appear at the extraction well within 50 days (Waegeningh, 1985).

Finally, the fate of pathogens in composting systems, including well-aerated latrines needs to be addressed to account for ultimate disposal of sludge from latrines and septic tanks. A temperature-duration curve (Figure 4, from Feachem *et al*, 1983, p79) demonstrates that with ample time at high temperature, such as those achievable in well-managed composting systems, pathogen inactivation can be highly effective. Indicated temperature-time requirements are at least 1 hour at $>62^0$C, 1 day at $>50^0$C, or 1 week at $>46^0$C. Processes within this 'safety zone' should be lethal to all excreted pathogens (with the possible exception of hepatitis A virus at short retention times).

The fate of nutrients in aquifers depends on the oxidation status of groundwater and the cation exchange capacity of aquifer material. Generally nitrogen in wastewater is predominantly in the form of ammonium or organic nitrogen. Once leachate escapes from the zone of high oxygen demand into the surrounding unsaturated zone or aerobic groundwater, nitrification occurs, ultimately to completion (Whelan and Barrow, 1984a). In the absence of anaerobic conditions denitrification does not occur, and the nitrate behaves as a conservative species in groundwater. An anaerobic core of the plume may develop

Table 17. Times for one log removal of viruses, bacteriophage, and bacteria in groundwater (from Pavelic et al (1996)

Microorganism	[a]Decay rate (day^{-1})	[b]Removal time (days)	Reference	Type of experiment
Poliovirus 1	0.046	22	Bitton *et al.*, (1983)	Lab
	0.21	4.8	Keswick *et al.*, (1982*a*)	McF
	0.03-0.09	11-33	Jansons *et al.*, (1989*a*)	Field
	0.04-0.08		Enriquez *et al.*, (1995)	Lab
Adenovirus 40	0.04-0.05	??	Enriquez *et al.*, (1995)	Lab
Adenovirus 41	0.04-0.05	??	Enriquez *et al.*, (1995)	Lab
Coxsackievirus	0.11	9.1	Keswick *et al.*, (1982*a*)	McF
	0.05	20	Jansons *et al.*, (1989*a*)	Field
Echovirus 6	0.11	9.1	Jansons *et al.*, (1989*a*)	Field
Echovirus 11	0.10	10	"	Field
Echovirus 24	0.05	20		Field
Rotavirus SA-11	0.36	2.8	Keswick *et al.*, (1982*a*)	McF
Coliphage f2	1.42	0.7	Bitton *et al.*, (1983)	Lab
	0.39	2.6	Keswick *et al.*, (1982*a*)	McF
Coliphage T2	0.17	5.9	Mazzeo and Ragusa, (1989)	Lab
Coliphage T7	0.15	6.7	Niemi, (1976)	Lab
Escherichia coli.	0.32	3.1	Keswick *et al.*, (1982*a*)	McF
	0.36	2.8	McFeters *et al.*, (1974)	McF
	0.16	6.3	Bitton *et al.*, (1983)	Lab
	0.26	3.9	Mazzeo and Ragusa, (1989)	Lab
	0.32	3.1	Yates *et al.*, (1985)	Lab
	0.05-0.11[c]	9.1-20	Dillon *et al.*, (1995)	Field
Fecal Streptococci	0.23	4.3	Keswick *et al.*, (1982*a*)	McF
	0.24	4.2	McFeters *et al.*, (1974)	McF
	0.03	33	Bitton *et al.*, (1983)	Lab
	0.12	8.3	Dillon *et al.*, (1995)	Field
S. Faecalis	0.31	3.2	Mazzeo and Ragusa, (1989)	Lab
	0.23	4.3	Yates *et al.*, (1985)	Lab
Salmonella typhimurium	0.13	7.7	Keswick *et al.*, (1982*a*)	McF
	0.22	4.5	McFeters *et al.*, (1974)	McF

[a]expressed as $\log_{10}(C_t/C_o)$, where C_t is the concentration of organisms after 24 hours and C_o is the initial concentration of organisms

