# The fate in the subsurface of contaminants associated with on-site sanitation: A review

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## Abstract

One of the possible solutions to the problem of providing all South Africans with access to adequate sanitation within the constraints of limited resources is the use of on-site sanitation. However, concerns exist that widespread use of these systems will cause subsurface migration of contaminants, ultimately resulting in disease transmission and environmental degradation. Although some work on the potential pollution from on-site sanitation was carried out in the early 1980s, there has been a need to update this work in view of its importance in the current debate.

This paper reviews the subsurface movement of contaminants associated with on-site sanitation, with a view to establishing a clear definition of the pollution risk associated with these systems. Although the literature was found to be highly fragmented, it was possible to establish certain principles that are consistent with published results.

The risks associated with migration of phosphates, helminths and protozoa appear minimal, with phosphates undergoing significant adsorption, particularly by clayey soils, and physical filtration restricting movement of helminths and protozoa to very small distances. Although bacteria, and more particularly viruses, are much more mobile, this has been found to be a problem only when either the water table or a horizon of fractured or karst bedrock occurs at shallow depths. Mobility of viruses and bacteria does not appear to be problematic when the latrine is underlain by a layer of unsaturated soil.

The topic of greatest uncertainty was the pollution risk posed by elevated nitrate levels. Nitrates are not adsorbed, or physically retarded in any way by soil, and may therefore travel large distances in soils with high hydraulic conductivities. Questions remain as to the effectiveness of denitrification processes, particularly whether or not they occur to a significant degree in the unsaturated zone.

## Introduction

### Objective of the paper

With the need to address the requirement of providing access to adequate sanitation facilities for the approximately 21 m. South Africans (DWAF, 1994) who are currently without such facilities, it is clearly going to be necessary to minimise the cost of these systems whilst ensuring that certain standards of quality are met. It is likely that on-site sanitation will be used to a significant degree in meeting these requirements. However, a problem that is often raised in relation to the use of on-site sanitation is the perceived pollution of groundwater that is associated with these systems (The term "pollution" or "pollutant" is used where the concentrations exceed acceptable levels. Otherwise the term "contamination" or "contaminant" is used). A newspaper article, reporting on a judgment of the Pretoria Supreme Court which dismissed an application by two residents' associations to have the Transvaal Provincial Administration (TPA) interdicted from settling the Zevenfontein community at Diepsloot north-west of Johannesburg, carried the following extract (*Saturday Star*, 1993):

> "...The residents' associations had said that the settlement process would unlawfully interfere with their rights, causing, among other things, increased air and water pollution, and an increase in crime...."

It needs to be pointed out that all types of sanitation (both on-site and off-site systems) pose a pollution threat. A key difference between the two is that any pollution from on-site sanitation will be diffuse whereas pollution from water-borne sanitation will be a point source. Experience within Umgeni Water's catchments with regards to water-borne sanitation has indicated that it can cause far worse environmental pollution problems than even basic unimproved pit latrines (Terry et al., 1993). Similar conclusions may be drawn from results presented by Hoffman (1994), who recorded very high levels of both phosphates and *E. coli* in the Kaalspruit immediately downstream of Tembisa (up to 23 mg/*ℓ* as P, and 900 000 counts/100 m*ℓ* respectively). This was attributed to blockages and overflows emanating from the Tembisa sewage reticulation system, resulting in river pollution close to Tembisa. Further downstream, where the catchment of the Kaalspruit included the informal settlement of Ivory Park, these values were much lower (up to 8 mg/*ℓ* as P and 350 000 counts/100 m*ℓ* respectively). Natural processes of purification that occurred in the river resulted in a drop in the level of these contaminants between Tembisa and Ivory Park. Of importance is the observation that Ivory Park did not cause a further rise in the levels of these contaminants. Nevertheless pollution from on-site sanitation remains a concern.

When considering pollution from on-site sanitation, one needs to define the problem clearly. There are a number of different aspects to what is a complex problem:

- Human excreta contain a number of different contaminants
- Our concern is for two different potentially harmful effects, each with different responses to the contaminants, namely that in sufficiently high "doses", these contaminants are potentially hazardous to:
  - human health and/or
  - the natural environment
- In order for a "contaminant dose" to be "administered" (i.e. to infect a host, be the host a person or the environment), these

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contaminants must be transmitted via some or other route from the source (i.e. the on-site sanitation system) to people or to the environment.

A key route of transmission to both people and the natural environment is via the subsurface.

The objective of this paper is to review the subsurface movement of contaminants associated with on-site sanitation (that has been reported in the literature), in order to understand clearly how they move and what factors affect their movement, with the ultimate objective of establishing an unambiguous definition of the potential risk of pollution associated with on-site sanitation systems.

Although some work on the potential pollution from on-site sanitation was carried out in the early 1980s, there was a need to update this work in view of its importance in the current debate.

## Difficulties in defining the pollution

There has been a tendency to treat pollution from on-site sanitation as a single entity, in the sense that the question that seems to be asked is: "Is there or isn't there a pollution risk from on-site sanitation?". Such a poorly posed question does not adequately address the nature of the problem. Pollution from on-site sanitation is made up of a number of different and complex components:

- There are different contaminants, which have different characteristics, and whose mobility is affected differently by conditions in the subsurface.
- There are different mechanisms of movement of the contaminants and the contaminants themselves are subject to alteration. There are different processes which affect these changes, which are usually temporal in nature.
- The subsurface conditions through which the contaminants travel are not uniform; perhaps the most critical distinction being between the vadose or unsaturated zone and the saturated zone.

