ENVIRONMENTAL IMPACT OF POINT POLLUTION SOURCES

BY

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To my parents

Steyn and Mattie,

who always believed in me

"Our most precious gift to you is an education"

- My Parents-

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CHAPTER 1

Introduction

1.1 Why study groundwater at all?

Anyone that has ever attended a geohydrology course will know that one of the first introductory lectures is the one about the hydrological cycle. Therefore it is quite common knowledge that the fresh water part of the total volume of water on earth is very small; only about 3%. The major part, 76% of the fresh water, is captured in the ice caps and snow of the Polar Regions. Groundwater makes up 23% and the other 1% consists of fresh water in dams, lakes, moisture in the ground, rivers, streams and the atmosphere (Van der Spuy and Rademeyer, 1997).

From the above it must be clear that the impact of pollution on the groundwater environment must be one of the most important study areas, when considering the sustainability of life on earth as we know it.

Over the past 15 years, the concern over the impact of humans on the environment has increased in leaps and bounds. Many animal species are close to extinction because of our greed for riches. The possibility that coral reefs could become only pictures and videos because of the effect of global warming might even become reality. All our natural resources are becoming more and more over-exploited and polluted because of the growing demands of the world population.

Without any water, life on earth is not possible. Surface water is easily contaminated because no barrier exists between it and man-made pollutants. Groundwater can be viewed as one of the world's last reservoirs available to man when trying to rescue what is left. A thorough knowledge of groundwater can ensure that it is managed and protected well enough so that future generations might also be able to live in a world where there are still elephants and rainforests.

1.2 Project objectives

This document is a continuation of a project sponsored by the Water Research Commission (**WRC**), to investigate the suitability of artificial and natural tracers, to formulate a management strategy for rural water supply in secondary aquifers.

In a previous document by Van Wyk (1998) the emphasis fell on the application of tracers in the saturated zone.

The main aims of this project are to determine the following:

1. To investigate the effect of the unsaturated (vadose) zone on pollutants and their migration route from the soil surface towards the groundwater environment.
2. To delineate borehole protection zones around the well heads to minimise the influence of potential pollution sources such as on-site sanitation systems.

This document will aim to use artificial and natural tracers to provide more information on:

1. Travel times of pollutants through the unsaturated zone.
2. Estimate of pollutant loads (nitrates and microbial) that could reach the groundwater.
3. Estimate of the radius of extent of horizontal or vertical fractures.
4. The influence of fractures on the migration velocities of pollutants.
5. Estimate of unsaturated zone parameters such as K-values.

The focus of this document is on the effect of point pollution sources on the environment. One of the problems with point pollution sources is that it depends on the scale of the problem. If you look at the world, a mine or waste disposal site can also be seen as a point pollution source. Thus it was decided that for the scope of this work a point pollution source would be regarded as a pitlatrine or a septic tank system.

Fluorecein was used as an artificial tracer and bacteriophages were used as natural tracers during the field tests for this investigation. The techniques involved in conducting tracer tests have been described in detail by Van Wyk (1998), therefore only the data obtained from the field tests and not the test itself will be discussed.

A simple program ***Borehole Protection Zone*** **(BPZONE)** was developed to help in the decision making processes concerning protection zones. The program was developed by making use of ***Microsoft Excel***.

CHAPTER 2

Nitrates

2.1 Introduction

Nitrates are one of the most widely studied, if not the most studied, ground and surface water contaminant attributed to septic tank systems and pitlatrines. It is a pollutant that is very mobile in the soil system and can reach ground and surface waters rather quickly.

The two major concerns when dealing with nitrate contamination are:

1. **Groundwater:** Cyanosis due to methaemoglobinemia, which is toxic to infants in the age group 0 – 6 months. Nitrate is reduced to nitrite in an acidic environment like the stomach. Nitrite combines with the oxygen-carying red blood pigment, haemoglobin to form methaemoglobin. Methaemoglobin is incapable of carrying oxygen (Tredoux, 1993).

2. **Surface water:** Eutrophication. Excess nitrate stimulates algal blooms that leads to eutrophication. The plants use all the oxygen in the water and over time the plants die and stagnant waterbodies with rotten plant material are created (Heaton, 1986).

Several mechanisms and processes affect the fate and transport of nitrogen following the application of septic tank effluent (STE). The complexity and degree in which each process affects nitrogen is dependent upon various soil and environmental factors. These processes are:

1. Immobilisation.

2. Volatilisation.

3. Plant uptake.

4. Mineralisation.

5. Nitrification.

6. Denitrification.

7. Cation exchange.

All of the above-mentioned are again influenced by the following parameters:

1. pH.

2. Soil moisture content.

3. Redox potential.

4. Oxygen (O_2) availability.

5. Cation exchange capacity (CEC).

6. Organic carbon form and availability.

7. Microbial population and diversity.

2.2 Processes influencing the fate and transport of nitrogen

2.2.1 Immobilisation

Immobilisation is the process by which natural occurring microbes utilise the nitrogen in organic compounds for cell functions. This process removes the nitrogen in the soil, which in turn will decrease the nitrate content of the soil. Microbes utilise organic matter as a carbon (C) and energy source. During this process available N is retained in the microbial cell for various synthesis reactions. Lance (1972) reported that the amount of N immobilised from STE is probably less than 5 to 10%.

2.2.2 Volatilisation

Volatilisation is where NH_4+ is converted to NH_3 by the following reaction:

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O$$

The NH_3 is in a gaseous form and will move towards the surface and evaporate. Movement of NH3 to the surface is dependent on pH. If the pH drops, or a lower pH is encountered during diffusion, NH3 might revert to the NH4+ form in accordance with the volatilisation reaction. When regarding septic tank systems and pitlatrines, the loss of N due to volatilisation is generally of minimal importance. It becomes only important at elevated pH values because of a high equilibrium pH of 9.5. The pH of wastewater is generally between 7.5 and 8.

2.2.3 Plant uptake

Nitrate is used by plants as nutrient and will decrease the nitrate load in the sub-soil surface. Loss of N due to plant uptake is generally minimal when septic tank systems are considered. The disposal of STE takes place in the subsurface and usually below the zone of plant uptake

2.2.4 Mineralisation

Mineralisation occurs when nitrogen compounds are incorporated in minerals or from an equilibrium point of view when nitrate salts are deposited as a result of over saturation. This process often occurs simultaneously with immobilisation, because the same microbes are responsible for both processes. With septic tank systems, N enters the soil primarily as NH_4^+ (75-85%), so that the rates of mineralisation have little bearing on rates of nitrification.

2.2.5 Nitrification

Nitrification is the biologically controlled oxidation of Ammonium (NH_4^+) to Nitrite (NO_2^-) and/or Nitrate (NO_3^-). The dominant microbes involved in nitrification are the obligate chemolithotrophic bacteria, Nitrosomonas and Nitrobacter. Rates of nitrification are dependent upon:

1. Available NH_4^+ or NO_2^-
2. pH.
3. Temperature.
4. O_2 availability.
5. Soil moisture content.

Table 2.1 lists the different parameters and their effects on nitrification.

Table 2.1: Parameters having an influence on nitrification.

Available NH_4^+ and NO_2^-	pH	Temperature	O_2 availability	Soil moisture content
The breakdown of organic matter and subsequent release of NH_4^+ is generally the rate controlling step for nitrification.	The optimum rate for nitrification in soils is 6.6 to 8. At pH values above 8.5, nitrification may be inhibited due to NH_3 toxicity to Nitrobacter.	The optimal temperature for nitrification is between 30 and 35°C. Rates of nitrification will decrease above and below this range in temperature.	The most important factor controlling nitrification rates is the availability of O_2 to nitrifiers. Nitrifiers are obligate aerobes that use O_2 as a terminal electron acceptor.	Nitrification is inhibited at high soil moisture content. During experiments in soil columns higher concentrations of NO_3^- were observed with distance from the point of application in a sandy loam soil. This suggested that nitrification was occurring away from the saturated conditions around the area of application.

2.2.6 Denitrification

Denitrification is the most important process for removing N applied to a septic tank system. N oxides are reduced to a gaseous form by facultative anaerobic bacteria. These bacteria use N oxides as terminal electron acceptors in the absence of O_2. Denitrification will only occur when:

1. Denitrifying bacteria are present.

2. Electron donors such as C, H_2 or reduced sulphur are available.

3. Anaerobic conditions exist.

4. Nitrogen oxides such as NO_3^-, NO_2^-, nitrogen oxide (NO) or nitrous oxide (N_2O) are available to serve as electron acceptors.

Rates of denitrification are dependent upon:

1. Concentration of NO_3^-.

2. Soluble carbon and oxygen.

3. pH.

4. Temperature.

5. Soil moisture content.

Table 2.2: Parameters having an influence on denitrification.

Concentration of NO_3^-	pH	Temperature	Soluble C and O_2	Soil moisture content
Experiments showed that at low NO_3^- concentrations the denitrification rates follow first order kinetics and at high NO_3^- concentrations zero order kinetics.	Soil pH does not affect denitrification rates. At high pH, levels of soluble C increase. Increases in rates of denitrification may be a response to the additional C released at higher pH.	Denitrification rates between 35 and 45°C are similar. A steady increase in rates occurs between 15 and 35°C, with each 10°rise a 2-fold increase is possible. Below 10°C rapid decreases in rates occur.	The more C that is available, the faster the denitrification rates. O_2 is not very important because denitrification is an anaerobic process.	More saturated soils will indicate better anaerobic conditions. This will have the effect of an increased denitrification rate.

2.2.7 Cation exchange

Cation exchange is important in holding NH_4^+ on the exchange sites until nitrification occurs. Leaching of NH_4^+ can occur if the exchange sites become saturated with respect to NH_4^+.

2.3 Discussion

2.3.1 Introduction

The following table is a summary of a study done by Bosch *et al.* (1950) where 139 cases were evaluated of cyanosis due to methaemoglobinemia. The age group was between 8 days and 5 months with 90% under the age of 2 months.

Table 2.3: Summary of a study done by Bosch *et al.* (1950).

Well information	Methaemoglobinemia occurrences (No.)	Methaemoglobinemia occurrences (%)
No. of wells with NO_3^- concentrations < 10 mg/L.	0	0
No. of wells with NO_3^- concentration 10–20 mg/L.	2	1.5
No. of wells with NO_3^- concentration 21–50 mg/L.	25	19
No. of wells with NO_3^- concentration 51–100 mg/L.	53	41
No. of wells with NO_3^- concentrations > 100 mg/L.	49	38

Walton (1951) described a survey done by the American Public Health Association to identify clinical cases of infantile methaemoglobinemia that were linked to ingestion of nitrate contaminated water. A total of 278 cases were reported but data on nitrate levels in water was only available for 214 cases. Data on the ages of the infants was not provided. Table 2.4 summarises the findings of Walton.

Table 2.4: Summary of the findings of Walton (1951) on infantile methaemoglobinemia and its association with ingestion of nitrate contaminated water.

Nitrate concentration (mg Nitrate-Nitrogen /L)	Methaemoglobinemia occurrences (No.)	Methaemoglobinemia occurrences (%)
< 10	0	0%
11–20	5	2%
21-50	36	17%
> 50	173	81

2.3.2 Nitrate isotopic analysis

According to Heaton (1986) there are three main causes of high nitrate concentrations in soils which contributes to the pollution of groundwater:

1. Enhanced mineralisation of soil organic nitrogen during the conversion of "virgin" land into arable land, and the subsequent cultivation of arable land.

2. Addition of nitrogenous fertilisers.

3. Concentrated disposal of animal or sewage wastes.

The sources mentioned above produce in many cases nitrate with distinguishable $^{15}N/^{14}N$ ratios. This basic isotopic data for nitrate has been successfully used for identifying the source of pollution in a wide variety of ground- and surface water environments.

Figure 2.1 shows the composition of the various sources of nitrates.

In Figure 2.1 the different ranges for the ^{15}N value that correlates with the different source of nitrates are indicated. If the value lies between +10‰ and +22‰, the possible source might be animal waste or sewage. A value between –5‰ and +5‰

will be indicative of fertilizer as the possible source. Between +5‰ and +10‰ the source might be soil organic nitrogen.

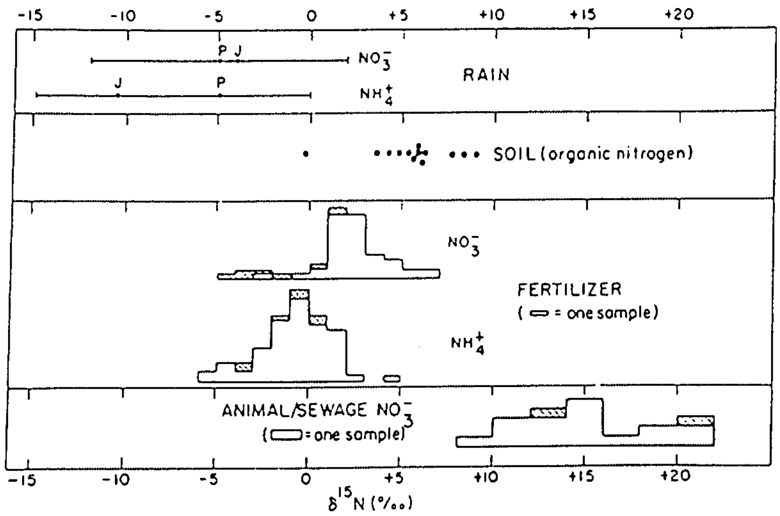


Figure 2.1: Summary of the range of ^{15}N values for the major potential sources in ground and surface water (Heaton, 1986).

Whenever the effects of nitrates are discussed, the argument whether the effort and labour involved is justifiable from a financial point of view. Another argument is the standards that are set by the different authorities regarding nitrate limits. The following is a direct quote from the Groundwater Digest mailing list (Number 1200 by Steve Short of New South Wales, Australia, 1999):

"For information of group members, I have been doing a little literature searching on this issue.

The WHO limit is 10 mg/L NO3-N (=44.3 mg/L NO3). The European administrative equivalent is 50 mg/L NO3 (=11.3 mg/L NO3-N).

There were about 3000 cases of methemoglobinemia reported worldwide between 1945 and 1985 (WHO, 1985). Most of the cases for the US, Canada and Western Europe were reported before 1970. Since 1970, reported cases from these regions have become very rare. The 1970 - 1985 database was overwhelmingly made up of cases from Hungary only.

Of the 3000 cases, only 74 dealt with cases ascribed to the use of water with less than 22.6 mg/L NO3-N (i.e. over twice the WHO limit). These have been reviewed (Bryson, *1988). 4 of the 74 cases have ambiguous water analyses. Of the remaining 70 cases, 52 are cases for infants also having enteritis before the onset of the disease.*

There were only 4 reported cases of methemoglobinemia in the US in the period 1971 - 1991 (Craun, 1992), with one death.

Most investigations of this disease show that the use of water containing 50-100 mg/L NO3 results in methemoglobinemia levels within the normal physiological range of 0.5-2% although possibly at the high end of this range.

I could find no references to proper animal studies on methemoglobinemia using well waters.

In recent years, attention has shifted from nitrates to bacteria as the main cause of this disease (eg campylobacter jejeuni enteritis; Dagan et al, 1988).

Australia has extensive areas of nitrate-rich groundwaters, especially in remote areas. After considerable debate and studies, NHMRC (1990) reported that there had been no verified cases of methemoglinemia in Aboriginal and Torres Strait Islander infants.

It seems likely that the WHO standard of 10 mg/L NO3-N or the European administrative equivalent of 50 mg/L NO3 provide considerable margins for safety."

2.4 Summary of literature study

Table 2.5 is a summary of literature and includes the authors, a brief description of the investigation and the results.

Table 2.5: Summary of literature study done on Nitrates.

Author(s)	Description	Results
Ardakani *et al.*, (1974a).	Reported on the effect of nitrification on pH.	A decrease in pH from 7.4 to 5 was observed.
Ardakani *et al.*, (1974b).	Examined the movement and transformation of N in a 40 m^2 plot after application of NO2+ or NH_4^+. Soil solution samples were collected in ceramic cup lysimeters.	Following the application of NO_2^-, concentrations of NO_2^- decreased until reaching a steady state at 26 days. Constant levels of NO_2^- implied the population of Nitrobacter in the system had reached a steady state. NO_2^- was restricted to the upper 6 cm of the soil. About 35 days were required before consistent levels of NO_3^- were recorded following addition of NH_4^+. These results implied that about 35 days were required for Nitrosomonas to reach equilibrium in the system. By the end of the experiment Nitrosomonas was present at all depths but Nitrobacter was primarily at the surface.
Bauman and Schafer, (1985).	Introduced a conceptual model to estimate the amount of N introduced into the groundwater from septic tank systems.	Suggested that 4 parameters should be estimated. 1) Diluting capacity of the aquifer, 2) N loading of the aquifer, 3) potential for denitrification and 4) importance of aquifer for drinking water. Aquifers leading to wetlands or lakes should be treated differently than those used primarily for drinking water. Several factors should be considered in determining the potential for N groundwater pollution. These include the depth to water table, conductivity of the aquifer, aquifer size, NO_3^- background, geology and potential of denitrification.
Brown *et al*, (1984).	Examined N movement after applying STE to undisturbed monoliths of three soils over 2 years. Soil monoliths were 1.8 m long and had a surface area of 3.1 m^2. Textures for the 3 soils were sandy loam, sandy clay, sandy clay loam, clay or clay loam and clay.	Effluent from the sandy loam showed only background levels of $NH_4^+$for the first 18 months of monitoring. Thereafter a dramatic rise was observed which continued throughout the study. The rise was thought to occur after the exchange sites within the soil have been filled to capacity.

Table 2.5: Summary of literature study done on Nitrates – continued.

Ford *et al.*, (1980).	Analysed the N concentration in 164 wells in Colorado, U.S.A.	Higher concentrations of N were found in wells in which housing density was the greatest. Concentrations of NO_3^- > 10 mg/L were associated with housing densities of > 2.5 septic systems/km^2. A separation distance of at least 61 m between ST-SAF and groundwater wells were proposed.
Lance, (1972).	Studied the immobilisation of N after addition of waste water to a soil.	Less than 5 to 10% of the N were immobilised.
Patrick and Wyatt, (1964).	Studied the loss of N from soils due to alternating submergence and drying.	Observed that after the first 3 submergence-drying cycles, changes in the N form did not occur. The conclusion was that after 3 cycles microbes had used all reactive organic matter and further NO_3^- reduction would not occur.
Reneau, (1979).	Examined lateral movement of N from 3 ST-SAF on the coastal plain of Virginia, U.S.A. Soils were either fine loamy or coarse loamy textured. High water tables were observed at various times during the study period.	The amount of NO_3^- in water samples was shown to increase for the first 5 m from the ST-SAF and then decrease. Increases were the result of nitrification as aerobic conditions increased with distance from the ST-SAF. Reduction in NO_3^- after the first 5 m was attributed to denitrification.
Sikora and Keeney, (1976).	Examined effects of temperature on denitrification rates in 64 cm columns packed with dolomite limestone chips. Methanol and KNO_3^- were added to aerated STE.	Reduction of NO_3^- followed first order kinetics with 5°C showing the highest correlation and 20°C the lowest.
Stewart and Reneau, (1988).	Reported on the movement of N in soils treated with STE. These soils had high water tables and STE was applied at < 30 cm below the soil surface. Soils were poorly drained, fine, loamy, siliceous Ochraquults. Wells were placed at distances of 2.8 and 8.4 m from the ST-SAF to monitor NO_3^- concentrations.	Ratios of NO_3^-:Cl^- declined with distance from the ST-SAF indicating that denitrification was occurring. Based on NO_3^-:Cl^- ratios more than 90% of the NO_3^- recorded under the ST-SAF could not be accounted for at 8.4 m. These results suggest that denitrification is substantial in these poorly drained soil systems and minimal N pollution to the groundwater occurs at distances greater than 9 m.

Table 2.5: Summary of literature study done on Nitrates – continued.

Volz and Starr, (1977).	Conducted continuous leaching experiments to determine NO_3^- reduction and changes associated with microbial populations. Columns were packed with fine sandy loam soil material and maintained in anaerobic conditions. The columns were leached with NO_3^- and glucose solutions for 96 hours.	In the first 18 hours NO_3^- disappeared but concurrent increases in NO_2^- were not observed suggesting that denitrification of NO_3^- was occurring without NO_3^- reduction. Between 18 and 60 hours NO_2^- concentrations increased and then decreased. With time denitrifiers became a larger portion of the microbial population. Most C usage was associated with NO_3^- reduction and not denitrification.
Walker *et al.*, (1973).	Studied transformations and distributions of N within a septic tank subsurface soil adsorption field (ST-SAF).	Most of the soil N occurred in an organic form within the clogging mat at the soil-gravel interface. Older ST-SAF had higher concentrations of organic N in the clogging mat than younger ST-SAF. The NH_4^+concentration was highest just below the clogging mat end decreased rapidly with depth. A concurrent increase with depth of NO_3^- indicated that $NH_4^+$was rapidly being transformed to NO_3^-. Most nitrification occurred within the first 6 cm below the clogging mat and occurred within a couple of hours.

2.5 Conclusions

1. Nitrate pollution will certainly have a negative effect on human (infants) health as well as ecological environments. The nitrate load will be an important factor when the effect on health and ecology is determined.

2. On a world-wide basis the study of nitrates have been considered as important, and the mechanisms and processes that will influence the migration of nitrates through the sub-surface system have been studied extensively.

3. The presence of nitrate pollution could be an indication of other types of contamination such as bacterial or viral contamination.

4. As with all types of groundwater contamination, it is difficult to try and "clean up" an aquifer. The pollution source must be identified. For this purpose the utilisation of ^{15}N isotopic analysis could be helpful.

5. In recent years, the concern regarding nitrate pollution became less and more emphasis is placed on bacterial and viral pollution when dealing with human health concerns.

CHAPTER 3

Bacteria

3.1 Introduction

When dealing with pitlatrines and septic tank systems, bacterial contamination is one of the major concerns regarding groundwater quality. Bacteria in the groundwater environment can initiate significant health problems and promote outbreaks of waterborne disease.

Pollution problems because of bacteria have been recorded all over the world and are a matter of utmost concern. Especially in third world countries where the infrastructure to cope with such an outbreak is either of a poor quality or non-existent.

Table 3.1 lists the major diseases associated with bacteriological pollution as well as the bacteria and their main sources. It also lists the frequency of monitoring and priority of monitoring.

Table 3.1: Overview of bacteria and the major diseases associated with each.

Bacteria			
Major disease	**Organism name**	**Major reservoirs/primary sources**	**Monitoring frequency**
Typhoid fever	*Salmonella typhi*	Human feaces	Frequent surveys. Identified as high priority.
Paratyphoid fever	*Salmonella paratyphi*	Human feaces	
Salmonellosis	Other Salmonella	Human/animal feaces	
Bacillary dysentery	Shigella	Human feaces	
Cholera	*Vibrio cholerae*	Human feaces	
Gastro-enteritis	*Escherichia coli*	Human feaces	
Gastro-enteritis	*Yersinia enterocolitica*	Human/animal feaces	
Gastro-enteritis	*Campylobacter jejuni*	Human/animal feaces	

3.2 Discussion

The concentration of bacteria movement through the soil is affected by the following two processes:

1. Inactivation (die-off time).
2. Attenuation.

The survival rate of bacteria in the soil as well as the groundwater environment is very important. This will be the deciding factor in whether the water quality in a nearby borehole or well will be influenced negatively. Under South African conditions fracture systems are dominant and this could complicate the matter even more. Even bacteria with a fast die-off rate would be able to reach a production well situated quite a distance away. Systems where vertical fractures intersect horizontal fractures are therefore a real headache when it comes to the influence of pitlatrines or septic tank systems on water quality.