[b]time for one log removal

[c] Faecal coliforms

Lab: flasks in laboratory conditions

McF: McFeter's type chambers immersed in flowing groundwater

Field: sampling from well under field conditions

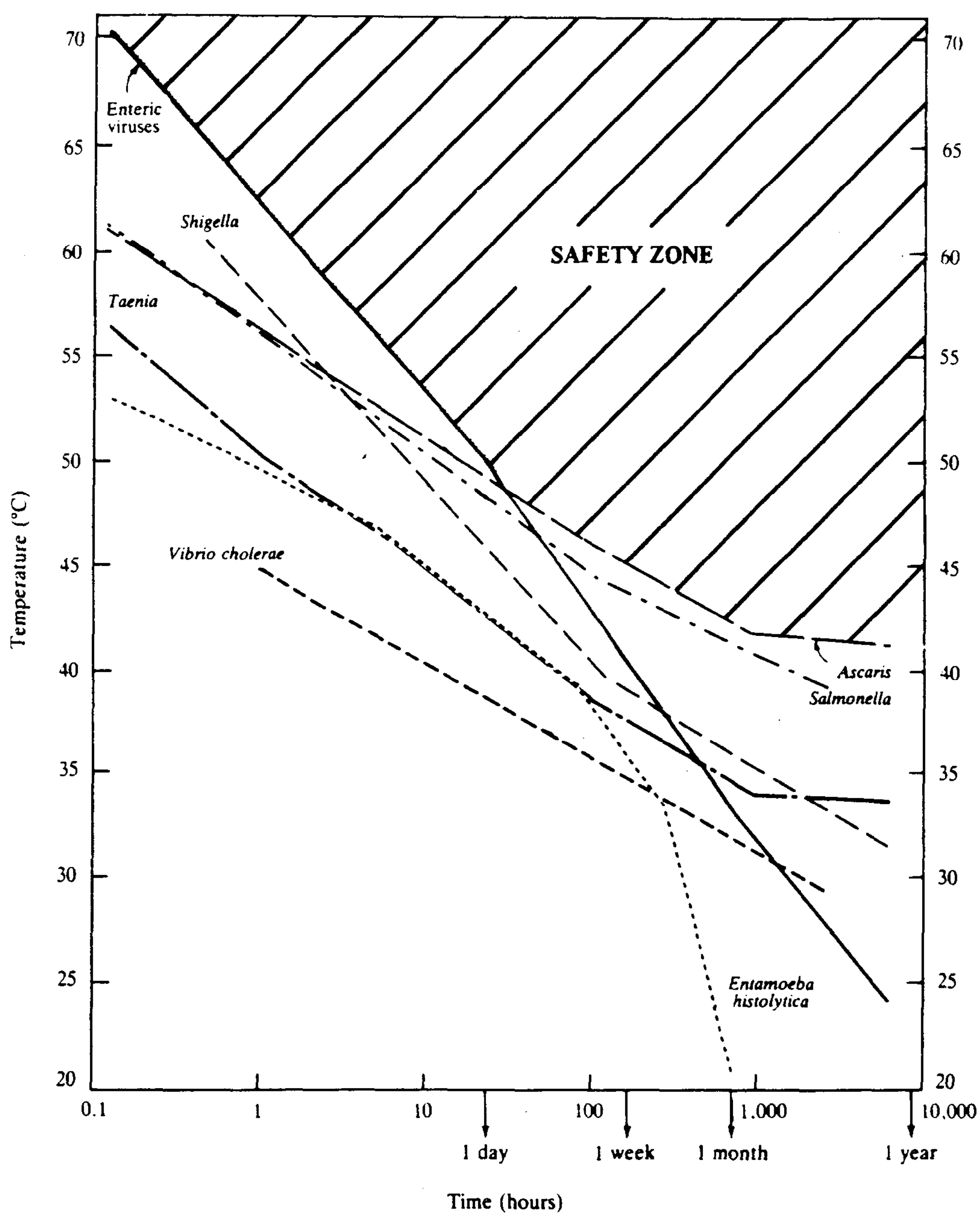

Figure 4. A temperature-duration curve for pathogen inactivation in night soil and sludge. Processes within the 'safety zone' should be lethal to excreted pathogens (from Feachem *et al*, 1983)

close to the source of the effluent if the rate of transport of oxygen in the aquifer is exceeded by the oxygen demand imposed by infiltrating effluent. Usually this 'core' will be devoid of nitrate, with all the nitrogen present in its reduced forms. Hence sampling for nitrate only may lead to gross errors in assessing the impacts of sanitation on groundwater quality. If groundwater is anaerobic, and there is a suitable reducing agent such as labile organic carbon or iron within the aquifer, denitrification can occur. Normally such groundwater would not be used for drinking water supplies without first aerating it to remove odour.

Phosphorus may also be transported through unsaturated and saturated porous media. Adsorption of phosphorus is common particularly in organic-rich soils, with high cation exchange capacity, and large surface area per unit volume (small particle sizes). Soils on small tropical islands, particularly coral and barrier islands generally have a very low capacity to adsorb phosphorus, and it may be relatively mobile in these systems. Adsorption however may be significant in carbonate aquifers. Several studies of phosphorous (P) transport from septic tanks have been undertaken (eg; Gilliom and Patmont, 1982; Bromssen 1984; Reddy and Dunn, 1984; and Whelan and Barrow, 1984b) indicating that phosphorus movement can be very variable with leachate concentrations varying between 1% and 100% of source concentrations, depending on the age of the sanitation system and the adsorptive properties of soils. Breakthrough of phosphorus was always retarded in comparison with nitrate, and less critical for groundwater quality, with the possible exception of groundwater discharge to freshwater ecosystems.

Finally, sodium adsorption ratio (SAR) should be mentioned, as this is sometimes considered to be a restriction on the potential for sustainable discharge of wastewater to soils. At high SAR's dispersing clays may disperse resulting in a decline in permeability of soils where effluent is discharged, and waterlogging may occur. This is an unlikely prospect for small tropical islands, where in general soils have low clay content, are free draining and due to the marine influences, have soil water SAR's which are similar to the effluent.

5. Investigation Methods

Numerous investigators have explored the fate of contaminants from septic tanks, enabling an assessment of the relative value of different investigation methods.

Robertson et al (1989) measured the impact of a domestic septic system on inorganic ion concentrations in a 3-dimensional grid of over 500 sampling ports in an unconfined sand aquifer in Ontario, Canada. They found sodium and nitrate concentrations in excess of 50% of the source concentration for a distance of more than 100m from the tile bed (Figures 5 and 6). In this instance sodium was a better tracer than nitrate as the ratio of concentrations in effluent to ambient groundwater were greater than ten and less than two respectively. (High ambient nitrate concentrations were due to fertilizers and animal wastes.) It is important to note that an evaluation of groundwater and effluent quality is needed to determine the most prospective tracers in effluent which may allow detection of a plume of wastewater constituents within the groundwater.

Robertson *et al* (1989) also monitored linear alkylbenzene sulfonate (LAS), a degradable organic compound which is present in some consumer products. In the unsaturated zone it has a half life of typically 5 to 20 days, and due to adsorption retarding its transport it takes about 70 half lives to reach the watertable. Therefore absence of detectable LAS in the groundwater is not surprising. There is evidence of acclimation to LAS biodegradation within the plume where degradation rates are higher than in sediments outside the plume. This is interesting as it provides an analogy to bacterial and viral attenuation, and may explain results of Brown *et al* (1979) who found faecal coliforms and coliphages in leachate through 120cm soil columns shortly after application began on initially pristine soils, but not later.