To add to these difficulties, monitoring in the subsurface zone, particularly in the vadose zone, is difficult and expensive. Probably as a result of this, literature on the subject is limited. There are two aspects to this:

- There is simply a shortage of any field data.
- The data that are available are often not comprehensive. It is therefore difficult to separate out all the effects referred to above.

## Approach to the problem followed in this study

How does one deal with these difficulties? There are two ways of approaching a problem as complex as this:

- Global/"black box" approach, where one reports overall movement of contaminants
- Rational approach, where one tries to isolate all the factors affecting contaminant movement, measure them individually and sum them

Data will be reported for both of these two approaches.

Furthermore, inasmuch as it is possible to extract certain generalisations as to how the different contaminants behave, this will be done at the end of the paper.

## On-site sanitation systems used in South Africa

Before discussing the findings reported in the literature, it is useful to provide a brief description of the various types of on-site sanitation system, (see Kalbermatten et al.(1982) for a more comprehensive description). On-site systems refer to those systems where the sanitary wastes are not transported to an off-site location for primary treatment.

In South Africa three types are more generally used:

- VIPs (ventilated improved pit latrines)
- LOFLOS (low flush on-site sanitation systems, also commonly referred to as aquaprivies)
- Septic tanks

Both VIPs and LOFLOS are similar in that they receive only human exctreta from a household (with occasional grey water addition); septic tanks on the other hand receive both grey water and human excreta.

A build-up of sludge in these systems inevitably means that they require periodic desludging. This sludge may be treated and re-used, or disposed of off-site. Problems associated with sludge treatment or disposal are not addressed in this paper.

Of these three types, this paper considers primarily VIPs and LOFLOS. Septic tanks are considered for comparative purposes (because it is well established as a technology and is widely used both in South Africa and around the world; however septic tank systems require a full water supply, whereas VIPs and LOFLOS do not. Consequently the cost of septic tanks is of the same order of magnitude as full water-borne sanitation).

## Contaminants that originate from on-site sanitation systems

Human excreta disposed of to on-site sanitation systems are the same irrespective of the system used, although contaminants discharged to the subsurface may differ if additional wastes (such as grey water) are disposed of to the system. Furthermore, the concentrations of contaminants entering the subsurface will be influenced by the degree of treatment taking place within the particular system. The understanding of these treatment processes is not sufficiently clear from the literature at this stage.

The composition of human excreta is typically as given in Table 1.

**TABLE 1**
**COMPOSITION OF HUMAN EXCRETA (AFTER GOTAAS, 1956)**

| | Approximate composition (per cent of dry weight) | |
|---|---|---|
| | Faeces | 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 |

Inorganic salts derived from on-site sanitation systems have not been identified in the literature as a significant component of contamination, and furthermore are considered to be of minor importance in domestic waste-water treatment (Ekama and Marais, 1984).

In addition to those in Table 1, there are other groups of contaminants which may be found in domestic waste-water:

- refractory organics, which include:
  - surfactants (e.g. detergents), particularly the nonionic variety that have seen a rapid increase in usage in recent years in place of the previously popular anionic varieties. Nonionic surfactants are potentially problematical because they are considerably less biodegradable than their anionic counterparts.
  - pesticides and agricultural chemicals.
  - cleaning solvents, eg benzene, toluene and carbon tetrachloride, which originate from sources such as toilet bowl cleaners, paint brush cleaners and stove and oven cleaners.
  - organics produced by processing of natural organics, (e.g. trihalomethanes).
  - mineral oils (e.g. engine oil, PCB's)
- toxic inorganic ions
  - heavy metals

This paper does not deal with contamination from refractory organics or toxic inorganic ions for two primary reasons:

- Reported investigations of their occurrence in waste-water are a recent development and there is not sufficient clarity on the magnitude of the problem as yet (Viraraghavan and Hashem, 1986; Zoller, 1992; 1993)
- They do not occur as a matter of course in domestic wastewater, particularly from low-income communities, but may be present where inappropriate disposal practices exist. It is tentatively suggested that these problems can be addressed by a combination of appropriate waste management systems, user education and regulatory mechanisms to control the use of toxic substances.

The contaminants of concern may therefore be divided into two broad groups: microbiological and chemical. The microbiological contaminants are typically viruses, bacteria, protozoa and helminths. The primary chemical contaminants are nitrogen and phosphorus. These contaminants each pose a risk to human health and/or to the environment.

## Mechanisms of transportation and characteristics of contaminants affecting their mobility in the subsurface

Implicit in this study is the assumption that one is concerned about contaminant transport to, and accumulation in, the groundwater. Systems which use more water will cause the contaminants to travel further, all other factors being equal, and this needs to be borne in mind when assessing the potential pollution impact of different types of on-site sanitation system.

The subsurface movement of contaminants will not exceed the rate of movement of the contaminated water, whether in the unsaturated or saturated zone, except in extremely exceptional circumstances. However, it is not sufficient to merely know the rate of subsurface water movement. Knowing that an influent (that may be contaminated) from a particular location will eventually reach a drinking-water well does not necessarily mean that the well will become contaminated. There are many processes, both physical and chemical, that serve to remove contaminants from the water during its movement through the subsurface. In the following sections the more important characteristics of contaminants that govern the degree to which this attenuation will take place are discussed.

