INVESTIGATION INTO THE SOUTH AFRICAN APPLICATION OF CERTAIN ALTERNATIVE TECHNOLOGIES FOR DISPOSAL OF SANITATION SYSTEM WASTES

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Dissertation submitted in partial fulfilment of the requirements
for the degree of

MASTER OF ENGINEERING (WATER RESOURCES ENGINEERING)

in the Faculty of
ENGINEERING, BUILT ENVIRONMENT AND
INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA

August 2000

SUMMARY

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SUMMARY

INTRODUCTION

The essence of the dissertation is as follows:

1. A broad introduction is given to the general sanitation situation in South Africa and some other developing countries, particularly among the poorer sections of the population. It is argued that there is a need for other appropriate technologies to address specific problems.
2. The development of a new type of interceptor tank for use in settled sewage sanitation systems is described. This tank is able to desludge itself automatically by means of a siphonic-type outlet mechanism.
3. The research, development and current status of urine diversion sanitation technology in the world is set out. The implementation of South Africa's first project utilising this concept is also described.

SANITATION: GENERAL ASPECTS DISCUSSED

A background to the general sanitation situation in South Africa and the developing world is presented in this dissertation, with particular emphasis on the poorer population groups. It is shown that existing systems and available resources are inadequate to deal with the serious problems which exist, and that the situation will not improve unless there is a significant change in the manner in which sanitation systems are chosen, designed and implemented. Vast amounts of improperly-managed faeces and untreated sewage contaminate the living environments of millions of people worldwide. These environmental problems, in turn, undermine the process of development.

Sanitation approaches based on flush toilets, sewers and central treatment plants cannot solve this problem. Pit toilets or septic tanks with soakpits are also not the solution in high-density urban areas. Sanitation systems must be appropriate for a particular project and circumstances. It is therefore important to look beyond the current restrictions for innovative ways and means of bringing adequate sanitation to the millions of people currently without access to proper facilities. Research and development for a wide range of cultural and environmental conditions is required, a demand for systems which reuse or recycle human excreta should be created, dependence on systems which use large amounts of potable water should be reduced, and systems should be promoted which are simple, reliable and easily maintained.

THE "SLUDGE SIPHON" SELF-CLEANSING INTERCEPTOR TANK FOR SETTLED SEWAGE SYSTEMS

Interceptor tanks in a settled sewage system must be designed to cater for various functions, namely solids interception, digestion of settled solids, and storage of digested solids. Interceptor tanks are usually designed so that up to two-thirds of the volume may be taken up by settleable solids (sludge), so the longer the anticipated interval between desludgings, the larger the tank has to be to cater for this. This is associated with an increase in capital costs, not only for the tank itself but also for labour and excavation. Desludging of tanks is also an expensive process.

The "sludge siphon" system eliminates the need for vacuum tankers and maintenance crews to physically empty an interceptor tank. The accumulated sludge is automatically siphoned out of the tank and flushed, together with the normal effluent, into the settled sewage reticulation system. Once it has entered the pipeline, the sludge from a whole suburb or village can be hydraulically transported to a single easily-accessible settling tank for uncomplicated collection, or perhaps even be transported all the way to a treatment works, where the sludge can be handled in the conventional manner.

URINE DIVERSION SANITATION SYSTEMS

The shortcomings of VIP toilets, particularly in high-density urban areas, are explained. To address these shortcomings, it is necessary to think beyond the limitations imposed by traditional methods of providing dry sanitation. This need is substantiated by increasing awareness worldwide of the environmental issues associated with sanitation. Furthermore, pressure on land to produce more food to feed the ever-growing populations of developing countries has made it imperative to utilise natural resources, including human excreta, wherever possible. The concept of ecological sanitation, or "eco-san" as it is also known, is seen as an alternative solution to some of the problems associated with pit toilets, environmental degradation and food shortages.

The basic requirement of a urine diversion sanitation system is a toilet pedestal which prevents urine and faeces from being mixed together. It is essential that the faeces remain as dry as possible and that moisture is prevented from entering the collection chamber. The urine can be collected in any suitable sealed container if its reuse for agricultural fertilizer is desired. Alternatively, it can be led into a soakpit. The desiccated faeces is, furthermore, a good soil conditioner.

CONCLUDING REMARKS

The research and development of alternative on-site sanitation technologies described in this dissertation was aimed principally at tackling the most common operational problem associated with these systems, namely sludge disposal. Other benefits which accrue due to the application of these new technologies, for example certain environmental improvements, easy and safe reuse of excreta, or lower capital and operational costs, are additional advantages. By offering improved sanitation methods which reduce the operation and maintenance burdens on both users and local authorities, it is believed that a significant contribution has been made to improving the quality of human life across all sectors of society.

KEY WORDS

Dehydration
Desiccation
Dry toilets
Ecological sanitation
Fertiliser
Health
Interceptor tanks
Recycling
Sediment transport
Septic tanks
Settled sewage
Sludge
Small bore systems
Solids-free sewers
STED systems
Urine diversion

SAMEVATTING

INLEIDING

Die verhandeling bestaan hoofsaaklik uit die volgende:

1. 'n Breë inleiding tot die huidige algemene sanitasie toestand in Suid-Afrika asook sommige ander ontwikkelende lande, veral onder die arm bevolkingsdele, word uiteengesit. Daar word aangevoer dat ander toepaslike tegnologieë benodig word om spesifieke probleme aan te spreek.

2. Die ontwikkeling van 'n nuwe soort septiese tenk vir gebruik in besinkte-riool sanitasiestelsels word beskryf. Die tenk word outomaties ontslyk deur middel van 'n hewel-tipe uitlaat meganisme.

3. Die navorsing, ontwikkeling en huidige status van urine-wegwending sanitasie tegnologie in die wêreld word uiteengesit. Die implementering van Suid-Afrika se eerste projek wat van hierdie tegnologie gebruik maak word ook beskryf.

SANITASIE: ALGEMENE ASPEKTE BESPREEK

'n Agtergrond tot die algemene sanitasie toestand in Suid-Afrika en die ontwikkelende wêreld word in hierdie verhandeling uiteengesit, met spesifieke verwysing na die arm bevolkingsdele. Daar word getoon dat huidige sisteme en beskikbare hulpbronne onvoldoende is om die ernstige probleme wat bestaan aan te pak, en dat, alvorens daar 'n betekenisvolle verandering intree in die manier waarop sanitasie stelsels gekies, ontwerp en implementeeer word, hierdie toestand nie sal verbeter nie. Die omgewing van miljoene mense wêreldwyd word deur groot hoeveelhede fekale materiaal en riool besoedel. Hierdie omgewingsprobleme ondermyn weer op hulle beurt die ontwikkelingsproses.

Sanitasie benaderings wat op spoeltoilette, riole en sentrale suiweringswerke gebaseer word kan hierdie probleem nie oplos nie. Puttoilette of septiese tenks met sypelriole is ook nie 'n oplossing in dig-bewoonde stedelike gebiede nie. Sanitasiesisteme moet vir sekere projek en omstandighede toepaslik wees. Dit is daarom belangrik dat daar verder as die huidige beperkinge gesoek word vir maniere en middele om voldoende sanitasiegeriewe vir die miljoene mense wat daarsonder is te verskaf. Navorsing en ontwikkeling vir 'n wye reeks kulturele en omgewingstoestande word benodig, 'n aanvraag vir sisteme wat menslike uitskeiding hersirkuleer behoort geskep te word, afhanklikheid van sisteme wat groot volumes drinkbare water gebruik moet verminder word, en sisteme wat eenvoudig, betroubaar en maklik onderhou kan word behoort bevorder te word.

DIE "SLYKHEWEL" SELF-REINIGENDE SEPTIESE TENK VIR BESINKTE-RIOOL SANITASIESTELSELS

Septiese tenks in 'n besinkte-riool stelsel moet vir verskeie funksies ontwerp word, naamlik opvang van vaste stowwe, vertering van vaste stowwe asook opgaring van vaste stowwe. Septiese tenks word gewoonlik ontwerp om tot soveel as twee-derdes van die volume vir slykopbouing te reserveer; dus, hoe groter die ontslykings tussenposes, hoe groter moet die tenk wees. Dit gaan gepaard met 'n toename in kapitaalkostes, nie alleen vir die tenk self nie maar ook vir arbeid en uitgrawing. Die ontslyking van tenks is ook 'n duur proses.

Met 'n "slykhewel" sisteeem word suigtenkwaens en onderhoudspanne nie benodig om septiese tenks te ontslyk nie. Die opgehoopte slyk word outomaties uit die tenk gesuig en, tesame met die normale uitvloeisel, in die besinkte riool retikulasiesisteem weggespoel. Sodra dit die pyplyn binnegegaan, kan die slyk vanaf 'n hele voorstad of dorpie na 'n maklik bereikbare besinkingstenk hidroulies vervoer word, waarvandaan dit sonder enige probleme verwyder kan word. Die slyk kan dalk ook hidroulies na 'n suiweringswerke vir konvensionele behandeling vervoer word.

URINE-WEGWENDING SANITASIESTELSELS

Die tekortkominge van VIP ("Ventilated Improved Pit")-toilette, veral in digbewoonde stedelike gebiede, word uiteengesit. Om hierdie tekortkominge aan te spreek is dit nodig om verby die beperkings wat deur tradisionele droë sanitasie metodes gestel word te kyk. Die stelling word gestaaf deur toenemende wêreldwye bewuswording van omgewingsaspekte rondom sanitasie. Daarbenewens, die druk wat in ontwikkelende lande op grond uitgeoefen word om meer voedsel vir die steeds toenemende bevolkingsgroei te produseer het dit noodsaaklik gemaak om natuurlike hulpbronne, insluitende menslike uitskeiding, sover moontlik vir hierdie doel aan te wend. Die konsep van ekologiese sanitasie, ook bekend as "eco-san", word as 'n alternatiewe oplossing vir die probleme wat met puttoilette, omgewingsdegenerasie en voedseltekorte gepaard gaan, beskou.

Die basiese vereiste van 'n urine-wegwending sanitasiestelsel is 'n toiletpan wat vermenging van urine en fekalieë verhoed. Dit is noodsaaklik dat die fekale materiaal so droog as moontlik bly, en dat vog nie die stoorkompartement binnedring nie. Die urine kan in enige geskikte verseëlde houer versamel word vir hergebruik as landboubemesting, indien verlang. Dit kan alternatiewelik na 'n sypelput gelei word. Die uitgedroogde fekale materiaal is ook 'n goeie grondopknapper.

SLOTSOM

Die navorsing en ontwikkeling van alternatiewe "op-erf" sanitasiestelsels, soos in hierdie verhandeling beskryf, is hoofsaaklik daarop gemik om die mees algemene operasionele probleem wat met hierdie sisteme gepaard gaan, naamlik slykwegdoening, aan te spreek. Verdere waarde wat deur die gebruik van hierdie stelsels verkry word, soos byvoorbeeld sekere omgewingsverbeteringe, maklike en veilige hergebruik van uitskeiding, of laer kapitaal- en gebruikskostes, word as addisionele voordele beskou. Deur verbeterde sanitasiestelsels wat die operasionele las op beide gebruikers en plaaslike owerhede verminder aan te bied, word geglo dat 'n betekenisvolle bydrae tot die verbetering van mense se lewenskwaliteit in alle aspekte van die samelewing gemaak is.

SLEUTELWOORDE

Dehydration
Desiccation
Dry toilets
Ecological sanitation
Fertiliser
Health
Interceptor tanks
Recycling
Sediment transport
Septic tanks
Settled sewage
Sludge
Small bore systems
Solids-free sewers
STED systems
Urine diversion

ACKNOWLEDGEMENTS

I wish to express my grateful appreciation to the following, without whom the research projects and writing of this dissertation would not have been possible:

- Almighty God, whose divine grace gave me the required courage, strength and perseverance to overcome certain obstacles which stood in my way.
- My wife and family, who supported me through some difficult times and put up with my frequent non-availability for a period of more than two years.
- The management of CSIR Building and Construction Technology, for a considerable measure of financial support and encouragement during the course of the research projects and other studies.
- My technician, Andy Murdoch, whose unfailing support, enthusiasm and inventiveness, as well as specialised plumbing skills, considerably facilitated the development of the sludge siphon.
- Louiza Duncker, anthropologist, who ensured the success of the urine diversion sanitation project, and for making me aware that not all problems can be solved by the application of engineering principles.
- The CEO and staff of the Eastern Cape Appropriate Technology Unit (ECATU), for financing the construction of the urine diversion toilet units and for invaluable assistance with the community work.
- Isabel Ringel and Michael Mavuso of the Boutek Information Centre, for vital assistance in obtaining a myriad of reference documents, which they always did with remarkable efficiency and friendliness.
- Professor S J van Vuuren, my supervisor, for his valuable guidance, constructive criticism, support and patience.
- Jurgen Hartel and Jack Wiid, directors of Pioneer Plastics (Pty) Ltd, for their enthusiastic support of the sludge siphon research and for providing the experimental tanks free of charge.
- Ronnie Böhmer, Issie Oberholzer and Lineke Slump of the Boutek drawing office, for production of illustrations and friendly service, even when asked to revise various drawings a number of times.
- Pauline Coubrough and Martella du Preez of CSIR Environmentek, for laboratory analysis of various materials originating in the urine diversion toilets, and especially for their time and patience in explaining some of the finer points of microbiology and parasitology to me.

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CHAPTER 1

INTRODUCTION

"It is a duty, not only to acquire learning by reading, but also, once having acquired it, to make oneself of use to people outside, by what one can say or write."

Ecclesiasticus: Foreword 4 - 6
(132 BC)

CHAPTER 1: INTRODUCTION

1.1 STRUCTURE OF THE DISSERTATION

1.1.1 General

This dissertation is submitted in partial fulfilment of the requirements for the degree of M.Eng (Water resources engineering) at the University of Pretoria. The purpose of the dissertation is fourfold, namely:

1. To give a broad introduction to the general sanitation situation in South Africa and some other developing countries, particularly among the poorer sections of the population, and to explain why conventional sanitation options are not always suitable for solving the serious problems that exist. Chapters 2 and 3 discuss these aspects. It is argued that there is a need for other appropriate technologies to address specific problems.
2. To introduce and describe the development (Chapters 4 to 6) of a new type of interceptor tank for use in settled sewage sanitation systems. This tank is able to desludge itself (i.e. extract the accumulated sludge) automatically without the need of a vacuum tanker or maintenance crew, by means of a siphonic-type outlet mechanism designed and patented by the author on behalf of CSIR Building and Construction Technology (Boutek).
3. To explain the research, development and current status of urine diversion sanitation technology in the world (Chapters 7 and 8). The implementation of South Africa's first project utilising this concept, which was piloted by the author on behalf of Boutek, is also fully described (Chapter 9).
4. To produce preliminary guidelines for the design, construction and operation of the two sanitation technologies mentioned in 2 and 3 above.

As a background to the argument for the introduction of other sanitation technologies, the dissertation commences with a broad discussion on the importance of sanitation in combatting disease and protecting the environment. This discussion includes the influence of different cultures on the choice of sanitation technology, as well as the various types of sanitation systems available and their associated methods of treatment and disposal of excreta. Reasons for successes or failures of various sanitation systems are also discussed. This is followed by an in-depth presentation of the two sanitation technologies mentioned above, as well as preliminary guidelines for their design, construction and operation. Because these two systems are new in the country and are presently being implemented for the first time, it is not possible to provide detailed or final guidelines at this stage. Research is still continuing, not only into the technical aspects such as design, operation and maintenance, but also into social factors like cultural acceptance and behaviour. It is the intention, however, to produce detailed guidelines which will eventually be included in Boutek's publication "Guidelines for human settlement planning and design", commonly known as the "Red Book". The author's employer, Boutek, is the custodian of the Red Book, on behalf of the Department of Housing, and is responsible for the book's continual updating.

1.1.2 Definition of some terms used in this dissertation

For the purpose of this dissertation, the word "sanitation" is taken to mean the safe management of human excreta. It therefore includes the "hardware" (toilets and sewers) and the "software" (regulation, hygiene promotion, etc) needed to reduce disease transmission. It also encompasses the re-use and ultimate disposal of human excreta.

A "wet" sanitation system is a generic term used to define systems which use water to dispose of human excreta, for example waterborne sewerage or septic tanks. A "dry" sanitation system, on the other hand, commonly refers to a toilet in which water is not added for the purpose of disposing or treating of excreta, for example pit toilets and other kinds of composting systems.

1.2 HYDRAULIC DISPOSAL OF INTERCEPTOR TANK SLUDGE IN SETTLED SEWAGE RETICULATION SYSTEMS

Septic tanks are regarded as an "intermediate" sanitation technology. This is so because, in South Africa at least, the lowest level of service recognized by the Government, and for which a subsidy will be granted for its implementation, is a ventilated improved pit (VIP) toilet. At the top end of the scale, the highest level of service is an in-house flushing toilet with a waterborne sewerage system. A septic tank, operating off a flushing toilet, bath, washbasin, kitchen sink, etc, and draining the effluent into a soakpit near the tank, is a commonly used technology fitting in between these two levels of service. This is an example of on-site sanitation, where partial treatment of the waste takes place on the site, i.e. in the septic tank itself, as well as in the soakpit. The settleable solids sink to the bottom of the tank as sludge, while the partially-treated effluent leaves the tank and drains into the ground, where further bacteriological treatment takes place.

Septic tanks together with their drainfields (also called soakpits, soakaways or french drains) represent a fairly high level of sanitation service, in the sense that they allow flushing toilets and sullage disposal. These systems have generally worked satisfactorily and without any problems on farms or plots, where space is plentiful and size of drainfield is not an important issue. There are situations, however, where these systems are inappropriate, for example in areas of relatively impermeable soil, where a drainfield cannot function efficiently. Septic tanks connected to drainfields are also inappropriate in areas with a shallow water table, where aquifer pollution is a very real possibility. Also, regions which are densely populated, with a relatively high concentration of septic tanks, may eventually result in the absorption capacity of the soil being exceeded, with concomitant environmental pollution.

Such limitations in the use of drainfields have led to the development of settled sewage technology. In these systems the effluent from all the septic tanks in an area, instead of soaking into the ground, is collected by a reticulation system of relatively small diameter pipes and led either to a formal treatment plant, or to stabilisation ponds or a wetland system for secondary treatment. Also known as "STED" (septic tank effluent drainage), "solids-free", "small-bore" or "variable-grade" sewer systems, settled sewage technology offers an efficient, healthy and environmentally friendly sanitation system if properly engineered and implemented (Austin 1996).

While settled sewage technology has been used for decades in other countries (e.g. Australia, Zambia and the USA), the installation of these systems in South Africa is still a relatively new experience, with the first projects only being commissioned during 1989 (Austin 1996). It has been found that a settled sewage installation, properly designed and operated, is not only a sound sanitation system but also a technology which, in many cases, can offer easier construction, lower maintenance requirements, cheaper treatment of effluent and generally lower overall cost when compared to a conventional waterborne system. The technology offers a viable alternative in situations where the provision of VIP toilets is problematic due to, for instance, geotechnical conditions. It is also an option where high population densities or poor soil conditions preclude the use of ordinary septic tanks with drainfields, or where the community desires a higher level of service but cannot necessarily afford a conventional waterborne system. This technology should also be considered in cases where the level of water supply is such that a waterborne sanitation system is not an option, for example where the community has access to yard taps only. Even where a full in-house water supply exists, there are many areas in the country, in both low and high income communities, where no conventional waterborne sanitation service is available but where a settled sewage system could offer a level of service higher than a conservancy tank or a septic tank with drainfield. In fact the level of service offered by a settled sewage system is virtually equivalent to that offered by a full waterborne system.

As with any sanitation system, there are certain disadvantages of settled sewage technology which need to be taken into account when considering the various alternatives available. One of the most important factors to be considered is the need for periodic desludging of the interceptor tanks (see chapter 4 for a description of the role of interceptor tanks). This task, illustrated in Figure 1.1, can comprise a large portion of the operation and maintenance costs of the system, as the local authority has to maintain vacuum tankers for this purpose (the number of tankers required will depend on the population served). Alternatively, private contractors may charge the householder between R300 and R500 (1999 rands), depending on the size of the load. In this respect the income level of the community is an important factor, as in all probability this represents an unaffordable amount to a poor family.

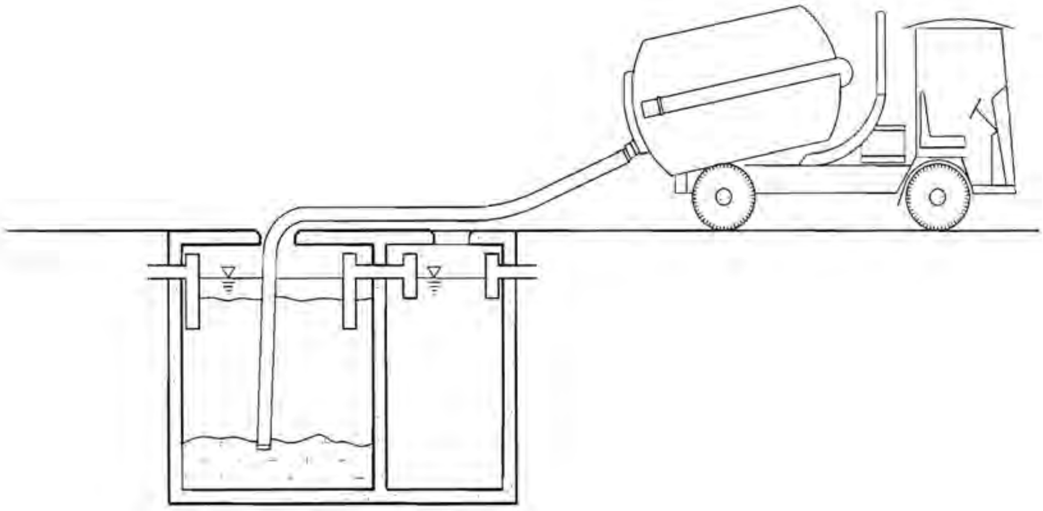


Figure 1.1: Emptying a septic tank by means of a vacuum tanker

Whether or not a settled sewage system operates without any problems, vacuum tankers are still required to desludge the interceptor tanks at certain intervals. In some areas this will be merely a nuisance and possibly a short-lived eyesore for the residents, while in other areas it may be a major undertaking. Where roads are in poor condition it is difficult, and sometimes impossible, for conventional vacuum tankers to reach the affected houses. In other areas, settlement densification often results in additional houses or shacks being constructed in between existing dwellings, thus making it problematic to gain access to the tanks. In some cases the interceptor tanks have to be emptied manually. Apart from the unpleasantness of the task, this may also be dangerous for the people involved, as toxic, anoxic or explosive atmospheres may result from the accumulation of gases produced in the tank (Otis & Mara 1985).

An alternative method of desludging interceptor tanks in a settled sewage system, which would reduce or possibly even eliminate the need for vacuum tankers to gain access to individual tanks, is thus proposed. This dissertation describes the conceptualisation and development of such a system. The accumulated sludge in an interceptor tank is automatically flushed into the reticulation network of the settled sewage system, and a vacuum tanker is not required for this task. The conceptualised process involves a siphon which is automatically activated by an inflow of wastewater into the interceptor tank. Once the sludge enters the outfall pipeline, it is transported hydraulically in the reticulation system, thereby obviating the need for it to be pumped out of the tank by mechanical means. The process of developing this system required an assessment of various hydraulic parameters such as flow volume, pipeline gradient, required pressure head, friction losses, etc.

1.3 URINE DIVERSION TECHNOLOGY AS AN ALTERNATIVE TO VIP TOILETS

The basic level of sanitation service in South Africa has been defined as a "ventilated improved pit (VIP) toilet in a variety of forms, or its equivalent, as long as it meets certain minimum requirements in terms of cost, sturdiness, health benefits and environmental impact" (DWAF 1996). Many community sanitation schemes have been successfully implemented utilising this technology. Unfortunately, others have failed, usually due to poor design and construction practices or to social factors such as lack of community buy-in, or a combination of these. New or unknown technologies are often viewed with suspicion or rejected out of hand. Some cultural beliefs and practices may also make it difficult to introduce alternative technologies into a community. Attempts have been made to find simple, universally applicable solutions to sanitation problems; however, these often fail because the diversity of needs and contexts is ignored. Urban needs usually differ from rural needs, the technological options offered are limited and often inappropriate, and critical social issues such as behaviour are either ignored altogether or badly handled (Simpson-Hébert 1995). Furthermore, the scope of environmental protection becomes so broad that the main purpose of sanitation provision is often lost. Current approaches also tend to stifle innovation.

VIP toilets, correctly engineered and implemented, are an excellent means of providing sanitation in areas where financial factors preclude the provision of a higher level of service. These systems are not without their problems, however. Geotechnical conditions, such as hard or rocky ground for instance, often militate against the choice of this technology. In other cases, non-cohesive soils will require a pit to be fully lined in order to prevent collapse of the structure. Pits should also be avoided in areas with shallow water tables, especially in fracture-flow type of aquifers, where rapid transmission of pollutants is possible.

Full pits are a further problem. In many cases the owners will not be in a financial position to empty them, even if the toilets have been constructed with this in mind. While there may be plenty of available space in rural areas to dig further pits, this will seldom be the case in high-density urban areas. This aspect does not even take the cost of digging a new pit and moving or rebuilding the superstructure into account, so for all practical purposes the initial investment is lost after 10 or 15 years. Some other solution should be sought in these cases. If a dry toilet is designed and constructed in such a way that the faeces receptacle can be quickly, easily and safely emptied, then one of the biggest operation and maintenance problems associated with these toilets will be obviated. If the excreta can also be productively and safely used, for example in agriculture, the technology will become even more attractive. In South Africa, where many rural communities rely on subsistence agriculture, often in poor soils, and with urban agriculture becoming more common in certain communities, this is an important aspect.

The technology of ecological sanitation, or "dry box" toilets, has been used successfully for decades in many developing countries, e.g. Vietnam, China, Mexico, El Salvador and other Central and South American states. Even in a highly developed country such as Sweden there is a great deal of interest in the technology (Esrey et al 1998; Hanaeus et al 1997; Höglund et al 1998; Jönsson 1997; Wolgast 1993). The most important difference between this technology and that of composting is the moisture content in the faeces receptacle. The urine is diverted at source by a specially designed pedestal and is not mixed with the faeces. A schematic representation is illustrated in Figure 1.2. A pit is not necessary as the entire structure may be constructed above ground, or may even be inside the dwelling. Ash, dry soil or sawdust is sprinkled over the faeces after each bowel movement. This serves to absorb the moisture and control odours and flies. The generally dry conditions in the faeces receptacle facilitate the desiccation of the contents, which thus become safe for handling within a relatively short time. The desiccated faecal matter makes a good soil conditioner, while the urine, when diluted with water, is an excellent source of fertilizer, being rich in nitrogen, phosphorus and potassium.

The most common sanitation technologies, be they pit toilets or waterborne sewerage, are based on the notion of human excreta as an unpleasant and dangerous waste product requiring disposal. The urine diversion or "dry box" toilet, however, is based on the notion of human excreta as a **resource** (Winblad 1993). Urine is basically water and dissolved micronutrients. Most of the nitrogen (N), phosphorus (P) and potassium (K) in human excreta are to be found in the urine, and the total amount of N+P+K in one person's urine each year is approximately 7 kg. As will be shown in chapter 7, this is enough to produce 230 kg of cereal. While faeces contain much less of these constituents, the important point is that when they are dehydrated they become odourless, while most of the bacteria and viruses are destroyed. A valuable soil conditioner is thus obtained, which ought not to be wasted (Winblad 1996a).

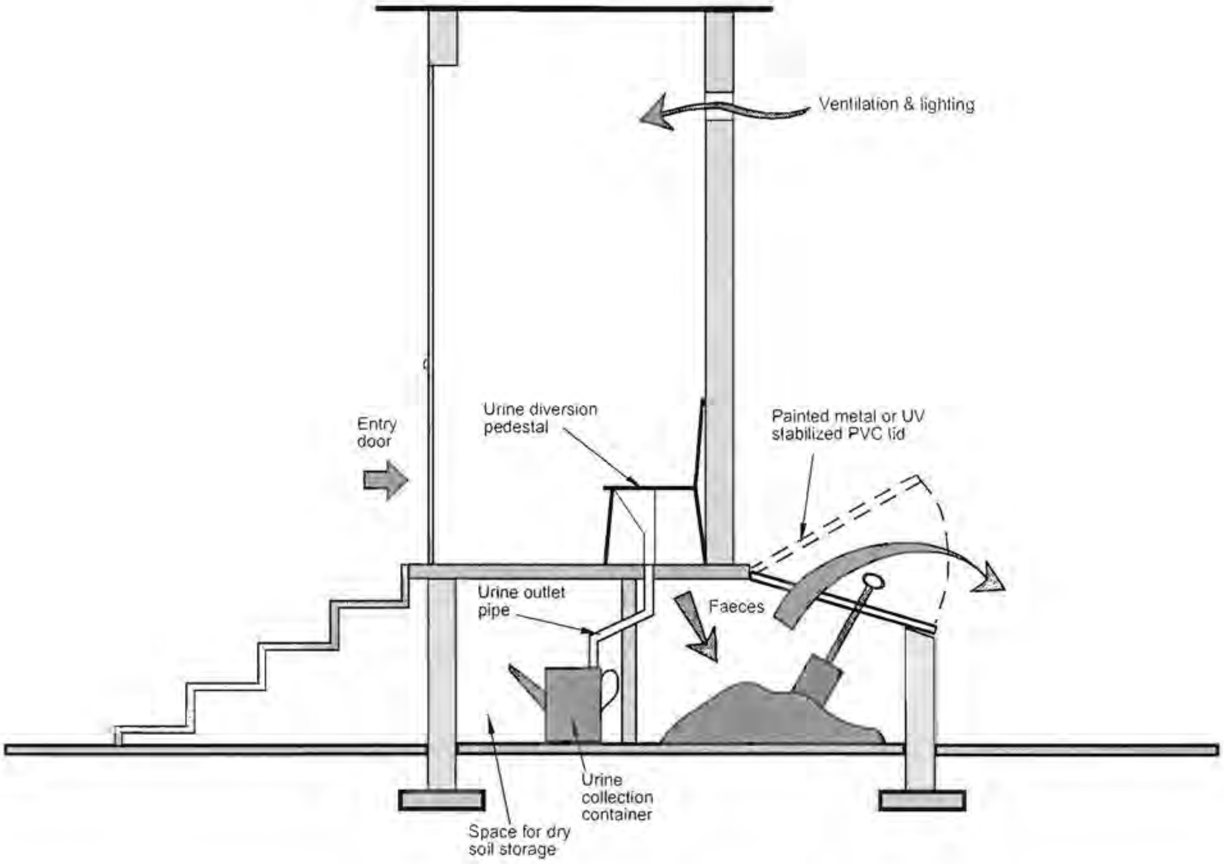


Figure 1.2: Schematic representation of a urine diversion ("dry-box") toilet

CHAPTER 2

THE IMPORTANCE OF SANITATION

"You are to have a place outside the camp where you can go when you need to relieve yourselves. Carry a stick as part of your equipment, so that when you have a bowel movement you can dig a hole and cover it up."

Moses' instructions to the ancient Israelites on keeping the military camp clean. Deuteronomy 23:12.

CHAPTER 2: THE IMPORTANCE OF SANITATION

2.1 SANITATION AND THE ENVIRONMENT

As a result of faulty sanitation systems design, their incomplete implementation, poor operation and improper use, human excreta are spread throughout the environment. Vast amounts of improperly-managed faeces and untreated sewage contaminate the living environment of millions of people, soils and water bodies. Existing systems and available resources are inadequate to deal with the associated social and behavioural factors. This inability of existing sanitation systems to properly manage the increasing volumes of human excreta has contributed much to the worldwide escalation in ecological problems. With the rapid population growth taking place, especially in urban areas, the situation will not improve unless there is a significant change in the manner in which sanitation systems are chosen, designed and implemented (Simpson-Hébert 1997).

Environmental problems in turn undermine the process of development, which is further hampered by rapid population growth. In all developing countries, especially in sub-Saharan Africa, the growth of the population in the urban areas alone is outstripping the capacity of these regions to provide for basic needs such as shelter, water and sanitation. In the city of Dar es Salaam in Tanzania, for example, pit toilets and septic tanks with drainfields serve about 76 % of the population, and this has caused serious faecal pollution of the groundwater, which is generally only 1 m to 3 m below ground level. Faecal coliform levels of up to 3 000/100 mℓ have been recorded (Kaseva 1999). This should be seen against the fact that continuous exposure to drinking water with faecal coliform levels above 10/100 mℓ represents a risk of infectious disease transmission.

Water quality is deteriorating all over the world due to pollution. Some cities in the developing world treat only about 10 % of their sewage (Björklund 1997). Even in South Africa, recent reports have indicated that an alarming proportion of sewage waste in many towns and cities across the country does not reach treatment plants, but flows untreated into the rivers. This is regarded as one of the most pressing water quality problems. In many cases, even when sewage waste reaches the treatment plant, poor operation or malfunctioning systems means that partially treated sewage effluent is discharged to rivers. Litter and other pollutants from poorly serviced areas have also impacted the natural functioning of river ecosystems to such an extent that many rivers near urban areas have lost their ability to assimilate pollutants (DWAF 1999).

One of the constraints to providing efficient sanitation in urban areas is the myth that the only good sanitation system in such places is conventional waterborne sewerage. While this type of sanitation system has been widely successful in controlling the transmission of excreta-related diseases in most cities of industrialised countries, it has also created severe damage to ecosystems and to natural water resources where the wastewater was inadequately treated. Since proper treatment increases the cost and energy requirements of the entire system without being essential to the day-to-day survival of the individual user, this part of the system was often omitted when financial resources were scarce. Consequently, in those cities of developing countries that have a conventional sewer system, only a very small percentage of the wastewater collected is treated at all. In many areas this has resulted in severe ecological damage, with heavy economic consequences (Simpson-Hébert 1997).

Globally, sewage discharges from centralised, waterborne collection systems are a major component of water pollution, contributing to the nutrient overload of water bodies. Although waterborne systems are acceptable to the vast majority of people, they are technologically complex and require institutional capacity and skills that are not always available in Third World cities. Over 90 % of all sewage in developing countries (98 % in Latin America) is discharged completely untreated (Esrey et al 1998).

The success or failure of a sanitation system depends on the interaction of environmental, human and technical factors. The most important environmental aspects are climate, soil and groundwater; these vary from place to place and have a great influence on the choice of the most appropriate sanitation system. The technology selected should therefore be adapted to the local environmental conditions (Winblad and Kilama 1980).

It is better to protect the environment from faecal pollution than to undertake expensive measures to reduce pollution when it has already taken place (Feachem and Cairncross 1978). The approach to the sanitation challenge should be ecologically sustainable, i.e. concerned with the protection of the environment. This means that sanitation systems should neither pollute ecosystems nor deplete scarce resources. It further implies that sanitation systems should not lead to degrading water or land and should, where possible, ameliorate existing problems caused by pollution. Sanitation systems should also be designed to recycle resources such as water and nutrients present in human excreta (Simpson-Hébert 1997).

2.2 SANITATION AND DISEASE

A large number of diseases are spread directly through man's contact with human excrement, indirectly via water, food and soil, or via carriers and vectors like flies, cockroaches and mosquitoes. These dangers of poor sanitation are compounded by increasing population densities. When people move from isolated farms or rural tracts into villages or urban squatter areas, they may be better off in a number of ways, but certainly not with respect to sanitation. Simple disposal methods like defecation in the bush, in fields or in open pits may have few adverse effects for small, scattered populations, but when used in densely built up areas, such practices are positively dangerous (Winblad and Kilama 1980).

Despite all efforts during the International Drinking Water Supply and Sanitation Decade (1981 - 1990), more than 2 500 million people in the developing world still do not have access to hygienic means of personal sanitation. The result has been "a horrifying toll in death and debilitating disease" (IRC 1999). Even at the start of the 21st century, diarrhoeal and other sanitation-related diseases remain highly endemic, despite large-scale attempts over the past few decades to control them. Human excreta is spread throughout the environment as a result of faulty sanitation systems design, their incomplete implementation, poor operation and improper use. Existing systems and available resources do not deal adequately with the associated social and behavioural factors. The inability of existing sanitation systems to manage adequately the increasing volumes of human excreta is the main cause of the high incidence of infectious diseases in most developing countries (Simpson-Hébert 1997).

Health promotion and protection from disease for both the user and the general public are important principles of sanitation provision. This means that sanitation systems must be capable of protecting people from acquiring excreta-related diseases as well as interrupting the cycle of disease transmission. Sanitation technologies should therefore have the demonstrated capacity to prevent the transmission of pathogens (Simpson-Hébert 1997).

Every year millions of people die from diarrhoea that could have been prevented by good sanitation, while millions more suffer nutritional, educational and economic loss through diarrhoeal diseases which proper sanitation could have prevented. Poor sanitation has led to the infection of nearly a billion people, largely children, with a variety of worm infections. Human excreta are also responsible for the transmission of schistosomiasis (bilharzia), cholera, typhoid and many other infectious diseases affecting hundreds of millions of people. While heavy investments have been made in water supply since 1980, the resulting health benefits have been severely limited by the poor progress in sanitation (Simpson-Hébert 1995).

Sanitation, hygiene and safe water can be considered to be the main barriers between the health of people and exposure to disease, with sanitation being the primary factor. Without sanitation the environment is exposed to pathogens. Improved water supply alone is not enough to break the disease cycle. Research on the joint effect of three types of water and sanitation systems (unimproved, intermediate and optimum) on incidents of diarrhoea and the nutritional status of young children, has shown that the highest rates of diarrhoea were found among children without improved sanitation, regardless of the level of water supply in operation (de Jong 1996).

The major communicable diseases whose incidence can be reduced by the introduction of safe excreta disposal are intestinal infections and helminth infestations, including cholera, typhoid and paratyphoid fevers, dysentery, diarrhoea, hookworm, schistosomiasis and filariasis (Franceys, Pickford and Reed, 1992). *Culex* mosquitoes in particular, which are the cause of filariasis and elephantiasis, breed in organically polluted water found in blocked drains, flooded pit toilets and overflowing septic tanks (Kolsky 1997). Table 2.1 lists some of the pathogenic organisms frequently found in faeces, urine and sullage (greywater).

Table 2.1: Occurrence of some pathogens in fresh urine,* faeces and sullage (Franceys, Pickford and Reed 1992)

Pathogen	**Common name for infection caused**	**Present in:**		
		Urine	**Faeces**	**Sullage**
Bacteria				
Escherichia coli	diarrhoea	•	•	•
Leptospira interrogans	leptospirosis	•		
Salmonella typhi	typhoid	•	•	•
Shigella spp	shigellosis		•	
Vibrio cholerae	cholera		•	
Viruses				
Poliovirus	poliomyelitis		•	•
Rotaviruses	enteritis		•	
Protozoa - amoeba or cysts				
Entamoeba histolytica	amoebiasis		•	•
Giardia intestinalis	giardiasis		•	•
Helminths - parasite eggs				
Ascaris lumbricoides	roundworm		•	•
Fasciola hepatica	liver fluke		•	
Ancylostoma duodenale	hookworm		•	•
Necator americanus	hookworm		•	•
Schistosoma spp	schistosomiasis	•	•	•
Taenia spp	tapeworm		•	•
Trichuris trichiura	whipworm		•	•

* Urine is usually sterile; the presence of pathogens indicates either faecal pollution or host infection, principally with *Salmonella typhi*, *Schistosoma haematobium* or *Leptospirosa*.

Those most at risk of contracting these diseases are children under five years of age, as their immune systems are not fully developed and may be further impaired by malnutrition. The diarrhoeal diseases are by far the major underlying cause of mortality in this age group, accounting for some 4 million deaths each year (Franceys, Pickford and Reed 1992).

Humans themselves are the main reservoir of most diseases that affect them. Transmission of excreta-related diseases from one host to another (or the same host) normally follows one of the routes shown in Figure 2.1. Poor domestic and personal hygiene, indicated by routes involving food and hands, often diminishes or even negates any positive impact of improved excreta disposal on community health. Technology by itself cannot break the cycle of disease transmission and accompanying ill health if hygiene awareness in a community is at a low level.

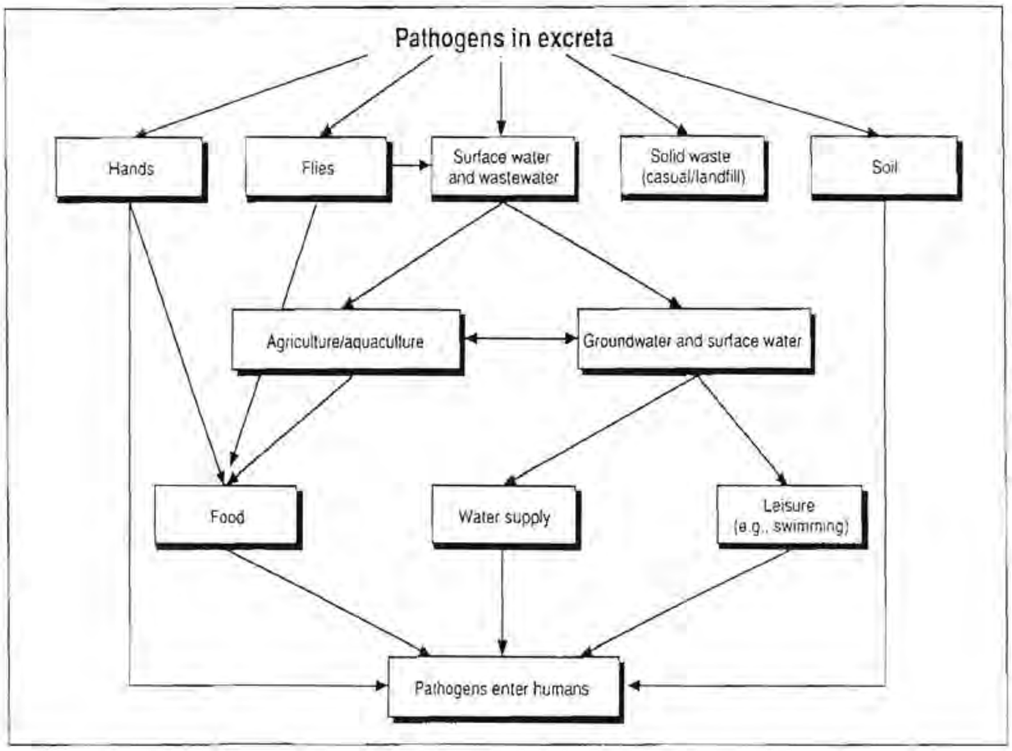


Figure 2.1: Transmission routes for pathogens found in excreta
(Franceys, Pickford and Reed 1992)

2.3 THE CURRENT SITUATION IN DEVELOPING COUNTRIES

2.3.1 General

In many cities, towns and rural areas of the world today, people live and raise their children in highly polluted environments. Urban and peri-urban areas in developing countries are among the worst polluted and disease ridden habitats of the world. Much of this pollution, which leads to high rates of disease, sickness and death, is caused by a lack of toilets and inadequate sanitation services. This lack of sufficient services is a result of many factors, such as inadequate financial resources, insufficient water, lack of space, difficult soil conditions and limited institutional capabilities. As cities expand and populations increase, the situation will grow worse (Esrey et al 1998).

In 1983 the World Health Organisation estimated that in the developing regions of Africa, Asia, Latin America and the Pacific, less than a third of the population had access to adequate sanitation. While urban areas were generally better endowed with some form of sanitation, less than 12 % of the rural people were so served. In most developing regions of the world, rural people traditionally use the field or the bush for defecation. Rural settlements, especially scattered communities, do not have the aesthetic incentive to demand sanitation and rely instead on the natural assimilative capacity of the surrounding countryside to serve their needs (UNCHS 1986).

In many urban centres, poorest groups face the most serious environmental hazards and the least possibility of avoiding them or receiving treatment to limit their health impact (Wall 1997). By early in the 21st century, more than half of the world's population is predicted to be living in urban areas. By the year 2025, this urban population could rise to 60 %, comprising some 5 billion people. The rapid urban population growth is putting severe strains on the water supply and sanitation services in most major conurbations, especially those in developing countries (Mara 1996). In Africa today, over half the population is without access to safe drinking water and two-thirds lack a sanitary means of excreta disposal. It is a situation in which the poor are adversely affected to a disproportionate degree. Lack of access to these most basic of services necessary to sustain life lies at the root of many of Africa's current health, environmental, social, economic and political problems. Hundreds of thousands of African children die annually from water- and sanitation-related diseases. Despite significant improvements during the International Drinking Water Supply and Sanitation Decade, progress has now stagnated. More people are today without adequate services in Africa than in 1990, and at the current rate of progress full coverage will never be achieved (WSSCC 1998a).

The excreta of most urban dwellers in developing countries are disposed of through on-site sanitation systems such as pit toilets and septic tanks. This is in contrast to industrialised countries where excreta are disposed of via flush toilets, city-wide sewerage systems and central wastewater treatment works, all of which constitute standard technologies. However, these are unaffordable to most urban inhabitants of developing countries. A major problem resulting from this is that faecal sludges collected from on-site sanitation installations are commonly disposed of untreated (Strauss and Heinss 1998). The problem is growing, and over the next few decades most Third World urban growth will take place in peri-urban areas without access to basic services (Winblad 1996a).

