NITRATE AND ASSOCIATED HAZARD QUANTIFICATION AND STRATEGIES FOR PROTECTING RURAL WATER SUPPLIES

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Elevated nitrate concentrations occurring in groundwater present a serious threat to certain water users, particularly infants and livestock. This health threat is related to the reduction of nitrate to nitrite in the digestive tract and the subsequent formation of methaemoglobin, a relatively stable compound, which prevents the blood from conveying oxygen to the cells in the body. In view of the risks involved, the criterion for nitrate in drinking water is generally set at 10 mg/L, expressed as nitrogen (N). Anecdotal information indicates that the ingestion of unpolluted water with a nitrate-N level exceeding 50 mg/L is fatal for infants. The presence of pathogens generally increases the morbidity at lower nitrate levels. It is also highly likely that spontaneous abortion of foetuses may be linked to the ingestion of high nitrate water. Some of the N-nitrosamine and N-nitrosamide compounds, which can form due to the presence of nitrate in drinking water, may have carcinogenic, teratogenic or mutagenic properties. Epidemiological studies have failed to confirm any link between the occurrence of nitrate in drinking water and such health impacts.

Based on the latest information, groundwater over large parts of Southern Africa has high nitrate values, often exceeding 50 mg/L (as N). In South Africa, this occurs mostly in a band approximately 100 to 250 km wide, stretching from east to west along the northern boundary of the country, across the four northernmost provinces. Some parts of this area are relatively densely populated, or under agriculture, but large tracts are sparsely populated and used only for grazing. Thus, although pollution may be an important source of the nitrate, other origins must exist and these will need to be understood.

The overall aim of this project was *to contribute to a groundwater protection strategy, which will take both pollution and the phenomenon of natural accumulation of nitrate in groundwater into account.* This project will provide the first version of a workable strategy for protecting rural and other water supplies in the Southern African context. It also aims to determine the additional, pollution associated risk, posed to rural water supply in the nitrate accumulation affected areas. It should also identify further needs for research into the processes and related natural mechanisms leading to the accumulation of nitrate in the subsurface and subsequent leaching into the groundwater.

Specific ***objectives*** for achieving the above aim were the following:

- ❒ to determine the extent and severity of nitrate and associated anthropogenic pollution in selected study area(s) in the rural community context, and to identify and interpret environmental conditions aggravating the situation;

- ❒ to attempt to establish environmental factors (climatological, pedological, geohydrological, etc) prevailing in affected areas which favour nitrate accumulation;

- ❒ to map out both existing nitrate occurrences based on analytical data to be obtained from the Department of Water Affairs and Forestry (DWAF), and potentially affected and vulnerable areas based on the prevalence of the identified nitrate accumulation factors;

- ❒ to develop strategies for eliminating, or at least diminishing, the accumulation of nitrate and associated pollutants in sensitive areas due to anthropogenic activities;

- to communicate the outcome of the research on natural accumulation and anthropogenic pollution (and the associated health) risks to water resource planners by means of appropriate publications, e.g. a booklet and a leaflet

The anticipated ***research products*** to be derived from this project were

- Map(s) and database of affected area(s) as determined by surveys, as well as map(s) of sensitive and vulnerable area(s)

- Strategy for preventing, or at least decreasing, the accumulation of nitrate and associated pollutants, in groundwater, which is due to anthropogenic activities

- Brochure for increasing public awareness of potential anthropological pollution (and the associated health) risks and preventative strategies

CONCLUSIONS

Nitrate Sources: Nitrate in groundwater can be derived from various sources. These can be grouped into two main categories:

- anthropogenic nitrogenous pollution, and

- natural nitrate accumulation, primarily in arid and semiarid regions.

In the highly-developed countries, the main anthropogenic source is agricultural nitrate, largely derived from excessive fertilizer and manure applications. Such sources are, however, controllable and particularly in Europe strict measures are in place for limiting the nitrogen fertilizer and manure application rates. In South Africa the available data show that this widespread diffuse source generally only provides a background concentration of nitrate in the water, largely derived from the soil nitrogen pool due to the tilling of the soil. This is particularly the case in areas with highly productive soils such as the black cotton soils overlying the basalts.

Point sources are generally associated with pollution activities, e.g. sewage sludge drying beds, land application of sludge, and irrigation of (partly) treated wastewater. At the large cities, high levels of sewage sludge application to land have caused serious groundwater pollution.

On-site sanitation: This nitrate source is discussed separately because the research results from South Africa, other southern African countries, and most developing nations show that on- site sanitation is the major source of groundwater nitrate in groundwater, apart from the naturally occurring groundwater nitrate in developing countries. The abandoning of well fields, mainly because of nitrate pollution, is continuing and it is also occurring in South Africa.

For large parts of southern Africa on-site sanitation remains the only viable option. Not all such practices lead to groundwater pollution, but in the wrong hydrogeological and environmental conditions, the effects on groundwater can be disastrous. On-site sanitation is generally a cost- effective approach and any nitrogen management strategy has to contend with realistic on-site sanitation options. However, it also means that on-site sanitation needs to be planned with the particular hydrogeological scenario in mind. There is no general rule that can be applied everywhere. It is necessary to have a pragmatic approach in this regard, but where sensitive and sole source aquifer systems are at risk, alternative sanitation options

have to be found. The occurrence of methaemoglobinaemia (also in developed countries such as the USA) was mostly associated with private drinking water wells which were polluted by on-site sanitation, e.g. french drains associated with septic tanks.

Nitrate pollution of groundwater from sanitation systems has tended to be overlooked or downplayed in many of the policies and strategies relating both to water supply and sanitation and to water quality management in South Africa. The reasons for this are varied, ranging from a historical focus on surface water in South Africa (where nitrate is less of a problem than for groundwater) to the drive to supply sanitation services as fast as possible to fulfil the obligations in terms of the sanitation policy and to reach all members of the previously disadvantaged sectors of the population.

Doubts have been expressed about the true severity of the nitrate impacts from this source, but little data have been collected to disprove the extent of the impacts. In the short term, health impacts from pathogens are a far more pressing issue and most recommended mitigation measures revolve around providing sufficient separation between sanitation systems and water supply points to ensure that bacterial contamination cannot migrate to the point of groundwater abstraction. Little consideration appears to have been given to the long-term sustainability of this approach, which may delay the impacts, but ultimately will not prevent nitrate contamination of the water supply.

Directed research is needed into the impact of this source. Such research should take into account and confirm or modify the impact “models” that have been developed elsewhere also for local use. These models take into account the type, density and loading of systems, the thickness of the unsaturated zone, the nature of the soil and geological strata. Field measurements and / or tests should be carried out to provide actual data on the various parameters in different field conditions. Once such a “impact assessment model” has been developed for local use, it will assist to identify those situations where on-site sanitation is the correct solution and will also confirm the appropriate type of system.

Mitigation of impacts by appropriate measures, e.g. *in situ* denitrification provides alternatives where on-site sanitation was not the ideal but the only practical solution.

For any rural water supply project using groundwater in an area where on-site sanitation is practised groundwater quality monitoring at strategically selected points is essential.

Management strategy: A management strategy has been developed consisting of a situation assessment, immediate actions, medium and longer-term actions. The management and reduction of groundwater nitrate levels depend on an understanding of the nitrogen sources and the pollution and nitrification mechanisms. A successful groundwater protection strategy has to consist of a dual approach, i.e. legislation for pollution control and for reducing nitrogenous inputs to the environment, which is supported by an education and public awareness programme.

With regard to natural nitrate accumulation, management options are limited and consist essentially of developing alternate low nitrate sources or denitrification.

Health risks: Nitrate in groundwater involves various risks for human consumption. Mortalities as a result of methaemoglobinaemia is a reality. New information became available on earlier cases of methaemoglobinaemia, while spontaneous abortion may constitute a further risk related to nitrate in water. Microbiological and other risks related to polluted water may aggravate the situation.

The risks associated with nitrate ingestion have to be evaluated in terms of the total dietary intake of nitrate and nitrite.

Livestock are also at risk and nitrate poisoning of livestock has been recorded in southern Africa and elsewhere.

Naturally occurring nitrate: In the semiarid to arid parts of the Southern African subcontinent, and elsewhere in the world, there are large tracts of land extending over hundreds of kilometres, where groundwater has high nitrate concentrations. These are mostly related to natural accumulation of nitrate in the groundwater. This indicates that nitrate can accumulate in the subsurface under certain natural conditions. A full understanding of this process is required for designing the groundwater protection strategy. It is hoped that the parallel research projects will provide the necessary understanding of these accumulation processes.

Groundwater nitrate trends: In most countries around the world, nitrate occurs in groundwater and the latest information confirms that the concentrations as a result of pollution are still increasing in many countries. Reliable information on groundwater nitrate concentration trends is essential for developing and evaluating a successful nitrogen management strategy. This is a key issue that requires a long-term monitoring programme focussed on yielding reliable analytical information that is largely unavailable for South Africa. The national groundwater monitoring programme will need to be designed to provide reliable groundwater nitrate results for a countrywide nitrate database. Nitrate is generally an unstable constituent that may need to be preserved between sampling and analysis when the samples have to be stored for any length of time.

RECOMMENDATIONS

Protection strategy implementation: It is recommended that the preliminary groundwater protection strategy be implemented as soon as possible. Early implementation of the strategy is deemed essential as in the case of groundwater nitrate pollution, the alternative result is longer-term degeneration of groundwater quality.

Water quality monitoring: The monitoring of nitrate level trends in groundwater at strategic points, such as rural water supply schemes, is a key part of the groundwater protection strategy. It is essential for obtaining reliable information on short-, medium- and longer-term groundwater nitrate trends. This has to take place in parallel to the implementation of the protection strategy for evaluating progress and determining the need for further measures. At the same time the final drinking water should be diligently monitored for microbiological purity.

Risk assessment: A reassessment of risks should take place using an epidemiological risk assessment in areas affected by elevated nitrate concentrations in the drinking water supply. This should take into account the total nitrate and nitrite intake from food and water. The microbiological quality of the drinking water is a key factor and has to be taken into account in such a study.

Strategy revision: Evaluation of the success of the groundwater protection strategy, followed by revision and improvement of the policies and strategies, is required. This should be carried out in selected rural areas and using the information gained from the water quality monitoring programme.

Research needs: Based on the outcome of the evaluation of the initial protection strategy, further research may be needed, particularly for understanding the pollution processes and the role of the unsaturated zone in groundwater protection. Monitoring of on-site sanitation processes should take place in all rural water supply projects using groundwater.