Two characteristics of the soil are of importance when the inactivation process is considered:

1. Temperature.
2. Soil moisture content.

Generally, cooler moist soils show longer survival rates of bacteria. Survival times of at least 70 days in groundwater were recorded (Bitton *et al.*, 1983) and in soil the survival times were greater than 120 days (Kibbey *et al.*, 1978).

Attenuation of bacteria in soil or aquifer matrix consists of the two following processes:

1. Filtration.
2. Adsorption.

Both the above-mentioned processes are primarily influenced by seven parameters:

1. Bacteria type and strain.

2. Flow conditions.

3. pH.

4. Soil moisture content.

5. Particle size distribution of the soil/matrix.

6. Degree of soil/matrix structure.

7. The nature and concentration of electrolytes.

A soil with fine texture, minimal structure and low pH will adsorb and filter nearly all bacteria. Therefore, concerns of bacteria polluting groundwater from septic tanks and pitlatrines situated in a region where the soil is well drained with a fine to medium texture are unfounded.

Bacterial pollution, however, has been shown to be of major concern in situations where the soils are coarse with considerable structure. Another indicator that should warn of possible groundwater contamination is areas where a shallow watertable is present.

Clogging is another process that enhances the filtration abilities of a soil. As the bacteria filters through the soil, a percentage will attach themselves to the soil particles. The effect will be clogging of the microscopic pores between the soil particles. As new bacteria filters from the top through the soil, this clogging mat that has formed will help in slowing down the migration of the newly added bacteria. This lengthening of travel time could ensure that the bacteria would die off before they are able to reach the groundwater.

Field studies done on the effect of saturated soil conditions regarding bacterial movement is one of the most researched topics in this field. Flow takes place primarily through the larger soil pores and channels under saturated conditions. If these pores are larger than the bacteria size and conditions for adsorption are less than ideal, significant movement of bacteria may occur.

3.3 Case Studies

A major factor that influences the retardation as well as inactivation of bacteria is the thickness of the unsaturated zone. Most studies done on pollution problems where bacteria are involved indicate a shallow watertable.

When analysing a water sample for bacterial contamination, indicator organisms of the human intestine, such as fecal coliforms and fecal streptococci, are most often assayed (Bouma *et al.,* 1972). Elevated levels of fecal coliforms indicate that water is contaminated and may be of risk to humans.

Bacterial pollution of groundwater from pitlatrines or septic systems appears fairly widespread. Dewalle and Schaff (1980), examined well records and water samples near Takoma, Washington over a 30 year period. The area has a population of 242,000 and 100,000 residents make use of an on-site wastewater disposal system (OSWDS). Glacial deposits underlie the study area. As many as 35% of the wells located in the areas served primarily by OSWDS were contaminated with coliforms.

A study by LeChevallier and Seidler (1980) in the rural areas in Oregon, U.S.A., found Staphylococcus aureous, a common agent of food poisoning, and coliforms in 6% and 15% of 320 rural drinking water samples respectively. However, no correlation could be found between the presence of coliforms and Staphylococcus aureous. Their conclusion was that coliform analysis alone may not be a satisfactory way to measure drinking water quality.

Sandhu *et al.* (1979) conducted a study on the effect of distance from an OSWDS in South Carolina, U.S.A. Data suggested that as the distance increased, the degree of pollution decreased.

Levels of bacteria in ground as well as surface waters of a small (80 ha) watershed in Virginia, U.S.A., were examined by Reneau and Pettry (1975). The soils that were encountered were divided into three groups based on their suitability for septic tank soil adsorption field (ST-SAF). Only 17% of the soils were suitable, 41% marginal and 42% unsuitable. During periods of high precipitation, ST-SAF systems constructed in marginal soils failed, while the failure rate in ST-SAF systems situated in the unsuitable soils was 100%. Samples of both surface and groundwater obtained near failing ST-SAF systems showed high numbers of total and fecal coliforms.

Table 3.2 is a summary of literature and includes the authors, a brief description of the investigation and the results.

Table 3.2: Summary of literature study done on Bacteria.

Author(s)	Description	Results
Bitton *et al.*, (1974).	Introduced 2 strains of Klebsiella Aerogenes in 2 cm diameter, 11.5 cm long soil columns. Four different soils ranging in particle size distributions from 90% sand to 58% clay were used.	A definite difference in retention was observed between the different bacteria strains. Sandy soils showed less retention of bacteria than clayey soils.
Bouwer *et al.*, (1976).	Examined the movement of fecal coliforms in a reticulated infiltration (RI) system.	Most fecal coliforms were attenuated in the upper 60 cm. After a drying period the movement of bacteria was enhanced. Drying removed clogging material and reduced natural microbial populations. This reduced the finer filter abilities of the soil as well as the competition for the fecal coliforms.
Brown *et al.*, (1983).	Examined the movement and distribution of bacteria below 3 septic tank systems. Soil types were sandy clay, clay and sandy loam. Sampling was done 120 cm below drain lines. Effects of vertical channels were also investigated up to a depth of 90 cm.	During second year only 3 out of 133 samples tested + for fecal coliforms. High levels for fecal coliforms were observed where vertical channels were encountered. Soils without channels did not have the same concentration of fecal coliforms with depth.
Cogger and Carlile, (1984).	Wells were placed at 1.5 and 7.5 m from septic tank systems. A total of 15 sites were used. The movement of bacteria was recorded at these different sites.	Continuously saturated systems showed bacterial concentrations significantly higher than systems with lower watertables. A substantial difference in concentration was also observed at different distances. Higher levels of bacteria were observed where the groundwater gradient was the highest.
Hagedorn *et al.*, (1978).	Introduced antibiotic resistant bacteria into poorly drained soil at depths of 30 and 60 cm. Clay contents varied from 27 – 45%.	Both E. coli and S. faecalis were present in the soil after 32 days.
Kibbey *et al.*, (1978).	Examined the survival of fecal streptococci under various soil moisture contents and temperatures. Five soils from A horizons were used. Soil moisture content ranged from saturation to air-dried and temperatures from 4 to 37°C.	Bacteria survived longer under cooler moister conditions, regardless of the soil type. This longer survival time could be accredited to lower activity from other competitive soil organisms due to cooler conditions. A 95% reduction in bacteria occurred within 53 days for 4 of the soils. 5% Bacteria were still alive in the other soil after 120 days.

Table 3.2: Summary of literature study done on Bacteria - continue.

McFetters *et al.*, (1974).	Comparison of survival rates of indicator bacteria and enteric pathogens in well water over 3 and 4 day periods.	Coliform death rates were greater with more variation than enterococcus. Results in terms of survival times: Aeromonas sp.>Shigellae>Fecal streptococci>Coliforms=Salmonella>Streptococcus equinus>Vibrio cholera>Salmonella typhi.
McGinnis and DeWalle, (1983).	Reported on the movement of typhoid organisms in saturated soils leading to an outbreak of typhoid fever in Yakima, Washington. A ST-SAF located 64 m from the groundwater well was responsible for the contamination. The watertable was at a depth of less than 2.1 m from soil surface and the soil type was terrace deposits.	Added dye to the ST-SAF reached the groundwater well within 36 hours.
Parker and Mee, (1982).	Examined survival of Salmonella adelaide and fecal coliforms in two coarse sands amended with septic tank effluent.	Both showed similar survival rates for one soil but not for another. The average survival of >10% of fecal coliforms was 64 days, with 46 days for equivalent survival of Salmonella.
Peterson and Ward, (1988,1989).	Presented results from simulation models used in predicting bacterial movement in coarse soils.	Results suggested that in unsaturated, coarse textured soils, bacterial movement may be more than 1.2 m from the point of application. Watertable depths below drain lines should therefore be more than 1.2 m in course textured soils.
Strenstrom and Hoffner, (1982).	Suggested that bacteria surface characteristics are more important than the actual bacterial size when explaining bacteria reductions in a soil. Made use of a sand soil of which the pores between soil particles were larger than the bacterial cell size.	The filtration process is inadequate to describe the decrease in bacterial concentration. Only adsorption could explain this. Adsorption can occur as bacteria actively attach to soils using extracellular polymers or fibria or as a result of electrical charges.
Tare and Bokil, (1982).	Tried to determine the effect of various particle size distributions on removal of bacteria in columns from 7.5 to 75 cm in length. Sand, silt and clay particles were mixed at various ratios from 0 to 100% sand.	Bacterial removal was highest in mixtures with higher percentages of clay and silt. It was concluded that a mixture of 40% < 75 µm and 60% > 75 µm soil particles was the most efficient for the attenuation of bacteria.

Table 3.2: Summary of literature study done on Bacteria - continue.

Tate, (1978).	Studied survival of E. coli in a muck and fine sand soil over an 8-day period.	In the muck 3 times more E. coli survived than in the fine sand. Initial bacterial population was shown to effect survival. A smaller initial bacterial population had a greater number of bacteria that survived 8 days.
Ver Hey and Woessner, (1988).	Movement of bacteria from septic tank subsurface attenuation fields (ST-SAF) placed in coarse textured alluvial soils in Montana, U.S.A.	Bacteria were found in samples collected just above the watertable at depths of 2.4 and 4.3 m below the surface.

3.4 Conclusions

1. Bacterial pollution of groundwater resources is problematic due to the diseases associated with it.

2. Most of the processes that will influence the migration of bacteria through the soil as well as the groundwater environment are well recorded in the literature.

3. Fractured aquifers are very vulnerable for bacterial pollution and to attempt to clean up a contaminated aquifer is costly as well as nearly impossible.

4. The escalation in world population, especially in third world countries, increases the possibility of bacterial pollution of groundwater and the diseases associated with it.

CHAPTER 4

Viruses

4.1 Introduction

Viruses are small microbes, generally less than 250 nm and humans excrete over 100 different viruses. Viruses behave as a colloid in the soil system.

Table 4.1 lists the major diseases associated with virus pollution, as well as the viruses and their main sources. It also lists the frequency of monitoring and priority of monitoring.

Table 4.1: Major diseases associated with virus pollution.

Viruses			
Major disease	**Organism name**	**Major reservoirs/primary sources**	**Monitoring frequency**
Poliomyelitis	Polioviruses	Human faeces	Infrequent surveys to ensure that the water source used for drinking water supply is free of enteric viruses.
Aseptic meningitis	Coxsackieviruses A	Human faeces	
Aseptic meningitis	Coxsackieviruses B	Human faeces	
Aseptic meningitis	Echoviruses	Human faeces	
Encephalitis	Other enteroviruses	Human faeces	
Upper respiratory illness	Reoviruses	Human/animal faeces	
Upper respiratory illness	Adenoviruses	Human faeces	
Gastrointestinal illness	Reoviruses	Human faeces	
Gastrointestinal illness	Adenoviruses	Human faeces	
Gastro-enteritis	Rotaviruses	Human faeces	
Gastro-enteritis	Norwalkviruses	Human faeces	
Infectious hepatitis	Hepatitis A virus	Human faeces	

4.2 Discussion

The two most important means of reducing the number of viruses in the soil or aquifer matrix are:

1. Inactivation.

2. Attenuation.

Different types and different strains of viruses will have different rates of survival. Inactivation of viruses is dependent on the following factors:

1. Temperature.
2. Degree of adsorption.
3. Soil type and composition.
4. Soil moisture content.
5. Amount of microbial competition.

The most important factor of the above-mentioned is the temperature. At lower temperatures the survival rate of the viruses increases and vice versa.

Adsorption is the primary process of attenuation regarding virus migration through the soil or matrix of the aquifer. Two types of forces are involved during the adsorption process:

1. Attractive and repulsive forces between the virus and the soil particles within the diffuse double layer.
2. Van der Waals forces.

The factors that come into play when the adsorption process are considered are:

1. The charge of the soil as well as the virus.
2. pH.
3. The isoelectric point (IEP) of the virus, which is the pH where the virus will have a neutral charge.
4. The concentration and valence of the cations present in the soil.
5. The amount of organic colloids in the system.

Viruses are amphoteric particles having either a positive or a negative charge, depending on the pH. This implies that soil particles with negative charges will attract positively charged viruses and adsorption will take place. Most viruses have an IEP larger than 5, which means that a reduction of pH will result in an increase in virus adsorption.

If any multivalent cations are present, they could act as a bridge between negatively charged soil particles and viruses. Thus an enhanced cation concentration will also increase the adsorption of viruses. Organic colloids in the system, however, can reduce adsorption of viruses due to the fact that they will compete with the viruses for adsorption sites on the soil particles.

Because of the fact that viruses are so much smaller than bacteria, it is believed by some that the effect of viruses on the groundwater environment is a greater threat than that posed by bacteria. The diseases or health risks from viral infection are also of a more serious nature when compared to those of bacteria.

Another problem encountered with the analysis of samples is the large number of viruses excreted by man. Making assays of all of these are not possible. These assay problems are magnified when the difficulties in concentrating viruses from groundwater into a sample small enough to assay are considered (Wellings *et al.*, 1974).

Viruses tend to clump together and are not very well distributed through the groundwater environment (Wellings *et al.*, 1975). It was also determined that there are some differences between viruses that are prepared and analysed in a laboratory environment, and the respective virus that occurs naturally. This could imply differences in survival rates, which could be vital in the concomitant decision making process and risk analysis regarding water quality (Wellings *et al.*, 1974).

As in any other science where analysis of samples are considered, sampling techniques are also one of the problems that contribute to wrong answers. Even using ceramic cup samplers during analysis could lead to inaccurate values because the viruses are small enough to be adsorbed by the pores in the cup's wall and a lower concentration value will be the result. A loss of up to 74% was measured by Powelson *et al.* (1990).

Viruses in wastewater could also attach themselves to solids. During concentration techniques, viruses attached to suspended particles may be filtered, discarded and therefore left undetected. Again this will indicate much less virus pollution than actually exists (Wellings *et al.*, 1976).

4.3 Case studies

Table 4.2 is a summary of the case studies found in the literature.

Table 4.2: Summary of literature study done on Viruses.

Author(s)	Description	Results
Gerba and Lance, (1978).	Examined the adsorption of Polioviruses to loamy and.	An increase in adsorption was observed with additions of 0.01 M $Cacl_2$, but not 0.001 M $Cacl_2$. Most viruses showed a significant positive correlation with pH. All of the viruses showed the most adsorption to 2 soils with pH values < 5.
Goyal and Gerba, (1979).	Compared adsorption of 28 viruses and 5 bacteriophages to 9 soils. Soils ranged in clay content from 3 to 54%.	Strains of Echo virus ranged in adsorption from 0 to 97%, while strains of Coxsackie ranged from 0 to 30% adsorption. No significant differences in adsorption were observed for strains of Poliovirus. These data suggested that virus strain is as important as type in explaining adsorptive properties of viruses.
Green and Cliver, (1975).	Examined adsorption of viruses in the presence of septic tank effluent (STE).	Adsorption to fresh sand was 96% and after STE had been applied adsorption was reduced to 50%. This shows that adsorption is affected by the mineral composition of the soil as well as the presence of organic matter.
Hurst *et al.*, (1980a).	Studied survival of viruses in a RI system. Viruses and sand were placed in a tube and the tube was buried vertically in the RI system.	A 2 day resting (drying) period accounted for inactivation of 83% of the viruses at a 2.5 cm depth and 50% inactivation at depths from 2.5 to 20 cm. Virus survival was greater at 60 cm depths than shallower depths. It was concluded that differences in virus survival in this system was related to lower aerobic conditions, lower level;s of aerobic microbes and lower degree of drying at the 60 cm depth.

Table 4.2: Summary of literature study done on Viruses – continued.

Hurst *et al.*, (1980b).	Examined various soil and environmental factors affecting survival of viruses in soil. Survival of 5 viruses and 2 bacteriophages were examined in 9 soils. Soil characteristics and properties were well documented and temperature, soil moisture content and O_2 conditions were varied during the studies.	Temperature was the most important factor in explaining survival, regardless of other properties. Lower temperature showed higher survival rates.
Jorgenson and Lund, (1985).	Looked at survival rates of viruses in sludge and soils. Temperatures ranged between 4 and 7°C.	Viruses were detected in sludge up to 21 weeks from inoculation. A 1 log reduction was observed in the population of viruses in a sandy soil within 8 weeks but a similar reduction in virus population was not recorded for a sandy loam soil until 20 weeks had passed. Viruses were still active after 34 weeks.
Koya and Chaudhuri, (1977).	Evaluated the adsorption of bacteriophage MS-2 to 3 soils. Soils were either silt or clay loams.	Most viruses adsorbed in the first 20 to 30 minutes. Minimal adsorption occurred after 80 minutes. Increases in soil pH decreased virus adsorption, while the introduction of a divalent cation increased virus adsorption.
Murray and Laband, (1979).	Studied the degradation of the Poliovirus by adsorption onto several inorganic compounds. Poliovirus was adsorbed to SiO_2, Fe_2O_3, Al_2O_3, Mn_2O and CuO. Inactivation of the poliovirus was monitored following desorption.	No inactivation and only minor amounts were observed following desorption of viruses from SiO_2 and Fe_2O_3 respectively. Significant amounts of inactivation were observed following desorption from MnO_2, Al_2O_3 and CuO. It was suggested that compounds with high van der Waals forces may inactivate viruses.
Sobsey and Hickey, (1985).	Looked at the adsorption of Polio and Reo viruses to soils.	Virus adsorption was shown to occur within 15 minutes. Lower pH values or addition of Mg_2^+ increased adsorption.
Sobsey *et al.*, (1980).	Studied the survival of polio and Reo viruses following the application of domestic sewage wastewater to soils.	Sterile soils showed greater survival times than unsterile soil, suggesting microbial activity affected survival rates. Average survival rates of reovirus was 35 and 123 days and poliovirus was 42 and 95 days for sterile and unsterile soil respectively.

Table 4.2: Summary of literature study done on Viruses – continued.

Yates *et al.*, (1985).	Samples from 11 wells throughout the U.S.A. were collected and kept at the same temperature as when sampled. The same samples were also kept at 2 other temperatures. Polio, Echo and MS-2 viruses were added to the samples and the survival rates documented. Samples were analyzed for NO_3^-, NH_4^+, SO_4^-, Fe, Ca, Mg, TDS and pH.	Over 77% of the variability in survival rates could be explained by temperature. Viruses maintained at lower rates survived longer. Survival of Polio, MS-2 and Echo viruses were similar.
Yeager and O'Brien, (1979).	Examined the inactivation of viruses following adsorption to soil. Poliovirus type 1 was applied to dry and moist sand and sandy loam soils.	Inactivation of viruses occurred in both dry and moist soils. In dry soils however, viruses could be eluted that were not inactivated. Yeager and O'Brien suggested that at least 2 separate mechanisms may be involved in virus inactivation depending upon soil moisture conditions.

4.4 Conclusions

1. Viruses might pose a greater threat than bacteria to the groundwater environment because they are much smaller than bacteria.

2. One of the main problems with viruses is that results from laboratory analysis often do not represent the concentration or type of strain of viruses from the sampling borehole.

3. The fact that viruses can survive up to 34 weeks (Jorgenson and Lund, 1985) again poses a major threat to fractured aquifers.

4. The possibility of outbreaks of viral diseases also becomes much more real with the escalation in world population.

CHAPTER 5

Case studies

5.1 University of the Free State Campus Test Site

5.1.1 Introduction

The Campus Test Site is located on the campus of the University of the Free State in Bloemfontein. An area of 34560 m^2 is covered by twenty-five percussion boreholes (0.16 m in diameter) and seven core boreholes (0.05 m in diameter). In an attempt intersect all possible fracture positions, two of the core boreholes were drilled at an angle of 45°.

Figure 5.1 shows the Campus Test Site with the borehole positions.

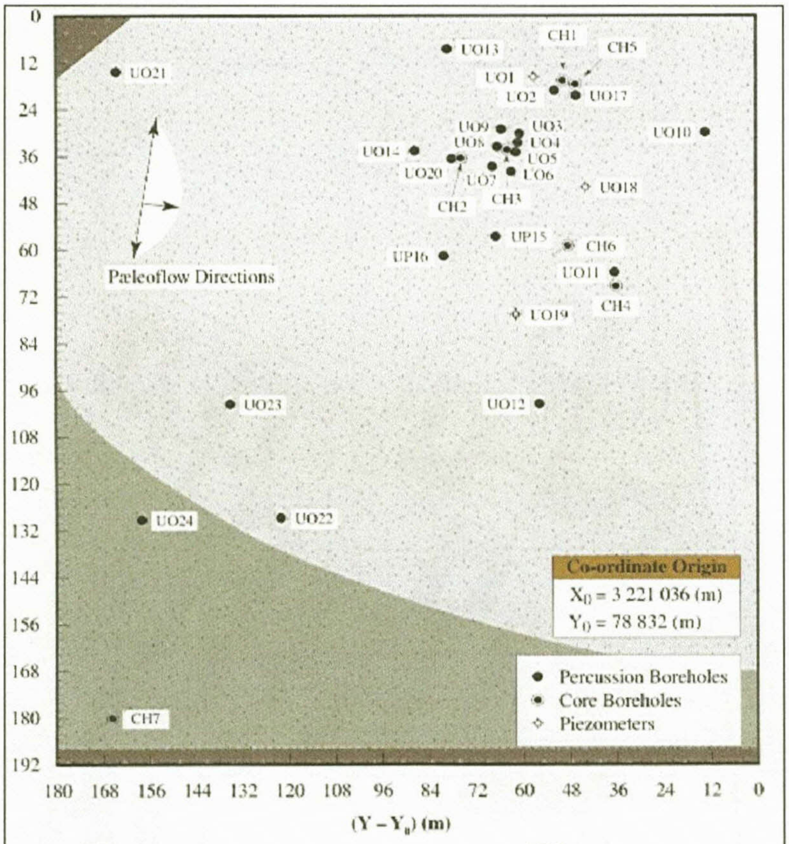


Figure 5.1: Plan view of the boreholes and geological map of the sandstones on the Campus Test Site, (Botha *et al.*, 1998).

5.1.2 General geology and geohydrology

According to Botha *et al.* (1998), the geology consists of sandstone, mudstone and shale (Adelaide subgroup of the Karoo Supergroup) deposited under fluvial conditions. Vertical lithofacies are present and are an indication of vertical accession of deposits in flood plains, shallow lakes and channels. The main geological unit of the aquifer consists of the sandstone and it exhibits a sheet-like to tabular structure, characteristic of deposition in fluvial environments.

Core samples indicate parallel bedding plane fractures of which the frequency decreases downward from the more weathered zones at the top to thicker and more competent units below. At a depth of about 21 m the most significant bedding plane fracture is encountered. It is a horizontal fracture that follows the contours of the sandstone unit. In the more weathered zones, diagonal fractures occur which intersect parallel bedding plane fractures, suggesting secondary fracturing caused by post-lithification processes.

The groundwater environment at the Campus Test Site can be regarded as one system. Although the black shale layer encountered at 14-17 m might be an aquitard, it is believed that if given enough time, recharge water will be able to migrate through it. The large number of boreholes at the site also serve as preferred pathways and water leaks from the upper, more dense formations (mudstone and siltstone) towards the lower formations via the boreholes.

The water-carrying formation below the shale layer consist of sandstone and is the main source of groundwater. High and low yielding boreholes are present. A bedding plane fracture zone at 21 m is responsible for the difference between high yielding boreholes and low yielding boreholes at the test site. If this fracture zone is not encountered, the yield of the borehole drops from approximately 3-4 L/s to 0.5 L/s.

Figures 5.2 and 5.3 show the geological profiles of 24 percussion boreholes and a schematic diagram of the different geological formations and the groundwater system present on the Campus Test Site.

