A strategy for evaluating the environmental impact of on-site sanitation systems

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Abstract

In order to ensure that all South Africans are provided with access to adequate sanitation within the constraints of limited national resources, policies currently being considered by the South African government envisage a significant amount of on-site sanitation in use in the urban areas of the country for the foreseeable future. However, concerns exist that widespread use of these systems will cause subsurface migration of contaminants which may have adverse impacts on human health and on the natural environment.

This paper provides an overview of the problem, reviews existing guidelines and presents a more rigorous strategy for evaluating the impact of on-site sanitation on human health and the natural environment.

The suggested strategy, which permits account to be taken of a multitude of variables encountered, is as follows:

- define compliance requirements in terms of both physical location (point of compliance) and allowable contaminant concentration;
- estimate risk of pollution by viruses and bacteria using a 'residence time' approach;
- estimate pollution risk by nitrates using a mass balance approach;
- for both microbiological and chemical contaminants, use a probabilistic approach (as far as the available data allow), allowing appropriate margins of safety in design, such margins of safety still to be determined
- carry out field monitoring of on-site sanitation schemes (if water resources are to be protected) to provide early warning of contaminant build-up.

The establishment of a set of general principles for compliance requirements together with the application of these principles to the different water bodies (both surface water and groundwater) in South Africa is the most urgent requirement for the implementation of the above strategy.

It is also suggested that evaluation of environmental impact of sanitation systems should not be confined to on-site sanitation alone, but should be extended to *all* forms of sanitation system, including water-borne sanitation systems as well.

Introduction

The subsidy cost of providing access to adequate sanitation facilities for the approximately 21 m. South Africans (DWAF, 1994) who are currently without such facilities is very significant in comparison with the funds available to central government (Van Ryneveld, 1995). In order to meet this challenge, it will be necessary to consider carefully what levels of service can be afforded by the country as a whole while still meeting acceptable standards of quality.

In 1991 the Water and Sanitation 2000 workshop suggested that the provision of ventilated improved pit (VIP) latrines for about half of the urban population as at the year 2000 was the kind of policy that the country needed to be looking at (Jackson, 1991). More recently, the Municipal Infrastructure Investment Framework (MIIF) study (Ministry in the Office of the President and the Department of National Housing, 1995) has proposed a programme of infrastructure provision that would eliminate much (but not all) of the backlog within 5 to 7 years and would match service levels with predicted household income levels in 10 years (i.e. by the year 2005). This programme would result in a 55:25:20 distribution nationally between full, intermediate and basic levels of service. A basic level of service for sanitation would comprise on-site sanitation (e.g. a ventilated improved pit (VIP) latrine), while an intermediate level of service would comprise simple water-borne sanitation. Simple water-borne sanitation may include on-site systems such as the LOFLOS (low flush on-site sanitation system, also referred to by some as an aquaprivy).

Both studies therefore envisage a significant amount of on-site sanitation in use in the urban areas of South Africa for the foreseeable future, an option which is significantly cheaper than the use of full water-borne sanitation throughout. However, a problem that is often raised in relation to the use of on-site sanitation is the potential pollution of water resources 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 review of the literature on the subsurface movement of contaminants associated with on-site sanitation has been carried out (Fourie and Van Ryneveld, 1995); however, there is a need to translate this knowledge into guidelines for evaluating the environmental impact of these systems in practice. This paper provides an overview of the problem, reviews existing methodologies and presents a more rigorous methodology for evaluating the environmental impact of on-site sanitation systems.

Use of on-site sanitation on a large scale in an area of scarce water resources is a significant departure from existing approaches which appear to follow one of two routes:

- **In developing countries**, where water-borne sewerage is largely unaffordable, on-site sanitation has been used as the only viable alternative. Substantial improvements in health and environmental quality are obtained by the use of **on-site** sanitation as compared with **no** sanitation coverage (or, alternatively, as compared with high standards for a few and minimal or no sanitation coverage for the rest of the population). Therefore, while environmental quality is a

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concern, little attention is given to contamination of water resources by on-site sanitation unless it poses a significant health risk (where a particular source is to be used for drinking purposes).

- **In developed countries**, where water-borne sewerage is largely affordable, it is used primarily for reasons of convenience, but also on the assumption that there is no associated pollution risk. Where on-site sanitation has been used on a large scale in developed countries, as in the case of the United States of America and Canada where it is estimated that some 60 m. people use on-site sanitation in the form of septic tank systems for waste water (Viraraghavan, 1982), it has been at relatively low densities (Septic tank systems are water-borne but not sewered).

The situation in South Africa straddles the above two scenarios. Its gross national product (GNP) *per capita* places it in the category of middle-income economies, on the border between the lower-middle and upper-middle income categories, alongside countries such as Malaysia, Brazil, Botswana and the Czech Republic (World Bank, 1994). In other words, it does not have the financial resources of a highly developed country which would allow it to side-step possible pollution from on-site sanitation by restricting use of on-site sanitation to low-density areas and by using well-managed high levels of service (full water-borne sanitation) in higher density areas. At the same time it is a water-scarce country and is concerned not to pollute the water resources it does have.

Such constraints force upon the country a more careful analysis of the problem. If one questions whether on-site sanitation can cause pollution, the answer is an emphatic yes, as shown by Lewis et al. (1980a) and Chairuca and Hassane (1991). In fact, this is true of all other forms of sanitation systems as well, e.g. Hoffman (1994). A far more difficult question, and one that does not appear to have been addressed, is what the implications of this potential pollution are as regards the viability of on-site sanitation in a particular instance, and whether these dangers can be dealt with in the planning and design stages.

In seeking to provide access to adequate sanitation for all its inhabitants, one of the options the country has is the widespread use of on-site sanitation at relatively high densities. It needs to be emphasised that the opportunity now exists for the actual planning of relatively high density use of on-site sanitation, particularly in the fast-growing urban areas.