The task for developing countries is considerably more difficult than for industrialised countries, even though the problems they face, viz. high costs and limited resources, are similar. Water in developing countries is generally much more seriously degraded and is still deteriorating rapidly. At the same time, far fewer financial resources are available for environmental protection, and institutional capacity is weaker (Wall 1997). In the urban areas of El Salvador, for instance, the wastewaters entering the reticulated sewer systems are presently not treated, but are discharged directly into ravines and rivers (Mejia 1997). In Vietnam most of the rivers, canals, lakes and ponds are seriously polluted with human excreta and untreated waste from hospitals, clinics and factories, as well as the uncontrolled use of insecticides in agriculture (Song 1997). In the city of Shanghai, China, about 20 % of the human waste is dumped untreated into rivers (Robson 1991).

Governments tend to base their expenditure on water and sanitation on political and social considerations rather than on purely economic criteria. In many countries this has led to heavy dependence on centralised command and control. The result has in many cases been unreliable projects that produce services but do not meet consumers' needs and for which they are therefore unwilling to pay. The absence of financial discipline, accountability for performance and political interference has furthermore often been the cause of inefficient operations, inadequate maintenance and financial losses (Wall 1997).

The failure of various sanitation technologies to prevent pollution is of particular concern to the Pacific island countries, for example the Cook islands, Micronesia, Kiribati and the Marshall islands. Nearly every Pacific island nation has identified critical environmental and public health problems resulting from the disposal of human excreta. These have included algal blooms and eutrophication in lagoons, dying coral reefs, contaminated drinking water wells and outbreaks of gastro-intestinal diseases and cholera. The causes of this pollution include overflowing latrines, privies, water-seal toilets, septic systems and sewage treatment plants, as well as the complete lack of sanitation facilities in some places (Rapaport 1997).

2.3.2 Why sanitation isn't happening

Despite years of rhetoric, good intentions and hard work, very little progress has been made in improving sanitary conditions for much of the world's population. Without major changes, the number of people without access to sanitary excreta management will not change, remaining above 3 000 million people. Professionals involved in sanitation agree that, with some exceptions, mankind is either losing ground or barely holding the line in its ability to dispose of wastes in a healthy, safe and ecologically sound manner (WSSCC 1998b).

The infrastructure challenges facing developing countries in the water and sanitation sector are formidable. Rapid population growth and urbanisation are stretching the limits of institutional capacities and natural ecosystems. Government budgets cannot accommodate competing demands for investment resources, and many public institutions suffer from weak management. Many initiatives also fall short because they are inflexible and unsustainable for a variety of reasons (Wall 1997).

The Water Supply and Sanitation Collaborative Council Working Group on the Promotion of Sanitation (WSSCC) has found that the barriers to progress are varied and complex, but can generally be grouped into nine linked and overlapping categories (Simpson-Hébert 1995):

1. *Lack of political will*:

There is little political incentive for governments to deal with a difficult subject. Politicians rarely lose their jobs because of poor sanitation, particularly as the people most in need have the least power.

2. *Low prestige and recognition*:

Low-cost sanitation facilities and hygiene promotion campaigns have never been prestigious. Politicians and movie stars do not demonstrate latrines. Among consumers, low-cost sanitation has no prestige in comparison with "conventional" waterborne sanitation as used by the industrialised world and by the economic elite of developing countries.

3. *Poor policy at all levels*:

There is too much attention given to water supply at the expense of sanitation, a focus on hardware rather than on long-term behaviour change, and subsidies that favour other than the poor and indigent.

4. *Poor institutional frameworks*:

Generally speaking, governments in developing countries have failed to promote sanitation, and existing institutional frameworks need to change. The institutional frameworks which are in place in some countries tend to fragment responsibilities between government departments and ignore the powerful role that non-governmental organisations and the private sector can play. Since the writing of the South African government's draft White Paper on national sanitation policy (DWAF 1996), however, the situation in this country is changing radically, albeit slowly.

5. *Inadequate and poorly used resources*:

Sanitation is at least as important for health as water supply and is a far more demanding problem, yet sanitation receives far fewer resources.

6. *Inappropriate approaches*:

Attempts are made to find simple, universal solutions which fail by ignoring the diversity of needs and contexts. Urban needs often differ from rural needs, the technological options offered are limited and inappropriate and critical issues of behaviour are ignored or badly handled. Furthermore, the scope of environmental protection and pollution control becomes so broad that the focus on basic household excreta management is lost.

7. *Consumer perceptions and neglect of their preferences*:

Low-cost technologies are often seen by consumers as low-status technologies, while many "appropriate" technologies are far beyond the economic reach of those most in need. Promoters try to sell sanitation facilities on health benefits, when all people really want is the privacy, comfort and status which good sanitation can offer.

8. *Ineffective promotion and low public awareness*:

People don't want to talk or think about faeces, so selling the idea of sanitation is difficult. Those in charge – the engineers and doctors responsible for selling sanitation – are not trained for the job of promotion.

9. *Women and children last*:

Women are potential agents of change in hygiene education and children are the most vulnerable victims, but men usually make the decisions about whether to tackle the problem, and how.

2.3.3 Responses to change

People resist change for many reasons. There may be resentment towards outside "experts" who know little of local customs and who are perceived to benefit more from the innovation than the local people. Leadership may not be united within a community. For example, those with traditional authority who fear a loss of power and status may oppose innovation supported by political or educated elites. New technologies may be aesthetically unacceptable or conflict with established patterns of personal and social behaviour. Furthermore, households vary widely with respect to the resources of money, labour and time available to them and have their own priorities. For those with limited resources, the costs in the short term of an apparently "low-cost" system may be too great when set against their need for food, shelter and clothing (Franceys, Pickford and Reed 1992).

In many cultures the handling of excreta is considered as taboo, and viewed as a disgusting and dangerous nuisance not to be discussed. No one wants to be associated with excreta; even those who reduce its offensive characteristics for others are stigmatized by association. Problems cannot be solved if people do not want to talk about them and do not want to be associated with their solution. What is needed to turn the sanitation sector around is no less than a revolution in thought and action. It is necessary to define principles, make priorities, create strategies and search for new technological, financial and institutional solutions (WSSCC 1998b).

2.4 THE SOUTH AFRICAN EXPERIENCE

"Adequate sanitation" has been defined in a Water Research Commission report as "easy access to a toilet facility close to or in the house/institution, where the toilet has been designed and constructed to prevent contact with faeces either directly or through vectors such as flies, and is regularly used by all members of the household/institution" (WRC 1995). The same report also revealed that approximately 95 % of rural domestic households, 90 % of rural schools and 50 % of rural clinics are without adequate sanitation. Another Water Research Commission report (WRC 1993) disclosed that at least 31 % of people living in the urban areas of the country do not have access to adequate sanitation, but that the actual figure is thought to be much higher.

With respect to sanitation provision in rural areas, there has been an almost complete failure to improve the situation in the abovementioned sectors (houses, schools and clinics). Public intervention has been largely restricted to crisis management where sanitation-related disease outbreaks have occurred or threatened. In the past, no government department assumed responsibility for rural sanitation. However, this responsibility has now been accepted by the Department of Water Affairs and Forestry, while the Department of Health is responsible for the health component of a national rural sanitation programme (WRC 1995).

Inadequately maintained sewer reticulation systems in urban areas have caused adverse environmental impacts, most often as a result of leaking or blocked sewers, but also sometimes as a result of overloaded or inadequately operated or maintained treatment works and failed pumping stations. In poor areas especially, most of the operational difficulties are concentrated at the user end of the systems, due to the fact that personal cleaning materials other than proper toilet tissue paper are used, and also due to a lack of education on the proper use of cistern flush toilets (WRC 1993).

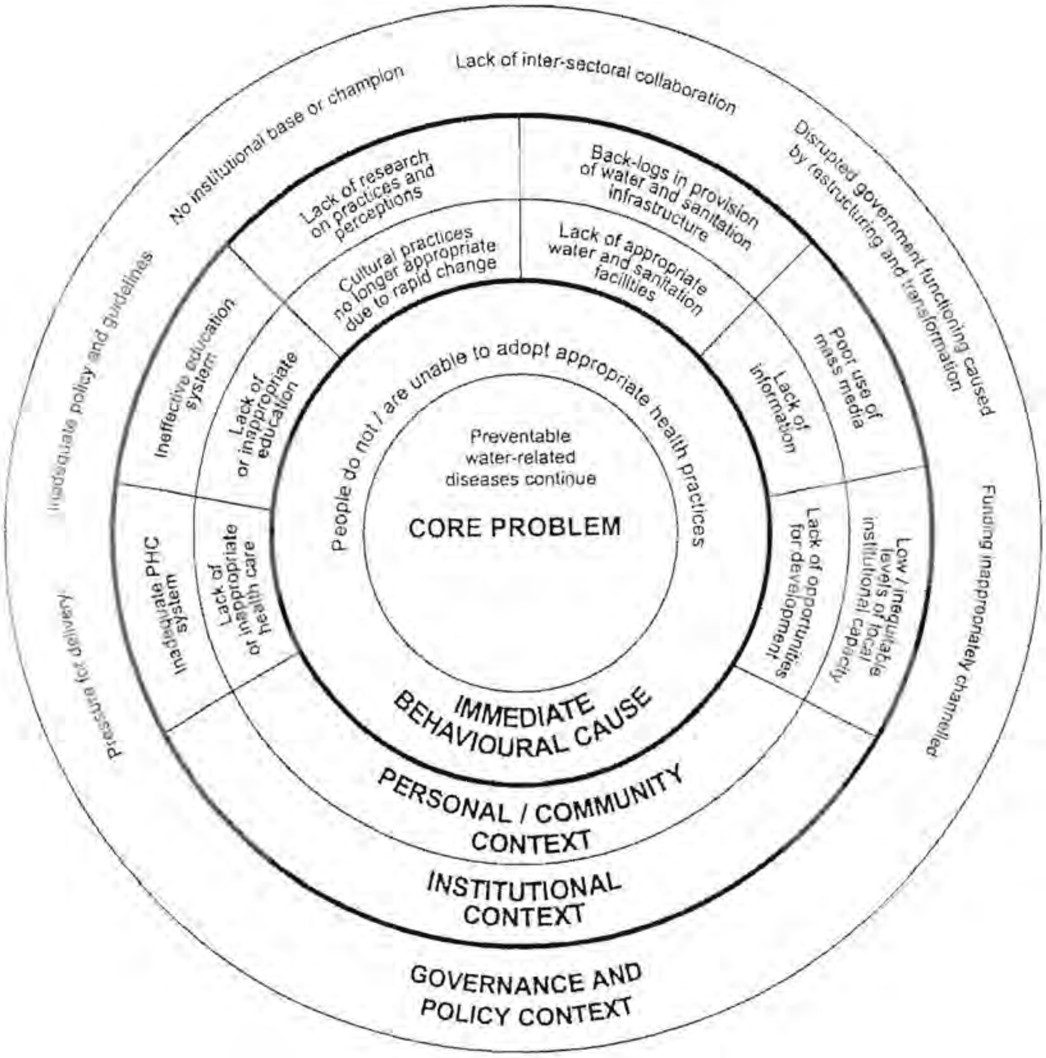
Currently, an estimated 21 million South Africans do not have access to adequate sanitation facilities. The situation is similar to that which exists in many other developing countries, in that it is usually the poorest section of the population that bears the brunt of a non-existent, or at best unsatisfactory, sanitation infrastructure, whether for financial or political reasons. In the past, sanitation provision in South Africa was generally characterised by extreme solutions, with the "privileged" enjoying well-maintained waterborne sewerage systems while the majority had either ordinary pit latrines, buckets or other equally unacceptable systems (Austin 1996).

Even bucket systems require a high level of organisation and funding in order to function properly; however, both were often lacking in many areas. In an attempt to provide a more cost-effective service, efforts were made to introduce other sanitation systems in developing communities, usually without consulting the intended users. The result was all too often a legacy of poorly planned and inadequately maintained systems provided by well-intentioned but shortsighted authorities, who gave very little attention to factors such as environmental impact, social issues, water supply service levels, reliability, upgradability, settlement patterns or institutional needs (Austin 1996). Now, at least, government policy states that the minimum acceptable level of sanitation is a "well constructed VIP toilet".

The link between sanitation and disease was described earlier in this chapter. However, there is still a lack of an integrated strategy for water- and sanitation-related health education and promotion in South Africa and, as a result, the problem merely continues to exist. In-depth research has brought to light a multi-level analysis of the problem, the components of which are illustrated in Figure 2.2 and described briefly below (HEATT 1997):

- The **core problem**, which continues to exist unabated, is that every year there are 1,5 million cases of diarrhoea in children under the age of five, while millions more suffer from diarrhoeal diseases.
- The **immediate behavioural causes** are people's inadequate health and hygiene practices.
- The **personal / community and institutional contexts** refer to the opportunities, resources and constraints that people experience in their lives. These could be economic, socio-cultural, political, or related to gender, class or race, and are also associated with a lack of a comprehensive primary health care (PHC) system.
- The **governance and policy context** relates to the fact that the country has been going through a period of rapid change, with attendant upheaval, complexity and confusion as a result of the major national re-focus of development policies and strategies.

It is seen that, at all levels, the problem is related to socio-cultural, educational and institutional issues, with the lack of appropriate facilities and inadequate guidelines being a contributory factor. New approaches need to be initiated, and technologies that support alternative sanitation efforts should be developed.



Note: PHC = primary health care

Figure 2.2: A multi-level analysis of the sanitation problem in South Africa
(HEATT 1997)

To redress existing inequalities the post-1994 government has developed a national sanitation policy, whereby it is made clear that sanitation is not simply a matter of providing toilets, but rather an integrated approach which encompasses institutional and organisational frameworks as well as financial, technical, environmental, social and educational considerations. It is recognized that the country cannot afford to provide waterborne sanitation for all its citizens, nor, for that matter, should it necessarily aspire to do so. The emphasis has shifted to promoting other "intermediate" technologies instead (Austin 1996). The government also realises that the question of sanitation, perhaps more than most development issues, needs to be seen in the context of an integrated development strategy. Water supply and sanitation are unavoidably linked to the broader development process: sanitation affects, and is affected by, a wide range of issues (DWAF 1996).

2.5 THE WAY FORWARD

It is clear that sanitation is an extremely complex issue. It is an issue which impacts on the daily lives of every human being inhabiting this planet, particularly in the developing countries where the level of service is either poor or nonexistent. There is no single solution that can be applied as a universal panacea, and the situation will continue to worsen unless new approaches are adopted. What then, should be the approaches to addressing the problem, with specific reference to the low-income communities in South Africa?

It is wrong to imagine that simply through construction of toilets, or even the use of toilets, that health conditions will improve. Hygiene is a major issue. Sanitation is not more toilets, but rather the introduction of a new way of life through education, behavioural change and personal hygiene practices. Improved sanitation is also a **process**, not a top-down decree. People must be consulted seriously and involved in sanitation programmes, from planning to implementation and follow-up (de Jong 1996). The technology should also be suitable for local environmental conditions, keeping in mind that urban and rural needs usually differ.

Simpson-Hébert (1996) proposes a number of interrelated guiding principles:

- Incremental change, one step at a time, is more sustainable than the wholesale introduction of new systems.
- Political commitment at all levels is a prerequisite for sanitation promotion. Communities seem more likely to be enthusiastic about a sanitation project they know has strong political support.
- The sanitation sector must continue to innovate low-cost sanitation facilities for people with different needs, from different climates, and with different customs. It is wrong to choose one or two technologies and push them as "the solution". A particular product may be right for a certain section of the market, but not for all consumers and conditions. More research and better designs are still needed.
- There is a need in some societies to recycle human waste as fertiliser, as has been done for centuries in various parts of the world. Human waste can be rendered harmless, and toilet designs that do this in harmony with agricultural and social customs hold promise for the future.

- Toilets are consumer products: their design and promotion should follow good marketing principles, including a range of options with attractive designs based upon consumer preferences, and also be affordable and appropriate to local environmental conditions.

Two major constraints to providing improved sanitation, which need to be addressed, have been identified by Simpson-Hébert (1997), namely, myths and the poor status of the sanitation sector:

Myths:

The first myth is that safe water alone will ensure better health. Since the key to health is pathogen control, it has been proven that for the control of diarrhoeal and other excreta-related diseases, safe excreta management and good hygiene behaviour are at least as important as access to safe water.

The second myth is that large quantities of water are needed for safe excreta management. While it is necessary to have water for personal and domestic hygiene, improving management of human excreta need not wait for improvements in water supply.

The third myth is the assumption that the only good sanitation system for urban areas is conventional waterborne sewerage. This is compounded by the belief that an entire urban area should have the same sanitation system, despite differences in physical and socio-economic conditions which may exist.

Poor status of the sanitation sector:

By associating sanitation with human faeces rather than public health and, more recently, with low-cost services for the poor, the technological approach has contributed to the dismal image of the sanitation profession. The technological approach on its own has ignored the social and behavioural dimensions of improved public health, and therefore lacks a sense of responsibility for the larger issues.

Meagre investment in research and development has contributed to sanitation's poor profile. The sanitation field is also not appropriately represented in academic institutions. Furthermore, the people most in need of improved sanitation services, the poor, have the least voice and limited ability to influence decision-makers to make sanitation a public health priority.

Simpson-Hébert (1997) further emphasises that the approach to the sanitation challenge should be human-centred and ecologically sustainable. It should be concerned with equity, protection of the environment, and the health of both the user and the general public:

> *Equity*, within the sanitation sector, means that all segments of society have access to safe, appropriate sanitation systems adapted to their needs and means. Currently, inequities are found at many levels, between rich and poor, men and women, and rural and urban.
>
> *Protection of the environment*, within the sanitation sector, means that future sanitation systems must neither pollute ecosystems nor deplete scarce resources.
>
> *Health promotion and protection from disease*, within the sanitation sector, means that systems should be capable of protecting people from excreta-related diseases as well as interrupting the cycle of disease transmission.

Sanitation programmes that fulfill all these principles simultaneously should lead to long-term sustainability. Simpson Hébert (1997) makes the following recommendations for implementing sanitation programmes:

- impetus should be provided for research and development for a range of systems applicable to differing cultural and environmental conditions;
- sanitation should be treated as a major field of endeavour in its own right, with sufficient levels of investment to revitalise training programmes and professional standing;
- a demand should be created for systems that move increasingly toward reuse and recycling of human excreta; and
- people for whom the systems are being built should be involved in the design process.

The International Water and Sanitation Centre (IRC 1999) makes it clear that there has been too much focus on providing clean water at the expense of proper sanitation. It is now widely realised that the most effective way of reducing water- and sanitation-related diseases is the safe disposal of excreta. This calls for special approaches to motivate people, that they use toilets, that the toilets are suitable for local conditions, and that people are willing to pay for, construct and manage them.

The Water Supply and Sanitation Collaborative Council Working Group on the Promotion of Sanitation (WSSCC 1998a) maintains that certain constraints to progress in the sanitation sector need to be urgently addressed, for example:

- Institutions responsible for water and sanitation service deliveries in most developing countries operate in an uncoordinated and inefficient way, leading to poor institutional management and low cost recovery;
- networking with key sectors (e.g. health and nutrition, education, environment) has not been given sufficient attention, resulting in a lack of synergy, information sharing and exchange of experiences; and
- the sector has not responded adequately to the problems of urbanisation, resulting in grossly inadequate services to residents of peri-urban areas and informal settlements.

Many urban areas in developing countries are served by on-site excreta disposal facilities, such as septic tanks for example, yet much of the faecal sludge produced, collected and disposed of within these areas remains unaccounted for. Haulage of relatively small volumes of sludge by motorised vacuum tankers over long distances through urban agglomerations is neither an economically nor ecologically sustainable solution. New excreta collection, transport and treatment concepts will therefore have to be developed in conjunction with sanitation systems selected or adapted to suit the varying socio-economic conditions of urban populations. It is of key importance to minimise the haulage of sludge, while at the same time guaranteeing safe sludge treatment and disposal. Furthermore, accessibility of septic tanks for emptying vehicles could be improved by locating them at easily accessible sites (Strauss, Heinss and Montangero 1999).

It is also of the utmost importance for development agencies to collaborate closely with communities, not only at the inception, but throughout all stages of a development project. This participation by the community should be coupled with capacity building through training. People should remain central to the process, and development should not be focused on the economic dimension alone. Due to the demand for delivery during the last decade, as well as a lack of skills within the communities, community participation was neglected in most projects. Community participation in new projects should be coupled with capacity building through training. Capacity building within the communities, as well as in the local authorities and institutions, is of major importance in the transfer of any technology and is the crux of sustainability of projects or services (Duncker 1999b).

With the continuous growth of urban populations and the high incidence of low-income people living in slums and peri-urban squatter areas, there is no possibility of providing conventional waterborne sewerage to all the urban inhabitants who are currently without adequate sanitation. Other systems have to be employed. Ideally, they should provide the same health benefits as waterborne sewerage but remain affordable to poor people. They should operate well without piped water and provide as great a convenience for users as possible. They should also be simple and reliable to operate and maintain (Cotton et al 1995).

Sanitation approaches based on flush toilets, sewers and central treatment plants cannot solve the sanitation problem. Nor can the problem, in high-density urban areas, be solved by systems based on various kinds of pit toilets. There exists an erroneous assumption that the basic problem is one of "sewage disposal", while in actual fact the problem is the disposal of human faeces and urine, not sewage. This is because the human body does not produce "sewage". Sewage is the product of a particular technology. To handle faeces and urine separately is not a great problem, as each human produces only about 500 litres of urine and 50 litres of faeces per year. The problem only arises when these two substances are mixed together and flushed into a pipe with water to form sewage (Winblad 1996a & 1996b).

While "conventional" sanitation options may be suited to certain situations, in other circumstances where both water and space are scarce there is a clear need for permanent, emptiable toilets which do not require water. Such circumstances are becoming increasingly common. When limits are placed on other variables, such as money and the depth of the water table, the circumstances where options such as sewers and pit toilets are viable become fewer, while the need for permanent, emptiable, waterless toilets grows (Dudley 1996).

Methods of providing good sanitation without the concomitant use of large volumes of water should be sought. Based on recent trends in water use and population growth, availability and utilisation of water have been projected to the year 2030. The results show that South Africa will reach the limits of its economically usable, land-based fresh water resources during the first half of the twenty-first century. A greater emphasis should therefore be placed on water conservation coupled to the most beneficial use of this scarce resource. This should be combined with a comprehensive programme to instill in the public an appreciation of the true value of water and the importance of a changed approach to water utilisation countrywide (DWAF 1997a). Alternative sanitation technologies which support this approach are an important component of the overall strategy.

CHAPTER 3

THE NEED FOR ALTERNATIVE SANITATION TECHNOLOGIES IN SOUTH AFRICA

> "Science and technology are neither hostile nor friendly towards human development. They provide tools, and it is the way in which these tools are used by decision-makers, politicians and others that determine whether they are destructive or constructive. The mistake made by scientists, technologists and engineers is that they have not educated people on how to use the tools they have created and the implications of the various uses."
>
> UNCHS, Habitat II: City Summit, Istanbul, June 1996

CHAPTER 3: THE NEED FOR ALTERNATIVE SANITATION TECHNOLOGIES IN SOUTH AFRICA

3.1 BACKGROUND

The importance of a sanitation system being appropriate for a particular project has been incontrovertibly established. What makes a system appropriate depends on a number of factors, with the actual technology itself being, in most cases, less important than the socio-cultural factors involved. Given South Africa's limited financial resources, as well as the urgent need to conserve water and protect the environment, it is essential to look beyond the current restrictions for innovative ways and means of bringing adequate sanitation to the millions of people currently without access to proper facilities. Chapter 2 sketched a broad picture of the existing situation in South Africa and various other developing countries, and provided some pointers for future action, for example:

- research and development for a range of different cultural and environmental conditions is required;
- a demand for systems which reuse or recycle human excreta should be created;
- there should be broad consultation with the people for whom the systems are being built;
- it is necessary to reduce the dependence on sanitation systems which use large amounts of (potable) water;
- capacity should be built within institutions and communities to facilitate the transfer of technology;
- systems should be promoted which are simple, reliable and easily maintained; and
- there is a need to move away from the current fixation with providing either full waterborne sanitation or VIP toilets.

It is necessary to examine some of these factors in more detail in order to develop an understanding of the type of thinking required to develop suitable alternatives to the status quo. Some important principles emerge from the discussion below.

3.2 CULTURE AND SANITATION

3.2.1 Social development perspectives

The days of solving water supply and sanitation problems with concrete and pipes alone are over. Integrated approaches to water supply and sanitation now have people at the centre. A social development perspective, which supports this approach, means understanding and involving users and responding flexibly towards their concerns. Social development objectives in water supply and sanitation should therefore ensure that dialogue and interventions are responsive to demand, reach poor or disadvantaged populations, promote empowerment and ownership, and recognise the different needs of men and women (DFID 1998).

The priorities of donors and governments do not always coincide with those of primary stakeholders – men and women in rural and urban communities, particularly the poor. In the past, the practice of water supply and sanitation provision hardly ever involved consumers in decision-making and management. Recipients of water supply and sanitation projects were referred to as *beneficiaries*, and assessment of needs was not made on the basis of wide consultation and participatory methods. As a result, the services provided often did not reflect user preferences, were not maintained, and were used inappropriately (or not at all), thus reducing potential benefits. It is now accepted that, for reasons both of equity and efficiency, programmes and projects need to be responsive to people's felt needs and based on genuine demand. Assessing these factors before project preparation and design helps achieve interventions that are socially acceptable (DFID 1998).

3.2.2 Cultural beliefs and practices

Excreta disposal, especially in rural areas, is far more complex socially than it is technically, and it is not appropriate to assign total responsibility for sanitation programmes to engineers (Feachem and Cairncross 1978). The introduction of on-site sanitation systems, for instance, is much more than the application of simple engineering techniques. It is an intervention that entails considerable social change. If sanitation improvements (in both rural and urban areas) are to be widely accepted, the relevant social and cultural factors have to be taken into consideration during planning and implementation. It is therefore necessary to understand how a society functions, including the communities and households within it, and what factors promote change (Franceys, Pickford and Reed 1992).

Culture shapes human behaviour in many different ways, including what is deemed to be acceptable personal and social behaviour. As regards sanitation behaviour, defecation is usually a private matter which people are unwilling to discuss openly. Contact with faecal matter is unacceptable to certain individuals in societies where it is the responsibility of low-income or low-caste groups, while taboos may dictate that separate facilities should be provided for particular social groups (Franceys, Pickford and Reed 1992; WRC 1995). The latter issue was clearly illustrated during the planning of the urine diversion sanitation project in Eastern Cape, discussed later in this dissertation. It became evident during the community workshopping process that, in those particular communities at least, use of the same toilet by a man and his daughter-in-law was considered to be socially unacceptable.

Social issues include, among other things, the attitude to defecation, and even the physical location of a toilet is important. Furthermore, issues such as preferences for sitting or squatting may also influence the technology choice. As social practices and preferences are likely to vary considerably from area to area, universal approaches to issues such as technical choice are likely to be inappropriate (WRC 1995).

One cultural practice which has direct technical consequences for consideration by the engineer, however, is the method of personal cleansing employed by the toilet users. Whether water, stones, mealie cobs or thick pieces of paper are used will affect the design of the sanitation system (Franceys, Pickford and Reed 1992). Measures to mitigate the effects of practices other than the use of soft tissue paper therefore need to be considered and taken into account in the technical approach to the provision of sanitation in a community. The approach is likely to differ between wet and dry sanitation technologies.

3.3 COMMUNITY EMPOWERMENT AND INSTITUTIONAL CAPACITY

For many years sanitation projects focused on purely numerical targets, such as the number of facilities installed. More recently, attention has turned towards the need to ensure that sanitation efforts are **sustainable** – not only in terms of maintaining the installed facilities, but also ensuring that the people are empowered with the necessary information and sense of ownership to **effectively use and manage those facilities**. This new emphasis has meant that sanitation efforts have changed to incorporate more participatory methods, with local communities playing a larger role in the design and management of sanitation projects (WSSCC 1998b).

The sustainability of a sanitation project can be heavily influenced by the development of a hygiene education strategy that focuses on personalised education for all family members through home visits, participation of organised women in the implementation of the whole education process, and educational materials as well as monitoring and evaluation instruments which are easy to use. The problems experienced with certain sanitation technologies, for instance some types of dry sanitation, are not the technology itself, but rather the interaction between the technology and the user. The need to achieve behavioural changes, as well as proper use and maintenance, is of vital importance (Gough 1997).

In South Africa it is essential to understand the attitudes and behaviours of developing communities towards water supply and sanitation. Most developing communities rely on the government to make sure that their projects are sustainable, but it is also necessary for the community to contribute towards the sustainability of their projects. This requires effective complementary inputs such as community participation, community capacity building and community training (Duncker 1999a). Any sanitation improvement programme should include resources to develop the necessary institutional capacity to manage the ongoing programme and future operational needs (DWAF 1996).

The type of institutional setup for delivery, as well as for operation and maintenance, has a major influence on the choice of sanitation technology. The simpler the system technically, the easier it is to operate and maintain, and the lower the institutional support requirements. However, even "simple" systems such as VIP toilets need a certain amount of institutional support, for example, the setting up of production centres for basic components such as slabs and pedestals, training of builders and monitoring of construction (WRC 1995). Desludging of full pits generally also requires some form of institutional assistance.

More complex systems may require substantial institutional support, which may not be available in rural areas. This is especially true where people with technical skills are required for operating and maintaining the system. Therefore, if the users will be without much institutional support, then the technology chosen should be as robust and durable as possible. In each situation, an analysis of the institutional requirements and the extent they will be available in an area will have to be made before a technology is chosen (WRC 1995).

Given the different stages of development of local government in South Africa, it is clear that institutional arrangements will vary in several ways. Approaches in developing areas will be different from those in established areas, and rural areas will generally have different requirements from urban areas (DWAF 1996).

3.4 TREATMENT AND DISPOSAL: CATEGORIES OF SANITATION TECHNOLOGY

Research by the World Bank has shown that the possession, proper use and maintenance of a sanitation facility is more important, in terms of improving health, than the actual sanitation technology employed, provided of course that it is affordable and socio-culturally acceptable (Mara 1996). The technical objective of sanitary excreta disposal is to isolate faeces so that the infectious agents in them cannot reach a new host. The method chosen for any particular area will depend on many factors, including the local geology and hydrogeology, the culture and preference of the communities, the locally available raw materials and the cost (Franceys Pickford and Reed 1992).

Basically, there are two ways to handle human waste. It can either be treated on site before disposal, or removed from the site and treated elsewhere. In either case, the waste may be mixed with water or it may not. On this basis the following four groups may be distinguished (CSIR 2000):

Group 1:	No water added - requiring conveyance
Group 2:	No water added - no conveyance
Group 3:	Water added - requiring conveyance
Group 4:	Water added - no conveyance.

Table 3.1 illustrates the sanitation systems associated with each of the above groups. It should be noted that some of the systems fall somewhere between the four categories as, for example, where solids are retained on site (primary treatment) while the liquids are conveyed elsewhere for secondary treatment (e.g. a settled sewage system), or where water may be added but only in small quantities. Since increasing the number of categories would complicate the table unnecessarily, these systems have been included in the categories which best describe the treatment of waste (CSIR 2000).

Table 3.1: Categories of sanitation systems (based on CSIR 2000)

	Off-site treatment: requiring conveyance (treatment at central works)	**On-site treatment: no conveyance (treatment, or partial treatment, on site)**
No water added	**Group 1** Chemical toilet	**Group 2** Ventilated improved pit toilet Ventilated improved double-pit toilet
Water added	Full waterborne sanitation Flushing toilet with conservancy tank Settled sewage system	Flushing toilet with septic tank and drainfield Aqua- privy toilet Pour-flush toilet

The operating costs of systems in which waste is conveyed and treated elsewhere can be so high that these systems may in the long term be the most expensive of all. The capital and installation costs of any conveyance network which uses large quantities of potable water to convey small quantities of waste are very high, and a possibly inappropriately high level of training and expertise (for the particular case under consideration) may also be required to construct and maintain such systems. A system that may be appropriate in one community may be a total failure in another because of cost, customs and religious beliefs, or other factors. Furthermore, merely because a particular technology has been traditionally implemented by developers or authorities, does not mean that it should be seen as the correct solution (CSIR 2000).

The disposal of human waste, whether on-site or off-site, needs to take into consideration the effect on the environment as well as the effect on people. It is not only the pathogen content of excreta that is of importance – the chemical composition of wastewater also requires assessment. Nitrate content, in particular, is important because of the possible effects of its accumulation in both surface and groundwater, on human health (methaemoglobinaemia in bottle-fed infants), and on the ecological balance in waters receiving runoff or effluent with a high concentration of nitrates. Although the major human activity resulting in the increase of nitrate levels is the use of chemical fertilisers, poor sanitation can contribute to this, particularly in groundwater (Franceys, Pickford and Reed 1992).

3.5 OPERATION AND MAINTENANCE ASPECTS

All sanitation technologies have certain negative aspects. These vary according to the specific conditions, both social and environmental, under which each type of sanitation system operates. In chapter 2, a broad background of the current sanitation problem was sketched, and it was made clear that, while improving the situation is not merely a matter of building more toilets, there is a definite need for new approaches and methods.

Proper operation and maintenance is an integral part of an efficient sanitation system. This applies to all systems, but becomes increasingly important as one moves up the sanitation hierarchy. At the top end, with full waterborne sanitation for instance, insufficient attention to operation and maintenance can have serious health and environmental consequences (WRC 1995).

The most common cause of breakdown in toilets is the false, but all too general, impression that once installed they may be left to take care of themselves. Even the best excreta disposal facilities, whether they serve large communities or single families, require some supervision and maintenance. Poorly-maintained toilets may be worse than none at all, especially if they lead people to associate toilets with filth (Feachem and Cairncross 1978).

This dissertation describes, in the following chapters, two new approaches to sanitation provision in which the operation and maintenance aspects are greatly simplified. The first represents an improvement on an ordinary settled sewage scheme, which is a wet system, and the second an alternative to a VIP toilet, which is a dry system. Chapter 1 outlined the basic disadvantages of each of these technologies, which can be summarised as follows:

Basic disadvantage of settled sewage systems:
The main problem with settled sewage systems is that the interceptor tanks have to be desludged periodically. This may be an extremely difficult task in some situations, and is also relatively expensive.

Basic disadvantage of VIP toilets:
There are two equally important negative aspects here. The first is the fact that geotechnical conditions may make it prohibitively expensive or environmentally inadvisable to dig pits. The second is that, when a pit becomes full it must either be desludged, or a new pit must be dug and a new superstructure erected; both these actions have a direct cost implication.

Desludging is therefore seen to be a common problem with both these technologies, as indeed it is with all on-site systems. Any new on-site technology which can facilitate this task, or eliminate the need for it altogether, will thus be a welcome addition to the range of options currently available. It will also raise the general status of on-site systems, which are often regarded as inferior options because of this aspect. Indeed, many communities perceive anything less than a full waterborne system to be an inferior option.

However, inadequate water supplies alone will preclude the possibility of reliable, conventional waterborne sewerage systems for many cities and communities. Sewers can rapidly block if water is shut off for periods. Communities with waterborne sewerage normally require more than 75 litres per capita per day (lcd), compared with less than 20 lcd used in many informal settlements. Alternative sanitation technologies will increasingly be needed on grounds of water unavailability, lack of construction skills, cost as well as sustainability (Mara 1996). Full waterborne sanitation systems should, furthermore, only be installed where residents are able to afford the full operation and maintenance costs of the system. If this policy is not adopted, the operation and maintenance of these systems will continue to drain fiscal resources, leading to lack of funding allocation and a concomitant rapid decline in the value of the assets (WRC 1993). Local authorities thus risk incurring economic disadvantages where low-income households cannot afford the running costs of an expensive system and extensive subsidies are required. Furthermore, where operational costs are not met for lack of consumer payments or ongoing subsidies, environmental problems and clean-up costs may follow (DWAF 1996).

It is not only local authorities who incur economic disadvantages when high-technology sanitation systems are provided to poor communities. Paying for the water required to operate the systems, as well as for the running of the treatment plants (even if these costs are subsidised) is only part of the equation. The proper operation of waterborne sewerage systems demands that only soft tissue paper be used for personal cleansing, and other materials commonly used by poor people (rags, newspaper, plastic bags, mealie cobs, stones, etc) must be strictly excluded from the systems. This is a rigid requirement which cannot be relaxed, and for millions of poor people it may be impossible to adhere to it. Simply stated, if a person's financial situation is such that he or she has to choose between buying a loaf of bread or a roll of toilet paper, then a waterborne sanitation system is simply not a feasible option, despite that person's aspirations.

While the capital cost of sanitation infrastructure is obviously an important consideration, it is the operation and maintenance costs which have the most influence on the sustainability of a project. Particularly in poor communities, therefore, it is essential to install robust, low maintenance systems, where the total life-cycle costs are minimised without the environment being compromised in any way.

CHAPTER 4

BACKGROUND TO THE "SLUDGE SIPHON" CONCEPT

"There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success than to take the lead in the introduction of a new order of things"

Niccolo Machiavelli

CHAPTER 4: BACKGROUND TO THE "SLUDGE SIPHON" CONCEPT

4.1 BASIC PRINCIPLES OF SETTLED SEWAGE SANITATION TECHNOLOGY

A schematic representation of a settled sewage sanitation system is illustrated in Figure 4.1. The operation of this type of system is based on the use of conventional septic tanks (also called interceptor tanks or digesters). However, instead of the effluent from the individual tanks passing into separate or communal soakaways (drainfields) and percolating into the ground, it is collected via a reticulation system of relatively small diameter pipes and conveyed for further treatment either to a system of stabilisation ponds, a constructed wetland or even a remote treatment plant.

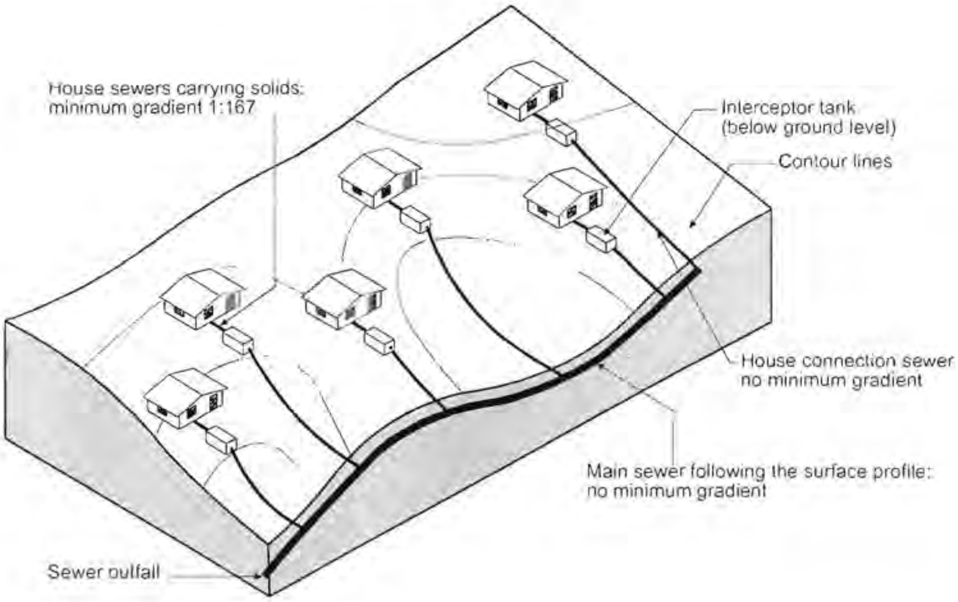


Figure 4.1: Schematic representation of a settled sewage system layout (Reed 1995)

Because the effluent pipes transport mostly liquid, and not the type of solids usually found in waterborne sewerage systems, they may be of a much smaller diameter (often as small as 40 mm). The interceptor tank also attenuates the wastewater flow by providing some surge storage, thereby reducing the peak-to-average flow ratio by more than 60% (USEPA 1991). Larger diameter pipes are only used when hydraulic considerations dictate this.

Furthermore, there may be a certain relaxation of construction standards – pipes may be laid at much flatter gradients and some irregularities in alignment can be tolerated. In Zambia, certain effluent pipes were laid at gradients as little as 1:1 000 and have operated satisfactorily for many years (Austin 1995). Problems eventually occurred in the latter case only because of a lack of regular desludging of the tanks, or because pipelines transporting conventional waterborne sewerage were connected to the settled sewage pipes.

Collector pipes may even be laid at inverse gradients and thus flow under pressure. Unlike conventional gravity sewers which are usually designed for open channel flow conditions, pipelines in a settled sewage system may be installed with sections depressed below the hydraulic grade line (Otis & Mara 1985). Thus, flow may alternate between open channel and pressure flow. Maintenance of strict sewer gradients to ensure the self-cleansing velocities required by conventional waterborne sewerage systems is not necessary. However, the design must be such that an overall fall exists across the system and that the hydraulic grade line does not rise above the outlet invert of any interceptor tank.

Treatment of the effluent from a septic tank is considerably facilitated, as primary treatment has already taken place in the tank (the sewage has been "settled" in the tank and the effluent contains less solids as well as reduced values of COD and other parameters). Table 4.1 gives a comparison between raw wastewater and settled sewage effluent for typical South African municipal conditions.

Table 4.1: Approximate average municipal wastewater characteristics for raw and settled wastewaters found in typical South African wastewater treatment facilities (WRC 1984)

Wastewater characteristic	Raw	Settled
Influent COD (mg COD/ℓ)	500 - 800	300 - 600
Total suspended solids (mg/ℓ)	270 - 450	150 - 300
Settleable solids (mg/ℓ)	150 - 350	0 - 50
Non-settleable solids (mg/ℓ)	100 - 300	100 - 300
Unbiodegradable particulate COD fraction	0,07 - 0,20	0,00 - 0,10

Sections 4.2 and 4.3 which follow hereunder discuss various aspects of the effluent drainage pipes and interceptor tanks in a settled sewage system.

4.2 EFFLUENT DRAINAGE PIPES

4.2.1 Hydraulic design considerations

There are two hydraulic parameters which have to be considered in settled sewage schemes, namely pipe diameters and pipe gradients.

Pipe diameters:

In contrast to conventional sewers, which transport relatively large objects, systems designed to receive wastes from interceptor tanks with a minimum of four to six hours' retention time need not be designed to transport such solids. A minimum pipe size of 75 mm is recommended but smaller pipes may be used provided they can carry the peak flow. However, systems with interceptor tanks designed for 24 hours' retention time may be designed to carry average-day flow rates. A minimum pipe size of 40 mm is usually recommended in these cases, but may be even less. Otis and Mara (1985) assert that the selection of minimum pipe sizes should be based primarily on maintenance conditions and costs, with a minimum of 100 mm being recommended for particular developing countries where specialised equipment for cleaning smaller pipes may not be generally available.

In South African settled sewage systems, the smallest pipe diameters have generally varied between 63 and 80 mm (CSIR 1996).

Pipe gradients:

Pipes exiting from small interceptor tanks can be laid at a minimum slope of 1:220 (Reed 1995). This assumes that the quality of materials and workmanship is good and that the interceptor tanks are regularly desludged. Pipe systems served by large interceptor tanks do not need a minimum gradient: provided there is an overall positive gradient on the system and all interceptor tanks are above the water level in the sewer, the pipe can follow the local topography (Figure 4.1). Short lengths of sewer with negative gradients are acceptable provided they are ventilated (i.e. air valves at high points) and provision is made for emptying. Such systems are completely dependent on regular desludging of the interceptor tanks for their reliability. According to Otis and Mara (1985), high points and points at the end of long flat sections are critical locations where the maximum elevation must be established above which the pipe may not rise. Between these critical points the sewer may be constructed with any profile as long as the hydraulic gradient remains below all interceptor tank outlet inverts.

Conventional sewer design is based on achieving "self-cleansing" velocities during normal daily peak flow periods, in order to re-suspend solids that have settled out in the sewer during low flow periods. However, for pipelines transporting settled sewage, the United States Environmental Protection Agency (USEPA) recommends a minimum flow velocity of 0,15 m/s rather than a minimum pipe gradient (USEPA 1991). The primary treatment provided in the interceptor tanks upstream of each house connection removes grit as well as grease and most settleable solids. Studies have shown that the remaining solids and slime growth which enter the collector pipe system are easily carried out when flow velocities of this magnitude are achieved. It is therefore not necessary to design for self-cleansing velocities as in conventional waterborne sewerage systems.

4.2.2 Pipe materials

Unplasticised polyvinyl chloride (uPVC) pipes similar to those used in potable water supply networks are commonly used. In South Africa, a problem exists because of a lack of pipes and fittings which are specially customised for settled sewage systems. In most cases, therefore, uPVC water pipes and specials have been specified, which are not manufactured to normal sewer configurations, i.e. Y-branches and bends other than 90 degrees (Austin 1996). These generally work without any problems, except that additional access points have to be provided for rodding purposes, and therefore the networks probably cost more than would normally have been the case if these fittings had been available. Cast iron pipes and fittings should not be used due to the septic (and therefore corrosive) conditions which exist in these systems.