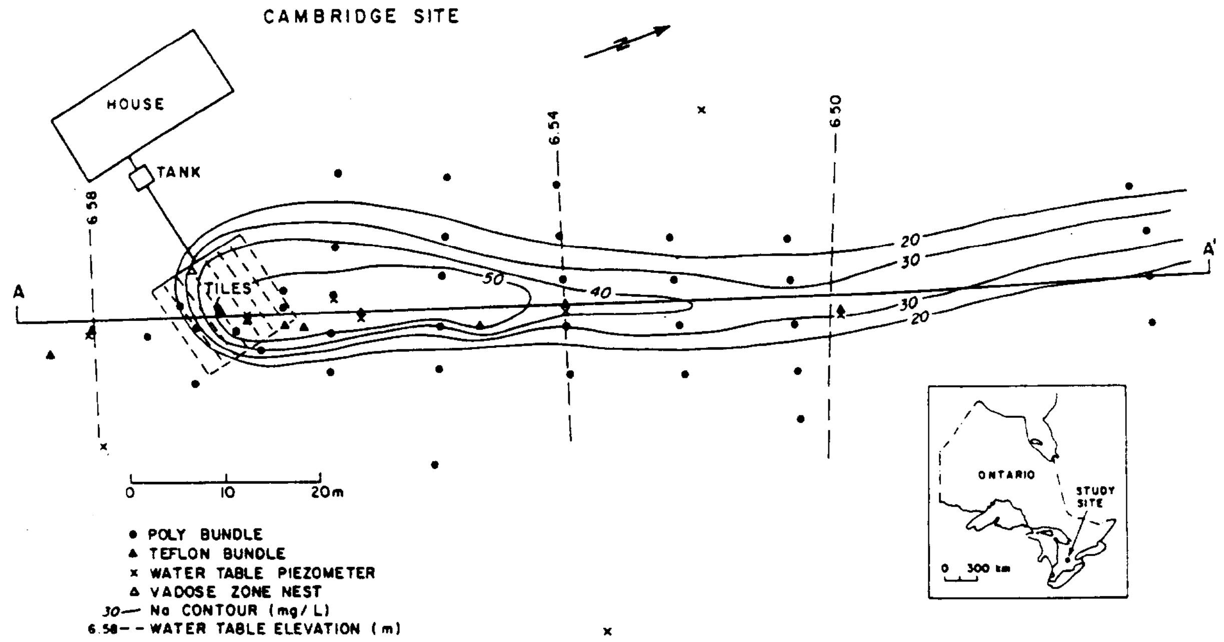

Figure 5. Plan view of a contaminant plume caused by a septic tank, showing vertically averaged sodium ion concentration, monitoring sites, and water table gradient in an intensively monitored surficial aquifer near Cambridge, Ontario (from Robertson *et al*, 1989)