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1 INTRODUCTION

The occurrence of high nitrate concentrations in groundwater presents a serious threat to certain water users. Particularly infants and livestock are vulnerable to the health impact of nitrate. However, the alleged carcinogenic properties of nitrate have not yet been substantiated. The health threat is related to the reduction of nitrate to nitrite in the digestive tract and the subsequent formation of methaemoglobin which prevents the blood from conveying oxygen to the cells in the body. In view of the risks involved, the World Health Organization (WHO, 1985, 1998) set the limit for nitrate in drinking water at 10 mg/L (expressed as nitrogen, N), with a recommended level of 6 mg/L (as N). In South Africa the nitrate criterion for drinking water is also set at 10 mg/L. Anecdotal information indicates that the ingestion of water with a nitrate-N level exceeding 50 mg/L is fatal for infants. The presence of pathogens in the drinking water generally increases the morbidity at low nitrate levels (see, e.g. WHO, 2004 in Appendix B) and this is one reason why the water quality criteria for nitrate are set at very low levels. It is also possible that spontaneous abortion of foetuses may be linked to the ingestion of high nitrate water (Weyer, 2001).

Nitrate in groundwater is a feature found in large parts of the world and a significant population uses water with nitrate levels in excess of the WHO maximum drinking water standard (Spalding and Exner, 1993). Evidence is accumulating that nitrate levels in many aquifers are rising and that the problem of increased exposure of the world population to high nitrate inputs, particularly in the developing nations, will become more pressing (WHO, 1985, Spalding & Exner, 1993, WHO, 2004, see Appendix B). This was recently demonstrated by a hydrogeological study at Ramotswa near Gaborone in Botswana (Staudt, 2003).

The presence of nitrates in groundwater is mainly perceived as a pollution problem, and in general this is valid. However, high groundwater nitrate and nitrate deposits occur in many arid and semiarid zones around the world. In most of these areas, recent anthropogenic impacts can be ruled out. Whereas nitrate pollution, which by definition is derived from anthropogenic sources, can be managed and reduced, natural nitrate sources generally cannot be controlled and other means will have to be adopted for managing the nitrate content of the groundwater. This report deals mainly with the management of anthropogenic activities that cause nitrate pollution, but it is evident that an understanding of the natural nitrate accumulation factors and pathways is essential. Such knowledge will contribute to the successful management of nitrate concentrations in groundwater as the factors favouring natural accumulation are also expected to intensify the problems related to pollution-derived groundwater nitrate.

1.1 Background

High nitrate levels in groundwater is the most frequent reason for groundwater sources to be declared unfit for drinking in South Africa, i.e. exceeding 10 mg/L as N (Marais, 1999). Based on the latest information, groundwater in South Africa has high nitrate values, often exceeding 50 mg/L (as N), mostly in a band 100 to 250 km wide, stretching from east to west along the northern boundary of the country, across the four northernmost provinces. Some parts of this area are relatively densely populated, or under agriculture, but large tracts are sparsely populated and used only for grazing. Thus, in densely populated rural settlements pollution derived from anthropogenic origin is an important source of groundwater nitrate, but in other areas sources, as well as transport and accumulation processes, are not well understood.

It is a well-known fact in the scientific community and amongst water-supply authorities that drinking water with an elevated nitrate level poses a serious hazard for infants. Other effects, such as livestock losses through nitrate poisoning, are not commonly known but these provide important evidence of the risks associated with the presence of nitrate (and

nitrite) in drinking water and in food. The overall lack of recorded information on the occurrence of infant methaemoglobinaemia and stock losses tends to obscure the seriousness of the situation in the developing nations.

In highly-developed countries, with their intensive agriculture, fertilizer and manure application to land were identified over the past few decades as the main source of anthropogenic nitrate entering the groundwater resources (Bouchard *et al.,*1992). Accordingly, a vast amount of research has been conducted into the impacts of agriculture on groundwater quality. Particularly in Europe, the land application of surplus nitrogenous wastes from intensive animal husbandry and dairy farms are being closely managed. These countries mostly have a humid climate and it remains to be seen in how far the approaches used in such countries can be applied locally. On the other hand, most of the methaemoglobinaemia mortalities in the USA and Europe have been associated with inadequate on-site sanitation systems affecting the local (private) drinking water supplies (Walton, 1951, O'Riordan & Bentham, 1993).

1.2 Objectives

The overall aim of this project was *to contribute to a groundwater protection strategy, which will take both pollution and the phenomenon of natural accumulation of nitrate in groundwater into account.* It is specifically aimed to determine the additional, pollution associated risk, posed to rural water supply in the nitrate accumulation affected areas.

Specific ***objectives*** for achieving the above aim were the following:

- ❒ to determine the extent and severity of nitrate and associated anthropogenic pollution in selected study area(s) in the rural community context, and to identify and interpret environmental conditions aggravating the situation;
- ❒ to attempt to establish environmental factors (climatological, pedological, geohydrological, etc) prevailing in affected areas which favour nitrate accumulation;
- ❒ to map out both existing nitrate occurrences based on analytical data to be obtained from Department of Water Affairs and Forestry (DWAF), and potentially affected and vulnerable areas based on the prevalence of the identified nitrate accumulation factors;
- ❒ to develop strategies for eliminating, or at least diminishing, the accumulation of nitrate and associated pollutants in sensitive areas due to anthropogenic activities;
- ❒ to communicate the outcome of the research on natural accumulation and anthropogenic pollution (and the associated health) risks to water resource planners by means of appropriate publications, e.g. a booklet and a leaflet

The anticipated ***research products*** to be derived from this project were

- ❒ Map(s) and database of affected area(s) as determined by surveys, as well as map(s) of sensitive and vulnerable area(s)
- ❒ Strategy for preventing, or at least decreasing, the accumulation of nitrate and associated pollutants, in groundwater, which is due to anthropogenic activities

- ❒ Brochure for increasing public awareness of potential anthropological pollution (and the associated health) risks and preventative strategies

1.3 Approach

The project was intended to concentrate on rural communities and settlements located in areas with known high nitrate levels in the groundwater. In collaboration with researchers studying various specific pollution aspects, e.g. on-site sanitation in rural settlements, the areas affected by the various types of on-site sanitation were to be determined. Subject to the hydrogeological conditions encountered and the known existence of nitrate and associated pollution, e.g. by horticulture associated with settlements, field investigations were planned at selected points within chosen areas. Two or at most three such areas where groundwater is actually being utilised were to be selected. Suitable test sites (e.g. in former Bophuthatswana, refer Letimela (1993) or in former Venda) were identified in consultation with DWAF, regional authorities and other researchers. Researchers from Australia have expressed an interest to join hands in a project of this nature, but apart from consultations no direct involvement could take place.

Although nitrate and nitrogen species form the central theme of the investigation due to their important long term impact, other related pollutants, such as other N-species, phosphate, organic compounds (e.g. DOC), coliforms, faecal streptococci, a spore former such as *Clostridium perfringens*, and a bacteriophage were to be considered. The detailed investigation plan included the following:

- ❒ confirmation of the origin of the nitrate by means of N-isotope ratios;
- ❒ delineation of the extent of the affected area;
- ❒ establishing the need to study of the health implications of ingesting nitrate-bearing water;
- ❒ assessment of any linkage to microbiological pollution, chloride, etc. and its associated health risks;
- ❒ anthropogenic pollution risk assessment;
- ❒ establishment of seasonal and long term trends of nitrate concentrations;
- ❒ formulation of suitable measures to
  - reduce nitrogen inputs;
  - find alternate sources;
  - denitrify the supplies;
  - ensure appropriate health surveillance.

In Australia, termites are thought to contribute to the nitrate accumulation. It was hoped to test this theory using nitrogen and oxygen isotope studies but this now forms part of a groundwater nitrate investigation in the Serowe area in Botswana (Schwiede, M, BGR, personal communication, October 2003). This research is being carried out by the BGR in collaboration with the Department of Geological Survey in Lobatse. Regional collaboration in Southern Africa was established in terms of a Department of Science and Technology contract and research results will be exchanged for the benefit of the region.

After the first year, the approach towards this WRC project was reconsidered and revised with the approval of the Steering Committee. Once the costs involved in the field studies were assessed, it was evident that these had to remain limited in scope at each site. It was planned to acquire information on more sites by making use of reports and other data from as many other studies as possible. This was intended to include work done in neighbouring countries. In that way a wider range of environmental conditions could be taken into account which may provide the same or possibly a better outcome for the project and the nitrate strategy. This change in approach needed an adaptation in timing and it was agreed that the

project would be rescheduled to run until June 2003. This also allowed better liaison with the parallel groundwater nitrate projects in the neighbouring countries. The total budget of the project remained the same, and it only entailed rescheduling.

On completion of the project, technology transfer workshops have to be held to transfer the information on the need for groundwater protection measures, the actual measures to be adopted and the public education programmes required. This aspect was not included in the budget for in the project proposal and will have to be considered subsequently.

1.4 Layout of the report

The report is composed of eight chapters with ***Chapter 1*** introducing the subject of nitrate in groundwater, giving a brief motivation, and outlining the objectives of the study.

In ***Chapter 2*** the distribution of nitrate in groundwater is discussed for three of the Southern African countries seriously affected by high nitrates, i.e. Botswana, Namibia and South Africa. The map included in the report was developed for a parallel project jointly being carried out in the three countries for investigating the sources and management of groundwater nitrate. The map helps to put the problem into perspective as it clearly shows that many nitrate occurrences extend across the international boundaries.

Chapter 3 gives an overview of the nitrogen cycle in the environment, the occurrence of nitrate, anthropogenic pollution sources, and natural accumulation processes. The hazards of nitrate in groundwater to human health and livestock are also described. Finally, the relevance of nitrate to irrigation is briefly addressed.

A description of the field studies follows in ***Chapter 4***. A limited number of sites were visited in South Africa and elsewhere but these had a number of factors in common.

In ***Chapter 5*** the information gained from the field observations is synthesized, while the processes and factors controlling the accumulation of nitrate in groundwater are summarised.

The preliminary strategy for the management of nitrogen sources and nitrate in groundwater follows in ***Chapter 6***. Vulnerability mapping and the identification of priority protection areas form part of the strategy. In view of the important role of on-site sanitation with regard to the nitrogen input into the subsurface, this aspect and the needs for groundwater protection are discussed in some detail.

The conclusions drawn from this project are described in ***Chapter 7*** while ***Chapter 8*** lists the recommendations.

At an early stage in the project, Dr Peter Dillon of the CSIRO, Adelaide, Australia, visited South Africa and his services were obtained to consider the preliminary results of the project. His comments and recommendations are included in ***Appendix A*** in this report.

The World Health Organization (WHO) has compiled fact sheets on water-related diseases, including one on methaemoglobinaemia that provides an authoritative statement on this disease. This is included in ***Appendix B*** with their permission (refer e-mail confirmation included in the appendix).