4.3 INTERCEPTOR (SEPTIC) TANKS

The following features of interceptor tank design and operation are important:

4.3.1 Operational principles

A typical septic tank is schematically illustrated in Figure 4.2. Generally, the purpose of a septic tank is to receive excreta and other wastes and to treat them in order to provide a satisfactory effluent for disposal into the ground or by other means (Pickford 1980). In a conventional septic tank / soakaway system the aim is to retain as much as possible of the solids in the tank in order to reduce the probability of clogging of the ground around the soakpit. If the effluent is to be transported for further treatment before discharge to surface water or irrigation, the objective is to provide an effluent with the minimum possible proportions of solids, of oxygen-demanding material and of disease-transmitting organisms.

The waste receives primary treatment in the tank itself. Waste material enters the tank, solids separate out to form sludge and scum and a partially-treated effluent is discharged (Pickford 1980). The second stage of treatment is biological breakdown of the effluent which usually takes place as it percolates into the soil from a soakpit. Alternatively the effluent from a large septic tank (such as one serving an institution or a group of houses, for example) may be collected and treated in a trickling filter or other biological treatment process before discharge to a watercourse or irrigation area. In a settled sewage system the effluent often passes to waste stabilisation ponds.

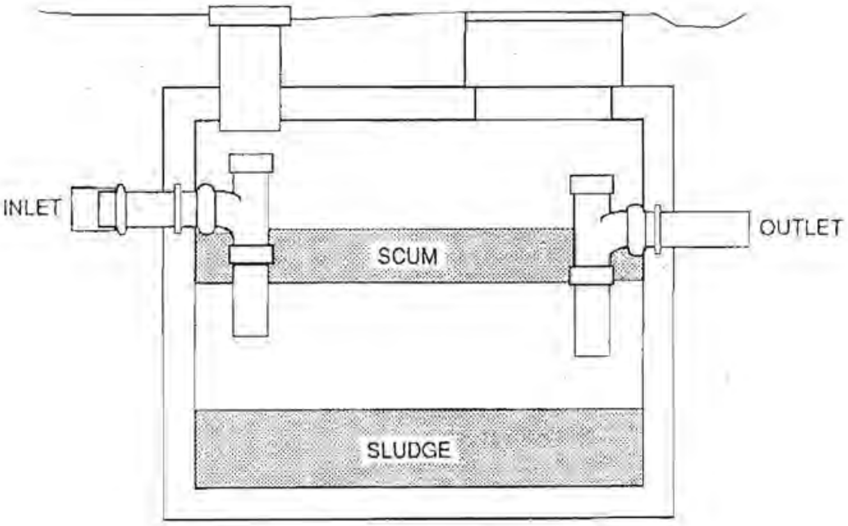


Figure 4.2: Typical interceptor (septic) tank (USEPA 1991)

Composition of sewage:

Most of the sewage entering the tank is water, with each litre of solid matter often accompanied by two or three thousand litres of water (Pickford 1980). The quantity of water used usually depends on the economic level of the household and the availability of water. In developing countries the range may be between 40 and 300 litres per person per day, depending on the level of service of the water supply. Solids entering septic tanks from toilets consist of excreta and personal cleansing material, while bath, laundry and kitchen wastes may also discharge solid material into the tanks. The solids consist of organic and inorganic matter which may be in solution or suspension, and also large numbers of micro-organisms such as bacteria. The organic matter includes carbohydrates and protein in faeces and food scraps, while inorganic matter may include salt and sand.

Solids in sewage:

The quantity of solid excreta (faeces) depends on the person's diet. Pickford (1980) asserts that, for an adult with a diet based on fine white bread, 115 g of faeces are produced per day, while a rice and vegetable diet will produce 410 g. According to Franceys, Pickford and Reed (1992) the amount of faeces and urine excreted daily by individuals depends on water consumption, climate, diet and occupation. Quoted amounts measured in various countries vary between 209 g and 520 g. Jönsson (1997) reports that, in Sweden, faeces represent roughly 10 percent of total daily human excreta (by mass) and amount to between 70 and 140 g; the other 90 percent (approx. 900 to 1 200 g) consists of urine.

4.3.2 Processes within the tank

The processes undergone by sewage in a septic tank are a complex interaction of physical, chemical and biochemical operations. Settlement and digestion take place at the same time.

Settlement of solids:

In still water heavy solids settle to form sludge (Pickford 1980). These may include materials such as sand, stones and ash, commonly used for scouring cooking utensils in lower-income areas. Grease, oils and other light materials rise to the surface to form a floating scum. A layer of liquid, sometimes called the supernatant, is left between the scum and the sludge (Figure 4.2). Very fine particles (colloids) initially stay in suspension, but later coagulate to form larger particles which fall or rise depending on their density. Coagulation is assisted by gases and particles of digested sludge rising through the liquid. Separation is facilitated as temperature rises, but the most important factor is the rate at which the liquid moves through the tank, and this depends on the retention time, as shown in Figure 4.3. It is seen that approximately 65 % of the settlement takes place within about six hours.

The efficiency of solids settlement may be as high as 80% (Franceys, Pickford & Reed 1992). However, much depends on the retention time, the inlet and outlet details and the frequency of desludging. Large surges of flow entering the tank may cause a temporary increase in the concentration of suspended solids owing to disturbance of the solids which have already settled out.

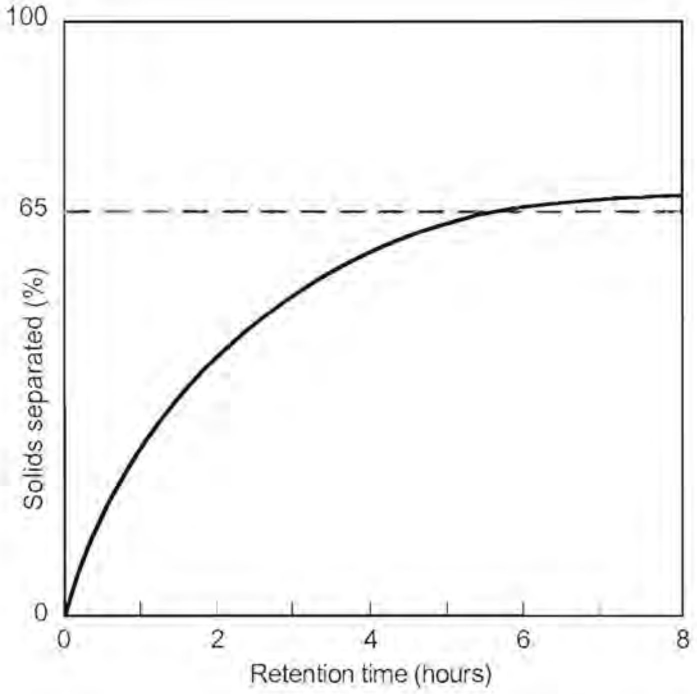


Figure 4.3: Typical relationship between solids separation and time of retention of sewage in a septic tank (Pickford 1980)

Digestion of solids:

Organic matter in the sludge, and to a lesser extent in the scum, is broken down by anaerobic bacteria and mostly converted to water, carbon dioxide and methane (Pickford 1980). The gases rise through the water, taking small particles of partially-digested sludge with them. Digestion is accelerated by an increase in temperature, and so takes place more rapidly (reaching a maximum at 35°C) in the tropics than in temperate climatic zones. During the digestion process the sludge volume is reduced, often by as much as 50 to 80 % (Otis and Mara 1985).

Stabilisation of liquor:

During its retention in the tank, organic material remaining in the liquor is also acted on by anaerobic bacteria, which break down complex substances into simpler ones (Pickford 1980). At first simple hydrocarbons like sugar and starch are reduced to water and carbon dioxide, while ammonia and other compounds containing nitrogen are broken down more slowly.

Mixing:

The flow into a septic tank usually comes in surges, as when a toilet is flushed or a bath or basin is emptied (Pickford 1980). These surges disturb the liquor, especially when the temperature of the incoming sewage is different from the liquor in the tank. According to Pretorius (1997) these disturbances, especially a load of warm water, have a beneficial effect on the rate of digestion.

Growth of micro-organisms:

Many kinds of micro-organisms grow, reproduce and die in the tank. Most are attached to organic matter and so separate out with the solids. Some, accustomed to living in the human intestine, die in the inhospitable environment inside the tank, while some of the heavier ones sink to the sludge layer (Pickford 1980). There is usually a reduction in the total number of micro-organisms present, but generally, viruses, bacteria, protozoa and helminths are present in large numbers in the tank.

4.3.3 Tank geometry and materials

Conventional septic tanks connected to drainfields have commonly been constructed with bricks and mortar, with the inside walls sometimes being plastered and coated with bitumen paint. In the past it was accepted practice to construct tanks with two interconnected chambers, as shown in Figure 4.4. In this case, most of the sludge settles out in the first chamber while the second chamber usually contains liquid only. This prevents drainfields from becoming blocked with sludge, as the outlet pipes are connected to the second chamber. Where settled sewage systems are installed in areas previously served by septic tanks, the practice is usually to modify the outlet fittings, disconnect the pipes leading to the drainfields and connect the tanks to the new reticulation network (Austin 1996).

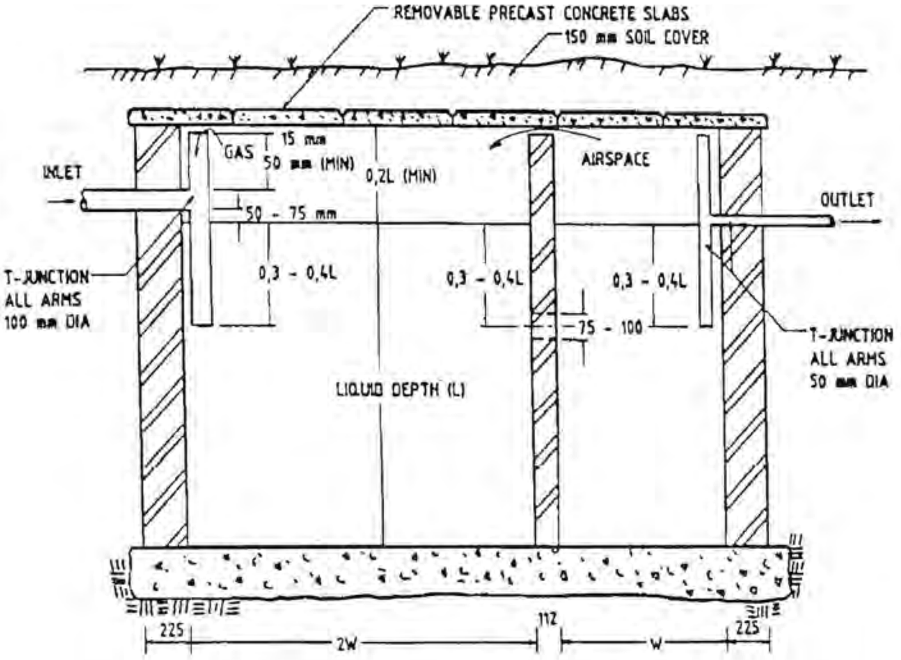


Figure 4.4: Twin-chamber masonry septic tank (De Villiers 1987)

Prefabricated tanks, usually made of moulded polyethylene, are more often used for new settled sewage schemes, due to their ready availability and ease of installation. These commercially available tanks usually consist of a single compartment and are manufactured in various shapes and sizes (round or rectangular), resulting in varying efficiencies which depend on the geometry and hydraulic retention period (Austin 1996). Shallow tanks, or tanks with a greater water surface area for a given volume are preferred designs because of the greater flow attenuation that they provide (USEPA 1991). Shallow tanks also ensure a greater reduction of outflow velocity as well as improved solids retention. However, the liquid depth should not be less than 0,9 m in order to ensure good removal of settleable solids (Otis and Mara 1985).

The preferred shape of an interceptor tank is rectangular with a length to breadth ratio of 2:1, or higher, in order to reduce short-circuiting of the wastewater across the tank, and to improve suspended solids removal (Otis and Mara 1985). The volume should provide sufficient hydraulic detention time for good settling at the estimated daily flow, while reserving a proportion of the total volume for sludge and scum storage. Hydraulic detention times typically vary from 12 to 24 hours. The volume reserved for sludge and scum storage depends on the total quantity of solids which reach the tank daily, the ambient temperature and the frequency of solids removal (i.e. desludging of the tank).

Interceptor tank volume:

Interceptor tanks should be designed to cater for four separate functions (Otis and Mara 1985):

- solids interception;
- digestion of settled solids;
- storage of digested solids; and
- storage of scum.

The expected sewage flow, as well as the rate of accumulation of sludge and scum, should be ascertained before a septic tank can be designed. For residential developments in low-income areas the wastewater flow is usually directly related to the level of water supply in the area, as shown in Table 4.2.

Table 4.2: Estimated wastewater flow in lower-income areas for various levels of water supply (after de Villiers 1987)

Level of water supply	Wastewater produced (litres/person/day)
Public street standpipes, dry sanitation system	12 to 15
Single on-site standpipe with dry sanitation system	20 to 25
Single on-site standpipe with WC connected to water supply (septic tank system possible)	45 to 55
Single in-house tap with WC connected to water supply (septic tank or full waterborne system possible)	50 to 70

In higher-income areas there is often a relationship between the number of occupants in the house and the number of bedrooms, and it is therefore possible to relate the wastewater flow to the number of bedrooms (Table 4.3).

Table 4.3: Estimated wastewater flow in middle to high income areas (after de Villiers 1987)

Size of house	Wastewater produced (litres/stand/day)
2 bedrooms	700
3 bedrooms	900
4 bedrooms	1100
5 bedrooms	1400
6 bedrooms	1600

The rate of sludge and scum accumulation will depend on various factors such as ambient temperature, living standard, diet, health of residents, their occupations and working conditions, etc. Tables 4.4 and 4.5 (de Villiers 1987) give an indication of the variable accumulation rates that may be expected. Recent research (CSIR 1996) has shown that these figures are somewhat conservative, however, and that an average sludge accumulation rate for design purposes in South Africa may be assumed to be 0,08 litres per person per day (about 29 litres per person per year) with no additional provision required for scum.

Table 4.4: Rate of sludge and scum accumulation for low-income areas (based on de Villiers 1987)

Materials used for personal cleansing	Sludge and scum accumulation (litres/person/year)
Undegradable material:	
Toilet wastes only	55
Additional household sullage	70
Hard paper, leaves and grass:	
Toilet wastes only	40
Additional household sullage	50
Water and soft paper:	
Toilet wastes only	25
Additional household sullage	40

Table 4.5: Rate of sludge and scum accumulation for middle- to high-income areas with multiple sanitary fittings (based on de Villiers 1987)

Desludging period (years)	Sludge and scum accumulation (litres/person)
1	85
2	140
3	185
4	220
5	255
6	290
8	360
10	440

Various methods exist for calculating the size of a septic tank to serve a household (or group of households). A common approach is to assume that the sludge and scum are allowed to occupy two-thirds of the tank capacity before being removed, and that the remaining one-third allows for a minimum liquid retention time of 1 day (Pickford 1980). The required capacity is thus three times the daily sewage flow multiplied by the retention time, as illustrated by the following formula:

$$C = 3Prq$$

where
C = tank capacity, litres;
P = number of people expected to contribute to the tank;
r = minimum retention time for sewage in the tank just before desludging (i.e. when tank is two-thirds full of sludge), days; and
q = sewage flow, litres per person per day

Example: For a 1 000 ℓ tank used by 6 persons with an average sewage flow of 60 litres per person per day, a minimum retention period of 1 day and a sludge accumulation rate of 30 litres per person per year, a desludging period of 4 years is obtained.

A large proportion of the tank volume is therefore taken up by accumulated solids, and the longer the anticipated period between desludgings, the larger the tank has to be to cater for this. Obviously, this is associated with an increase in costs, not only for the tank itself but also for the labour and excavation involved in installing the tank.

4.4 THE "SLUDGE SIPHON" HYPOTHESIS

4.4.1 Background

The problems which are often encountered when interceptor tanks require desludging have been described in chapter 1. Consideration of these problems led to the conceptualisation of the "sludge siphon" as a solution.

When interceptor tanks are desludged, the vacuum tankers are supposed to transport the septage (sludge, scum and supernatant) to the municipal treatment works. Some private contractors may, however, illegally empty their loads into the nearest convenient sewer manhole for further waterborne transportation to the treatment works. Depending on the size of the interceptor tanks, the capacity of the vacuum tankers and the operating conditions, the input of energy for desludging the tanks and transporting the septage by road (even for a relatively short distance) may affect the life cycle cost of installing and operating a settled sewage scheme to such an extent that the technology may not be regarded as a worthwhile investment.

Due to the fact that the sludge eventually ends up in the municipal wastewater system in any case, a method has been proposed whereby it can be automatically flushed out of the interceptor tank and into the settled sewage reticulation system, without intervention by a maintenance crew and without conscious thought by the householder. If the sludge can be automatically removed from the tank and transported along the settled sewage network, even for only a limited distance, then the following savings are realistically achievable:

(a) At the very least, there will be no need for vacuum tankers to gain access to individual interceptor tanks, therefore poor roads or densely built-up areas will not be an issue.

(b) If the sludge can be transported hydraulically for a great enough distance, it can possibly be taken all the way to the final treatment works without having to make use of road tankers at all. This would be the best outcome.

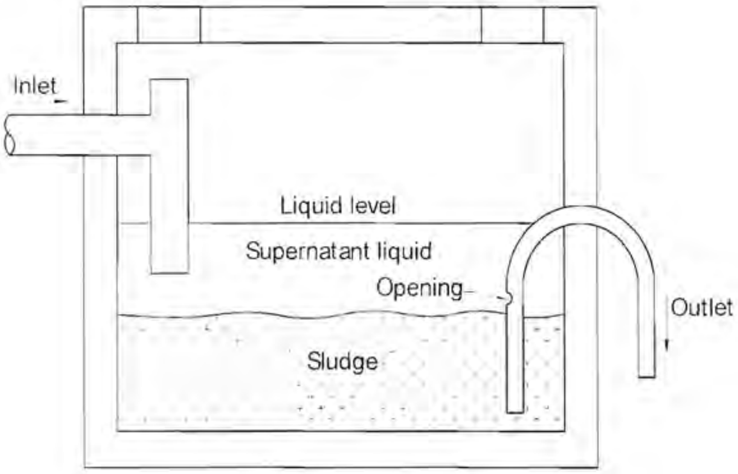
(c) Should it not be possible to transport the sludge hydraulically beyond a certain (as yet to be determined) distance, then this maximum transportable distance can be ascertained. This information can then be used for positioning a settlement tank in an easily accessible position (e.g. within the road reserve) from which it will be a simple task to extract the sludge on a routine basis by means of a vacuum tanker. In this way, then, only one or two large collector tanks per suburb might be required, instead of numerous individual ones situated on private property, and could be easily and cheaply serviced.

(d) If any of the scenarios described above are found to be feasible, it is possible that large fleets of vacuum tankers could be reduced, with local authorities requiring less vehicles than would normally be the case. Large financial savings could thus be realised and the operation and maintenance of settled sewage schemes could become an even more attractive option, with concomitant benefits for society.

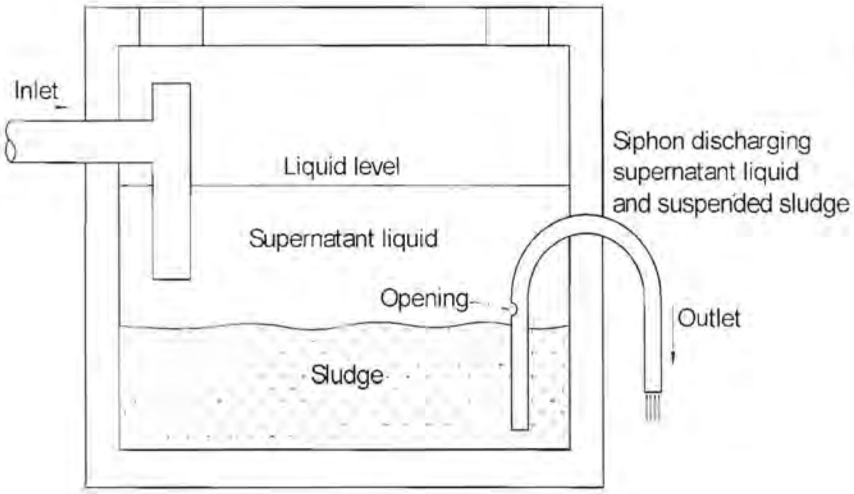
It is important that any system purporting to do this should perform its task automatically, without conscious thought or effort by the householder. The system should also preferably operate without any additional plumbing fixtures needing to be fitted into the house and without additional use of water, i.e. beyond that which the householder would use in the normal course of events. The system should therefore be self-contained and self-activated, if possible.

4.4.2 The proposed concept

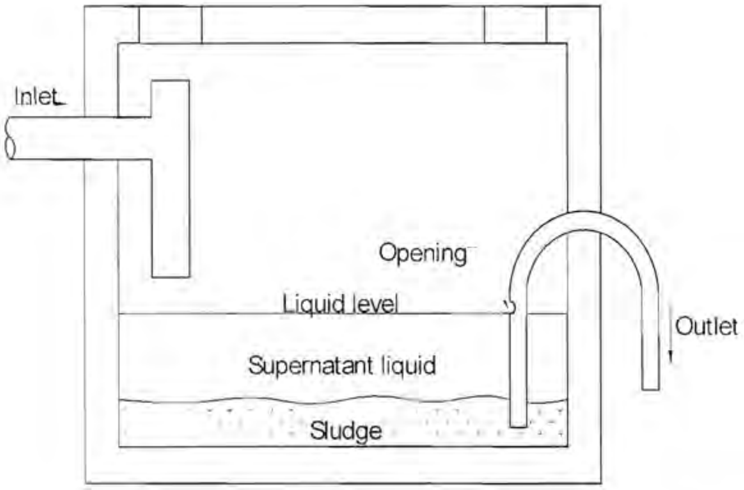
If the configuration of the outlet pipes can be arranged in such a way that a natural siphon is created, as illustrated in Figure 4.5, then it should be possible to activate such a siphon automatically by simply passing a large enough quantity of wastewater at a sufficiently rapid rate into the tank. The rate of incoming wastewater will initially need to be sufficiently greater than the rate exiting via the outlet pipe in order to allow the water level to rise above the summit of the siphon This siphonic action should then draw the septage from the tank and discharge it into the outlet pipeline. The rate and velocity of flow should be sufficient to keep the sludge in suspension.



(a) Situation just before activation of flush



(b) Situation at activation of flush



(c) Situation at end of flush

Figure 4.5: Definition sketch for the investigation: Automatic desludging of an interceptor tank by siphonic action

In the situation illustrated by Figure 4.5 (a) the liquid in the interceptor tank is at the normal equilibrium level, i.e. where any further input into the tank will cause effluent to flow via the outlet pipe into the settled sewage reticulation system. Should a relatively large inflow of wastewater enter the tank rapidly enough so that the level of the liquid has an opportunity to rise above the summit of the siphon, then the siphon should theoretically be activated and start emptying the effluent, including sludge, from the tank. This is illustrated in Figure 4.5 (b). Moreover, the siphon should continue discharging until the lower pressure at the summit, which produces the flow, is nullified by the entry of air into the system via the hole in the internal siphon leg (Figure 4.5 (c)). Note that the actual design of the prototype system, described in section 6.7 of this dissertation, prevents the air hole from becoming clogged with scum or other floating matter.

Because domestic septic tanks are usually designed so that up to two-thirds of the volume can be occupied by accumulated solids before they require desludging (see section 4.3 above) they are commonly 1 750 ℓ to 2 000 ℓ in size. It is rare that they are less than 1 000 ℓ. Tanks smaller than this will require desludging too frequently and thus not be an economical proposition. It is therefore also postulated that, should the proposed sludge siphon be found to be a feasible option, then interceptor tanks fitted with this device could be very much smaller, as no space would be required for storage of sludge. The sludge would be withdrawn from the tank before it has an opportunity to accumulate. This would have definite and sizeable cost advantages, not only for the householder but also for the local authority. The householder will only need a tank large enough to provide a hydraulic retention period sufficient to ensure adequate separation of solids in the wastewater, and will thus save on the purchase and installation costs. The local authority will derive the benefit of seldom, if ever, having to send a vacuum tanker and maintenance crew to desludge the community's interceptor tanks – these will only be needed for routine maintenance work or for emergency situations such as blockages or other problems which may occur in the settled sewage system.

It is unlikely that the quantity of influent produced by an ordinary flushing toilet will be sufficient to activate the siphon, as even a 10 ℓ flush entering a 1 000 ℓ septic tank will only raise the liquid level by between 10 and 13 mm, depending on the shape of the tank, while outlet pipes are usually not less than 40 or 50 mm in diameter. Therefore the system design should be such that it can be activated by either a bath or a washtub being emptied into the tank. For a dwelling with in-house plumbing fixtures this should be easily achieved. However, where the level of service is such that there is no in-house plumbing and where the toilet and septic tank are separate from the dwelling, then the minimum requirement will be a washtub attached to the toilet structure, with the outlet drain discharging directly into the septic tank. Systems such as these are fairly common in South Africa, as illustrated in Figure 4.6.

Figure 4.6: Typical washtub attached to exterior toilet with outlet discharging directly into septic tank (aqua privy). Thusang (Northern Province)

CHAPTER 5

PRINCIPLES OF SIPHONS AND SEDIMENT TRANSPORT

"Imagination is more important than knowledge."

Albert Einstein

CHAPTER 5: PRINCIPLES OF SIPHONS AND SEDIMENT TRANSPORT

5.1 SIPHONIC THEORY

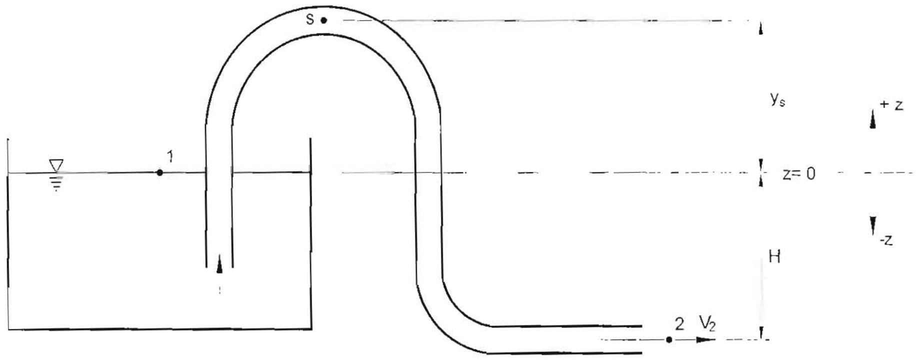


Figure 5.1: The simple siphon

Consider the simple siphon illustrated in Figure 5.1 above. Assuming that the siphon is flowing full, with a continuous liquid column throughout, application of Bernoulli's energy equation between points 1 and 2 yields (Streeter 1951)

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + \text{losses}_{1\text{-}2} \qquad \text{(units in m)} \;\ldots\ldots\ldots\ldots\ldots\ldots(5.1)$$

where

$\frac{P}{\gamma}$ = pressure head, with suffixes referring to respective measuring positions

$\frac{V^2}{2g}$ = kinetic energy head, suffixes referring to respective measuring positions, and

z = potential energy head.

The loss term (loss in kinetic energy) can be expressed as

$$k \cdot \frac{V_2^2}{2g}\;, \text{ where k is a dimensionless coefficient}$$

In other words, the losses are expressed as a factor of the velocity at point 2.

This equation results in

$$H = \frac{V_2^2}{2g} + k.\frac{V_2^2}{2g}$$

The losses are usually minor and can be neglected, unless precise work is required (Streeter 1951).

Therefore $V_2 = \sqrt{2gH}$ ....(5.2)

where V = fluid velocity, m/s
g = gravity constant, m/s^2 and
H = pressure head, m

Therefore the exit velocity V_2 is proportional to the square root of the head H (V decreases as the tank empties).

Using the same symbols as before, and also neglecting the minor losses, between point 1 and the siphon summit S the energy equation yields

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_s}{\gamma} + \frac{V_2^2}{2g} + y_s \qquad \text{..........(5.3)}$$

i.e. $$\frac{P_s}{\gamma} = -y_s - \frac{V_2^2}{2g} \qquad \text{..........(5.4)}$$

P_s is thus negative (gauge pressure) and is proportional to y_s and V_2^2 (i.e. P_s decreases as the tank empties).

The low pressure at the summit S, which causes the siphon to discharge water from the tank, is produced by the length of the water column y_s + H (Streeter 1951). Discharge will take place as long as y_s plus the vapour pressure is less than the local atmospheric pressure expressed in length of fluid column (approximately 9 m for water, less losses). It is assumed that air is excluded from the siphon.

5.2 HYDRAULIC TRANSPORT OF SEDIMENT

5.2.1 General

In order to transport solids hydraulically, they have to be kept in a state of suspension by the liquid medium. In conventional sewers the solids will remain suspended only for as long as there is a large enough volume of liquid flowing at a suitable velocity through the pipeline. The specific gravity of the solids is also an important factor, as light solids will be transported more easily than heavy solids.

Effluent flow in the upper reaches of a pipe system is marked by extended periods of minimal or no flow interspersed by short periods of high discharge (Reed 1995). Further down in the network the increasing number of branch pipelines contributing to the discharge produces a virtually continuous effluent flow which varies throughout the day. The flow usually tends to be a minimum sometime during the night and a maximum at some time during the day. The exact time at which the maximum and minimum flows occur will depend on the local patterns of domestic water use, the quantity and type of industrial effluent present and the distance the effluent has to flow to reach the sewer. For the purposes of this investigation, only domestic effluent is considered, i.e. effluent discharging from septic tanks in residential areas.

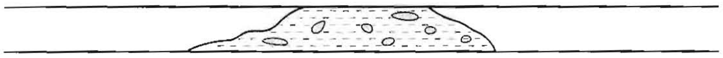
The scope of this project and dissertation required only a limited investigation into sediment transport theory. The purpose of the experimentation was to test the hypothesis that it is possible to extract sludge from a domestic septic tank by means of a simple siphon. This hypothesis was proved to be valid. In the laboratory where the experimental equipment was set up, the length of pipeline along which the suspended sludge was transported after passing through the siphon was only 8,0 m (see figure 6.12), and moving the sludge for long distances was thus not required. The investigation of sludge transport over longer distances will be the focus of a further research project. For this dissertation, therefore, only the basic principles of sediment transport are given, which are sufficient for an understanding of the processes taking place. However, some further study into the physical laws governing sediment transport, which will form the basis for the further investigations, was undertaken. This is included in this dissertation as Appendix C.

5.2.2 Solids transport in the upper reaches of a pipeline

When effluent is discharged into a sewer it produces a short, highly turbulent wave which may fill most of the pipe section (Reed 1995). This is illustrated in Figure 5.2 (a). As the wave travels along the sewer, boundary layer friction causes the top of the wave to flow faster than the bottom, which has the effect of attenuating the wave (Figure 5.2 (b)). When solids are being carried along in the effluent, they are kept in suspension initially by the turbulence in the wave (Figure 5.2 (c)). As the wave attenuates, the solids settle to the bottom and are pushed along by the pressure of the water behind them, as long as the flow is sufficient (Figure 5.2 (d)). Eventually effluent upstream of the solids drains away and the solids are left behind – they will be moved further along the sewer by successive effluent waves until they reach an area of continuous flow, whereupon they will remain in a state of permanent suspension as long as the flow velocity is sufficient.

(a) Discharge profile close to source

(b) Discharge wave further downstream attenuated by friction



(c) Wave close to source carrying solids in suspension

(d) Attenuated wave pushing solids along pipe invert

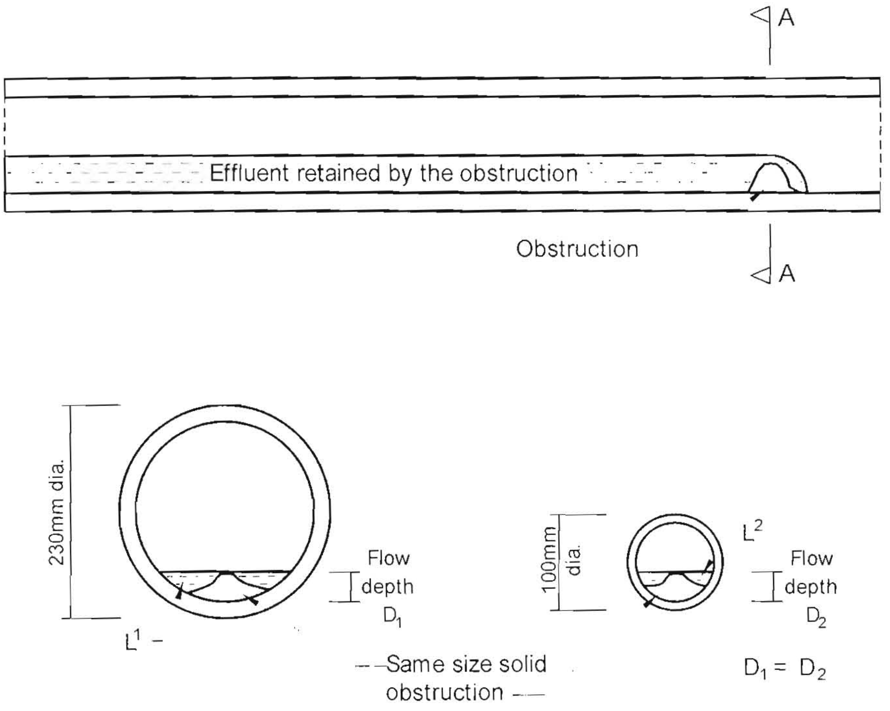
Figure 5.2: Solids transport mechanisms in the upper reaches of a sewer network
(Reed 1995)

5.2.3 Solids transport in the lower reaches of a pipeline

Further down the system the flow is virtually continuous. Most solids will be kept in suspension and transported by the flow. Heavier solids will either be pushed along in a way similar to that produced by the attenuated flow or else they will be re-suspended during the periods of peak flow (Reed 1995).

5.2.4 Effect of different pipe diameters

In the upper reaches of sewerage systems solids are, as described above, transported by hydraulic forces. Figure 5.3 illustrates how, in the case of solids which have been deposited in a pipeline, larger diameter pipes require a greater volume of effluent to produce the same depth of upstream flow as a smaller pipe, and there is a greater amount of "leakage" around the solids. For a given flow rate, smaller pipes have a higher liquid flow velocity and thus a greater momentum to act on the transported solids (Reed 1995).



Note: In a large sewer, the area of effluent (L^1) surrounding an obstruction is greater than that surrounding an obstruction of the same size in a smaller sewer (L^2), assuming the same depth of flow for each (the flow rates and pipe slopes will not be the same for both cases). Effluent in a large sewer will generally drain away faster than in a smaller one, because of the greater "leakage" around the solids. As it is the effluent trapped behind the obstruction that moves it along the pipe, movement of the solids will tend to take place easier in the smaller pipe (Reed 1995).

Figure 5.3: Effect of pipe diameter on solids movement efficiency.
Top: section through pipe length; Bottom: alternative cross-sections through A-A
(Reed 1995)

Sludge particles are of a particulate nature, low specific gravity, and unlike the type of solid matter usually encountered in conventional waterborne sewerage systems. The "sludge siphon" concept is therefore based on the supposition that the sludge which is siphoned out of a septic tank is not dependent on strict minimum pipe diameters and gradients for its suspension and transport in a fluid medium. Rather, the fluid/sludge mixture is assumed to be homogenous (i.e. a continuum) and the sewer can therefore be designed using hydraulic principles.

CHAPTER 6

METHODOLOGY FOR DEVELOPING THE SLUDGE SIPHON

> "Scientists explore what is; engineers create what has never been."
>
> Theodore von Karman (1911)

CHAPTER 6: METHODOLOGY FOR DEVELOPING THE SLUDGE SIPHON

6.1 INITIAL EXPERIMENTATION

The first objective was to cause a siphon immersed in a container of water to discharge automatically when additional water was poured rapidly into the container. This was to simulate the situation hypothesised in Figure 4.5, where the entry of liquid into the septic tank inlet would cause the siphon at the outlet to commence discharging effluent into the outfall pipeline.

A 50 litre plastic container was fitted with a siphon fabricated from 50 mm diameter uPVC water pipe (Figure 6.1). The siphon consisted of two vertical legs joined to a horisontal branch by means of elbows. The longer leg of the siphon extended through the bottom of the container to form the effluent pipeline. The container was first slowly filled up to the level of the invert of the horisontal pipe branch, until the water just started to flow from the pipe outlet. At this stage additional water was poured rapidly into the container so that the soffit of the horisontal pipe became completely immersed. Although this additional water drained out of the tank via the outlet leg of the pipe system, the siphon did not charge itself and start emptying the container as expected. It was assumed that air had probably become trapped in the elbows, thus preventing the siphon from activating.

Figure 6.1: 50 ℓ container and 50 mm diameter prefabricated pipe system intended to simulate a siphonic-type outlet

In order to test this assumption, the pipe system was first fully charged with water, in order to expel all air bubbles, before being inserted into the container. On this occasion, when the container was rapidly filled up again, the siphon commenced operation and emptied the water from the tank. It was thus deduced that, for the siphon to commence emptying the container without itself first needing to be charged with water, it would be necessary to improve its design. Either all air trapped inside it would need be expelled while the container was filling or, alternatively, any air bubbles still inside the pipe should not interfere with the operation of the siphon. After various attempts, the pipe configuration illustrated in Figure 6.2 was found to operate satisfactorily without requiring to be charged with water first. As the container was filled above the soffit of the "horisontal" branch of the pipe system, the siphon commenced discharging and continued doing so until the container had been emptied. It was concluded that the air bubble trapped inside the pipe had been forced into the highest point of the system, into the very corner of the top elbow, so that it no longer interfered with the free flow of water through the siphon.

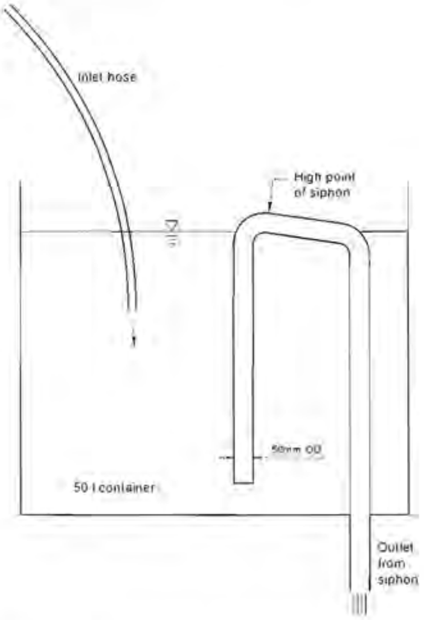
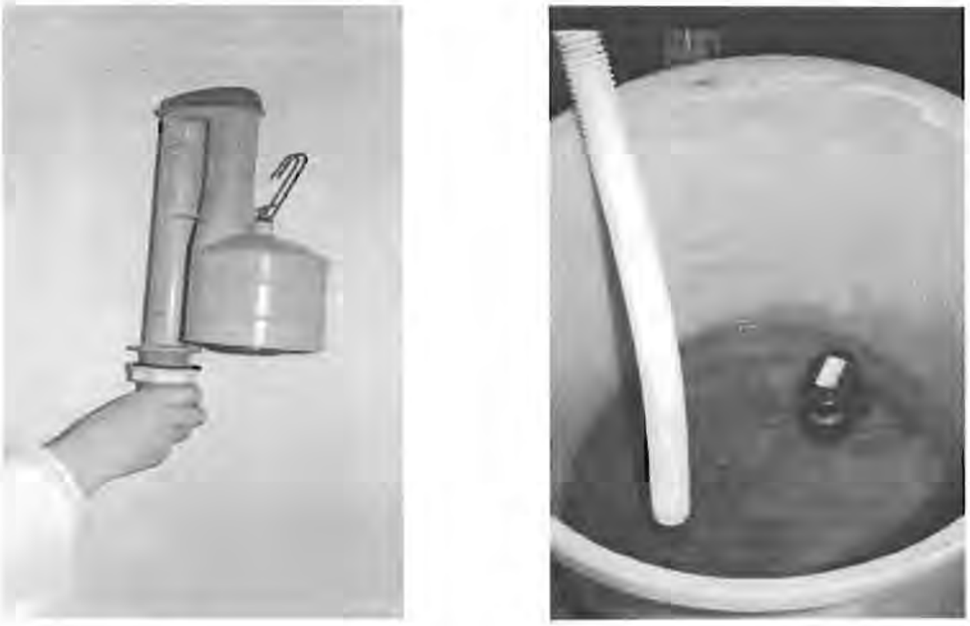


Figure 6.2: Modified pipe configuration in order to negate effect of air bubbles on activation of siphon

It became clear that a moulded pipe system, i.e. one which had smooth bends instead of prefabricated elbows, would reduce the likelihood of air bubbles being trapped in the system and interfering with the activation of the siphon. For this purpose a standard plastic siphonic cistern valve was taken and the top part cut off in order to serve as the summit of the siphon arrangement in place of the uPVC pipe and elbows. This is illustrated in Figure 6.3. The basic shape of the valve summit is similar to the configuration adopted in Figure 6.2. It was found that this device worked excellently – upon rapid addition of water to the container the siphon charged itself and emptied the container without any problems occurring.



(a) (b)

Figure 6.3: Standard siphonic cistern valve forming outlet mechanism of container:
(a) unmodified valve shown separately; and (b) the summit of the valve cut off and fitted into the bottom of the container.

It was now necessary to simulate this effect in a larger container, with a water surface area closer to what it would actually be in, say, a small septic tank. This step was required in order to determine the minimum volume of water needing to be fed into the tank in order for the siphon to automatically commence discharging. The greater the water surface area in the tank, the greater the amount of additional water required to activate the siphon. Initially, a plastic tank with a diameter of 530 mm was fitted with the pipe system used previously. The result was satisfactory in so far as the siphon worked as desired, except that the minimum flush volume required was found to be not less than 14 ℓ for this specific tank size. This presented a problem, as it implied that the siphon could not be activated merely by a toilet cistern being flushed, as insufficient water would be discharged into the tank in this case, especially if a tank with a larger water surface area was being used. A plumbing unit which could rapidly discharge a larger amount of water would be required, for example a bath. However, basing the design of the system on the use of something the size of a bath would effectively prevent all dwellings without large in-house plumbing fixtures from incorporating such a system into their sanitation arrangements.

It was therefore necessary to devise a system which would enable the siphon to charge itself and commence emptying the tank without an unnecessarily large volume of water being required. It was perceived that if the system could be made to work by emptying a fixture like the washtub illustrated in Figure 4.6, Chapter 4 (about 25 - 35 ℓ) into the tank, then the scope for implementation of such a system could be broadened considerably to include communities of virtually all income levels. A different pipe arrangement would be required, whereby the effective functioning of the outlet siphon could be made independent of the size of the tank, i.e. one that would work with a flush the size of a washtub (or greater) irrespective of the size of the septic tank.

The very high inflow rate required to activate the siphon, without the concomitant use of large quantities of water, required a different type of inlet mechanism. The configuration shown in Figure 6.4 was eventually adopted. In this system the toilet wastes would still enter the tank via the standard T-piece inlet, but larger volumes of greywater (e.g. from a washtub or larger unit) would enter a separate, smaller compartment on the side of the tank, above the siphon. This separate compartment, which would be connected to the main tank by an opening, would be able to charge the siphon with a minimum amount of water, because the water level would rise rapidly above the summit of the siphon, i.e. faster that what it would flow into the tank itself. This would then cause the siphon to charge itself and start emptying water from the tank. The system was found to operate perfectly – water discharging from the washtub into the side compartment of the tank immediately caused the water level to rise above the summit of the siphon and initiate the flush. It was also found that the volume of water flushed from the tank could be controlled by making a hole in the side of the siphon leg, which allowed air to enter the system when the water surface fell to this level. This nullified the pressure differential around the summit and caused the siphon to stop discharging.