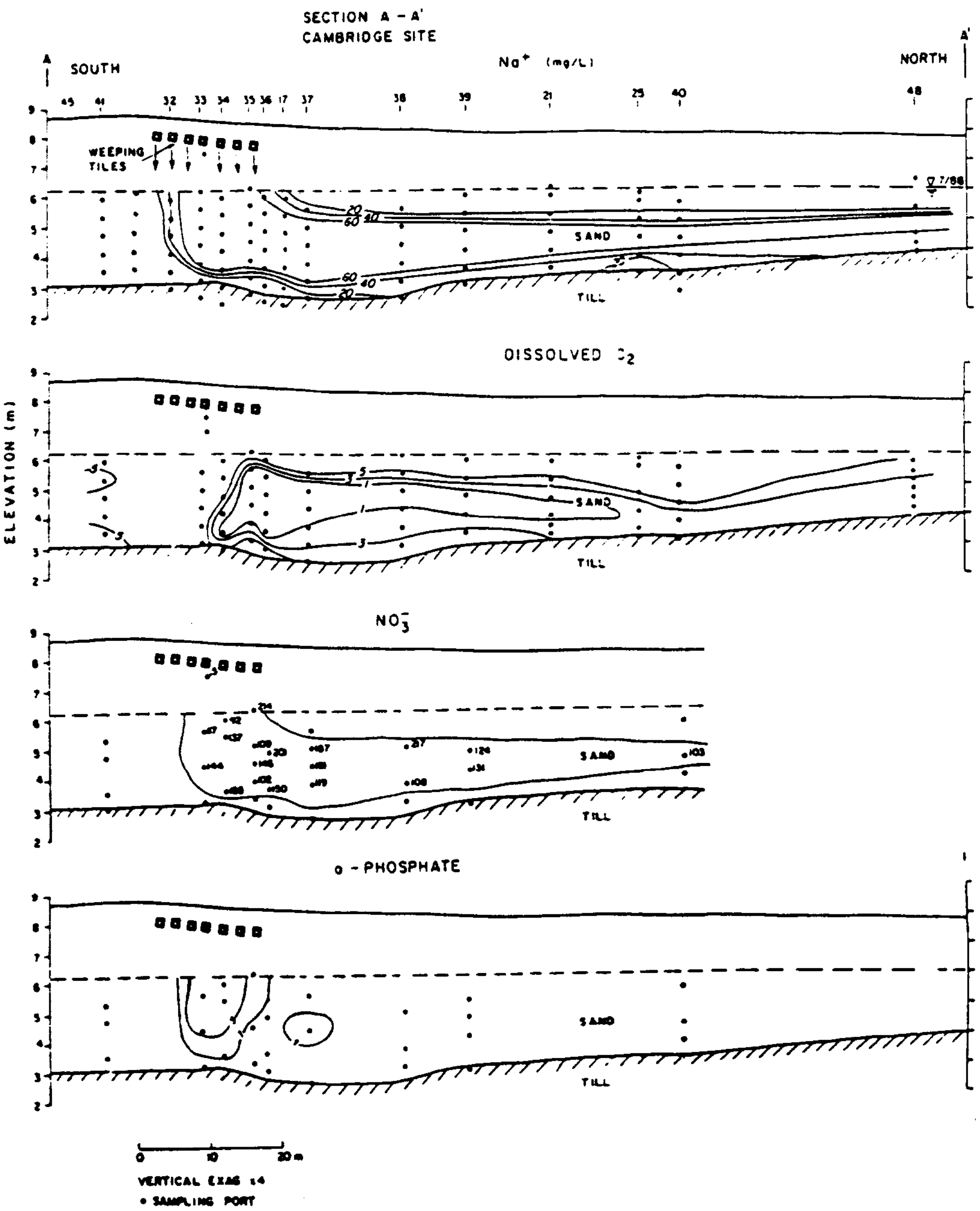

Figure 6. Vertical cross-section along the centre-line of the contaminant plume, showing sodium, dissolved oxygen nitrate, and phosphate concentrations (mg/L) (from Robertson *et al*, 1989)

At Robertson *et al*'s site a bromide tracer test was performed which showed the septic tank mean residence time was about 2 days, and the time of passage to the water table 1.4 to 1.9 m below the tile drains was on the order of 10 days. Maximum vertical velocity of 1.7 cm/day and a horizontal velocity of 5cm/day (18m/year) is estimated from the bromide tracer test over 120 days.

Note that while long, thin, single-stranded plumes, such as shown in Figures 5 and 6 are common in homogeneous aquifers, many other plume structures are possible, including multiple-stranded plumes, and oblate plumes. The form of plume depends on aquifer heterogeneity and anisotropy, groundwater velocity, and the consistency of source loadings and groundwater flow direction over time.

Reneau and Pettry (1975) studied the lateral movement of faecal coliforms from septic tank drainlines in sandy loams in coastal plain soils of Virginia over a two year period. They observed from piezometer samples a 3 log reduction in most probable numbers (MPN) of total and faecal coliforms over a 6 metre distance at each of their three sites. Sources were not controlled, and residence times were not determined, so the experimental results contain enormous temporal variability (up to 4 log units). This is a warning that field studies without source control are unlikely to yield reliable attenuation rates.

In studies on sands of the Swan Coastal Plain, Western Australia, Parker *et al* (1981) had observed a rapid decline in concentration of faecal and total coliforms in the first 0.8 m beneath the effluent-sand interface. They also observed that removal of faecal bacteria improved once a slime layer had built up on the soil-effluent interface for new (less than 9 month old) septic systems. A subsequent saturated column study of the breakthrough of E. Coli, MS-2 coliphage, and Rhodamein WT dye in these coastal sands was reported by Parker (1983, p265-274). This showed breakthrough of first E. coli, then MS-2 coliphage, then Rhodamine-WT. While Parker did not evaluate the reasons for retardation (factor of 5) of the dye, it is thought to be caused by adsorption to organic components of the effluent which are adsorbed or filtered in the soil profile (Figure 7). This suggests that Rhodamine dye tracer studies in effluent are likely to overestimate the period before breakthrough of pathogens to water supply wells.

Geophysical techniques have been used successfully to detect groundwater contamination plumes where electrical conductivity in the plume contrasts with that of the native groundwater, where water tables are shallower than a depth of 30 metres, and where pipelines, cables, and fencing wire are absent (Mack and Maus, 1986). In general, background salinity will need to be very low in order to detect a plume associated with a septic tank. This is likely to be problematic in a coastal environment.

In conclusion, the techniques used for field studies of the subsurface fate of domestic effluent need to be tailored to the objectives of the study and to local conditions. Typical study objectives could range from assessment of impacts of current sewage disposal systems, to provision of data upon which groundwater protection policies will be based.

Field studies of transport of contaminants are likely to have site-specific outcomes which depend strongly on local values and the heterogeneity of aquifer hydraulic and adsorptive properties. If it is intended to extrapolate the results of such studies, knowledge of aquifer properties, and of the source loadings will be essential. In general, for the assessment of travel time, inorganic tracers such as bromide, appear to perform better than dyes and degradable organic substances which may be adsorbed on organic matter present in effluent, and retarded. Contrasting water quality parameters, such as nitrate, dissolved oxygen, bicarbonate, or microbial indicators (including fecal sterols), determined by comparing analyses of wastewater-affected and unpolluted groundwater, are likely to provide the best means of discriminating the spatial extent of groundwater pollution.