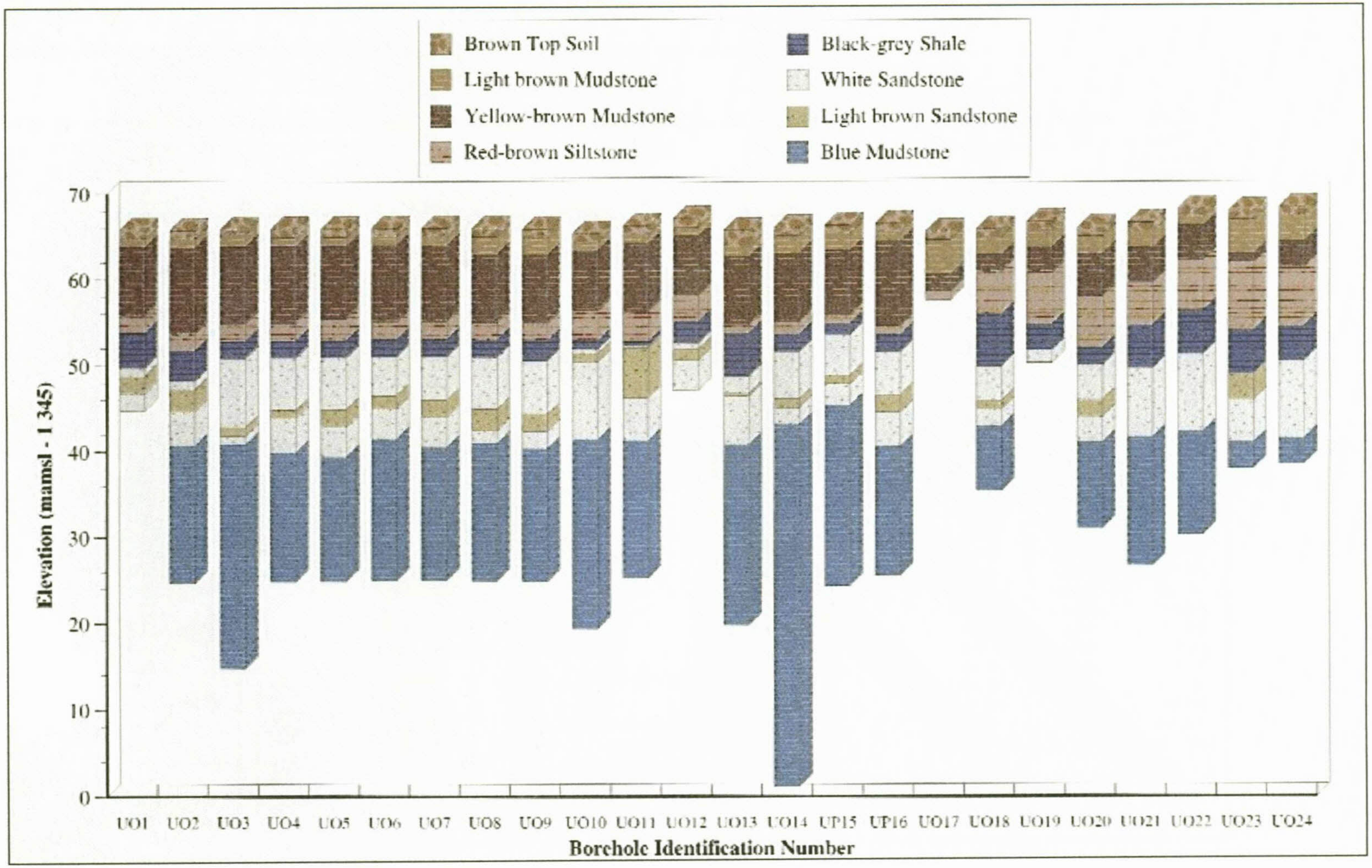


Figure 5.2: Geological profiles of 24 percussion boreholes drilled on the Campus Test Site, (Botha *et al.*, 1998).

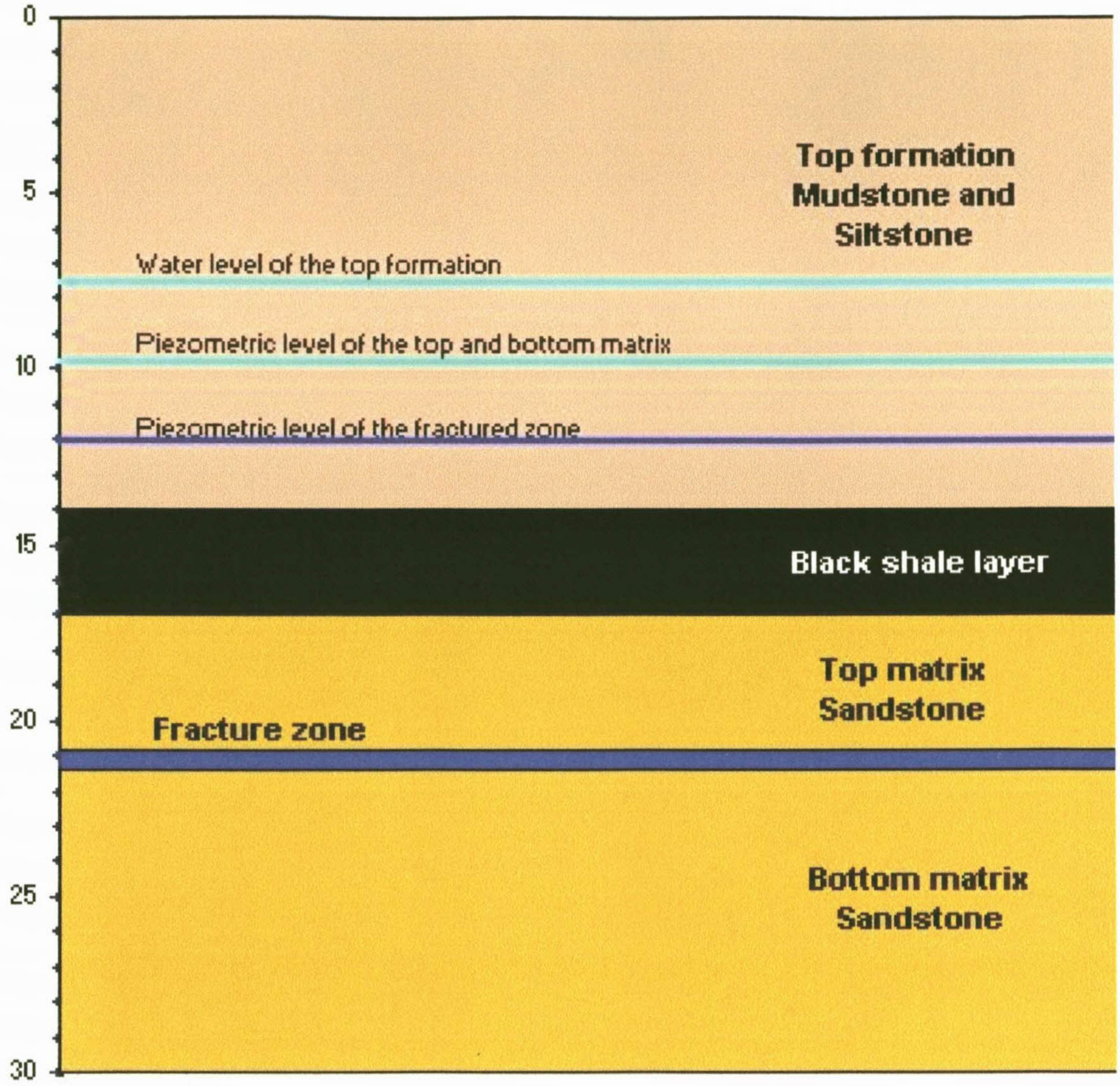


Figure 5.3: Schematic diagram of the different geological formations and groundwater system present on the Campus Test Site.

5.1.3 Tracer tests

Tracer tests were conducted on the Campus Test Site as part of a project sponsored by the WRC to determine the suitability of artificial and natural tracers in order to formulate a management strategy for rural water supply in secondary aquifers. A tracer is an identifiable substance which, from the examination of their behaviour in a flow regime, may be used to infer the general behaviour of the medium (Van Wyk 1998). Tracers can be devided into (Van Wyk 1998):

1. Natural tracers.
2. Artificial tracers.

Artificial tracers can be categorised by their method of analysis (Van Wyk 1998), e.g.:

1. Radioactive tracers: These elements are detected by means of their radioactive emissions.
2. Activated tracers: Elements are stable during use, but activated to emit radioactivity during analysis.
3. Chemical tracers: Detection is based on mass (mass spetrometry), orbital electron arrangements (chemical reactions) or shell binding energies (adsorption or emission properties).
4. Particulate tracers: Tracers detected by collection, weighing or counting of individual particles.

The tests done on the saturated zone were conducted by Van Wyk (1998) and the following is a short summary of the work done by him.

Tracer tests can be divided into two main groups:

1. Natural gradient tracer tests.
2. Forced gradient tracer tests.

In fractured formations natural gradient tracer tests are scarce. Because of the heterogeneity of secondary aquifers, natural gradient tests are usually associated with porous media such as unconsolidated sands.

One type of tracer test that can be used under natural or forced gradient conditions is the dilution tracer test. A dilution test is where the tracer is introduced into a borehole and the decay in concentration of the tracer is measured in the same borehole. By making use of this technique, the groundwater flux can be estimated.

Forced gradient tracer test can be classified into the following flow fields (Van Wyk 1998):

1. Radial convergent.
2. Radial divergent.
3. Injection-withdrawal.

Radial divergent and convergent flow fields can be created, by either pumping water into the aquifer or abstracting water from it. While the radial convergent test is easier to conduct under field conditions the advantage of the divergent test is that by introducing one tracer into one borehole, more than one observation borehole at different distances can be used. The injection-withdrawal method may be conducted in a recirculating or non-recirculating mode. For the recirculating mode, water is pumped from an abstraction borehole and reintroduced into the aquifer by means of an injection borehole. Under field conditions the non-recirculating method is easier to conduct and the data gathered easier to analyse.

5.1.3.1 Saturated zone

An extensive study by Van Wyk (1998) was conducted regarding tracer tests on secondary aquifers in the saturated zone. His work is summarised in Tables 5.1-5.3.

Table 5.1: Summary of the tracer tests conducted on the Campus Test Site, (Van Wyk, 1998).

Test ID	Type	Flow conditions	Borehole(s)
DT 1	Dilution	Natural	UO 20
DT 2	Dilution	Natural	UO 20
DT 3	Dilution	In convergent flow field	UO 20
DT 4	Dilution	In convergent flow field	UO 20
DT 5	Dilution	In convergent flow field	UO 20
CV 1	Tracer migration test	Radial convergent	UO 20-UO 5
CV 2	Tracer migration test	Radial convergent	UO 20-UO 5
CV 3	Tracer migration test	Radial convergent	UO 6-UO 5
CV 4	Tracer migration test	Radial convergent	UO 8-UO 5
CV 5	Tracer migration test	Radial convergent	UO7-UO 5

Table 5.2: Summary of the test conditions for tracer experiments conducted on the Campus Terrain during 1996/1997 using a radial convergent flow format (Van Wyk, 1998).

TEST ID	**CV 1**	**CV 2**	**CV 3**
Date	02/10/96	11/03/97	16/03/97
Injection well	UO20	UO20	UO6
Pumped well	UO 5	UO5	UO5
6 Well radius(m)	0.0825	0.0825	0.0825
Radial distance (m)	15	15	4.5
INJECTION WELL			
Well conditions	Packer unit	Packer unit	Packer unit
Position of packer/mixing pump (m)	21m below collar	21.3 m below collar	23.07 below collar
Injection well volume (l)	20	-	20
Injection method	In-situ	In-situ	From surface
Tracer	NaBr	NaBr / Fluorecein	Fluorecein
Volume of tracer solution (ml)	200	200	-
Concentration of tracer solution (g/l)	300	-	-
Time of tracer injection	16:15	12/03/97 at 15:40	16:06
Tracer concentration after injection (C_0) (mg/l)	3000	N.A.	250
Tracer mass injected (g)	60	NaBr = 9,24 Fluorecein = 1,55	5
Rate of tracer decay in the injection well:	See dilution test (DT4)	-	-
PUMPING WELL			
Well conditions	Open	Open	Open
Pump position (m below collar level)	23	23	23
Abstraction rate (l/sec)	0.35	0.205	0.217
Std. Deviation of flow rate (l/sec)	-	-	-
Head difference after steady state (m)	0.316	-	0.02
Tracer detection technique	Sample collection	Sample collection (both tracers)	On-line (Fluorometer)
Time of first tracer detection (min)	58	85	60
Time of peak arrival (min)	148	180 (Both tracers)	155
Tracer concentration of peak, C_P (mg/l)	6.59	NaBr = 0.673 Fluorecein = 0.098	0.42
Tracer mass recovery (g)	33	Fluorecein = 0.507	1.523

Table 5.2: Summary of the test conditions for tracer experiments conducted on the Campus Terrain during 1996/1997 using a radial convergent flow format (Van Wyk, 1998) - continued.

TEST ID	**CV 4**	**CV 5**	**CV6**
Date	21/04/97	07/05/97	
Injection well	UO8	UO7	UO23
Pumped well	UO5	UO5	UO5
Well radius (m)	0.0825	0.0825	0.0825
Radial distance (m)	4	7	84
INJECTION WELL			
Well conditions	Packer unit	Packer unit	Packer unit
Position of packer/mixing pump (m)	22.8	23.01	-
Injection well volume (l)	20	20	20
Injection method	From surface	From surface	From surface
Tracer	Fluorecein	Fluorecein	Fluorecein
Volume of tracer solution (ml)	-	-	-
Concentration of tracer solution (g/l)	-	-	-
Time of tracer injection	16:35	16:12	-
Tracer concentration after injection (C_0) (mg/l)	50	50	1000
Tracer mass injected (g)	1	1	20
Rate of tracer decay in the injection well:	-	-	-
PUMPING WELL			
Well conditions	Open	Open	Open
Pump position (m below collar level)	23	23	23
Abstraction rate (l/sec)	0.217	0.225	0.225
Std. Deviation of flow rate (l/sec)	-	N.A.	-
Head difference after steady state (m)	0.06	-	-
Tracer detection technique	On-line (fluorometer)	On-line (fluorometer)	On-line (fluorometer)
Time of first tracer detection (min)	28	60	545
Time of peak arrival (min)	108	176	665
Tracer concentration of peak, C_P (mg/l)	0.441	0.232	0,00189 = 1,897 ppb
Tracer mass recovery (g)	1.24	0.865	0,029

Table 5.3: Summary on the results of the modelling exercise of the tracer data, (Van Wyk, 1998).

TEST ID	CV1 UO20-U05	CV2 UO20-UO5	CV3 UO6-UO5	CV4 UO8-UO5	CV5 UO7-UO5
MODEL INPUT DATA					
Mass (kg)	0,0358	0,000507	0,001523	0,001248	0,0008728
Distance between wells (m)	15	15	4,5	4,5	6,3
Abstraction rate(m^3/day)	30,24	17,712	18,748	18,734	19,44
MODEL RESULTS					
Mean pore velocity, v (m/day)	76,65	67,55	22,57	29,03	30,195
Longitudinal dispersivity, α_L	2,65	2,24	0,84	1,255	1,0868
Aquifer thickness (m)	0,173	0,178	0,055	0,103	0,0695
OTHER CALCULATIONS					
Mean pore velocity from hand calculations (m/day)	90	54	26,12	36,82	33,85

5.1.3.2 Unsaturated (Vadose) zone

Tracer tests in the unsaturated zone were conducted to simulate flow from a septic tank or pitlatrine. Fluorecein was used as a tracer to determine vertical travel times of a pollution source through the unsaturated zone and the further migration thereof towards a production borehole.

Two shallow boreholes were drilled to a depth of 5 m on the upstream side of boreholes UO7 and UO23. Fluorecein was introduced into these "pitlatrine" boreholes and UO7 and UO23 were pumped for a duration of 1 hour per day at 0.2 L/s. The reason for the low abstraction rate was to keep conditions as natural as possible and not to create a too large cone of depression. While the borehole was pumped, the outflow was channelled through a fluorometer to measure the concentration of Fluorecein in the water.

Figure 5.4 is a graphic representation of the setup that was used on the Campus Test Site.

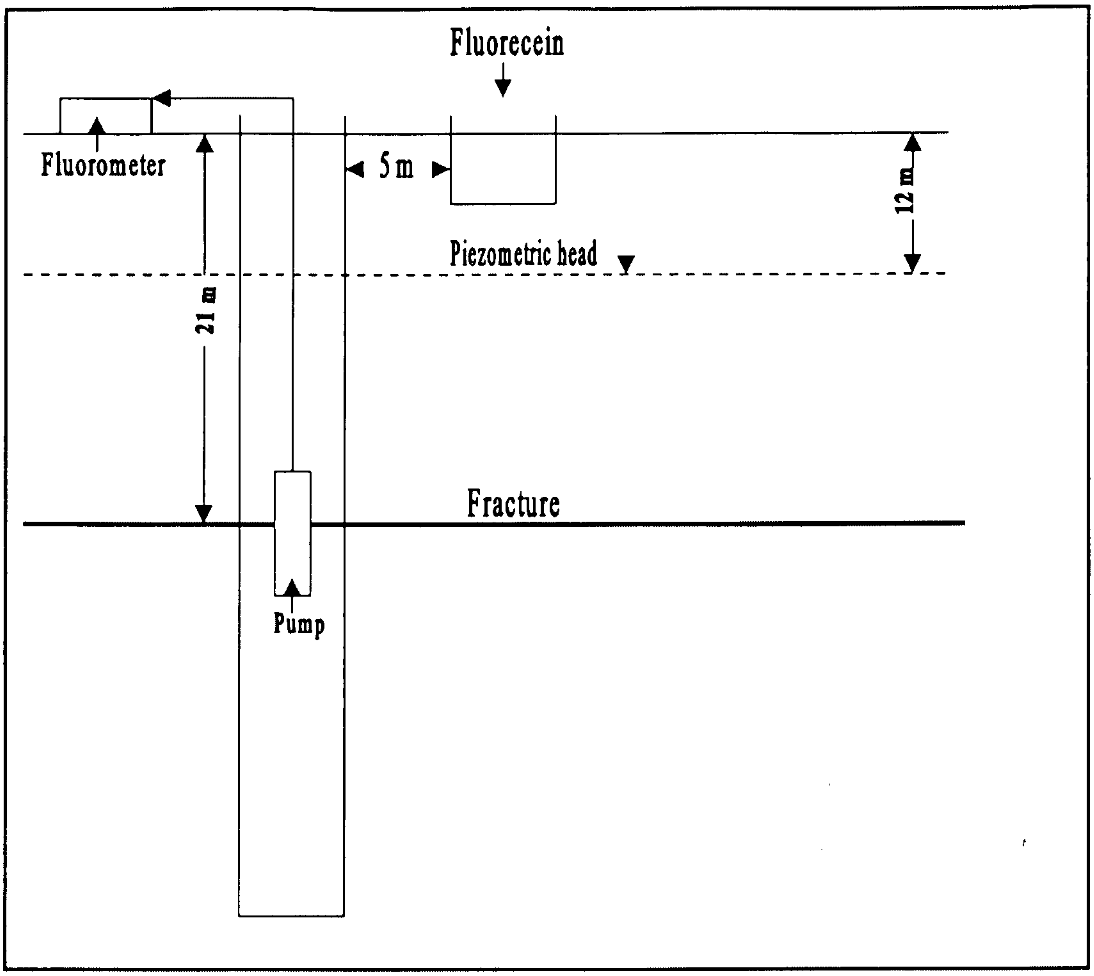


Figure 5.4: Graphic representation of tracer test setup for the unsaturated zone at the Campus Test Site.

When the migration of the tracer is considered, the importance of piezometers cannot be stressed enough. The "waterlevels" measured in boreholes UO7 and UO23 must be the piezometric head of the bottom and main aquifer. This can be seen if we compare the waterlevel of borehole UO 1 at ±8 m with the piezometric heads measured in boreholes UO7 and UO23 of ±12 m. Any leakage from the first aquifer down to the second aquifer by means of preferred pathways (boreholes) will be compensated for by the high K-value of the fracture.

The importance of piezometers is realised when the migration process of the tracer is considered. The reasons can be described by the following two scenarios:

1. If the level measured in boreholes UO7 and UO23 are waterlevels, then the gradient from the "pitlatrine" borehole towards boreholes UO7 and UO23 will have a major influence on the tracer migration as soon as it reaches the watertable.

2. If the level measured is the piezometric head of the bottom aquifer, then the tracer will have to travel through the unsaturated zone and matrix of the aquifer to reach the fracture. Only then will it be possible to detect the tracer when water is abstracted from the borehole.

On March 10, 1999 the tracer tests were started. 30 g of Fluorecein was mixed with 10 L of water and introduced into the "pitlatrine" boreholes. For each day afterwards the waterlevels in the "pitlatrines" were monitored and UO7 and UO23 were pumped for one hour at 0.2 L/s while the Fluorecein concentration was measured by means of a fluorometer.

Table 5.4 summarises the tracer test that was started on March 10, 1999.

Table 5.4: Summary of tracer tests conducted on March 10, 1999 at the Campus Test Site.

Date	Fluorecein concentration (ppb)		Waterlevels (m)	
	UO7	UO23	Pitlatrine UO7	Pitlatrine UO23
March 10, 1999	1.030	3.199	1.270	3.530
May 24, 1999	0.720	4.537	1.380	4.070

As was anticipated, Table 5.4 confirms that the tracer has not reached the fracture and no Fluorecein was detected. The difference in the concentrations between UO7 and UO23 is because UO23 has already been contaminated by earlier tests conducted on it.

By making use of the derived equation (Equation 5.1) of Darcy's law for falling-head experiments (De Marsily, 1981), the K-values for the formations under the two "pitlatrine" boreholes were calculated.

$$K = \frac{aL}{A(t - t_0)} \quad \ln \frac{h}{h_0} \qquad \textbf{(Equation 5.1)}$$

Where:

K = Saturated vertical hydraulic conductivity.

A = Larger cross-sectional area.

a = Smaller cross-sectional area.

L = Legnth over which flow takes place.

t_0 = Start time.

T = Time at end of test.

h_0 = Head at time t_0.

h = Head at time t.

The diameter of the "pitlatrines" are constant and this implies that $a = A$ in Equation 5.1 and thus it becomes:

$$K = \frac{L}{(t - t_0)} \ln \frac{h}{h_0}$$ **(Equation 5.2)**

By using Equation 5.2 the values in table 5.5 were obtained for the saturated vertical K-value at the two "pitlatrine" boreholes.

Table 5.5: Saturated vertical K-values calculated for "pitlatrine" boreholes UO7 and UO23.

Borehole Nr.	Saturated vertical K (m/day)
"Pitlatrine" UO7	1.17×10^{-4}
"Pitlatrine" UO23	1.7×10^{-2}

The values calculated show a greater difference (than expected) on two locations approximately 80 m apart in the same area. This justifies the decision made in chapter 6 where it is proposed that protection zone II should cover the whole extent of the fracture, if one is present.

To further demonstrate the importance of protecting the whole fracture extent, the program ***BPZONE*** (chapter 6) was used to determine the travel time of a pollutant when a vertical fracture is present. The hydraulic conductivity of a fracture can be over 1000 m/day (Van Wyk, 1998). If a hydraulic conductivity value of 1000 m/day is used, the travel time for a pollutant is 0.002 days to reach the horizontal fracture. Since it is impossible to determine the positions of vertical fractures, the importance of protecting the whole horizontal fracture extent is again fully justified.