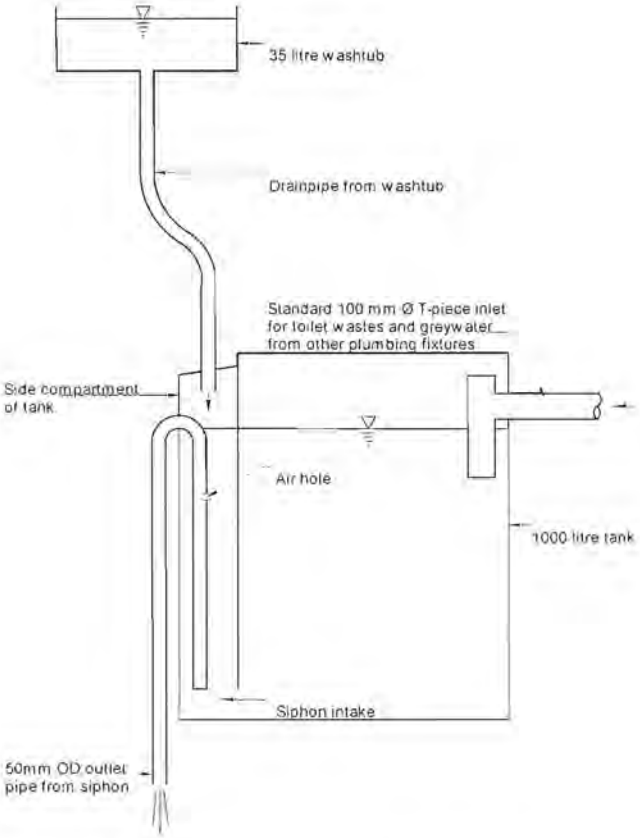


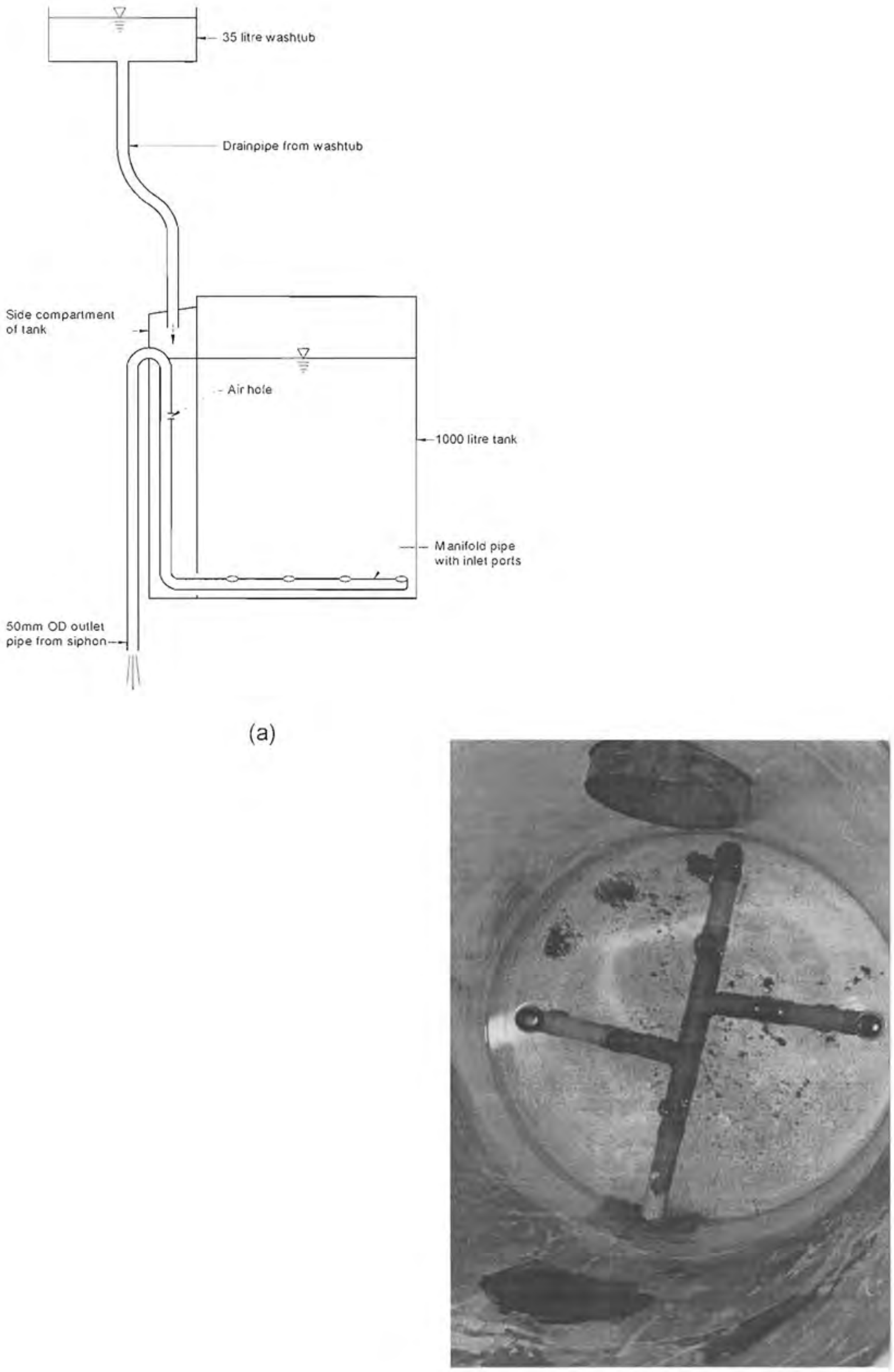
Figure 6.4: Modified outlet arrangement to facilitate charging of the siphon

6.2 EXPERIMENTATION WITH "SIMULATED SLUDGE"

Having achieved satisfactory results with a self-activating siphon which proved to be capable of extracting any desired amount of liquid from the tank, the next step was to experiment with a mixture of water and suspended sediment. Due to the fact that septic tank sludge is a dangerous substance to work with, it was decided to postpone the testing thereof and initially use an inert material which would reasonably simulate the physical characteristics of the fine, particulate sludge matter. Then, once it was certain that the siphonic outlet arrangement worked as intended using this "simulated sludge", the testing could be continued with actual septic tank sludge.

Because septic tank sludge is a material with a low specific gravity, which settles very slowly to the bottom of the tank, it was necessary to find a material which behaved similarly in water. Sawdust was found to work satisfactorily and the experimentation was continued using water mixed with suspended sawdust. A tank with a volume of 1 000 ℓ was set up on a platform with the 35 ℓ washtub above it in the same configuration as before, except that the floor was made sloping towards the siphon intake with the intention of assisting the movement of sawdust. This system did not work satisfactorily; the mass of saturated, settled sawdust tended to remain piled up on the floor of the tank with only a portion around the siphon intake being drawn out of the tank. The remainder of the sawdust was not drawn towards the siphon intake at all.

It became clear that a single inlet into the siphon was not sufficient and that a multiple-inlet type of pipe system, similar to a manifold, would be required in order to withdraw the sawdust effectively from the tank. Towards this end the arrangement shown in Figure 6.5 was assembled. By providing a total of seven inlet ports it was hoped that any sawdust building up to above the level of the manifold pipe would be withdrawn from the tank. This proved to indeed be the case – sawdust deposited into the tank built up to the level of the top of the manifold, but any excess was sucked into the siphon via the multiple inlet ports and removed from the tank. Figure 6.6 illustrates the successful tank and outlet arrangement. The maximum available head, measured from the summit of the siphon to the outfall pipeline, was 1,0 m in this case.



(a)

(b)

Figure 6.5: Multiple siphonic intake for withdrawing settled sawdust from tank (a) schematic illustration; (b) photograph of manifold inside tank

Figure 6.6: Working arrangement with washtub draining into the tank and siphonic outlet discharging into the pipeline (available hydraulic head between summit of siphon and outfall pipeline = 1,0m)

6.3 EXPERIMENTAL EQUIPMENT AND PROCEDURE

The 1 000 ℓ tank with fabricated manifold, siphon and side compartment was erected on a platform with the 35 ℓ washtub installed in position above it in order to simulate an actual washtub draining into a septic tank, such as illustrated in Figure 4.6, Chapter 4. A 46 mm internal diameter perspex pipe was connected to the siphon outlet to form a transparent outfall pipeline. Numerous buckets of sawdust were added to the tank which was simultaneously filled with water up to the level of the siphon outlet. After a minimum period of a day all the sawdust had settled to the bottom of the tank and covered the manifold ports. Although the sawdust could not, strictly speaking, be equated physically to digested septic tank sludge, the two materials were similar enough for the purposes of this experimentation. What was required was a light, particulate material which would settle slowly to the bottom of the tank and be easily re-suspended upon agitation. An inert material was preferable to a hazardous substance such as septic tank sludge. Once the design of the sludge siphon had been refined and any operating problems ironed out, then further experimentation and observation could be continued using actual sludge obtained from functioning septic tanks.

The equipment setup is illustrated in Figure 6.6. The perspex pipeline was suspended from the roof of the laboratory by means of adjustable steel hangers (Figure 6.7). The first and last hangers were related by absolute levels measured from the concrete floor; the pipeline could then be set at any desired slope by adjusting the height of the other hangers according to a taught length of building line stretched between these two. The length of pipeline was about 8 m and at the end it drained the fluid/sawdust mixture into a holding tank for subsequent reuse.

When the plug was pulled out of the full washtub, the water entering the side compartment of the tank charged the siphon which, in turn, extracted the settled sawdust from the bottom of the tank. At the same time the water in the tank drained down to the level of the air hole, when discharge ceased. The volume of water drained from the tank could be predetermined by adjusting the level of the air hole. The volume could be selected according to the quantity of settled sawdust extracted. An ideal situation was reached when the top of the settled sawdust dropped to the level of the inlet ports on the manifold and the siphon continued pumping water from the tank. The result was a "plug" of relatively clean water which followed the sawdust and thus largely flushed the pipeline clean. Figure 6.7 shows the water/sawdust mixture discharging from the siphon leg into the pipeline, while Figure 6.8 illustrates the small amount of sawdust left on the invert of the pipe after completion of the flush. Subsequent flushes resuspended this remaining sawdust and transported it further down the pipeline again. The result was that the sawdust never had an opportunity to accumulate on the pipe invert.

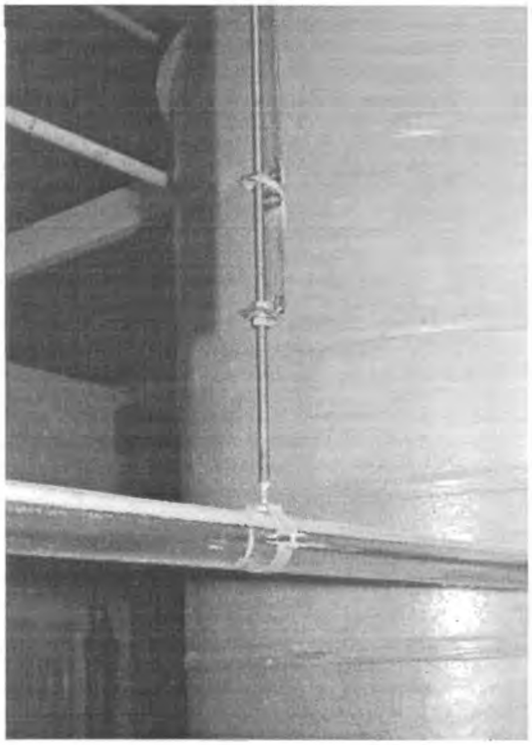


Figure 6.7: Adjustable pipe hanger and clamp attached to roof of laboratory. Pipe is discharging a mixture of water and sawdust.

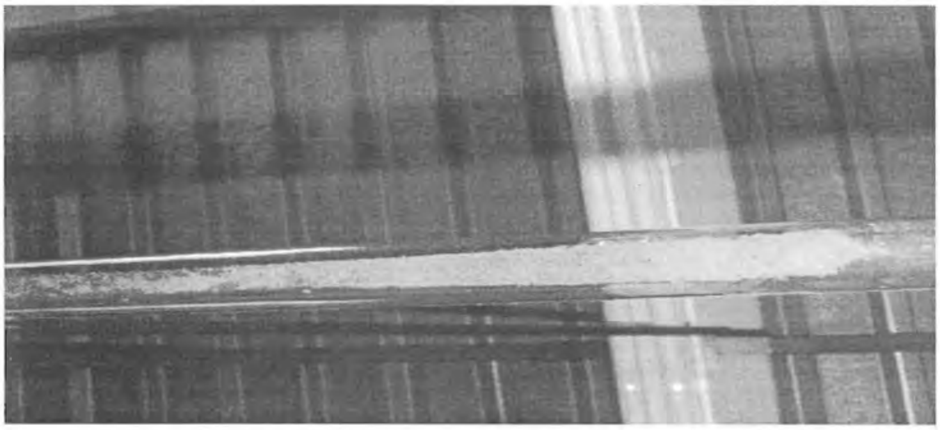


Figure 6.8: Small amount of sawdust left on invert of pipe after completion of flush (seen from underneath). Direction of flow is from right to left.

The testing equipment illustrated was full-size. The washtub, tank, manifold, siphon and pipeline used were not scaled-down models, and therefore no interpretation or manipulation of the results in order to account for scale factors was required. The measured flows and velocities during the siphonic flush could therefore be accepted as those which would actually occur under normal operating conditions.

6.4 OBTAINING TRUE SEPTIC TANK SLUDGE

Once the siphon had been proved to operate satisfactorily with suspended sawdust, the project team was prepared to proceed with the real purpose of the project – getting the siphon to extract actual sludge from the tank. The necessary health precautions were taken: team members were vaccinated against hepatitis and cholera, and wore protective clothing, including gloves, whenever working with the substance, even if only pumping it from one tank to another.

It was decided to experiment with sludge from a middle-income household initially. Septic tank sludge from various communities can be expected to differ somewhat in composition. This is due not only to the people's differing diets but because low-income families often use sand or grit to scour pots and pans while washing them. This material then finds its way into the tank. Due to its different physical characteristics such as density, particle size, etc, it was thought that it could possibly exhibit different flow behaviour when compared with sludge particles obtained from higher-income households.

Sludge was initially obtained from a domestic septic tank at a plot in Cynthiavale near Wonderboom Airport, north of Pretoria. The existing situation inside the tank was first investigated by means of the perspex coring tube illustrated in Figure 6.9. Using this apparatus the depth of sludge, supernatant and scum inside a tank can be ascertained by extracting a sample core of the material. The brass rod is inserted into the tank until it reaches the bottom, whereafter the perspex tube is inserted over it and the wingnut on top tightened in order to seal the contents inside. The tube is then withdrawn from the tank and a perfect sample of the contents is obtained. Figure 6.10 shows the core extracted from the tank - it was observed that the tank was operating well, without any problems.

The septage (mixture of sludge, scum and supernatant liquor) was extracted from the tank by means of a small sludge pump. The mixture was pumped into a storage tank on the back of a light delivery vehicle before being transported to the laboratory. In Figure 6.11 the process of extracting the septage is illustrated.

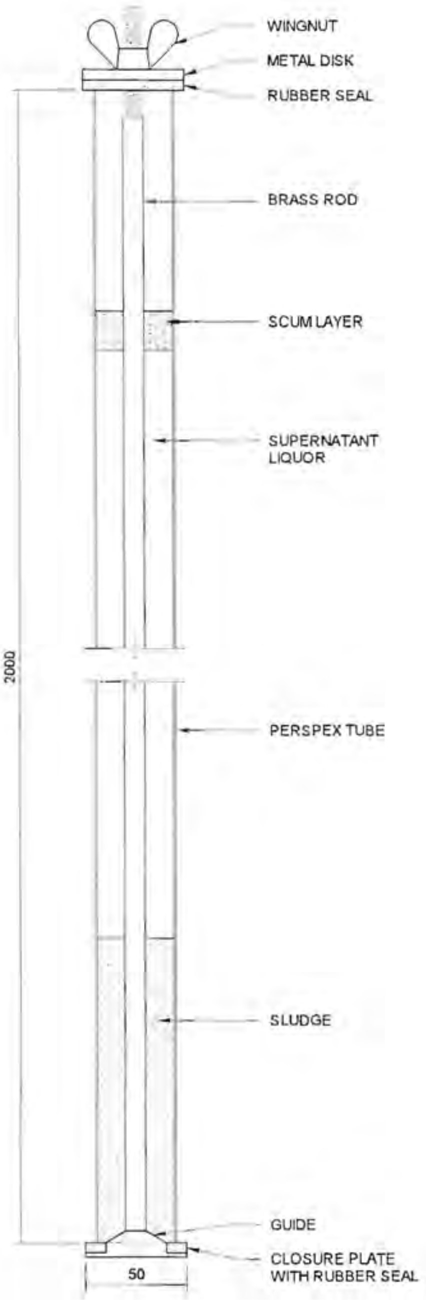
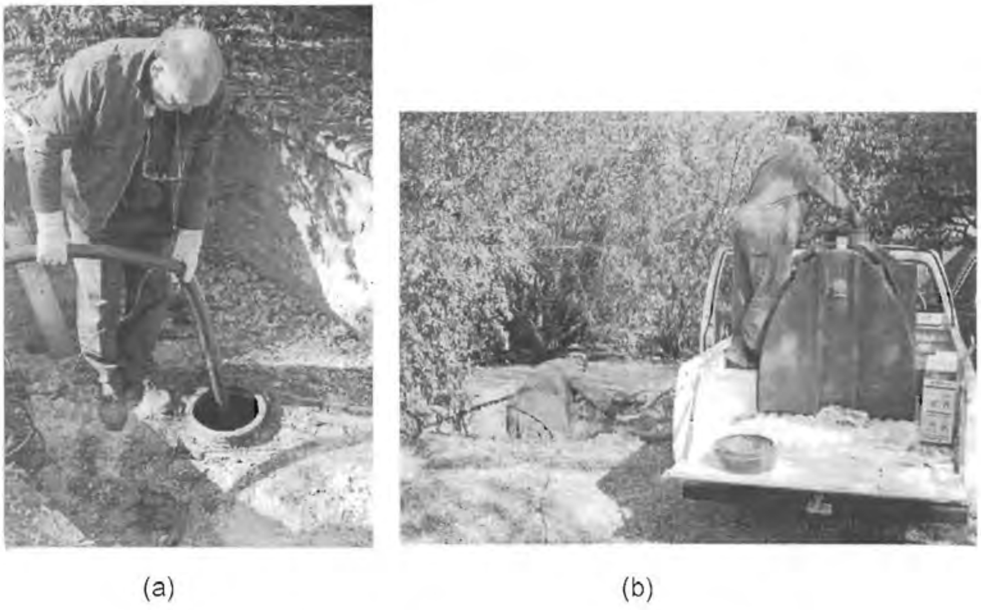


Figure 6.9: Perspex coring tube used to examine contents of septic tank

Figure 6.10: Sample core extracted from septic tank on plot near Wonderboom Airport



(a) (b)

Figure 6.11: Extracting septage from a septic tank: (a) lowering the sludge pump into the tank; (b) pumping septage into the storage tank on the back of the vehicle

At the laboratory the equipment shown in Figure 6.12 was assembled. The septage was first pumped across from the transporting tank on the back of the vehicle into a holding tank on the floor of the laboratory. From this holding tank the septage was pumped up to the siphon tank on the platform beneath the washtub. This configuration was used for all subsequent tests: the septage, after being siphoned out of the top tank, flowed into the holding tank at the end of the pipeline, from where it could again be pumped to the top tank in order to repeat the procedure. The available hydraulic head between the summit of the siphon and the 46 mm diameter outfall pipeline was 1,0 m.

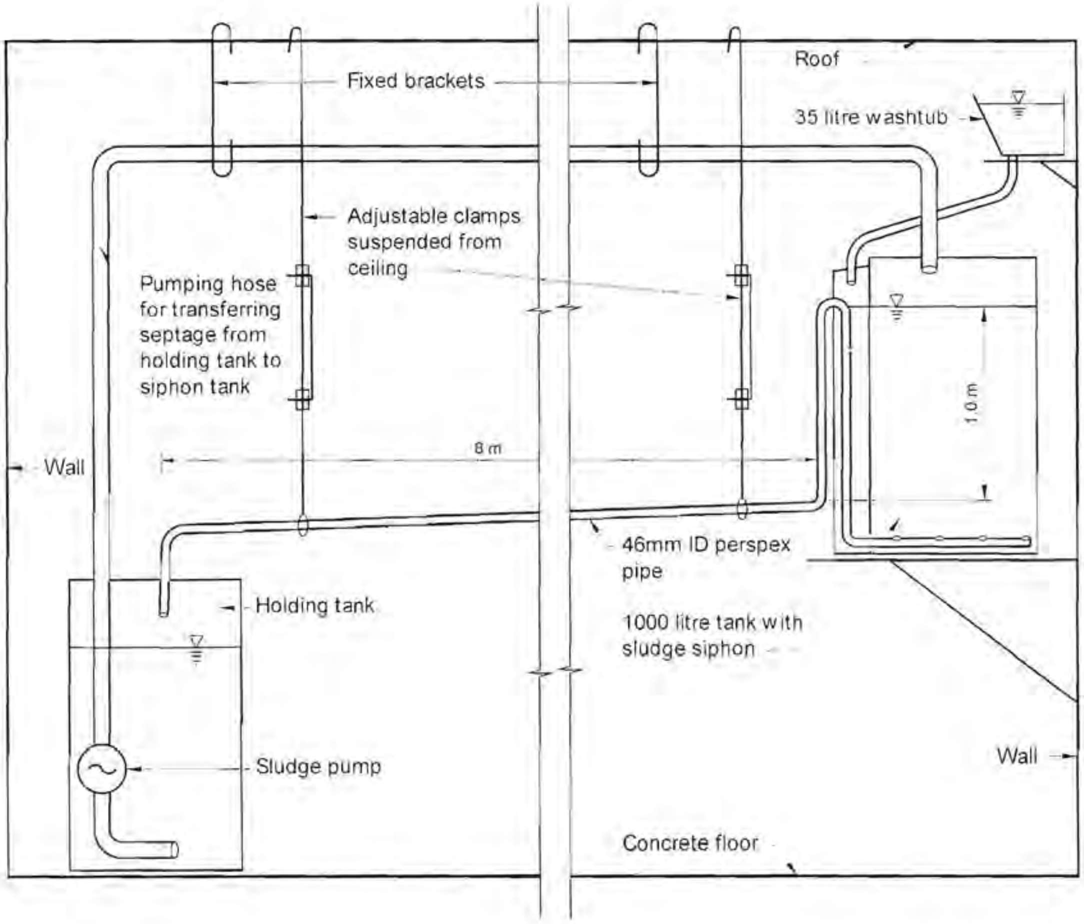


Figure 6.12: Equipment setup for testing of sludge siphon, utilising actual septage

6.5 PROPERTIES OF DOMESTIC SEPTIC TANK SLUDGE

6.5.1 General

For the purposes of studying the flow of septage in a pipeline, it is useful to understand its physical, chemical and biological characteristics. Septage is the combination of sludge, scum and supernatant liquid pumped from individual on-site wastewater disposal systems, mainly septic tanks and cesspools (Metcalf and Eddy 1991). The actual quantities and constituents of septage vary widely, with the greatest variations being found in communities which do not regulate the collection and disposal thereof. They also vary with the tank size and frequency of pumping. Information on septage properties is not readily available; however, some data on the constituents of septage in the USA are presented in Table 6.1. Most are presented for general interest only – the characteristics of importance for hydraulic transportation of the sludge particles are generally confined to the physical properties relating to the amount of solids present in the septage.

Table 6.1: Typical characteristics of septage in USA (Metcalf & Eddy 1991)

Constituent	Concentration, mg/ℓ	
	Range	Typical
Total solids (TS)	4 000 - 100 000	40 000
Suspended solids (SS)	2 000 - 100 000	15 000
Volatile suspended solids (VSS)	1 200 - 14 000	7 000
Chemical oxygen demand (COD)	5 000 - 80 000	30 000
Total Kjeldahl Nitrogen (TKN as N)	100 - 1 600	700
Ammonia, NH_3 as N	100 - 800	400
Total phosphorus, as P	50 - 800	250
Heavy metals	100 - 1 000	300
Grease	5 000 - 10 000	8 000

6.5.2 Specific sludge data

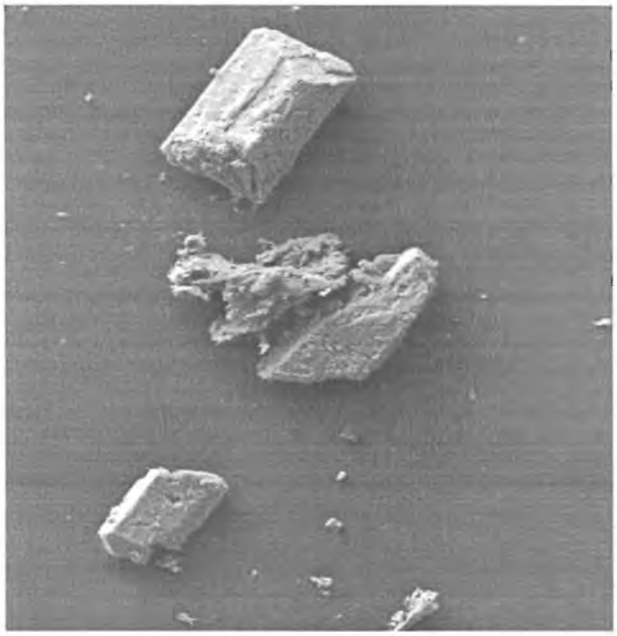
Due to the paucity of available information concerning the constituents and properties of the solid fraction of septage, it was decided to analyse the sludge obtained from the septic tank near Wonderboom Airport which was actually used in the original laboratory tests. Furthermore, because the characteristics of septic tank sludge will in all probability, as explained in section 6.4 above, differ between communities in varying income groups, tests were also conducted on sludge emanating from a poor community. For this purpose, sludge was also extracted from a septic tank in the village of Mogogelo, approximately 60 km from Pretoria in North-west Province. Table 6.2 presents a summary of the analyses, which were carried out at the CSIR Division of Materials Science and Technology. Only the relevant physical properties were analysed, and these should be seen in the context of the average concentrations shown in Table 6.1.

Table 6.2: Summary of sludge analyses

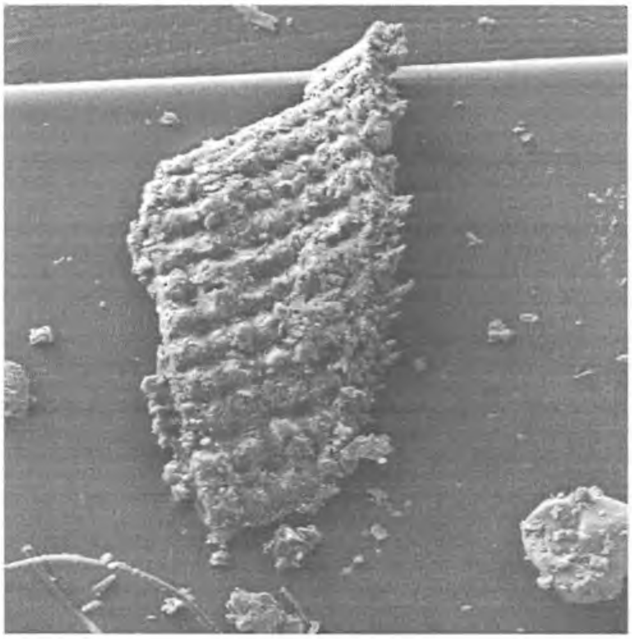
Parameter	Sample A: Sludge from middle-income family (Cynthiavale, Pretoria)	Sample B: Sludge from poor community (Mogogelo, NW Prov)
Density:		
Density of supernatant	0,99 g/mℓ	1,00 g/mℓ
Density of wet solids	1,00 g/mℓ	1,01 g/mℓ
Density of dried solids	±0,20 g/cm^3	±0,20 g/cm^3
Amount of inorganic elements in dried solids (mostly silicon & calcium)	12 g per 100 g	23 g per 100 g
Particle size distribution:		
Mean particle size, dry state	8,84 μm	16,30 μm
Mean particle size, wet state	11,92 μm	12,71 μm

Scanning electron microscopy results:

The specific constituents which make up sludge particles are of some interest in terms of the type of substances which have to be transported hydraulically. Selected inorganic particles were subjected to qualitative scanning electron microscopy (SEM) and the relevant photographs are shown in Figure 6.13 . The scale of the photographs is indicated in each case.

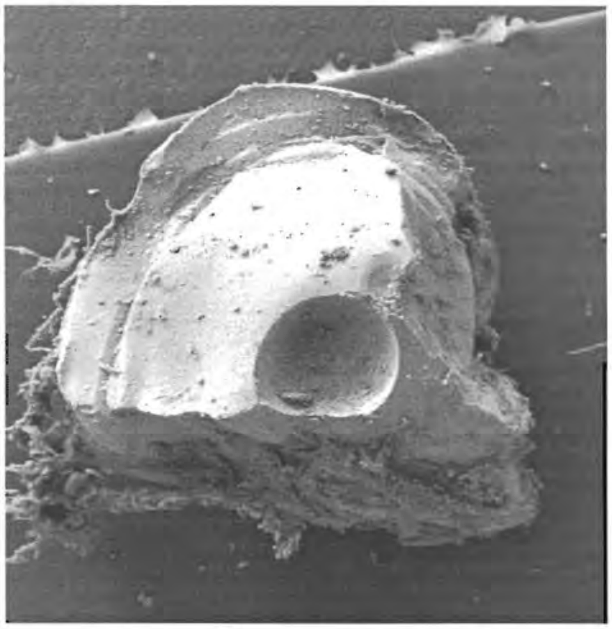


(a) Crystalline, white flakes: Main constituents: P, Mg, Ca (Magnification 59X)

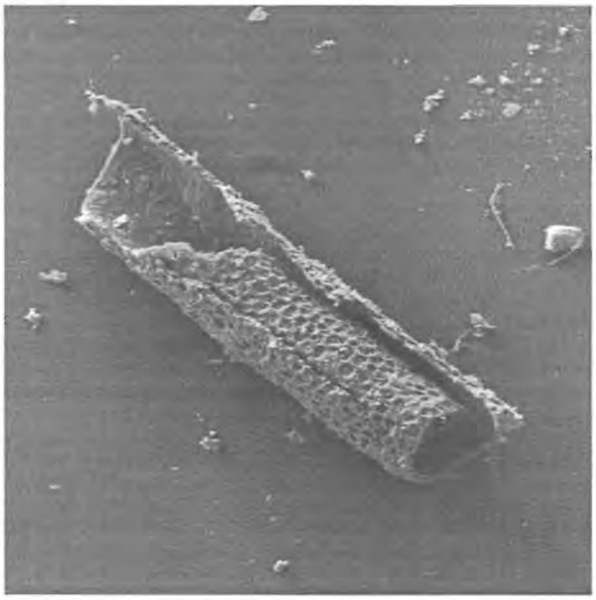


(b) Knobbly particle: Main constituents: Si, Cl, Ca, K, S, P, Fe, Al (Magnification 57X)

Figure 6.13: SEM photographs of inorganic particles in septic tank sludge



(c) Shiny black particle: Main constituents: Fe, Si, Ca, Mn, K, Cr, S, Al (Magnification 43X)



(d) Curled particle: Main constituents: S, Ca, Si, P, Cl, K, Al, Fe (Magnification 35X)

Figure 6.13 (cont): SEM photographs of inorganic particles in septic tank sludge

6.5.3 Interpretation of results of the physical analyses of sludge samples

The physical properties of the samples of sludge tested indicated that the following assumptions could be made with reasonable confidence:

- The small size of the sludge particles implied that the flow containing the suspended particles was likely to be pseudohomogenous, i.e. flow where the particles are uniformly distributed over the pipe cross-section. This aspect was not specifically tested, however. Aspects of pseudohomogenous flow are described more fully in Appendix C.
- The very small difference between the densities of the supernatant liquid and the wet solids meant that the sludge particles would be very easily suspended and hydraulically transported. This was supported by the visual observation (described in section 6.6 below) that any sludge particles deposited on the pipe invert after the flow had ceased were immediately resuspended by the following flush and transported further along the pipeline. The mixture was thus largely of the non-settling type. Settling and non-settling mixtures are explained in Appendix C.
- Most importantly, from the point of view of the sediment transport theory and experimental work described in Appendix C, it is seen that very little of this work is actually applicable to domestic septic tank sludge. Much of the literature deals with sediment which is either spherical in shape, or of a constant size or uniform grading, while the SEM photographs clearly show the wide variety of particle shapes and sizes found in the sludge. Although the sludge from the poor community contained practically double the quantity of inorganic material, the very small differences in particle sizes and distribution meant that little, if any, differences in flow behaviour between the two samples could be expected.

  While the basic theory of bed-load movement, critical shear stress, settling and non-settling mixtures, etc still applies, it is clear that there will be very little point in attempting to predict the precise hydraulic behaviour of the sludge particles by theoretical means. All results obtained and predictions made in this project were therefore based on observation and measurement.

6.6 EXPERIMENTATION WITH SEPTIC TANK SLUDGE

6.6.1 General

The previous experimentation, which was conducted using sawdust, was now repeated using actual sludge from the septic tanks in Cynthiavale (middle-income community) and Mogogelo (poor community) respectively. The sludge siphon concept proved to operate well in the laboratory and fulfilled all the original expectations. Using the setup shown in Figure 6.12, the sludge was successfully extracted from the tank via the manifold, while at the end of the flush, when the flow ceased, there was a deposition of particulate matter on the invert of the pipeline (Figure 6.14). Subsequent flushes were found to resuspend this material and transport it further down the pipeline, with the result that the deposited material never had a chance to accumulate.

There was no discernable difference between the flush, flow and deposition characteristics of the two samples of sludge. This was to be expected, given the relatively small differences in composition, particle size, etc. However, this observation does not rule out the possibility of sludge samples from other communities containing much coarser or heavier sediment exhibiting different deposition and re-suspension characteristics. Nevertheless, it seems unlikely that the overall performance of the sludge siphon will be affected to any great extent.

Figure 6.14: Actual septic tank sludge deposited on invert of pipeline after completion of flush (seen from underneath). Pipe gradient = 0,25 %; pipe ID = 46 mm.

For economy in the installation of a sludge siphon system, it will be advantageous if the effluent pipeline can be buried as shallow as possible. A test was therefore also carried out with a head of only 0,5 m (Figure 6.15). There was no visible difference in the sludge-carrying ability of the effluent, which was relatively clear by the time the flow had ceased. For the full duration of the flush, the suspended sludge was easily transported along the pipeline between the upper and lower tanks. Due to the very low specific gravity of the solids (see section 6.5 above) the effluent was easily able to keep the particles suspended, and only deposited its load when the flow had virtually ceased. Although the length of pipeline was only 8 m, the initial results obtained would seem to indicate that the sludge particles could in actual fact be transported very much further than that. This specific aspect will be the subject of a further research project at the Division of Building and Construction Technology, CSIR.

The minimum volume of water needing to be discharged from the washtub in order to activate the siphon was found to be 21 litres. The average inflow rate was experimentally determined to be about 1,6 ℓ/s.

Figure 6.15: Apparatus set up to produce a discharge head of 0,5 m

6.6.2 Graphic representation of flows

In order to establish the velocities and quantities of effluent discharging from the tank, it was necessary to resort to physical measurements. Theoretical calculations based on Bernoulli's equation were inapplicable in this case because the tank depth and outflow velocity in the pipeline were constantly varying. The following series of graphs were drawn up by means of visual observations aided by a stopwatch, and were repeated a number of times in order to obtain good average values. In all cases, time zero was taken when the plug was pulled out of the washtub to start the flushing process.

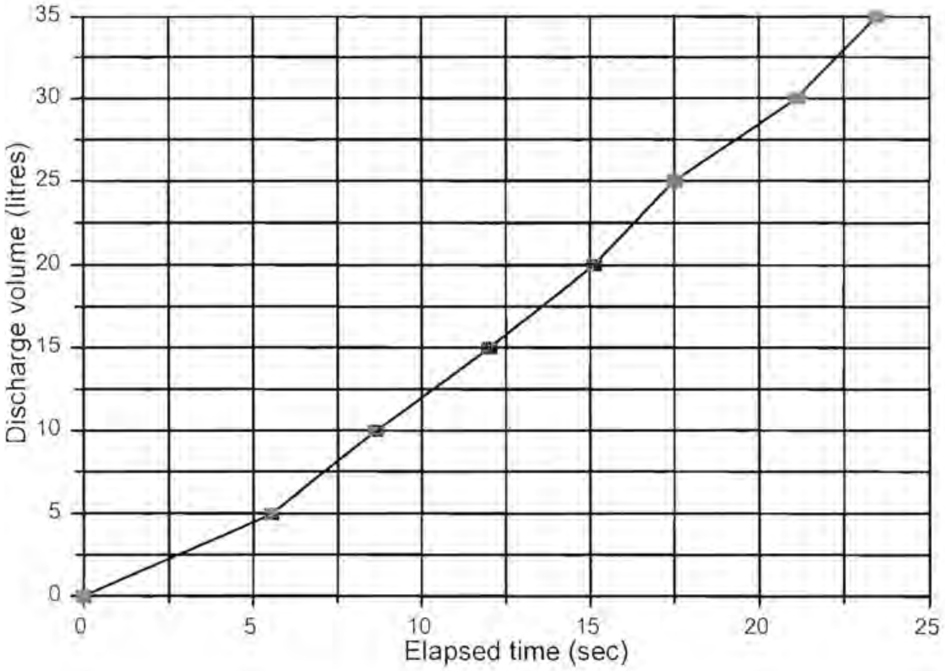


Figure 6.16: Discharge from washtub

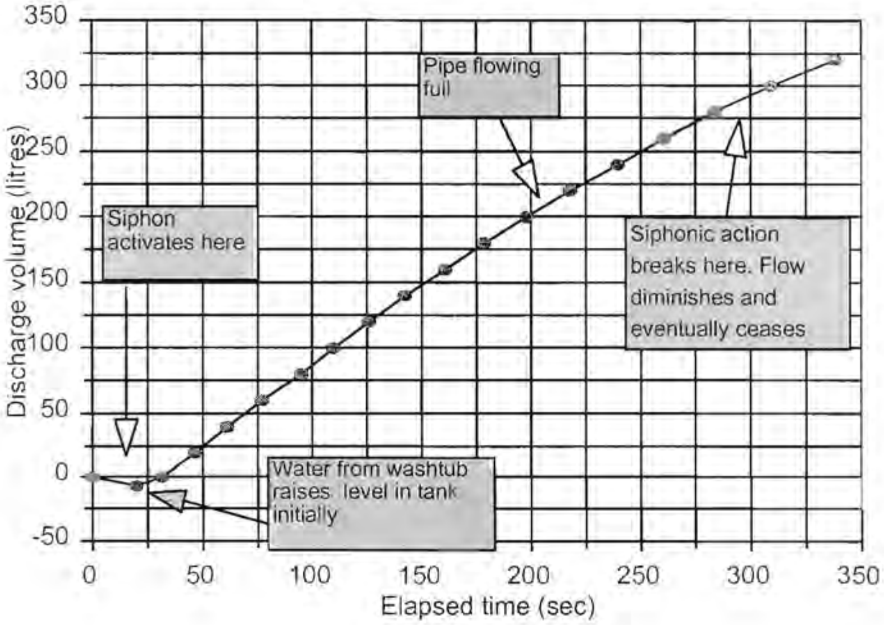


Figure 6.17: Discharge from tank

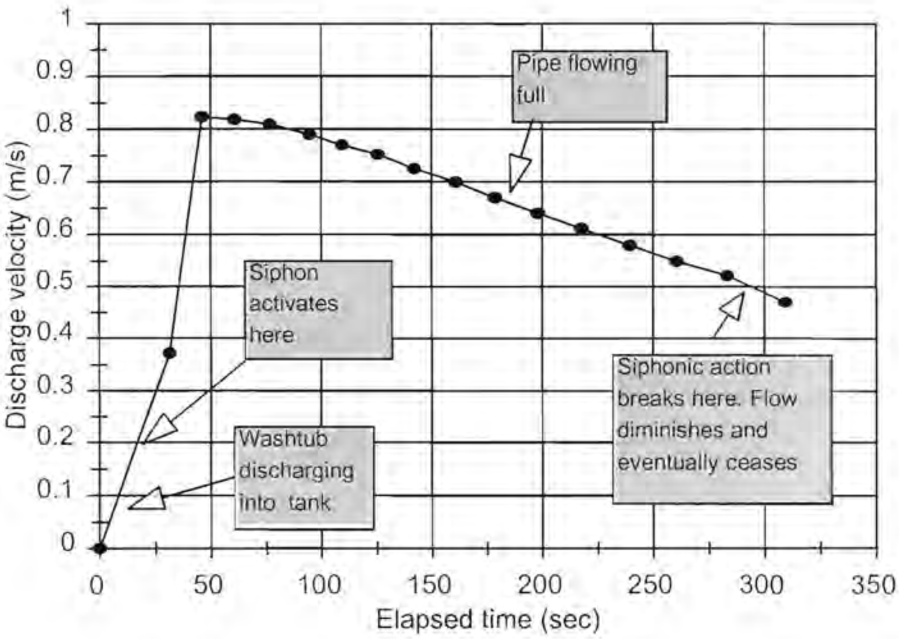


Figure 6.18: Outflow velocity from tank

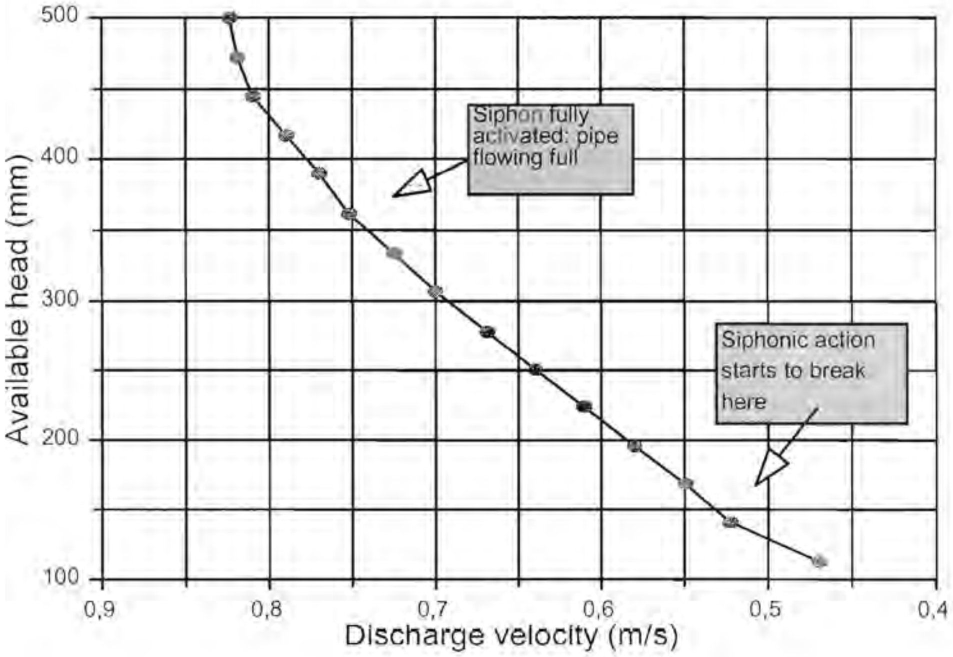


Figure 6.19: Variation in discharge velocity relative to available head

6.6.3 Observations

- The siphon activated after about 21 litres had flowed out of the washtub. It was perceived that this volume could possibly be reduced by improving the design of the inlet compartment at the side of the tank.

- Flow behaviour was much as expected – the rate of flow (as evidenced by the volume and velocity) became progressively less as the available head in the tank decreased.

- Flow behaviour became erratic at about the time the siphonic action started breaking. Although the flow velocity was still sufficient to allow sediment transport to take place, the carrying capacity of the liquid obviously started to diminish from this point. However, there was no visible lessening of sediment-carrying ability of the flow for the full duration of the siphon activation, even with a relatively small available head.

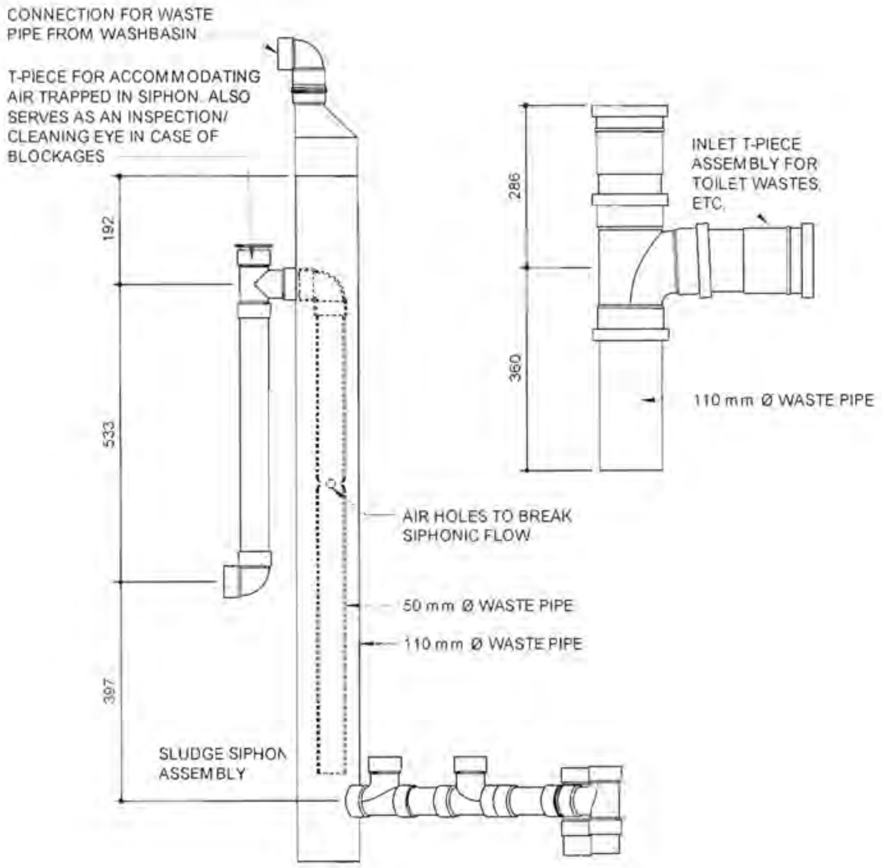
6.7 DEVELOPMENT AND TESTING OF FIRST PROTOTYPE UNDER ACTUAL FIELD OPERATING CONDITIONS

6.7.1 Background

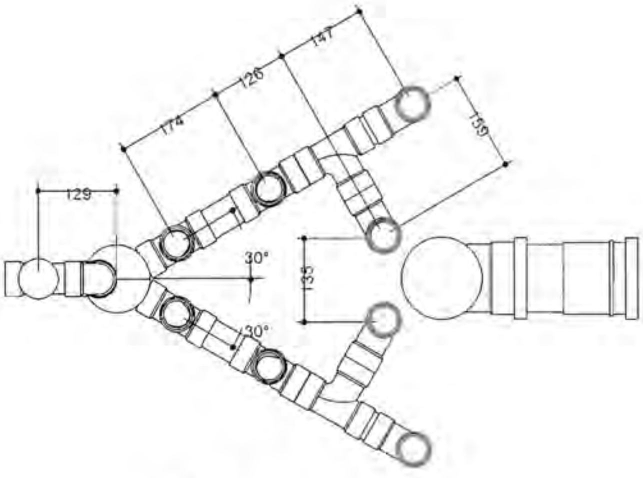
After it had become evident that the sludge siphon performed satisfactorily in the laboratory, and indeed fulfilled all the design team's expectations, it was necessary to proceed with the following phase of the project. This was to develop a prototype model of the system for testing under conditions which would normally be expected in a settled sewage scheme – connection to an actual domestic-type wastewater system where it would have to handle fresh toilet wastes and sullage instead of "ready-made" sludge from another septic tank. The prototype tank would then be expected to settle and digest the solids to produce its own sludge – in effect, it would have to perform exactly as a conventional interceptor tank in a settled sewage system.