To reach the groundwater, travel through the unsaturated zone will usually be necessary. Once a particular contaminant has reached the groundwater, the rate of transport will be much greater (than in the unsaturated zone), and movement will be in the direction of the regional groundwater movement. Micro-organisms may be carried up to several hundred meters in this zone. Vertical restriction of drainage by an impermeable soil layer or bedrock may lead to saturated flow conditions in a zone just above the contact between the permeable soil and the impermeable layer. In a situation similar to this, McCoy and Hagedorn (1979) recorded bacterial movement at rates of between 1 and 10 m/h in a strongly sloping silt loam.

An interesting observation made by Romero (1972) was that the contamination travelled primarily in a thin sheet at the surface of the saturated zone. He found no evidence of dispersion, and highlighted the benefit of drawing water from great depth in screened wells, where much lower potential for contamination exists.

It is often assumed that the subsurface soil conditions are homogeneous and continuous. A problem that has been identified in certain soil profiles is that of so-called macropore flow. This refers to flow that may occur along channels formed by decomposed roots, or along fissures in rock or residual soil profiles, amongst others. Once again advection is the primary means of transport, although flow is now along discreet "channels", rather than through a porous continuum.

While it is difficult to be categorical in general terms about which of these contaminants are the most mobile, and thus likely to travel the furthest in a particular subsurface environment, there are certain specific characteristics of contaminants which affect their transportation. It is possible to be more categorical about these e.g. for helminths, protozoa and bacteria it can be said that their mobility will be inversely proportional to their physical size.

Mobility comprises two components:

- the physical movement of the contaminants themselves.
- the growth or degradation of the contaminants irrespective of movement

During the movement of contaminated water through this zone a number of processes may occur that alter the concentration and composition of the contamination. Retardation processes such as complexation, sorption, precipitation, and solution should be accounted for, where appropriate, when trying to quantify the magnitude of groundwater contamination that may occur. The subsurface transport of contaminants is therefore not merely an advection/diffusion process. However, it is apparent from the literature that the magnitude of the effect of these retardation processes has not been quantified to any significant degree.

### Microbial contamination

Microbial contamination is usually divided into four categories, namely the four different groups of organisms:

- Viruses
- Bacteria
- Protozoa
- Helminths

There are two major considerations affecting their mobility:

- Physical size
- Chemical and other processes

### Physical size

The large size of helminths and protozoa (typically >25μm), which is the same size as silt particles, will usually result in highly efficient physical filtration of these contaminants by the soil below and adjacent to the source. Exceptions could be coarse sand deposits, or fissured soil conditions. The effectiveness of a particular soil in filtering these contaminants can be evaluated by using the conventional Terzaghi and Peck filter criteria (1967). Bacteria and viruses, however, are of significantly smaller size, with some examples given below:

| | |
|---|---|
| *Escherichia coli* | 0.5 μm x 1.0 μm x 2.0 μm |
| *Salmonella typhosa* | 0.6 μm x 0.7 μm x 2.5 μm |
| *Shigella sp.* | 0.4 μm x 0.6 μm x 2.5 μm |
| Psittacosis virus | 0.25 μm dia. |
| Bacteriophage virus | 0.1 μm dia. |
| Poliomyelitis virus | 0.01 μm dia. |

The bacteria in the above list may be filtered out by soil that is predominantly clayey, i.e. clay-sized particles would be small enough to filter out most bacteria. The question remains as to how much of the soil must be clay-sized in order for the filtration process to be completely effective. Better understanding of this can only really be achieved by appropriate laboratory lysimeter testing.

The contaminant of most concern in terms of transportability through soil is then clearly the range of water-borne viruses that may be derived from on-site sanitation. Viruses are too small for even the finest grained clays to have anything but a slight filtration effect. One must look to other processes, such as adsorption, for effects that will attenuate virus concentrations in the subsurface zone. A mitigating factor is that viruses cannot survive outside a host, and therefore generally have a very low survival time, particularly when compared with bacteria.

### Chemical and other processes

It appears that the removal of viruses in the subsurface region depends almost entirely on the process of adsorption (the process whereby foreign atoms or molecules become attached to the surface of e.g. a soil particle, thus lowering the free energy of the surface).

What is of importance is that virus adsorption cannot be considered a process of complete immobilisation of the virus from the carrier liquid. Therefore although adsorption is effective in decreasing the concentration of a virus, it is essentially a reversible process, and adsorbed viruses may be flushed out of a soil by heavy rains, or similar events. For example, Wellings et al.(1974) recorded a burst of virus levels in groundwater obtained from both 3m and 6m deep wells at a waste-water land disposal site following a heavy rainfall. Whilst recognising this problem, it should be emphasised that viruses cannot reproduce in soil and have a finite survival time, and simply by fixing the virus for a certain time the concentration of the virus will have been decreased. Since virus adsorption is likely to be negligible in the saturated zone, maximisation of effluent residence times in the unsaturated zone is the key factor affecting the removal and elimination of viruses.

In general, adsorption of viruses is best in clayey soils, and is largely due to electrostatic double-layer interactions and van der Waals forces (Drewry and Eliassen, 1968; Tim and Mostaghimi, 1991). In laboratory tests of a range of soil types, Bitton et al. (1979) found that Echovirus 1 was least adsorbed by a "sandy soil". The **rate** at which adsorption occurs varies with the type of virus, and for a particular type of virus will vary with the rate of water movement. A further point worth noting, and that is of importance when considering ways of modelling subsurface virus movement, is that all viruses are not biochemically identical and adsorptive behaviour may not be similar under identical environmental conditions for all viruses.