5.2 Meadhurst Test Site

5.2.1 Introduction

The Meadhurst Test Site is situated approximately 16 km outside of Bloemfontein in the Bainsvlei smallholdings area. In the 1950's, the farm Meadhurst was subdivided into smaller plots. A number of pitlatrines and septic tanks, as well as active cultivation of the land, have been in operation since then. Boreholes were drilled by the owners to supply water for domestic purposes, irrigation and stock.

During June 1997, IGS started developing the new Meadhurst Test Site. The reasons for picking the Meadhurst terrain as a site were:

1. It is an opportunity to conduct tracer tests along a dyke and to move away from the type of formation that was prevalent on the Campus Test Site at the University of the Free State.
2. The nature of the setup is such that expensive equipment can be situated inside one of the residences, to minimize the possibility of theft.
3. The whole of the test can be monitored 24 hours a day by one of the live-in students.
4. The presence of existing pitlatrines and septic tanks to estimate their impact on the quality of the groundwater.
5. Twenty boreholes already exist on the site of which twelve are equiped with pumps.

The program for developing the test site consisted of the following:

1. Geophysics. Siting of new boreholes was done by using a magnetometer.
2. Drilling of six new boreholes as well as cleaning up and casing of existing boreholes.
3. Slug tests on all the open boreholes.
4. Pumping tests on some of the boreholes.
5. Tracer tests.

Figure 5.5 shows the layout of the area and the position of the boreholes, pitlatrines and septic tanks.

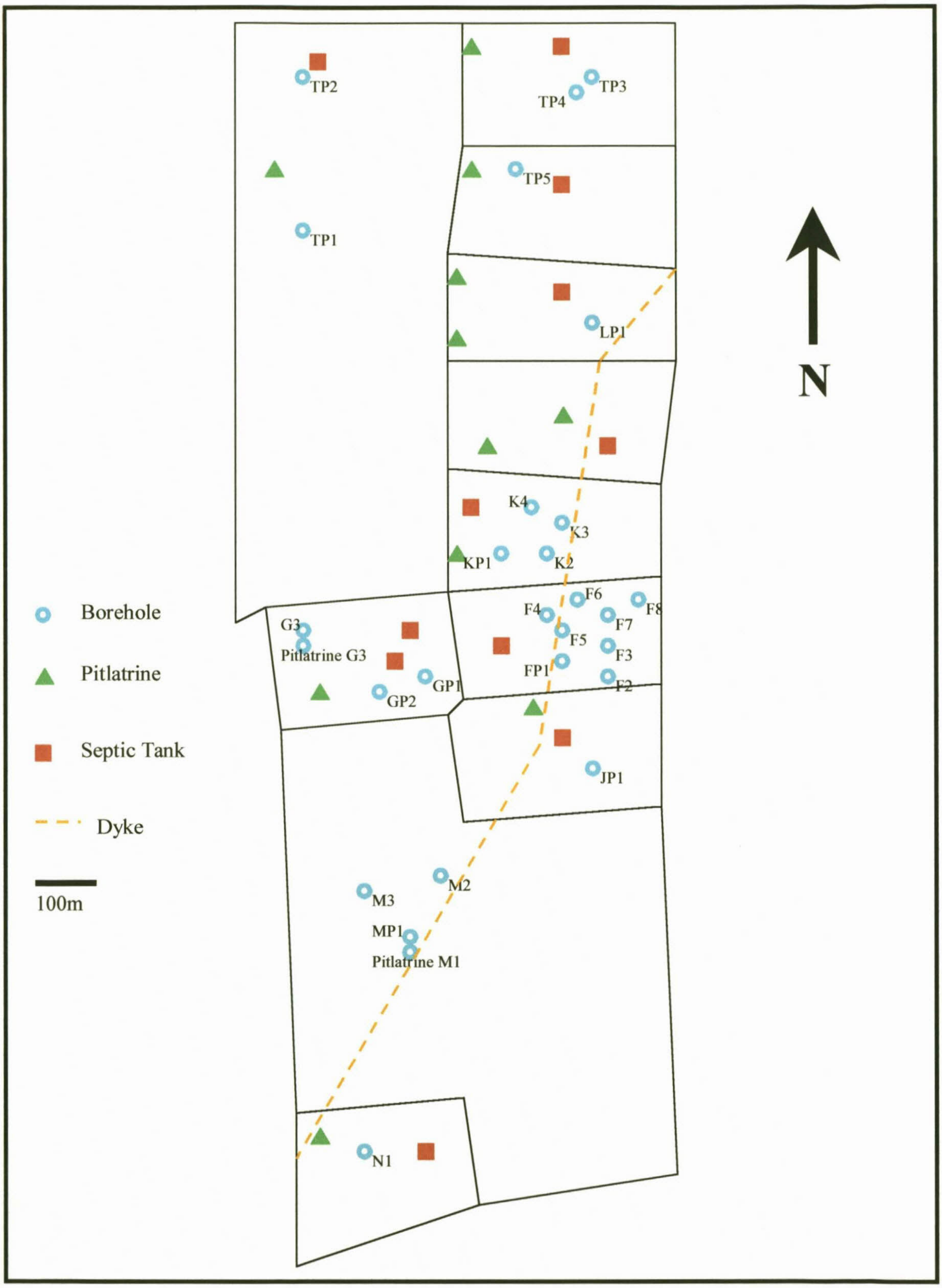


Figure 5.5: Meadhurst Test Site with the borehole, pitlatrine and septic tank positions.

On February 13, 1998, an additional six boreholes were sited and drilling commenced. These boreholes were used in an attempt to simulate pitlatrines and their effect on the groundwater.

5.2.2 Geology

The general geology of the area is mainly made up of Karoo sandstone, dolerite sills and dykes and shale. The top layer consists of soil and the sand is very deep. The depth varies between 18 – 21 m with an average water level of about 19 m below surface.

During the drilling phase at the site several of the boreholes were logged. A typical log of one of the boreholes is given below (Table 6.6).

Table 5.6: Lithology of borehole FP1.

Depth	Formation
0-10m	Reddish soil
10-18m	Orange-red sand
18-21m	Light brown sand
21-28m	Sandstone
28-31m	Sandstone (coarser)
31-36m	Shale

5 boreholes were drilled along the dyke. Because of the width of the dyke - about 50 m – the yield of these boreholes varies between 0,7 and 3 l/s. It was found that when the width of a dyke is more than 11 m, the yield of a borehole (Van Tonder, pers. com. 1999).

5.2.3 Water Quality

Samples for chemical analysis were taken from all the boreholes. The results from the laboratory can be seen in Table 5.7.

Table 5.7: Results of chemical analysis at Meadhurst test site.

Nr.	pH	EC	Ca	Mg	Na	K	PAlk	MAlk	Cl	SO4	NO3 as N	F	Br	COD	TDS
FP1	7.94	67	64	34	39	2.9	♣	250	39	9	12	0.21	0.36	♣	491
F2	8	61	60	31	36	2.9	♣	248	40	9	4.2	0.2	0.28	♣	447
F3	8.01	61	60	32	36	2.7	♣	270	35	9	0.5	0.2	0.24	♣	449
F4	7.91	66	62	34	39	2.7	♣	255	38	10	11.4	0.21	0.34	<10	489
F5	7.95	406	109	54	726	12.8	♣	254	999	11	8.3	0.27	751	♣	2965
F7	7.71	64	61	33	43	3.2	♣	269	28	14	6.99	0.22	0.27	♣	482
F8	8.23	65	67	32	38	2.7	♣	265	23	8	12.5	0.18	0.26	♣	491
G3	8.04	67	64	38	34	2.7	♣	222	34	9.5	22.5	0.2	0.56	♣	505
KP1	8.34	67	67	38	36	3	5	244	34	11	18.3	0.2	0.46	♣	487
K2	7.95	70	64	37	37	2.7	♣	245	34	11	17.2	0.21	0.44	♣	507
K3	7.91	64	63	36	36	2.9	♣	242	35	7.5	14.3	0.21	0.35	♣	486
K4	8.03	62	58	31	43	3	♣	270	27	8	6.5	0.28	0.19	♣	469
GP1	7.84	67	62	37	38	2.8	♣	233	35	9	19.1	0.22	0.45	♣	509
GP2	7.89	70	69	40	38	2.8	♣	238	33	13	25	0.23	0.55	♣	545
J1	8.08	63	57	30	35	2.1	♣	256	36	7	8.1	0.21	0.32	♣	471
LP1	7.92	72	70	40	40	3.3	♣	263	43	13	16.6	0.21	0.5	♣	547
N1	8.4	63	47	31	37	2.3	10	190	32	9	25.5	0.25	0.72	♣	473
TP1	7.45	65	66	39	31	2.4	♣	249	29	10	17.4	0.19	0.43	♣	503
TP2	7.91	72	69	41	35	2.5	♣	257	34	12	23.1	0.21	0.45	♣	552
T3	7.79	72	67	38	36	2.3	♣	265	37	7	17.8	0.22	0.399	♣	536
T4	7.8	72	60	35	35	2.2	♣	249	35	6	24.4	0.21	0.43	♣	535
T5	7.57	73	68	40	35	2.2	♣	282	39	10	14.3	0.21	0.45	♣	544
M1	7.67	64	59	35	34	2.5	♣	202	27	8	24	0.26	0.62	3	486

According to the South African standards for drinking water the maximum level for nitrate as N is 9 mg/l while the recommended maximum is 5 mg/l. Only boreholes F2 and F3 have values less than the recommended value. The high values for the rest of the boreholes could be a result of contamination from the pitlatrines and septic tanks in the area. Another origin of the nitrates could be the fertiliser that is used during the planting season.

Samples of boreholes GP2, G3, FP1, LP1 and TP2 were sent to the Council for Scientific and Industrial Research (**C.S.I.R.**) for isotopic analysis (*chapter 2*) to determine the ratio of contribution from the above mentioned sources of contamination.

The results from the **C.S.I.R.** for the ^{15}N values were as follow (Table 5.8)

Table 5.8: Results of ^{15}N isotopic analysis from samples at the Meadhurst Test Site.

Borehole Nr.	^{15}N value (‰)
FP1	+4.8
GP2	+5.5
G3	+5.0
LP1	+5.2
TP2	Analytical error in laboratory.

If the values of the water samples are compared to figures 2.1 and 2.2 (chapter 2), it seems as if the major contributor to the nitrate abundance is the soil organic matter (Figure 5.6). It will also seem as if the risk of nitrate contamination by means of pitlatrines and septic tanks is very low at the Meadhurst Test Site. The only other source of nitrate, according to the isotopic analysis, could then be the fertiliser used by the farmers in the vicinity.

The high values in borehole F5 for most of the parameters is because NaCl, NaBr and Fluorecein were used to conduct a tracer test between borehole F5 and borehole F4.

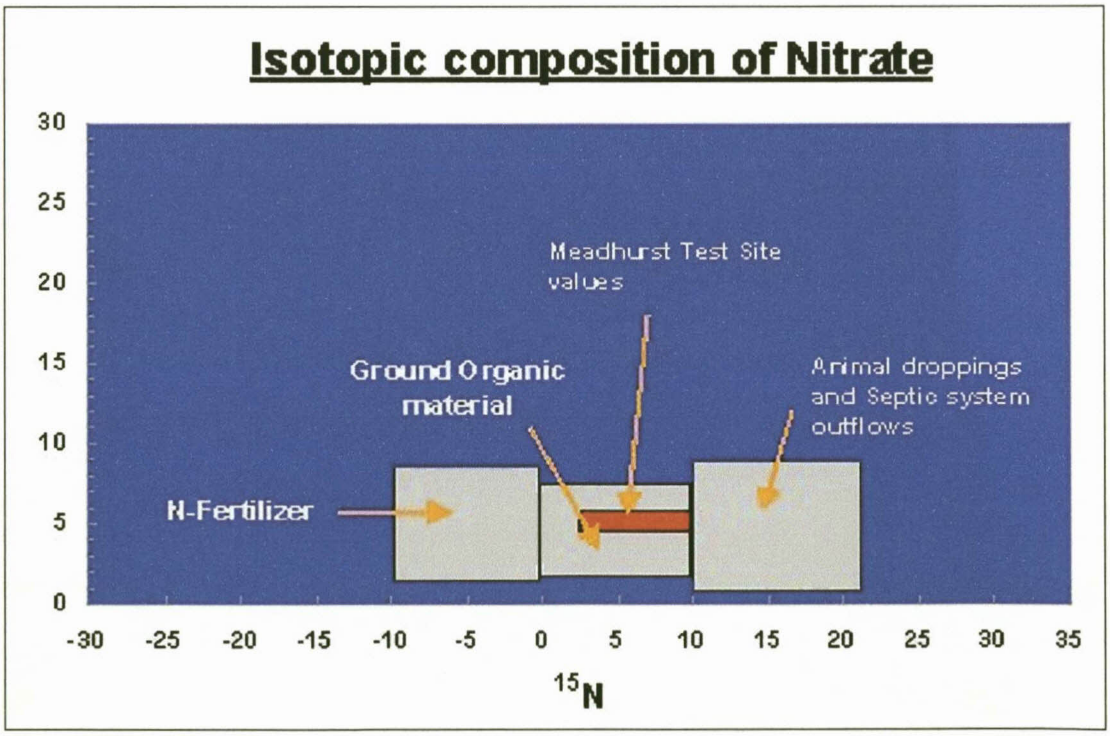


Figure 5.6: ^{15}N analysis at Meadhurst Test Site.

5.2.4 Borehole Tests

5.2.4.1 Slug Tests

Several slug tests were performed on boreholes at the Meadhurst Test Site. The results of the slug tests are given in Table 5.9 below. The borehofle yields were obtained from a graph proposed by Viviers (1993).

Table 5.9: Slug test results at Meadhurst Test Site.

Borehole Nr.	Recovery time (s)	Yield (l/s)
FP1	56	0.49
F4	18	1.9
FP1	9	4.6
K3	26	1.3
G3	16	2.3

5.2.4.2 Pumping Tests

Pumping tests were conducted on boreholes FP1, F4, GP1 and G3. Boreholes F4, FP1, F6 and F7 were used as observation boreholes during the duration of the tests. No observation holes were available for the tests conducted on GP1 and G3

The tests were analysed with the programs ***Aquitest*** and ***RPTSOLV*** to calculate values for the storativity (S) and the transmisivity (T) of the aquifer. The calculated values can be seen in Table 5.10.

Table 5.10: Calculated T- and S-values.

Borehole nr.	Cooper - Jacob		Theis - Recovery		RPTSOLV	
	T-Value(m^2/d)	S-Value	T-Value(m^2/d)		T-Value(m^2/d)	S-Value
F4	34.2	4.63E-03	34.6	♣	30	2.90E-03
F4 (Obs)	123	♣	133	♣	260	3.50E-02
F4 (Obs)	205	1.13E-06	♣	♣	♣	♣
FP1	41.7	2.29E-05	♣	♣	♣	♣
FP1 (Obs)	116	9.14E-04	119	♣	260	4.90E-03
FP1 (Obs)	129	1.11E-03	♣	♣	♣	♣
F6 (Obs)	120	1.52E-03	127	♣	♣	♣
F6 (Obs)	329	1.92E-04	♣	♣	♣	♣
F7 (Obs)	305	1.05E-03	♣	♣	♣	♣
GP1	157	4.21E-12	223	♣	♣	♣
G3	133	1.14E-01	194	♣	♣	♣

Harmonic mean T-value = 97.5 m^2/d.

Harmonic mean S-value = 2.4 E-004.

5.2.5 Tracer Tests

5.2.5.1 Saturated Zone

On October 27, 1997 a tracer test was conducted between boreholes FP1 and F4 over a distance of 30.4 m. Borehole F4 was used as the injection borehole and borehole FP1 as the abstraction borehole. The test was conducted under forced gradient conditions. This means that borehole FP1 was pumped until the water level stabilised and a pseudo steady state was reached. The abstraction rate was 1 L/s (Table 5.11).

Two types of tracer tests were combined during this exercise. A point dilution test was performed on borehole F4, while a forced gradient test was conducted between borehole FP1 and borehole F4. The graphical representation of the point dilution test can be seen in Figure 5.7.

Table 5.11: Summary of tracer test between boreholes FP1 and F4.

TEST ID	**CV 1**
Date	27/10/97
Injection well	F4
Pumped well	FP 1
Well radius(m)	0.0825
Radial distance (m)	30.4
INJECTION WELL	
Well conditions	Open
Position of mixing pump (m)	22
Injection well volume (l)	20
Injection method	In-situ
Tracer	Fluorecein
Volume of tracer solution (ml)	5000
Concentration of tracer solution (g/l)	20
Time of tracer injection	13:55
Tracer concentration after injection (C_0) (mg/l)	78
Tracer mass injected (g)	100
Rate of tracer decay in the injection well:	See figure 6.8.
PUMPING WELL	
Well conditions	Open
Pump position (m below collar level)	22
Abstraction rate (l/sec)	1
Std. Deviation of flow rate (l/sec)	
Head difference after steady state (m)	0.195
Tracer detection technique	Sample collection
Time of first tracer detection (min)	1028
Time of peak arrival (min)	3412
Tracer concentration of peak, C_P (mg/l)	0.07
Tracer mass recovery (g)	64

The shape of the dilution graph in Figure 6.7 represents an almost straight line, which indicates that the mixing of the tracer in borehole F4 was successful. From the point dilution test the value of the Darcy velocity (q) can be determined.

The data of the tracer test was fitted with an analytical model and the groundwater velocity was estimated as 10 m/d (Figure 5.7).

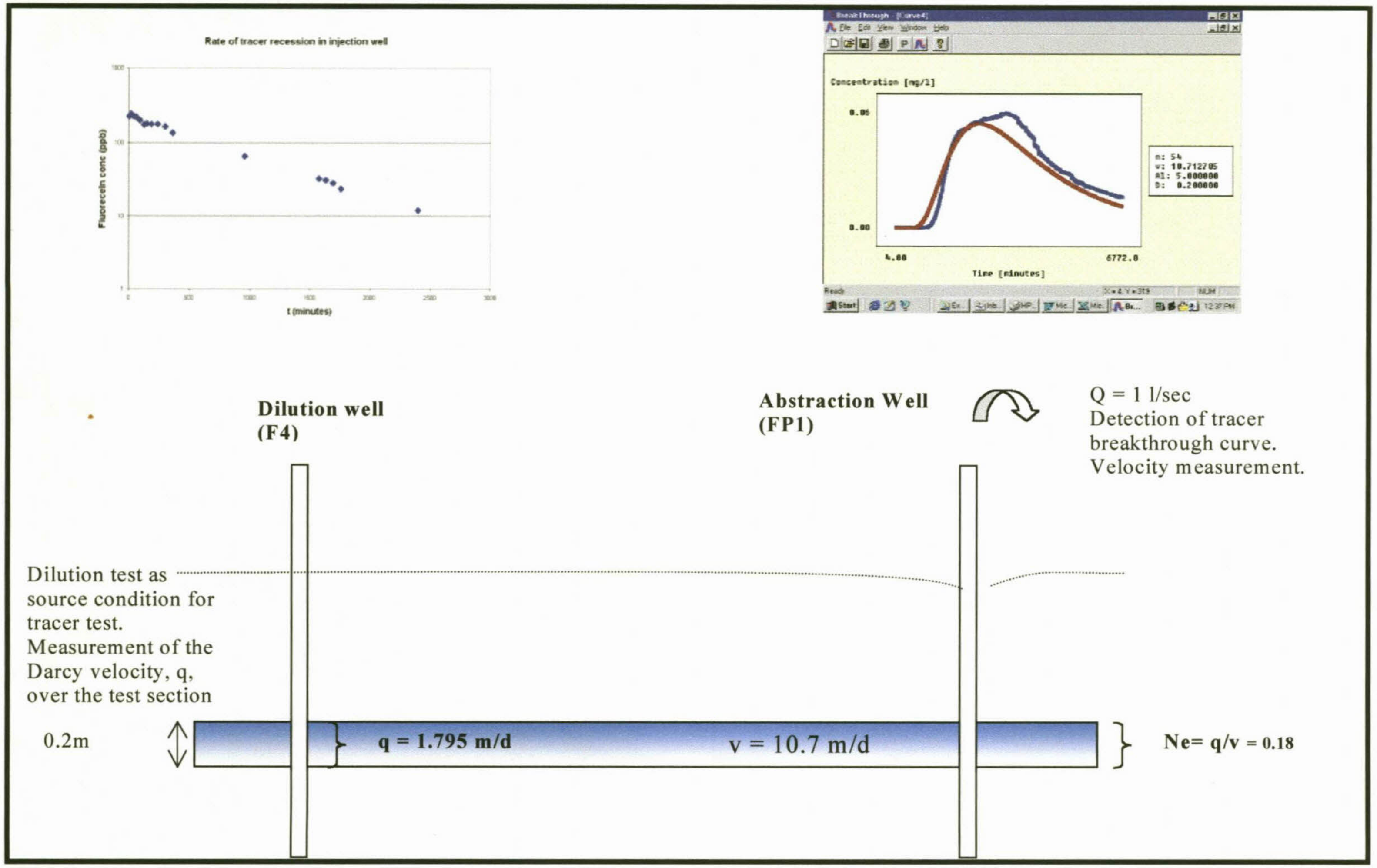


Figure 5.7: Output of analytical model used to determine the groundwater velocity.

5.2.5.2 Unsaturated zone

The new boreholes drilled at the Meadhurst Test Site on February 13, 1998 were used to try and simulate pitlatrines and the effect of the unsaturated zone on the effluent from pitlatrines. Three boreholes were drilled to a depth of 38 m. These boreholes were positioned to form three corners of a triangle. This was done to ensure that the gradient of the watertable could be determined. Another borehole was drilled to a depth of 15m. The waterlevels measured in the other three boreholes are approximately 18 – 19m. An unsaturated zone of ± 3m was left to conduct the tests on.

Two other shallow boreholes were drilled (boreholes not reaching water table). One was drilled upstream from borehole FP1 to a depth of 12m and another to a depth of 9m upstream from borehole G3.

Samples were taken at depths between 14 and 24 m in borehole M1. Lab measurements on these samples, yielded the following parameters:

1. K = 5 m/d
2. Porosity (n) = 0,41
3. Kinematic porosity = 0,33

Tracer tests were also conducted to determine the effect of the vadose zone on bacteriological contaminants. In these tests, bacteriophages were used as tracers together with Fluorecein. A bacteriophage is a virus, which infects bacteria. The bacteriophages are believed to be more representative of the behaviour of viral and bacteriological contaminants in the groundwater environment. The reason for this line of thinking lies in the fact that their small size puts them on the same scale as pathogenic viruses of eucaryotic organisms, and they are non-pathogenic as well as non-toxic (Rossi, 1994). Similar tests on surface water, karst type aquifers as well as porous medium aquifers in Switzerland seem to support this theory (Rossi, 1994).

The bacteriophages that were used as tracers, held no risk for the groundwater environment, as it is non-reactive as long as it is not in contact with its host bacteria. Their host bacteria only occur naturally in the marine environment and not in groundwater, therefore there is no risk of the bacteriophages being able to reproduce and contaminate the groundwater. The bacteriophages are united with the host bacteria only after the samples have been taken from the extraction wells. This happens in the laboratory. The use of bacteriophages is not expensive and the analysis can be done within two days after the sample has been taken.

Tracer tests where a fluorescent dye as well as bacteriophages were used, were conducted at Willerwald, Switzerland (Rossi, 1994). Although the tests were not done in a fractured type of groundwater environment, the results were very informative in terms of migration differences between a conservative type tracer and a bacteriological tracer.