Using the experience gained in the development of the initial laboratory model of the sludge siphon, the arrangement illustrated in Figure 6.20 was designed and assembled. The total volume of the tank was 780 ℓ, while the available retention volume, measured from the bottom of the tank to the apex of the siphon, was 620 ℓ. In Figure 6.21 photographs of the various parts making up the complete system are shown. The siphon assembly was put together using ordinary uPVC sewer fittings, and incorporated a simple device to accommodate any trapped air so that it would not interfere with the activation of the siphon. This took the form of a standard T-junction fitting, which could also serve as an inspection eye to clean out any blockages which might occur. As will be described later, the system was found to operate satisfactorily. Adverse operating conditions causing differences in performance of the system, including non-activation of the flush (i.e failure of the system) were identified, and the preliminary guidelines in Appendix A were drawn up accordingly. These included factors such as the length of unhindered straight pipeline run before an inverse gradient was encountered, and the distance between the washtub and tank. These are important considerations for the correct installation of a sludge siphon system. The height of the washtub above the tank was found to have a negligible effect on the operation of the siphon, probably due to the fact that no (or very little) flow attenuation could occur because of the vertical drop experienced by the inflowing wastewater.

The latter factor is important due to the flow attenuation which actually does take place over the horisontal length of inlet pipeline. This aspect is discussed further in section 6.7.3 below.

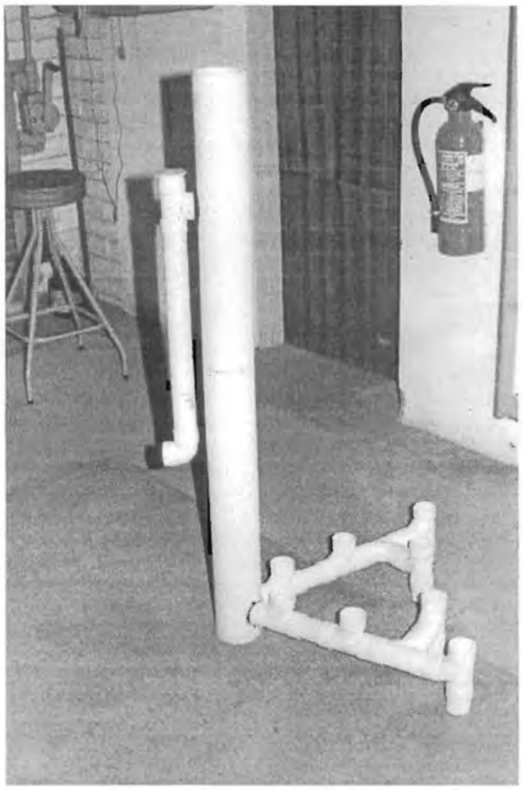


(a) Section

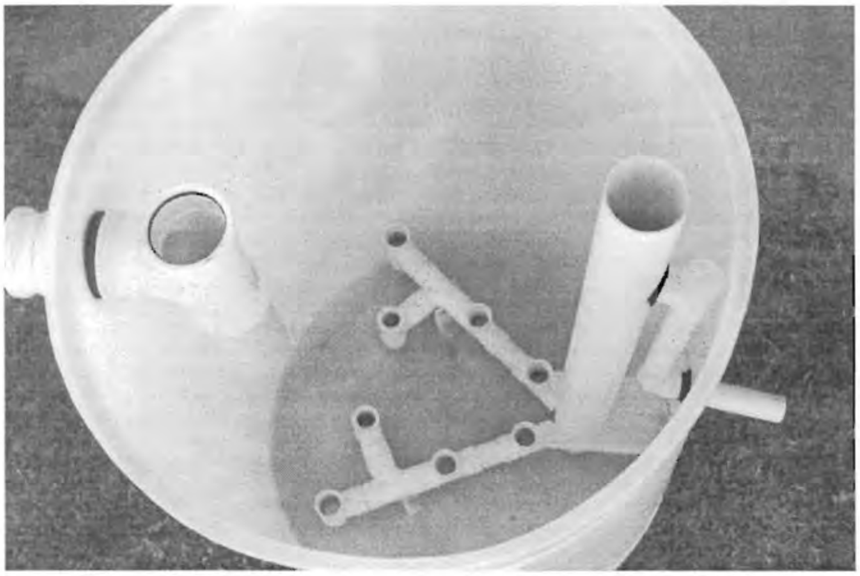


(b) Plan

Figure 6.20: Arrangement of waste inlet and sludge siphon assembly

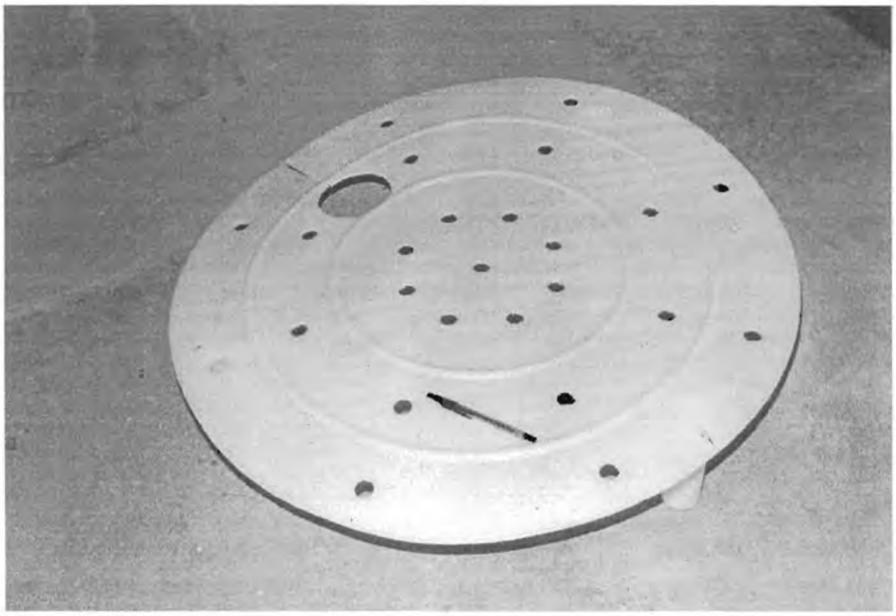


(a) The sludge siphon assembly

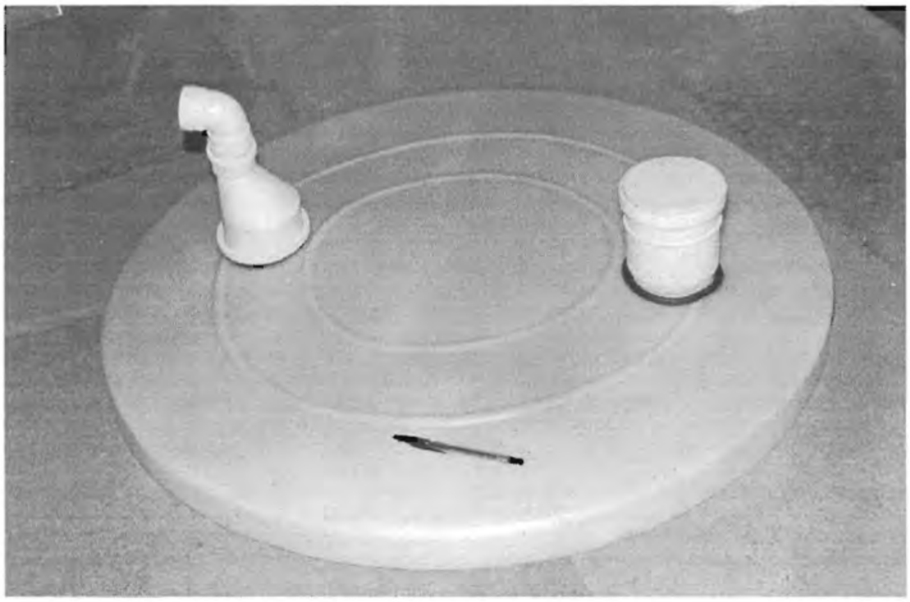


(b) Siphon assembly and conventional waste entry pipe fitted into tank

Figure 6.21: Photographs of various parts making up the complete tank



(c) Grille which fits above manifold. It was found to be necessary to drill many more holes than those shown, in order to allow efficient operation of the siphon.



(d) Lid of tank showing entry point for pipe from washbasin (left) and inspection eye above entry T-piece of toilet wastes, etc (right).

Figure 6.21 (cont): Photographs of various parts making up the complete tank

(e) The complete tank, fully assembled

Figure 6.21 (cont): Photographs of various parts making up the complete tank

6.7.2 Design and construction of the site installation

A suitable location on the CSIR campus at Scientia was found where experimentation with the prototype could take place. The CSIR day-care centre for pre-school children was ideally situated on a hillside, with the outfall sewer from the premises easily accessible next to a stone retaining wall where the tank could be placed and connected. The photographs in figure 6.22 illustrate the experimental layout. A survey established that the average number of people at the centre at any one time was 10 adults and about 70 children, which was obviously not representative of a normal domestic situation. Measurements of the average daily flow revealed that the tank would only be able to provide a retention period of about one hour under these circumstances, which was not sufficient. It was considered important to have a retention period of about 24 hours in order to ensure adequate settling and digestion of the solids, as would be the case in a properly designed and operated domestic septic tank. A Y-junction was therefore inserted in the main sewer pipe which diverted a smaller amount of waste into the tank. A special valve was also fabricated and installed in the Y-junction assembly in order to "choke" the flow, thereby regulating the influent to ensure that the required retention time was obtained.

The effect of the manipulations described above was that the normal design procedure for sizing an interceptor tank, as described in chapter 4.3, was carried out in reverse: the tank size was already fixed, so the inflow had to be adjusted to suit. With a retention volume of 620 ℓ in the tank, it was necessary to reduce the average inflow rate to ensure that this volume was not exceeded in a 24 hour period. After some experimentation with the valve, a suitable setting was obtained which produced the desired flow rate. Other than these experimental settings, there was no difference between the operating conditions of this setup and a normal interceptor tank in a settled sewage scheme. The centre produced wastewater containing human excrement, toilet paper, food scraps, sullage from washing machines and kitchen sinks, etc, all being entirely representative of a conventional domestic situation.

Figure 6.22 also illustrates how the outflow pipe from the sludge siphon was arranged on adjustable supports. This was done in order to provide conditions for experimentation with variable pipe gradients, and to produce places where pressure flow could take place. It was essential to be able to realistically reproduce conditions which would occur naturally in a working settled sewage system, and to ascertain whether the sludge could be efficiently transported under all these circumstances.

The washtub mounted on the retaining wall was responsible for activating the sludge siphon. Sections of transparent perspex pipe were installed in the outfall pipeline at strategic places in order to be able to observe the behaviour of the effluent flow. Due to the relatively long period of time required for sludge to build up to above the level of the inlet ports in the manifold (approximately two to three weeks), it was necessary to recover the sludge extracted from the tank in order to reuse it again for further experimentation. It was therefore allowed to settle in a second interceptor tank while the liquid effluent drained into the existing sewer pipe from the centre. From the second tank the sludge was pumped back into the main tank. In this way it was possible to repeat a number of experiments on a regular basis, without having to wait weeks for more sludge to develop each time.

(a) General view from above

(b) Tank / washtub inlet and outlet assembly (before installation of valve in Y-junction)

Figure 6.22: Experimental layout of prototype interceptor tank with sludge siphon at the day-care centre on the CSIR campus

(c) Butterfly valve ready for insertion into the Y-junction

(d) Y-junction with valve in place

Figure 6.22 (cont): Experimental layout of prototype interceptor tank with sludge siphon at the day-care centre on the CSIR campus

(e) Adjustable support for altering pipe gradient

(f) Flow emerging from tank before activation of flush (i.e. normal overflow from influent)

Figure 6.22 (cont): Experimental layout of prototype interceptor tank with sludge siphon at the day-care centre on the CSIR campus

The design of the siphonic assembly shown in figures 6.20 and 6.21 was such that, assuming an unhindered pipeline run for at least 12 m, an outflow volume of only 16 ℓ from the washtub was required to initiate the flush. This represented a significant improvement of nearly 24 % over the initial amount of 21 ℓ required in the laboratory experiments. Where pipeline conditions such as 90 degree bends and negative gradients close to the tank were introduced, the required minimum flush volume was found to increase accordingly. The increased resistance caused by the bends, as well as by standing water and sludge at low points in the pipeline, caused a delay in activating the flush. The reason for this is thought to be that more water from the washtub was forced into the main chamber of the tank while the initial resistance in the pipeline was being overcome, thus requiring additional water to activate the siphon. This aspect is discussed further in section 6.7.3 below. This section also describes the experimentation carried out on the site. Various hydraulic and other factors which influenced (or were thought might influence) the performance of the system, are discussed in detail.

Figure 6.23: Calibration of the water volume in the washtub

6.7.3 Experimentation carried out on the site

(a) Deposition and resuspension of sludge particles:

In a properly operated sludge siphon system, the sludge level should remain more or less static at the height of the manifold openings. Only the "excess" sludge building up above this level will be removed from the tank when the siphon activates. In a normal domestic situation (i.e. where the tank is not biologically overloaded), activating the siphonic flush as little as once or twice a week will ensure that the sludge level never has an opportunity to increase by more than a few centimetres above this level. The result will, in most cases, be that the sludge/water mixture siphoned out of the tank will generally be relatively dilute – much more so than in the laboratory experiments, where a large amount of sludge was intentionally deposited in the tank, resulting in the effluent being fairly concentrated.

However, in an attempt to simulate less favourable conditions than what would normally be expected in practice, the sludge was allowed to accumulate to about 10 or 15 cm above the grille level before initiation of the flush. Figure 6.24 illustrates a typical sludge sample cored from the tank during the testing process. It was observed that the solid matter was not always fully digested by the time a test was carried out, and often still contained small undegraded pieces of paper, food scraps and faeces. As this served to make the situation even less favourable for efficient operation of the siphon, it was considered advantageous for testing purposes.

Figure 6.24: Typical sludge sample cored from the tank before testing of the system (the core represents the sludge accumulated above the level of the grille).

The extraction of sludge from the tank, and its subsequent deposition on cessation of the effluent flow, followed much the same pattern as in the laboratory tests. No problems were encountered with the re-suspension of sludge deposited on the invert of the pipeline. Activation of the siphonic flush was, however, adversely affected if a negative gradient was encountered within 12 m of the tank outlet (see (b) below). It was also observed that the algae which formed inside the perspex pipeline (due to it being exposed to direct sunlight) was also removed by the scouring action of the sludge particles. It is expected that this scouring action will be beneficial in removing any accumulations of biological slime which may be deposited on the walls of the effluent pipeline in practice.

(b) Pressure flow with a negative gradient:

In practice, sections of pipeline in a settled sewage scheme may be laid with inverse gradients (see chapter 4.1). The implication of this for a sludge siphon system is that, not only will sludge be deposited on the pipeline invert after cessation of the flush, but a "dam" of septage will actually collect in the low points formed by the change from a positive to a negative gradient. This will result in a substantially increased resistance to a new effluent "plug" moving along the pipeline, because the inertia of the standing septage must first be overcome before normal pipeflow can resume.

Obviously, if the obstruction caused by the standing septage is far enough removed from the tank outlet, no interference with the activation of the siphonic flush can occur. However, in both the laboratory and the site experiments, it was observed that if there was a change from a positive to a negative gradient within about 12 m from the tank outlet, the siphon would not activate without a substantially greater water volume than normal being supplied (i.e. more than the 16 ℓ usually required). As mentioned in section 6.7.2 above, it is likely that the delay in getting the siphon activated is due to the need for the flow to first overcome the inertia of the standing septage before normal pipeflow can take place. This means that more water is forced into the main chamber of the tank before the water in the siphon can get moving uniformly.

Once the flow was properly underway, of course, a negative gradient merely resulted in pressure flow in the pipeline, and as long as the highest point in the pipe did not rise above the crown of the siphon, no problems were encountered with transporting the sludge. Figure 6.25 illustrates the experimentation carried out with the pipe gradient changing from a positive to a negative value.

The requirement for a minimum distance of 12 m between the tank outlet and the first section of inverse gradient has therefore been incorporated into the preliminary guidelines for the design and installation of sludge siphon systems in Appendix A. It is probable that this distance is related to the design of this specific siphon and tank, and that other values could possibly be obtained with different sizes of siphon assemblies, etc.

Figure 6.25: Experimentation with inverse pipe gradients

(c) Additional hydraulic or biological loading on the tank:

The correct sizing of a septic tank is crucial to its effective operation, from both the hydraulic and biological points of view. In a conventional settled sewage system, two criteria govern the required tank volume. The first is settling and digestion of the solids, for which a retention period of about 24 hours is preferably required. The second is a desludging period of at least three to five years, in order to minimise operational costs. The basic design parameter is the number of people expected to use the tank; coupled to this is the expected volume of water consumption, which in turn is dependent on the level of service of the water supply. These aspects of septic tank design have been discussed in chapter 4.

The hydraulic and biological loading of a septic tank are fairly easy to predict in middle to high income residential areas, as these are usually provided with the highest level of service regarding water supply, and calculation of the expected wastewater flow is straightforward. The average number of people expected to use a certain tank will generally also remain fairly stable in these conditions. However, in low or very low income areas, these aspects are notoriously difficult to calculate. Observation by the author of a number of settled sewage schemes in South Africa has shown that tanks in these areas are often undersized. This is seldom due to poor design, however, but more often as a result of unforeseen housing densification taking place after a system has been installed. Additional shacks are erected around the dwelling which has a toilet, in order to provide shelter for extended families, who then also make use of the toilet facility. It is not uncommon for up to 30 people to use one toilet in such cases, and the results are always predictable. Tanks with volumes of 2 000 ℓ and larger have been examined, where the rate of overloading was so great that digestion had ceased to take place and a layer of faeces crud up to 300 mm thick was found floating on top. The situation in such cases is usually exacerbated by unknowing users depositing personal cleansing materials such as plastic bags, thick wads of newspaper and rags into the toilet. Naturally, the tank ceases to operate under such conditions, and the whole settled sewage system is therefore also affected.

Various hydraulic and biological loading rates were also experienced in the prototype tank installed on site. As already explained, due to the large amount of users connected to the system, it was necessary to divide the sewage flow from the day-care centre and install a special valve in the pipeline in order to reduce the loading to acceptable limits for the specific size of tank used. While this experimentation with the flow was taking place, it was clearly seen what effect overloading would have on the system. A high rate of wastewater flow resulted in a very short solids retention time, with digestion being greatly inhibited. This was aggravated by wads of heavy paper towelling (used for drying of hands and general cleansing purposes) being flushed down the centre's toilets, as well as objects such as sanitary pads, etc. Materials of this nature are generally not a problem in a conventional waterborne sewerage system, but are definitely not supposed to go into a septic tank, as they degrade either very slowly or not at all, dramatically increase the rate of sludge accumulation, and negatively affect the operation of the tank. In a sludge siphon system they also block the grille and prevent sludge from being sucked through the manifold ports, which then results in failure of the flushing device.

The guidelines in Appendix A stress that the care and operation of the system should be regarded as being similar to that of an ordinary septic tank, in that the householder is responsible for ensuring that the toilet is used properly, i.e. only soft tissue paper is used for personal cleansing, no objects such as sanitary pads, newspaper or cigarette butts are disposed of in the toilet, and that only approved disinfectants are used, etc. If normal precautions such as these are adhered to, there is no reason why a sludge siphon system should not give the same trouble-free operation as a properly operated conventional septic tank.

(d) Distance between washtub and tank.

While the distance between the toilet(s) and the tank are not a factor in the operation of a sludge siphon system (or any septic tank system, for that matter), the distance between the tank and the plumbing fixture (bath, washtub, etc) feeding the siphon is of cardinal importance. It is essential that the incoming wastewater enters the siphon compartment as rapidly as possible. If this is not done then either the siphon will require a greater volume of influent before it activates, or it will not activate at all, as the influent has a greater chance of being forced into the main compartment of the tank before it is able to charge the siphon. A greater distance between the plumbing fixture and the tank will generally result in the flow being attenuated to some extent, depending on the layout of the waste pipe. It was thus considered necessary to investigate this aspect in order to be able to provide guidelines for the installation of the system.

Figure 6.26 illustrates how the waste pipe was extended in order to conduct the necessary experimentation. The washtub nearest the tank provided a wastewater flow distance of about 1,5 m, which resulted in a volume of only 16 ℓ being required to activate the siphon. The hydraulic head available between the washtub invert and crown of the siphon was 950 mm, and the waste pipes were standard 50 mm diameter. The washtub furthest from the tank provided a flow distance of 7 m, which prevented the siphon from activating, even with a washtub volume of 35 ℓ. In the latter case activation of the flush only occurred when the tub was continually fed with a supply of water from a hosepipe, and an undetermined amount of water had drained into the tank. This implies that a wastewater source this far from the tank will probably require a bathtub or similar fixture to activate the siphon.

Figure 6.26: Testing the effect of different wastewater flow distances on the operation of the siphon.

The furthest washtub was subsequently moved nearer to the tank in one metre increments, and the average volume of water required to activate the siphon determined from a number of trials in each case. The results are shown in Table 6.3.

Table 6.3: Average wastewater volume required to activate flush with various flow distances between washtub and tank

Distance between washtub and tank (m)	Flush volume required to activate siphon (ℓ)
7	> 35
6	25
5	25
4	25
3	25
1,5	16

A few important conclusions can be drawn from the above results:

- For this specific siphon and tank configuration, any flow distance greater than about 6 m will require a volume of water larger than what can be provided by a 35 ℓ washtub (e.g. a bath discharging probably at least 50 ℓ) to activate the siphon. The implication is that this situation would probably only lend itself to application in a house with full plumbing fixtures.

- There is clearly no difference in performance between the 6 m and 3 m washtub positions, although the volume of water required to activate the flush is still considerably greater (approximately 56 %) than that of the closest washtub position. The reason for the required flushing volume being the same over this distance was not investigated, but it is obvious that the flow rate is still sufficient to raise the water level in the siphon chamber quickly enough to activate the siphon. After a distance of about 6 m, the attenuation of the flow becomes such that this does not happen, and a constant feed into the washtub is required. Up to a distance of 6 m, however, the siphon will still activate with a full washtub. Again, this must only be regarded as being valid for the particular siphon and tank configuration under consideration – different tank sizes or pipe diameters will in all likelihood give other results.

- The closer the washtub is to the tank, the easier it becomes to activate the siphon, i.e. the less volume of wastewater is required. Therefore the tank should preferably be buried as close as possible to the plumbing fixture which activates the siphon. With an exterior "aqua-privy" type of arrangement as shown in Figure 4.6, Chapter 4, this will not present any problems. For a dwelling with indoor plumbing, the tank will need to be buried as close as possible to the outside wall of the room (toilet, bathroom, laundry, etc) where the activating fixture is situated.

(e) Height difference between washtub and tank:

The first washtub, which was mounted at a distance of 1,5 m from the tank, was selected for the purpose of determining whether varying height differences between the tank and the washtub would have any effect on the operation of the siphon. It was thought that an increased vertical fall distance for the wastewater, before flowing into the last (almost horisontal) section of the waste pipe, might affect the uniformity of flow, increase the turbulence and possibly lead to an additional amount of wastewater being required to activate the siphon. Figure 6.27 illustrates the washtub arrangement assembled on the site.

Figure 6.27: Testing the effect of varying washtub heights on the operation of the siphon.

During the preliminary experimentation, the height difference between the invert of the washtub and the crown of the siphon was arbitrarily set at about 950 mm. In general, washtub or hand-washing basins are set with their top rims approximately 800 to 900 mm above floor level, and with their inverts (depending on the shape and depth) being between 600 and 700 mm above floor level. Obviously a bathtub's invert is much lower, being roughly the same as the floor level. Assuming the floor level of a house is at least 200 mm above the surrounding ground, and the crown of the siphon about 300 to 500 mm below the ground, the vertical distance between the invert of the bath or tub and the siphon is thus likely to be a minimum of between 700 mm and 1 400 mm – and could very well be much more than this. With a head of 500 mm between the crown of the siphon and the effluent pipeline, the pipeline is likely to be in the order of 800 to 1 000 mm deep at this point.

The washtub on the site was accordingly raised up to a maximum of 2 200 mm above the crown of the siphon, and the volume of water required to activate the flush measured in this case. This was found to average about 25 ℓ. Taking this into account, and considering the results of the horisontal flow distance tests described in (d) above, a minimum flush volume of 25 ℓ is recommended in the guidelines contained in Appendix A.

6.7.4 Conclusions from the site experimentation

The hydraulic design of the sludge siphon is satisfactory. However, there are certain critical requirements which must be adhered to when the system is installed. These are taken up in the guidelines in Appendix A, and the information must obviously be disseminated in the form of an information brochure with each system sold by the manufacturer. The engineers and contractors involved with the design and installation of a settled sewage system will need to take heed of the requirements, as will the builders who actually install the tanks and associated plumbing.

The hydraulic and biological loading on the system must be determined by the designer in the same way as for any septic tank system, with the exception that no allowance needs to be made for sludge build-up. It must also be assumed that the system will be properly operated and maintained, as to over-design the tank with the intention of providing a "safety factor" will merely result in increased capital costs, and unnecessarily so. It will thus be essential, particularly in lower-income areas, to ensure that proper user education is carried out by competent community workers.

It will be necessary, once the commercialisation of the system gets underway, to produce a few standard sizes of tank, in order to allow for the differing requirements of various purchasers. The only factor which will be of importance here is the expected number of users.

For installations where kitchen and similar wastes also go into the tank, it is advisable to install a grease trap in the pipe carrying this wastewater. This is a common practice in many septic tank installations, and will be advantageous in reducing the layer of scum which collects in the tank, as well as in preventing fatty substances from clogging the siphon pipes.

CHAPTER 7

BACKGROUND TO URINE DIVERSION TECHNOLOGY

"The mundane act of defecation has wrought profound effects on every aspect of our social history."

Lewis, D (1996). *Kent Privies*. Countryside Books, Berkshire, UK.

CHAPTER 7: BACKGROUND TO URINE DIVERSION TECHNOLOGY

7.1 THE NEED FOR AN ALTERNATIVE TO VIP TOILETS

In chapters 1 and 2 the main construction and operational disadvantages of VIP toilets were described. These can be summarised as follows:

- Adverse geotechnical conditions, for example hard ground or non-cohesive soils, have a negative effect on the capital cost of constructing VIP toilets, while a shallow water table presents a danger of aquifer pollution;
- when pits become full, it is not always a feasible option, either physically or economically, to empty them or to build new toilets;
- a perception exists that this technology is a "poor man's solution" to the sanitation problem;
- various socio-cultural, educational and institutional issues associated with VIP toilets have not been adequately addressed;
- there exists a lack of innovation for people with differing needs and customs; and
- they are unsuitable for densely-populated urban or peri-urban areas.

To address these shortcomings, it has been necessary to think beyond the limitations imposed by traditional methods of providing dry sanitation. This need has been supported by increasing awareness worldwide of the environmental issues associated with sanitation. Furthermore, pressure on land to produce more food to feed the ever-growing populations of developing countries has made it imperative to utilise natural resources, including human excreta, wherever possible. The concept of ecological sanitation, or "eco-san" as it is also known, is seen as an alternative solution to some of the problems associated with pit toilets, environmental degradation and food shortages.

In chapters 2 and 3 the problems of conventional sanitation approaches were expounded upon at some length. These vary from the poor status of the sanitation sector, inadequate institutional capacity to deal with the sanitation process, the fixation with providing either a full waterborne system or a VIP toilet, the social acceptability of different systems, and the perception that dry, on-site sanitation systems are inherently inferior. It was also emphasised that the basic purpose of any sanitation system is to contain human excreta (chiefly faeces) and prevent the spread of infectious diseases, while at the same time avoiding damage to the environment. If an alternative sanitation technology can do all these things with fewer operational and maintenance problems than those associated with conventional VIP toilets, and also produce a free, easily accessible and valuable resource for agricultural use, then the implementation of such a technology should be actively encouraged.

Ecological sanitation systems are neither widely known nor well understood. They cannot be replicated without a clear understanding of how they function and how they can malfunction. They have some unfamiliar features such as urine diversion pedestals or squatting plates, which raise questions about their cultural acceptability. In addition, they require more promotion, support, education and training than ordinary pit or VIP toilets (Esrey et al 1998).

A concern is often expressed that some ecological sanitation systems are too expensive for low-income households in developing countries. Eco-san systems need not cost more than conventional systems. While some systems may be sophisticated and expensive, others are relatively simple and low-cost. There is often a trade-off between cost and operation: lower cost solutions mean more manipulation and care of the sanitation system, while with higher cost solutions manipulation and care can be reduced. Eco-san systems need not be expensive to build because:

- the entire structure is built above ground – there is thus no need for expensive digging and lining of pits;
- urine is diverted, no water is used for flushing and the volume of the processing vault is fairly small, as it is emptied periodically; and
- the contents of the processing vault are dry, which means that there is no need for expensive watertight constructions (Esrey et al 1998).

The introduction of eco-san systems is bound to lower the total costs of urban sanitation in particular. If a waterborne system is being considered, the sewers, treatment plants and sludge disposal arrangements will cost several times as much as an eco-san system, while for ordinary VIP toilets the institutional capacity required for desludging full pits may be nonexistent . These are important considerations for developing countries, where public institutions face stringent financial limits (Esrey et al 1998).

7.2 HUMAN EXCRETA – WASTE PRODUCT OR VALUABLE RESOURCE?

7.2.1 Biology of human excreta

For adult persons who maintain approximately the same mass during their lifetimes, the excreted amounts of plant nutrients are about the same as the amount eaten. The excreted amounts of plant nutrients depend on the diet and thus differ between different persons as well as between different societies (Jönsson 1997). A great deal of research on the subject has been carried out in Sweden and Table 7.1 is based on the average Swedish diet and Swedish circumstances. Although the comparative figures for other countries can be expected to be somewhat different, the overall picture will be essentially the same.

Table 7.1: Estimated Swedish averages for mass and distribution of plant nutrient content in urine and faeces (based on Jönsson 1997)

Parameter	Urine		Faeces		Total toilet waste	
	g/p/d	%	g/p/d	%	g/p/d	%
Wet mass	900 - 1200	90	70 - 140	10	970 - 1340	100
Dry substance	60	63	35	37	95	100
Nitrogen	11	88	1,5	12	12,5	100
Phosphorus	1,0	67	0,5	33	1,5	100
Potassium	2,5	71	1,9	29	3,5	100

Roughly 65 to 90 % of the excreted nitrogen, phosphorus and potassium are estimated to be found in the urine. Furthermore, plant nutrients excreted in urine are found in chemical compounds that are easily accessible for plants. Initially 80 - 90 % of the nitrogen is found as urea, which rapidly degrades to ammonium and carbon dioxide as follows:

$$CO(NH_2)_2 + 3H_2O \leftrightharpoons CO_2 + NH_4^+ + 2OH^-$$

The urea degradation increases the pH value of the urine from its normally slightly acidic state (pH ±6 when excreted) to a value of approximately 9. The phosphorus in the urine is in the form of phosphate, while the potassium is in the form of ions. Many chemical fertilisers contain, or dissolve to, nitrogen in the form of ammonium, phosphorus in the form of phosphate and potassium in the form of ions. Thus, the fertilising effect of urine ought to be comparable to the application of the same amount of plant nutrients in the form of chemical fertilisers (Jönsson 1997).

The faeces contain undigested fractions of food with plant nutrients. However, organically bound plant nutrients are not plant available. The undigested food residuals have to be degraded before their plant nutrients become available, therefore the plant availability of the nutrients in faeces is expected to be slower than the plant availability of the nutrients in urine (Jönsson 1997).

7.2.2 Potential for reuse of human excreta

Key features of eco-san are prevention of pollution and disease caused by human excreta, treatment of human excreta as a resource rather than waste, and recovery and recycling of the nutrients. In nature, excreta from humans and animals play an essential role in building healthy soils and providing valuable nutrients for plants. Products of living things are used as raw materials by others. Conventional approaches to sanitation misplace these nutrients, dispose of them and break this cycle (Esrey et al 1998).

The fertilisers excreted by humans are sufficient to grow the 230 kg of crops they need each year, as illustrated in Table 7.2 below. The table is based on an average human production of 500 litres of urine and 50 litres of faeces per year.

Table 7.2: Annual excretion of fertiliser by humans compared with fertiliser requirement of cereal (Wolgast 1993)

Fertiliser	**500 ℓ urine**	**50 ℓ faeces**	**Total**	**Fertiliser need for 230 kg cereal**
Nitrogen	5,6 kg	0,09 kg	5,7 kg	5,6 kg
Phosphorus	0,4 kg	0,19 kg	0,6 kg	0,7 kg
Potassium	1,0 kg	0,17 kg	1,2 kg	1,2 kg
Total N+P+K	**7,0 kg (94 %)**	**0,45 kg (6 %)**	**7,5 kg (100 %)**	**7,5 kg**

Obviously human urine is the largest contributor of nutrients to household wastewater. If no phosphate detergents are used, at least 60 % of the phosphorus and 80 % of the nitrogen in household wastewater comes from urine. The total quantities of nutrients in human urine are significant when compared with the quantities of nutrients in the mineral fertilisers used in agriculture. For example, it is estimated that in Sweden the total yearly production of human urine contains nitrogen, phosphorus and potassium equivalent to 15 - 20 % of the amounts of these nutrients used as mineral fertilisers in 1993. Thus, by source-separating human urine, the amounts of nutrients recycled to arable land can be significantly increased while at the same time the nutrient load of wastewater can be significantly decreased (Jönsson 1997).

The fertilising effect of source-separated urine has been tested in some experiments in Sweden and appears to be almost as good as that of the corresponding amount of chemical fertiliser, provided that ammonia emission from the urine is restricted. The uptake of urine nitrogen by barley harvested at flowering stage was found to be 42 % and 22 % at two application rates, while the uptake of ammonium nitrate nitrogen at the same application rates was 53 % and 28 % respectively. The lower uptake of urine nitrogen has been explained by higher gaseous losses of nitrogen (i.e. ammonia) from urine than from ammonium nitrate. The utilisation of urine phosphorus, however, was found to be 28 % better than that of chemical fertiliser. The barley fertilised with urine derived 12,2 % of the phosphorus, while that fertilised with dipotassium hydrogen-phosphate derived only 9,1 % from the fertiliser. In a field experiment, the nitrogen effect on oats of stored urine was compared to that of ammonium nitrate fertiliser at three different application rates. The human urine, which was surface spread and immediately harrowed into the ground, gave approximately the same yield as the corresponding amount of chemical fertiliser. Using the recycled toilet products as fertilisers will therefore save chemical fertilisers containing almost the same amount of nutrients and thus also the resources needed to produce and distribute them (Jönsson 1997).

A major advantage of using human urine instead of chemical fertilisers or sewage sludge is the very low concentrations of heavy metals found in urine (Jönsson et al 1997). This viewpoint is supported by Hanaeus et al (1997) who state that the quality of sewage sludge is not fully trusted by agriculturalists due to the risk of hazardous compounds being present. According to Höglund et al (1998), human urine in Sweden contains less than 3,6 mg Cd/kg P, while commercial chemical fertilisers contain approximately 26 mg Cd/kg P. Furthermore, the sludge from the 25 largest sewage plants in Sweden was found in 1993 to contain an average of 55 mg Cd/kg P.

Although faeces contain fewer nutrients than urine, they are a valuable soil conditioner. After pathogen destruction through dehydration and/or decomposition, the resulting inoffensive material may be applied to the soil to increase the organic matter content, improve water-holding capacity and increase the availability of nutrients. Humus from the decomposition process also helps to maintain a healthy population of beneficial soil organisms that actually protect plants from soil-borne diseases (Esrey et al 1998).

CHAPTER 8

REVIEW OF URINE DIVERSION EXPERIENCE AND APPLICATION

"Science knows now that the most fertilising and effective manure is the human manure............ Do you know what these piles of ordure are, those carts of mud carried off at night from the streets, the frightful barrels of the nightman, and the fetid streams of subterranean mud which the pavement conceals from you? All this is a flowering field, it is green grass, it is the mint and thyme and sage, it is game, it is cattle, it is the satisfied lowing of heavy kine, it is perfumed hay, it is gilded wheat, it is bread on your table, it is warm blood in your veins".

Victor Hugo, *Les Miserables*, 1862

CHAPTER 8: REVIEW OF URINE DIVERSION EXPERIENCE AND APPLICATION

8.1 URINE DIVERSION THEORY AND PRACTICE IN THE WORLD

8.1.1 Some examples of urine diversion sanitation technology

Sanitation using the technique of urine diversion is applied in many parts of the world and has been shown to be a feasible option that works. Some examples are described below (based mostly on Winblad 1996b, except where otherwise indicated).

The first example is from Sanaa, in Yemen (Figure 8.1). A single-chamber dehydrating toilet with urine diversion is placed in a bathroom several floors above street level. In a traditional Yemeni town house the upper floors have toilet-bathrooms next to a vertical shaft that runs from the top of the house down to the level of the street. The faeces drop through a hole in the squatting slab and down the shaft, while the urine drains away through an opening in the wall and down a vertical drainage surface on the outer face of the building. Personal cleansing with water takes place on a pair of stones next to the squatting slab. The water is drained off in the same way as the urine. As Sanaa has a hot, dry climate, the urine and water usually evaporate before reaching the ground, while the faeces dehydrate quickly. They are collected periodically and used as fuel.

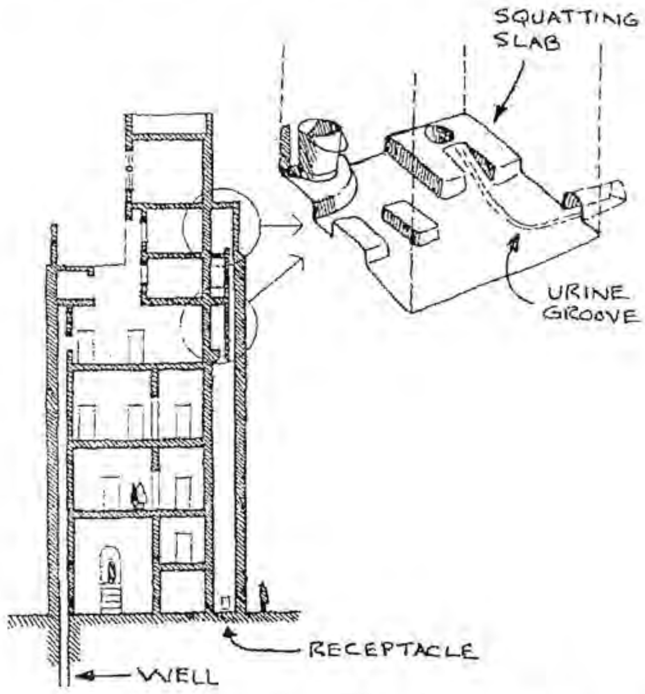


Figure 8.1: Section through a house in the old part of the town of Sanaa, Yemen
(Esrey et al 1998)

The second example is from Vietnam (Figure 8.2). It is a double chamber dehydrating toilet with urine diversion. The toilet chambers are built above ground. Urine is collected and piped to a container or soakpit. Faeces are dropped into one of the chambers while the other one is kept closed. Paper used for personal cleansing is put into a bucket and later burnt, while the dehydrated faecal material is used as a soil conditioner.

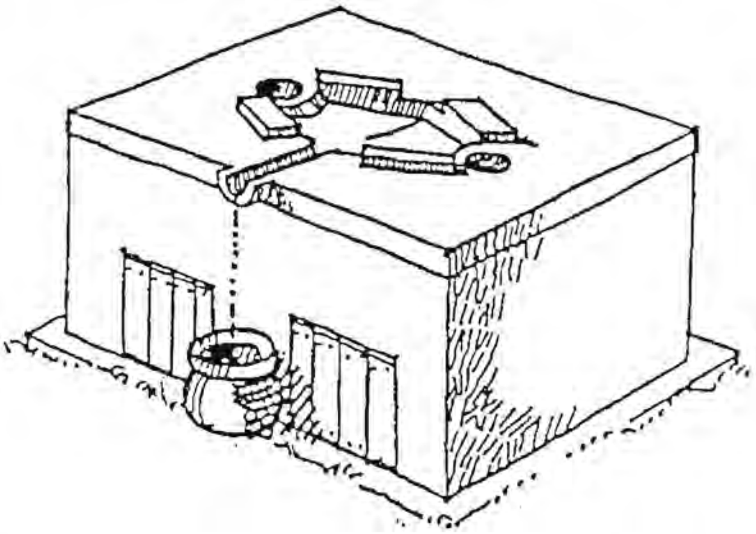


Figure 8.2: The Vietnamese double vault dehydrating toilet, shown here without the superstructure (Winblad 1996b)

Before a chamber is used, its bottom is covered with a layer of powdered earth. The faeces are covered with kitchen ashes, which absorb moisture and deodorise them. When the chamber is two-thirds filled its contents are levelled with a stick before it is filled to the brim with dried, powdered earth to create conditions conducive for anaerobic composting.

The Vietnamese double-vault originated in the 1950s when peasants who were using human excreta as manure found that composting reduced the smell and improved its fertiliser value. This became the key component of a rural sanitation programme for disease prevention and increased food production that began in North Vietnam in 1956. After much experimentation it was found that the addition of kitchen ashes effectively neutralised the bad odours normally associated with anaerobic composting, and also effected the destruction of intestinal worm ova – after a two-month composting period 85 % of the ova were found to have been destroyed. The anaerobic composting also played an important role in converting organic nitrogen to inorganic forms more readily available to plants (World Bank 1982). According to Van Buren et al (1984), these composting latrines produce more than 600 000 t of organic fertiliser each year and have also been responsible for a substantial reduction in intestinal diseases.

A toilet of similar type to the Vietnamese version is the Guatemalan LASF toilet (*Letrina Abonera Seca Familiar*), which is an adaption of the Vietnamese version and is provided with two pedestals rather than squatting holes. It is also used in high density urban squatter areas, for instance in the centre of San Salvador, the capital of El Salvador (Figure 8.3).