Framework of understanding

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.

There are a number of different aspects to what is a complex problem:

To start with:
- The term 'on-site sanitation' needs clear definition.

Following that:
- Wastes that originate from on-site sanitation systems 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 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.
- Lastly, the risks associated with on-site sanitation need to be viewed in relation to risks from other forms of sanitation systems.

These topics are expanded on in the following sections.

On-site sanitation systems used in South Africa

There are various types of on-site sanitation, which are described and illustrated in a World Bank publication (Kalbermatten et al., 1982). On-site systems refer to those where the sanitary wastes are not transported to an off-site location for primary treatment, but are treated on-site by a combination of:

- Transformation into harmless products
- Dissipation

Residual wastes, in the form of sludge, require periodic removal (typically between one- and three-yearly intervals), followed by treatment and reuse or disposal off-site. Problems associated with sludge treatment or disposal are not addressed in this paper.

In South Africa three types of on-site sanitation are more generally used:

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

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

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 are significantly more expensive than VIPs and LOFLOS partly because of the capital cost of the sanitation system and partly because they require a full water supply, whereas VIPs and LOFLOS do not. As a result, the cost of septic tanks is of the same order of magnitude as full water-borne sanitation (Kalbermatten et al., 1980; Palmer Development Group in association with University of Cape Town, 1993). There is therefore little benefit to be gained by using them instead of full water-borne sanitation in large-scale high density applications.

Contaminants that originate from on-site sanitation systems

Sanitary wastes consist of:
- Human excreta (human faeces and urine)
- Sullage or grey water (discharge from kitchen sink, bathroom excluding the toilet, and the laundry).

These in turn typically consist of:

- Biodegradable and non-biodegradable organics
- Pathogenic micro-organisms
- Nutrients
- Refractory organics
- Toxic inorganic ions such as heavy metals
- Dissolved inorganic salts.

In considering VIPs and LOFLOS, our primary concern is for human excreta rather than sullage or grey water.

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 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 mass)	
	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

Suspended solids settle out in the soakaway of the on-site sanitation system while biodegradable organics degrade relatively quickly.

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).

Refractory organics (which include surfactants, pesticides and agricultural chemicals, cleaning solvents, organics produced by processing of natural organics, and mineral oils) and toxic inorganic ions (e.g. heavy metals) are not dealt with in this paper for two 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 and 1993)
- They do not occur as a matter of course in domestic waste water, 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:

- Pathogenic micro-organisms
- Chemical contaminants, particularly nutrients (nitrogen and phosphorus)

These contaminants each pose a risk to human health and/or to the environment.

Risks to human health associated with sanitary wastes

Pathogenic micro-organisms

Pathogenic micro-organisms comprise viruses, bacteria, protozoa and helminths (parasitic worms) (Feachem et al., 1983). The latter two categories of micro-organism have been shown to be effectively filtered over short distances of soil (Lewis et al., 1980b) and are therefore not further considered in this paper. Viruses and bacteria, being very much smaller, are not necessarily as efficiently filtered by soil and are therefore the micro-organisms of concern.

For health risks arising from both pathogenic micro-organisms and from chemical contaminants, there are two questions to be asked:

- What are the diseases/illnesses associated with the different contaminants?
- How does one become ill from these contaminants?

A variety of bacteria and the illnesses/symptoms associated with them are detailed in Table 2 (Lewis et al., 1980b); similar data for viruses are given in Table 3 (after Grabow, 1991a).

TABLE 2
BACTERIA AND THEIR ASSOCIATED ILLNESSES
(LEWIS ET AL., 1980b)

Micro-organism	Associated illness
Vibrio cholerae	Cholera
Salmonella typhi	Typhoid fever
Salmonella paratyphi	Paratyphoid fever
Shigella spp.	Bacillary dysentery
Enterotoxigenic *E. coli* Enteroinvasive *E. coli* Enteropathogenic *E. coli* *Salmonella* spp. *Campylobacter petus* ssp. *jejuni*	Diarrhoeal diseases

As regards becoming ill from pathogenic micro-organisms, the first point to be made is that there is a distinction between being ill and being infected. Being ill involves showing symptoms of the disease. The distinction is that one can be infected without being ill. Infection will be used in this study rather than illness as the indicator of a problem.

What constitutes an infective dose is therefore a concept of prime importance. The magnitude of an infective dose depends on:

TABLE 3
VIRUSES AND THEIR ASSOCIATED ILLNESSES/SYMPTOMS
(AFTER GRABOW, 1991a)

Micro-organism or group of micro-organisms	**Associated illnesses/symptoms**
Enteroviruses including polio, echo, Coxsackie A and B, entero and hepatitis A viruses	Fever, rash, diarrhoea, respiratory disease, herpangina, pleurodyna, myocarditis, congenital heart anomalies, meningitis, and viral hepatitis (Gerba, 1988)
Hepatitis E virus (previously known as epidemic non-A non-B hepatitis virus	Water-borne viral hepatitis (Byskov et al., 1989)
Gastroenteritis viruses, which includes a wide variety of families and types of viruses: 1 Reoviridae: Rota 2 Adenoviridae: Adeno types 40 and 41 3 'Small round structured viruses' (SRSV) · Caliciviridae: Calici · SRSVs with names e.g. Norwalk, Montgomery, Hawaii, Snow Mountain · Astro: Marin Country · Large number of SRSVs without name 4 'Small Round Viruses' (SRV) · Parvo-line: Wollan (W) · Entero-like: e.g. Ditchling, Cockle, Parramatta · Large number of different SRVs without name 5 Retroviridae: Human immunodeficiency virus 6 Coronaviridae: Corona 7 Toroviridae: e.g. Breda, Berne 8 Picobirnaviridae An important common feature of these viruses is that the great majority cannot be detected by conventional laboratory techniques	Fever, abdominal pain, nausea, dehydration, vomiting and diarrhoea (Monroe et al.,1991)
Other viruses associated with water and related environments, including · certain adenovirus types · molluscum contagiosum · papilloma viruses	These in turn cause: · pharyngo-conjunctival fever known as 'swimming-pool eyes' and pharyngitis · benign skin tumours · warts (Grabow, 1991b)

- The characteristics of the micro-organism as well as
- The response of the host (person being infected).