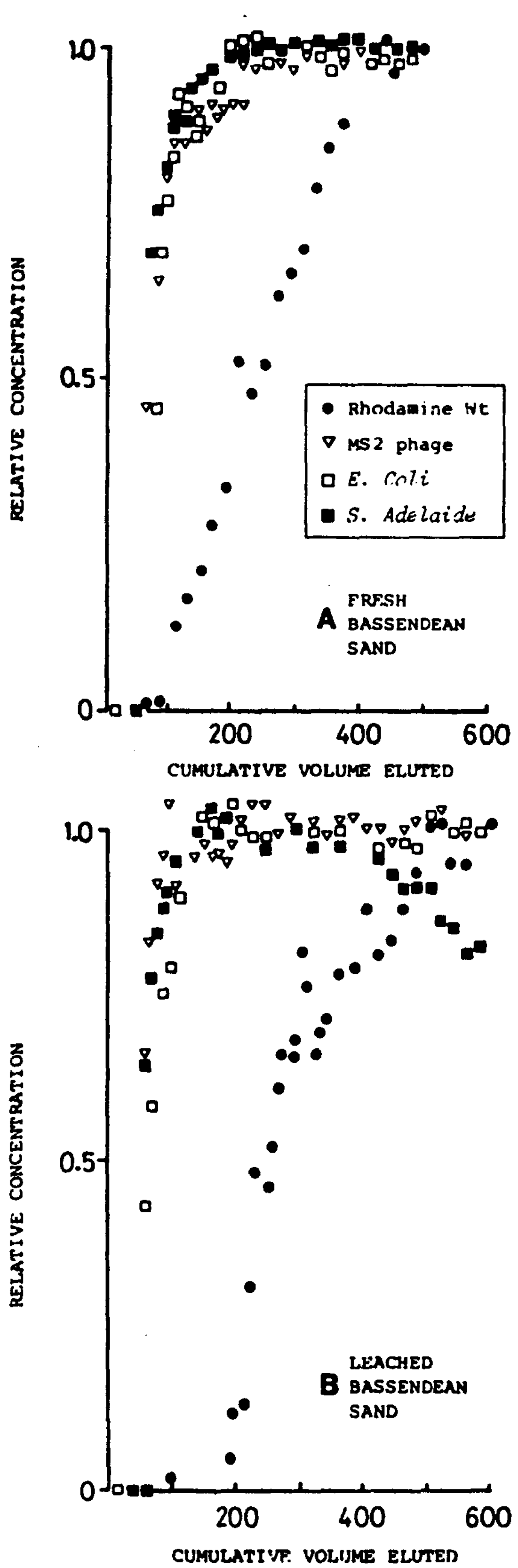

Figure 5a,b. Breakthrough curves for ***S. adelaide E. coli,*** **MS 2 phage and Rhodamine dye in fresh(a) and leached(b) Bassendean sand.**

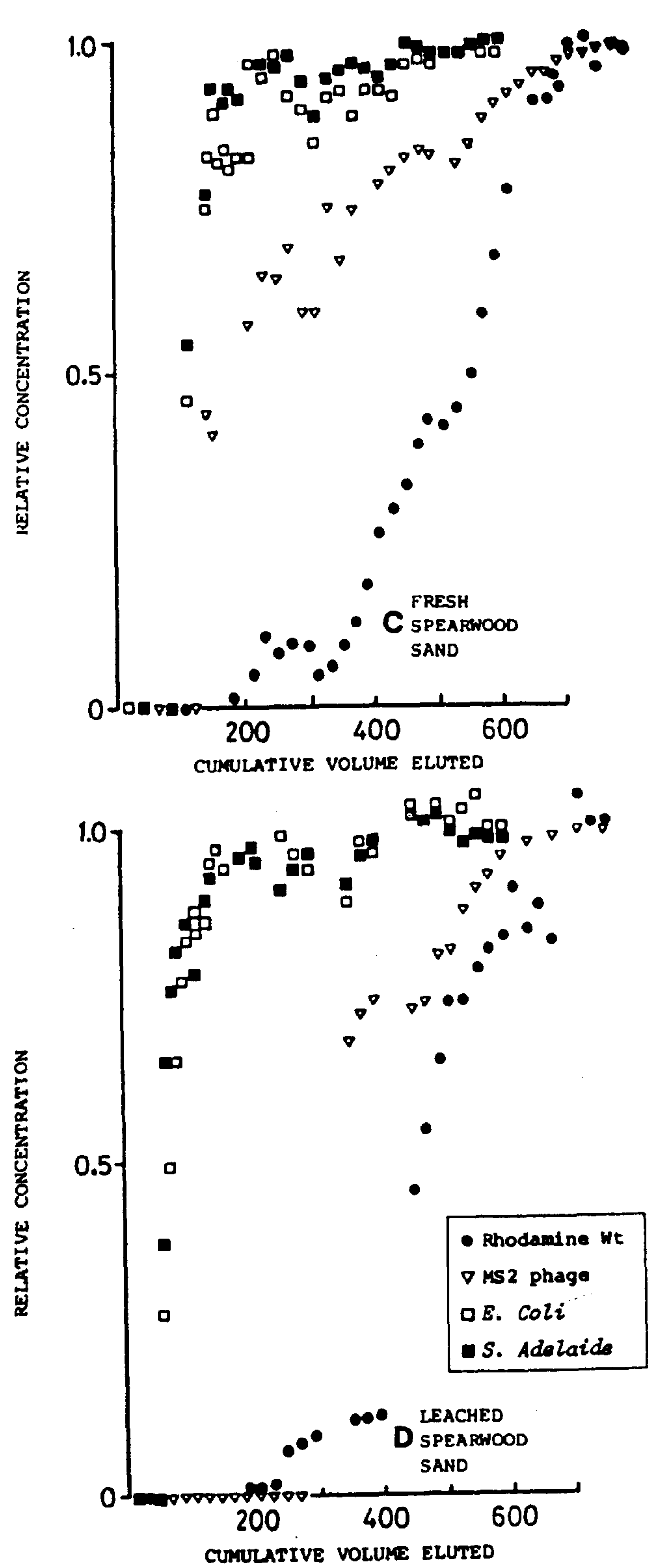

Figure 5c,d. Breakthrough curves for ***S. adelaide, E. coli,*** **MS2 phage and Rhodamine dye in fresh(a) and Leached(b) Spearwood sand.**

Figure 7. Breakthrough curves in Bassendean and Spearwood sands of the Swan Coastal Plain, Western Australia, initially, and after acclimation, when eluted with effluent containing Rhodamine Wt dye.

Laboratory column studies, and McFetters chambers used in wells, give more reliable estimates of degradation rates of microorganisms, but fail to provide information on the speed of transport of contaminants in the natural subsurface environment. Rates of attenuation of pathogens are generally higher in the unsaturated zone than below the water table, so knowledge of the thickness and infiltration rates in the unsaturated zone beneath the septage discharge are important variables to measure. A comprehensive analysis would require both field and laboratory investigations. However, data on one-log removal times (Table 17) together with local hydrogeological and public health information, may be used together to provide a preliminary assessment of the potential for drinking water contamination by sanitation, and to indicate those control measures which are most likely to be effective in each locality.