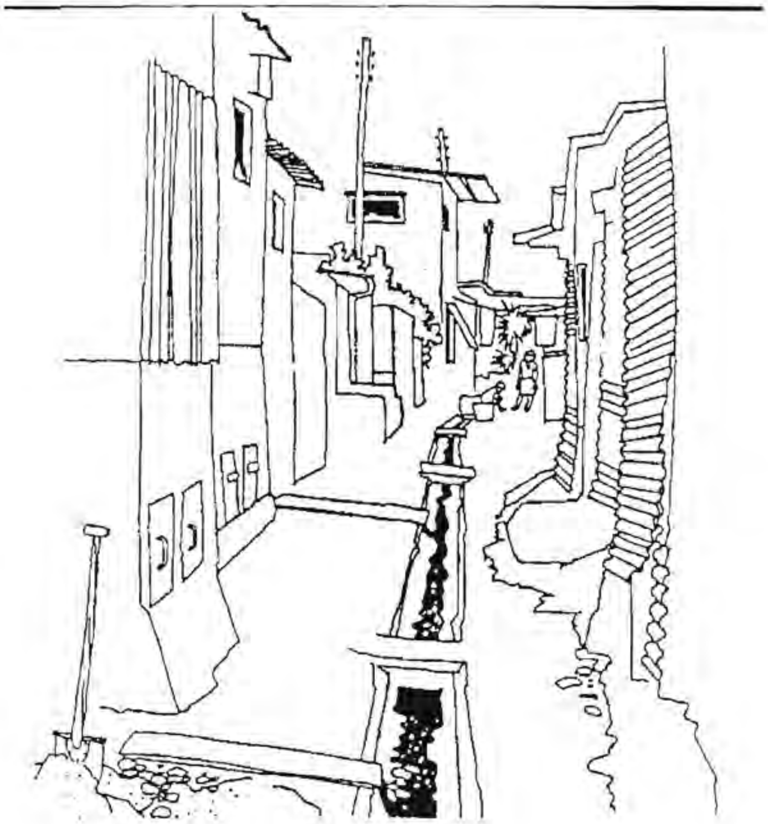


Figure 8.3: LASF toilets in a densely populated squatter area in central San Salvador. The open drain is carrying sullage (Winblad 1996b)

A further development of the LASF toilet has been equipped with a solar heater (Figure 8.4). The main purpose of the heater is to increase evaporation in the chamber. The example shown is from the community of Tecpan, near San Salvador. Figure 8.5 illustrates an example of a double chamber solar-heated composting toilet in Ecuador, high up in the Andes Mountains. At this altitude there is no need for urine diversion as the natural evaporation takes care of any excess liquid. Although termed a composting toilet, it is more likely to function as a dehydrating toilet.

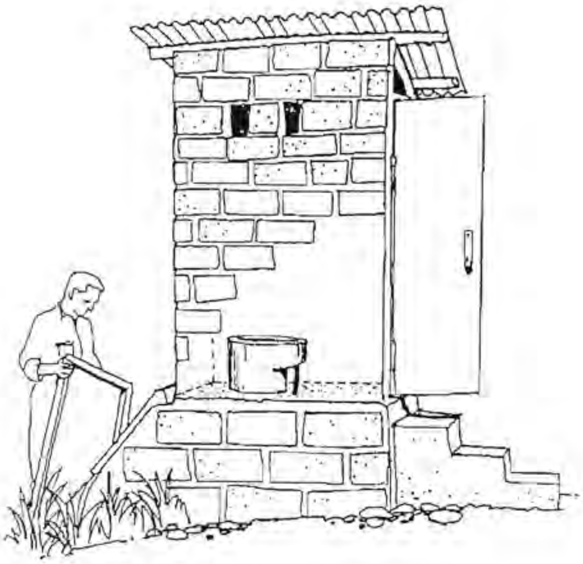


Figure 8.4: A dehydrating toilet with urine diversion and solar-heated vault, El Salvador (Winblad 1996b)

Figure 8.5: A solar-heated dehydrating toilet in Ecuador (Winblad 1996b)

8.1.2 Comparison: desiccation and composting

When something is dehydrated all the water is removed from it. In a *dehydrating toilet* the contents of the processing chamber are dried with the help of heat, ventilation and addition of dry material. The moisture content should be brought below 20%. At this level there is rapid pathogen destruction, no smell and no fly breeding. A requirement for dehydration is, except in very dry climates, the diversion and separate processing of urine (Winblad 1996b). The waste chamber is solar-heated by means of an inclined black-painted lid and small amounts of ash, sawdust or dry soil are added after each use. The faeces may be desiccated within a few weeks. The desiccation process, while not producing a material as rich as true compost, still acts to enrich soil to which it is added (Dudley 1996).

Composting is a biological process in which, under controlled conditions, various types of organisms break down organic substances to make a humus. In a *composting toilet*, human excreta is processed together with organic household residues. Optimal conditions for biological decomposition should be sought. This means that sufficient oxygen should be able to penetrate the compost heap to maintain aerobic conditions. The material should have a moisture content of 50 - 60% and the carbon : nitrogen balance (C:N ratio) should be within the range 15:1 to 30:1 (Winblad 1996b).

In order to function correctly, a composting toilet requires the addition of carbonaceous (organic) matter to maintain the correct C:N balance. In some cases it may also be desirable or necessary to add lime to maintain a more or less neutral pH, but this depends on the nature of the material entering the toilet. Further, in order to get true composting, air must be able to reach all parts of the toilet contents. The need to turn and ventilate the heap is not just to allow oxygen to play its part in the chemical process, but also to facilitate evaporation in the depths of the heap. The most common problem with composting toilets is an excess of moisture which slows or stops the aerobic decomposition process and leads to bad smells. A conceptual problem with the composting toilet is that to be successful at composting, it must create conditions which encourage bacteria to thrive. If part of the intention of a toilet is to kill harmful bacteria, this may be counter-productive. On the other hand, when a desiccating toilet is well managed, the contents of the processing chamber can be reduced to an apparently innocuous state very rapidly (Dudley 1996).

8.1.3 System hardware and operational requirements

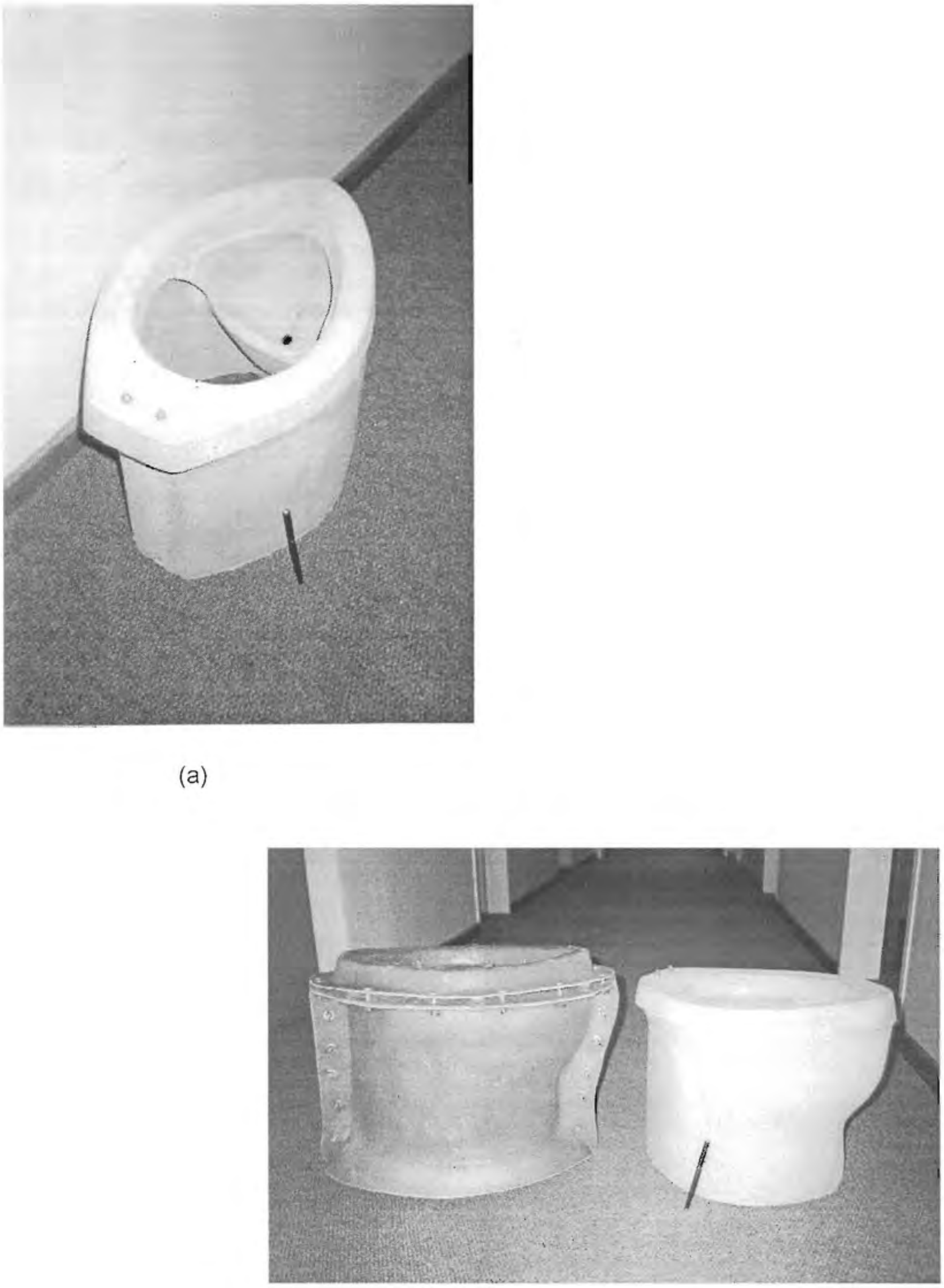
The basic requirement of a urine diversion sanitation system is a toilet pedestal (or squatting plate) which prevents urine and faeces from being mixed together. Examples of pedestals for both the dry box and flushing systems found in Sweden are illustrated in Figure 8.6. Both are indoor toilets. In the dry-box version, small amounts of ash, dry soil or sawdust are sprinkled on the faeces after each bowel movement; this serves to absorb the moisture which is an inherent part of fresh faeces and thus also to prevent odours. It is essential that the excreta remains as dry as possible and that moisture is prevented from entering the waste compartment. Paper and other material used for personal cleansing is not deposited in the receptacle but is stored in a separate container and disposed of by burning. The urine can be collected in any suitable sealed container if its reuse for agricultural fertilizer is desired. Alternatively, it can be led into a soak pit. The urine bowl is washed with water periodically, while the rear chute may be cleaned with a damp toilet brush when necessary.

In the flushing version, the urine is collected and stored in underground vaults, from where it is collected by farmers for use as agricultural fertiliser. The faeces are in most cases flushed into a conventional sewer system for further treatment, and the reduced nutrient load due to the exclusion of nitrogen and phosphorus found in the urine results in lower treatment costs. The front compartment of the bowl, used for urine collection, is flushed with a spray of approximately 200 ml of water from a nozzle on the side of the bowl, while the rear compartment is flushed from a conventional toilet cistern.

(a) (b)

Figure 8.6: Urine diversion pedestals for (a) dry system and (b) flushing system. Photographed in Sweden.

In Mexico a pedestal cast in mortar, using a fibreglass mould, is used (Figure 8.7). This pedestal is usually painted and provided with a conventional seat and lid, after which it looks quite attractive.



(a)

(b)

Figure 8.7: Mexican urine diversion pedestal cast in mortar.
(a) The pedestal, which can be fitted with a conventional seat and lid.
(b) The pedestal shown together with its fibreglass mould.

The practice of covering fresh faeces with earth, ash, etc is not new. In England, Rev Henry Moule patented an earth closet in 1860 (Figure 8.8). This wooden structure had a seat and hopper. The hopper was filled with dry earth, charcoal or ash. A pull of the handle in the seat released the earth onto the contents of a bucket set below the seat.

Figure 8.8: Rev Henry Moule's earth closet patented in 1860.
Found in the grounds of Cooling Castle, Kent, UK.
(Lewis 1996)

8.2 AGRICULTURAL PROSPECTS: SOME EXAMPLES

8.2.1 Introduction

The potential value of human excreta as fertiliser and soil conditioner was introduced in chapter 7.2, where the plant nutrient content of urine and faeces was described. In this section, some policies and examples of human excreta reuse for agricultural purposes in various countries are described.

In order to grow plants that supply our food, fertilisers such as nitrogen, phosphorus, potassium and about 25 other additional elements have to be supplied. Today, artificial fertilisers account for the largest share of these nutrients, but at the present rate of use the available resources will be rapidly depleted. Use of human excreta as fertiliser has been implemented only to a very limited extent. Rather, they have been flushed out into the rivers with consequent growth of algae, etc, resulting in a lack of oxygen in the aquatic resources. These resources have also been polluted with pathogenic micro-organisms to the extent that many large rivers have become virus infected more or less permanently. It is thus better to create a closed system, with no pollution from bacteria or viruses and where *human* fertilisers are harvested and used to feed the following year's crops (Wolgast 1993). Nutrients are removed from fields with the harvested crops; in sustainable agriculture therefore, the same amounts of nutrients that are removed from a field should be returned to it (Jönsson 1997).

8.2.2 Recycling: how nutrients are returned to the soil

Ecological sanitation regards human excreta as a resource to be recycled rather than as a waste to be disposed of. The very idea that excreta are waste with no useful purpose is a modern misconception. It is at the root of pollution problems that result from conventional approaches to sanitation. In nature there is no waste – all the products of living things are used as raw materials by others. Recycling sanitised human urine and faeces by returning them to the soil serves to restore the natural cycle of life-building materials that has been disrupted by our current sanitation practices (Esrey et al 1998).

There are many reasons for recycling the nutrients in excreta. Recycling prevents direct pollution caused by sewage being discharged or seeping into water resources and ecosystems. A secondary benefit is that recycling returns nutrients to soil and plants, and reduces the need for chemical fertilisers. It restores good soil organisms to protect plants, and it is always available locally, wherever people live (Esrey et al 1998).

8.2.3 Examples

Japan:

Japan has a unique practice of collection and treatment of nightsoil (human urine and faeces). This country introduced the practice of reusing human excreta for agriculture in the 12th century, possibly influenced by monks of Zen Buddhism who studied in China (the Chinese practice of reusing human excreta arose at a very early stage in the country's development). This practice continued in Japan until the middle of the 19th century. Cities were so clean that Portugese missionaries reported their astonishment to the Vatican during the 16th century. From the 17th to the middle of the 19th century Japan became a closed society, and the recycling of human excreta was encouraged. Farmers purchased human urine and faeces from customers in the urban areas, and, due to the country's closed policy, typhoid, cholera and other communicable diseases were virtually unknown. Farmers placed a bucket at street corners in the towns and villages, collecting free urine from pedestrians and providing a simple public toilet at the same time (Matsui 1997).

China:

In China's city of Shanghai, only 13 % of the population has waterborne sewerage facilities. The Shanghai Bureau of Environmental Sanitation (SBES) collects the major part of the city's human waste. The vacuum trucks of the SBES remove more than 8 000 t of nightsoil each day from public toilets, septic tanks and nightsoil dumping stations. During the night, the wastes are shipped by river and canal in sealed barges to depots on the outskirts of the city. There the waste is stored for between 10 and 30 days in covered tanks, after which it is sold to farmers who apply it to their fields as manure (Robson 1991).

Growing vegetables in Mexico City, Mexico:

In response to rapid inflation, high unemployment and inadequate nutrition in Mexico City, Anadeges (a network of NGOs) has perfected a method of growing vegetables in containers using human urine as fertiliser. The project was launched in 1988 and more than 1 200 urban households are currently participating.

The technology used was selected and adapted to fit the local circumstances, which include no land available for conventional kitchen gardens, participants unable to afford the required investment in containers and fertilisers, and the need for growing containers of lightweight material to allow rooftop cultivation.

Vegetables are grown in containers such as 20 ℓ plastic buckets or discarded car tyres filled with deciduous tree leaves or grass clippings and topped with a 30 - 50 mm layer of soil. The soil is made up of plant material from the previous year's containers that has composted into a rich humus, and household garbage that has been composted with worms. Urine, which has been stored in separate receptacles for 3 weeks, is applied to the vegetable containers after dilution with water on a 1:10 ratio.

After several years of study, certain observations were made, and it became clear that plants fertilised with urine grew more rapidly, and were larger and healthier than those grown with conventional agricultural techniques. Furthermore, less water was required (Esrey et al 1998).

Guatemala:

In Guatemala, deforestation and erosion are serious problems throughout the highland areas. This is the result of the high population density in these zones, together with inequitable land distribution and the use of the more gently sloping and flatter lands for the cultivation of cash crops, thereby forcing the subsistence crops to be cultivated on steep slopes. To counteract this situation of increased soil loss, the use of human faecal matter as soil conditioner by subsistence farmers is of particular value. While it is recognised that this practice may not solve the area-wide problems of deforestation and soil erosion, it is regarded as an appropriate and low-cost method for improving the fertility and productivity of the soil of the individual farming family and for the country as a whole. The farmers are aware that the application of chemical fertilisers to the fields without replenishing the organic fraction leads to an impoverishment of the soil (Strauss and Blumenthal 1990).

The LASF latrine described earlier was introduced here because it was regarded as the most suitable technology for the people of the area. Ash, or a mixture of ash and soil or of lime and soil, is added after each defecation. This, together with the separation of urine, renders the faecal material alkaline, with a pH of around 9. This enhances the die-off of bacterial pathogens. The mixture of decomposed, humus-like material of faecal origin and ash, called "abono", is dried in the sun and then stored in bags upon removal from the vault until the farmer uses it in his fields at the time of tilling. The potassium levels of the "abono" are much higher than ordinary excreta due to the addition of ash, which is very rich in potassium. On average, the application rate of "abono" amounts to the equivalent of about 2 500 to 3 000 kg/ha for each plant cycle. With the average "abono" production rate of about 425 kg per year per family, the family's fertilising potential for maize crops is approximately 1 900 m^2 on the basis of the phosphorus content of the "abono" and 2 580 m^2 on the basis of potassium, but only about 123 m^2 on the basis of the nitrogen content. The fertiliser from these latrines is therefore complemented by the collected urine, or else nitrogen-fixing crops such as legumes are planted in rotation with other crops (Strauss and Blumenthal 1990).

Zimbabwe:

A unique tree-panting method that is combined with a composting or dehydrating toilet, called the *arborloo*, is used in Zimbabwe. A small hole suitable for planting a tree is dug; the size is approximately 600 x 600 x 600 mm, thus forming a shallow pit for a toilet. A lightweight, removable slab is placed over the hole and a simple toilet structure, which is also able to be moved easily, is erected above it. The unit is fitted with a urine diversion pedestal or squat plate. The urine is thus diverted and reused as liquid fertiliser, while the shallow pit fills up relatively quickly with faeces. These are treated in the same way as in any other dehydrating toilet, by being covered with ash or dry soil. As soon as the hole is full, the superstructure is moved to another similar hole, while the first hole is topped up with soil and a fruit tree planted in it. In this way, whole orchards of productive fruit trees are grown. The most commonly planted trees are avocados, paw-paws, mulberries, mangoes and guavas.

Sweden:

Sweden is probably the country with the most advanced system of collection and reuse of human urine, where it is practised by farmers on a large, mechanised scale. There are a number of settlements, called *eco-villages*, in the country, where the residents have ecological sanitation systems with urine diversion toilets. The urine from all the houses is collected in large underground tanks, and what the residents do not use themselves is collected by farmers in road tankers and used for fertilising their crops. The usual practice is to spray it onto the lands while they are being prepared for planting, and then harrow it into the soil before sowing the seed.

The country also has an agricultural research farm a short distance from Stockholm, where the Department of Agricultural Engineering of the Swedish University of Agricultural Sciences, Uppsala, has for a number of years been actively researching the plant uptake of urine fertiliser compared with conventional chemical fertilisers. The fields are divided into lots where various dilutions of urine are applied (see Figure 8.9), and cuttings from the growing plants are analysed in the laboratories to determine the uptake and utilisation of the various fertiliser constituents in the urine.

Figure 8.9: Part of the agricultural research farm near Stockholm. The fields are divided into lots for experimentation with various dilutions of urine. The crop being tested here is barley.

8.3 HEALTH ASPECTS OF EXCRETA REUSE

8.3.1 Transmission routes of pathogens

The health hazards associated with excreta reuse are of two kinds: the occupational hazard to those who handle the excreta, and the risk that contaminated products from reuse may subsequently infect humans or animals through consumption or handling (Feachem et al 1983).

The main pathogenic organisms of interest in sanitation are viruses, bacteria, protozoa and helminths (worms). There are a number of different varieties of all these organisms. In developing countries especially, excreta-related diseases are very common, and the excreta thus contain high concentrations of pathogens that cause diseases in man. Pathogenic organisms can enter the human body by a number of routes, as illustrated in Figure 2.1, Chapter 2.

The most important property of any sanitation system is the ability to break the cycle of transmission of these diseases. Obviously this depends as much, if not more, on human factors as on purely technical issues. Proper operation and maintenance of a sanitation system, as well as observance of good personal hygiene habits, are essential components of a healthy lifestyle. The reuse of human excreta for agricultural purposes must therefore, as far as possible, not expose people to the risk of infection. Sanitation systems designed for reuse of the excreta thus pose a special challenge to the engineer to design and develop technologies that will not pose unacceptable risks to public health.

8.3.2 Destruction of pathogens

(a) General

As the death or survival of excreted pathogens is an important factor influencing transmission, these organisms need to be either destroyed or otherwise rendered harmless. In principle, pathogens die off upon excretion, as environmental conditions outside the human host are generally not conducive to their survival. Prominent exceptions are pathogens whose transitional stages multiply in intermediate hosts, such as *Schistosoma*, which multiply in aquatic snails and are later released into the water body (Strauss and Blumenthal 1994). Also some viruses, although they cannot multiply outside a suitable host cell, may survive for many weeks in certain environments, especially where temperatures are cool (<15°C) (Feachem et al 1983). Another important factor is the *infective dose* of a pathogen, i.e. the dose required to create disease in a human host. For helminths, protozoa and viruses, the infective dose is low ($<10^2$), while for bacteria it is medium ($\pm10^4$) to high ($>10^6$). The manifestation of a disease is different for the various pathogens: with viruses, protozoa and bacteria, an infected person may or may not become sick, while with helminths an infected person will exhibit various degrees of disease intensities depending on the number of worms he carries in his intestines (Strauss and Blumenthal 1994).

According to Golueke (1976), environmental factors of importance in the die-off rate of pathogens are high temperatures, low moisture contents and time. A high temperature, especially, is the most important consideration, as all living organisms, from the simplest to the most complex, can survive at temperatures only up to a certain level. Above that level, they perish. Regarding moisture content, all biological activity comes to a halt at moisture contents of 12 % or less, although the process would be disastrously slowed long before that level was reached. Generally, moisture content begins to be a severely limiting factor when it drops below 35 to 40 %. Also, time *per se* does not kill the microorganisms; rather, it is the *continued exposure to an unfavourable condition* that does the job.

A further important factor is pH. While microorganisms will often grow over wide ranges of pH, there are limits to their tolerance. Drastic variations in pH can harm microorganisms by disrupting the plasma membrane or inhibiting the activity of enzymes. External nutrient molecules may also be negatively affected, thus reducing their availability to the organisms. The pH limits for the survival of *E. coli*, for example, are between 4,4 and 9,0, with the optimum between 6,0 and 7,0. In general, pH values greater than about 9,0 are detrimental to all microbial growth (Prescott, Harley and Klein 1990). This was clearly illustrated in the Eastern Cape pilot project, described in Chapter 9, where ash was sprinkled over the faeces in the toilets. Ash from wood fires generally has a pH of 10 or above, and the microbiological tests carried out on the desiccated faeces samples bear testimony to the large reduction in pathogenic organisms which took place as a result of an elevated pH.

(b) Urinary pathogens

While urinary excreted pathogens are of less concern for environmental transmission than are faecal pathogens (see Table 2.1, Chapter 2), there remains a possibility that faecal contamination can still enter the urine bowl of the pedestal. This usually happens where users are suffering from stomach disorders, when the faeces are watery and tend to spray on emission. Experiments in Sweden have established that six months of storage time for source-diverted urine is usually sufficient for the destruction of pathogenic organisms. However, this is also dependent on the temperature and dilution of the mixture – lower temperatures and higher dilutions tend to increase the survival time of the pathogens (Olsson 1996; Höglund et al 1998).

(c) *Faecal pathogens*

Desiccation of faeces maximises the destruction of enteric microorganisms. This greatly increases their value and manageability as an agricultural resource, both as a fertiliser and soil conditioner, as well as reducing pollutant burdens on the aquatic environment and health hazards associated with handling. Experimental data has confirmed that dry storage of faeces for a minimum period of one year usually results in a product of substantially improved microbiological quality (Wheeler and Carroll 1989).

The main factors influencing die-off over time are temperature, dryness and UV light (Strauss and Blumenthal 1994; Feachem et al 1983). Figure 8.10 shows the average survival periods of pathogens in untreated faecal sludges applied to fields in warm climates.

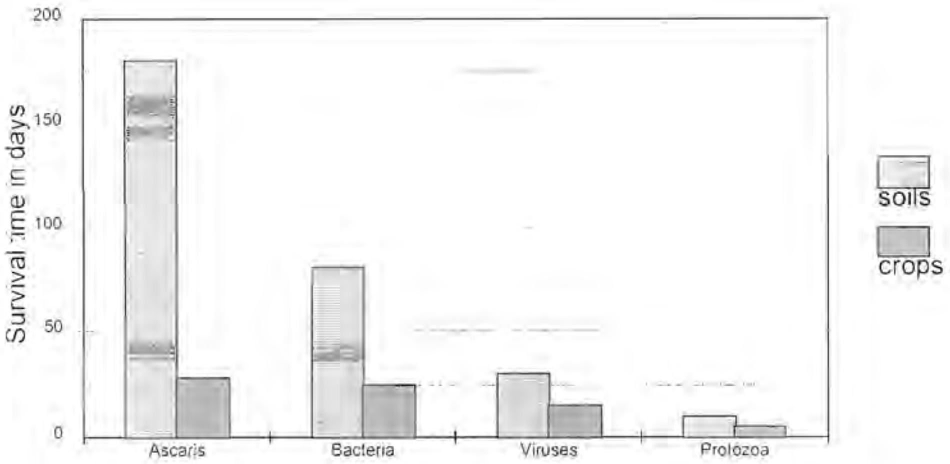


Figure 8.10: Survival times of pathogens in untreated faecal sludges applied to fields in warm climates (Strauss and Blumenthal 1994)

It is possible that the product from toilets with short retention times (less than one year) carries some potential risk. The risk in epidemiological terms would depend on the extent of exposure and susceptibility to the infection. If farmers handle the fertiliser with bare hands then, depending on hygiene practices, there is a potential for transmission of infection via the oral route. This could occur in the case of helminth infections, such as *Ascaris*. Where the fertiliser is used before or at the beginning of the growing cycle of an edible crop, and dug into the soil, there would be no risk to consumers of the crop. However, in cases where the fertiliser is used in a way that brings it into contact with the edible portion of the crop, then a risk of transmission of helminth infections could occur (Strauss and Blumenthal 1990).

Helminth ova are the most hardy of the pathogens of interest in faecal matter intended for handling and reuse. However, most evidence suggests that, provided storage exceeds one year, the number of even these pathogens is likely to be very low. Even the most persistent eggs, e.g. *Ascaris*, are usually rendered non-viable by storage after more than one year in sludge at moderate temperature, e.g. 25°C (Wheeler and Carroll 1989).

Feachem et al (1983) conducted an intensive investigation into the relationship between temperature and rate of die-off of various pathogenic organisms. According to this seminal study, there is a so-called "safe zone" which represents a combination of time and temperature above which no pathogens can survive (Figure 8.11). Various pathogens have different combinations of time and temperature which are destructive to them, the most hardy of all being *Ascaris*. These various combinations have been plotted on the figure, and the importance of the two parameters, namely time and temperature, is clear.

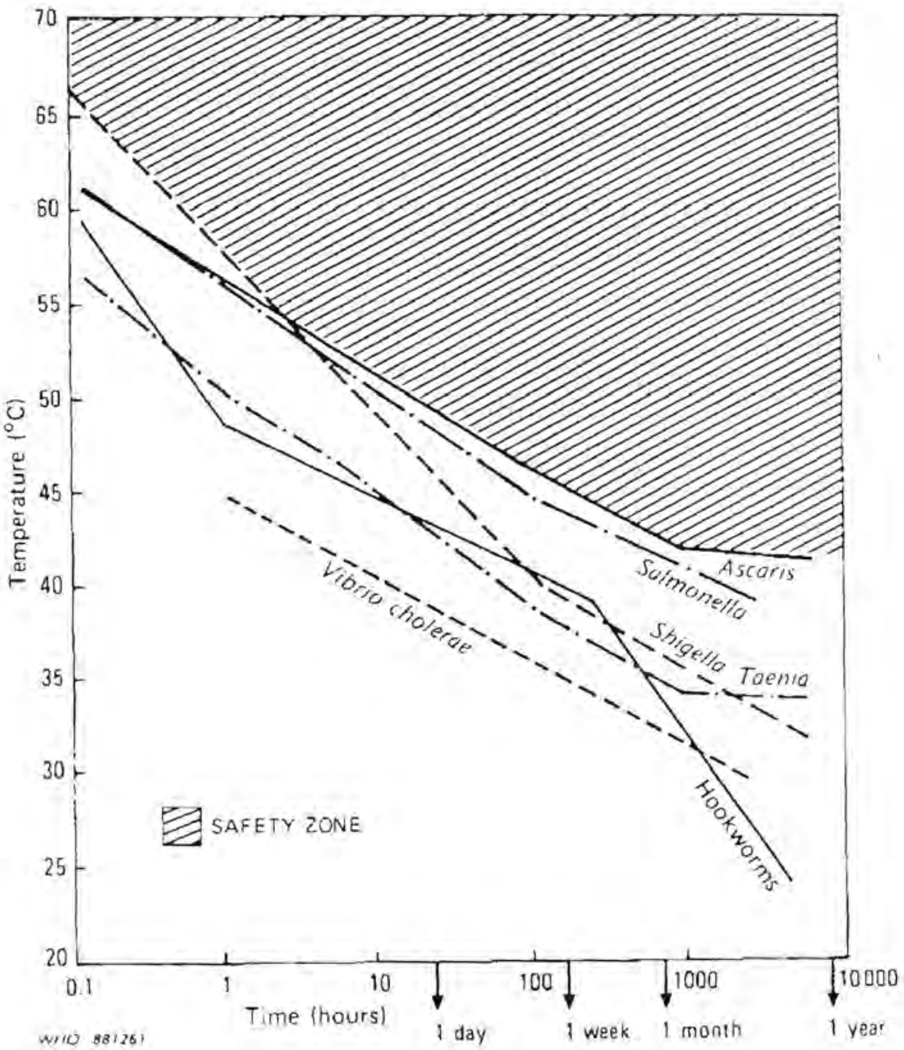


Figure 8.11: Survival times of various pathogens as a function of temperature
(Feachem et al 1983)

8.3.3 **The human element** (Feachem et al 1983)

It is difficult to predict how people will respond to technical innovations, because many factors enter into their choice. However, much can be gained by the planner's appreciation of the user's position and looking at innovations from the user's point of view. For the user, the toilet itself is a most important element in the excreta disposal system, and even a few minor disadvantages in its operation (for instance the need to physically remove the desiccated faeces from the waste compartment of a urine diversion toilet, no matter how simple the task) may be perceived reason enough to reject the proposed innovation. The willingness to reuse the excreta for agricultural purposes obviously plays an important role here.

It is widely accepted among agricultural and sanitation planners that reuse of human wastes is a desirable objective if it can be hygienically achieved. This conclusion brings experts into line with the large part of mankind that has always favoured reuse. In many parts of the world, however, the problem is not reuse, but how to persuade people that additional stages of treatment are sufficiently important for their health to warrant the increased time and expense that treatment requires. Proper education and hygiene awareness are thus essential parts of any strategy aimed at promoting excreta reuse.

CHAPTER 9

THE SOUTH AFRICAN PILOT PROJECT

"If there is technological advance without social advance, there is, almost automatically, an increase in human misery."

Michael Harrington (American writer, 1962)

CHAPTER 9: THE SOUTH AFRICAN PILOT PROJECT

9.1 IDENTIFICATION OF COMMUNITIES

The author became aware of the potential of urine diversion technology during 1996. While still gathering basic research information, he was approached by the Eastern Cape Appropriate Technology Unit (ECATU), a parastatal of the Eastern Cape provincial government, with inquiries about the efficacy of these systems. ECATU had recently become interested in the technology and expressed a wish to implement some systems on an experimental basis. An agreement was reached on launching a pilot project whereby Boutek would direct the engineering and social research, while ECATU would be responsible for financing the building and supervisory work. Because ECATU worked closely with all the communities under its jurisdiction and thus knew them on a fairly intimate basis, it was agreed that this organisation should also assist Boutek with the required workshopping process.

ECATU indicated that they wished to implement the pilot project among certain of the rural communities, where poverty was rife and sanitation facilities either rudimentary or non-existent. The toilet units were to be fully subsidised. Boutek was initially opposed to this arrangement, as it was concerned about the sustainability of the project should there be no financial commitment from the communities. However, ECATU maintained that the technology was still unknown in South Africa, and that the communities were being expected to take part in an "experiment", so the acceptability of the toilet units was not necessarily a foregone conclusion. Boutek eventually agreed to this course of action, but with an increased determination to carry out the social process very thoroughly in an effort to ensure that the communities took complete ownership of the systems.

ECATU budgeted for a total of 45 toilet units over a two-year period. The intention was to provide fifteen units each in three selected villages, where the residents would be consulted about who the potential owners would be in each case. Due to constraints such as lack of experienced local builders as well as capacity within ECATU itself, it was decided to implement the systems in three phases of five each in communities only a short distance from Umtata. This would divide the project up into more manageable phases and making the logistics of material transport and supervision less taxing for the organisation. The villages identified by ECATU were Manyosini, Sinyondweni and Gwebinkundla, each approximately 30 minutes travel by road from Umtata. The villages were all in completely rural settings, despite their proximity to the city, and all had the same rolling topography and clayey soil. Most of the dwellings consisted of thatched-roofed mud huts, with the occasional brick and mortar house in evidence (see Figure 9.1). Availability of water was a major problem common to all three communities, the women and children having to walk long distances every day to fetch water from local streams. The few toilets that existed were ordinary pit latrines, mostly in a very poor and unsanitary condition. Residents generally relieved themselves in the veld, and the level of personal hygiene was observed to be low.

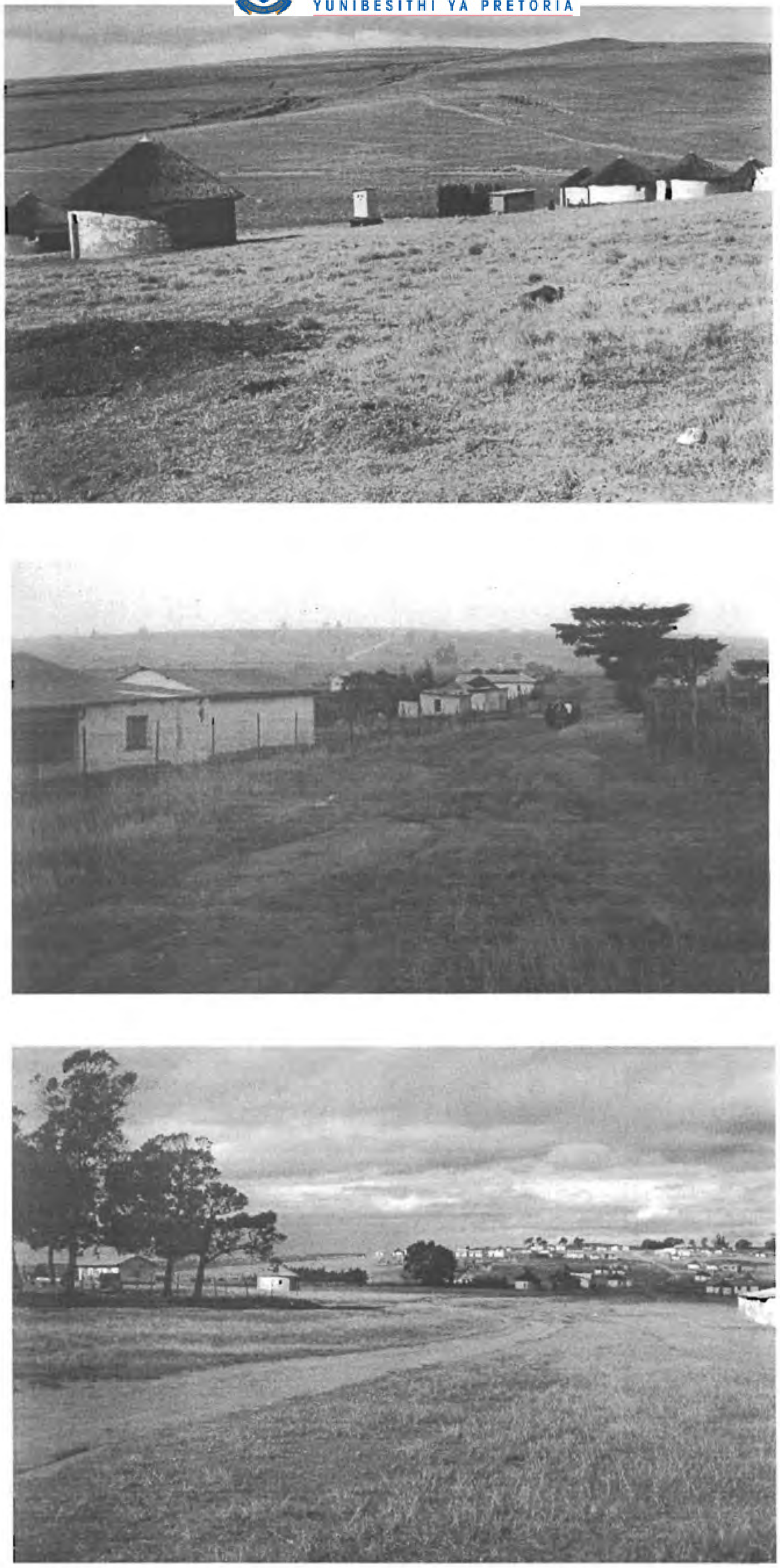


Figure 9.1: Typical views of the villages selected for the pilot project. Top: Manyosini; middle: Sinyondweni; bottom: Gwebinkundla

9.2 THE COMMUNITY WORKSHOPPING PROCESS

Boutek's first task was for the author and an anthropologist (social scientist) to familiarise themselves with the three villages. They were accompanied by Ms Sybil Lila, ECATU's social worker, as well as the organisation's chief technician. Apart from getting to know the physical layout of the villages, it was important to understand the social structure and dynamics existing within the communities. Although the people were all Xhosas, each community had its own distinct characteristics, beliefs and behaviour. It was indeed an eye-opening event for the author, for whom this was the first time he was required to deal with project communities on an intimate, face-to-face level. Needless to say, the learning curve was extremely steep. However, having the assistance of an experienced social scientist to direct the proceedings facilitated the task enormously.

The community meetings had been arranged earlier by Ms Lila. The procedure in each village followed more or less the same pattern, with Ms Lila introducing the Boutek personnel (Figure 9.2) and explaining that ECATU and Boutek were there to talk about the possibility of implementing a new type of sanitation scheme for the community. She explained that it was a system being introduced into South Africa for the first time, which might seem foreign to them, and that only fifteen units in each village were going to be built initially. Volunteers would therefore be sought to take part in the project. These introductions were all conducted in Xhosa. The author, having been duly instructed in the correct procedure by Boutek's social scientist, was then required to take the floor and explain the concept of the new technology.

Speaking in English, with Ms Lila translating, the author made use of a fibreglass mock-up of a urine diversion pedestal to explain the basic operating principles of the system (Figure 9.3). The advantages of no pits being required, the desiccation process, the lack of odour if properly operated, the ease of emptying the faeces receptacle and the agricultural potential of the excreta were all explained to the villagers. A number of questions were asked and it was interesting to observe that, while much of the debating was done by the men, it was actually the women who prompted them to ask questions. The subservient role of the women in these particular societies was thus clearly illustrated.

While there were some sceptics who eventually decided not to participate further, the overall result of the introductory talks was generally positive. Most of the residents were generally quick to see that the proposed toilet systems, while being somewhat strange to them, were in actual fact superior to pit toilets in many respects. There was some difficulty, however, in understanding that only fifteen toilets were going to be built in each village, but ECATU's budgetary constraints were eventually accepted. The result was that there were more than enough volunteers to participate in the pilot project, and the communities indicated that they would democratically decide where the toilets were to be constructed. It was also interesting to note that, in the final list of fifteen people in each case, the village headman and sub-headman were always included.

The meetings were held either in the local school classroom or, if there were too many people present, outside the classroom (Figures 9.4 and 9.5).

Figure 9.2: ECATU's Ms Sybil Lila introducing the subject of the meeting

Figure 9.3: The author demonstrating the concept of the sanitation technology with the help of a fibreglass model of a urine diversion pedestal

Figure 9.4: Community workshop at Gwebinkundla School

Figure 9.5: Community workshop at Manyosini School

At Sinyondweni the residents were always particularly pleased to see the project team, and after each meeting they would sing as a way of showing their appreciation (Figure 9.6). The songs were usually traditional thanksgiving hymns to God.

Figure 9.6: Sinyondweni residents singing for the project team

Cultural taboos and beliefs which needed to be addressed during the implementation of the project were then discussed. For example, the necessity for keeping all foreign materials except ash or dry soil out of the faeces receptacle was the first problem to be overcome. It was brought to the attention of the project team that the people considered it unacceptable to burn the material used for personal cleansing because they believed they would get anal infections if they did so. This belief was taken care of in the project design by making available a plastic bucket next to the pedestal for storing the used cleaning material, which could then be buried at regular intervals. These buckets were fitted with lids, so flies or odour were not a problem.

Another important point was that the residents considered it unacceptable to collect and reuse the urine, although most of them were not opposed to the concept of utilising the desiccated faeces. This was an interesting development, as just the opposite was expected (i.e. that the reuse of human faeces would be more of a problem). While not opposed to using cattle manure to improve soil fertility, some cultures are opposed to the concept of "human manure". It was concluded that this aspect would need to be further researched among the various tribal people in the country in order to gain a better understanding of each culture's viewpoint on the issue. However, the fact that the residents were disinclined to reuse the urine was not considered to be a problem, and it was arranged to lead it into soakpits instead. The drainage pipes were arranged in such a way (see Figure 9.7) that the option of collecting the urine could still be adopted at a later stage should the residents decide to do so.

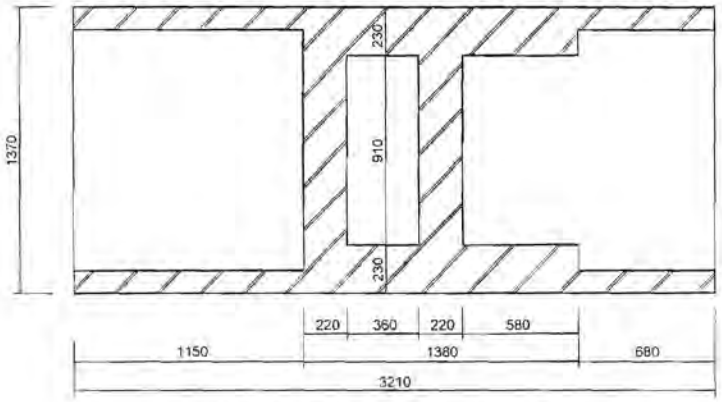
A further interesting aspect of social life in these villages was that it was considered unacceptable for a family's daughter-in-law to use the same toilet as her father-in-law. For the author, it was a further striking example of the massive gulf of ignorance existing in the civil engineering fraternity, which until fairly recently has assumed that all sanitation problems could be solved with technology alone. Fortunately, however, this specific social issue did not become a problem for the project, as the matter appeared to sort itself out among the families who eventually took part in the project.

Follow-up meetings developed into planning sessions, where the process of building the toilets was discussed. Options regarding the type of brick, colour of paint, type of faeces receptacle (i.e. plastic, wood, etc) and the type of urinal were all decided by the communities. The residents also indicated that they would point out exactly where, on their plots of land, they wished their toilets to be built. It was further agreed that each family would take responsibility for looking after all building materials delivered to their premises.

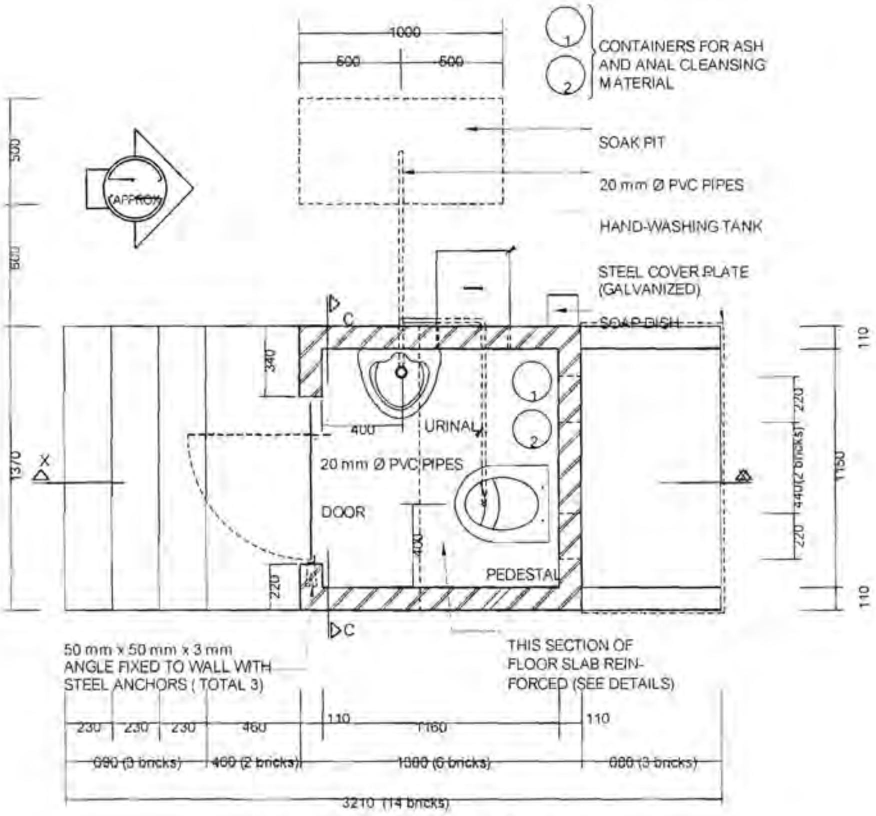
9.3 DESIGN OF THE TOILET UNITS

9.3.1 The superstructure

The entire process of designing the toilet superstructures, including all fittings except the urine diversion pedestals, was undertaken by a junior engineer in Boutek, working under the direct supervision of the author. The main aspects of the structures are illustrated in Figure 9.7. Details of fixings and fittings are not included here.