The nitrate distribution shown in ***Appendix C*** is a research product and is based on data obtained from DWAF superimposed on a modified geological map compiled by CSIR.

2 GROUNDWATER NITRATE DISTRIBUTION IN SOUTHERN AFRICA

The purpose of this project is to develop a protection strategy for groundwater in South Africa, but the nitrate problem extends into the neighbouring countries and, therefore, reviewing the occurrence of nitrate over a larger part of the subcontinent provides a more holistic perspective on the problem. Initially, a map was compiled for South Africa showing the nitrate distribution in groundwater. The main purpose was to identify problem areas which could be studied more intensively. Subsequently, a large number of overlays were prepared which conformed to the factors of the DRASTIC approach (Aller *et al*., 1987) in an attempt to identify those factors controlling nitrate accumulation in groundwater. These are discussed in Section 6.2 dealing with vulnerability mapping. Subsequently, the information on groundwater nitrate for the neighbouring countries, Botswana and Namibia, became available through a parallel project funded by the Department of Arts, Culture Science and Technology, and a nitrate distribution map could be compiled covering all three countries (see Section 2.2).

2.1 Sources of data

The main groundwater database in the country is the National Groundwater Database (NGDB) kept at the Directorate of Geohydrology, DWAF in Pretoria. The water quality data were stored separately in the hydrochemical database and the Department was approached to query these databases for evaluating all new data that were collected since the preliminary nitrate study in the early 1990s. The Cape Town office provided the necessary support and all the new hydrochemical data were extracted. The Directorate of Macro Planning and Information Services established its own detailed groundwater quality database for the rural areas with higher population densities. This Directorate was approached for obtaining insight into and access to their database. A consultant, located in Polokwane (formerly Pietersburg), maintains the database on the behalf of the Directorate and that consultant was visited, the database queried and several data sets generated. This proved to augment the existing data sets obtained from the NGDB and it contained considerably more information on the northern provinces. An indication of the population densities could be obtained as the number of people served by each water supply scheme was also recorded. Study site identification was based on this information (see Section 4.1).

2.2 Mapping of available data

As described above, the DWAF data were used to compile a groundwater nitrate distribution map for the country as a whole, which clearly delineates areas where groundwater nitrate presently exceeds the drinking water quality criteria. Attempts were made to link the data to other overlays, e.g. population densities. However, the latest census data were not available in a suitable format, e.g. magisterial districts, for this purpose. The compilation of a preliminary groundwater nitrate map for South Africa was a primary step in the project, as it provided the background for developing the nitrogen management strategy. Meanwhile, several reports were received of elevated nitrate concentrations in the neighbouring countries and in 2000 the author was requested to assist the Botswana Department of Geological Survey (DGS) in an initial assessment of the problem. In collaboration with the German Federal Geological Survey (BGR, Bundesanstalt für Geowissenschaften und Rohstoffe) several potential projects were identified. In 2001 a regional collaborative initiative was launched to integrate data and research results from Botswana, Namibia and South Africa. The purpose was to assess the extent of nitrate occurrences in the region, investigate the groundwater nitrate accumulation mechanisms and study its consequences. This initiative involves researchers from Namibia, Botswana, and Germany.

The distribution of groundwater nitrate in the Southern Africa region is shown in Figure 1 (Tredoux *et al*., 2001). This is a simplified version of a more detailed map that is based on the analytical information of more than 50 000 groundwater sources, which could be linked to

a geographical location, and for which data were currently available in electronic format. For the purposes of this map, the data from each country have been divided into three subsets of nitrate concentration. Then these subsets for each country were plotted in order to create contour maps for the different concentration ranges. These contour maps were overlain to produce a simplified groundwater nitrate map for each country that together form the map in Figure 1. The coverage for Namibia is based on work completed much earlier (Huyser, 1982) than those for Botswana and South Africa, which are derived from currently active databases. The Botswana data coverage is sparse at this stage since only a limited number of chemical analyses have been satisfactorily linked to geographical locations. This is receiving attention.

The nitrate concentrations are shown as NO_3 as the paper was presented in Europe where the general approach is to express nitrate concentrations in this way. The lowest contour level shown, is 100 mg/L as NO_3, which is equal to 22.3 mg/L as N. This slightly exceeds the maximum allowable limit for drinking water in all three countries, which is 20 mg/L as N. In large parts of each of the three countries groundwater nitrate exceeds 10 mg/L as N. This simplified map, covering approximately 3 million km^2, cannot portray the detailed information available in some areas, but serves to highlight the larger areas with elevated nitrate concentrations. Isolated sources with high nitrate occur widely in certain areas, but these are not shown on the map. Although these are important due to the presence of localized pollution, the larger tracts of land, where higher concentrations are found, warrant closer inspection. Even though no cleanup was done at the edges of the maps, it is evident that certain features extend from one country into the other across the borders. Extended areas in the arid Northern Cape Province have elevated groundwater nitrate levels. The high nitrate levels in the more humid Springbok Flats in Limpopo Province can also be clearly identified.

Anthropogenic generation of nitrate is well known and includes on-site sanitation, application of nitrogenous material such as sewage sludge to land, tilling of the soil, irrigation and other activities. Groundwater pollution problems related to on-site sanitation have been known for decades in the southern African sub-continent and several studies have been carried out (Lewis, *et al*., 1978, 1980, Palmer, 1981, Jacks *et al*., 1999). These features can be seen in Figure 1 as high nitrate levels around urban areas and also in the high-density rural settlements of Eastern Botswana, and the Limpopo Province, South Africa.

It is evident that the nitrate distribution also follows a regional pattern. Whereas many smaller areas with high nitrate groundwater are scattered widely throughout the region, there is a virtually continuous manifestation of high nitrate levels occurring roughly along the fringes of the southern part of the Kalahari basin. In these semi-arid to arid regions of the Northern Cape Province, Namibia and Botswana, significant groundwater nitrate occurrences are found in areas where anthropogenic influences can be excluded. In these areas, the (human and animal) population density is low and even confined groundwater can have significant nitrate levels (Tredoux & Kirchner, 1981). In such areas significant nitrogen loss has to take place from the soil zone into the subsurface. Therefore, accumulation of high levels of nitrate in groundwater would seem to be possible under natural conditions. Various factors are involved, which may include the nature and thickness of surface deposits, rainfall quantity and distribution, depth to the groundwater level, distribution of vegetation types and presence of nitrogen-fixing plants (Tredoux & Kirchner, 1985).

The Ghanzi ridge in western Botswana and its extension into Namibia, the Kamtsas Formation, are both clearly discernible.

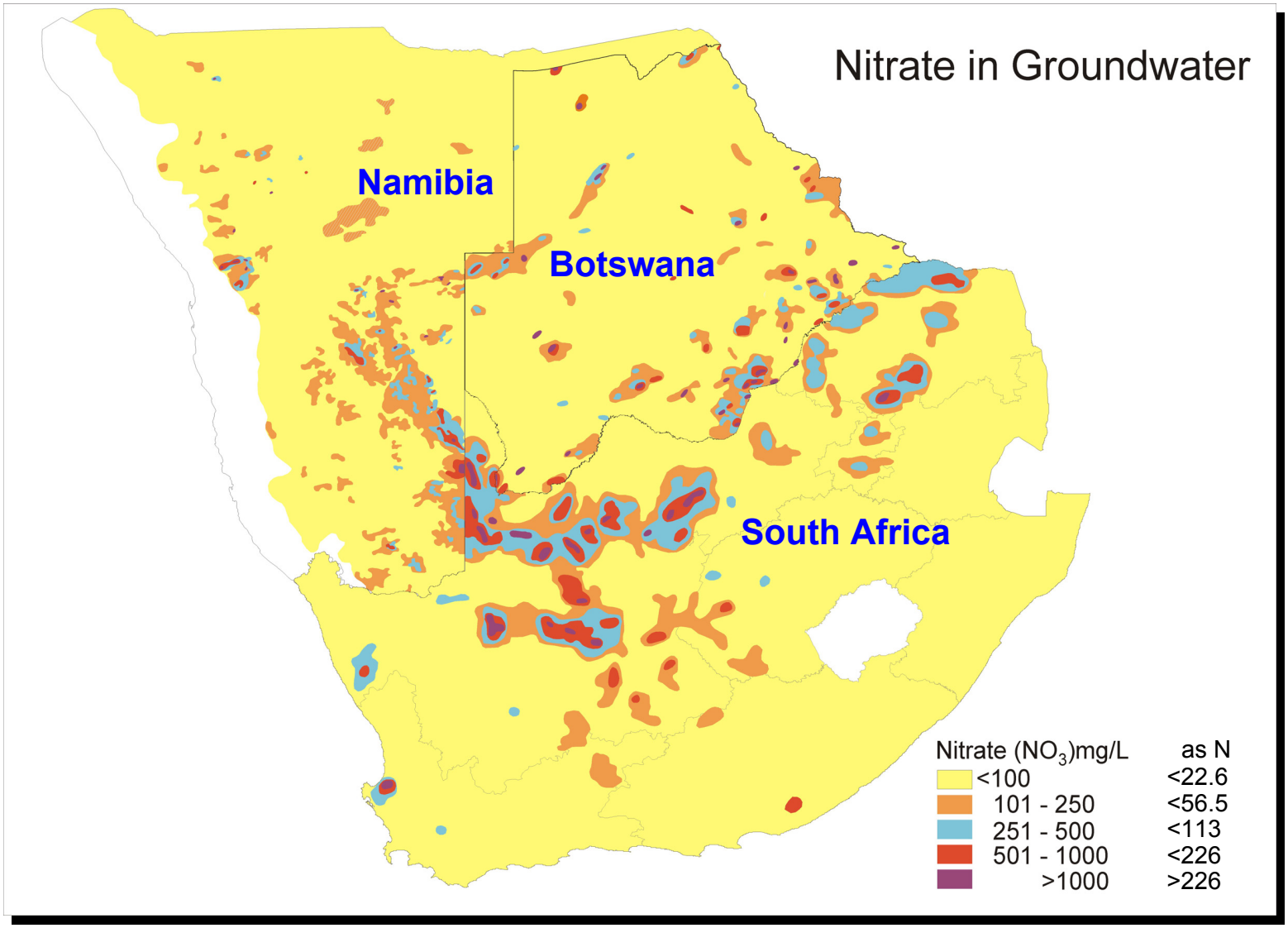


Figure 1: Groundwater nitrate distribution in Southern Africa *(Tredoux et al., 2001)*

2.3 Groundwater quality monitoring requirements

Establishing reliable groundwater nitrate trends requires long term monitoring as nitrate concentrations may show seasonal and other short term variations. Such information is a primary requirement for nitrate management. This requires reliable analytical data extending over decades. Previous attempts to determine such trends have generally provided inconclusive results (e.g. Van der Merwe & Levin, 1990, in the Springbok Flats), mainly because of a lack of consistent data sets for determining nitrate concentration trends. The lack of consistency has many causes, which range from inconsistent sampling methods, to the problem of analytical techniques. In addition, nitrogen compounds in water can be transformed and/or lost from solution through bacterial action or algae. Unpolluted samples may not need preservation if stored briefly under suitable conditions, but even unpolluted water may contain sufficient denitrifying bacteria (also in spore form) which could denitrify the water, e.g. when the dissolved oxygen concentration is low enough.