6. Control Measures

Control measures to prevent sanitation impacts on water supplies and human health on tropical islands may include one or more of the following:

- providing public information on the linkage between sanitation and drinking water quality
- implementing planning regulations to restrict population density of unsewered areas
- developing public health regulations on the design and maintenance of sanitation systems
- specifying well-head protection zones (minimum separation distances for contaminant sources)
- establishing monitoring procedures for pathogens and nitrogen in drinking water supplies, and developing contingency plans for occasions when water does not meet the required quality
- disinfection of water supply wells or finding alternative water supplies (eg rainwater tanks)
- establishing centralised water supply or sanitation systems

The acceptability and effectiveness of the various measures will obviously depend on the attitude of the local community.
Various authors have commented on the difficulties of managing groundwater quality on islands and have described the options available in general terms. For example, Detay et al. (1989) proposed a four point groundwater protection strategy for Micronesia:

1. establishment of planning and management practices
2. improvement of government coordination
3. improvement of utility system management, and
4. provision of information for decision making and public education.

Bryson (1988) and Nemickas *et al*, (1989) concluded that for USA Atlantic barrier islands, where nitrate concentrations were of major concern, population pressures forced the construction of centralised sewerage systems.

density of on-site sewage disposal

From a planning perspective, *'the single most important means of limiting groundwater contamination by septic tanks is to restrict the density of these in an area'* (Yates, 1985). Following a county-scale review, the United States Environmental Protection Agency (1977) designated counties with an on-site sewage disposal density greater than 15 per square kilometre (1 per 6.3 Ha) as having potential contamination problems. Most states regulate septic tank siting by imposing setbacks, minimum percolation rates, and the minimum size for the tile drainage area. In at least seven states a minimum lot size is specified for the issue of a permit to install a septic tank. This ranges from 0.1 to 0.18 Ha (Yates, 1985).

On tropical islands subsurface attenuation rates are expected to be lower than for continental temperate United States, as discussed in Section 4. Therefore if lot size was used as the sole means of protecting groundwater from septic tank contamination, the minimum lot size would need to be larger than the figures quoted above. As land is at a premium on small islands, lot size regulations alone are unlikely to be a satisfactory means of protecting groundwater quality.

Walker *et al* (1973) determined that the average nitrogen in excreta in Wisconsin is 8kg/person/year. They advocated a nitrogen balance be determined to find the maximum acceptable population density for on-site waste disposal where water supplies are drawn from local wells. Holzer (1975) applied this approach to Eastern Connecticut and estimated the maximum septic tank density to be one per 0.4 Ha. Developing this idea further, and assuming; the same per capita nitrogen loading rate, that there is no attenuation of nitrogen (complete nitrification and no gaseous losses), and that the human population covers the entire area of the aquifer which contributes to water supply wells, the maximum population density for which the mean nitrate-N concentration in groundwater will be less than 10 mg/L is given by Equation 1;

$$n < R / 80 \qquad \text{(Equation 1)}$$

where : n = maximum population density (people per hectare), and
R = average groundwater recharge rate (mm/year).

If recharge is 400 mm/year, a population density of 5/ha (500 per square kilometre) is the maximum achievable under the assumptions. In reality, the nitrogen concentrations in plumes will be much higher than the average concentration, and if any plume reaches a water supply well, the well may be polluted regardless of population density. An average concentration well below the WHO guideline may be a better target, to decrease the probability of polluting supply wells. On the other hand, this analysis ignores gaseous losses of nitrogen, and the effects of flow dilution from unpopulated (and unfertilized) areas within the catchment area of drinking water wells.

Volatilisation (of ammonia gas) depends on pH and only takes place significantly above pH 9 (such as can occur on hydrolysis of urea), at high temperatures, and where there is a rapid rate of air exchange. Below the water table volatilisation is unlikely to be significant. Denitrification (of nitrate to nitrogen or nitrous oxide gases) is favoured under anaerobic conditions and at high temperatures. Unless nitrate has already formed before the effluent leachate reaches the water table, denitrification is unlikely, as labile organic carbon required by denitrifying bacteria, is usually exhausted before aerobic conditions enable nitrification to occur. In some localities the resulting nitrate-rich groundwater may flow into anaerobic zones containing labile organic carbon, such as in the vicinity of swamps, or the riparian fringes of perennial streams, or buried seagrass beds. These facilitate denitrification. Normally however, volatilisation is likely to be the larger of the gaseous losses, and then only in the immediate vicinity of the latrine or septic tank.

Hence Equation (1) is thought to be a reasonable indicator of the upper limit on population density for the sustainability of coexisting on-site sewage disposal and domestic water supply wells, from a nitrogen perspective where aquifers are unconfined and thin. At higher population densities centralised water supply or sanitation schemes will become a necessity. Note that Equation (1) based on nitrate concentration, is a tighter constraint on the potential for development than the quantity of water available unless per capita consumptions exceed an enormous 800 cubic metres/year (for all rates of recharge). Pathogen effects are considered below from the point of view of well-head protection.

well-head protection

Minimum separation distances for on-site sewage disposal and water supply wells may be determined based on the travel time between them, and on the rate of decay of pathogenic organisms.

Yates *et al* (1986) described a geostatistical approach to calculating septic tank setback distances. This was based on kriging to interpolate between points at which groundwater samples were taken, dosed with MS-2 coliphage (as a model virus), and decay rates calculated. The separation distance was determined by the distance travelled in the aquifer with estimated hydraulic conductivity and porosity, for the average hydraulic gradient, over the time required for a 7-log reduction in viral numbers. The effects of pumping from wells on hydraulic gradients were ignored. This resulted in separation distances of between 15 and 150 metres for an alluvial aquifer at Tuscon, Arizona. Viral decay rates were uncorrelated beyond a distance of 6km.