Data on infective doses are very hard to acquire as it entails administering a known dose to a human volunteer, and observing the consequences. In general viruses require low infective doses (typically <100 organisms); similarly a single egg or larva can infect a person in helminthic infections; bacteria on the other hand generally require large infective doses (of the order of 10 000 or more) (Lewis et al., 1980b). The response of the host also varies from person to person and from community to community. It depends on immunity as well as on general health (and hence resistance to infection). An infective dose is therefore usually expressed as the dose required to infect half of those exposed to the particular organism (ID_{50}) (Feachem et al., 1983).

Pathogens are generally difficult to detect and to quantify. As there are some 100 pathogenic bacteria/viruses that are commonly found in water, it is not feasible to test for each individually. Use is therefore commonly made of indicator organisms. *E. coli* is one such organism which is often used as an indicator of faecal contamination (Feachem et al., 1983; Grabow, 1996).

A key point to be recognised is that while the presence of the indicator organism indicates the presence of faecal contamination, the absence of the indicator organism does not necessarily prove the absence of faecal contamination.

For an excreted infection to be transmitted, an infective dose of the disease agent has to pass from the excreta of a patient, carrier, or reservoir of the infection to the mouth or some other entryway of a susceptible person. The risks of an infective dose being transmitted depend on the following factors (Feachem et al., 1983):

- Excreted load of an infected individual
- Latency (the interval between the excretion of a pathogen and its becoming infective to a new host)
- Persistence (viability of the pathogen in the environment, or how quickly it dies after leaving the human body)
- Multiplication (certain pathogens will multiply under favourable conditions; originally low numbers can thus produce a potentially infective dose. Important to note is that while bacteria are able to multiply outside their hosts, viruses are not).

Chemical contaminants

The chemical contaminant of primary concern in sanitary wastes as encountered in on-site sanitation is nitrate (Ward and Schertenleib, 1982; Franceys et al., 1992).

High nitrate levels in drinking water may cause methaemoglobinaemia (also called infantile cyanosis) (which is the conversion of haemoglobin to methaemoglobin, and results in the inability of the bloodstream to transport oxygen) in infants. This condition is also known as 'blue baby' syndrome. Methaemoglobinaemia is non-carcinogenic.

High nitrate levels have also been linked to stomach cancer in adults, although the link is at present still tenuous. A recent European study on the subject concluded that recent epidemiological research provided no evidence that nitrate induces cancer in man (ECETOC, 1988).

In terms of becoming ill from chemical substances, the approach is split between:

- Non-carcinogenic (acute or chronic toxicity) and
- Carcinogenic substances (cancer-causing).

Dose thresholds such as the infective dose for microbiological contaminants do not exist for all chemical contaminants; in particular there is a probably unverifiable assumption that dose thresholds **do** exist for non-carcinogenic effects, while there is an unverifiable assumption that dose thresholds **do not** exist for carcinogenic effects (Cotruvo, 1989).

It should also be noted that chemicals can have acutely toxic effects at one dose level and carcinogenic effects at another dose level. A further point to be made with respect to cancer is that although the proportion of individuals who get cancer is related to the degree of exposure to the carcinogenic chemical, the severity of the cancer (i.e. the extent of the tumour spread) is independent of exposure (Kamrin, 1988).

What are the risks to the environment associated with sanitary wastes?

Contaminants of primary concern are chemical contaminants, particularly nutrients (nitrogen and phosphorus).

The enrichment of water bodies with plant nutrients (nitrogen and phosphorus) causes a change in the ability of the water body to support life. The ability of the water body to support life is termed the "trophic state" ("trophic" = concerned with nutrition or the food chain); and this change in the trophic state of the water body is termed 'eutrophication'.

The Department of Water Affairs (1986) gives an overview of problems caused by eutrophication (referring to deoxygenation and excessive algal growth), which include the following:

- Increased water purification costs
- Increased expertise required for operation and control of water purification works
- Toxins produced by algae may result in fish and stock losses
- Deoxygenation may cause disturbances in biological activity and water chemistry
- Algal growths on canal linings which result in loss of hydraulic capacity
- Water surfaces aesthetically degraded
- Recreational use of water surfaces affected
- Values of lakeside properties decreased
- Trihalomethanes (THMs) may be formed when eutrophied water is chlorinated during treatment

The impact of nutrient addition on the trophic state of a water body is also dependent on whether the flow is continuous or intermittent. A continuous low flow such as effluent from a sewage treatment works has a much greater impact than does high intermittent flow such as polluted storm-water runoff. This issue is a particular concern in relation to pollution from on-site sanitation (Ashton and Grobler, 1988) in that contamination tends to take the form of a continuous low flow.

The subsurface transport of phosphorus from on-site sanitation systems does not appear to be a major concern. All previous studies have shown virtual complete removal of phosphorus by the soil within relatively small distances from the source (Jones and Lee, 1979; Sawhney and Starr, 1977). This topic is therefore not further pursued in this paper.

The problem of chemical contamination is therefore that of nitrogen, as dealt with in a later section.