Until now, the determination of nitrate trends in South Africa has been restricted to a small number of repeat analyses for boreholes at pollution point sources with totally predictable results. These few cases do not constitute a statistically valid data base for drawing any final conclusion on the overall nitrate trend in the country. However, it is certain that in those instances where pollution is known to occur, the general trend showed increasing nitrate concentrations except in those cases where the pollution source was removed.

The degree to which the present National Groundwater Monitoring Programme fulfils this need will have to be established. In this regard an evaluation of the existing information collected in the National Groundwater Monitoring Programme may help to fill this gap. Following such an evaluation, the resource directed measures may need to be adapted to account for the occurrence, or potential occurrence of nitrate, and the selection criteria for monitoring points in the National Groundwater Monitoring Programme may need to be revised. This will ensure that eventually, after another decade or more, reliable information will be available for evaluating nitrate trends in groundwater. Despite this lack of information, experience from abroad demands that a first nitrogen management strategy be developed to protect the groundwater resources. Once the trend data becomes available, the strategy can be adapted or refined to take the new information into account.

3 THE OCCURRENCE AND HAZARD OF NITRATE IN GROUNDWATER

Nitrate in groundwater is a feature found in large parts of the world and a significant population uses water with nitrate levels in excess of the WHO maximum drinking water standard (Spalding and Exner, 1993). Evidence is accumulating that nitrate levels in many aquifers are rising and that the problem of increased exposure of the world population to high nitrate inputs will become more pressing (WHO, 1985, Spalding & Exner, 1993, Staudt, 2003).

Tredoux (1993) provided a preliminary overview regarding the distribution of nitrate in groundwater in South Africa and highlighted certain problem areas. High nitrate levels in groundwater is the most frequent reason for groundwater sources to be declared unfit for drinking in South Africa, i.e. exceeding 10 mg/L as N (Marais, 1999).

In Section 3.4 the natural factors responsible for the generation and accumulation of nitrate in groundwater are discussed, also considering the role of geological formations in these processes. Anthropogenic activities and many land use practices play a role in causing and aggravating nitrate accumulation in the subsurface and these are discussed in Section 3.5 and in Chapter 6.

3.1 The nitrogen cycle in the environment

The lithosphere serves as the main nitrogen reservoir in the global context with an estimated 98 per cent of the total (Stevenson, 1965). This includes the organically bound soil nitrogen which amounts to approximately 0.15 % of the total (Söderlund & Svensson, 1976). The large quantity of nitrogen contained in the rock mass only becomes available very gradually through weathering and the atmosphere (with two per cent of the reserves) together with the soil nitrogen are the main sources of nitrogen for most biogenic reactions. Figure 2 shows the main nitrogen transformations in the global biogeochemical cycle (Rohmann & Sontheimer, 1985).

3.2 Natural occurrence of nitrogen and nitrate in the environment

South African geology extends over the whole of the geological time scale from the Archaean Complex (para- and granitic gneisses, granites) through to the Quaternary. Karoo sediments occur extensively and occupy approximately 40 per cent of the country. In total hard-rock formations ranging from the earliest Pre-Cambrian to Jurassic in age are present at or close to the surface over 90 per cent of the country's area.

The presence of geological nitrogen in reducing environments such as glacial till and carbonaceous shale, has been documented for other continents (e.g. Hendry *et al*., 1984, Reeder and Bert, 1977 and Power *et al*., 1974) and this may also be the case in the Karoo (Cavé, 1999). Groundwater in contact with these rocks leaches ammonia that is oxidized to nitrate when redox conditions change. Other such occurrences have not been confirmed elsewhere in southern Africa and indications are that these generally contribute comparatively little to the high levels of nitrate found in the groundwater in this region.

In discussing the mineral deposits in South Africa, Coetzee (1976) stated that climatic conditions in the country are not conducive to the formation of nitrate deposits and none had been discovered which was economically workable. It was stated that such deposits are only found in very arid localities because nitrates are very soluble in water. This identifies two of the factors of importance in the subsurface accumulation of nitrate, the climate and the easy leachability of nitrates. Coetzee (1976) also discussed the nitrate deposits between Prieska and Griqua Town but gave no indication of a possible origin. In the case of the potassium nitrate which had been extracted from a cave on the farm Abjaterskop (107 KP), Marico

District, and which formed a fairly high-grade crust on the floor of the cave, it was speculated that it originated through the oxidation of ammonia derived from bat guano.

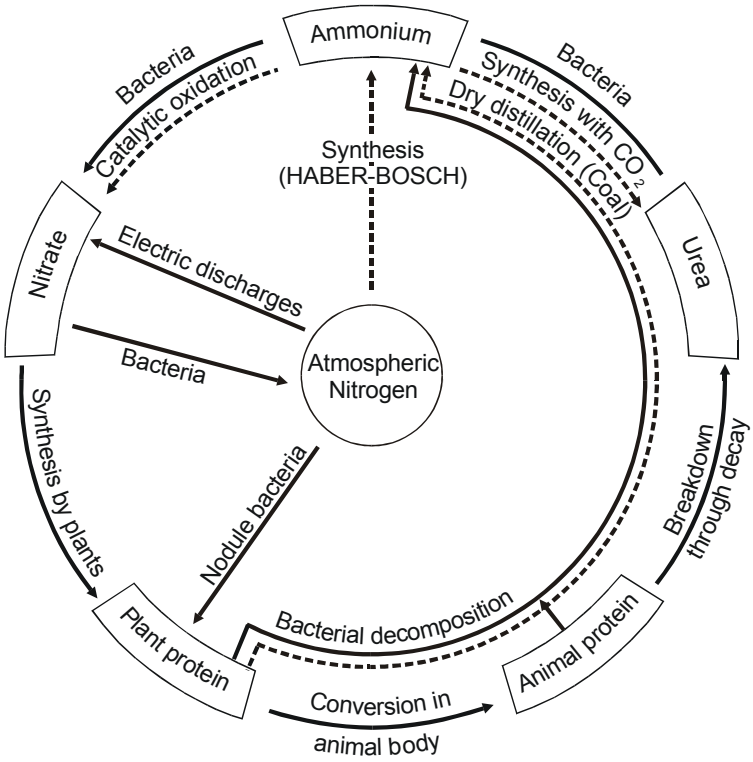


Figure 2: Main transformations in the global biogeochemical nitrogen cycle. Natural processes are indicated with solid lines; synthetic processes are indicated with dotted lines. *(Rohmann & Sontheimer, 1985)*

In the arid Northern Cape saltpans frequently contain (Na, Cl, HCO_3) brines (Hugo, 1974), but only those in the southern Kalahari and near Prieska have nitrate contents in excess of 500 mg N/L. Solid nitrate deposits are found, mostly along cliff faces, in the area between Prieska, crossing the Orange River towards Griqua Town. The deposits occur in the banded ferruginous slates and jaspers belonging to the Asbestos Hills Formation of the Griquatown Group, Transvaal System (Frood & Hall, 1919). Two samples taken by the author consisted of 96 per cent KNO_3 (see Fig 3). This is distinctly different from the $NaNO_3$ of the extensive "Chile saltpetre" deposits in the Atacama Desert in Chile (Mueller, 1968). The fact that the Northern Cape deposits contain potassium in stead of sodium indicates that either the nitrogen source or the enrichment process or both differ from those in Chile. Groundwater in the Kalahari has shown a characteristic prevalence of potassium, nitrate and silica (Kirchner & Tredoux, 1975) with certain similarities to groundwater in the basalt.

The lithosphere is the main nitrogen reservoir in the environment. As mentioned above, in specific instances geological formations do yield nitrogen that can be converted to nitrate and then be transported to the groundwater. This is generally not the main source of nitrates in groundwater and isotope analyses have confirmed it also in the South African context. In the case of the Springbok Flats, Verhoef (1973) discounted the basalt as source of nitrate on the basis that basalts usually contain very little nitrogen. Heaton (1985) agreed with this viewpoint but added that a 'geologic' origin of any type can be excluded in view of the groundwater chemistry. He argued that nitrate-rich horizons may occur in rock formations, but in all such cases the nitrate is accompanied by higher concentrations of other soluble anions (e.g. SO_4^{2-} and Cl^-). The chemistry of the groundwater in the Springbok Flats showed that an increase in nitrate is accompanied by very little increases in the other anions.

Therefore, a geological origin has to be discounted in this case. Analyses of nitrogen isotopes aid in the identification of nitrate production processes (Kreitler, 1975, Heaton, 1984).



Figure 3: Rock salt below a cliff on a farm near Niekerkshoop, Northern Cape Province

In a study in neighbouring Namibia it was attempted to identify the influence of the geological formations on the chemical quality of the groundwater (Tredoux & Kirchner, 1985). Several areas underlain by different rock types were studied. The nitrate distribution was determined for 927 water samples derived from nine different formations north-west of the village of Outjo in northern Namibia. Here the nitrate distributions in the groundwater from the various rocks differ significantly. It is noteworthy that some of the older (even igneous) units showed higher nitrate concentrations. Similarly, Marrett *et al*. (1990) have found up to 73 mg/kg of water- extractable nitrate in volcanic rocks in the eastern Mojave Desert (USA). As the rock minerals do not contain nitrate, the observed phenomena must be ascribed to secondary factors. These include the nature of the weathering products, or the presence, type and density of vegetation. It is, therefore, recognised that the characteristics of geological formations could favour the accumulation of nitrates and in this way exercise a 'secondary' control on the nitrate concentration in groundwater.

From a geohydrological perspective and particularly with respect to the accumulation of nitrate in groundwater, permeable formations such as dolomite (northern Cape Province and Transvaal), coarse sandstones and unconsolidated deposits (e.g. Kalahari sands) are important. Areally, much of the Tertiary and Quaternary successions in the Kalahari and along the west coast lie above the water-table. Such formations, however, provide the opportunity for rapid infiltration of rainfall and, therefore, the accumulation of nitrate in groundwater, provided the conditions for the formation and leaching of nitrate (as discussed below) are also met.