From the breakthrough curves it was observed that bacteriophage migration was faster than both chemical and fluorescent tracers in a porous medium (Figure 6.8). Another observation was that the bacteriophages moved over greater distances and in larger quantities through an aquifer with permeable interstitial porosity, while in aquifers that are less permeable and more silty, the adsorption of bacteriophages on the matrix substrate is believed to be the main cause for the dramatic reduction in the number of particles in suspension (Rossi, 1994).

Bacteriophages will logically have a higher migration velocity in the most granular part of a system. This characteristic might be used to try and predict certain types of contaminant flow and behaviour where conventional tracers fail to give any conclusive results (Rossi,1994).

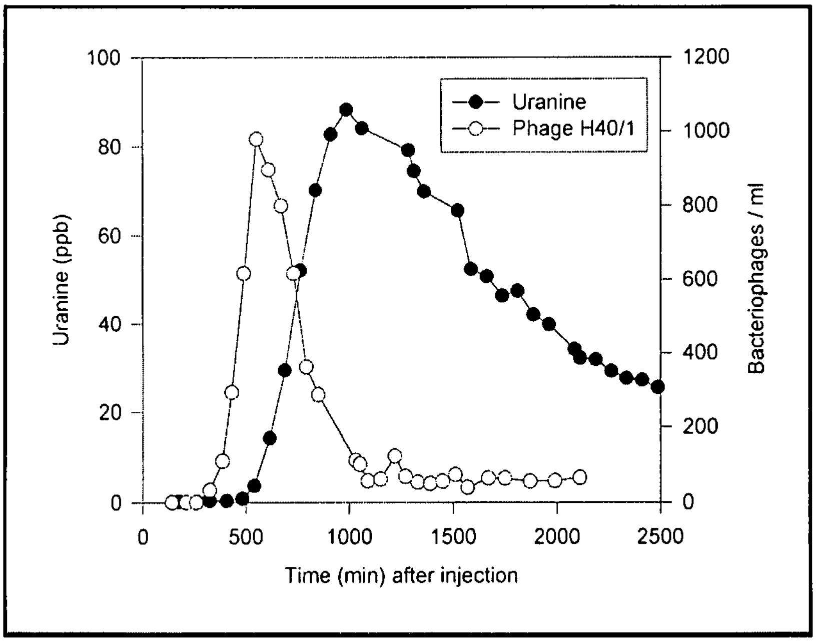


Figure 5.8: Graph showing the difference in travel time between Fluorecein (Uranine) and bacteriophage H40/1.

From the data gathered during the tracer tests on the unsaturated zone, it was thought the Fluorecein were detected after a time of about three days. No traces of the bacteriophages were detected even after sampling continued for a duration of one month. After the second series of tracer tests it became apparent that the differences in concentration were only oscillations when performing the analysis for Fluorecein.

The apparent breakthrough curves over a period of 1 day for the Fluorecein in the different boreholes are given in Figure 5.9.

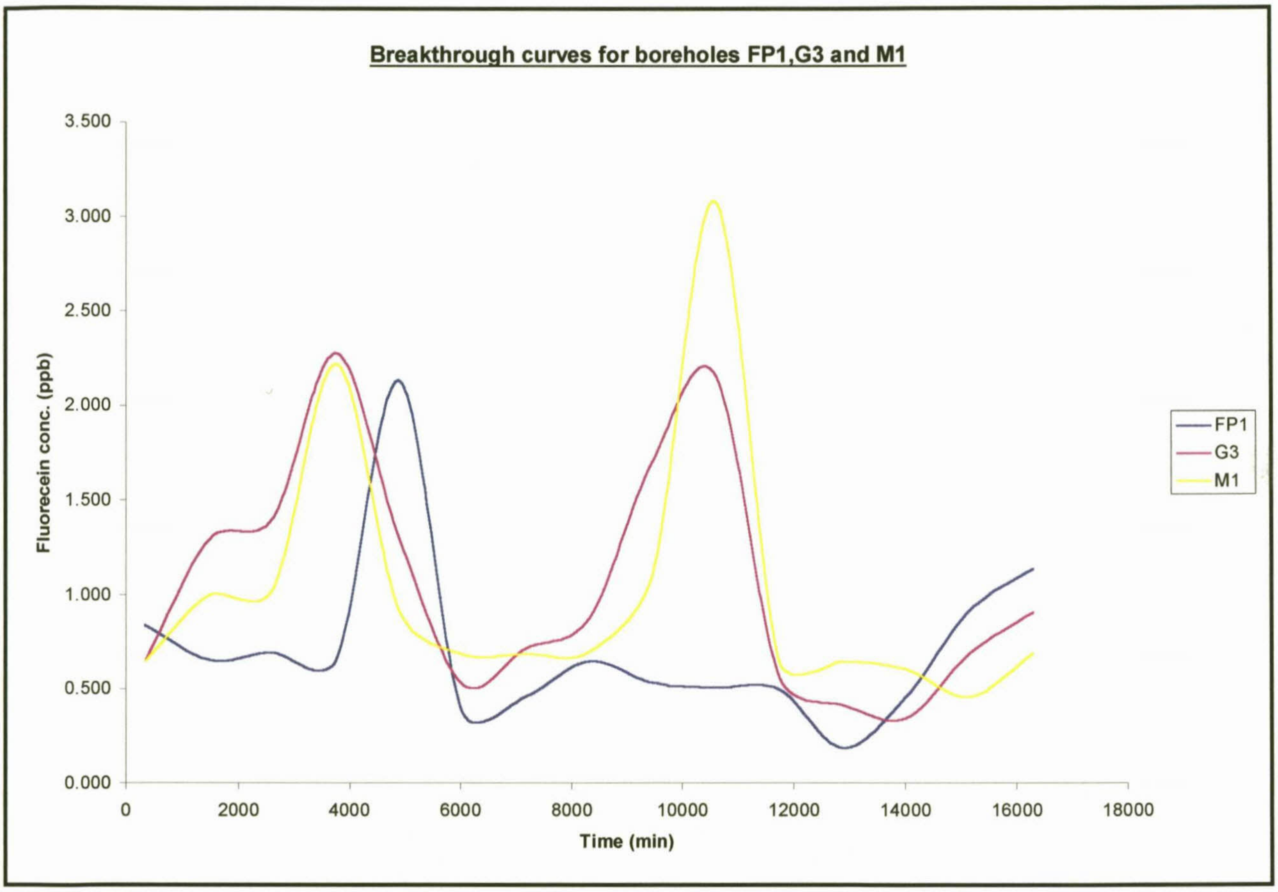


Figure 5.9: Apparent Fluorecein breakthrough curves in boreholes FP1, G3 and M1 for a period of 1600 minutes.

The tracer tests were again carried out after a drying out period of about three months. For a duration of one week, 10 liters of water was added to the "pitlatrine" boreholes every second day. Thereafter 5 liters of water was added every third day for a peiod of three weeks. For the further duration of the test, 5 liters of water was added only when no waterlevel could be measured in the "pitlatrine" boreholes. No bacteriophages were used for these tests and only Fluorecein was used.

The results from the tracer tests are given in Table 5.12.

Table 5.12: Fluorecein concentration at the start and end of the tracer tests conducted at the Meadhurst Test Site.

Date	Fuorecein concentration (ppb)		
	FP1	M1	G3
March 10, 1999	0.531	4.080	0.990
May 24, 1999	736.29	4.690	1.530

Table 5.13: Differences in waterlevels in the "pitlatrine" boreholes over a one-day period.

Date	Difference in waterlevel (m)		
	Pitlatrine FP1	Pitlatrine M1	Pitlatrine G3
03/23/99-03/24/99	0.9	0.5	0.2

After applying equation 5.2 the values in table 5.14 were calculated for the saturated K-value of the unconsolidated zone.

Table 5.14: Saturated vertical K calculated for "pitlatrine" boreholes FP1, M1 and G3.

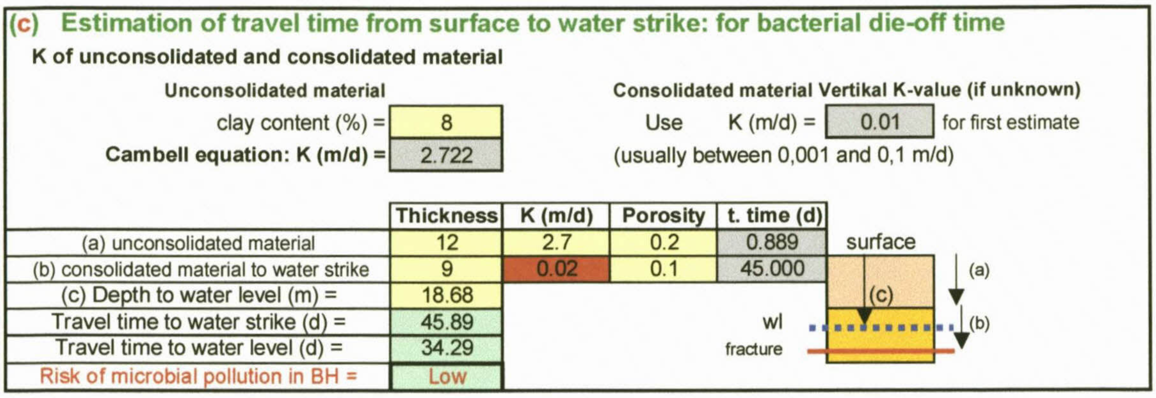
Borehole Nr.	Saturated vertical K (m/day)
"Pitlatrine" FP1	2.2
"Pitlatrine" M1	0.7
"Pitlatrine" G3	0.009

Again, three totally different saturated vertical K-values are encountered in an area no larger than 1 km^2 which emphasises the problems when homogeneity is assumed.

The K-values in table 5.14 explains why Fluorecein was detected in only borehole FP1 and not in the other boreholes. The small K-value at borehole G3 correlates very well with the geology encountered when it was drilled. Much more clay was encountered during the drilling phase and after heavy rains the water ussually accumulates in that part of the test site.

Borehole FP1 also has the advantage in that the pump is permanently installed whereas in boreholes M1 and G3 a smaller pump was only inserted for the duration of the sampling period. More emphasis was therefore placed on the tracer test at borehole FP1 because of the better conditions for continuous sampling that exists.

After the saturated vertical K-value for the unconsolidated zone was calculated for "pitlatrine" FP1, this value together with the travel time was used in the programme BPZONE to determine the saturated vertical K-value for the consolidated zone (Figure 5.10).



(c) Estimation of travel time from surface to water strike: for bacterial die-off time

K of unconsolidated and consolidated material

Unconsolidated material		Consolidated material Vertikal K-value (if unknown)
clay content (%) =	8	Use K (m/d) = 0.01 for first estimate
Cambell equation: K (m/d) =	2.722	(usually between 0,001 and 0,1 m/d)

	Thickness	K (m/d)	Porosity	t. time (d)
(a) unconsolidated material	12	2.7	0.2	0.889
(b) consolidated material to water strike	9	0.02	0.1	45.000
(c) Depth to water level (m) =	18.68			
Travel time to water strike (d) =	45.89			
Travel time to water level (d) =	34.29			
Risk of microbial pollution in BH =	Low			

Figure 5.10: Estimation of travel time from surface to water strike with emphasis on the K-value of 0.02 m/d suggested by the programme BPZONE.

The breakthrough curve measured in borehole FP1 is depicted in Figure 5.11.

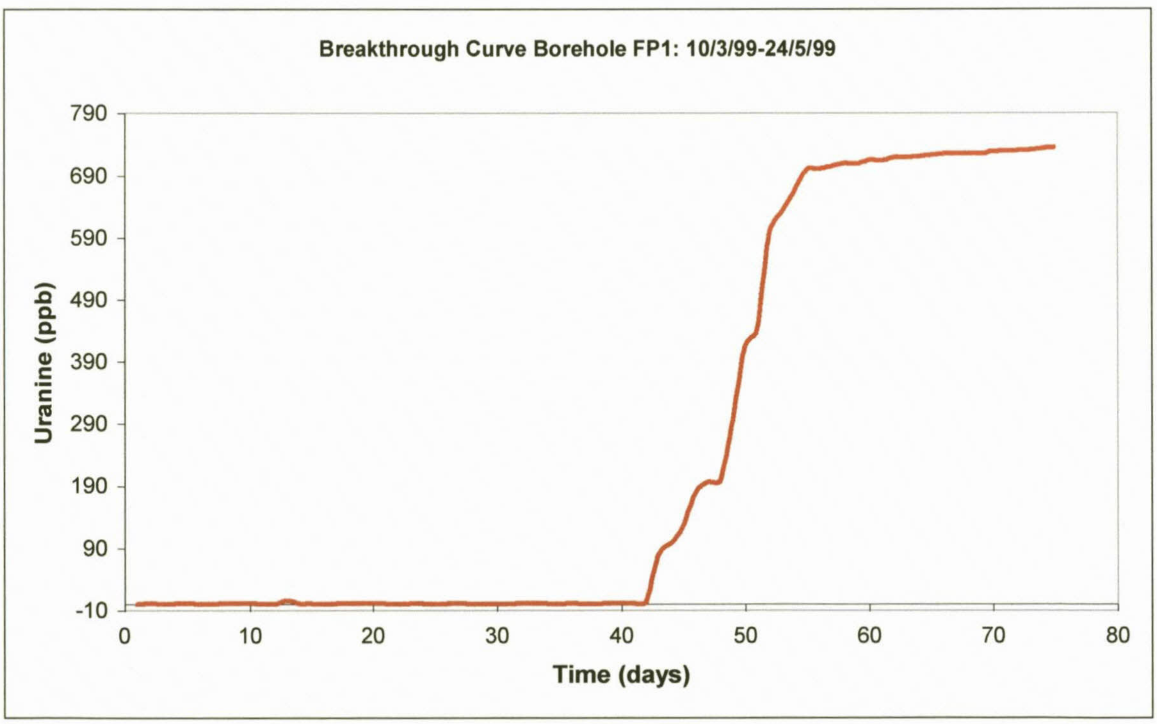


Figure 5.11: Breakthrough curve measured in borehole FP1 for a period of 75 days.

5.3 Conclusions

Determining the characteristics of the unsaturated zone might prove to be a more daunting task than anticipated, if not impossible. This impression is strengthened if one considers the outcome of the study done on the Campus Test Site and especially the Meadhurst Test Site.

On two such small areas different K values were encountered which in turn indicate different travel times. This illustrates the heterogeneity that exists and the dangers involved when assumptions are made about the homogeneity of formations.

The Meadhurst area is situated in an agricultural environment where typical cultivation involving fertilisers is taking place. Its locality within a rural environment is also a perfect opportunity to study the effects of pitlatrines and septic tank systems on the groundwater quality. Even though interpretation of the preliminary isotopic analysis suggests that the pitlatrines and septic tanks have not contributed much to the nitrate contamination of the groundwater there is still a margin of uncertainty about whether this is really true.

Much more effort will have to go into trying to determine the effect of the unsaturated zone where the effect of known pollutants on the environment is concerned.

CHAPTER 6

Delineation of Borehole Protection Zones

6.1 Quality management of groundwater

If enough groundwater is available, but the quality is not suitable for domestic use, the water is useless. In the following discussion, the focus will be on the influence of on-site sanitation point pollution sources (especially pitlatrines) on groundwater quality.

For sanitation quality management in SA, the following two documents are used as guidelines:

a.) A Guideline for Groundwater Protection for the Community Water Supply and Sanitation Programme (Xu and Braune, 1995) and

b.) A Protocol to manage the potential of groundwater contamination from on-site sanitation (National Sanitation Co-ordination Office, Directorate of Geohydrology, 1997).

Special emphasis is placed on the concept of minimum separation distances between boreholes and point pollution sources in document (a) above. To provide protection against degradable pollutants, the minimum distance of 15 to 50 meters is proposed in this document based on both theoretical and practical considerations.

Document (b) provides a brief background to the current understanding of groundwater contamination by on-site sanitation systems and present a protocol for those individuals involved in implementing new or upgraded on-site sanitation systems. A number of very important issues are covered and the following is a direct abstract from the document:

"It has been well established that on-site sanitation systems can impact on groundwater quality (Fourie and van Ryneveld, 1994), with microbial and nitrate contamination being the two main issues of concern. However, it is also well recognised that the environment has, within limits and under many conditions, an ability to protect itself against human inputs. Once these limits are exceeded, contamination and then pollution occur. The concern of VIP-induced contamination of groundwater is

countered by a concern that the risks of groundwater pollution are overestimated. Foster (1985) states that "except perhaps in the most unfavourable hydrogeological conditions, the groundwater pollution risk associated with the low costs sanitation measures being introduced is not such as to warrant the abandonment of such activities". Jackson (1994) recommended that the risk of groundwater pollution should be evaluated against the background of alternative water supplies and alternative sanitation systems. There are two clear camps, which are split over the issue of groundwater contamination from pit latrines.

Both use theoretical consideration to substantiate their arguments and points of view. The lack of scientifically sound data will prevent clarity on the matter being developed. A very strong argument exists for allocating only 0.1% of the R 13 billion needed for rural water supply and sanitation over the next 10 years (Jackson, 1997) for research into the problem. It is only with appropriate field measurement and research that the contamination risk can be assessed and appropriate mitigatory measures developed. Concerns over groundwater contamination resulting from on-site systems is normally associated with elevated bacterial, parasite, viral and nitrogen concentrations in groundwater. The risks of groundwater contamination are related to a number of factors, but ultimately risk depends on aquifer vulnerability and the magnitude of the pollutant threat. The issue of acceptable risk was poorly addressed by the literature reviewed. Roads are built knowing that a certain number of fatal accidents will take place over a certain period at an "acceptable" level of risk. The debates around the use of on-site sanitation systems and groundwater contamination do not consider the risk associated with contamination occurring but rather on whether contamination takes place or not. Tredoux (1993) records that out of a population of some 10 million people, 26 fatalities and 1653 cases of methaemoglobinaemia were reported in Hungary for the period 1976 to 1990. This equates to a risk of 1 in 5 700 000 and 91 000 respectively with respect to methaemoglobinaemia. These risks should be seen in light of 3 out of 4 people in South Africa not having access to adequate sanitation. A means of quantifying the risk and the setting of an acceptable risk are issues that need to be urgently addressed.

- ***Types of sanitation systems***

Numerous types of rural sanitation systems are used, including simple pits, borehole pits, VIPs, pour-flush, double pit, composting, overhung, bucket, conservancy tanks and soakaways (Franceys et a.l, 1992). In South Africa the VIP appears to be the most acceptable solution to the rural sanitation problem, particularly from a health and economic perspective. VIP systems are essentially dry, but small amounts of liquid may periodically be disposed of in the pit.

- ***Waste disposal rate***

The loading in a specific area depends on the density of latrines per hectare and the number of people utilizing each pit. Muller (1989) defined population densities as follows:

- *50 houses/ha:* *low*
- *50 - 150 houses/ha:* *medium*
- *150-300 houses/ha:* *high*
- *> 300 houses/ha:* *very high*

In rural communities, population densities tend to be lower. Densities ranging between 10 and 30 houses/ha are common (Palmer, pers.com., 1997) while densities above 150 houses/ha are regarded as high.

***Each person generates between 4 and 5 kg of nitrogen per year**, with each gram of excrement containing 109 types of bacteria. The risk of nitrogen or bacteria reaching the groundwater is increased if grey water is also disposed in the latrine. Franceys et al. (1992) suggests that the hydraulic loading in a pit latrine should be less than 50 l/m2/day.*

*Loading should take into account the population density and the total size of the settlement. Settlement of under 500 people would provide a limited nitrogen loading, while the loading from large settlements (10 000 people) would be a far greater threat to regional groundwater resources. The amount of nitrogen leached out of the pits to groundwater depends not only on the hydraulic loading, but also on the prevailing geological conditions. Lewis et al. (1980) assumed that 10% of all nitrogen entering the pits is leached to the groundwater, although Foster and Hirata (1991) noted that between **20 - 60%** leaching is possible.*

- ***Geological conditions***

Geological conditions play a major role in attenuating pollutants entering the subsurface system. As a basic principle, the longer it takes the contaminants to reach the groundwater, the lower the impact on water quality. Data exists showing that bacterial and viral levels generally decrease to background levels within 1 to 3m of movement in the unsaturated zone (Lewis et al., 1980; Fourie and van Ryneveld, 1994). Even in the saturated zone, 99% of all viruses die off within 10 days. Enteric bacteria can, however, survive for longer, with periods of up to 100 days being reported.

Frequent reference is made in the literature to a "requirement" of 3m of unsaturated zone below the base of the pit. Adequate thickness for the unsaturated zone does, however, depend on the prevailing permeabilities. Required unsaturated thicknesses previously reported include:

- *+20m* : *Taussig & Connelly, 1991*
- *+ 2m (if fine grained sands)* : *Franceys et al, 1992*
- *+ 10m* : *Xu & Braune, 1995*

It is pertinent to note that South African researchers involved in investigations in fractured rock environments proposed far greater unsaturated thickness than American and European researchers. This is related to the different attenuation ability of porous and fractured rock.

The use of the travel time for contaminants to pass through the unsaturated zones has previously been utilized as an indicator of attenuation potential (Parsons and Jolly, 1994). ***Travel times of between 30 - 50 days are seen as being suitable for the die-off of bacteria and viruses.*** *Problems associated with unsaturated zone travel time in South Africa are thin soil cover and the fractured nature of the bedrock. Under fractured conditions flow can be exceptionally rapid. Lewis et al.(1980) measured rates of flow as high as 3m in 25 minutes. If the unsaturated zone consists of permeable sands or fractured bedrock, attenuation of the pollution would be limited and the risk of groundwater pollution would be high. A travel time in excess of 30 days from the base of the pit to the groundwater level appears reasonable.*

A considerable amount has been written concerning the horizontal distance between pits and supply boreholes. However, this protocol assesses risks to groundwater resources rather than to specific boreholes. It is a guiding principle of this protocol that a 50m-protection zone should exist around a supply borehole. Further, the protection zone should be increased to 75m if the borehole is downgradient of zones of high pollution loading e.g. schools, cattle kraals and other sources of nitrogen, bacteria and virus contamination.

- ***Hydrogeological conditions***

Groundwater resources are vital supplies for the rural areas, especially for the western half of the country. Approximately 60% of all rural communities use groundwater as a source of water. Contamination of groundwater resources is hence unacceptable, especially if alternative resources are unavailable.

To assess the threat and impacts of contamination the prevailing water usage and hydrogeological conditions have to be assessed. A hydrocensus should therefore be undertaken and the following data collected:

- *position of boreholes and distance relative to sanitation systems*
- *details of groundwater use and volumes used by the different users*
- *compliance with water quality guidelines related to the suitability for human consumption (measurement of electrical conductivity and nitrate concentrations)*
- *static water levels*
- *borehole yields and current abstraction rates*

The data collected during the hydrocensus will be used to assess:

- *nature of the aquifer (confined or unconfined)*
- *groundwater flow direction and impact of pumping on flow directions*
- *supply potential of the aquifer*

If the aquifer has an important role in supplying water, contamination has to be limited, either by altering the sanitation system or by moving the source of water. Even though progress in addressing sanitation needs in South Africa is regarded as being critical, it should not be achieved at the expense of the sustainable ability of aquifers to provide water to the people. The contamination of these water sources will also have a major economic impact and could prevent the goals of the RDP being met. The positive benefits to public health resulting from the installations of on-site sanitation systems and the negative impact of sanitation systems on the environment, and in particular groundwater quality, are the two cost-benefit trade-off's which have to be considered. A practical approach to this issue based on sound theoretical considerations will ensure that many previously disadvantaged communities will be provided with a basic level of service in a safe, sustainable and cost-effective manner."