Pathways for transmission of contaminants

There are a number of different possible points of contact with human excreta and grey water. In considering the health impact of on-site sanitation, the routes of transmission for both microbiological and chemical contaminants that we are considering are:

- By contact with fresh human excreta and grey water
- By contact with soakaway effluent (say, from a failed soakaway, where the effluent has surfaced)
- By contact with soil in the vicinity of the soakaway
- By ingesting water which has been contaminated by the effluent from the on-site sanitation. This may be either groundwater, or surface water into which contaminated groundwater has discharged.

The first two may be controlled by ensuring good hygiene practices and a properly designed and constructed on-site sanitation system. Both are beyond the scope of this study. Here, we will consider the latter two: hazards from a well-operating system.

The impact of on-site sanitation on the environment follows a similar pattern to human impact, the difference being that with impact on the environment, the focus is on the resource (surface or groundwater) whereas with human impact, the focus is on people.

In a well-operating system, contaminants originate below the surface (i.e. from the soakaway or pit). Therefore before coming into contact with groundwater (or borehole water) or surface water, the contaminants must first travel through the subsurface. As indicated by Fourie and Van Ryneveld (1995) the movement of these contaminants in the subsurface is a complex problem:

- The different contaminants have different characteristics, and their 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.

Recognition of the risks associated with other forms of sanitation system

It is useful to consider risk associated with pollution from on-site sanitation relative to other forms of sanitation system. As pointed out by Fourie and Van Ryneveld (1995), all types of sanitation (both on-site and off-site systems) pose a pollution threat. Effluent from conventional sewage treatment plants contains significant concentrations of viruses, bacteria, protozoa and helminth ova, even if it meets quality standards of oxygen demand (organics) and suspended solids. Effluents are certainly not suitable for reuse without additional treatment, and may often be unsuitable for discharge to freshwater bodies where those water bodies are used for domestic water supplies by downstream populations. Waste-water treatment also does not remove dissolved inorganic or organic chemicals. Dangerous chemicals are controlled at source. Reliance is therefore placed on a combination of:

- dilution;
- the ability of the natural watercourses to continue the cleansing process; and
- the water treatment process.

to ensure acceptable health impact of this sanitation system.

Furthermore, unless sewers are well constructed and maintained, water-borne sanitation can contribute significantly to environmental contamination. For example, in a study of diffuse (non-point source) pollution in the Hennops River valley, Hoffman (1994) reported very high levels of ammonia, phosphates and *E. coli* emanating from Tembisa, which is a well-reticulated settlement. The problem was attributed to pipe blockages in Tembisa. This emphasises the fact that water-borne sewerage systems are potentially major contributors to environmental contamination because they accumulate and concentrate raw sewage. This is in contrast to on-site systems, which dispose of wastes in a much more diffuse manner.

Effluent from water-borne sanitation is therefore not without negative impact on human health or on the environment. Nevertheless pollution from on-site sanitation remains a concern.

Summary

Risk of pollution from on-site sanitation may be seen to consist of three main components:

- source
- pathway
- receptor

The concentration of the contaminant at the source may be above acceptable levels. However, in moving from the source to the receptor, various attenuation processes may reduce these concentrations to acceptable levels.

In the following section existing guidelines for the prevention of pollution from on-site sanitation are discussed. With few exceptions these guidelines appear to have the following assumptions implicit in them:

- that by specifying a minimum distance between source and receptor, pollution is prevented (This approach does not take into account the different attenuation mechanisms that apply to different contaminants).
- that pollution of groundwater is the only concern.

As is argued later, both of these assumptions require more careful consideration.

Guidelines for minimising environmental impact of on-site sanitation

Existing guidelines

One of the earliest guidelines to ensure that on-site sanitation did not cause pollution of groundwater was provided by Dyer and Bhaskaran (1945), who recommended minimum distances between an on-site latrine and water withdrawal points. Based on field studies, they concluded that in sandy soils bored latrines could be placed as close as 6 m to a water supply well. This was soon found to be unrealistic, and a minimum distance of 15 m became accepted practice, until more rigorous guidelines were developed (Lewis et al., 1980b).

Recognising that guidelines of the above type were overly simplistic, because they ignored factors such as site hydrogeology,

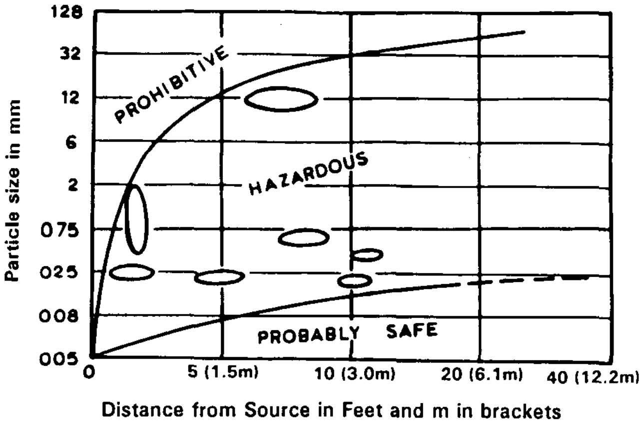
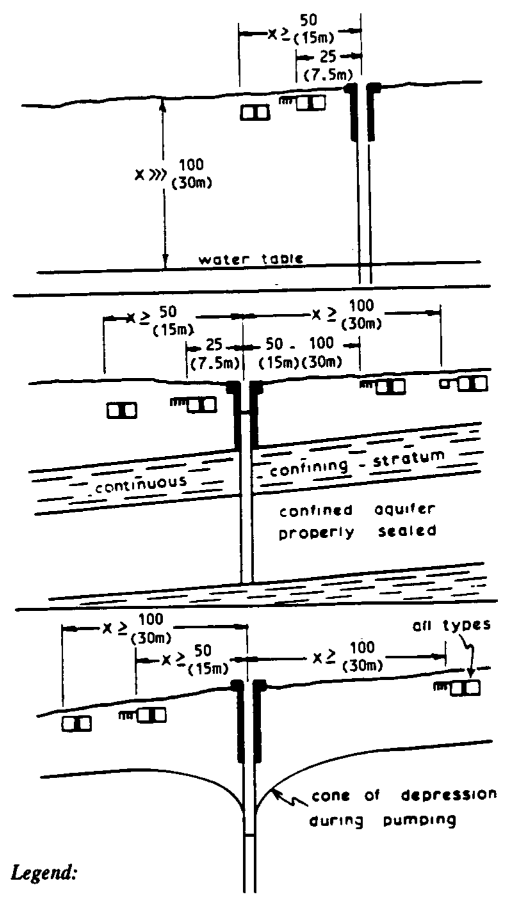