In the semi-arid to arid regions of Namibia and the Northern Cape Province significant groundwater nitrate occurrences are found in areas where anthropogenic influences can be excluded. In these areas, the (human and animal) population density is low and even confined groundwater with an apparent age of several thousands of years can have significant nitrate levels (Tredoux & Kirchner, 1981). Therefore, under natural conditions significant loss of nitrogen from the soil zone can occur in such areas, causing enrichment of groundwater with high levels of nitrate. Various factors are involved, which may include the nature and thickness of surface deposits, rainfall quantity and distribution, depth to the

groundwater level, distribution of vegetation types and presence of nitrogen-fixing plants (Tredoux & Kirchner, 1985). High levels of "natural" nitrate only occur in groundwater, when most or all of the above factors are acting in unison. Natural disturbances of the plant cover, for example droughts (and possibly also bush fires) affect the nitrogen cycle, leading to nitrate leaching beyond the root zone, particularly during subsequent heavy rainfall events.

In the Australian arid zone nitrate occurrences were originally ascribed to biological nitrogen fixation (Murray & Siebert, 1962), or a combination of nitrogen fixation and termite activity (Barnes *et al*., 1992), and finally mainly to nitrate accumulation in termite mounds (Harrington, 1999). Similarly, naturally high groundwater nitrate concentrations in the Sahel have been ascribed to leguminous vegetation and leaching of nitrate due to varying climatic cycles (Edmunds & Gaye, 1997).

3.3 Anthropogenic sources of nitrate in groundwater

Apart from the natural sources of nitrate discussed above, most groundwater nitrates are derived from a wide range of anthropogenic sources. Anthropogenic generation of nitrate is well known and includes on-site sanitation, application of nitrogenous material to land, tilling of the soil, irrigation and other activities. Whereas agriculture is the main source of nitrate in the highly-developed countries such as Europe and the USA, on-site sanitation is seen as the main anthropogenic source of nitrate in Southern Africa. Groundwater pollution problems related to on-site sanitation have been known for decades in the southern African sub-continent and several studies have been carried out (Lewis, *et al*., 1978, 1980, Palmer, 1981, Muller, 1989, Jacks *et al*., 1999). These features can be seen in Figure 1 as high nitrate levels around urban areas and also in the high-density rural settlements of Eastern Botswana, and the Limpopo Province, South Africa.

Sanitation technologies: A range of toilet types are currently used in South Africa, including (Mvula Trust, 2001):

- ❒ buckets;
- ❒ chemical toilets;
- ❒ simple pit toilets;
- ❒ ventilated improved pit toilets;
- ❒ dehydrating and composting toilets;
- ❒ aqua-privies;
- ❒ flush toilets with septic tanks;
- ❒ flush toilets with small bore solids free sewers; and
- ❒ flush toilets with full waterborne and central treatment works.

A brief description of the sanitation systems widely used in rural areas in South Africa or with a proven track record in rural or peri-urban areas is given in Table 1 together with an indication of their water requirements (PDG, 1995).

Pit latrines with no water flushing are the most common systems in use in rural South Africa. In most rural situations, socioeconomic, technical and water supply conditions do not suit waterborne sanitation systems (DWAF, 1997). Low cost, robust systems are favoured for the rural areas and the ventilated improved pit (VIP) latrine has been widely promoted by the Department of Water Affairs and Forestry and various development agencies as the most suitable sanitation option for rural areas. Peri-urban communities are likely to aspire to flush systems, but affordability is a major constraint (PDG, 1995).

Table 1: Hierarchy of rural sanitation technologies in current use in South Africa *(PDG, 1995)*

System	Description	Water use (L per flush)
Traditional pit	Pit dug into the ground with a shelter placed over - built largely by individuals without specialist assistance. Used by 60% of rural households in South Africa.	Nil
SANPLAT	Very simple pit-based sanitation option. Has a sealed slab cover over the pit to stop flies and vermin and a smooth surface to facilitate cleaning of the floor. Widely used in other African countries, but not always socially acceptable in S.A.	Nil
Ventilated improved pit (VIP)	Pit latrine improved with strong foundation and flooring, sealed pit, ventilation pipe extending above the roof and fly screen.	Nil
Low flow on-site sanitation (LOFLOS)	Includes aqua-privies, pour-flush latrines, low-flush systems discharging to a soakpit and low-flow septic tanks. All these systems include digestion and soakaway capacity.	0.5 to 1
Septic tank	Traditional flush toilet with septic tank digester. Widely used in higher income rural and peri-urban areas in South Africa. Soakaway needs proper design and construction for expected usage and soil conditions.	6 to 15
Septic tank effluent drainage system (STED)	Based on a system of sewers draining septic tank effluent to a treatment works. Also called “solids free sewer” or “small bore sewer”.	3 to 15
Full waterborne system	Conventional cistern-flushed water sealed toilets connected to a network of underground sewer pipes which carry sewage to a central treatment works. Stabilisation ponds and artificial wetlands (reed beds) may be considered as alternative treatment options in rural areas.	6 to 15

The choice of sanitation technology is influenced by many factors, including (DWAF, 2002):

- affordability to the household.
- operation and maintenance requirements. High service levels e.g. flush toilets have costly operation and maintenance requirements. Local community members can readily undertake maintenance of on-site toilets.
- sustainability. The system should be manageable by the local community and be sustainable over the long term.
- improvements to health.
- compliance with environmental protection regulations.
- ability of community based contractors to implement the installation.

Pearson *et al*. (2002) prepared guidelines for choosing appropriate sanitation technologies for developing communities. These give little consideration to the potential nitrate pollution of groundwater, other than the acknowledgement that high nitrate arises from seepage from sanitation systems along with other possible natural and anthropogenic sources. Service provision: At the beginning of 2001 it was estimated that 18 million people (3 million households) in South Africa did not have access to a basic level of sanitation, defined as a ventilated improved pit latrine or equivalent. The majority of these live in rural areas, peri-urban areas or informal settlement areas. An estimated 76 % of rural households are considered to have inadequate sanitation. Eighty percent of the national backlogs in water supply and sanitation delivery are in KwaZulu-Natal, Limpopo and the Eastern Cape (DWAF, 2002).

Sanitation policy: A National Sanitation Policy was developed by the National Sanitation Task Team (NSTT), a collaborative effort of 6 government departments in 1996. This policy paper sets out a number of policy principles which apply to sanitation in South Africa (NSTT, 1996):

1. Development should be demand driven and community based.
2. Basic services are a human right.
3. Equitable access – "Some for all" rather than "all for some".
4. Equitable regional allocation of development resources.
5. Water has economic value.
6. The user pays.
7. Integrated development, especially with water supply and health education.
8. Environmental integrity.
9. Sanitation is about health – more than just providing toilets.
10. Sanitation is a community responsibility.

Household sanitation is not a free government service, but a household responsibility and is demand-driven, i.e. communities and households must demonstrate their willingness to pay a significant portion of the cost involved in providing and running a sanitation system. Government must create an enabling environment through which all South Africans can have access to services and support in obtaining a basic level of services, but individuals are ultimately responsible. DWAF defines a "basic level of sanitation service" as a Ventilated Improved Pit (VIP) toilet in a variety of forms, or its equivalent. Under this definition, unimproved pit latrines and bucket systems would be considered "inadequate sanitation" and should eventually be phased out.

The environment must be considered in all development activities and appropriate protection of the environment applied. Sanitation services which have unacceptable environmental impacts cannot be considered to be adequate. The way in which sanitation services are provided must also take into account that fact that good quality water is a scarce commodity in South Africa. The costs of sanitation services involve not only costs of installation and maintenance, but also environmental costs, especially in the pollution of water resources (Van Ryneveld *et al*., 2001). The value of sanitation services must be reflected in such a way that it does not undermine long term sustainability and economic growth (NSTT, 1996).

More recently, the Department of Water Affairs and Forestry have released a draft position paper on The Development of a Sanitation Policy and Practice in South Africa (DWAF, 2002). The document states that: "the South African government is committed to ensuring that its entire people have access to adequate sanitation (and) ... intends to completely remove the (sanitation) backlog by the year 2010."

Sanitation policy is strongly driven by the need to support the supply of sanitation services where these do not exist or to upgrade the levels of service where they are considered inadequate. The provision of basic services is one of the ways in which the government has sought to redress past discrimination. Environmental concerns, although included in sanitation policy documents, appear to be a secondary concern, with little consideration given to the possibly conflicting issues of service provision and potential environmental pollution. While access to adequate water is entrenched as a human right in the Constitution, access to sanitation is not specified in the Bill of Rights (Chapter 2, Constitution of South Africa, Act 108 of 1996). What is specified, is that: "everyone has the right to an environment that is not harmful to their health or well-being; and to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development". It could be argued that both a lack

of adequate sanitation and polluted groundwater resources would infringe on this right. Clearly, a balance needs to be sought.

On-site sanitation: On-site sanitation is economically attractive but it presents a groundwater pollution risk. In most cases this risk can only be evaluated by carrying out a detailed hydrogeological field study before implementation of any such scheme. Generally, such studies have not been carried out and therefore pollution could be expected from many of these settlements which may be located in vulnerable areas. In the vicinity of rural settlements in the former Venda (Limpopo Province) Connelly & Taussig (1991) found that nitrate concentrations in many boreholes exceeded 20 mg/L and in one case it even reached 54 mg/L. The nitrate was ascribed to two possible sources: mobilization of natural nitrate by cultivation of the soil or on-site sanitation. Undoubtedly both factors can contribute to elevated nitrate levels. Rawhani (1986) reported on the incidence of microbial, fluoride and nitrate pollution in groundwater in the former Bophuthatswana (Northwest and Limpopo Provinces). It was established that 17 per cent of the boreholes sampled between 1981 and 1986 exceeded the 10 mg/L limit for nitrates. Agricultural developments, inadequate waste disposal and sanitation practices, were considered to be the main contributors to high nitrate concentrations. Xu *et al*. (1991) ascribed the high nitrate concentrations to the situation of kraals close to water sources as well as the effect of sewage effluent and sewage sludge disposal to land overlying aquifers.

Hesseling *et al*. (1991) studied the occurrence of nitrates at Rietfontein in the north-western Cape Province. They found unacceptably high levels of nitrate in the centre of the village, considered to be likely due to human and animal pollution, while water of better quality was present on the periphery of the village.

Despite the widespread occurrence of on-site sanitation in South Africa the information is largely anecdotal as quoted above. Even in relatively densely populated areas pit latrines are used. Depending on local geohydrological conditions such sanitation can cause serious pollution if no precautionary measures are taken (Lewis *et al*., 1980). This problem has been studied in some detail at places in neighbouring Botswana (Lewis *et al*., 1978; Palmer, 1981) and in Moçambique (Muller, 1989). Some details are provided below.