It was noted above that, in general, bacteria are larger than viruses, and are much more efficiently filtered by all soils. This does not mean that emphasis should be placed on preventing only the movement of viruses, since e.g. bacteria have the ability to multiply outside the host, which viruses do not have. In addition, their survival time in a soil may be significant, as shown in Table 2. In general it appears that 2 to 3 months is sufficient time for bacteria to be reduced to negligible numbers once they have been applied to the soil, although exceptions have been reported (Rudolfs et al., 1950).

**TABLE 2**
**TIME OF SURVIVAL OF FAECAL BACTERIA (AFTER PATTERSON ET AL., 1971)**

| Type of organism | Survival time | | |
|---|---|---|---|
| | Septic tank | Soil | Other |
| *S. typhosa* | | | 52 d |
| *S. typhosa* | | | 165 d |
| *S. typhosa* | 27 d | 25-41 d | |
| *S. typhosa* | 24 d | | |
| *E. coli* | | | 2 yr 8 mon |
| *E. coli* | | 2 yrs | |
| Coliform bacteria | | 3 mon | |
| Coliform bacteria | | 4-7 d | |

The question of developing a predictive capacity for determining the likely movement of viruses and bacteria is obviously extremely difficult. Not only will it be necessary to characterise the soil profile and its hydraulic conductivity parameters, but some account of factors such as temperature, soil pH, moisture retention capacity, and organic matter in the soil may be necessary. The clay content of the unsaturated zone would, however, appear to be the single most important parameter when attempting to develop a predictive capacity.

### Chemical contamination

The chemical contaminants of greatest significance are:

- Nitrogen
- Phosphorus

Most soils (exceptions being coarse, clean gravels) appear to have the ability to immobilise (by adsorption) phosphate very effectively within a very short distance of the contamination source (Beek and De Haan, 1973; Steenvoorden, 1976). Phosphate contamination is therefore not further considered in this paper.

In view of the potential health hazards associated with nitrate-rich water, it is surprising that so little has in fact been done to characterise and quantify the amount of nitrate contamination that may result from on-site sanitation facilities. Information in the literature is rather scant and incomplete.

Various attempts have been made to predict the subsurface movement of nitrates. The most common (and most conservative) approach has been to treat nitrate as a conservative species, i.e. no denitrification is accounted for (Oakes et al., 1980). Nitrogen removal mechanisms such as volatilisation, adsorption, fixation, biological denitrification, incorporation into cell tissue, removal by vegetation, and leaching, are ignored. The paucity of experimental data in the literature on these topics means that modelling of the complete subsurface denitrification process is unlikely to be attainable in the near future.

The attenuation of nitrates in the subsurface does not depend on physical processes such as filtration, but rather on microbiological processes. Nitrates and other mobile contaminants such as chloride also have a very low affinity for sorption to solid particles. Denitrification occurs under anaerobic conditions, as bacteria couple oxidation of organic carbon with nitrogen reduction. According to Kinzelbach et al. (1989) in aerobic aquifers nitrate behaves, to a good approximation, like an ideal tracer.

The required conditions for denitrification are the presence of denitrifying bacteria, existence of reducing conditions, and the availability of an adequate supply of readily biodegradable organic carbon. Denitrification only occurs in anaerobic conditions. This does not, however, necessarily mean that it is restricted to the saturated zone. It can occur in the vadose zone, since isolated, local "pockets" of saturation may occur. A study by Starr and Gillham (1989) showed that under certain conditions, if there were sufficient labile (i.e. able to participate in very fast reactions) organic content present in the subsoil, the dissolved oxygen would be reduced, causing localised anaerobic conditions. Based on these findings, the authors stress the importance of maximising the residence time in the relatively organic-rich vadose zone. The organic content of any soil is, however, finite. In a study by Rödelsperger (1989), decreasing denitrification processes in an aquifer were attributed to exhaustion of the natural supplies of organic substances. Another problem associated with nitrates in the subsurface is that a significant rainfall after an extended dry period may flush nitrates that have accumulated during the dry period out of the soil.

## Hydrogeological factors affecting contaminant transportation

The permeability (or hydraulic conductivity) of the soil between a pit or soakaway and the groundwater level is obviously of paramount importance in determining the possible extent of contamination due to such facilities. Soil permeability is, however, notoriously difficult to measure, and varies over many orders of magnitude for different soil types. There are also many other problems, e.g. most natural soil profiles are to some extent heterogeneous, and may also have different hydraulic conductivities in the vertical and horizontal directions. Furthermore, it is usually difficult to obtain undisturbed, representative soil samples for carrying out laboratory tests, and recourse must often be made to field permeability testing. Unfortunately there are many different types of field permeability tests in current use, and they do not necessarily all give the same value. It has already been mentioned that the risk of groundwater contamination can be decreased by maximising the residence time in the unsaturated (or vadose) zone. Measuring the permeability of soil in the vadose zone presents an additional set of difficulties. This is because the permeability varies with the degree of soil saturation (i.e. the moisture content). The highest permeability occurs when the soil is fully saturated, and the permeability decreases as the moisture content decreases. There is no universally accepted technique for measuring this property, and it is in fact currently the subject of investigation world-wide.