Figure 1
Biological pollution travel in unsaturated soil (after Romero, 1972)



Legend:

Septic tank with absorption trench or seepage bed

Septic tank with seepage pit

Septic tank with no absorption system

Note:

- Dimensions in feet, followed (in brackets) by dimensions in metres
- All diagrams sectional elevations of unconsolidated sand and gravel unless otherwise indicated
- Diagrams apply to areas in which the zone of saturation is greater than 10 feet (3m) from the source of contamination

later workers suggested guidelines that attempted to address this deficiency. Romero (1972) consolidated data from a number of international case studies to produce graphs such as shown in Fig. 1.

This graph shows the travel of bacterial pollution in unsaturated soil profiles as a function of the particle size of the soil. Three zones are indicated on the graph. These define distances from the contaminant source that could be considered probably safe, hazardous or prohibitive. Although an improvement on simplistic, minimum distance guidelines, Fig. 1 is still deficient, particularly since it is impossible to characterise a soil by a single particle size, as has been implied in this figure.

In the same publication Romero (1972) also provides an improved version of the 'minimum distance' guidelines. An example is shown in Fig. 2, which suggests minimum horizontal distances from septic tanks, that are dependent on underlying hydrogeological conditions.

In a more recent attempt to account for varying hydrogeology, and how it impacts on pollution from on-site sanitation, Lewis et al. (1980b) proposed a 'pollution risk array', which is illustrated in Fig. 3. This figure indicates the type of soil profile within which the pollution risk may be minimal or high, or where insufficient knowledge is available to make a judgement. Although useful, the figure only illustrates relative pollution potential, and does not quantify the pollution risk associated with different soil types.

As noted in their report, the most pervasive form of pollution resulting from on-site sanitation is likely to be nitrate pollution. Lewis et al. (1980b) and, more recently, Foster (1985) presented a theoretical relationship between the density of a settlement using on-site sanitation, the rainfall infiltration into the soil, and the resulting nitrate concentration in water infiltrating local groundwaters (see Fig. 4). This approach, which is based on a simple mass balance, has also been utilised by Palmer (1981), and Muller (1989).

Foster (1985) (as did Lewis et al. (1980b) and Muller (1989)) presented data which may be used to verify the reasonableness of this graph. However, a number of assumptions have to be made (e.g. actual infiltration as a percentage of precipitation or the magnitude of denitrification processes in the unsaturated zone) that are difficult to verify. Figure 4 should therefore be regarded merely as a reasonable first estimate.

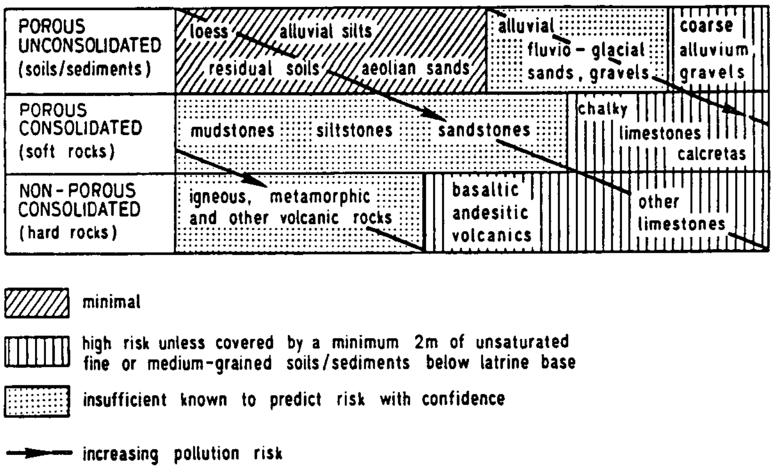
In terms of regulations, Table 4 shows the recommended safe distances between a range of on-site sanitation systems and domestic wells that have been used in the United States in the past

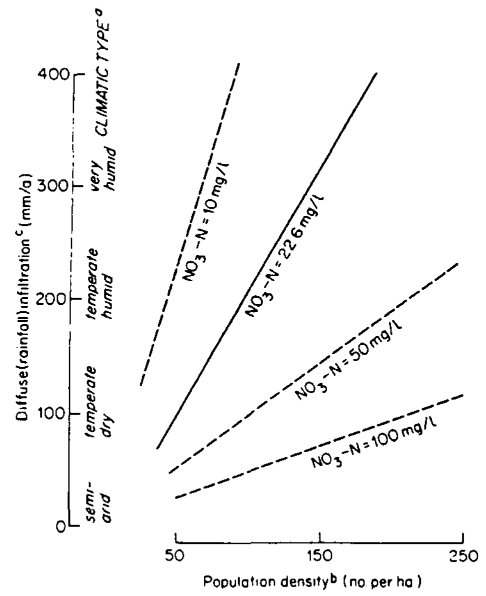
Figure 2 (top)

"Safe" distances between septic tanks and drinking water wells (after Romero, 1972)

Figure 3 (right)

Classification of soils and rocks in an array of relative risk (after Romero, 1972)





[a] General indication only; depends on soil-vegetation system and proportion of surface run-off.