Lewis *et al*. (1978) refer to extremely high nitrate concentrations in water supply boreholes in many villages in eastern Botswana causing serious concern about groundwater pollution. As a result a detailed investigation was carried out at Mochudi village. It was shown by means of tracers that the transit time between the pit latrines and the neighbouring water supply borehole some 25 m distant was less than 4 hours. This should be viewed against the background of the geohydrological conditions. The village is situated at the foot of an escarpment compound of Waterberg sandstones and shales resting on granites of the Basement Complex. The area is underlain by Waterberg talus and weathered Basement Complex rocks. The dark, clayey soils are thin and grade downwards within 2 to 3 m into the weathered rock material. The water level is mostly less than 10 m below surface.

A study of the soil indicated that generally the highest nitrate concentration was found in the layer directly above the consolidated rock (Lewis *et al*., 1978). From the soil analyses it was estimated that the total mass of nitrate in each square metre of soil column within a radius of 15 m around the pit latrine varied from 0.4 to 2.4 kg/m^2, representing a massive quantity of potentially leachable nitrate. What is even more disconcerting is the bacterial contamination risk which is aggravated by the short travel times of liquid from the pit latrines to the borehole.

Septic tanks: Septic tanks may be a localised or regional source of groundwater pollution (Canter & Knox 1985). This depends on the density of septic tanks and the population in a given area. A density of 40 systems per 2.6 km^2 is considered as having a significant

contamination potential at discharge rates of 170 L/person per day (Canter & Knox 1985). The design, construction and maintenance are important. For example, the systems should be cleaned every three years. The effluent quality and the efficiency of constituent removal depend on the underlying soil and the thickness of the unsaturated aerobic soil below the leach field. Nitrification generally occurs at a depth of 60 to 150 cm (Andreoli *et al*., 1979). The nitrogen originates from several sources such as urine, faeces, organisms and household wastewater, and may be in the forms of urea, faecal proteins and ammonia. This has been estimated as ranging from 11 to 22 g N/capita per day (Kaplan 1991). Other studies have given an average for the seepage of 62 $\pm$ 21 mg N/L (Bauman & Schafer, 1985) of which 75% is in the ammonium (NH_4^+) form. This nitrogen undergoes the processes of the nitrogen cycle in the septic tank and leach field (see Fig 4). These are outlined below and are of major importance in reducing the amount of nitrogen.

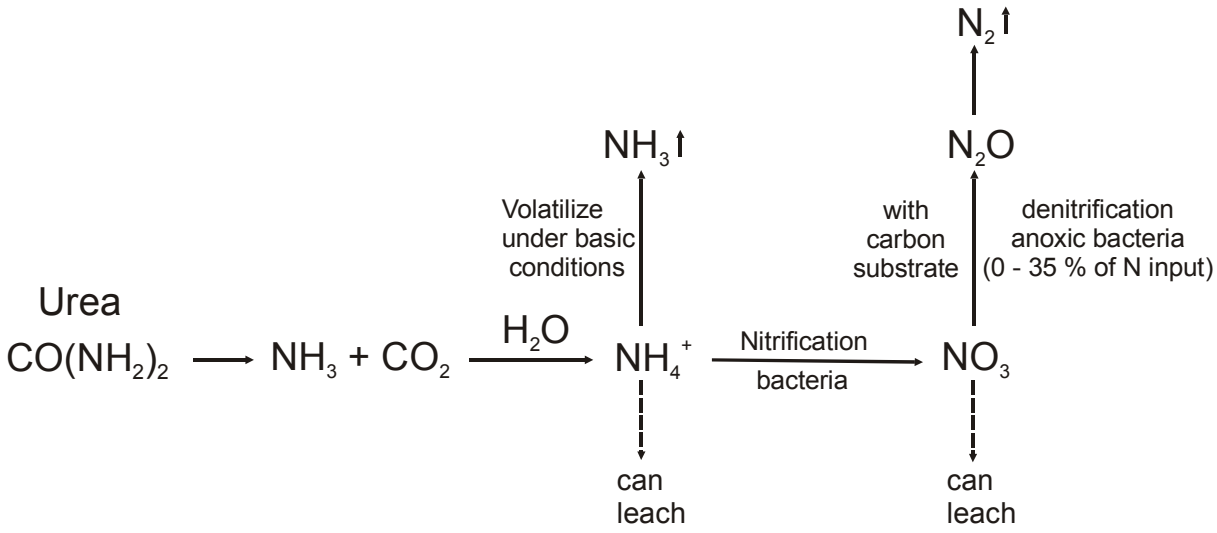


Figure 4: Urea conversion in septic tank leachate *(Bauman, & Schafer, 1985)*

The transport of ammonium (NH_4^+) and nitrate (NO_3^-) ions are affected by environmental factors such as soil moisture, temperature pH and availability of organic matter, as well as straining and adsorption. In the anaerobic conditions that normally prevail below the upper layers of soil beneath a soil absorption system NH_4^+ ions are adsorbed onto negatively charged soil particles. This process is generally completed in the first few centimetres of the soil. Subsequently, NH_4^+ travels through the saturated soil to other unoccupied exchange sites. Ammonia may move into groundwater under such conditions but this is slow and may be aided by the presence of organic matter. Cation exchange may also take place but is also subject to equilibration and site availability (Canter & Knox, 1985). Nitrate ions are not attracted to soils which have a negative charge. As a result they tend to be more mobile in both saturated and unsaturated soils. Therefore, when it is not removed by incorporation into biomass (e.g. by the planting of crops around the sewage system that have a long growing season and high nitrate requirement) or the denitrifying process, it will reach the groundwater without transformation. Once nitrate reaches the aquifer, it is very mobile due to its solubility and negative charge (Canter & Knox 1985).

Palmer (1981) stressed the risks involved in introducing water-based on-site sanitation systems such as the septic tank. For a low nitrate impact dry system a modified pit latrine is recommended. Muller (1989) proposed a type of flow chart approach consisting of sets of questions relating to nine parameters for assessing the on-site sanitation risk to any local groundwater supply.

Ward (1984) described a methodology for investigating sources of groundwater pollution giving details of the placement and construction of sampling holes. It also clearly stated that this kind of study has its limitations and negative results do not justify unmonitored sanitation and water supply programmes. Even in an urban development with water-borne sewage and stormwater run-off systems, groundwater pollution is possible (Wright, 1991). This was found to be the case in the township of Khayelitsha, which is situated on the Cape Flats aquifer. Nitrate was one of the pollutants observed in the groundwater.

Sewage sludge disposal to land is widely practised in and around most cities and towns (Engelbrecht *et al*., 1981). Sludge drying beds and sludge disposal to land, as well as sanitary landfills, constitute important sources of groundwater pollution. Very few local studies have been published but data from the Cape Flats (Tredoux, 1984) suggests that groundwater pollution could be severe in such permeable soils. Conrad *et al*. (1999) also confirmed serious nitrate pollution at a sewage works in the Gauteng Province. Xu *et al*. (1991) discusses aquifer protection strategies in Bophuthatswana and briefly mentions that there is much evidence to show sewage effluent and sewage sludge are disposed to land overlying aquifers as in the case of Mothibistad.

Effluent disposal by irrigation is legally practised in at least 240 instances. Table 2 summarises the number and type of permits are as well as the effluent volumes and land areas involved (Fuls & Du Plessis, 1977 in: Du Plessis, 1985). The maximum effluent volume irrigated is at least 127 x 106 m^3/a of which some 85 per cent involve municipal sewage effluents of various qualities. Although the actual quality is unknown it could be assumed that it will contain nutrients and for this reason these irrigated areas are often planted with grass, e.g. kikuyu. It is highly likely that at least in some areas leaching of nitrates could occur also in areas underlain by usable aquifers. Considering the estimated area of 25 471 ha involved the impact could be significant.

Table 2: Maximum effluent volumes permit holders may use for irrigation and areas under effluent irrigation *(Du Plessis, 1985)*

Permit holder category	Number of permits	Max. effluent volume (10^3 m^3/a)	Estimated area irrigated (ha)	Mean area per permit holder (ha)
Municipalities (sewage effluent)	134	127 356	25 471	190
Agricultural product processors	60	8 777	1 755	29
Mines	29	8 323	1 666	88
Industries	17	5 593	2 404	141
Totals	240	150 055	31 296	136

Du Plessis (1985) indicates that some reservations exist with respect to the use of lower quality effluents for irrigation but states that these are mostly applied according to scientific principles based on water quality and soil type.

Agriculture: Agricultural farming consists of a variety of activities ranging from extensive dry land grazing to intensive animal feeding units, and from dry land cultivation to large irrigation schemes. The nitrate pollution potential of these activities vary widely. Vast areas of the country are used for dry land grazing and this in itself is expected to have little or no influence on the nitrate accumulation process. Gathering of the livestock in kraals or around feeding or watering points, however, significantly increases the risk of groundwater pollution due to the increased nitrogen loading per unit area and the increased availability of moisture.

The area covered by the most important arable crops grown in South Africa constitute approximately 9 per cent of the total farming area of 82,9 x 106 ha. The larger part of the remaining farming area is used for grazing. The area of arable crops grown and the production is directly dependent on the climatic conditions and therefore these numbers vary from year to year. Considering the production in 1981/82 and that in 1990/91, nine years later, in the case of maize, the area grown has shrunk by approximately one-quarter, while the production remained virtually the same. This indicates a higher production per unit area. In the case of wheat, the area grown shrunk slightly while the production decreased considerably (although the estimated 1991/92 crop was virtually the same as for 1981/82). The area on which oats was grown more than doubled while the production halved. The reason for this change is unknown. Barley, sunflower seeds and soya beans production increased considerably but most of the other crops remained practically the same over the nine year period.

Considering the above information, it is evident that the largest individual impact is due to the growing of maize. Most of the maize is grown under dry land cultivation and to maintain and even increase the production per unit area, fertilization is essential. Tilling of the soil causes oxidation of organic soil nitrogen followed by leaching (Kreitler, 1975). This was also confirmed in the case of the Springbok Flats (Heaton, 1985). In addition, nitrification is enhanced due to the low organic carbon to nitrogen ratio of South African soils, high ambient temperatures and other factors. Vrba *et al*. (1985) concluded that in agricultural areas, leaching generally increases with increased fertilizer application. This is possibly also the reason for the observation of nitrate occurrences in the maize growing areas of the northern and north-western Free State (Henning & Stoffberg, 1990; Cogho, 1991).

In a study of the relative nitrate leaching potential related to land-use Juergens-Gschwind (1989) found a largely consistent pattern based on information from a number of countries (e.g. Germany, France and the USA). Other factors such as soil types can, however, affect the leaching potential but in general woodland has the lowest potential while maize in has a higher potential than other cereals. The highest leaching potential occurs when a change in cultivation occurs, ploughing up of pasture land and when the land is laid bare.