An important factor in the prevention of contaminant migration, particularly bacterial contamination, is the particle size distribution of the soil. A well-graded soil will be a much more effective filter than a similar, but uniformly or gap-graded soil. The importance of this filtration mechanism has been recognised in many studies (Gerba et al. 1975), and it has often been noted that very efficient removal of bacteria occurs within the first few centimetres of the soil. For example, a study in Romania (Romero, 1972) showed that 92 to 97% of the coliforms were retained in the uppermost centimetre of the soil tested, and Gerba et al. (1975) suggest that "straining" of bacteria occurs right at the soil surface, and that a finer filter is gradually built up by accumulation of retained bacteria. This process has sometimes been termed "clogging", and it has even been claimed that, "until the clogged zone has been established, the pit latrine poses a potential source of pollution", (Taussig and Connelly, 1991). However, as pointed out by Lewis et al. (1980b), pore clogging may result in system failure in the form of surfacing of effluent. In a comprehensive study by Kropf et al. (1975), this was found to be improbable as long as the effluent contained minimal solid matter and grease. They found that the infiltration interfaces never become irretrievably clogged, but that the growth and die-off of the biomass filter reaches an equilibrium with the nutrients available in the liquid.

What then constitutes the ideal soil for minimising the potential for contamination as a consequence of on-site sanitation? Based on studies at the University of California, Richmond, Romero (1972) concluded that passage through 1 to 2m of coarse sand would provide acceptable quality drinking water. Similar emphasis on the suitability of coarse-grained soils for use of on-site sanitation systems has been put forward by Fekpe et al. (1992). They discuss a number of field percolation tests that were undertaken in Kumasi, Ghana, to determine the infiltration capacities of a range of soils. The more free-draining (and thus higher permeability) soils were classified as most suitable for on-site sanitation systems. This, of course, conflicts with the requirement to maximise the residence time in the vadose zone. Other workers (e.g. Taussig and Connelly, 1991) have expressed a preference for fine, "graded" soil below a pit latrine, with suggested thicknesses of 2 to 3m. Still another view (Lewis et al. 1980b) is that fine grained soils such as clays are most suitable. Stolzy and Fluhler (1978) found a correlation between clay content and the disappearance of nitrate due to denitrification, which is of course highly desirable. Muller (1989) substantiates this finding, and concludes that clayey soil is better for inhibiting nitrate contamination than is free-draining soil. There is thus obviously a conflict of viewpoints, with some workers attempting to satisfy one set of criteria (perhaps minimising bacterial movement), whilst others attempt to satisfy another (e.g.

| TABLE 3<br>SUMMARY OF VIRUS REMOVAL BY SOILS (AFTER GERBA ET AL., 1975) | | | | | |
|---|---|---|---|---|---|
| **Nature of fluid** | **Virus** | **Nature of media** | **Flow rate ($\ell$/min.m$^2$)** | **Travel (mm)** | **Percentage removal (%)** |
| Spring water | coxsackie | garden soil | unknown | 900 | 50 |
| Spring water | T4 | garden soil | unknown | 560 | 22 |
| Sewage effluent | polio 1 | soil high in iron oxide | unknown | 1 160 | unknown |
| Effluent | polio 1 | 0.65 mm $\phi$ sand | 112.5 | 200 | 82-99.8 |
| Tap water | coxsackie | sand | unknown | 700 | 0 – >90 |
| Tap water | polio 1 | unsat. sand | 1 000-2 000 | 600 | 99.5-99.9 |
| Oxidation tank effluent | polio 3 | sand, sandy loam | unknown | 320 | unknown |
| Tap water | polio 1 | coarse, fine sand | 0.4 | 600 | 1 – >98 |
| Distilled water with added salts | T1, T2 and f2 | Arkansas soil | 0.078 to 0.295 m$\ell$/min | 400-500 | >99 |
| Distilled water | polio 2 | latersol | 5-7 000 | 40-150 | 96-99.3 |
| Distilled water | T4 | latersol | 5-7 000 | 40-150 | 100 |
| Distilled water | polio 2 | cinder | 1.7 m. | 150-400 | 22-35 |
| Distilled water | T4 | cinder | 1.7 m. | 150-400 | 100 |
| Distilled water with added salts | polio 1 | dune sand | 1-2 m$\ell$/min | 200 | 44-27 |
| Distilled water with added salts | polio 1 | dune sand | 1-2 m$\ell$/min | 200 | 99.8-99.9 |
| Distilled water | polio 1 | sandy soil | unknown | 200 | 97 |
| Distilled water | T7 | sandy soil | unknown | 200 | 88 |
| Treated sewage | polio 1 | sandy soil | unknown | 200 | 98.6 |
| Treated sewage | T7 | sandy soil | unknown | 200 | 99.6 |

maximising denitrification).

The above discussion has focused on the migration of contamination through a soil profile that is essentially continuous. A situation which has proved to be potentially hazardous from the point of view of rapid travel times of contamination is when macropore flow may occur. This effect may be due to anything from root holes to fracturing of the bedrock, or soil fissures. Whatever the cause, the subsurface flow regime will be significantly altered by the presence of these macro-pores. As reported by Taussig and Connelly (1991), latrines founded on highly jointed Sibasa formation lava, 8m above the water table, caused extensive pollution, resulting in nitrate levels of up to 310 mg $NO_3/\ell$. (Nitrate levels are commonly expressed either as nitrate ($NO_3$) or as the concentration of nitrogen in that nitrate ($NO_3$-N). A nitrate concentration of 100 mg $NO_3/\ell$ is equivalent to a concentration of 22.6 mg $NO_3$-N/$\ell$. In this review nitrate concentrations are quoted as they appeared in the paper cited). In their study in Botswana, Lewis et al. (1980a) carried out tracer tests, and found that movement took place very quickly, with the tracer travelling through the 4m of fissured bedrock between the pit latrine and the water table in only 25 min. There was thus obviously very little time for natural elimination of faecal bacteria to occur. The foregoing has once again served to illustrate the confusing nature of the influence of hydrogeological parameters on the subsurface movement of contamination.