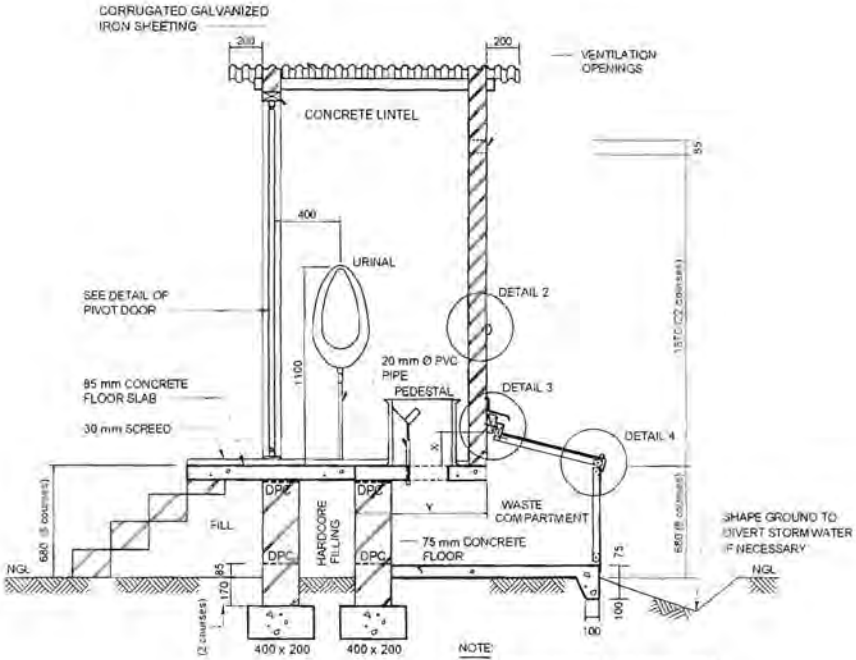


FLOOR PLAN ABOVE GROUND LEVEL



FLOOR PLAN ABOVE SLAB

Figure 9.7: General design aspects of the toilet units

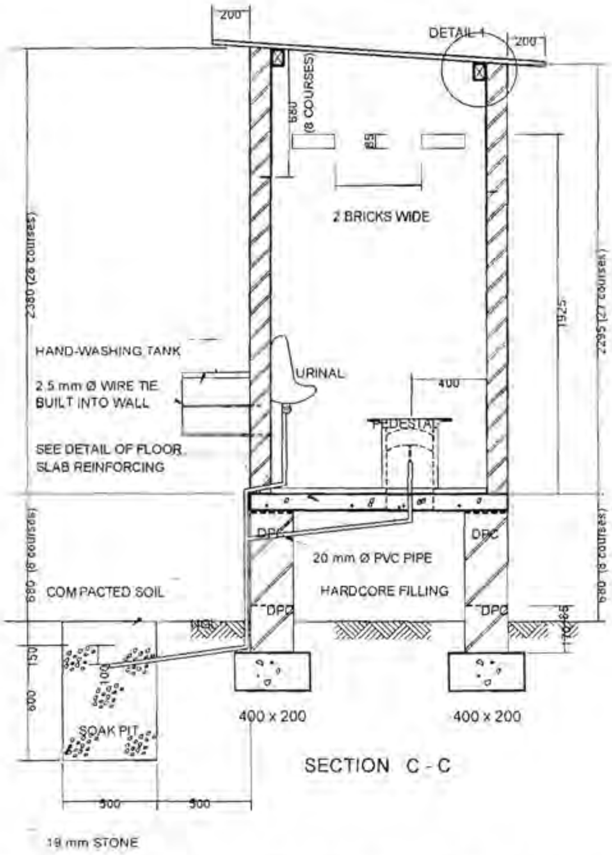


SECTION X - X

NOTE:

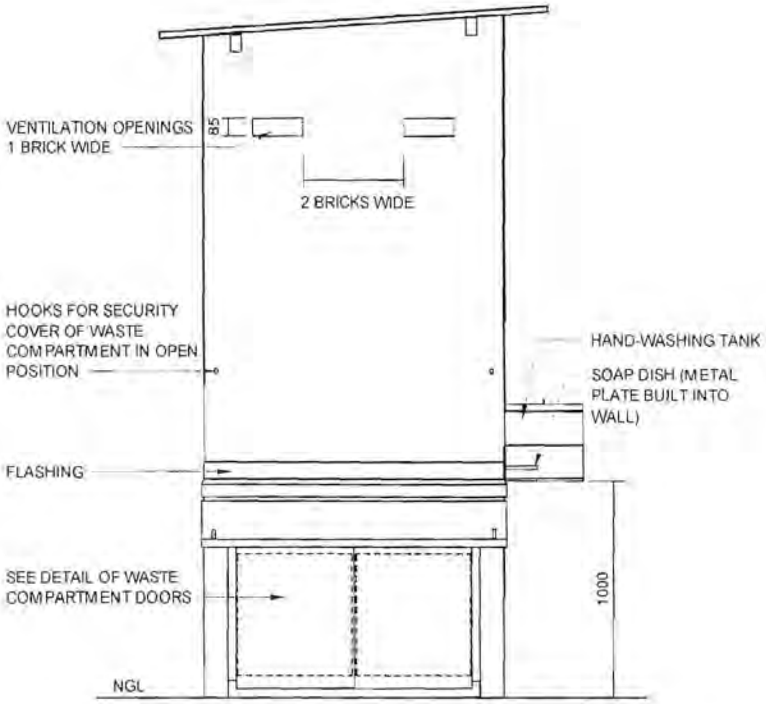
X POSITION OF TIMBER TO BE DETERMINED BY WALLS ON BOTH SIDES OF WASTE COMPARTMENT

Y THIS SECTION OF FLOOR SLAB IS REINFORCED (SEE DETAIL)

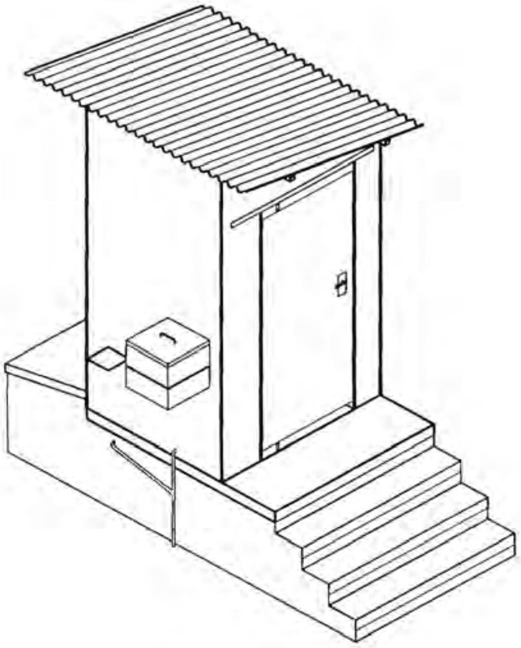


SECTION C - C

Figure 9.7 (cont): General design aspects of the toilet units



REAR ELEVATION



ISOMETRIC VIEW

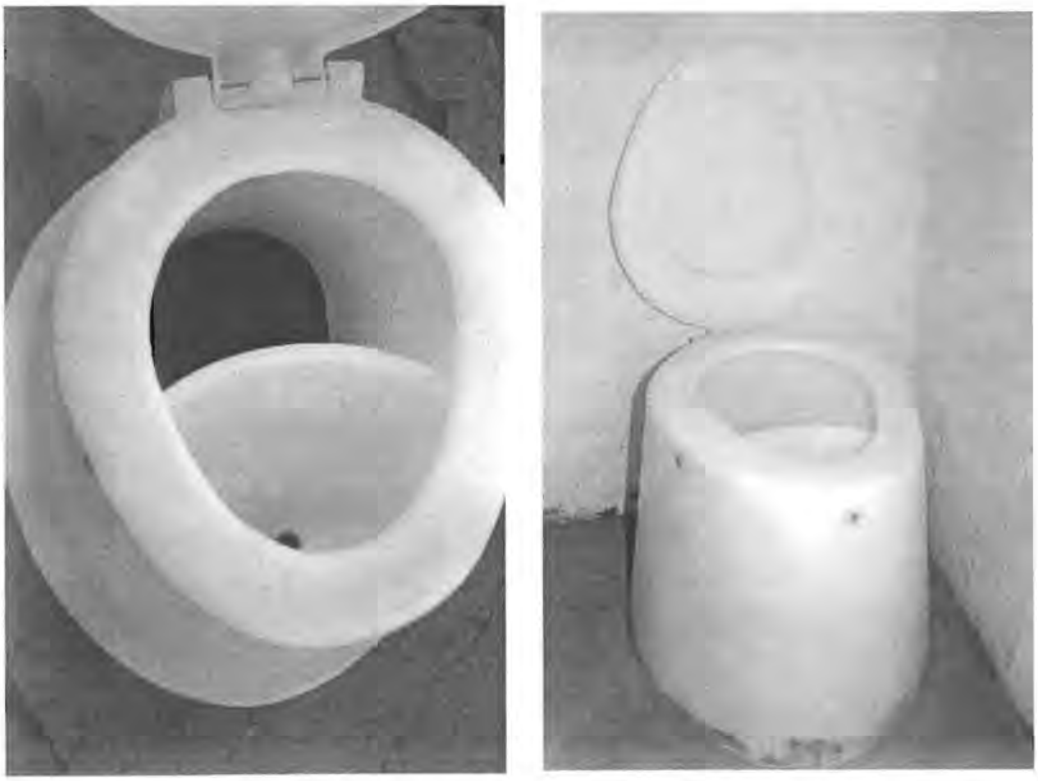
Figure 9.7 (cont): General design aspects of the toilet units

9.3.2 The urine diversion pedestals

The design of the pedestals was undertaken by the author. Based on measurements and photographs taken during a study trip to Sweden (see Figure 8.6(a), Chapter 8) the conceptual drawings were prepared and given to a plastics manufacturer in Pretoria for fabrication of the end product. Preliminary models were first made up for testing purposes.

The testing process involved some delicate negotiations with the author's wife and female colleagues, as well as much persuasion. As the correct positioning of the urine collection bowl is of vital importance for female users, it was essential that various women of different shapes and sizes test the model and provide constructive criticism on this aspect. As a result of the feedback obtained, the position of the bowl was adjusted up or down, back or forward, until a position was obtained which best suited the average woman.

Figure 9.8 illustrates the completed pedestal, fabricated in moulded plastic. The required number of pedestals for the project were transported to ECATU in Umtata.



(a) (b)

Figure 9.8: The plastic urine diversion pedestal designed by the author. (a) View showing the urine collection bowl; (b) pedestal installed in toilet unit (floor topping and final cleaning not completed yet).

9.4 HYGIENE EDUCATION IN THE COMMUNITIES

As explained previously (section 9.1), there was a low level of personal hygiene in the three villages. The residents were generally very poor, and water had to be fetched from muddy streams some distance away from their houses. For this project to be sustainable, and to uplift the standard of living of the people, it was essential for them to understand that the provision of proper sanitation facilities had to necessarily go hand in hand with an improvement in their personal hygiene habits.

Boutek's social scientist prepared a hygiene awareness training guide and explained to Ms Sybil Lila how to implement it. The main elements of the guide consisted of the following:

- The training should take place shortly before the handing over of the completed toilets to the families, and should be spread over a period of two to three days.
- Training should take place at a house in the community where the toilet had already been built.
- The purpose of the training programme should be explained to the people.
- The purpose of this specific type of toilet, as explained at the first community workshop, needed to be impressed again. Specifically, the separate collection and disposal of urine and faeces, and the reasons for this, were to be thoroughly understood.
- The proper operation and management of the toilets. This consisted of showing how the toilets in general, and the pedestals and urinals in particular, were supposed to be kept clean. Water could be used for rinsing the urinals and urine collection bowls. However, any soiling of the rear chute of the pedestal was not to be washed off but rather brushed clean with a damp toilet brush, as it was important to avoid adding unnecessary moisture to the faeces pile. Disposal of paper used for personal cleansing was also discussed and the people were once again reminded that this was not to be dropped into the faeces container. Finally, the necessity for sprinkling ash or dry soil over the fresh faeces was explained.
- The importance of personal cleanliness and the reasons for washing of hands, etc, was emphasised. The link between sanitation-related diseases, personal hygiene and food preparation was coupled to this aspect.
- The purpose of having two containers for faeces collection was explained. When the first container was full, it was to be kept to one side in the rear compartment of the toilet unit until proper desiccation had occurred, after which disposal could take place. For residents wishing to use the desiccated faecal matter on their vegetables and other crops, the necessity for allowing sufficient time for desiccation was explained. Otherwise it was to be simply buried. In both cases, however, the observance of personal hygiene was stressed. Ms Lila pointed out that the author would be returning at various intervals for the purpose of sampling the material to determine the rate of pathogen die-off. It was interesting to observe that the residents took this matter very seriously and would not empty the

containers "until the CSIR had said that it was all right to do so". Research into the rate of pathogen destruction is still continuing (see section 9.7).

- Time was to be allotted for questions and clarifications, and a "refresher course" was to be undertaken about a month after the toilets were handed over. The general condition of the toilets with regard to cleanliness was also to be checked at this time.

Matters not discussed:

- The question of storage time for urine did not arise. The communities were disinclined to reuse the urine as plant fertiliser, so all urine was led into soakpits, and not collected for reuse. No hygiene education was thus required for this aspect.
- The issue of possible HIV-AIDS transmission through handling of excreta was discussed with a medical doctor. Apparently this virus is very sensitive, and once it enters the human digestive tract, it is already under attack. The probability of it being excreted alive is, to quote the doctor, "small enough to be ignored", but should this happen (e.g. a woman's menstrual blood contaminating the urine), the hostile conditions encountered in any type of sanitation system will ensure its very rapid destruction. This aspect was therefore not considered to be of concern.

Generally speaking, the hygiene awareness training proved to be successful, with most residents scrupulously observing all that was taught them. There was an occasional need for Ms Lila to remind certain families about operational matters, the most common being the addition of sufficient ash to the faeces containers. Interestingly, the villages of Sinyondweni and Manyosini showed the best results, while Gwebinkundla residents needed the most attention. It was necessary for Ms Lila to do more follow-up work here than in the other two communities. When questioned as to possible reasons for this phenomenon, Ms Lila was of the opinion that the level of literacy in Gwebinkundla was generally lower than in the other two villages. This could not be proved at the time, though, and Boutek intends conducting a further research programme among the communities in order to scientifically establish whether there is indeed any connection between literacy and proper operation of the toilet units.

9.5 CONSTRUCTION AND HAND-OVER

9.5.1 The construction process

While very little in the way of building skills existed in the villages, the communities nevertheless offered to assist the builders appointed by ECATU wherever they were able to do so. This assistance generally took the form of helping with foundation excavations, mixing mortar and similar unskilled jobs. The standard of workmanship of the builders was initially very poor, and became a source of great frustration to the author. It quickly became clear that the problem of the dearth of experienced builders in the area was being seriously compounded by a lack of supervisory skills and capacity within ECATU. The result was that more trips to Umtata to inspect the progress of the work, as well as to offer general advice and assistance, had to be undertaken by the author. The initial project planning as regards timing of the various phases of the work was eventually discarded as worthless, and the author resorted (in desperation) to appeals to ECATU's top management to provide better staff and more commitment. These appeals were of necessity couched in terms which were actually thinly-veiled threats that Boutek would withdraw from the project, as the CSIR was not prepared to put its name to a scheme which was likely to become an embarrassment for all concerned. In addition to this cajoling, the author spent a great deal of time (far more than was initially thought necessary) in visiting all the building sites and pointing out simple and avoidable building errors and unacceptable quality of work.

Most of the problems, which could have been avoided through adequate supervision, were either overlooked or simply ignored, and were only attended to when the author demanded their rectification. As the building work progressed, however, the quality improved somewhat, because the builders came to understand what was required of them. By the time the first phase of 15 units had been completed, the builders had gained a lot of experience; this facilitated the progress of the second phase considerably, although quality still had to be carefully monitored.

As a result of the building problems experienced, as well as ECATU's lack of capacity, only two of the three phases had been completed at the time of writing, i.e. a total of 30 toilet units. Figure 9.9 illustrates various aspects of the completed units.

9.5.2 Handing over of completed units

On 31 July 1998 a large function was arranged at Sinyondweni School by the local communities to celebrate the completion of the first phase of the project. The occasion was marked with much pomp and ceremony, with many delegates from provincial government and semi-government institutions being invited. Speeches were given by

ECATU and various dignitaries, with the author also being required to make a speech on behalf of CSIR. The local schoolchildren entertained the dignitaries with song and dance, after which refreshments and a meal were served.

One of the toilet units at Sinyondweni was designated to represent the official opening of phase 1. A ribbon was tied around it and one of the dignitaries officially cut the ribbon and handed the keys of the toilet over to the proud owner.

Phase 2 was only completed in June 1999. The units were handed over to their owners as soon as they were completed.

(a) (b)

Figure 9.9: The completed toilet units.
(a) Front view; (b) rear view.

(c)

(d)

Figure 9.9 (cont): The completed toilet units.
(c) The ferrocement hand washing tank and urine drainage pipes from the urinal and pedestal.
(d) Resident illustrating the use of the hand washing tank. The small hole releases a thin stream of water out of the tank and is closed off with a twig.

Figure 9.9 (cont): The completed toilet units.

(e) An improved (and cheaper) hand washing arrangement incorporated into phase 2 units: the water is released and shut off by a simple nipple-type valve underneath the plastic container.

9.6 MONITORING OF PATHOGEN DESTRUCTION

9.6.1 Introduction

Chapter 8.3 sets out some health aspects of excreta reuse. Figure 8.11 in particular illustrates the importance of time and temperature in pathogen destruction. Because of the promotion of urine diversion technology as environmentally friendly sanitation, with the advantages of reusing the desiccated faeces as soil conditioner, it was considered essential to quantify the health aspects of handling the product under typical South African conditions. Obviously this single project is not regarded as being representative of all South African conditions, but it nevertheless does illustrate circumstances in a fairly wide range of climatic conditions. Summers in Umtata are mostly hot and humid, with a fairly high rainfall, while the winters may be extremely cold. When further projects are implemented in other areas, this aspect should be researched at the same time, in order to build up a reliable database of pathogen destruction conditions in the country as a whole.

Accordingly, samples were extracted from various toilet units at certain times (Figure 9.10). These were subjected to microbiological testing in the laboratories of the CSIR Division of Water, Environment and Forestry Technology (Environmentek) in Pretoria.

Figure 9.10: Extracting samples from the faeces containers for laboratory testing.

9.6.2 Results of microbiological tests

Table 9.1 indicates the results obtained from the microbiological tests on the desiccated faeces samples, while Table 9.2 shows comparative values in the natural soil around toilet unit E.

Notes on the use of indicator organisms:

It is impossible to test for all the possible organisms which could present a health risk. Indicator organisms are therefore used to give a general indication of water or effluent quality. No organism or group of organisms meets all these criteria, but the "coliform group" of organisms fulfills most of them. This group comprises organisms such as *Escherichia coli*, *Klebsiella pneumoniae* and *Enterobacter aerogenes*. *E.coli* are commonly found in the human intestine, but only some of them are pathogenic.

While coliforms are not an ideal indicator, they are still the most reliable indicators of the presence of faecal pollution. Faecal coliforms are indicative of faeces of warn-blooded animals, but do not distinguish between human and animal faecal contamination.

Faecal streptococci in water or effluent indicate faecal pollution and refer to those streptococci commonly found in human and animal faeces. They are useful as a supplementary bacteriological indicator and in locating the origin of faecal contamination in polluted water (the ratio of faecal coliform organisms to faecal streptococci is greater than 3:1 for human waste and smaller than 0,7:1 for animal waste). Faecal streptococci are usually more resistant to unfavourable environmental conditions than faecal coliforms.

The heterotrophic plate count is an additional screening step and is useful for monitoring changes in the bacteriological quality of water.

A coliphage is a virus hosting on the coliform bacteria. Coliphages have similar survival patterns as enteric viruses during water purification processes and although they do not provide an absolute indication of the presence of enteric viruses in all conditions, they may provide an acceptable indication of the presence of viruses in general.

The principal pathogenic parasites, protozoa and worms that may escape sanitary barriers in public water supplies include *Giardia* cysts and *Cryptosporidium* oocysts. These worms, cysts and oocysts are hardy; for example, they are not completely destroyed by chlorination, and require sedimentation and filtration.

The following guideline values do not relate to any standards for the desiccated sludge samples extracted from the toilet units, but are given for comparative purposes only, in order to facilitate an understanding of the degree of pollution of the various samples described. The symbol D indicates drinking water according to SABS 241:1984, while the symbol R indicates recreational water.

Indicator	Recommended limit	Max permissible limit
Heterotrophic plate count (D)	100 colonies per mℓ	not specified
Total coliforms (D)	0 per 100 mℓ	5 per 100 mℓ
Faecal coliforms (D)	0 per 100 mℓ	0 per 100 mℓ
Faecal streptococci (R)	40* per 100 mℓ	not specified
Coliphages (R)	50* per 100 mℓ; or 500** per 100 mℓ	not specified

* in 50 % of samples
** in 99 % of samples

9.6.3 Discussion of results

Unit E was always seen to have a higher moisture content in the faeces receptacle, usually due to insufficient ash being added. This was one of the units in Gwebinkundla where repeated visits were found to be necessary in order to monitor operation. It is seen that coliforms and coliphages are more viable at higher moisture contents.

The lack of parasites, especially Giardia, is somewhat surprising, as these organisms are often found in the water sources of poor communities.

The microbial population, with the exception of the heterotrophic plate counts, generally shows a good reduction over the sampling period. Temperatures measured in the faeces piles were never higher than 23 °C, however, and it is therefore only as a result of the passage of time, and not because of heat, that the pathogen destruction took place. It is surmised that the reason for this was that the piles were generally anaerobic, as the ash which was added was very fine, which therefore did not "bulk" the mixture and aerate it. Further experimentation with a coarser type of material needs to be carried out in order to determine the best method of keeping the pile aerobic, which would lead to higher temperatures. It may be necessary to turn the pile occasionally.

The heterotrophic plate count shows an increase over time. This is to be expected, as there are more nutrients available, in the form of rotten organic matter, for the bacteria to feed on. Bacteria multiply easily, and are not necessarily pathogenic.

The best results were repeatedly shown in unit C. This unit is in Sinyondweni, and is extremely well maintained, with the family showing the most commitment to the proper usage of the toilet.

The relatively high pH values recorded play an important role in pathogen die-off.

Table 9.2 reveals that even natural soil may have a relatively high microbial count, which may be due to bird droppings, cattle dung, worm castings, etc. Normal precautionary hygiene principles therefore also need to be observed after working with soil.

Table 9.1: Analytical results of laboratory testing

(Toilet units commissioned at the beginning of August 1998)

(a) Sample date: 4 February 1999 (± 6 months)

Sample ref	Heterotrophic plate count (per gram)	Total coliforms (per gram)	Faecal coliforms (per gram)	Faecal streptococci (per gram)	Sal-monella	Clos-tridia	Coli-phages (per gram)	Giardia cysts	Crypto-sporidium oocysts	Percent moisture	pH
A	60 x 10^6	50 x 10^4	15 x 10^2	47 x 10^2	+	+	300	ND	ND	22	
B	86 x 10^7	65 x 10^4	41 x 10^3	23 x 10^4	+	+	45 x 10^3	ND	ND	19	
C	80 x 10^5	165	115	655	+	+	600	ND	ND	35	
D	60 x 10^7	78 x 10^4	20 x 10^4	22 x 10^4	+	+	22 x 10^3	ND	ND	28	
E	26 x 10^7	48 x 10^6	33 x 10^6	13 x 10^5	+	+	75 x 10^4	ND	ND	60	

(b) Sample date: 9 June 1999 (± 10 months)

Sample ref	Heterotrophic plate count (per gram)	Total coliforms (per gram)	Faecal coliforms (per gram)	Faecal streptococci (per gram)	Sal-monella	Clos-tridia	Coli-phages (per gram)	Giardia cysts	Crypto-sporidium oocysts	Percent moisture	pH
A	14 x 10^8	24 x 10^2	25 x 10^2	40 x 10^2	+	+	0	ND	ND	11	9,4
B	29 x 10^8	12 x 10^4	18 x 10^3	13 x 10^3	+	+	200	ND	ND	15	8,6
C	64 x 10^7	52	0	14	+	+	0	ND	ND	21	9,6
D	11 x 10^8	98 x 10^2	10 x 10^2	69 x 10^2	+	+	45	ND	ND	4	9,2
E	19 x 10^8	11 x 10^6	55 x 10^5	11 x 10^4	+	+	14 x 10^3	ND	ND	40	9,4

Table 9.2: Analysis of natural soil around toilet unit E (sample date 9 June 1999)

Sample ref	Heterotrophic plate count (per gram)	Total coliforms (per gram)	Faecal coliforms (per gram)	Faecal streptococci (per gram)	Sal-monella	Clos-tridia	Coli-phages (per gram)	Giardia cysts	Crypto-sporidium oocysts	Percent moisture	pH
E	76 x 10^4	19 x 10^2	41	15	+	+	0	ND	ND		

\+ = "too high to count"
ND = "not detected"

9.7 RESEARCH CURRENTLY IN PROGRESS

9.7.1 Introduction

There are two main aspects of this project which are either currently being researched, or are scheduled for research in the near future. It is therefore not possible to include these ongoing research results in this dissertation, other than some preliminary observations and tentative conclusions. However, it is intended to publish these results as they become available, and also to include guidelines for implementing the technology in the Red Book.

9.7.2 Pathogen destruction

Although relatively good pathogen die-off was experienced, the faeces pile did not heat up as much as was expected or hoped. As already mentioned, it is thought that this may be as a result of the pile being anaerobic. It is therefore necessary to examine other options to increase the heat generated in the pile, and thereby speed up the process of pathogen destruction.

Experiments are currently being planned to let the faeces collect on the floor of the rear compartment instead of in a receptacle, so that the pile may be easily raked and turned with simple hand tools. It is expected that this action will contribute to the aeration of the pile and thus the heat generated, which in turn will accelerate the pace of pathogen destruction. The use of other mixing materials besides ash, for example coarse soil, will also be examined.

In the meantime, however, it has been possible to conduct a simple experiment to test the effect of increased aeration, temperature and desiccation on the rate of pathogen destruction. A sample of the faeces pile in unit E (the unit with generally the poorest results) was subjected to air drying and heat (sunshine) on the roof of Boutek's building. This was carried out in the middle of winter (July 1999) and the sample was therefore brought indoors at night. Temperature measurements were observed at 14:00 on certain days over this period. The ambient temperature varied between about 15 °C and 30 °C, while the temperature in the pile reached a maximum of 40 °C for a short time, but usually remained only a few degrees warmer than the ambient value (mostly due to the effect of cold winds).

The sample was tested after this period, with the following results:

Table 9.3: Sun-dried sample from unit E

Heterotrophic plate count (per gram)	Total coliforms (per gram)	Faecal coliforms (per gram)	Faecal streptococci (per gram)	Salmonella	Clostridia	Coliphages (per gram)	% mois t-ure
42×10^5	38×10^4	310	11×10^5	+	+	5	1,4

Discussion:

- The vast resistance of faecal streptococci towards unfavourable environmental conditions is evident.
- The other indicators, when compared with the previous results, show a reduction of around two to three orders of magnitude as a result of exposure to sunshine.
- It is likely that a higher rate of pathogen destruction will occur during the hot summer months.

Clearly, more research is needed on methods to increase the rate of pathogen destruction if it is intended to handle the desiccated faeces and use them for agricultural purposes. Alternatively, a longer storage period is required.

9.7.3 Community acceptance of the technology

Part of the follow-up research work planned in the near future is to conduct a thorough survey among the project participants in order to establish the general acceptability of this sanitation technology. Preliminary observations have indicated a very good acceptance, but in order to produce a sound, scientific treatise on the subject, it will be necessary to conduct a knowledge, attitude and practices (KAP) survey. This type of survey takes cognisance of various factors such as income level, literacy level, hygiene practices, attitude towards hygiene practices, acceptance of unfamiliar technologies, sanitation as a need, etc. In other words, the survey is not merely technology based. In this way, a good indication can be obtained of how the technology fits in with a specific culture.

9.7.4 A few preliminary observations

In general, the attitude of the residents towards the technology has been very positive. Many have stated that the new toilets are much better than pit toilets, or even VIP toilets. The lack of odours and flies, as well as the ease of maintenance, are particularly appreciated, while the secondary advantage of having a free agricultural resource available is welcomed by some people.

CHAPTER 10

SUMMARY AND CONCLUSIONS

> "Furthermore, my child, you must realise that writing books involves endless hard work, and that much study wearies the body."
>
> Ecclesiastes 12 : 12

CHAPTER 10: SUMMARY AND CONCLUSIONS

10.1 SANITATION – GENERAL ASPECTS DISCUSSED

A broad-based, yet fairly comprehensive, background to the general sanitation situation in South Africa and the developing world has been presented in this dissertation, with particular emphasis on the poorer population groups. It has been shown that existing systems and available resources are inadequate to deal with the serious problems which exist, and that the situation will not improve unless there is a significant change in the manner in which sanitation systems are chosen, designed and implemented.

Vast amounts of improperly-managed faeces and untreated sewage contaminate the living environments of millions of people worldwide. These environmental problems, in turn, undermine the process of development.

The myth that the only good sanitation technology in urban areas is waterborne sewerage is a factor which actually constrains the provision of efficient sanitation. While this technology has been widely successful in controlling the transmission of excreta-related diseases in most cities of industrialised countries, it has also created severe damage to ecosystems and natural water resources where the wastewater has been inadequately treated. It has furthermore been shown to be an unsustainable technology in many Third World cities where the required institutional capacity and skills are often lacking.

A large number of diseases are spread directly through contact with human excrement, indirectly via water, food and soil, or via carriers and vectors like flies, cockroaches and mosquitoes. The inability of existing sanitation systems to manage adequately the increasing volumes of human excreta is the main cause of the high incidence of infectious diseases in developing countries.

In many urban centres poorest groups face the most serious environmental hazards and the least possibility of avoiding them. The rapid population growth is furthermore putting severe strains on the water supply and sanitation services of the urban areas in developing countries. In Africa especially, lack of access to basic water supply and sanitation services lies at the root of many of the current health, environmental, social, economic and political problems.

The excreta of most urban dwellers in developing countries are disposed of through on-site sanitation systems such as pit toilets and septic tanks. A major problem which results is that faecal sludges collected from these systems are commonly disposed of untreated. The problem is growing, and over the next few decades most Third World urban growth will take place in peri-urban areas without access to basic services.

Very little progress has been made in improving sanitary conditions for much of the world's population. Without major changes in delivery mechanisms, the number of people without access to sanitary excreta management will remain above 3 000 million people, and mankind will not make any headway in its ability to dispose of wastes in a healthy, safe and ecologically sound manner. A revolution in thought and action is required – it is necessary to define principles, make priorities, create strategies and search for new technological, financial and institutional solutions.

In many of the developing regions, squatter areas and informal settlements of South Africa, the situation is much the same as in other poor regions of Africa and the world. Vast urban and peri-urban slums exist with no provision for excreta management of any kind, formal or informal. The situation is not confined to urban areas, however: the majority of rural households, schools and even clinics are also without adequate sanitation. An estimated 21 million South Africans, the vast majority belonging to the poorer sections of the population, do not have proper sanitation facilities.

The core problem in South Africa remains the fact that preventable diarrhoeal diseases continue, particularly in young children. The problem is related to socio-cultural, educational and institutional issues, with the lack of appropriate facilities and inadequate guidelines being a contributory factor. New approaches need to be initiated, and technologies which support alternative sanitation efforts should be developed. Sanitation is not simply a matter of providing toilets, but rather an integrated approach which encompasses institutional and organisational frameworks, as well as financial, technical, environmental, social and educational considerations. Because water supply and sanitation are both inextricably linked to the broader development process, the question of sanitation needs to be seen in the context of an integrated development strategy.

It has been shown that sanitation is an extremely complex issue, and that there is no single solution which can be universally applied to solve the problem. Improved sanitation is a **process**, and people must be seriously consulted and involved in sanitation programmes, from planning to implementation and follow-up. Innovative, low-cost sanitation facilities are needed, and it is wrong to promote one or two technologies as "the solution". More research and better designs are needed, in order to develop a range of systems applicable to differing cultural and environmental conditions.

Sanitation approaches based on flush toilets, sewers and central treatment plants cannot solve the problem. Pit toilets or septic tanks with soakpits are also not the solution in high-density urban areas. Certainly, "conventional" sanitation options may be suited to certain conditions. However, with the continuous growth of urban populations and the high incidence of low-income people living in slums and peri-urban squatter areas, there is no possibility of successfully increasing the overall sanitation coverage by these methods.

Sanitation systems must be appropriate for a particular project and circumstances. It has been shown that the appropriateness of a sanitation system depends on a number of circumstances, with the actual technology itself being, in most cases, less important than the socio-cultural factors involved. It is therefore important to look beyond the current restrictions for innovative ways and means of bringing adequate sanitation to the millions of people currently without access to this basic human right. Research and development for a wide range of cultural and environmental conditions is required, and a demand for systems which reuse or recycle human excreta should be created. Dependence on systems which use large amounts of potable water should be reduced, and systems should be promoted which are simple, reliable and easily maintained.

Excreta disposal, especially in rural areas, is far more complex socially than it is technically, and the introduction of on-site sanitation systems involves much more than the application of simple engineering techniques – it is an intervention that entails considerable social change. It is therefore necessary to understand how a society functions, including the communities and households within it, before embarking on a sanitation programme. Social issues have been shown to influence the choice of technology, and personal cleansing practices have direct technical consequences which have to be considered by the engineer.

It is essential that sanitation projects are not focused on purely numerical targets (i.e. how many toilet units have been built) but on ensuring that the projects are sustainable, and that the people are empowered with the necessary information and sense of ownership to effectively use and manage the facilities. Sanitation efforts must therefore incorporate more participatory methods. The development of a hygiene education strategy, in which women are included in the whole process of behavioural change, has a major impact on the sustainability of a project.

The choice of a sanitation technology is also heavily influenced by the type of institutional setup for delivery, operation and maintenance. All systems require a certain amount of institutional support, with the more complex technologies necessitating a level of funding and skills which may not be available in, for instance, rural areas. Due to the different stages of local government development in South Africa, institutional arrangements will vary in several ways, depending on the type of area involved. Operation and maintenance aspects play a major role in the success or failure of a sanitation project. Particularly in poor communities, it is essential to install robust, low-maintenance systems, where the total life-cycle costs are minimised without the environment being compromised in any way.

This dissertation has described the development of two new approaches to sanitation provision in which operation and maintenance aspects are greatly simplified. The first represents an improvement on an ordinary settled sewage scheme, which is a wet system, and the second an alternative to a VIP toilet, which is a dry system. A common problem associated with both of these existing technologies, as indeed it is with all on-site systems, is the removal and disposal of accumulated sludge and liquid effluent in a manner which is safe for humans and which does not put the environment at risk. It has been shown how the proposed technologies resolve this problem. The first method automatically flushes the sludge out of the interceptor tank and into the effluent pipeline, while the second avoids the need for a pit and dehydrates the faeces pile in an easily accessible compartment beneath the toilet pedestal, producing a product quite unlike pit toilet sludge. The difference is largely due to the fact that urine is not added to the faeces pile, but is diverted at source, thus keeping the pile relatively dry and assisting in the destruction of pathogenic organisms, as well as preventing the leaching of disease-carrying liquids into the surrounding ground.

The development of these two technologies, and the promotion of their use in South Africa, is likely to enhance the status of on-site sanitation systems. In some instances, on-site systems are regarded as inferior technologies because of the operation and maintenance aspects (for example sludge removal) associated with them.

10.2 THE "SLUDGE SIPHON" SELF-CLEANSING INTERCEPTOR TANK FOR SETTLED SEWAGE SYSTEMS

Septic tank technology which includes soakpits is well established virtually everywhere in the world. Settled sewage systems which reticulate the septic tank effluent for further treatment to off-site locations are less common, however. Most development has taken place in the United States, Australia and a few African countries, with South Africa being a relatively late starter some ten years ago. The operation of these systems has been described in this dissertation, and the principal advantage of soakpits not being required was emphasised. This has major environmental benefits, especially in densely populated urban areas, or where unfavourable geotechnical or geohydrological conditions are present. The major disadvantage has been shown to be the necessity for periodic desludging of the interceptor tanks. This is an unpleasant and sometimes difficult task to perform, which may even be impossible where access to the tanks is restricted.

Interceptor tanks in a settled sewage system must be designed to cater for various functions, namely solids interception, digestion of settled solids, and storage of digested solids. The rate of sludge accumulation depends on factors such as ambient temperature, living standard, diet, health of users, their occupations and working conditions, etc. Interceptor tanks are usually designed so that up to two-thirds of the volume may be taken up by digested solids (sludge), so the longer the anticipated interval between desludgings, the larger the tank has to be to cater for this. This is associated with an increase in capital costs, not only for the tank itself but also for labour and excavation. Consideration of these cost factors, as well as the problems involved in desludging of tanks, led the author to the conceptualisation and development of the "sludge siphon" as a solution.

Due to the fact that the sludge extracted from the interceptor tanks is usually deposited either in a nearby sewer manhole, or transported directly to the municipal sewage treatment works, the sludge eventually ends up in the municipal wastewater system in any case. The "sludge siphon" system eliminates the need for vacuum tankers and maintenance crews to physically empty an interceptor tank by siphoning the accumulated sludge out of the tank and flushing it, together with the normal effluent, into the settled sewage reticulation system. Once it has entered the pipeline, the sludge from a whole suburb or village can be hydraulically transported for an as yet undetermined distance, and can therefore either be taken to a single easily-accessible settling tank for uncomplicated collection, or perhaps even be transported all the way to a treatment works, where the sludge can be handled in the conventional manner.

Due to the fact that the sludge is automatically removed from the interceptor tank without intervention by a maintenance crew and without conscious thought by the householder, and then transported for some distance along the settled sewage pipe network, many savings can be achieved by both the householder and the local authority. There will be a vastly reduced need for vacuum tankers to gain access to individual interceptor tanks, so poor roads or densely built-up areas will be a lesser problem. Tanker fleets can be decreased and the operation and maintenance costs of a settled sewage scheme drastically reduced, with concomitant benefits for society.

It is thus seen that settled sewage schemes incorporating "sludge siphon" systems in the interceptor tanks result in savings in both initial capital costs as well as operational costs.

The concept of the "sludge siphon" is based upon the arrangement of the interceptor tank's outlet pipe in the form of a natural siphon. This siphon is activated by a rapid inflow of wastewater from either a washtub or a bath, with a certain minimum flow volume being required. The sludge siphon is suited to either an outside flushing toilet connected to a settled sewage system (the lowest level of service for which it is possible to operate the siphon) or a house with full water connections (highest level of service). The functioning of the siphon has been illustrated by Bernoulli's energy equation, which shows that the negative (gauge) pressure at the summit is responsible for its successful operation. Due to the low specific gravity of the sludge particles, they are easily kept in suspension by the effluent passing through the outlet siphon, and thus readily transported along the pipeline for as long as there is a sufficient volume of flow.

Initial experimentation was carried out in the laboratory, and was aimed at developing a method to initiate the flush by the simple addition of a quantity of water to the tank in which the siphon was installed. The method eventually perfected was based on, firstly, eliminating the inhibiting effect of the air bubble which formed naturally at the apex of the siphon, and secondly, reducing the volume of water needed to activate the flush. Once these problems had been overcome, experimentation was continued using sawdust to simulate digested sludge. It was found that the siphon intake did not extract the settled sawdust effectively and had to be modified in order to do so. A manifold-type of inlet with multiple inlet ports was then developed, which carried out the job successfully. Thereafter, actual septic tank sludge was used for further experimental work.

The physical properties of typical domestic septic tank sludge were analysed. Two sources of sludge were investigated, namely a middle income family and a poor community. As expected, it was found that the sludge emanating from the poor community's septic tank contained a much larger proportion of inorganic elements and dried solids, and the mean particle size was also considerably greater. This is generally due to the fact that poor communities often use sand and grit to scour pots and pans, and may also have more dirt particles in their clothing, which then end up in the wastewater. Scanning electron microscopy results showed further that the inorganic particles in sludge are so small, and the density so close to that of water, that the flow containing the particles is in all probability pseudohomogenous, with the mixture being of the non-settling type. The wide variety of particle shapes and sizes also indicated that very little of the work done to date on sediment transport theory and experimentation is actually applicable to the hydraulic transportation of septic tank sludge.

The siphon could be activated with a flow of about 21 litres of wastewater from the washtub. It was later possible to reduce this amount to about 16 litres by improving the design of the inlet compartment of the siphon. Flow behaviour was much as expected in terms of volume and velocity – the rate of flow became progressively less as the available head in the tank decreased, but there was no visible lessening of the sediment-carrying ability of the flow for the full duration of the siphon activation, even with a relatively small available head.

After successfully concluding the laboratory experimentation, the project team developed a prototype model of the sludge siphon system for installation under actual operating conditions on the CSIR campus at Scientia. The system was connected to the creche's outfall sewer, the flow being diverted through the tank which then operated as a conventional interceptor tank in a settled sewage system. The effluent outflow pipeline, with transparent sections to facilitate observation of the flow, was arranged in a zigzag pattern in order to produce friction losses at bends. The pipeline was laid above ground on adjustable supports, which facilitated the arrangement of different gradients for testing purposes. This included sections with a negative gradient in order to produce pressure flow, which is often a feature of settled sewage schemes. The siphon was activated by water flowing from a washtub installed near the tank, and this setup was used for further experimentation.

Various hydraulic and other factors which were thought may effect the performance of the system were then tested:

- Normally, the sludge equilibrium level would be at the height of the manifold ports. The sludge level was allowed to build up to about 150 mm above the level of the grille over the manifold, with insufficient retention time for full digestion to take place. The sludge thus contained small undegraded pieces of paper, food scraps and faeces. This did not result in any visible deterioration in the operation of the siphon, nor in the sludge-carrying ability of the flowing effluent. However, when the tank was hydraulically and biologically overloaded by increasing the wastewater inflow and being fed with materials such as large wads of paper towelling, sanitary pads, etc, the grille became blocked and whatever sludge formed was prevented from entering the manifold ports and being flushed out of the tank. This served to reinforce the fact that a sludge siphon sanitation system should be operated and cared for in the same manner as a conventional septic tank, where no problems are experienced if normal precautions are observed.
- Negative gradients were introduced into the effluent pipeline, which resulted in a "dam" of septage collecting at low points after normal flow had ceased. With subsequent flushes, the inertia of this standing septage had to be overcome before normal pipe flow could resume. This in turn caused a delay in activation of the flush, as more water was forced into the main chamber of the tank before

the water in the siphon could attain uniform flow. Additional water was then needed to activate the flush than what was normally the case – usually about 25 ℓ instead of the usual 16 ℓ. It was found by experimentation that, as long as a minimum distance of 12 m was maintained between the tank outlet and the first section of inverse pipe gradient, the siphon was able to activate normally and the energy of the full pipeline flow was sufficient to overcome the resistance of the standing septage.

- Tests were carried out to determine the effect of distance between the washtub (which activated the flush) and the tank. These were performed for varying horisontal as well as vertical distances. It is essential that the incoming wastewater enters the siphon compartment of the tank as rapidly as possible, otherwise the siphon will not activate at all or will require a greater volume of influent in order to do so. It was found that, at the shortest horisontal distance of 1,5 m between the washtub and the tank, a volume of only 16 ℓ was required to initiate the flush, while between 1,5 m and 6 m a volume of 25 ℓ was needed. At a distance of 7 m and beyond, a minimum of 35 ℓ had to be fed into the tank before the siphon activated. Vertically, it was found that raising the washtub higher than a nominal 950 mm above the crown of the siphon also resulted in additional water being required to initiate the flush. A volume of about 25 ℓ was needed in this case. This volume was thus adopted as the minimum required in order to ensure effective operation of the siphon, and the tank should be buried as close as possible to the plumbing fixture which activates the siphon. These results have been included in the guidelines in Appendix A.