Most states in the USA have imposed minimum separation distances of 10 to 90 metres (Yates *et al* 1986), with the median around 15 metres. Where soils are highly permeable and water tables are shallow and fluctuate, separation distances of 30m are not considered safe (McGinnis and deWalle, 1983). From the incidence of disease outbreaks (reported in Section 2) these separation distances are frequently inadequate to prevent pollution of water supply wells. The Yates *et al* approach is intended primarily to demonstrate that separation distances will depend on viral attenuation rates which may vary at least spatially, and possibly temporally (with acclimation). In their example measured attenuation rates varied from 0.07 to 0.7 log PFU/day.

In small tropical islands data is likely to be scarce, but some measurements of pathogen (or MS-2 coliphage) decay would provide a valuable first step. For example, such measurements could be made using McFetter's cells (chambers with membrane walls which allow water but not viruses to pass through) which are suspended in wells. This combined with hydrogeological information, and accounting for drawdown around an adjacent well at any specified distance, would provide the best possible measure for minimum separation distance if the aquifer was homogeneous. Modelling, such as described by Yates and Yates (1991), but adapted to deal with flow and bacterial transport between a source and a water supply well, could prove valuable, at least as a demonstration, possibly as graphics on video, to enable communities to visualise the way pollution occurs.

In coral, limestone, and fractured rock (eg basalt) aquifers, short circuiting of flow via preferential flow paths may occur, and travel distances for attenuation to acceptable levels may be so long as to severely limit development. Under these circumstances, which may commonly occur, the best form of control is to minimise emission of pathogens at their source, the on-site sewage disposal system. Techniques are currently being developed to model transport of microorganisms and solutes in radial flow within dual porosity media. Such models are unlikely to be used to design separation distances due to a lack of information on the presence, dimensions, and connectivity of macropores, but graphical displays of the outputs of these models may provide a strong stimulus for communities to deal with sewage pollution at source. They could also show the extent of contamination possible under worst case scenarios.

In Europe the 50 day transit time guideline (Waegeningh, 1985) is subject to local interpretation of groundwater flow direction and velocity to map the well-head protection zone. In the absence of other information, this provides a principle upon which well-head protection could be based, and protection areas are mapped and refined as information on water quality in wells, public health, and hydrogeological conditions become available.

Urish and Ozbilgin (1989) referred to the particular problems of coastal communities (on Rhode Island) where tidal fluctuations can be important in determining groundwater flow directions and the shape of contaminant plumes emanating from pollutant sources. Fluctuating flow fields in general accelerate dispersion of contaminants, and expand the width of pollution plumes. This may therefore affect the shape and size of well-head protection zones.

design and maintenance of on-site sewage disposal

The design of sanitation has a significant effect on the potential for groundwater contamination, as described in Section 3. In general septic tanks give superior protection of groundwater than pit latrines due to the greater thickness of the unsaturated zone available beneath locations where leaching of effluent occurs. For septic tanks the spatial extent of the leaching field is larger assisting dilution in the underlying aquifer. Use of water as a flushing agent also dilutes initial concentrations of contaminants. Newer latrine designs, such as self-composting toilets, which enable exothermic aerobic digestion of wastes, have the potential to allow significant gaseous losses of nitrogen, disinfection of pathogens, and reductions in the quantity of leachate due to evaporation. However no literature was found to verify the extent and reliability of these processes nor to assess the impacts on groundwater quality. Encouragement of these designs should be await an investigation of their environmental performance with respect to well-designed septic tanks.

When siting and designing sanitation facilities every effort should be made to ensure that seepage does not enter the water table directly. Therefore where water tables are shallow, even intermittently, latrines which could be inundated should not be considered an acceptable sanitation system. Mounding may be required in order to provide an adequate thickness of unsaturated zone beneath the septic tank drain field. In fine sands a minimum of 60cm above peak water table levels should be provided. Increasing this thickness will substantially increase the level of protection for nearby water supply wells. McGaughy (1975) suggested among other schemes that the leachate of septic tank effluent after its passage through sand beds could be collected and applied to the soil surface, where plants could take up nutrients and water, and the whole of the unsaturated zone was available for further polishing of infiltrating water.

Keswick (1984) reported that contamination of groundwater occurs because septic tanks fail where they are improperly installed and poorly maintained. Septic tanks (and latrines) need maintenance. When they become full of sludge any treatment afforded by residence time in the tank is lost, and sludge can clog the perforated pipe and cause effluent to back up in the septic system, and continuous rather than intermittent seepage through the tile drains occurs. These conditions favour groundwater contamination. Sludge removal at intervals, typically 2 to 10 years, prevents this problem, but creates a potential new problem of how to dispose of the sludge. This can be incorporated with compost in garden soils but should be spread at a sufficiently low rate, and not in close proximity to water supply wells.

When a pit latrine fills a new latrine is dug and the old one is covered. This should prevent runoff into the pit. If subsidence occurs, or the cover fails, any depression should be filled with low permeability material and the pit recovered. This very simple task, and ensuring that each new pit is constructed so that its base is at least one metre above the highest groundwater level will do much to prevent needless contamination from pit latrines.

Use of chemicals for unclogging septic tanks has been reported to cause groundwater pollution. Noss (1989) warned against the use of chlorinated organic solvents which could contaminate wells, and had been banned from use in septic systems in several states. Bicki and Bettler (1988) found that use of hydrogen peroxide resulted in rapid oxidation of organic nitrogen and ammonia and resultant nitrate concentrations were exceedingly high. Alhajjar *et al* (1987) and Mitchell and Ashworth (1985) reported that detergents and fluorescent whitening agents degraded rapidly and were not useful as tracers of septic tank effluent in groundwater. Therefore it is suggested that maintenance by desludging should be performed sufficiently frequently that chemical procedures for unclogging septic tanks and tile drains are not required. If such treatments are needed only biological cleaners should be applied (Noss, 1989) as these have been found to degrade rapidly.