[b] Assumes initial generation of 5 kg N/capita.annum but 90% return directly or indirectly, to atmosphere.

[c] In some cases dilution from regular aquifer throughflow, streambed infiltration or effluent liquid itself will also be significant.

Figure 4

Grossly simplified estimation of impact of unsewered sanitation schemes on nitrate concentration in local groundwater (after Foster, 1985)

(Romero, 1972).

In South Africa, the approach to limiting pollution from on-site sanitation has generally been to adopt the "minimum distance" approach. De Villiers (1987) summarised the guidelines for areas where the groundwater is used for household purposes, and the water source is located down-gradient from a latrine as follows:

- 15m from the water source if the water table is quite shallow (1 m to 5 m below the bottom surface of the pit or soakaway)
- 30m from the water source if the water table is very shallow
- 7.5m from the water source if the highest seasonal water table is more than 5m below the bottom surface.

He noted that these criteria are not applicable to areas where fissured rock, limestone or very coarse subsoils occur.

The same approach as above was followed in guidelines for the provision of services for developing communities (the so-called "Green Book", Department of Development Aid, 1988), which in turn has been carried over into the more recent so-called "Red Book' (Department of Housing in collaboration with the National Housing Board, 1995).

A particularly simple approach to the problem is provided by the National Building Research Institute (NBRI, 1984), who state that VIP latrines are suitable for use in residential areas with a maximum of 250 persons/ha.

A more integrated approach to groundwater protection has been suggested in the most recent guidelines produced in South Africa, for the Community Water Supply and Sanitation Programme (Xu and Braune, 1995). They are intended to provide "... a technical basis for the formulation of a non-

TABLE 4

RECOMMENDED SAFE DISTANCES BETWEEN DOMESTIC WELLS AND VARIOUS ON-SITE SANITATION SYSTEMS (AFTER ROMERO, 1972)

Source of pollution	**Recommended distance (m)**			
	California	**Colorado**	**FHA***	**USPHS****
Septic tank	16	30m from point of juncture between well casings and aquifer	16	16
Sewer lines with watertight joints	3	As above	3	3
Percolation field	30	---	30	30
Absorption bed	30	8m minimum horizontal distance	30	-
Seepage pit	30	As above	30	30

* Federal Housing Authority
** United States Public Health Service

regulatory but realistic strategy for protecting aquifers and drinking-water supply boreholes (or wellfields) on which the rural and peri-urban communities rely". The guidelines utilise what they term a "three-tiered" solution strategy as follows (Xu and Braune (1995); Xu and Reynders (1995):

- The first tier comprises short-term measures to ensure that potential sources of contamination are dealt with immediately (e.g. through the use of minimum distances between pit latrines and boreholes).
- The second tier incorporates a classification of groundwater resources with the medium-term objective of providing for the implementation of what is termed "differentiated protection" (whereby more strategic aquifers are afforded a higher level of protection).
- The third tier entails the zoning of areas around specific groundwater sources, with a view to protecting these sources in the longer term.

The minimum distance approach of the first-tier strategy proposes a matrix of minimum distances between on-site sanitation and borehole of between 15 and 50m, with intermediate values of the minimum distance for specific sites being based on aquifer geology and on the type and thickness of the overlying soil. The minimum distances have been calculated assuming a travel time of 30 d (to ensure microbiological degradation) and a borehole pumping rate of 5 l/s (Other aspects of the short-term strategy set out in the guidelines include borehole or water point construction standards, minimum sanitation and waste disposal requirements and follow-up monitoring (upon which particular stress is placed).

Suitability of existing guidelines

There are three key areas where it is suggested that existing guidelines need some modification:

- Recognition of the nature of contamination
- In the use of minimum distances (or acceptable densities)
- In the choice of compliance requirements.

Nature of contamination

The nature of contamination refers to whether it is microbiological or chemical contamination that is of concern.

As discussed by Fourie and Van Ryneveld (1995), nitrate is highly likely to be the most mobile of the contaminants. On the other hand, the infectious doses of viruses (or even some types of bacteria) are much smaller than are those of nitrate. Many guidelines refer only to microbiological contamination, not to chemical contamination. With respect to the nature of contamination, all risks need to be identified and provision made where necessary.

Formulation of guidelines in terms of minimum distances

With respect to the second key area, virtually all existing guidelines for the prevention of pollution from on-site sanitation are formulated in terms of safe distances between on-site sanitation and source of drinking water. Some of these guidelines propose different requirements for different hydrogeological conditions. While the minimum distance approach offers the advantage of being simple to apply in the field, there are nevertheless significant difficulties associated with the approach.

The first difficulty with regard to the use of minimum distances is that sites often do not conform to any of the hypothetical hydrogeological profiles implicit in the above guidelines. This means that at a particular site, there may be a mixture of very different conditions, which are difficult to categorise, which in turn makes the permeability of the subsurface very difficult to predict. Permeabilities vary over several orders of magnitude for different hydrogeological conditions in the saturated zone alone. Permeabilities can vary even more between the saturated and the vadose zone. The result of this is that guidelines may be far too conservative for many hydrogeological conditions, while permitting significant risk in others. Difficulty in classifying different hydrogeological conditions also leads to uncertainty regarding other factors which affect contaminant migration, such as filtering or adsorption ability of the soil.

The second difficulty with regard to minimum distances is that the die-off rates of micro-organisms or breakdown rates of chemical contaminants can vary considerably. With respect to the die-off rates of micro-organisms, factors affecting the survival of enteric bacteria in soil are given by Gerba et al. (1975).