10.3 URINE DIVERSION SANITATION SYSTEMS

The shortcomings of VIP toilets, particularly in high-density urban areas, have been explained. Apart from the obvious problems such as excavation of pits in difficult ground, negative factors are also to be found in operation and maintenance aspects, social perceptions and poor institutional support capacity. To address these shortcomings, it has been necessary to think beyond the limitations imposed by traditional methods of providing dry sanitation. This need has been substantiated by increasing awareness worldwide of the environmental issues associated with sanitation. Furthermore, pressure on land to produce more food to feed the ever-growing populations of developing countries has made it imperative to utilise natural resources, including human excreta, wherever possible. The concept of ecological sanitation, or "eco-san" as it is also known, is seen as an alternative solution to some of the problems associated with pit toilets, environmental degradation and food shortages.

Ecological sanitation systems are presently neither widely known nor well understood. They cannot be replicated without a clear understanding of how they function and how they can malfunction. However, long term economic factors are an attractive feature of these systems, for the following reasons:

- the entire structure is built above ground – there is thus no need for expensive digging and lining of pits;
- urine is diverted, no water is used for flushing and the volume of the processing vault is fairly small, as it is emptied periodically;
- emptying of the processing vault is easily carried out and does not require expensive equipment; and
- the contents of the processing vault are dry, which means that there is no need for expensive watertight construction methods.

The introduction of eco-san systems is thus bound to lower the total costs of urban sanitation in particular. This is an important consideration, especially for developing countries where public institutions have stringent financial limits.

It has also been shown that human excreta should not be regarded as a waste product, but rather as a valuable resource, as it (urine in particular) contains high percentages of plant nutrients such as nitrogen, phosphorus and potassium, with the added advantage of an organic fraction as well. The annual excretion of these plant nutrients by humans is enough to produce the 230 kg of crops they need each year, with an efficacy almost as good as, and in some cases better than, conventional chemical fertilisers. There are many reasons for recycling the nutrients in excreta. Recycling prevents direct pollution caused by sewage being discharged or seeping into water resources and ecosystems. A secondary benefit is that recycling returns nutrients to soil and plants, and reduces the need for chemical fertilisers. It restores good soil organisms to protect plants, and it is always available locally, wherever people live.

Examples of excreta reuse from many countries have been cited. In some countries the practice has been carried out for centuries, while in others it is a comparatively recent phenomenon. The benefits of this practice for subsistence farmers in particular has been pointed out.

Health aspects of excreta reuse have been dealt with in some detail, and it was seen that the health hazards associated with this practice are of two kinds: the occupational hazard to those who handle excreta, and the risk that contaminated products from reuse may subsequently infect humans or animals through consumption or handling. The main pathogenic organisms of interest in sanitation are viruses, bacteria, protozoa and helminths (worms). There are a number of different varieties of all these organisms. In developing countries especially, excreta-related diseases are very common, and the excreta contain high concentrations of pathogens that cause diseases in man. Sanitation systems designed for reuse of the excreta thus pose a special challenge to the engineer to design and develop technologies that will not pose unacceptable risks to public health.

As the death or survival of excreted pathogens is an important factor influencing transmission, these organisms need to be either destroyed or otherwise rendered harmless. Environmental factors of importance in the die-off rate of pathogens are high temperatures, low moisture contents and time. A high temperature, especially, is the most important consideration, as all living organisms, from the simplest to the most complex, can survive at temperatures only up to a certain level. Regarding moisture content, biological activity becomes severely restricted at moisture contents less than about 35 %, while pH is another important controlling factor, with a value above about 9 generally being lethal to most pathogenic organisms.

Some examples of urine diversion sanitation technology, as applied in various parts of the world, have been described. A common feature of the various examples was seen to be the ease of excreta disposal and the many possibilities for its reuse. The critical distinctions between desiccation, or dehydration, and composting were also explained, the chief variation being the difference in moisture content of the faeces pile. For desiccation to occur effectively, the diversion and separate processing of urine is imperative, except in very dry climates.

The basic requirement of a urine diversion sanitation system is a toilet pedestal (or squatting plate) which prevents urine and faeces from being mixed together. In the dry-box version, small amounts of ash, dry soil or sawdust are sprinkled on the faeces after each bowel movement; this serves to absorb the moisture which is an inherent part of fresh faeces and thus also to prevent odours. It is essential that the excreta remains as dry as possible and that moisture is prevented from entering the waste compartment. Paper and other material used for personal cleansing are not deposited in the receptacle but are stored in a separate container and disposed of by burning or burial. The urine can be collected in any suitable sealed container if its reuse for agricultural fertilizer is desired. Alternatively, it can be led into a soakpit. In the flushing version, the urine may be collected and stored in the same way, while the faeces are usually flushed into a conventional sewer system for further treatment.

A pilot urine diversion sanitation project in three rural villages near Umtata, Eastern Cape, was carried out by Boutek and the Eastern Cape Appropriate Technology Unit (ECATU). Boutek directed the engineering and social research while ECATU was responsible for the financial and construction aspects (the latter also under Boutek's supervision). The original intention was to build a total of 45 toilet units over a two-year period (15 units in each village). Due to capacity problems within ECATU, however, only 30 units were built during this time. The villages selected were Manyosini, Sinyondweni and Gwebinkundla, all in rural settings and with the same rolling topography and clayey soil. The residents of these villages were generally very poor, and availability of water was a major problem. The few toilets that existed were ordinary pit latrines, mostly in a very poor and unsanitary condition. Residents generally relieved themselves in the veld, and the level of personal hygiene was observed to be low.

Boutek's first task was for the author and an anthropologist (social scientist) to familiarise themselves with the physical layout of the villages, as well as the social structure and dynamics existing within the communities. Although the people were all Xhosas, each community had its own distinct characteristics, beliefs and behaviour. The proposed pilot project was thoroughly discussed with the residents and the basic aspects of the technology explained. While there were some sceptics who eventually decided not to participate further, the overall result of the introductory talks was generally positive. Most of the residents were generally quick to see that the proposed toilet systems, while being somewhat strange to them, were in actual fact superior to pit toilets in many respects.

Cultural taboos and beliefs which needed to be addressed during the implementation of the project were also discussed at this time. These included matters such as the disposal of personal cleansing materials, the collection and reuse (or disposal) of excreta, and various social issues affecting traditional family life in the various communities. Building options such as type of bricks, colour of paint, etc were further matters that required clarification and agreement.

The design of the toilet units was undertaken by Boutek. The author personally researched and designed the urine diversion pedestals, which were then fabricated by a plastics manufacturer in Pretoria and delivered to ECATU for installation in the completed structures.

For this sanitation project to be sustainable, and to uplift the standard of living of the communities, it was essential for the people to understand that the provision of proper sanitation facilities had to necessarily go hand in hand with an improvement in their personal hygiene habits. Accordingly, Boutek's social scientist prepared a hygiene awareness training guide which was implemented by ECATU's social researcher. This consisted generally of details such as proper operation and maintenance of the toilets, the importance of personal cleanliness, the link between hygiene and sanitation-related diseases, etc. Generally speaking, the hygiene awareness training proved to be successful, with only a few families needing repeat visits to ensure proper compliance with operational requirements.

Very little in the way of building skills existed in the villages, and the standard of workmanship was initially very poor. Compounding this problem was a lack of supervisory skills and capacity within ECATU. The result was that the author was required to spend a great deal of time (far more than was initially thought necessary) in visiting all the building sites and pointing out simple and avoidable building errors and unacceptable quality of work. As the building work progressed, however, the quality improved somewhat as the builders came to understand what was required of them.

After the owners had taken possession of their new toilets, the research project entered a very important phase. This was the monitoring of pathogen destruction in the faeces pile. Because of the promotion of urine diversion technology as environmentally friendly sanitation, with the advantages of reusing the desiccated faeces as soil conditioner, it was essential to quantify the health aspects of handling the product. Accordingly, samples were extracted from randomly selected toilet units at certain times, which were then subjected to microbiological testing at CSIR's laboratories in Pretoria. The results of the testing showed, inter alia, the following:

- Coliforms and coliphages are more viable in higher moisture contents.
- The microbial population generally displayed a good reduction over the sampling period. However, due to the relatively low temperatures experienced, this was due more to the passage of time rather than to heat.
- The low temperatures recorded in the faeces piles are thought to be due to conditions being anaerobic. It may be necessary to turn the pile occasionally in order to obtain aerobic conditions, which should then lead to higher temperatures and thus more rapid destruction of pathogens.
- The relatively high pH values (caused by the addition of ash) played an important role in pathogen die-off.

In general, the attitude of the residents towards the technology has been very positive. The lack of odours and flies, as well as the ease of maintenance, are particularly appreciated, while the secondary advantage of having a free agricultural resource available is welcomed by some.

10.4 CONCLUDING REMARKS

The majority of sanitation problems cannot be solved by the application of conventional engineering technologies. It is necessary to recognise toilets as being consumer products, which are subject to personal and community preferences. On-site technologies have, in many instances, been regarded as inferior or second-rate, often due to the operation and maintenance factors involved. While being true in certain cases, this is actually an incorrect generalisation. Some on-site technologies are able to offer a level of service very close to full waterborne sewerage, and for many poor communities especially, even a simple sanitation device is certainly a vast improvement to relieving onself in the veld.

The research and development of alternative on-site sanitation technologies described in this dissertation was aimed principally at tackling the most common operational problem associated with these systems, namely sludge disposal. Other benefits which accrue due to the application of these new technologies, for example certain environmental improvements, easy and safe reuse of excreta, or lower capital and operational costs, are additional advantages. By offering improved sanitation methods which reduce the operation and maintenance burdens on both users and local authorities, it is believed that a significant contribution has been made to improving the quality of human life across all sectors of society.

CHAPTER 11

RECOMMENDATIONS FOR FURTHER RESEARCH

CHAPTER 11: RECOMMENDATIONS FOR FURTHER RESEARCH

11.1 INTRODUCTION

In this chapter, comment will be restricted to the two technical issues covered in this dissertation, namely the sludge siphon and urine diversion technology. Many of the general sanitation and health issues discussed in the early chapters point to the requirement for sanitation approaches to be more human-centred, i.e. technologies should be responsive to human needs in an appropriate way. Using a toilet should not be an unpleasant experience and maintenance should also not be a burden. If it is, then users will tend to relieve themselves elsewhere, thus defeating the whole object of providing a toilet in the first place. This is where the development of appropriate technologies becomes so important. The promotion of good personal hygiene habits, especially among the poorest sections of the population, is inextricably linked to sanitation, and if the engineer has a basic understanding of the social issues involved, then the research and development of improved sanitation technologies will be correctly focused. In the interests of society as a whole, research needs to be concentrated on technologies which serve not only the user's interests but take into account the institutional capacity of local authorities as well.

11.2 FURTHER RESEARCH ON SLUDGE SIPHON TECHNOLOGY

The real challenge in using this technology is to get the suspended sludge transported for the maximum possible distance. This dissertation has been concerned with the development of an efficient siphon to automatically extract sludge from an interceptor tank in a settled sewage system, without conscious thought by the toilet user, and ensure its delivery into the effluent pipeline. While it has not been proved, it seems likely that the sludge could be carried in suspension for many kilometres. The ideal situation would be to transport the sludge from a whole suburb or town all the way to the treatment works without the need for intermediate settling tanks or the use of vacuum tankers. Thus the most important questions to be addressed in further research are:

- What is the maximum concentration of suspended sludge that can be efficiently transported in the effluent pipeline? This will ultimately determine the maximum number of users that can be connected to a single network.
- Allied to the first topic, what are the most hydraulically efficient pipeline sizes and gradients for various sludge concentrations? Here it will be necessary to examine not only suspended flow conditions but also the ability of the effluent flow to re-suspend sludge deposited on the pipeline invert.

- Will the inorganic particles in suspended sludge be responsible for undue pipeline wear? In other words, will it be necessary to specify a higher class pipe wall than would normally be necessary for pure hydraulic considerations? If this is the case, the savings achieved by implementing sludge siphon technology may be effectively negated.
- Is it possible to further refine the design of the siphon assembly such that the volume of wastewater needed to activate the siphon is reduced, irrespective of the distance or height difference between the activating fixture (washtub, bath, etc) and the interceptor tank? Due to the fact that Boutek holds a patent on the sludge siphon, this specific aspect will need to be researched by Boutek itself.
- Bearing in mind the composition of septic tank sludge, it is possible that a lighter duty sludge pump than what would normally be required for conventional sewage could be used, should a pumping station and rising main be required in the pipeline network. This aspect ought be investigated, as further savings could be achieved in such a case.

11.3 FURTHER RESEARCH ON URINE DIVERSION SYSTEMS

Most of the technical issues regarding design, operation and use of urine diversion sanitation systems have been thoroughly researched in other countries. However, the following aspects need to be further investigated for South African conditions, as at this stage the experience has been limited to a very narrow population and climatic sample:

- The social acceptability of these toilets in general (excluding the issue of excreta reuse for the purpose of this question) for all the various cultural groups in the country.
- Detail matters such as disposal of used personal cleansing material as well as desiccated faeces for the various cultural groups.
- The social acceptability of excreta reuse for agricultural purposes among the various cultural groups.
- The critical issue of pathogen destruction. While it is certain that the process will occur more rapidly in the hotter regions of the country, ways need to be found to accelerate the tempo of pathogen die-off under less favourable climatic conditions. Particularly, ways of ensuring that the faeces pile is kept aerobic are essential to the safe operation of these systems. In this respect, the use of bulking agents other than fine ash will probably play an important role. Otherwise, the feasibility of manually turning the pile occasionally (e.g. by raking) should be researched.
- Finally, a contribution to the nationwide issue of job creation and small business development can be made by examining ways of manufacturing the pedestals by communities themselves. The plastic pedestal used in the Eastern Cape pilot

project currently sells at just under R200 (1999 rands), but this may be too expensive for some very poor communities. The Mexican-type mortar pedestal described in chapter 7 is cheaper to produce, but its successful manufacture is highly dependent on factors such as local availability of good quality sand, the use of a suitable mortar mix, people's experience with working with mortar and moulds, etc. In addition, the fibreglass mould used for its manufacture is not easy to work with (assembly, stripping, etc) and its durability is a problem. Other materials and methods, and possibly even alternative designs, should be examined.

APPENDIX A

PRELIMINARY GUIDELINES FOR THE INSTALLATION AND OPERATION OF "SLUDGE SIPHON" SYSTEMS

A1 INTRODUCTION

The design and operation of settled sewage systems using conventional interceptor tanks is well documented (Smith 1993; USEPA 1991; WRC 1998a; WRC 1998b). In Chapter 11 (Recommendations for further research) it was suggested that experimentation be conducted to examine the flow behaviour of various concentrations of suspended sludge, using different pipeline sizes. It is therefore not possible, at this stage, to suggest guidelines for the reticulation network attached to a sludge siphon system other than to refer to what was observed in the experimental installation on the CSIR campus. However, for the correct operation of an interceptor tank containing a sludge siphon system, it will be of critical importance that certain installation and operating guidelines are adhered to. These are suggested below and are the direct outcome of the research and development carried out to date.

A2 PRELIMINARY GUIDELINES

A2.1 Installation guidelines

1. The activating plumbing fixture (i.e. washtub, bath, etc) should be as close as possible to the tank, and in any case not more than 6 m away. Longer distances tend to cause attenuation of the flow, with the result that a much larger volume of wastewater is required to activate the siphon, or it may not even activate at all. It is essential that wastewater enters the siphon system as rapidly as possible.

2. The excavation for the tank should have the base accurately trimmed in order to ensure that the bottom of the tank is horizontal. The level of the effluent pipe will be approximately 500 mm lower than in the case of a conventional interceptor tank, and the pipeline excavation will therefore be initially deeper than usual by this amount. It is recommended that the first 12 m of pipeline length has a minimum positive gradient of at least 0,25 % (i.e. 1:0,0025).

3. The effluent pipeline may contain sections with a negative gradient, as long as the elevation of the highest point in the pipeline does not exceed that of the crown of the siphon. It is essential, however, that a negative gradient not be introduced within the first 12 m of pipeline length commencing at an interceptor tank. This minimum distance is necessary to ensure full activation of the siphon, and thus full-bore pipe flow under maximum head, before the inertia of the standing septage at the vertical kink in the pipeline is able to be effectively overcome by the new flow. If this requirement is not complied with, it is likely that the siphon will not activate.

4. Where an effluent pipeline from an interceptor tank joins up with a collector pipeline, for example in the street reserve, the connecting joint should be made such that the effluent in the household pipeline has an unobstructed flow into the collector pipeline. This can be achieved by fitting the joint with the intersecting leg pointing in an upward direction, so that the incoming flow can "drop" into the collector pipeline.

5. Ensure pedestrian access to the tank is not obstructed, in order to facilitate inspection and maintenance if necessary. The tank should also be installed so that the inspection covers are accessible. If possible, the tank should be installed in a position where vehicular loads are unlikely, otherwise care should be taken that adequate protection is provided.

6. Normal tank ventilation through the incoming blackwater pipeline (i.e. not the pipeline from the activating fixture) should be ensured, as for any conventional septic tank system.

A2.2 Operating guidelines

1. The siphon should be activated, by means of the plumbing fixture connected for this purpose (the activating fixture), at least once a week if possible. Longer flushing intervals may lead to a larger accumulation of sludge in the tank, where the lower layers tend to be compacted by the mass of sludge above. In some cases this may require more than a single flush to activate the siphon properly.

2. The minimum flushing volume should be 25 litres, i.e. the activating fixture should contain at least this amount of wastewater before being emptied at the weekly period. Smaller flushes may not necessarily activate the siphon.

3. The interceptor tank should be treated with the same care as any conventional septic tank i.e. no harmful detergents and no materials other than proper toilet tissue paper should be flushed down the toilet. Items such as sanitary pads and wads of heavy paper or plastic should be specifically excluded.

4. It is essential that the waste pipe from the activating fixture be kept free-flowing. This means that, if the outflow rate decreases due to a blockage, even a minor one, the waste pipe should be cleared immediately. When performing this task, it is essential to ensure that the material responsible for the blockage is not pushed further down the waste pipe towards the tank. The U-trap (if there is one) beneath the fixture will probably need to be loosened and cleaned out.

APPENDIX B

PRELIMINARY GUIDELINES FOR THE DESIGN AND OPERATION OF URINE DIVERSION SANITATION SYSTEMS IN SOUTH AFRICA

B1 INTRODUCTION

As mentioned in Chapter 11 (Recommendations for further research), most of the technical issues regarding the design and operation of urine diversion sanitation systems have been thoroughly researched in other countries (Dudley 1996; Esrey et al 1998; Gough 1997; Hanaeus et al 1997; Höglund et al 1998; Jönsson 1997; Mejia 1997; Winblad 1993; Winblad 1996b; Wolgast 1993). South African experience is currently very limited, and these guidelines are of necessity restricted to the learning experience associated with the pilot project in Eastern Cape. However, the generic structure of the guidelines is such that they are not confined to this specific experience only; rather, they are considered to be applicable generally, in all regions and for most population groups.

B2 PRELIMINARY GUIDELINES

B2.1 Design guidelines

1. Community participation in the project, from the conceptual stage right through to completion, is of primary importance. Due to the novelty of the technology especially, more social involvement than usual will be required during the project planning stage, so that the eventual users will know exactly what they are getting and how the units differ from conventional VIP or other composting toilets. It will be useful if a full-size pedestal can be shown to the communities during the initial introductory phase, as well as samples of the proposed building materials for the superstructure.

2. Toilet units may be free-standing or part of another structure, such as a dwelling for instance. The main criterion in the latter regard is adequacy of the other structure in terms of size, materials, durability and compatibility. Any suitable building material may be used, as long as it provides a sound, waterproof structure. Traditional building materials and methods may be especially suited to rural areas. However, proper provision for stormwater drainage around the toilet unit should be ensured.

3. The floor area of the toilet superstructure should provide sufficient space for the pedestal as well as containers for bulking agent (soil, ash, etc) and used cleansing materials. The need for a men's urinal inside the unit should be carefully researched as, besides its purchase and installation costs, it also requires additional floor area. It may be found that men will be satisfied without a special urinal being provided inside the toilet unit, as in rural areas particularly, they can often urinate in relative privacy outside. However, should this be a problem, for example in areas which are more densely populated, the feasibility of providing a common exterior urinal should be investigated. This may be a relatively informal

type of structure serving a number of dwellings, and may be a simple arrangement consisting of a privacy wall enclosing a shallow pit filled with wood shavings or ash which is replaced when odour becomes a problem. This urine-soaked material makes an excellent soil conditioner and fertiliser, should this practice be acceptable to the community.

4. The floor slab of the toilet unit should be raised above the surrounding ground by about 600 mm, as this provides sufficient space in the area beneath the pedestal to collect the faeces, either in separate containers or simply in a heap on a hardened substratum. The latter option is preferable if the users are prepared to turn the heap periodically by rake or spade, as aeration is important to facilitate rapid pathogen die-off (see the operating guidelines below).

5. The toilet pedestal may be obtained commercially, in rotationally-moulded plastic, porcelain etc, or it may be custom-built by local entrepreneurs using any suitable material, such as mortar for instance. In the latter case, it is important that only moulds with proven designs are used, as the shape and size of the pedestal, especially the position of the urine collection compartment, are crucial factors. It is also important that the material used has a smooth finish, in order to minimise the accumulation of bacteria, etc, and to facilitate cleaning.

6. A vent pipe as found in a conventional VIP toilet is generally not required, as odour and flies are not a problem with this type of toilet if it is properly used. However, if the maintenance of aerobic conditions in the pile is likely to be problematic, then it may be preferable to install one. The installation of air bricks (with flyscreen gauze for safety) in the side walls of the faeces chamber can also help to facilitate ventilation. See the operating guidelines which follow.

B2.2 Operating guidelines

1. Care should be taken that no personal cleansing materials are deposited into the faeces receptacle. Due to the dry conditions inside the receptacle, these materials will not degrade easily. Furthermore, faeces covered by these materials will be prevented from dehydrating properly. Used cleansing materials should be kept inside a covered bin next to the toilet pedestal and disposed of when necessary, either by burning or burying.

2. Moisture should, as far as possible, be prevented from entering the faeces receptacle or pile. Therefore, should it become necessary to clean the rear chute of the pedestal, a dampened toilet brush should preferably be used, without actually washing or rinsing the chute walls, as excess water in the faeces receptacle will interfere with the dehydration process. However, water may be freely used to clean the urine bowl.

3. Should the reuse of urine as fertiliser be desired, it may be collected in any

suitable container, otherwise it should merely be led into a soakpit. Alternatively, the urine from a number of toilet units may be collected and reticulated to an evaporation pond if climatic conditions favour this process. Should the urine be reused, it will need to be diluted by the addition of at least four to five times as much water. The most suitable concentration for each crop will differ, and this should be experimentally determined by the user.

4. Desiccation of the faeces is very dependent on the achievement of aerobic conditions, as this facilitates the development of high temperatures in the pile. This in turn promotes the rapid destruction of pathogenic organisms. For this reason, a coarse bulking agent should preferably be used, for example wood shavings. Ash from wood fires has a high pH which is lethal to most pathogens, but due to its fine, powdery nature, it is not conducive to aeration of the pile. The best way to keep the pile aerobic is to turn it frequently, if users are prepared to do so (in which case the use of ash as a bulking agent will be satisfactory).

5. Reuse of the desiccated faeces for agricultural purposes should not be undertaken before at least six months after the last excreta has been added to the pile. During this period of storage the pile should be kept aerobic, as discussed above. In general, the product should not be used on edible root crops (carrots, beetroot, etc) unless it has been established that all pathogens have been destroyed. Disposal of the desiccated faeces, should agricultural reuse not be desired, can be undertaken in various ways. It can be buried, which is a relatively simple task due to the ease of access to the collection chamber, reduction in volume of the faeces, and general lack of odour and flies. Alternatively, it can be bagged and either disposed of in conjunction with other solid waste from the household, or made available as soil conditioner to persons wishing to make use of it. The disposal process makes entrepreneurial opportunities possible, as many people would probably be prepared to pay for its removal.

APPENDIX C

SEDIMENT TRANSPORT: BRIEF REVIEW OF LITERATURE

C1 GENERAL

Septic tank sludge from domestic origin consists mostly of discrete and flocculent particles of fine sediment. The physical, chemical and biological properties of sludge are described in Chapter 6.5. Although the fluid/sludge mixture, while flowing in a pipeline, has been observed to be relatively homogenous, some sludge particles are deposited on the invert of the pipeline when the flow ceases or becomes too little to continue transporting the load in suspension (this occurs when the siphonic action ceases). These sludge particles remain as a deposited bed of sediment until such time as a sufficiently large wave of effluent picks them up again and transports them further down the pipeline. This process of deposition and subsequent re-suspension of sludge particles will be repeated continuously as long as there is a repetitive cycle of effluent flushes from the tank to the pipeline.

If open channel flow was being considered instead of pipe flow, the effect of this movable bed load of sludge particles would be the same as in a loose-boundary channel. In open channel flow the boundary of movable material deforms under the action of flowing water, while the deformed bed with its changing roughness (bed forms) interacts with the flow. A dynamic equilibrium state of the boundary can be expected if and when a steady and uniform flow has developed (Featherstone and Nalluri 1988). The resulting movement of the bed material (sediment) in the direction of flow is referred to as sediment transport and a certain critical bed shear stress (τ_c) must be exceeded to start the particle movement. This critical shear stress is termed the incipient (threshold) motion condition, below which the particles will be at rest and the flow is similar to that on a rigid boundary.

Sediment transport occurs only if there is an interface between a moving fluid and an erodible boundary (Chadwick and Morfett 1986). The activity at this interface is extremely complex, because once sediment is being transported, the flow is no longer a simple fluid flow, since two different materials are involved. Sediment transport may occur in one of two modes:

(a) by rolling or sliding along the bed of the channel – this is termed *bed load*; or
(b) by suspension of finer particles in the moving fluid – this is called *suspended load*.

C2 INCIPIENT (THRESHOLD) MOTION

In the case of an erodible boundary, or where sediment is deposited on a rigid bed (as in a pipeline) the sediment particles will only start to move when the applied force is sufficient to overcome their natural resistance to motion. The particles are usually non-uniform in size. At the fluid/sediment interface, the moving fluid will apply a shear force τ_0 (Chadwick and Morfett 1986); this is depicted in Figure C.1 for a granular bed material. A proportionate force will then be applied to the exposed surface of a sediment particle. If the shear force is gradually increased from zero, a point is reached at which particles will start to move at various places over the bed. A further small increase in τ (and therefore

in the velocity u) is usually sufficient to generate a widespread sediment motion of the bed load type. This is the critical bed shear stress τ_c and describes the "threshold of motion". After further increments in τ another point is reached at which the finer particles begin to be swept up into the fluid; this is the inception of suspended load transport.

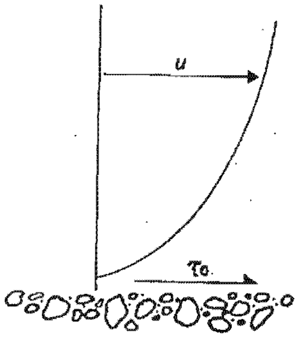


Figure C.1: Shear force on a granular bed, showing velocity profile
(Chadwick & Morfett 1986)

In practice, virtually all sediment transport in channels occurs either as bed load or as a combination of bed load and suspended load (Chadwick and Morfett 1986). The combined load is known as total load. In natural channels suspended load rarely occurs in isolation, except for certain cases involving very fine silts. However, experimental observations during this particular research project have shown that, in a pipeline flowing full, hydraulically transported septic tank sludge of domestic origin is, due to its fine particle size and low specific gravity, virtually entirely of the suspended load type. Only after the flow has diminished and reverted to open channel conditions does the velocity decrease to the extent that some of the solid particles slide or roll along the pipe invert before settling out.

Various bed load and suspended load formulae have been developed in order to analyse the movement of sediment particles in water (mostly in channel flow). Some formulae are based largely on the assumption that the particles are spherical (Graf 1984), which is not valid for sludge (see the description of septage in Chapter 6.5). The formulae may also assume that the suspensions are relatively dilute (Graf 1984), which was not always the case during this experimentation. Moreover, most formulae apply primarily to coarse sand or possibly to some gravels, or are based on a single "typical" particle size (Chadwick and Morfett 1986); others are based on a relative sediment density of 1,65 or on flow in wide channels (Featherstone and Nalluri 1988), neither of which are valid in this instance. These formulae are thus mostly inapplicable in the case of the rigid boundary type of pipe flow under investigation in this project. The following section describes some of the work done by Mara (1996), Graf (1984) and others in determining the flow behaviour of liquids transporting sediments in closed conduits. It is necessary to examine this behaviour in order to understand and thus be able to predict what happens when transported sediment

settles out on a pipe invert and has to be subsequently resuspended by a following wave of liquid in order for it to be transported further down the pipeline again.

The concept of threshold-of-motion value was addressed by Mara (1996) in a study on the self-cleansing criterion. This study found that the threshold-of-motion value for recently deposited solids is similar to the average boundary shear stress τ experienced by a pipe of internal diameter D (mm) laid at a gradient of 1 in D and flowing full:

$$\begin{aligned} \tau &= \rho g \, (D/4) \, (0{,}001/D) \\ &= 2{,}5 \text{ N/m}^2 \end{aligned} \quad \ldots\ldots\ldots\ldots (C.1)$$

The Metropolitan Water, Sewerage and Drainage Board in Sydney, Australia, has specified limiting gradients S (%), for self-cleansing, as

$$S = 0{,}0135/R \quad \ldots\ldots\ldots\ldots (C.2)$$

where R = hydraulic radius, m

This formula is based on the above unit tractive force or boundary shear stress approach. The average boundary shear stress will be reduced for flows and proportional depths below half full.

Mara (1996) also addressed the relationship between bed-load movement and critical tractive force required to initiate motion of the bed-load. An empirical model for the removal of single grain particles of varying specific gravities was developed:

$$V = [\, (8Kg/f) \, (S_p - 1) \, D_g \,]^{1/2} \quad \ldots\ldots\ldots\ldots (C.3)$$

where
V = wastewater velocity, m/s
K = dimensionless parameter with the value 0,4 to initiate motion and 0,8 for adequate cleansing
g = gravity constant, m/s^2
f = dimensionless friction factor
S_p = specific gravity of material removed, and
D_g = particle diameter, m.

Based on this model, the self-cleansing velocity is independent of the sewer diameter.

There is a direct relationship between the self-cleansing velocity and the critical boundary shear stress or tractive tension (Mara 1996):

$$V = (K/n)\, R^{1/6}\, (\tau_c/w)^{1/2} \quad \text{(C.4)}$$

where
n = Manning's roughness coefficient
R = hydraulic radius, m
τ_c = critical shear stress, N/m^2
w = specific weight of water, N/m^3

This model indicates that as the diameter of the sewer increases for a given tractive tension, the necessary self-cleansing velocity must increase. Therefore designs should not be based on a constant minimum velocity for all sewer sizes, otherwise larger sewers will be under-designed while smaller sewers will be over-designed.

C3 SEDIMENT TRANSPORT IN CLOSED PIPES

Consider a horisontal pipe, the bottom of which is covered with a plane, stationary bed of loose, cohesionless, solid particles of uniform size. The remainder of the pipe cross-section is filled with water. If the liquid starts to flow, energy dissipation takes place which, in turn, manifests itself as a pressure drop (Graf 1984). The loss of energy per unit length of pipe, $\Delta h/\Delta L$, is termed the *head loss* and is proportional to the flow velocity V^n, or

$$(\Delta h/\Delta L) \propto V^n \quad \text{where } n > 1 \quad \text{(C.5)}$$

This relationship has been plotted for a specific case in Figure C.2 (Graf 1984). As soon as the liquid flows, hydrodynamic forces are exerted on the solid particles of the bed. Further increases in the flow cause a corresponding increase in the magnitude of these forces until, eventually, the particles in the movable bed are unable to resist them and start to move. This condition of initial movement of some bed particles is called the *critical condition*.

In Figure C.2 the data with the smallest head loss and velocity represent the critical condition for this particular case (point C on the curve). As the flow velocity is increased, the head loss increases proportionately. The quantity of moving solids, or *concentration*, increases at the same time. A bed (deposition) is noticeable, which first deforms and forms dunes, while at higher velocities these dunes are washed out. At lower flow velocities the movement of particles is generally restricted to a narrow band in the lower part of the pipe, while at higher velocities the movement is spread over the whole of the pipe cross-section.

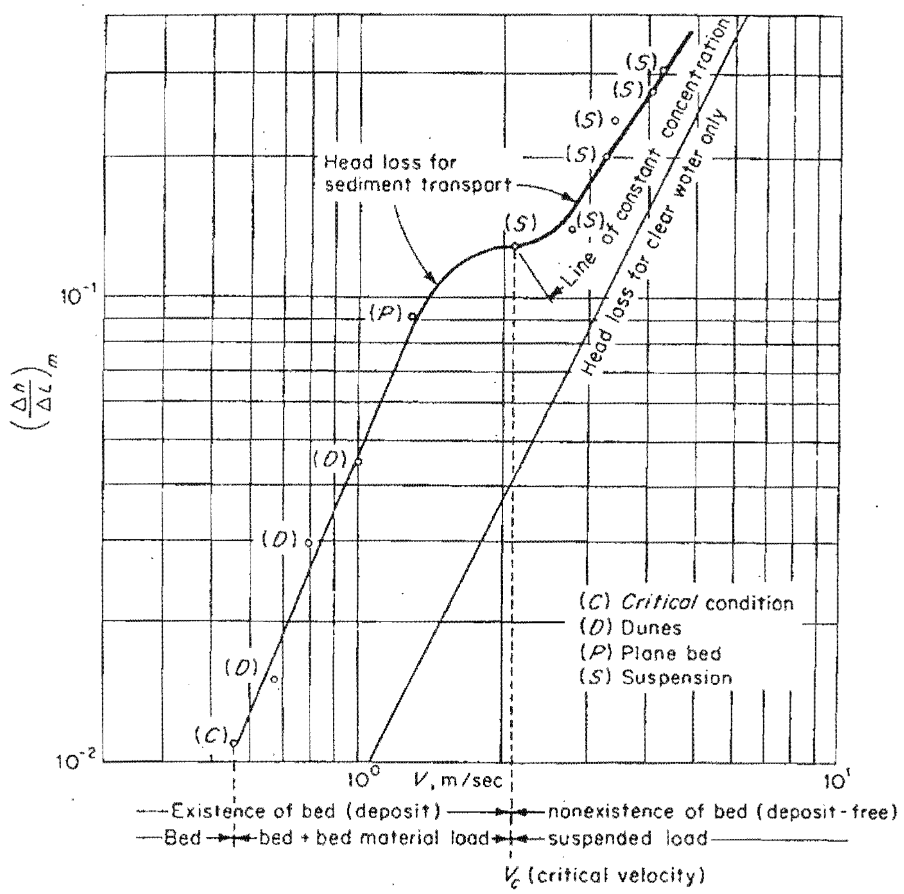


Figure C.2: Head loss vs velocity relationship for closed-conduit flow, for sand with d = 2,0 mm (Graf 1984)

Between the lower and upper legs of the curve there appears to be a discontinuity, where, although the flow velocity increases, the head loss remains more or less constant. In this region the stationary bed material (the deposition) is scoured away and starts to move. It should be noted that this specific example is valid only for material with a nominal diameter of 2,0 mm.

Along the entire upper leg of the curve, the concentration of transported solid particles remains constant. An increase in the flow velocity results in a proportionate increase in the head loss. All of the particles which originally formed the bed are now in suspension. At lower velocities the concentration distribution is such that the majority of the particles are transported in the lower half of the pipe cross-section, while at higher velocities the particle distribution may tend to become uniform over the entire cross-section.

Within the transition zone there is a velocity designated as the *critical velocity*, as indicated in Figure C.2. Below this velocity deposits will occur, while above it no deposit will be found in the pipe. Information on this velocity is important, as it defines two separate zones, namely:

1. For flow velocities below the critical velocity, deposits occur, while the sediment transport is due to an exchange between the stationary-bed and moving bed material;
2. for flow velocities larger than the critical velocity, no deposit will take place and the sediment is transported as suspended load.

If the sediment material is uniformly distributed over the entire cross-section, the flow is referred to as *pseudohomogeneous*, while if it is non-uniformly distributed it is called *heterogeneous*. In Figure C.2 above, this information is compared to the head loss vs velocity relation for water without sediment. It is clear that the head loss for a water and sediment mixture is greater than the head loss for water on its own.

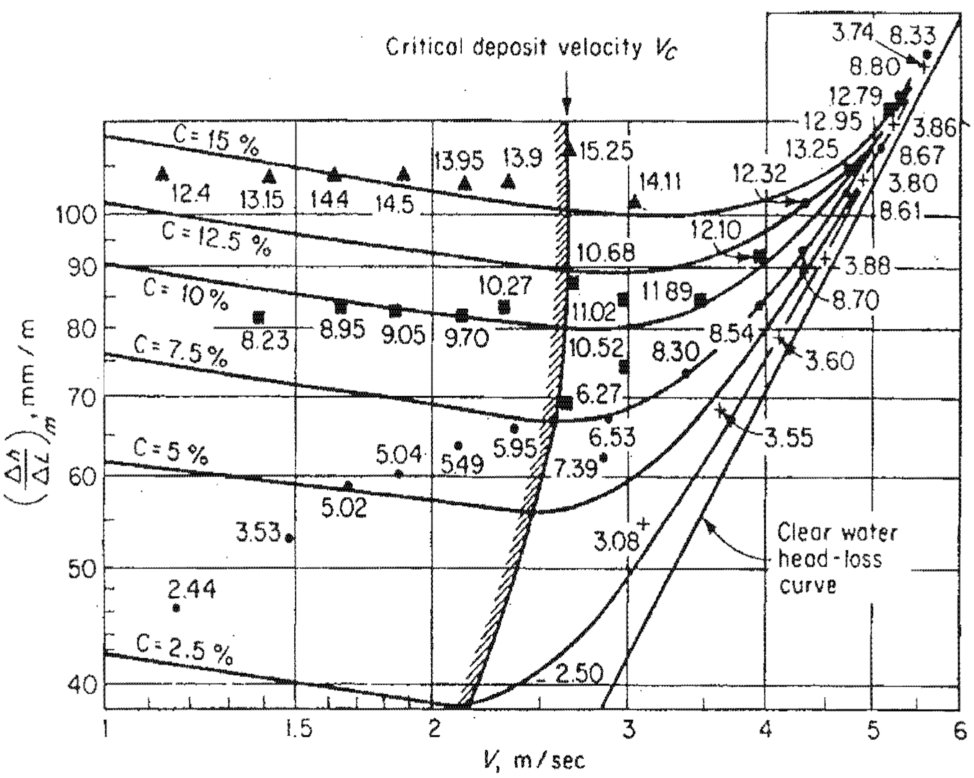


Figure C.3: Head loss vs velocity relationship with equiconcentration lines, for sand graded to 0,44 mm (Graf 1984)

Figure C.2 was obtained for an initial condition of a stationary bed of a given thickness. If the thickness of the stationary bed is changed and the experiment repeated, a further set of data becomes available. If this procedure is repeated for a number of different bed thicknesses, points of the same transport concentration can be connected to form lines of equiconcentration, as illustrated for a typical example in Figure C.3 (Graf 1984).

Settling and non-settling mixtures:

Settling mixtures are defined as those where the settling velocity of the solid particles is above 0,6 to 1,5 mm/s (Graf 1984). Non-settling mixtures have solid settling velocities below this range. Settling velocity is not only dependent on the physical properties of the individual particles, but also on the concentration of the mixture. In pseudohomogeneous flow the solid particles become fully suspended in the liquid and are almost uniformly distributed over the entire pipe cross-section, whereas with heterogeneous flow a suspension distribution over the pipe cross-section is evidenced. If the flow velocity is sufficiently high, most materials will behave as pseudohomogeneous suspensions, although investigations have indicated that pseudohomogeneous flow is usually limited to particles of less than $d = 30\ \mu$ (Graf 1984). In mixed-size sediments, if a significant fraction of fine material exhibiting pseudohomogeneous flow is present in the mixture, it is responsible for a noticeable decrease in the head loss of the mixture.

Velocity and concentration distribution:

Visual and photographic observations together with hydraulic considerations allow a schematic representation of both concentration and velocity distributions, as shown in Figure C.4 (Graf 1984). Three kinds of flow are distinguished, namely, pseudohomogeneous flow, heterogeneous flow and bed material transport with a bed (deposit). Within the heterogeneous flow zone, two extremes are illustrated. For $V > V_c$ the suspended load will be fairly uniformly distributed, but for $V \approx V_c$ the suspended load will move close to the bottom of the pipe. The figure shows distributions of the local concentration and local liquid velocity for each kind of flow. A decrease in flow velocity, i.e. moving from graph A to graph D in Figure C.4, results in less uniform concentration distributions. The velocity distribution shows the same tendency - if the flow velocity V is below the critical velocity V_c, as shown in Figure C.4D, deposition occurs.

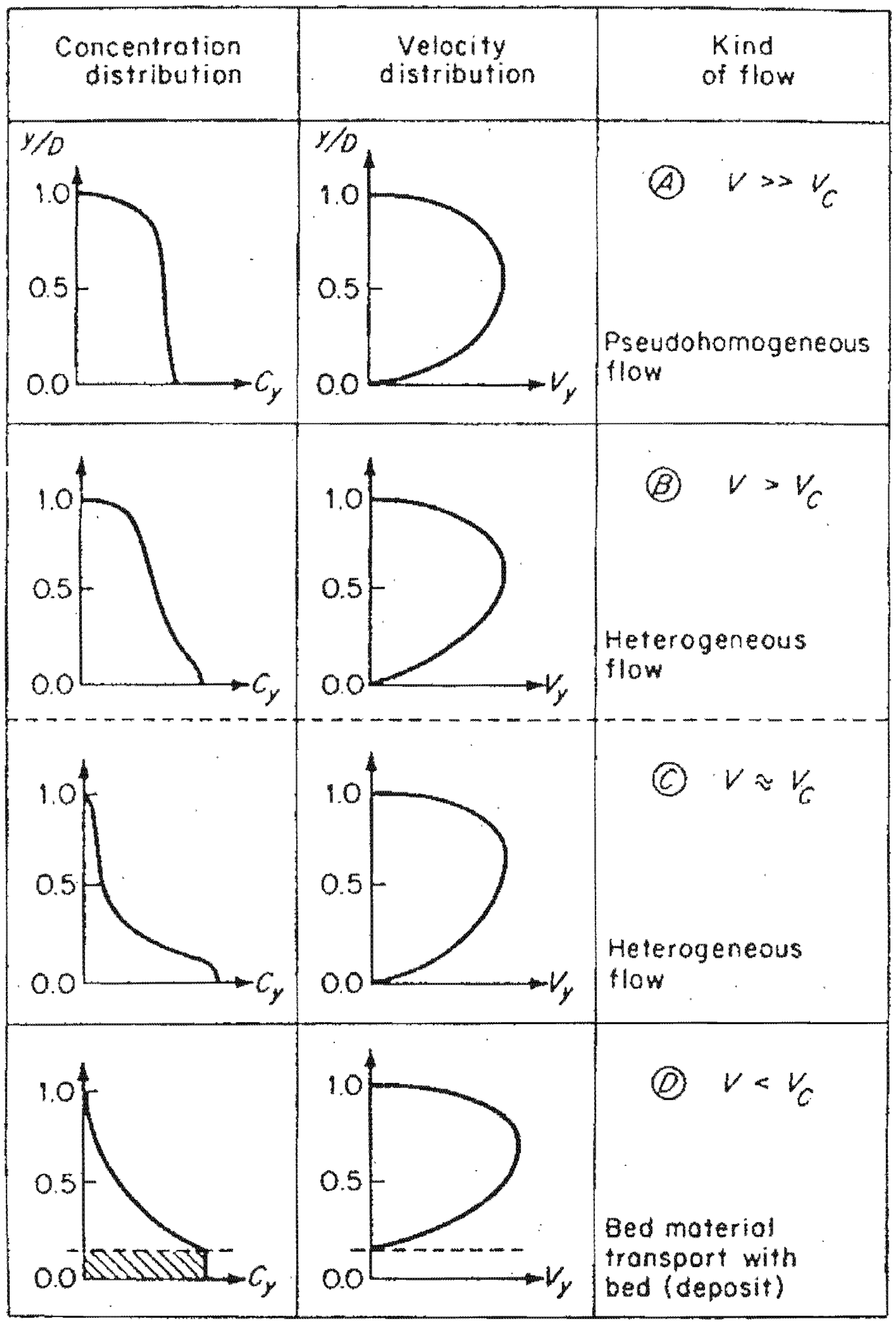


Figure C.4: Schematic representation of concentration and velocity distributions
(Graf 1984)

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Abbreviations:

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DFID	Department for International Development, United Kingdom
DWAF	Department of Water Affairs and Forestry, South Africa
HEATT	Health Education and Awareness Task Team, South Africa
UNCHS	United Nations Centre for Human Settlements (Habitat)
USEPA	United States Environmental Protection Agency, USA
WEDC	Water, Engineering and Development Centre, Loughborough University, UK
WRC	Water Research Commission, South Africa
WSSCC	Water Supply and Sanitation Collaborative Council Working Group on Promotion of Sanitation (World Health Organisation, Geneva)

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