The periodic droughts in South Africa further complicate the situation because during such periods, the soil remains bare and the nitrate (from natural nitrification or applied fertilizer) is not intercepted by plant roots at all. Juergens-Gschwind (1989) concluded that bare land causes the highest losses by percolation with the soil releasing up to two times more nitrate than crop land. Thus, if crops are lost due to drought, the potential leaching of nitrate into the underground after the first significant rainfall event could be considerable.

Fertilizer consumption in South Africa was very low in 1955 and it only increased at a low rate until 1966. During the fifteen years from 1966 until 1981, when the highest consumption was recorded, fertilizer consumption increased at a high rate but crop production did not increase at the same rate (Van der Merwe, 1991). This would mean that an increased surplus quantity of nitrogen was available in the soil for oxidation to nitrate and subsequent leaching. Considering the experience in countries abroad, a considerable quantity of this nitrate could still be present in the unsaturated zone in areas where the groundwater level is deeper below surface. In areas where the water table is shallow (< 10 m below surface) it is expected that the nitrate derived from the nitrogen applied during the previous two decades has already reached the groundwater.

A further important aspect with respect to soil nitrogen inputs is highlighted by Power & Schepers (1989). Fertilizer nitrogen has largely replaced legume nitrogen as the primary source of nitrogen for American agriculture. According to Power & Schepers (1989) there was a steady increase in fertilizer nitrogen usage from about 1950 to 1980 while there was a corresponding decrease in legume production. The nitrogen provided by the legumes, is in

an organic form and has to be mineralized and oxidised before leaching into the subsurface can occur. In South Africa nitrogen fixed by legumes (including grain legumes, lucerne and legume- based pastures) amounted to 95 000 ton in 1981 (Strijdom & Wassermann, 1984). Should all agronomic soil and natural pasture suited for legume pastures be exploited for this purpose the total contribution by nitrogen fixation could rise to over 400 000 tons.

A nitrogen balance sheet was compiled for the agricultural soils in South Africa (Biesenbach, 1984). This balance sheet considered additions such as fertilizers, atmospheric contributions, nitrogen from irrigation water and natural nitrogen fixation. Nitrogen derived from manure and compost was excluded in the compilation as no statistics were available. It was also stated that the quantities were relatively small and would not play a significant role in the balance sheet. The nitrogen removals included in the balance sheet were the following: crops and plant residues, soil erosion by wind and water, as well as losses through leaching, denitrification and volatilisation. The data were compiled for a number of years over the period from 1960/61 to 1980/81. For the purpose of this report only the years 1960/61 and 1980/81 are of importance as it shows the relative weights of the various components as well as the changes over the 20 year period. The balance sheets calculated (Biesenbach, 1984) for these years are given in Table 3.

Table 3: An agricultural nitrogen balance sheet *(after Biesenbach, 1984)*

YEAR	**1960/61**		**1980/81**	
Fertilized area (10^6 ha)	12.3		14.4	
Irrigated area (10^6 ha)	0.7		1.1	
	kg/ha	total (t)	kg/ha	total (t)
Additions				
fertilizers	3.8	46 046	32.3	466 385
irrigation	2.4	1 680	2.4	2 678
atmosphere	(10)	(122 660)	(10)	(144 250)
N-fixation	?	unknown	?	unknown
Total		47 726		469 063
Removals				
crops & plant materials	14	181 715	26.7	414 397
erosion	3	36 798	3	43 274
losses (leaching, denitrification, volatilisation)	?	(122 660 + unknown)	?	(144 250 + unknown)
Total		218 513		457 672
Net gain (+) / loss (-)		-170 787		+11 391

It is noteworthy that in 1960/61 there was a considerable net loss of nitrogen from the soil while in 1980/81 there was a slight gain according to these balance sheets. The loss in 1960/61 was due to the small fertilizer input which could not cover the nitrogen losses due to removal of crops and plant materials. Two decades later the total fertilizer application had increased ten fold (8.5 fold for the application rate per hectare) while the removal by crops and plant materials had only doubled.

Biesenbach (1984) had no estimate for nitrogen fixation in the soil and assumed that together with the nitrogen derived from the atmosphere it balanced the losses due to leaching, denitrification and volatilisation. Strictly speaking this might not be true. In the case of Danish agriculture (Schroder *et al*., 1985) it was found that biological nitrogen fixation decreased as other nitrogen inputs increased. Thus, even though the nitrogen balance sheet for agricultural soils in South Africa has certain shortcomings, trends are evident which point toward a nitrogen surplus developing in the soil zone, possibly creating a greater potential for leaching of nitrates to the subsurface.

When comparing the fertilizer application rate per unit area in Denmark in 1980 with that in South Africa it is evident that the nitrogen application rates in Denmark are some ten times higher. That explains at least part of the very high losses calculated for Denmark. The calculations of Biesenbach (1984) although incomplete could, therefore, give an acceptable approximation of the situation in South Africa. This would mean that by 1960/61 there was a considerable over exploitation of the soil, while in 1980/81 fertilizer application rates were slightly too high.

There are clear indications that nitrogen recovery by crops vary considerably under South African conditions (Dijkhuis *et al*., 1984). Nitrogen recovery was found to range from 31 to 122 per cent with exceptional cases as high as 258 per cent. They came to the conclusion that nitrogen recovery by crops may be governed by weather conditions, soil form and management. It was also concluded that more mineralisable nitrogen, than is normally accepted, may be stored in the soil and it was recommended that more local research is needed on the nitrogen delivery potential of soils.

Animal husbandry/intensive animal feeding units: Dry land grazing of stock in itself is expected to have little influence on nitrate accumulation. The gathering of livestock in kraals or around feeding/watering points, significantly increases the risk of groundwater pollution. Dairy farming presents a special problem as additional feeds are provided and the concentration of animals around the milking facilities is usually higher. In their discussion of pollution sources in Bophuthatswana, Xu *et al*. (1991) refer to agricultural practices including stock-farming which tends to increase the nitrate load in the underlying aquifer. They state that farmers often build their livestock enclosures close to the water sources. This is also the situation in the western Kalahari (Heaton, 1984). At such sites, manure is concentrated and its leachate contains coliform organisms as well as inorganic substances. Xu *et al*. (1991) link the death of cattle of very high nitrate groundwater in the District of Kudumane to such conditions.

Intensive animal feeding units (feedlots) represent the most significant threat to groundwater quality. Information from the United States indicates that the risk of groundwater pollution is relatively low while the feedlot is in full operation (Mielke & Ellis, 1976). Under such conditions, nitrogen remains in reduced form and is largely lost as ammonia. However, when feedlots are only used partially or intermittently, or eventually abandoned, nitrification and transport of nitrates to the groundwater take place. Botha (1984) estimated the total quantity of nitrogen contained in manure produced annually in intensive feeding units at 69 313 t/a. This was based on data for 1981.

No statistics could be found with regard to the present number and distribution of feedlots in South Africa. Furthermore, it is expected that pollution could be a problem at feedlots and until 1992 no studies had been published in this regard (Steyn, 1992). From an analysis of the numbers of livestock it would seem that the total number has remained relatively constant over the last two to three decades. However, meat production has increased by approximately 50 per cent over the past thirty years. Based on these numbers, the pollution potential is expected to have increased considerably. Cogho (1991) found nitrate concentrations exceeding 30 mg/L near feedlots in the northern Orange Free State.

Irrigation: Irrigation is generally practised in areas where the rainfall is relatively low and has to be supplemented with irrigation water. In most cases, over-application of water for the purpose of salinity leaching forms part of the management of the irrigation system. It is therefore, to be expected that nitrate occurrences ascribed to percolate from irrigated lands will occur. In the case of the Hex River Valley, Weaver (1991) found nitrate levels of up to 33 mg/L in some of the wells monitoring shallow groundwater (< 3 m below the surface). The higher nitrate values were accompanied by potassium values which were also considerably above the natural background levels.

It was noticed that nitrate concentrations exceeding 20 mg/L were quite common in boreholes within the irrigated areas extending over 80 km along the Crocodile River in the Northwest Province. The fact that the electrical conductivities of the water from these boreholes were also high, implied irrigation percolate as the source.

3.4 Nitrate accumulation processes

A number of site-related factors control nitrate generation in the soil, leaching to the subsurface and accumulation in groundwater. Under natural conditions nitrate generation is primarily dependent on the availability of organic nitrogen in the soil. This nitrogen pool is maintained through nitrogen fixation by specific plant species (e.g. the Acacia spp.) and the accompanying microflora in the soil. At the same time uptake of nutrients by plants as well as natural denitrification serves to balance nitrate generation. Vegetation is, therefore, a prerequisite in the whole sequence.

Plant growth is dependent on a number of factors of which climatic conditions and particularly rainfall (quantity and distribution) is of overriding importance. In a high rainfall area, the natural vegetation cover is dense and interception by the root systems of the plants of nitrate generated in the soil is virtually complete. Under similar conditions in more arid regions, the interception of soil nitrate is not necessarily complete, mainly because the plant cover is sparser. Furthermore, the high variability of rainfall leads to a periodic die-off of plants and thus a varying the summer rainfall areas leaching of nitrate, therefore, can be expected to be at its highest at the start of the rainy season.

In studying the Chilean nitrate deposits, Mueller (1960) came to the conclusion that the primary nitrate generating mechanisms are present in all arid areas and that the average availability of nitrate in the area as a whole is no higher than in other areas. Secondary factors are responsible for the concentration of nitrates. In this case, salts are leached from the soil and collect as evaporites in salt pans. As the pans dry out, the remaining solution (consisting mainly of nitrates due to their solubility) migrates by 'capillary migration' to adjacent areas where the nitrates finally crystallize out.

In the Chilean example, the drainage systems end in salt pans. In the Kalahari and the Springbok Flats, similar situations occur. Both these cases are associated with areas with poor surface drainage systems. However, there is an important difference. Whereas the generation of nitrate both in Chile and the Kalahari takes place in an area with a rainfall of some 200 to 250 mm/a the Chilean nitrates are subsequently washed down into salt pans situated in the coastal plain in the desert where the rainfall is 10 mm/a or less. There, secondary concentration processes lead to the nitrate enriched surface deposits (Mueller, 1968). In the Kalahari occasional flood plains (pans) exist between the sand dunes but these are not linked to any active river drainage system. Rainwater enriched in nitrate thus seeps into the underground leading to the observed subsurface nitrate accumulation. Similarly, the Nyl River in the Springbok Flats ends without reaching any major river. It is therefore postulated that the absence of active drainage systems favours accumulation of nitrate in the area as it limits the export of solutes. Conversely, active drainage systems allowing efficient

transport of run-off and interflow, should promote the export of nitrate and other salts, thus preventing accumulation.