6.2 Protection zones

Results from many tracer tests indicate that the minimum distance between a pitlatrine and borehole as proposed by Xu and Braune (1995) will not be adequate in many practical cases to protect the borehole from being polluted. The idea of three protection zones, like in Germany (Kinzelbach *et al.*, 1991), for boreholes at on-site sanitation areas is proposed.

The U.S. Environmental Protection Agency (EPA) was also involved in delineating wellhead protection areas (WHPA). In order to achieve the overall goal of delineating the zone of influence (ZOI) or the zone of contribution (ZOC) of a well in an unconfined fractured-rock aquifer, the methods used were (EPA, 1991):

1. Arbitrary fixed radius.
2. Calculated fixed radius.
3. Vulnerability mapping.
4. Flow-system mapping:
   - with time of travel (TOT) calculations.
   - with analytical equations.
5. Residence time approach.
6. Numerical flow/transport modeling.

After the WHPA is determined, the following steps are proposed by the EPA to protect the groundwater resource (Xu, 1998):

1. Identifying potential sources of contamination in the WHPA.
2. Establishing management approaches to protect the groundwater in the WHPA.
3. Developing a contingency plan for pollution events.
4. Instituting programs for public education and participation.

The difference between this dissertation and previous work by Xu (1998), is the method of information and data gathering. For the program ***BPZONE*** (section 6.4), developed as a more applicable way to delineate protection zones, a pumping test of 5 minutes would be sufficient to get the information needed. To get the necessary data for the approach by Xu, a complete dual tracer test must be conducted that could take weeks.

The equations and mathematics behind the ***BPZONE*** program is also much simpler and applicable than that proposed by Xu.

6.2.1 Protection zone I: Fencing

For protection zone I (i.e. the immediate fenced area around the borehole), it is proposed that the distance of the fence around the borehole must be at least 5 m. For a borehole that is supplying water to less than say 20 persons, a well-constructed sanitary seal is regarded as enough. Quality monitoring is, however, very important.

6.2.2 Protection zone II : Microbial and nitrate pollution

A second protection zone around the borehole is proposed. The idea with this zone is to protect the drinking water from microbial (bacteria and viruses) and nitrate pollution. Many case studies have shown that bacteria usually die within 30 days after being introduced into the soil. For the delineation of this zone, table 6 in the report by Xu and Braune (1995) will be adequate in some cases. They proposed an absolute minimum distance of 50 m between a pitlatrine and a borehole. However, in many cases in fractured aquifers, this will not be adequate as shown in a following section.

6.2.3 Protection zone III : Hazardous elements

If persistent hazardous non-degradable elements are present, the whole catchment area of the borehole must be protected. Because of the use of the word "hazardous", some consideration must be given to its implications. Therefore the importance of risk assessment must be considered.

Risk assesment and management

The word "hazardous" is the adjective of the word "hazard" and according to the ***Random House Dictionary***, "hazard" means:

> **"a foreseeable but unavoidable danger."**

Professor Gilbert M. Masters (Stanton University) explains the importance of risk assessment and risk management very well in his book ***Introduction to Environmental Engineering and Science***. The following quotation is his introduction to chapter 4 on risk assessment of the aforementioned book and is quoted fully.

> ***"All substances are poisons; there is none which is not a poison. The right dose differentiates a poison and a remedy. –Paracelsus (1493-1541)***

One of the most important changes in environmental policy in the 1980s was the acceptance of the role of risk assessment and risk management in environmental decision making. In early environmental legislation, such as the Clean Air and Clean Water Acts, the concept of risk is hardly mentioned; instead, these acts required that pollution standards be set that would allow adequate margins of safety to protect public health. Intrinsic to these standards was the assumption that pollutants have thresholds, and that exposure to concentrations below these thresholds would produce no harm. All of that changed when the problems of toxic waste were finally recognized and addressed. Many toxic substances are suspected carcinogens; that is, they may cause cancer, and for carcinogens the usual assumption is that even the smallest exposure creates some risk.

If any exposure to a substance causes some risk, how can air quality and water quality standards be set? When cleaning up a hazardous waste site, at what point is the project *completed; that is, how clean is clean? At some point in the cleanup, the remaining health and environmental risks may not justify the continued costs and, from a risk perspective, achieving zero risk would cost an infinite amount of money, so policy makers have had to grapple with the tradeoff between acceptable risk and acceptable cost. Complicating those decisions is our very limited understanding of diseases such as cancer coupled with a paucity of data on the tens of thousands of synthetic chemicals that are in widespread use today. Unfortunately, those who have responsibility for creating and administering environmental regulations have to take action even if definitive answers from the scientific community on the relationship between exposure and risk are not available.*

The result has been the emergence of the controversial field of environmental risk assessment. Hardly anyone is comfortable with it. Scientists often deplore the notion of condensing masses of frequently conflicting, highly uncertain, often ambiguous data that have been extrapolated well beyond anything actually measured down to a single number or two. Regulatory officials are battered by the public when they propose a level of risk that they think a community living next to a toxic waste site should tolerate. Critics of government spending think risks are being systematically overestimated, resulting in too much money being spent for too little real improvement in public health. Others think risks are underestimated since risk assessments are based on data obtained for exposure to individual chemicals, ignoring the synergistic effects that are likely to occur when we are exposed to thousands of them in our daily lives.

Some of the aforementioned conflicts can best be dealt with if we make the distinction between risk assessment and risk management. Risk assessment is the scientific side of the story. It is the gathering of data that are used to relate response to dose. Such dose-response data can then be combined with estimates of likely human exposure to produce overall assessment of risk. Risk management, on the other hand, is the process of deciding what to do. It is decision making, under extreme uncertainty, about how to allocate national resources to protect public health and the environment. Enormous political and social judgment is required to make those decisions. Is a one-in-a-million lifetime risk of getting cancer acceptable and, if it is, how do we go about trying to achieve it?"

The following is a summary of a CSIR report on environmental health risk assessment (Schwab and Genthe, 1998).

Management of risks involves:

1. Identifying the risk involved.
2. Evaluating the risk.
3. Selecting actions to reduce the risk.

4. Implementing the actions.

It must be kept in mind that for each of the four above-mentioned steps there are stakeholders involved. Emphasis is placed on good communication between risk assessor and stakeholders.

An environmental risk is the probability that a substance or situation will produce human harm under specified conditions. Two factors combine to produce a risk:

1. The probability that an adverse event will occur.

2. The consequences of the event.

An adverse event is defined as an event, which involves exposure to potentially hazardous substances or situations at a dose that can cause harm to the exposed individual.

An example of the above is when the problem of ingestion of contaminated water is considered. The statement that "there is a 25% chance that a person in our target community will drink contaminated water" is the probability that the adverse event will occur. The statement "if people drink the contaminated water they will get diarrhea" is an example of the consequence of the event.

A definition for risk assessment is:

- **The process or method of determining if an activity (man-made or natural) will negatively impact humans or their surrounding physical environment.**

Four distinct but interactive phases are involved when the risk of a given hazard is determined.

1. **Hazard identification.** A hazard is the intrinsic 'dangerous'or 'harmful' property of a substance or a situation. During this phase it is determined whether a given substance will have a harmful or negative effect on the population or environment. This step determines if the risk assessment process should continue or be abandoned. If a hazard is identified, then the properties of the hazard must be described as well as its acute and chronic effects.

2. **Exposure assessment.** Exposure means the contact between the hazardous substance and a person or population. Here the intensity, frequency and duration of human contact with the hazard are established. Factors that must be considered are an estimation of environmental concentrations of the hazard and demographic or behavioral descriptions of the exposed population.

3. **Dose-response assessment.** Dose is the amount of the contaminant that actually enters the body, where it can cause harm. The relationship between the dose of a hazardous substance and the incidence of an adverse effect on the exposed population is examined.

4. **Risk characterisation.** By taking the information gathered during the exposure and dose response assessments, the extent of the health effect must be determined. Information important to both the stake holders and risk managers must be gathered during the risk characterisation phase.

No risk is involved if exposure to the harmful substance or situation cannot, does not or is not expected to occur. If the dose is not sufficient to have any harmful effects on individuals or the environment, then again no risk is involved. However in both cases the risk must be assessed over a certain length of time into the future. For example if at the time of the risk assessment it is decided that no risk is involved because there are no people living in or near the area, the possibility of future development must be taken into account. The same must apply when considering the dose of a substance, if the concentration increases with time the effect thereof in the future must also be taken into consideration.

A very young or elderly person may be more susceptible to the effects of a given type of exposure and dose. The same applies to malnourished and ill individuals.

The following questions should be asked during the risk characterisation phase:

- i Considering the hazard and the exposure, what is the nature and likelihood of the health risk?
- ii Which individuals are at risk? Are some people more likely to be at risk than others?

iii How severe are the anticipated adverse effects?

iv Are the effects reversible?

v What scientific evidence supports the conclusions about risk? How strong is the evidence?

vi What is uncertain about the nature or magnitude of the risk?

vii What is the range of informed views about the nature and probability of the risk?

viii What other sources cause the same type of effects or risks?

ix What contribution does the particular source make to the overall risk of this kind of effect in the affected community?

x How is the risk distributed in relation to other risks in the community?

When trying to solve a problem with risk assessment, the complex interaction along the path from the sources of contamination (e.g., industrial or traffic emissions) to the potential health effects (e.g., cancer or asthma) must be understood. **This set of linked interactions is often referred to as the source to effect continuum.**

For example, the source to effect continuum for human health as depicted in Figure 6.1. The figure illustrates it is not sufficient to simply identify a source of contamination when assessing potential health effects.

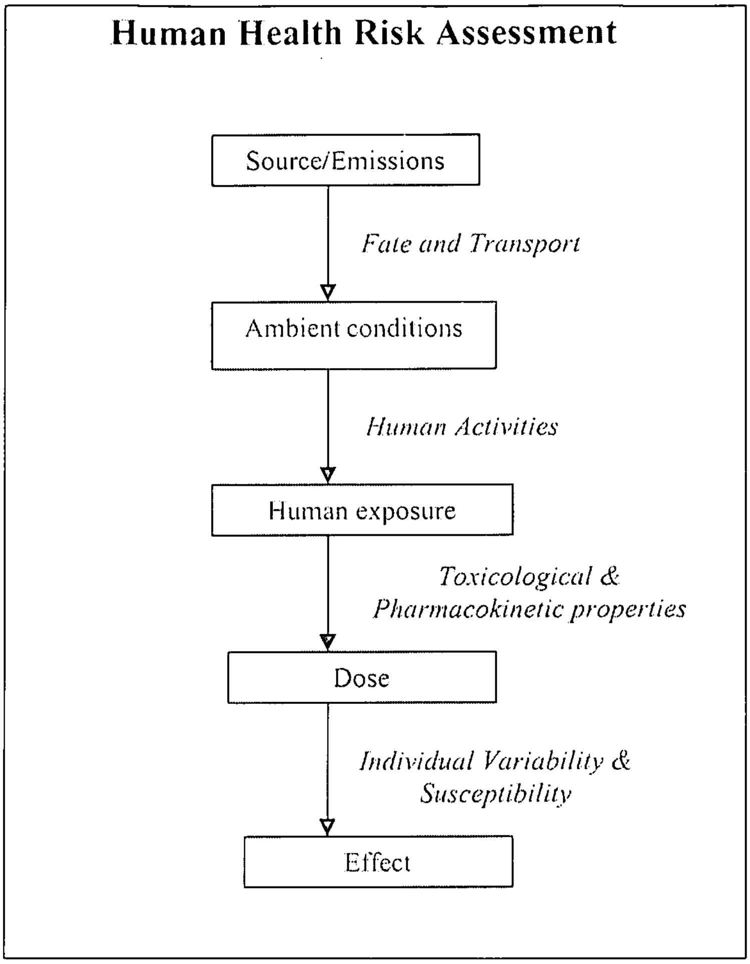


Figure 6.1: Flow chart of the source to effect continuum with regard to human health (Schwab and Genthe, 1998).

6.3 Theoretical considerations for delineation of protection zones in fractured-rock aquifers

6.3.1 Protection zone II

In the case of the delineation of protection zone II, the areal extent of the fracture is very important, and a fracture could be viewed as an extended borehole with a very high T-value and a small S-value. It is thus very important to estimate the areal extent of the fracture. Once bacteria or an element reaches the fracture, its movement will be very rapid towards the abstraction borehole and one of the major mechanisms that will play a role in bacterial die-off time, is the distance from the ground surface to the water level. If a vertical fracture intersects a pitlatrine, the movement of the pollutant to the water level could be very rapid, even in the case of a very deep water level (chapter 6). This illustrates the difficulty to estimate travel times from the surface to the water level in a fractured aquifer. For this reason it is proposed that the whole domain above the fracture be regarded as protection zone II and must be protected. In the following section a method to estimate the size of this capture zone is discussed.

6.3.1.1 Estimation of fracture extent

a.) General

A very good idea of the areal size of the fracture could be obtained by making use of early pumping test data. Considering early data of a pumping tests, it was found that the ratio s/Q (i.e. drawdown in abstraction borehole/ abstraction) after 1 minute of abstracting water from a borehole, gives a good first approximation of the extent of the fracture and the following generalisation applies:

1. If $s/Q < 0.5$ — very good fracture extent
2. If $s/Q < 1$ but > 0.5 — good fracture extent
3. If $s/Q > 1$ — limited fracture extent

b.) Estimating the T-value of the fracture

The following equation (Equation 6.1-adapted Logan equation) will give an estimate of the T-value of the fracture:

$$T = 10^{(Log\frac{104Q}{s} + Log15Q)/2}$$ **(Equation 6.1)**

where:

T = Transmissivity in m^2/d.

Q = abstraction rate in L/s.

s = drawdown in m after 1 minute.

c.) Estimating the S value of the fracture

For the estimation of the S-value of the fracture, two other parameters must first be determined:

i) First the theoretical specific storage (S_s) must be determined. The S_s is calculated by applying Equation 6.2 (Kruseman and De Ridder, 1994).

ii) Secondly the thickness of the fractured zone (D) must be determined (Equation 6.3).

i) Estimation of S_s.

$$S_s = \rho g\,(\alpha + n\beta) \qquad \textbf{(Equation 6.2)}$$

The following values for n and α (obtained from inverse modeling and tracer tests) are proposed:

$\rho g = 9804$ (= specific weight of water)

$n = 0.13$ (=porosity)

$\alpha = 5.56\text{x}10^{-9}$ (= compressibility of the rock)

$\beta = 4.74\text{x}10^{-10}$ (=compressibility of water)

After the application of Equation 5.2 a proposed value for S_s is:

$5.6 \text{ x } 10^{-5}$.

ii) Estimating the thickness of the fractured zone (D)

To estimate S, the thickness of the fracture zone is required and the following equation (obtained from experience from the tracer tests) can be used:

$$\textbf{Thickness D(m) of fracture zone} = (0.2^*Q/s)^*0.14 \qquad \textbf{(Equation 6.3)}$$

Where:

s = drawdown (m) in borehole after 1 minute of abstraction water at a rate of Q (L/s) from borehole.

After the specific storage and thickness of the fracture zone have been estimated the S-value for the fracture can be estimated by the following equation:

$$S = S_s \times D \qquad \textbf{(Equation 6.4)}$$

with:

S_s = Specific Storage.

D = Thickness of fracture zone.

d.) Estimating the fracture half length

By applying the Equtions 6.5 – 6.9, the half-length of the fracture (x_f in the case of vertical fractures) or the radius of the fracture extent (r_f for horizontal fractures) can be estimated.

i) Vertical fracture (Gringarten and Ramey, 1974)

$$x_f = \frac{Q\sqrt{t}}{2s_w\sqrt{\pi T_f S_f}} \qquad \textbf{(Equation 6.5)}$$

x_f = half length (m)

Q=abstraction rate in m^3/d

s_w = drawdown in m after time t (minutes)

T_f=T-value of fracture

S_f=S-value of fracture]

ii) **Horizontal fracture: early storage (Gringarten and Ramey, 1974)**

$$r_f = \sqrt{\frac{Qt}{\pi s_w S_f}} \qquad \textbf{(Equation 6.6)}$$

iii) **Vertical or horizontal fracture (Proposed equation - assumed bi-linear flow at early time in fracture).**

$$r_f = \frac{Q(t)^{0.25}}{4s_w(T_f S_f)^{0.25}} \qquad \textbf{(Equation 6.7)}$$

iv) **Vertical or horizontal fracture (Proposed equation - assumed a combination of linear/bi-linear flow in fracture at early time).**

$$r_f = \frac{Q(t)^{0.333}}{4s_w(T_f S_f)^{0.333}} \qquad \textbf{(Equation 6.8)}$$

v) **Adapted Bohmer equation (bi-linear flow in vertical dyke/fault)**

$$x_f = \frac{Q(t)^{0.25}}{2.74s_w(T_f S_f)^{0.25}} \qquad \textbf{(Equation 6.9)}$$

6.3.2 Examples

6.3.2.1 Borehole UP16 on the Campus Test Site

Table 6.1 on the next page shows early time-drawdown data collected during a pumping test conducted on borehole UP16. The abstraction rate (Q) was 4 L/s.

Table 6.1: UP16 early time pumping test data.

t (min)	s (m)	t (min)	s (m)	t (min)	s (m)
0.014	0.129	0.077	0.800	2.000	2.755
0.015	0.150	0.100	1.000	3.000	3.110
0.020	0.200	0.149	1.200	4.000	3.415
0.030	0.300	0.239	1.500	5.000	3.690
0.040	0.400	0.397	1.800	10.000	4.825
0.053	0.530	0.592	2.000	15.000	5.675
0.066	0.660	1.000	2.275	20.000	6.355

Drilling on the Campus Test Site showed that the lateral extent of the fracture is at least 97 m (i.e. the distance between boreholes UO5 and UO23, which intersects the same bedding plane fracture).

The first aim is to identify the inner boundary conditions of borehole UP16 (i.e. well bore storage (**WBS**) and the type of flow at early times, i.e. linear or bi-linear). Figure 6.2 shows the log-log drawdown plot of the data and the characteristics derived from this plot.

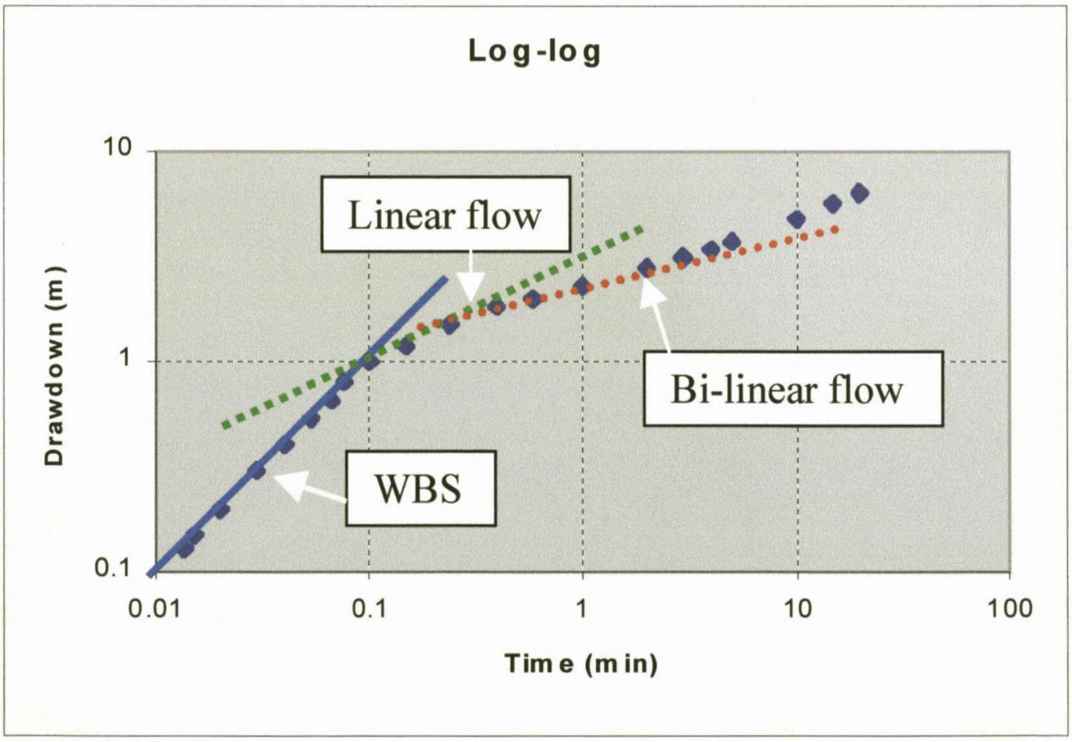


Figure 6.2: Log-log drawdown plot of UP16

The following characteristics are clearly seen on Fig. 6.2:

- **Well bore storage (WBS) till 0.1 minutes**
- **Linear flow from 0.1 – 0.4 minutes (water from fracture alone)**
- **Bi-linear flow from 0.4 – 5 minutes (water from fracture and matrix)**

By applying the five proposed equations for the estimation of the fracture extent the following is obtained:

Table 6.2: Estimated half length/radius of the fracture: UP16.

Data used (t,s)	**Eq.6.5**	**Eq.6.6**	**Eq.6.7**	**Eq.6.8**	**Eq.6.9**	**Mean**
(0.014, 0.128)	17	33	101	55	148	**71**
(1.0, 2.275)	71	67	49	53	71	**62**
(2.0, 2.755)	95	86	51	60	75	**73**

The mean radius of the fracture from the estimates in table 6.2 ranges between 62 and 73 m. This in turn implicates an estimated fracture extent of between 120 and 160 m when different early times are used. These estimated values are well within the range that was expected for the fracture extent on the Campus Site. It is known to be at least 97 m.

Thus, Protection Zone II = radius of 2 x 62 m = 124 m around borehole UP16 at least if the drawdown data after 1 minute is used.

6.3.2.2 Borehole UO5 on the Campus Test Site

Table 6.3 shows the estimates of the radius of the fracture obtained for borehole UO5 by using early data from the pumping test. The abstraction rate (Q) was 1.25 L/s.

Table 6.3 Application of the five equations to borehole UO5 to estimate the extent of the fracture

Data used (t,s)	Eq.6.5	Eq.6.6	Eq.6.7	Eq.6.8	Eq.6.9	Mean
(1.5, 0.171)	164	165	149	148	218	**169**
(2.0, 0.34)	164	137	108	119	157	**137**

By using Equation 6.1, the estimated T of the fracture zone can be determined as:

$T_f = 118\ m^2/d$

and

s/Q = 0.14 (which implies a very good fracture extent)

The estimated thickness of the fracture zone is determined by applying Equation 6.3.

D(m) = (0.2*Q/s)*0.14

= (0.2*1.25/0.171)*0.14

= 0.2 m

Thus:

$S_f = S_s * D$

$= 5.6 \times 10^{-5} * 0.2$

$= 1.12 \times 10^{-5}$

And finally:

$r_f = 149$ m (Equation. 6.7)

The mean estimated extent of the fracture has a radius of 149 m, but the exact geometry of this zone is not known and to be safe an area of two times this radius is proposed.

Then: Protection zone II = circle with radius ±300 m around borehole UO5.

The estimation of the extent of the fracture is dependent on the early time data used and it is proposed that the drawdown data after 1 minute be used for the estimation of the extent of the fracture.

6.3.3 Protection zone III

In the case of persistent hazardous elements, the whole catchment area of the borehole must be protected and this area is dependent on the recharge of the aquifer and the abstraction rate of the borehole, i.e.:

AREA = Q/Recharge **(Equation 6.10)**

6.3.3.1 Example of borehole UO5 on Campus Test Site

The calculated sustainable yield for borehole UO5 with a 95 % safety factor is:

Q = 0.36 L/s.