## Extent of contaminant transport reported in the literature

Instances of where the movement of contaminants has been recorded in the literature are discussed below. The movement of viruses, bacteria, and nitrates is dealt with separately. Although the discussion is not exhaustive, it gives a good indication of the order of magnitude of how far the various contaminants may travel, depending on other factors, e.g. hydrogeology.

### Reported movement of viruses

Most of the reported studies of viruses indicate that virtually complete die-off occurs within 3m of the source. Laboratory studies have shown that this is true even of movement through relatively permeable soil, e.g. studies at the University of California showed that complete virus die-off occurred within 0.75m to 1.0m in a "sandy soil" (Romero, 1972). Most field studies have tended to confirm these observations, as shown by the data summarised in Table 3.

It can be seen from this table that, except for one reported instance, the travel distance of viruses did not exceed 1m. It is not clear from the paper by Gerba et al. (1975) which of the cited cases are for saturated soil and which are for unsaturated soil. However, in soil column tests on both saturated and unsaturated soils reported by Powelson et al. (1990), it was found that little removal of an inoculated bacterium (MS-2 bacteriophage) occurred in the saturated column, whereas the unsaturated column was extremely effective. After the passage of as many as 18 pore volumes, the virus concentration maintained an exponentially declining profile with depth. At the end of the tests on unsaturated soil, the soil was removed, and number balances of the virus were carried out. Approximately 61% of the input viruses were accounted for, and the reduction was attributed to inactivation of the virus (in contrast, all the input viruses were accounted for in the saturated column tests). Even more dramatic are the results presented by Cochet et al. (1990), for laboratory tests on columns of silty sand subjected to intermittent flooding with sewage effluent. Virus removal in the first 20mm of the soil was 63 to 90% of the influent value. Although the information given in Table 3 on the soil particle size distribution is very limited, it is apparent that poorer attenuation is achieved in coarser soils (e.g. <50% for polio 2 virus removal by cinder, and for polio 1 virus removal by dune sand), which is consistent with the earlier discussion. Whatever the degree of saturation for the results reported in Table 3, it is clear that the subsurface movement of viruses is usually very limited, and the rate of removal by soil is high.

Although it appears from the foregoing that the potential for viral contamination of groundwater as a consequence of on-site sanitation is negligible, as reported by Lewis et al. (1980b), there are cases where outbreaks of illness have been associated with such facilities. According to Vogt (1961), an epidemic of infectious hepatitis was attributed to contamination of well water by septic tank effluent in Posen, Michigan. In another instance, poliovirus was isolated from a well responsible for a gastroenteritis outbreak in Michigan (Van der Velde, 1973). The pollution source was identified as a septic tank drain field located 43 m from the well. It is important to note that in both cases the wells were finished in limestone, and therefore the potential for rapid lateral movement of water could have been predicted. With the pressure to develop land underlain by dolomites in South Africa, particularly in the Gauteng province, the above reports serve to reinforce the potential dangers of building on such formations.

### Reported movement of bacteria

Studies of bacterial movement in the subsurface, as reported in the literature, are summarised in Table 4.

**TABLE 4**
**DISTANCE OF TRAVEL OF MICRO-ORGANISMS (AFTER PATTERSON ET AL., 1971)**

| Type of organism | Distance transported (m) | |
|---|---|---|
| | Vertical | Horizontal |
| *E. coli* | | 70 |
| *E. coli* | 3-9 | |
| *E. coli* | | 24 |
| *E. coli* | | 122 |
| Coliform bacteria | | 33-122 |
| Coliform bacteria | 0.6-0.9 | |
| Coliform bacteria | | 55 |
| Coliform bacteria | 46 | |
| *Clostridium welchii* | 2.1-2.4 | |
| "Lactose Fermenters" | 0.8 | 0.6 |
| "Bacteria" | 1.8 | 0.5 |
| "Bacteria" | | 610 |

These studies did not give information concerning the source of the contamination, and it is difficult to extrapolate this information to other sites. In the paper by Romero (1972), however, details of this kind are given, and it is instructional to review some of these studies. Baars (1957) studied the bacterial contamination associated with 1m deep pit latrines at a camping ground in the Netherlands. The groundwater level varied between

3 m and 4 m below surface, and drinking water was obtained from 40 m deep wells located within the camping ground. Loadings of 10 000 kg of faecal matter and 400 $m^3$ of urine were deposited each season. The underlying soil was a fine sand. In bacterial analyses of cores obtained directly adjacent to the tested pit latrines, *E.coli* could not be detected at depths exceeding 1.5 m. An important point to note is that the contaminants were washed below the bottom of the pit latrines by urine and rain water only, i.e. no water flushing was used.

Caldwell and Parr (1937) and Caldwell (1938) have reported on a number of studies of groundwater contamination caused by pit latrines extending **below** the water table. In one study, a 4.5 m deep latrine, located in sand and sandy clays, was accepting the wastes from a family of six. The latrine penetrated about 1.5 m into the groundwater, and was underlain by a stratum of clay. This factor, coupled with the water table gradient of 35 m/km, would have resulted in primarily lateral flow of the groundwater. In observation wells located at 1.5 m intervals up to 10 m from the latrine, faecal coliforms were detected at 3 m after 5 weeks of the start of the experiment. After 2 months faecal coliforms were detected in 90% of the samples at 8 m, and an occasional organism was detected at 10m. After about 7 months an interesting phenomenon occurred. A retreat of the bacterial stream practically all the way back to the latrine was observed. A similar experience was reported by Brown et al. (1979), who monitored water quality at a depth of 1 200 mm below septic tank soakaways in 3 different soil types. Shortly after application of sewage effluent had begun, faecal coliforms were detected at levels up to 5% of input concentrations. However, these values rapidly decreased, and in the second and subsequent years zero coliforms were detected.