TABLE 5
FACTORS AFFECTING SURVIVAL OF ENTERIC BACTERIA IN SOIL (GERBA ET AL., 1975)

Factors	**Remarks**
Moisture content	Greater survival time in moist soils and during times of high rainfall
Moisture-holding capacity	Survival time is less in sandy soils than in soils with greater water retention capacities
Temperature	Longer survival times at low temperatures; longer survival in winter than in summer
pH	Shorter survival time in acid soils (pH 3 to 5) than in alkaline soils
Sunlight	Shorter survival time at soil surface
Organic matter	Increased survival time and possible regrowth when sufficient amounts of organic matter are present

Gerba (1979) gives a similar table, which applies to both viruses and bacteria, and includes an additional comment on the effect of antagonism from soil microflora on survival of viruses and bacteria as follows: "Increased survival time in sterile soil, soil microflora compete with bacteria for nutrients; aerobic soil micro-organisms adversely affect virus survival while anaerobic micro-organisms have no effect". Variations in survival time therefore add to the uncertainties of the minimum distance, although to a significantly lesser extent than variations in permeability.

TABLE 6
SURVIVAL TIMES OF EXCRETED PATHOGENIC BACTERIA AND VIRUSES IN SOIL AT 20 TO 30°C (FEACHEM ET AL., 1983)

Pathogen	Survival time (d)
Viruses	
Enteroviruses	<100 but usually <20
Bacteria	
Faecal coliforms	<70 but usually <20
Salmonella spp.	<70 but usually <20
Vibrio cholerae	<20 but usually <10

TABLE 7
SURVIVAL TIMES OF EXCRETED PATHOGENIC BACTERIA AND VIRUSES IN FRESHWATER AND SEWAGE AT 20 TO 30°C (FEACHEM ET AL., 1983)

Pathogen	Survival time (d)
Viruses	
Enteroviruses	<120 but usually <50
Bacteria	
Faecal coliforms	<60 but usually <30
Salmonella spp.	<60 but usually <30
Shigella spp.	<30 but usually <10
Vibrio cholerae	<30 but usually <10

Feachem et al. (1983) carried out a comprehensive review of sanitation and health issues (following their review of 1980). They provided the following summary tables for survival times of pathogens in soil and in freshwater and sewage respectively.

It should be noted that these are typical values rather than maximum values. The following references to survival times for bacteria and viruses clearly include several survival times higher than those given in the above tables, as well as several values that are higher than the value of 30 d used in the most recent South African guidelines (Xu and Braune, 1995).

From the studies quoted by him in Table 8 and other studies, Gerba et al. (1975) concluded that it appeared that 2 to 3 months (60 to 90 d) were sufficient for reduction of pathogenic bacteria to negligible numbers once they had been applied to the soil, although survival times as long as 5 years (1 825 d) had been reported (Rudolfs et al., 1950).

All of the above references refer to bacteria. Data on survival times of viruses are more sparse.

Lewis et al. (1980b) quote work by Gerba et al. (1975) and Bitton et al. (1979) as giving possible survival times of viruses of 175 d or more, depending on factors such as moisture and temperature. They also quote work by Yeager and O'Brien (1979) who found that the poliovirus survived in saturated soils up to 92 d at 22°C and up to 180 d at 4°C. The study found that the virus survived up to 12 d at 37°C. In tests on groundwater (stored in the laboratory at constant temperature of 22°C), Bitton et al. (1983) reported a decrease in plaque-forming units (PFUs) of the poliovirus type 1 of 14% in a period of 15 d. The rate of decay was linear (correlation coefficient of 0.985), which if extrapolated to a reduction of PFUs of seven orders of magnitude, gives a time of 106 d.

With respect to survival times, it should be noted, as pointed out by Lewis et al. (1980b), that there does appear to be an inconsistency between the **implied** survival times of recorded travel distances (around 10 d) and the **actual** survival times measured in laboratory studies and controlled field studies (100 d or more). Lewis et al. (1980b) do point out, however, that the distance over which the enteric bacteria can be traced will depend not only on groundwater velocity and bacterial die-off rate, but also on their initial concentration, dispersion within the groundwater body, the sample volume tested and the sensitivity of the method used to detect them. From the above comments, it would appear therefore that actual survival times may be more

TABLE 8
SURVIVAL TIMES OF PATHOGENIC BACTERIA

Pathogen	Medium	Survival time	Reference
Salmonella typhosa	Soil	25-41 d	Beard (1938)*
Coliform bacteria	Soil	90 d	Malin and Snelgrove (1958)*
Salmonella typhosa		165 d	Warrick and Muegge (1930)*
E. coli	Soil	730 d	Mom and Schaafsma (1933)*
E. coli	"Other medium"	970 d	Warrick and Muegge (1930)*
Salmonella	Sand	44 d	Yitzaghi (1971)#
E. coli	Water (recharge well)	63 d	Goldshmid et al. (1972)#
E. coli	Groundwater	90-105 d	Kudryavtseva (1972)#
E. coli	Groundwater	120-135 d	Kudryavtseva (1972)#

* (cited by Patterson et al., 1971; in turn cited by Viraraghavan, 1978; although original references not given by Viraraghavan)
\# (cited by Gerba et al., 1975; original reference provided)

representative than implied ones.

The above data clearly illustrate the wide range of survival times that have been encountered in laboratory and field studies. In the choice of this and other key parameters, there appears to be a need for some probabilistic approach, as well as some indication of what constitutes an acceptable risk of contamination to people or to a particular resource. Yates and Yates (1989) give an indication of how this might be done in relation to septic tank setback distances.