The average recharge on the Campus Test Site is estimated at 15 mm/a. Using these two values the catchment area of borehole UO5 can be calculated:

A = Q/recharge

= 31*365/0.015

=754 333 m^2

i.e. a circle with a radius of ± 490 m around borehole UO5.

6.3.4 Practical considerati on of protection areas

If say only one pitlatrine is situated in protection zone II or III, it would be unpractical to protect the whole area as given above because the load and impact of the pollutant will probably have no serious impacts on domestic use. Take for instance the case of nitrate pollution. A typical value for NO_3 as N in urine is in the order of 13 000 mg/l (Kuyl, pers. com. 1999). If it is assumed that 50% of the N could reach the groundwater (Foster and Hirata, 1991), the maximum concentration of N can be estimated from the following equation (see Figures 6.3 and 6.4).

$$\textbf{Max. N (mg/l) expected in BH} = \frac{0.5 \times Conc.\,urine(N) \times number\ of\ persons}{(Q \times 86400)}$$

(Equation 6.11)

Where Q is in L/s and converted to m^3/day by multiplication with 86400.

In this case a permanent source injection at a constant rate is assumed together with immobility (i.e. no dispersion) of the pollutant. The estimated concentration is:

$$C = \frac{\sum M}{Q}$$

(Equation 6.12)

Where:

M = injection rate of the pollutant (kg/d).

Q = abstraction rate of the production borehole (m^3/d).

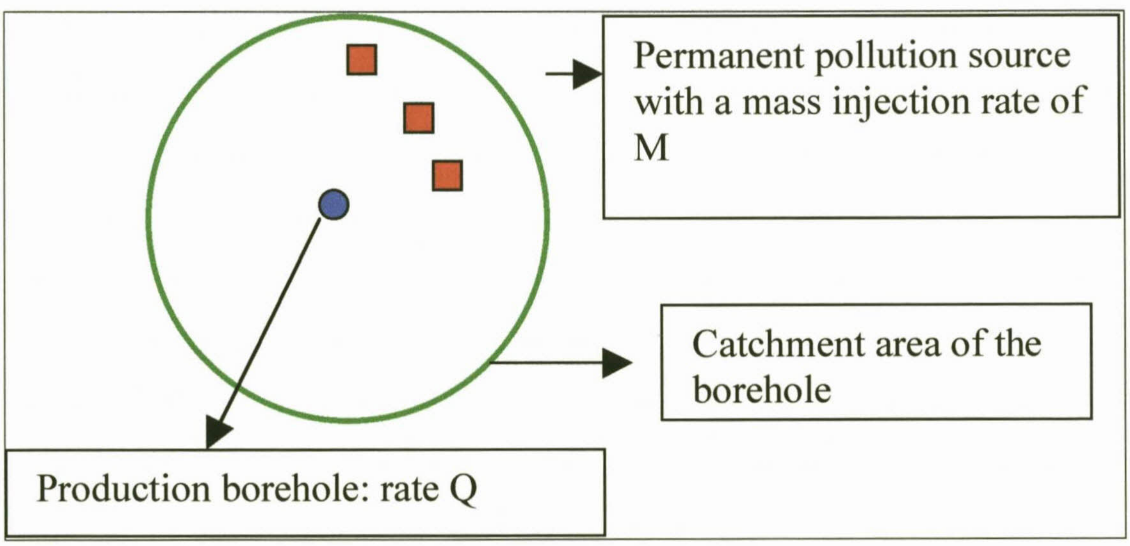


Figure 6.3: Concept of permanent immobile pollution source in the catchment area of a borehole

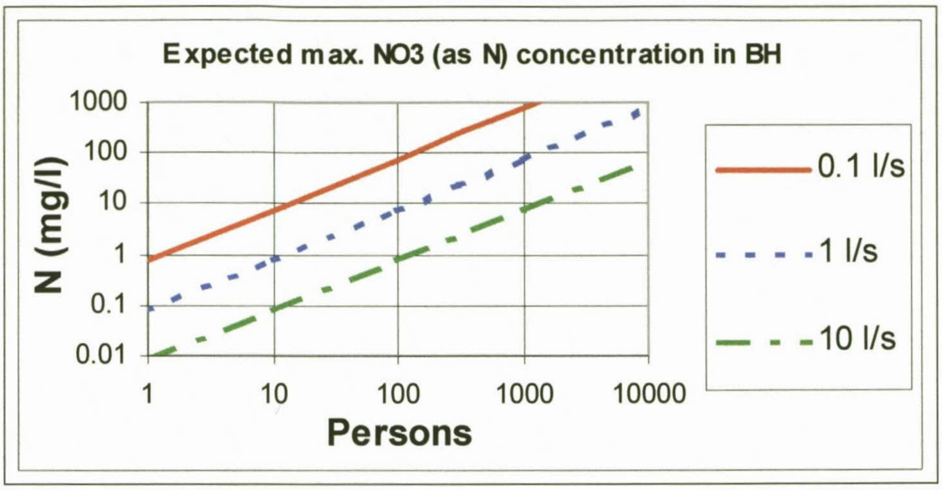


Figure 6.4: Estimation of maximum nitrate load as a function of the number of persons and the abstraction rate of the borehole.

By making use of ***Microsoft Excel***, a program was developed to try and estimate the different protection zones and the nitrate load. This program is called ***Borehole Protection Zone (BPZONE)***.

6.4 Program *BPZONE*

Figure. 6.6 shows the outputs of program ***BPZONE*** for borehole UO5 (see end of chapter).

6.4.1 Explanation of program *BPZONE*

6.4.1.1 Protection Zone I

If more than 20 persons are using pitlatrines, it is proposed that a fence of at least 5 m must be constructed around the borehole. Otherwise just a sanitary seal is required.

6.4.1.2 Protection Zone II

(a) The maximum expected NO3 (as N) is estimated by using the following information:

1. Concentration of urine = 13000 mg/l (can be changed)
2. Percentage N leaching = 50% (can be changed).
3. Volume urine/person/day = 1 L (can be changed).

4. Average annual recharge in mm.

5. Abstraction rate of the borehole (i.e. sustainable yield) in L/s.

6. Number of persons using on-site sanitation in the catchment area of the borehole (the catchment area is estimated from the abstraction rate and recharge).

Program BPZONE then estimated the maximum expected N in boreholes and the risk to infants according to table 5.4:

Table 6.4: Nitrate value intervals and the risk (to infants) associated with each interval.

Parameter	no risk	low risk	high risk	very high risk
N (mg/l)	<5	5-10	10-20	>20

(b) The next step is to estimate the extent of the vertical or horizontal fracture by using early pumping test data (i.e. the drawdown after 1 minute). To estimate the extent, the program uses the five equations presented earlier (Equations 5.5 – 5.9). The mean of the estimated fracture extent together with the standard deviation is given.

(c) Step 3 is the estimation of the travel time from the surface to the water level and the position of the water strike. For the estimation of travel times a number of parameters is required, i.e.

i) **The saturated vertical K-value of the unconsolidated material.** If the K value is not known, it was decided to try and estimate it by means of the clay content of the unconsolidated material. Data was gathered of soils with known values for clay content and K-values. A graph was drawn of clay content vs. K-value and the equation of the exponential trendline fitted with the data was incorporated in the program BPZONE.

$$K_u = 30\ e^{-0.3*cl}$$ **(Equation 6.13)**

Where:

cl = clay content (%)

ii) **Verical K-value of the consolidated material.** If unknown it is suggested that a value of 0.01 be used (usually between 0.001 and 0.1 for South African rocks).

iii) Distance from surface to water level.

iv) Thickness of the unconsolidated and consolidated material and their kinematic porosities.

The total travel time to the water strike is estimated from:

$$t = \frac{n_{eu} D_u}{K_u} + \frac{n_{ec} D_c}{K_c}$$ **(Equation 6.14)**

[t=travel time (d); n=kinematic porosity; D=Thickness (mm) and K=hydraulic conductivity (m/d) . Subscripts u and c denote unsaturated and saturated zone repectively]

Risk of microbial pollution is assigned by using the following criteria:

Table 6.5: Travel times and the risk of microbial pollution assigned to each.

Parameter	no risk	low risk	high risk	very high risk
Travel time (days)	>100	30-100	3-30	<3

The program then estimates protection zone II by using the following criteria:

Table 6.6: Criteria involving risk and proposed distances for protection zone II.

Risk	Protection zone II
High or very high risk of microbial pollution.	2 times fracture half-length.
Low risk for microbial pollution.	1 times fracture half-length.
No risk for microbial pollution.	0.5 times fracture half-length.
High risk for N for infants.	2 times fracture half-length.
Low risk for N for infants.	1 times fracture half-length.
No risk for N for infants.	0.5 times fracture length.

6.4.1.3Protection zone III

If hazardous chemical elements are present the program estimates the catchment area of the borehole by using the recharge and the abstraction rate (Equation 6.10).

a.) Example of borehole Bacl in the Northern Province

Information:

ii) Geology: Gneiss.
iii) Number of persons using on-site sanitation = 123.
iv) Abstraction rate of Bacl =1.91 L/s.
v) Depth to water level from surface = 7 m.
vi) Thickness of unconsolidated material = 6m with porosity of 0.2.
vii) Clay content of unconsolidated material = 3%.
viii) Water strike below surface = 23 m.
ix) Vertical K-value of consolidated rock above fracture = 0.1 m/d with porosity of 0.1.
x) Average annual recharge = 20 mm.
xi) No hazardous pollutants are present.

Figure 6.7 shows the applications of program ***BPZONE*** to borehole Bacl (see end of chapter).

The risk of N for infants is very low but the risk for microbial pollution is very high and the recommendation is thus to protect a zone around borehole Bacl with:

Radius = 2 times 50 m
=100 m.

b.) Example of borehole GP1 at the Meadhurst Test Site

There are 12 pitlatrines and 10 septic tanks on the Meadhurst Test Site and the farmers abstract water from 12 boreholes for domestic and irrigation purposes. Figure 6.8 shows the applications of program ***BPZONE*** for borehole GP1 on this site (see end of chapter).

For borehole GP1 at Meadhurst, protection zone II = circle with radius 138 m around borehole GP1. The estimated nitrate load (as N mg/l) is, however, very low and the depth from surface to the water level is 19 m. For all practical purposes, a pitlatrine could be very close to GP1 without having any serious impact on the nitrate load of the groundwater but the risk for microbial pollution is very high due to the quick travel time from the surface to the water level (i.e. 0.31 d). It is thus proposed that a pitlatrine must be at least 138 m away from GP1.

c.) Other applications of BPZONE

Program ***BPZONE*** was applied to 73 boreholes in different geological formations and Table 6.9 shows the results. The value for the half-length of the fracture of the 52 boreholes varies between 21 and 321 m. If the estimated nitrate load would be high for all boreholes, the value for protection zone II would be a minimum distance of between 41 and 642 m.

An evaluation of 150 boreholes drilled in the Karoo Formation in the Thaba Nchu area in the Free State showed that more than 25 of these boreholes have nitrate values higher than 10 mg/l N (Ncube, 1998). The only reason for these elevated N values, is the large number of pitlatrines in the area. At Itsoseng (dolomitic terrain, Mafikeng) 17 of the 22 boreholes have nitrate values in excess of 20 mg/l N. Some of the boreholes also show signs of bacterial pollution. Once again the only reason for this pollution is the large number of pitlatrines in the area.

6.5 Justification with *Modflow* generated examples

The well-known ***MODFLOW 3D*** finite difference program (***PMWIN***, Chiang and Kinzelbach, 1998) was used to generate three typical case studies in fractured-rock aquifers. The model constructed has 10 layers with a thickness of 1 m each, except for the bottom layer (i.e. the fracture zone) which was assigned a thickness of 0,2 m (i.e. the typical situation on the Campus Aquifer). The following parameters were assigned to the different layers (Table 6.7):

Table 6.7: Parameter values assigned for the generated Modflow model

Layer	S_s	K_h(m/d)	K_v(m/d)
1-9	5e-5	0.1	0.005
10	5e-5	3600	.005

where

S_s = specific storativity [1/m]

K_h = horizontal K-value

K_v = vertical K-value

(This gives a T-value of the matrix = 1 m^2/d and T-value of the fracture = 720 m^2/d as on the Campus Site)

A fracture zone was input into the bottom layer (i.e. layer 10) and three fracture radii were used, i.e. 60m, 100, and 200m (i.e. the case of a horizontal bedding plane fracture). The model was run for 300 minutes for each of the set ups and the drawdown after 1 minute (with an abstraction rate of 1.25 l/s) was supplied to the ***BPZONE*** program and the results are shown in Table 6.8.

Table 6.8: Comparison between *Modflow* and *BPZONE* results (mean and standard deviation of the 5 equations) for the estimation of the radius of the fracture

	r_f(m)	r_f(m)	r_f(m)
Modflow (value assigned)	60	100	200
BPZONE (mean of 5 equations)	76 ± 15	113 ± 19	175 ± 40
Eq.6.7 in ***BPZONE***	60	99	167

Figure 6.5 shows the ***BPZONE*** results for each of the cases.

Modflow case1: real radius = 60 m	**t(min)**	**s(m)**	**Q (l/s)**			
	1.01	0.6500343	1.25			
Enter other values for t,s,Q if required						
t,s,Q used =	1.010404	0.6500343	1.25			
Est. of D(m) =	0.054	(D(m)= thickness of fracture zone)			Est. of S_f =	2.68E-06
D(m) =	0.054	T_f=	61		61	
	Gringarten					
	$(x_f^2 S_f)$=	0.0253				
	x_f (m)=	97	x_f = half length of vertical fracture (use early linear flow)			
	r_f (m)=	70	r_f = radius of horizontal fracture (use early storage)			
	r_f (m)=	60	Use early bi-linear flow in fracture			
	r_f (m)=	67	Combination of linear/bilinear flow in fracture			
	x_f (m)=	87	Adapted Bohmer equation			
Average half length/radius of fracture =	76					
with standard deviation (m) =	15					

Modflow case2: real radius = 100 m	**t(min)**	**s(m)**	**Q (l/s)**			
	1.01	0.2929897	1.25			
Enter other values for t,s,Q if required						
t,s,Q used =	1.010404	0.2929897	1.25			
Est. of D(m) =	0.119	(D(m)= thickness of fracture zone)			Est. of S_f =	5.90E-06
D(m) =	0.119	T_f=	91		91	
	Gringarten					
	$(x_f^2 S_f)$=	0.0834				
	x_f (m)=	119	x_f = half length of vertical fracture (use early linear flow)			
	r_f (m)=	105	r_f = radius of horizontal fracture (use early storage)			
	r_f (m)=	99	Use early bi-linear flow in fracture			
	r_f (m)=	101	Combination of linear/bilinear flow in fracture			
	x_f (m)=	144	Adapted Bohmer equation			
Average half length/radius of fracture =	113					
with standard deviation (m) =	19					

Modflow case3: real radius = 200 m	**t(min)**	**s(m)**	**Q (l/s)**			
	1.01	0.1249509	1.25			
Enter other values for t,s,Q if required						
t,s,Q used =	1.010404	0.1249509	1.25			
Est. of D(m) =	0.280	(D(m)= thickness of fracture zone)			Est. of S_f =	1.39E-05
D(m) =	0.28	T_f=	140		140	
	Gringarten					
	$(x_f^2 S_f)$=	0.2981				
	x_f (m)=	146	x_f = half length of vertical fracture (use early linear flow)			
	r_f (m)=	160	r_f = radius of horizontal fracture (use early storage)			
	r_f (m)=	167	Use early bi-linear flow in fracture			
	r_f (m)=	154	Combination of linear/bilinear flow in fracture			
	x_f (m)=	244	Adapted Bohmer equation			
Average half length/radius of fracture =	175					
with standard deviation (m) =	40					

Figure 6.5: *BPZONE* fracture radius estimatons for the *Modflow* examples.

From Table 6.8 it is clear that the ***BPZONE*** results were all within 24% within the ***Modflow*** assigned fracture radii which shows that program ***BPZONE*** can be used with confidence to estimate the extent of a fracture. Especially Equation. 6.7 in the ***BPZONE*** program (i.e. using bi-linear equation at early time) performed extremely good.

A fourth ***Modflow*** example was also generated by using, instead of a horizontal fracture, a vertical fracture with half length = 200 m (width =0,5 m and extending over a thickness of 10 m in the vertical direction). In this case the estimated half length of the fracture with program ***BPZONE*** was 249 m with standard deviation of 75 m, which showed that the program also estimates acceptable fracture half lengths in the case of vertical fractures.

BPZONE

Estimation of:
(i) Protection Zones I, II and III.
(ii) Maximum NO_3 as N.
(iii) Areal extent of Fracture.
(iv) Travel Times.

Borehole Name:UO5

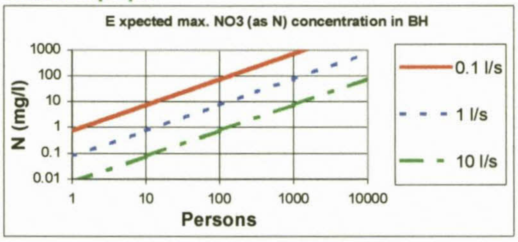
(I) Protection Zone I : Fencing around borehole and sanitary seal

Dependent on number of persons using on-site sanitation

(II) Protection Zone II : Protection against microbial and nitrate pollution

(a) Maximum NO3 (as N) estimation for different number of people

Concentration of urine as N (mg/l) =	13000
Percentage N reaching water level =	50
Volume urine/person/day [L] =	1
Recharge (mm/a) =	15
Sustainable abstraction rate [l/s] =	0.43
Number of persons using on-site sanitation =	0
in an area with circle around BH (m) =	537
Expected max. N (mg/l) in borehole =	0.000
Risk for Infants =	No risk



(b) Areal extent of fracture (vertical or horizontal fracture)

Use early time and drawdown during pumping test

	t(min)	s(m)	Q (l/s)		
Enter other values for t,s,Q if required	1.50	0.177	1.26		
t,s,Q used =	1.5	0.177	1.26		
Est. of D(m) =	0.199	(D(m)= thickness of fracture zone)		Est. of S_f =	9.87E-06
D(m) =	0.199	T_f=	118	118	

Gringarten		
$(x_f^2S_f)$=	0.2659	
x_f (m)=	164	x_f = half length of vertical fracture (use early linear flow)
r_f (m)=	165	r_f = radius of horizontal fracture (use early storage)
r_f (m)=	150	Use early bi-linear flow in fracture
r_f (m)=	148	Combination of linear/bilinear flow in fracture
x_f (m)=	218	Adapted Bohmer equation

Average half length/radius of fracture =	169
with standard deviation (m) =	29

(c) Estimation of travel time from surface to water strike: for bacterial die-off time

K-values of unconsolidated and consolidated material

Unconsolidated material

clay content (%) =	3
K (m/d) =	12.197

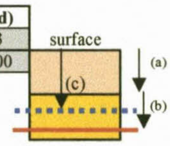
Consolidated material Vertical K-value (if unknown)

Use K (m/d) = 0.01 for first estimate

(usually between 0,001 and 0,1 m/d)

(Note: if more than one layer exists, use the harmonic mean of the K-values of the layers)

	Thickness	K (m/d)	Porosity	time (d)
(a) unconsolidated material	2	12.197	0.2	0.033
(b) consolidated material to water strike	19	0.005	0.1	380.000
(c) Depth to water level (m) =	6			
Travel time to water strike (d) =	380.03			
Travel time to water level (d) =	80.03			
Risk of microbial pollution in BH =	Low			



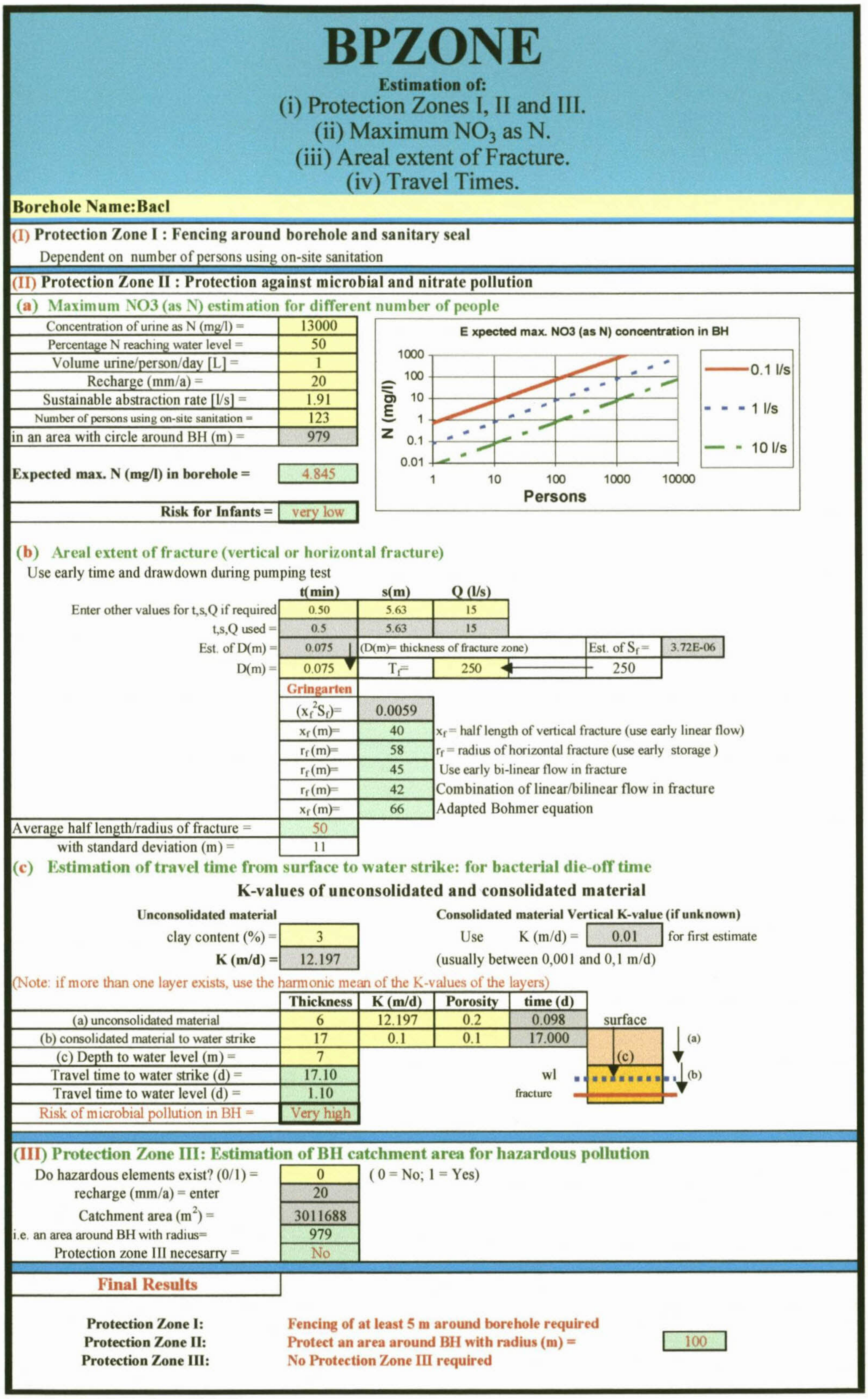
(III) Protection Zone III: Estimation of BH catchment area for hazardous pollution

Do hazardous elements exist? (0/1) =	0	(0 = No; 1 = Yes)
recharge (mm/a) = enter	15	
Catchment area (m^2) =	904032	
i.e. an area around BH with radius=	537	
Protection zone III necesarry =	No	

Final Results

Protection Zone I:	No fencing around borehole required : only sanitary seal	
Protection Zone II:	Protect an area around BH with radius (m) =	85
Protection Zone III:	No Protection Zone III required	

Figure 6.6: Sample output of program BPZONE for borehole UO5 on the Campus Site.