The above phenomenon has been attributed to so-called soil "self-defense" mechanisms. It is more likely a manifestation of the observation of Romero (1972), that the nature of the soil immediately in contact with the contamination largely governs how far it will travel. As the soil immediately in contact with the source becomes clogged due to filtration of solid particles, the grading of the soil will effectively be altered, perhaps finally resulting in complete filtration of bacteria. This could also be what Lewis et al. (1980b) meant when they observed that a sterile soil first has to "mature" before it becomes a very effective bacteria filter.

In a second study, reported by Caldwell (loc.cit.) a latrine overlying beds of fine sand with some coarse sand and fine gravel, extended to a depth of 2.5 m. These sediments were also underlain by a clay stratum. The water table was between 1.5 m and 2 m deep, and the water table gradient approximately 6 m/km. The contaminant source was once again the faecal matter from a family of six. Observation wells were located at 3 m intervals up to a distance of 24 m from the latrine. Significant numbers of faecal coliforms were initially carried the full 24 m, but at the termination of the experiment (the time period was not reported) the length of the faecal coliform stream had been reduced to some 16 m, where only an occasional faecal coliform was detected.

In a more recent study, Viraraghavan (1978), found high concentrations of indicator organisms at horizontal distances of 15 m from a septic tank tile, the bottom of which was located at a depth of 0.6 m. The soil at this site consisted of sandy clay for about 0.6 m, underlain by clay with a low sand content (i.e. a decreasing permeability with depth). At the time of the test, the groundwater level was 0.15 m below the bottom of the trench. The volume of source material was not given. Although in this instance the latrine did not penetrate the groundwater, the horizontal extent of the contamination was similar to the above two cases, probably because of the additional water associated with a septic tank as opposed to a pit latrine.

An extensive field study on the movement of septic tank effluent through unsaturated silty sand has been reported by Andreoli et al. (1979), who found almost complete coliform removal within 0.6m of the source of contamination. Further evidence that movement of bacteria from pit latrines that are constructed above the water table can be expected to be minimal, is provided by the results of a study in Maseru, Lesotho, reported by Lister and Stewart (1984). A large number of test pits were dug adjacent to, and immediately down-gradient of two pit latrines. The soil profile consisted of a permeable silty sand upper layer of 0.3 m to 0.45 m thickness, overlying an impermeable clayey lower horizon. Despite the fact that some of the down-gradient test pits were only 1 m from the pit latrines, tests on soil samples recovered from the test pits produced zero readings for faecal coliforms, *Salmonella*, and *Streptococci faecalis* bacteria. Provided that additional water (e.g. sullage) is not poured directly into the pit, it appears that this type of system may be well suited to minimising transport of contaminants within the subsurface.

In general, it appears that as long as there is a sufficient depth of intact, unsaturated soil between the source of the contamination and the groundwater, bacterial contamination should not be a major problem. There is no consensus on exactly what constitutes "sufficient depth", and there is a need to establish appropriate guidelines. This is not addressed in the present paper.

## Reported movement of nitrates

A particular requirement for quantifying the degree of nitrate contamination due to on-site sanitation is the evaluation of background levels, since elevated background levels can result from a range of activities. As an example, a study by Schmidt (1972) showed widely fluctuating nitrate levels, with some values as high as 155 mg $NO_3/\ell$ (compared with World Health Organisation standards of 45 mg $NO_3/\ell$). These elevated, *in situ* nitrate levels were attributed to farming activities. Even higher levels were reported for soil under livestock feedlots (Smith, 1967), who found amounts of nitrate of 150 to 200 mg $NO_3/\ell$ of soil (and therefore much greater concentrations per litre of soil moisture). In a more recent study in Venda (Taussig and Connelly, 1991), nitrate levels of >150 mg $NO_3/\ell$ were measured up-gradient of the village under study, and were located in large cultivated lands. High nitrate levels are, therefore, not necessarily such good indicators of contamination from on-site sanitation as, for example, are bacteriological indicators, and care must be taken to obtain representative background readings.

There are, however, instances of nitrate contamination that have been reported in the literature that were directly attributed to on-site sanitation systems. In a densely populated low-income residential area of Delaware (USA), where only septic tanks were in use, 28% of the groundwater supplies were found to have nitrate concentrations exceeding 17 mg $NO_3$-N/$\ell$. In a study in Botswana by Lewis et al. (1980a), concentrations in excess of 110 mg $NO_3$-N/$\ell$ (500 mg $NO_3/\ell$) were found in a water-supply borehole in close proximity to a village with a population of 20 000 people. Of particular interest in this study was their finding that immediately adjacent to the base of the pit latrines, nitrate concentrations were higher than 220 mg $NO_3$-N/$\ell$ (1 000 mg $NO_3/\ell$). Pollution associated with a much smaller village, with a population of about 500, in Central India was reported by Cook and Das (1980). A very distinct plume of nitrate contamination extending down-gradient of the village was measured, with concentrations of 200 mg $NO_3$-N/ℓ being found in the subsoil at a distance of about 30m from the edge of the village.