Where sewage systems are installed there are various guidelines for the reuse of wastewaters, such as *USEPA (1977)*. These limit application rates so that concentrations of salt, nitrate, and pathogens are at acceptable levels for the beneficial uses of the aquifer. More recent Australian guidelines, developed under the *National Water Quality Management Strategy,* are in draft form and include; groundwater protection (1992), and wastewater reuse (1995).

monitoring

The planning, operation, and analysis of groundwater monitoring programs are described at length by Canter et al (1988). Assuming that the budget will initially be quite limited, it is important to have a clear focus for the monitoring program. This will depend on the actions which can be taken if contamination is detected. Initially such a program may revolve around objectives such as protection of public water supplies, then of private supplies, and finally to demonstrate the effects of alternative methods for controlling pollution sources.

Monitoring would commence with groundwater and sewage analyses to determine the most prospective indicators of the contamination of water supplies by sewage (and other potential pollutants), and the parameters most important for health. Selection of parameters for monitoring would also take account of the cost of analyses, and their reliability including effects of sample storage. It is likely that a set of surrogate variables could be identified, which could be monitored and analysed locally, and used as a screen to minimise the number of more sophisticated and costly analyses. Distance and direction from the nearest effluent disposal facilities (current and historical), their type, depth to water table, and type of aquifer, should be recorded at the time of sampling.

Implementation of such a program, covering all water supply wells, is likely to have greater consequences than studying in detail the fate of contaminants from an individual septic tank or latrine alone. In the latter case, extrapolation may be confounded by unknown variations in hydraulic properties, including heterogeneity within aquifers. However, an understanding of the impacts of source features which can be controlled (eg height of septic tank tile drains above peak water table, hydraulic loading rate of tile drains, effect of placing a blanket of loam or organic material between the tile drains and the watertable, or of planting vegetation above the tile drains) on the groundwater quality in the immediate vicinity would be valuable in helping to rectify current problems, and ensure that any new septic systems would be designed to improve groundwater quality protection. In particular, there appears to be a lack of information on the environmental effects of self-composting latrines.

treatment of sewage or water supply

As population densities increase, with corresponding increases in the density of on-site sanitation systems, mean nitrate concentrations in groundwater will increase and ultimately centralised sewage collection or more sophisticated treatment methods will be required. Threshold population densities for this changeover are reported above. In general, however, the cost of establishing a centralised water supply system are cheaper than the cost of establishing a common effluent system.

Disinfection is feasible for public water supplies, and methods, such as chlorination, ozonation, and ultra-violet (UV) disinfection, are beyond the scope of this report. Denitrification however is a relatively expensive process. Small scale UV disinfection systems for household supplies are becoming cheaper and simpler to operate, but in comparison with piping costs, or costs of increasing rainwater storage, are possibly economic only in exceptional cases. Small volumes of drinking water can be disinfected with tablet treatments or by boiling. Considering the potential investment which would be required in treatment systems for water supplies, substantial effort in prevention of contamination is warranted.

public education

Provision of information to communities about the consequences of sanitation on the quality of drinking water and public health, is basic to health, science, and environmental education. Community awareness and understanding is an important step towards finding acceptable solutions to existing problems, and prevention of future problems. It is hoped that this report would be of value to those who need to develop long-term plans for siting of new developments, developing guidelines for minimum lot size (with and without common effluent schemes), and conserving and developing water resources. The means of communication of the essential information to villagers concerning siting, design, maintenance and monitoring of domestic sanitation and water supply systems, and public health, will need to be determined at local level. It has been found that graphical displays and videos are effective vehicles for learning. Combining simple models with video-style outputs on PC screens may provide a generic tool which could be simply adapted to local situations using local expertise.

7. Conclusions

Sanitation systems with on-site disposal to unconfined aquifers which are used as drinking water supplies are notorious for their impacts on public health, primarily through pollution by pathogens. These problems are particularly severe on low lying tropical islands, where water tables are shallow, soils and aquifers are highly permeable, well depths are limited by underlying saline groundwater, and options for locations of water supply wells and septic systems may be constrained.

The review found that septic systems are preferable to latrines for groundwater quality protection, especially where water tables are shallow. However no information was found on the impacts of aerobic self-composting latrines on groundwater, and this would be most valuable to determine any conditions under which such systems are superior.

The thickness of the unsaturated zone through which septage leaches was found to be the most significant determinant of groundwater contamination. Groundwater contamination by pathogens has been recorded more than 1 km from sanitation systems. Generally guidelines of 30 metres separation between domestic septic tanks and water supply wells have been applied and found to give inadequate protection from pathogens, especially in permeable aquifers. A fifty day residence time in the subsurface is needed to provide effective pathogen removal for drinking water. Nitrate concentrations may be a concern, and can dictate the threshold population density beyond which common effluent schemes are needed.

Investigation and monitoring methods and their effectiveness in meeting various monitoring objectives were evaluated. It was found that wastewater residues such as nitrate and sodium can be effective determinants of the extent of groundwater contamination by sanitation systems. Degradable organics, and organic dyes are poor tracers of pollution by sewage, but bromide has been used effectively to measure travel times. Monitoring programs based on pathogens and surrogate variables are the best indicators of the current and potential incidence of water supply well contamination.

A series of control measures spanning from sanitation planning; well-head protection; design, maintenance and monitoring of on-site sanitation; treatment of sewage and water supplies, and public education were discussed. These provide a range of measures which can be adapted by local communities to meet their needs for safe water supplies, and assurance of this, within reasonable costs.

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