BPZONE

Estimation of:
(i) Protection Zones I, II and III.
(ii) Maximum NO_3 as N.
(iii) Areal extent of Fracture.
(iv) Travel Times.

Borehole Name:Bacl

(I) Protection Zone I : Fencing around borehole and sanitary seal
Dependent on number of persons using on-site sanitation

(II) Protection Zone II : Protection against microbial and nitrate pollution

(a) Maximum NO3 (as N) estimation for different number of people

Concentration of urine as N (mg/l) =	13000
Percentage N reaching water level =	50
Volume urine/person/day [L] =	1
Recharge (mm/a) =	20
Sustainable abstraction rate [l/s] =	1.91
Number of persons using on-site sanitation =	123
in an area with circle around BH (m) =	979
Expected max. N (mg/l) in borehole =	4.845
Risk for Infants =	very low

(b) Areal extent of fracture (vertical or horizontal fracture)
Use early time and drawdown during pumping test

	t(min)	s(m)	Q (l/s)
Enter other values for t,s,Q if required	0.50	5.63	15
t,s,Q used =	0.5	5.63	15

Est. of D(m) =	0.075	(D(m)= thickness of fracture zone)		Est. of S_f =	3.72E-06
D(m) =	0.075	T_f=	250	←	250

Gringarten

$(x_f^2 S_f)$=	0.0059	
x_f (m)=	40	x_f = half length of vertical fracture (use early linear flow)
r_f (m)=	58	r_f = radius of horizontal fracture (use early storage)
r_f (m)=	45	Use early bi-linear flow in fracture
r_f (m)=	42	Combination of linear/bilinear flow in fracture
x_f (m)=	66	Adapted Bohmer equation
Average half length/radius of fracture =	50	
with standard deviation (m) =	11	

(c) Estimation of travel time from surface to water strike: for bacterial die-off time

K-values of unconsolidated and consolidated material

Unconsolidated material
clay content (%) = 3
K (m/d) = 12.197

Consolidated material Vertical K-value (if unknown)
Use K (m/d) = 0.01 for first estimate
(usually between 0,001 and 0,1 m/d)

(Note: if more than one layer exists, use the harmonic mean of the K-values of the layers)

	Thickness	K (m/d)	Porosity	time (d)
(a) unconsolidated material	6	12.197	0.2	0.098
(b) consolidated material to water strike	17	0.1	0.1	17.000
(c) Depth to water level (m) =	7			
Travel time to water strike (d) =	17.10			
Travel time to water level (d) =	1.10			
Risk of microbial pollution in BH =	Very high			

(III) Protection Zone III: Estimation of BH catchment area for hazardous pollution

Do hazardous elements exist? (0/1) =	0	(0 = No; 1 = Yes)
recharge (mm/a) = enter	20	
Catchment area (m^2) =	3011688	
i.e. an area around BH with radius=	979	
Protection zone III necesarry =	No	

Final Results

Protection Zone I:	**Fencing of at least 5 m around borehole required**	
Protection Zone II:	**Protect an area around BH with radius (m) =**	100
Protection Zone III:	**No Protection Zone III required**	

Figure 6.7: Output of program BPZONE for borehole Bacl.

BPZONE

Estimation of:

(i) Protection Zones I, II and III.
(ii) Maximum NO_3 as N.
(iii) Areal extent of Fracture.
(iv) Travel Times.

Borehole Name:GP1

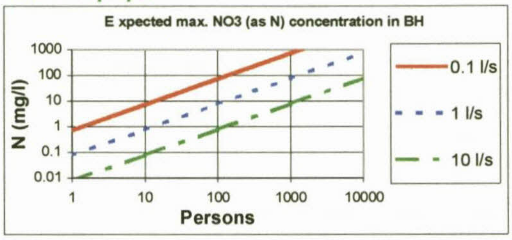
(I) Protection Zone I : Fencing around borehole and sanitary seal

Dependent on number of persons using on-site sanitation

(II) Protection Zone II : Protection against microbial and nitrate pollution

(a) Maximum NO3 (as N) estimation for different number of people

Concentration of urine as N (mg/l) =	13000
Percentage N reaching water level =	50
Volume urine/person/day [L] =	1
Recharge (mm/a) =	15
Sustainable abstraction rate [l/s] =	1.1
Number of persons using on-site sanitation =	30
in an area with circle around BH (m) =	858
Expected max. N (mg/l) in borehole =	2.052
Risk for Infants =	very low



(b) Areal extent of fracture (vertical or horizontal fracture)

Use early time and drawdown during pumping test

	t(min)	s(m)	Q (l/s)
Enter other values for t,s,Q if required	1.00	0.9	1.5
t,s,Q used =	1	0.9	1.5

Est. of D(m) =	0.047	(D(m)= thickness of fracture zone)	Est. of S_f =	2.33E-06
D(m) =	0.047	T_f= 62		62

Gringarten

$(x_f^2 S_f)$=	0.0185	
x_f (m)=	89	x_f = half length of vertical fracture (use early linear flow)
r_f (m)=	65	r_f = radius of horizontal fracture (use early storage)
r_f (m)=	53	Use early bi-linear flow in fracture
r_f (m)=	60	Combination of linear/bilinear flow in fracture
x_f (m)=	78	Adapted Bohmer equation
Average half length/radius of fracture =	69	
with standard deviation (m) =	14	

(c) Estimation of travel time from surface to water strike: for bacterial die-off time

K-values of unconsolidated and consolidated material

Unconsolidated material

clay content (%) = 3

K (m/d) = 12.197

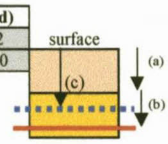
Consolidated material Vertical K-value (if unknown)

Use K (m/d) = 0.01 for first estimate

(usually between 0,001 and 0,1 m/d)

(Note: if more than one layer exists, use the harmonic mean of the K-values of the layers)

	Thickness	K (m/d)	Porosity	time (d)
(a) unconsolidated material	19	12.197	0.2	0.312
(b) consolidated material to water strike	8	0.01	0.1	80.000
(c) Depth to water level (m) =	19			
Travel time to water strike (d) =	80.31			
Travel time to water level (d) =	0.31			
Risk of microbial pollution in BH =	Very high			



(III) Protection Zone III: Estimation of BH catchment area for hazardous pollution

Do hazardous elements exist? (0/1) =	0	(0 = No; 1 = Yes)
recharge (mm/a) = enter	15	
Catchment area (m^2) =	2312640	
i.e. an area around BH with radius=	858	
Protection zone III necesarry =	No	

Final Results

Protection Zone I:	No fencing around borehole required : only sanitary seal	
Protection Zone II:	Protect an area around BH with radius (m) =	138
Protection Zone III:	No Protection Zone III required	

Figure 6.8: Output of program BPZONE for borehole GP1 at the Meadhurst Test Site.

Table 6.9: Application of program BPZONE to 73 boreholes situated in different geological formations.

BH	Rock type	t (min)	s(m)	Q(l/s)	D(m)	S_f	T_f	x_f (m)	r_f (m)	Bilin	lin/bilin	Bohmer	Mean
Bacl-north prov	Gneiss	0.50	5.63	15	0.075	3.70E-06	250	40	58	45	42	66	50
BH4-citrusdal	sandstone	0.50	3.86	28	0.203	1.01E-05	563	44	96	78	62	114	79
F05E-kentane	shale/mud	1.00	10.4	4	0.011	5.34E-07	49	48	31	19	25	28	30
GR2-graaff reinette	sandstone	0.50	4.09	28	0.192	9.51E-06	547	43	93	75	60	110	76
HKM-hermanus	sandstone	0.50	9.228	14.7	0.045	2.21E-06	191	35	45	33	32	48	39
LBH3-Cape prov	sandstone	0.50	9.106	23	0.071	3.51E-06	301	35	57	41	38	60	46
Solo3-north prov	gabbro	0.50	9.05	18	0.056	2.76E-06	236	35	50	37	35	54	42
UO5-campus	sandstone	1.50	0.171	1.25	0.205	1.02E-05	119	165	167	152	150	222	171
H01-0063-north prov	Gneiss	0.50	2.44	5	0.057	2.85E-06	126	49	51	44	44	64	50
H01-0709-north prov	gabbro	0.50	8.09	4	0.014	6.87E-07	56	36	25	19	22	27	26
H01-0792-north prov	Gneiss	0.50	5.21	1.8	0.010	4.80E-07	31	41	21	16	21	24	25
H01-0835-north prov	Gneiss	0.50	4.7	10	0.060	2.96E-06	182	42	52	41	40	60	47
H01-0837-north prov	Gneiss	0.50	7.61	11	0.040	2.01E-06	157	37	43	32	32	47	38
H01-0851-north prov	Gneiss	0.50	3.21	2.5	0.022	1.08E-06	55	46	31	26	30	38	34
H04-000322-north prov	Gneiss	0.50	5.76	5	0.024	1.21E-06	82	40	33	26	28	37	33
H10-008-north prov	Gneiss	0.50	3.22	2	0.017	8.63E-07	44	46	28	23	28	34	32
Madg2-north prov	gabbro	0.50	16.95	5	0.008	4.10E-07	48	30	19	13	17	19	20
Maph1-north prov	gabbro	0.50	2.34	4	0.048	2.37E-06	103	50	47	40	41	59	47
Solo4-north prov	gabbro	0.50	3.51	13	0.104	5.15E-06	274	45	69	56	50	82	60
T1443-north prov	gabbro	0.50	1.3	5	0.108	5.34E-06	173	57	70	65	60	95	69
A01B-kentane KZN	shale/mud	1.00	4.87	0.3	0.002	8.56E-08	5	58	13	8	15	12	21
B02B-kentane	shale/mud	1.00	7.8	1.9	0.007	3.38E-07	27	52	25	16	22	23	27
G04D-kentane	shale/mud	1.00	0.8	0.4	0.014	6.95E-07	18	92	36	30	41	43	48
I01A-kentane	mudstone	1.00	1.7	1.5	0.025	1.23E-06	45	76	47	36	44	52	51
J01A-kentane	mudstone	1.00	5.07	4	0.022	1.10E-06	70	58	45	30	35	43	42
ACVV-postmasburg	dolomite	1.00	0.39	6	0.431	2.14E-05	379	110	198	180	147	262	179
Boich-postmasburg	dolomite	1.00	0.2	11	1.540	7.64E-05	971	130	374	369	251	539	333
F&C-postmasburg	dolomite	1.00	0.43	20	1.302	6.46E-05	1205	107	344	309	209	451	284
Hanibal-postmasburg	dolomite	1.00	0.26	7.6	0.818	4.06E-05	589	121	273	261	194	381	246
Houtstraat-postmasburg	dolomite	1.00	5.92	22.3	0.105	5.23E-06	362	56	98	63	58	92	74
Kooperasie-postmasburg	dolomite	1.00	0.37	8	0.605	3.00E-05	519	111	235	215	166	313	208
Makoudam-postmasburg	dolomite	1.00	0.21	6.3	0.840	4.17E-05	543	128	276	271	203	396	255
Tsanseb-postmasburg	dolomite	1.00	4	31	0.217	1.08E-05	612	61	141	95	79	139	103
Kokstad	mudstone	0.50	3.98	16	0.113	5.59E-06	317	43	72	58	50	84	62
Dewetsdorp	shale/mud	1.00	3.1	1.3	0.012	5.83E-07	29	65	33	23	31	33	37
GP1-meadhurst	sandstone	0.50	1.52	1.3	0.024	1.19E-06	42	55	33	30	35	44	40
Jacobsdal1	shale/mud	1.00	1.21	22	0.509	2.53E-05	790	83	215	170	128	248	169
Jacobsdal2	shale/mud	1.00	3.13	10	0.089	4.44E-06	223	65	90	63	61	92	74
Vryburg1	quartsite	1.10	0.4843	3.5	0.202	1.00E-05	199	109	142	123	113	179	133
Vryburg2	quartsite	1.00	0.3679	3.15	0.240	1.19E-05	205	111	148	135	122	197	143
Surene-namibia	dolomite	1.00	1	2.5	0.070	3.47E-06	99	87	80	64	68	94	79
Shed	sandstone	0.5	3.895	20	0.144	7.13E-06	400	44	81	65	55	96	68
BH1_bosch	sandstone	0.50	1.38	27	0.548	2.72E-05	908	57	158	146	102	212	135
BH3_bosch	sandstone	0.50	5.75	10	0.049	2.42E-06	165	40	47	36	36	53	42
BH2_bosch	sandstone	0.50	3.82	15	0.110	5.46E-06	303	44	71	57	50	84	61
BH5_bosch	sandstone	0.50	4.85	8	0.046	2.29E-06	143	41	46	36	36	53	42
BH4_bosch	sandstone	0.50	3.86	28	0.203	1.01E-05	563	44	96	78	62	114	79
FP1-meadhurst	sandstone	1	0.8	1	0.035	1.74E-06	44	92	56	47	56	68	64
F1-meadhurst	sandstone	1	2	1.66	0.023	1.15E-06	46	73	46	34	42	50	49
G3-meadhurst	dolerite	2	1.25	2	0.045	2.22E-06	71	116	90	60	71	87	85
GP1-meadhurst	sandstone	1	1.95	1.3	0.019	9.26E-07	37	73	41	31	39	45	46
WWW29655 -namibia	Schist	1.00	1.92	1.75	0.026	1.27E-06	50	74	48	36	44	52	51
WWW29890 -namibia	Schist	1.00	3.47	2.31	0.019	9.25E-07	49	64	41	28	36	42	42
WWW29655 -namibia	Schist	1.00	0.86	2.7	0.088	4.36E-06	115	90	89	74	76	107	87
UP16-campus	sandstone	1	0.36	1	0.078	3.86E-06	66	112	84	77	84	113	94
Epukuro30512-namibia	quartsite	1	0.25	0.416	0.047	2.31E-06	33	123	65	62	75	91	83
Epukuro36704-namibia	marmer	1.00	0.15	0.84	0.157	7.78E-06	86	139	119	122	123	178	136
Matukeng-Lesotho	sandstone	2	3.60	5	0.039	1.93E-06	104	89	84	49	57	71	70
Maruthuane-Lesotho	sandstone	2.00	10.74	5	0.013	6.47E-07	60	68	49	25	33	36	42
H06-1-North Prov	gabbro	1.00	4.79	3	0.018	8.70E-07	54	59	40	27	33	39	39
H06-2-North Prov	gabbro	1.00	4.65	1	0.006	2.99E-07	18	59	23	16	23	23	29
H03-1691-North Prov	gabbro	1.00	5.6	22	0.110	5.46E-06	367	56	100	65	60	95	75
H03-2228-North Prov	gabbro	1	0.5	4.2	0.235	1.17E-05	235	103	146	129	115	188	136
H03-2230-North Prov	gabbro	1	0.49	6.5	0.371	1.84E-05	367	104	184	162	134	237	164
H03-2235-North Prov	gabbro	1	2.87	6	0.059	2.90E-06	140	67	73	52	54	75	64
H03-2255-North Prov	gabbro	1	9.92	9.5	0.027	1.33E-06	119	49	49	30	34	44	41
H03-2327-North Prov	gabbro	1	2.27	3	0.037	1.84E-06	79	71	58	42	48	62	56
H45512-North Prov	gabbro	1	1.84	1.9	0.029	1.43E-06	55	74	51	38	46	56	53
Boshof: BH1	calcrete	1	5.825	0.2	0.001	4.77E-08	3	56	9	6	12	9	18
Boshof: BH2	calcrete	1	6.775	2.63	0.011	5.39E-07	40	54	31	20	27	29	32
Boshof: BH3	calcrete	1	5.825	4	0.019	9.54E-07	65	56	42	27	33	40	39
Boshof: BH4	calcrete	1	5.770	4	0.019	9.63E-07	66	56	42	27	33	40	40
Boshof: BH5	calcrete	1	10.355	7.14	0.019	9.58E-07	88	48	42	25	30	37	36

6.6 Conclusions and recommendations

1. Due to the heterogeneity of South African conditions concerning the groundwater environment, this document can be seen as a continuation of the work that has already been done on delineating protection zones. The information in this chapter must be regarded as such and not as the ultimate solution to assigning protection zones. There is room for many more approaches as well as studies on this topic.

2. In this document the focus is on nitrates and microbes due to their association with pitlatrines and septic tanks. The same approach can be applied to more parameters depending on what type of study is being done.

3. The application of risk assessment and management is of great importance. However, great care must be taken and the person(s) responsible should be adept in the process and be able to evaluate a given situation with care before any major decisions are reached.

4. The program BPZONE must be used with great care and the answers obtained must be viewed within the existing conditions of a given situation or problem.

CHAPTER 7

Conclusions and recommendations

7.1 Conclusions

At the completion of this two and a half year study, the following conclusions were reached:

1. The effect of point pollution sources should be of great concern to the person(s) involved with water quality. During this study, the vast amount of complexities involved when dealing with groundwater contamination, has become apparent.

2. To assume areal homogeneity is one of the worst mistakes that can be made when assessing the impact of a pollution source on groundwater. Vertical fractures should be an important consideration.

3. The protection zones proposed in this document should be considered wherever the possibility of groundwater contamination is present.

4. Tracers are definitely an important aid in gaining a better understanding of groundwater flow mechanisms as well as the effect of the groundwater environment on groundwater movement.

5. The unsaturated zone is of great importance when dealing with groundwater contamination.

6. The program ***BPZONE*** is a more practical approach when delineating boreholes.

7. This study is only the tip of the iceberg, in understanding groundwater and the effects of pollutants on the groundwater environment.

7.2 Recommendations

1. The protection of our groundwater resources should be of major importance and more research should be done on how to ensure a minimal impact of pollution sources on groundwater quality.

2. The application of the proposed protection zones, should be tested over a wide variety of regions.

3. Now that the effect of point pollution sources on groundwater has been established, this type of study should be expanded to pollution sources with a larger areal extent, like mines, waste sites and industrial areas.

4. When conducting an impact study, more emphasis should be placed on the use of tracers to gain more information and data.

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Summary

Due to the importance of groundwater as an alternative for supplementing existing sources of this precious fluid, any study that may help in understanding the complexity of the groundwater environment is an asset. Therefore this dissertation was written with the sincerest hope that the people and organisations involved with groundwater will gain a better understanding of it.

The need to protect our groundwater sources has become very important and therefore a different, more practical approach to delineate borehole protection zones was considered based on the existing standards set by Germany and other European nations.

As part of the study, emphasis was placed on the effect of the unsaturated (vadose) zone on the migration of pollutants before it reaches the groundwater environment. Field tests on the saturated as well as unsaturated zones were conducted with a conservative tracer (Fluorecein) as well as microbial tracers (bacteriophages), to assist in the delineation process. Thereafter it was decided to propose that three protection zones should be assigned depending on **i)** the size of the population and **ii)** the vulnerability and importance of the aquifer. The effect of a pollutant on human health and the possibility of fatalities were the criteria for deciding which protection zone is applicable under given circumstances.

Protection zone I involves fencing off the immediate area around the borehole (a radius of 5 m is proposed) as well as the necessity of a well-constructed sanitary seal. Where a borehole supplies water to less than 20 people, a sanitary seal will be sufficient.

To determine the extent of protection zone II, the idea was to protect the drinking water from microbial (bacteria and viruses) and nitrate pollution. Emphasis was placed on these two parameters because of their association with pitlatrines and septic tanks. Methods to estimate the fracture extent are proposed and, depending on the estimation of the nitrate and bacterial travel times and loads, a guideline to use **i)** half the fracture extent, **ii)** the whole extent of the fracture or **iii)** double the fracture extent, is proposed.

Only if there is the possibility of a hazardous substance that may pollute the groundwater, it is proposed that protection zone III be assigned. The use of the word "hazardous" could make the decision more complex and therefore the issue of risk assessment and management is also addressed very generally in this dissertation. The proposed extent for protection zone III is the whole catchment area of the borehole.

A programme called ***Borehole Protection Zone*** **(BPZONE)** was developed by making use of ***Microsoft Excel*** to assist the person(s) responsible in the decision making processes of delineating borehole protection zones.

Information gathered during the field tests conducted at the Campus Test Site of the University of the Free State as well as the Meadhurst Test Site outside Bloemfontein, yielded very positive results, in terms of delineating protection zones.

Opsomming

A.g.v. die belangrikheid van grondwater as 'n alternatief ter aanvulling van die kosbare vloeistof, is enige studie wat sal meebring dat die ingewikkelde meganismes van die grondwateromgewing beter verstaan word, 'n voordeel. Dus is die verhandeling saamgestel met die hoop dat persone en organisasies wat met grondwater te doen het, baat daarby sal vind.

Die beskerming van ons grondwaterbronne het baie belangrik geword en dus is gepoog om met 'n verskillende, meer praktiese benadering, boorgatbeskermingsones toe te ken. Huidige standaarde wat deur Duitsland en ander Europese lande gebruik word, is as basis gebruik.

As deel van die studie is klem gelê op die effek van die onversadigde sone op die beweging van besoedeling voordat dit die grondwater bereik. Veldtoetse in die versadigde, sowel as onversadigde sones, is gedoen met 'n konserwatiewe spoorder (Fluorecein), asook mikrobiese spoorders (bakteriofages), om met die toekenning van beskermingsones te help. Daar is besluit om sones toe te ken wat beïnvoed word deur **i**) die populasie en **ii**) die kwesbaarheid en belangrikheid van die akwifeer. Die effek van besoedeling op menslike gesondheid en die moontlikheid dat sterfgevalle kan voorkom is gebruik as kriteria om te besluit watter beskerming sone is toepaslik onder sekere omstandighede.

Vir beskermingsone I word voorgestel dat die onmiddelike omgewing rondom die boorgat toegekamp moet word ('n afstand van 5 m word voorgestel) asook die oprig van 'n goeie sanitêre seël. Waar 'n boorgat water verskaf aan minder as 20 mense, behoort slegs 'n sanitêre seël genoegsaam te wees.

Met die toekenning van beskermingsone II was die idee om die drinkwater teen mikrobiese (bakterieë en virusse) asook nitraat besoedeling te beskerm. Die klem het op die twee parameters geval a.g.v. hulle assosiasie met pitlatrines en septiese tenksisteme. Metodes om die grootte van 'n fraktuur te skat word voorgestel en afhangende van die mate van nitraat en bakteriologiese bewegingstye (E. travel times) en ladings word drie riglyne voorgestel. **i**) helfte van die fraktuurgrootte, **ii**) die hele fraktuurgrootte en **iii**) dubbeld die fraktuurgrootte.

Slegs as daar 'n moontlikheid is dat 'n gevaarlike (E. hazardous) stof die grondwater kan besoedel, word voorgestel dat beskermingsone III toegeken word. Die gebruik van die woord "gevaarlik (E. hazardous)" maak die besluit meer kompleks en daarom is die kwessie van risikowaardering en bestuur baie algemeen in die verhandeling aangespreek. Die voorgestelde grootte vir beskermingsone III sluit die hele opvangsgebied van die boorgat in.

'n Program genoem ***Borehole Protection Zone*** **(BPZONE)** is ontwikkel deur gebruik te maak van ***Microsoft Excel*** om die persoon(e) wat verantwoordelik is vir die besluitnemings proses t.o.v. toekenning van boorgat beskerming sones met dié besluit te help.

Inligting wat gedurende veld toetse versamel is by die Kampus Toetsterrein van die Universiteit van die Vrystaat asook by die Meadhurst Toetsterrein buitekant Bloemfontein, het baie positiewe resultate opgelewer.