Choice of compliance requirements

With respect to the choice of compliance requirements, it needs to be recognised that compliance requirements may vary, depending on the objectives of these requirements. If groundwater is to be used for drinking purposes, then there will be a particular compliance requirement (in terms of both physical location (point of compliance) and allowable contaminant concentration), whereas if surface water resources are the primary concern, and protection of the groundwater is not a consideration, some other compliance requirement will prevail. To ensure this required flexibility, guidelines should provide a methodology for evaluating the effect of on-site sanitation on the environment, specifically water resources, and for evaluating whether compliance requirements will be met. Existing guidelines generally restrict their attention to the protection of the groundwater for drinking purposes. Recent formulation of the three-tier approach to the protection of groundwater in South Africa (Xu and Braune, 1995; Xu and Reynders, 1995) does appear to recognise the dependance of compliance requirements on the use to which the resource will be put in the second and third tiers of the guidelines. Nevertheless, more explicit provision needs to be made for other situations, where protection of groundwater may not be an issue, but where protection of surface water may be important. In addition, the choice of compliance requirement is an essential component of any short-term strategy and cannot be postponed to the medium or longer term.

In summary, therefore, there are numerous factors affecting the extent of the various processes which influence the movement of contaminants. These factors vary from site to site. There are also different contaminants of concern and different points of compliance. It is therefore not appropriate to produce guidelines in the form of an unqualified set of rules for the suitability of a site for on-site sanitation.

In the following section a strategy for evaluating the environmental impact of on-site sanitation is presented that has a different point of departure from that of protection of groundwater. Attention is focused on a specific source of contamination (high density use of on-site sanitation) and a procedure suggested for evaluating movement through and impact on the environment of the various contaminants associated with this source of contamination.

Rather than being a strategy to protect a particular 'receptor' from any (undefined) source of contamination, the proposed procedure seeks to provide a means to quantify the impact of a particular contaminant source on a range of possible receptors (e.g. individual human beings via groundwater, or surface water resources via groundwater). Although the approach suggested here does differ in certain respects from the recent three-tier South African guidelines, the two approaches are not contradictory.

Recommended strategy for the evaluation of the environmental impact of on-site sanitation

In seeking to provide access to adequate sanitation for all its inhabitants, one of the options the country has is the widespread use of on-site sanitation at relatively high densities. Concerns about the associated health and environmental risks may be addressed by siting such developments with very clear criteria for acceptance in mind.

Simplistic guidelines that consist of a few, easy-to-follow rules are unable to take account of the multitude of variables that influence the potential environmental effect of on-site sanitation. The following strategy is therefore suggested:

- Define compliance requirements that must be met, in terms of both physical location (point of compliance) and allowable contaminant concentration.

- Estimate the risk of pollution of water resources by viruses or bacteria using the 'residence time' approach. This entails a calculation of how long it would take a 'particle' of water to travel from a latrine to the point of compliance. If the latrine is situated above the water table, then this residence time might include time spent in both the vadose and the saturated zones. Techniques for doing this could vary from simple, hand calculation techniques, to sophisticated finite element computer analyses, depending on the complexity of the hydrogeological conditions underlying the latrine. If the travel time exceeds about 150 to 200 d, then according to survival times recorded in the literature, microbiological contamination should be eradicated in all but exceptional circumstances.

- To estimate the risk of pollution of water resources by nitrates, use a mass balance approach. This approach requires knowledge of a number of factors, including the proportion of nitrogen leached from the on-site sanitation system, the amount of rainfall that infiltrates the subsurface, and the rate of denitrification in the subsurface. Very rough estimates of these factors have been made by various authors, which require further investigation.

- For both microbiological and chemical contaminants, use a probabilistic approach (as far as the available data allow), allowing appropriate margins of safety in design. What constitutes an appropriate margin of safety is still to be determined.

- Until such time as adequate data relating to the input parameters that are required for the above approach become available, it will be necessary to carry out field monitoring of at least selected on-site sanitation schemes if the water resources are to be protected. This approach is necessary to provide an early warning system that contaminant levels may build up to hazardous levels at some time in the future, and to allow alternative sanitation strategies to be implemented, or remedial measures to be taken.

In the light of evidence such as presented on p. 284 of this paper, evaluation of environmental impact of sanitation systems should not be confined to on-site sanitation alone, but should be extended to **all** forms of sanitation system, including water-borne sanitation systems as well.

Where to from here

While conservative assumptions based on the available data, together with monitoring of at least selected on-site sanitation schemes to provide an early warning of contaminant build-up, may be adequate as a first estimate to address most of the uncertainties in the factors used in the strategy set out above, there is one issue (probably the most critical issue to be addressed in implementing the strategy set out above) for which such assumptions cannot as easily be made. This is the choice of compliance requirements. Inherent in this choice are decisions as to which water resources (be they surface water or groundwater resources) one wishes to protect and what levels of contamination one is prepared to permit. Such decisions are likely to vary from resource to resource. As a matter of urgency therefore, a set of general principles for compliance requirements needs to be established and applied to the different water bodies (both surface water and groundwater) in South Africa. The establishment and application of such a set of principles could be seen as an extension of the higher tiers of the three-tier approach to the protection of groundwater in South Africa (Xu and Braune, 1995; Xu and Reynders, 1995). Such principles will need to have a threefold basis:

- the first is that the understanding of the contaminants, their characteristics and their impact on human health and the natural environment must be technically sound;
- the second is that some value must be assigned to the resources, to any possible damage caused and to possible remedial measures, using environmental economics principles;
- the third is that a policy decision regarding appropriate compliance requirements must be made, to which technical and economic principles can lend support but cannot fully guide.

Until such compliance requirement principles have been established, it will be difficult to make any consistent and comprehensive decisions as to what sanitation systems may be permitted in which areas, particularly in the urban areas of the country. Many of these areas rely on surface water for their water supply and face urgent demands for sanitation services in the face of limited water resources and financial resources.

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