Results from a series of shallow wells in the Maputo aquifer have clearly linked the nitrate concentrations within the groundwater to the density of settlements making use of on-site sanitation, (Muller, 1989). Although it is not entirely clear in any of the above studies, it appears that the depth to groundwater below the sanitation facilities was small (2 m to 3 m). Furthermore, in the first two cases discussed above, rapid migration to the groundwater was possible, with the subsurface material consisting of either sandy, well-drained soil or fractured, weathered rock.

The question remains as to what are the ideal conditions for minimising nitrate contamination of groundwater. Maximising the residence time in the unsaturated zone (which has a smaller hydraulic conductivity than the saturated zone), delays the time at which nitrates will enter the groundwater. However, conditions within the aerobic unsaturated zone are rarely conducive to the processes of denitrification. This is well illustrated by the experiments of Ebers and Bischofsberger (1987), who carried out identical tests on two 2.5 m high lysimeters; one filled with fine, silty sand and the other with fine gravel. The hydraulic loading rate, coupled with the low permeability of the silty sand resulted in anaerobic conditions in this column, whereas the gravel column remained aerobic. Almost complete denitrification occurred in the sand, whereas in the gravel there was virtually no nitrate removal.

The problem of nitrate accumulation in the unsaturated zone has been illustrated by Lawrence (1983), although this work was in the context of contamination caused by over-fertilisation. His studies of nitrate levels at a number of locations in Australia showed values that exhibited recent (at that time) increases, the implication being that natural processes within the unsaturated zone were incapable of neutralising high nitrate levels.

In spite of the above findings, it may be possible to manipulate conditions within the unsaturated zone to some extent, in order to improve denitrification rates. Many studies have shown greatly increased denitrification if supplementary sources of carbon were added to either the soil itself, or to the influent (Cochet et al. 1990; Sikora and Keeney 1976).

### Comparative movement of various contaminants reported in the literature

Unfortunately, in the literature most studies of contamination due to on-site sanitation have been restricted to only one or two contaminants, e.g. tests may be done for bacteria, but not for nitrates, or vice versa. In two reported comparative studies, nitrates have been shown to be significantly more mobile than the other contaminants mentioned above. Yamaura et al. (1986) conducted experiments using laboratory soil columns and lysimeters, as well as full-scale field tests. Septic effluent was added to the soil in these apparatuses on a daily basis, and the quality of the effluent monitored. In general, removal efficiencies of around 90% were obtained for BOD, total phosphorus, and coliforms, whereas for total nitrogen the removal efficiency was less than 50%. The field experiments were continued for 10 years, and no apparent change in removal efficiency was detected. This is one of the few long-term studies reported in the literature. In a field study reported by Robertson et al. (1989), contaminant migration from a 100 $m^2$ weeping tile bed was monitored at a number of locations down-gradient from the tile bed. Residence time in the vadose zone was monitored using a NaBr tracer, and was found to be approximately 10 days. They found an extremely long, thin plume of impacted groundwater, with nitrate levels of about 50% of their source concentration occurring at distances of 100 m from the tile bed. No trace of other contaminants was detected at these distances.

## Conclusions

A number of conclusions may be drawn from this review of the literature as follows:

- Contamination from on-site sanitation is not a single entity, but has a number of components, which may be divided into two broad categories:
  - Microbiological contaminants: Viruses, bacteria, protozoa and helminths.
  - Chemical contaminants: nitrogen and phosphorus, in the form of nitrate and phosphate respectively.

- There are different mechanisms of movement of the contaminants and the contaminants themselves are subject to alteration. There are different processes which affect these changes, which are usually temporal in nature:
  - Movement takes place primarily by advection, with little diffusion occurring.
  - There are numerous other processes which retard or reduce mobility. The following processes affect specific contaminants:
    - **Physical filtration** removes helminths and protozoa very effectively. This factor is of course very dependent on the particle size distribution of the soil, with a well-graded soil being the most effective.
    - Phosphate is removed by **adsorption**; although this process is usually extremely effective, the mechanisms of release are not clear. The soil has a certain adsorption capacity and will not adsorb phosphate beyond that limit.
    - Nitrate appears to act like an ideal tracer, but the effects of **denitrification** are not clear.
  - The movement of viruses and bacteria is retarded by various processes, including filtration, adsorption and complexation

- Certain clear statements may be made concerning pollution risk in specific hydrogeological conditions:
  - Firstly, there is a major difference between the vadose or unsaturated zone and the saturated zone. The hydraulic conductivity in the vadose zone is usually substantially less than in the saturated zone. The rate of movement of contaminants through an unsaturated soil may be a number of orders of magnitude slower than through a saturated profile of the same soil.
  - Secondly, one may make certain limited comments about different subsurface geological conditions:
    - Dolomitic/fractured bedrock close to or at the soil surface is problematic for **all** contaminants.
    - By contrast, sandy soils do not pose a risk for microbiological contamination, unless the hydraulic conductivity is extremely high (e.g. a coarse gravel). However, even in sandy soils nitrate contamination remains a potential risk.

- With respect to the quality of the data, there is a lack of good-quality long-term data, in which the movement of all the contaminants of concern (e.g. indicator bacteria and viruses, and nitrates) has been simultaneously monitored.

- Since the seminal work of Lewis et al. (1980b) almost 15 years ago on the risk of groundwater pollution by on-site sanitation, there has been no research that advances this particular topic. There have been, as indicated in this paper, a number of projects that address one or other aspect of the problem, but there has been no concerted effort to establish unequivocally the health and environmental risks associated with on-site sanitation.

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