Tredoux & Kirchner (1985) postulated the need for a soil cover of sufficient thickness and permeability to allow rapid percolation and adequate storage of rainfall. This is considered to be part of the hydrodynamic requirements for nitrate accumulation discussed above.

As explained in Section 3.2 it would seem that in general nitrate occurrences cannot be related to a geological formation as being the primary origin. However, occurrences of elevated nitrate concentrations over vast areas sometimes closely follow the areal distribution of a geological formation and/or the resultant soil overburden. It follows that although the geological formation itself does not serve as the primary source of nitrate, certain of its characteristics and/or those of the soil overburden enhances the generation and accumulation of nitrate.

The ***environmental conditions*** under which natural leaching of nitrate from the soil zone and accumulation in groundwater has been observed are summarised below:

- *Vegetation:* Maintenance of the nitrogen pool in the soil through nitrogen fixation by specific plant species and the accompanying microflora in the soil. Without the proper nitrogen fixing vegetation soil organic nitrogen will be insufficient to allow any substantial nitrate accumulation. In more temperate and humid conditions (much higher rainfall than the 200 - 250 mm mentioned below), the type of soil can play an important role in nitrogen fixation, e.g. the black cotton soil in the Springbok Flats, Pandamatenga in Botswana, and elsewhere.

- *Soil:*
  - low C:N ratio for mineralisation;
  - low clay content;
  - soil cover of sufficient thickness and permeability to allow rapid percolation and adequate temporary storage of rainfall for groundwater recharge; alternatively a geological formation with such characteristics is needed;

- *Rainfall:* The climate and particularly the quantity and distribution of rainfall are critical factors both from the vegetation and the recharge and leaching perspective. It must be:
  - adequate to support the required vegetation type(s);
  - relatively low (possibly ~150 - 250 mm/a) to cause semi-arid conditions limiting total plant cover;
  - highly variable causing periodic die-off of plants and thus a varying plant cover;
  - consisting, at least at times, of storm events large enough to ensure relatively rapid natural recharge and leaching of nitrate.

- *Temperature:* sufficiently high to ensure microbiological nitrification (oxidation).

- *Hydrology:* absence of active open drainage systems (i.e. rivers ending in pans). Otherwise export of solutes such as nitrate (which is highly soluble) will take place as in Chile.

Wherever nitrate accumulates naturally, a combination of most of these factors has been identified. This phenomenon has lead to extensive areas in South Africa and adjacent territories naturally having elevated nitrate concentrations in groundwater. Natural nitrate

accumulations are also known from Chile, Australia and the USA. Obviously these factors would also enhance accumulation of anthropogenically induced nitrate generation.

3.5 Health hazards of nitrate in water

In the process of developing measures which may need extensive planning for implementation and could require considerable investments, it is essential that the question be asked at each stage whether the problems are overestimated or exaggerated. Accordingly, the known health effects of nitrate (and nitrite) are discussed below. As stated in an earlier report (Tredoux, 1993), exposure to high doses of nitrate is generally perceived to be associated with adverse health effects in humans and other species. These range from the 'hot dog headache' and methaemoglobinaemia to cancer and other effects. More recently, the question emerged of spontaneous abortion and still-births due to nitrate in the drinking water ingested by the mother.

Methaemoglobinaemia: Nitrate itself has a low primary toxicity (Rohmann & Sontheimer, 1985) but when it is reduced to nitrite (NO_2) it becomes an oxidising agent, capable of converting haemoglobin in the blood to methaemoglobin (see below).

Nitrate	**Primary toxicity:**	minor health risk
but when bacteriologically reduced, yields:		
Nitrite	**Secondary toxicity:**	methaemoglobin formation with high risk of methaemoglobinaemia in infants and livestock
	Tertiary toxicity:	reaction of nitrite with amines and amides to form N-nitroso compounds, (e.g. nitrosamine and nitrosamide) some of which are known to have carcinogenic properties
		(Rohmann & Sontheimer, 1985)

Methaemoglobin is significantly more stable than the oxygen haemoglobin complex that fulfils the oxygen transport function of the blood. The first symptoms of 'cyanosis' are generally noticeable when the concentration of methaemoglobin in the blood is between 5 and 10 per cent, while death results at levels of 50 per cent and higher (Terblanche, 1991). It is generally known that nitrate consumed with food or drink poses a serious hazard for infants and, therefore, the total dietary intake of nitrate needs to be taken into consideration (see Fig 5). Once the nitrate-N concentration in the ingested water exceeds 50 mg/L it can be fatal. Comly (1945) is generally credited with being the first to recognise the clinical relationship between the occurrence of infant methaemoglobinaemia and the consumption of water with high nitrate concentrations. The observations of Roe (1933), who reported fatal methaemoglobinaemia in a one month old infant when treated with bismuth nitrate for diarrhoea, provided the clue for Comly's conclusion. Following a literature survey, Walton (1951) concluded that 10 mg/L (NO_3- N) was a safe limit for drinking water. Shuval & Gruener (1977) confirmed a direct relationship between the occurrence of methaemoglobinaemia in infants and the presence of high concentrations (>10 mg/L) of nitrate in water. The presence of nitrate or nitrite in the ingested water is the principal determinant of the occurrence of methaemoglobinaemia in infants, but it is not the only one.

Ross & Desforges (1959) listed other factors important in the pathogenesis of the disease. It would seem that the risk significantly increases if the infant has developed diarrhoea due to bacterial infections (Follett & Walker, 1989). Methaemoglobinaemia is, generally, not classified as a notifiable disease, and, therefore, its true incidence is unknown. Hungary is

possibly the only exception as methaemoglobinaemia has been a notifiable disease since 1968 (WHO, 1985). Although relatively few cases of methaemoglobinaemia have been recorded, the indications are that infant mortality has occurred in several places without being recognised as such. One such instance was discovered on a farm in Namibia where a number of infant graves were found which are directly linked to methaemoglobinaemia.

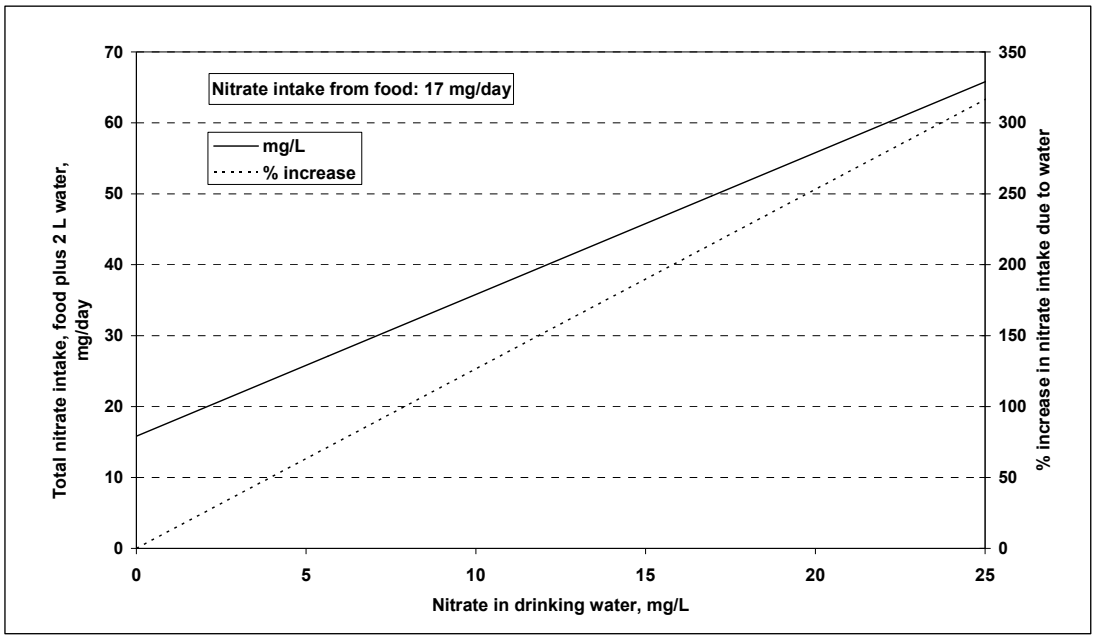


Figure 5: Percentage increase in total daily nitrate-N intake due to drinking water
(after Rohmann & Sontheimer, 1985)

In Southern Africa nitrate levels in groundwater are such that infant methaemoglobinaemia is known to occur (e.g. Super *et al*., 1981, Hesseling *et al*., 1991), although it mostly relates to anecdotal data without comprehensive statistics. In order to minimize the risk for transfer of HIV/AIDS from HIV positive mothers to their babies, these mothers are presently advised to refrain from breast-feeding (Colvin, 1999). The bottle-fed infants, however, run an increased risk of ingesting high nitrate water. Thus, the HIV/AIDS pandemic in southern Africa has introduced an urgency element for groundwater nitrate control measures in the region. Losses of livestock by nitrate poisoning occur occasionally in all three neighbouring countries, Botswana, Namibia and South Africa. This is known from anecdotal reports and from the author's investigations but also this phenomenon cannot be statistically quantified. Although infants are sensitive to the occurrence of nitrate in drinking-water, healthy adults generally can ingest large quantities without any apparent ill-effects (Tredoux, 1993). However, adult groups especially susceptible to methaemoglobin formation include pregnant women and humans deficient in glucose-6-phosphate dehydrogenase or methaemoglobin reductase (Speijers *et al*., 1989).

Nitrite poisoning can, however, kill older children. In July 2000 a seven-year-old child of Delft, in the Cape Flats, died after eating sodium nitrite which is used to give meat a red colour (Die Burger, 27 July 2000). In May 2001 three children died while seven other family members survived when sodium nitrite was used for cooking in the belief that it would relieve pain in their joints (Die Burger, 2 May 2001).

Spontaneous abortion or still-birth: Two cases of still-birth came to the author's attention (in October 2000 and March 2001) when visiting the Ghanzi area in Botswana where approximately 200 heads of cattle died of nitrate poisoning in 2000. Groundwater in most of that area has a high nitrate-N concentration, sometimes exceeding 500 mg/L. Anecdotal

reports say that there were many more cases, but this will have to be confirmed. The phenomenon of spontaneous abortion has been noted amongst livestock (see Section 3.6 below) and raised the question whether it also happened in the case of humans. Enquiries on the Internet brought several affirmative responses and this will be followed up. The following response was received from a researcher at the University of Iowa on this question:

> *"With respect to spontaneous abortion occurring in women consuming high nitrate water, there have been some anecdotal reports in the US documenting that. For example, a case study in LaGrange County, Indiana (in the Midwestern US) described where three women experienced a total of 6 spontaneous abortions during a two year time period (1991-93). These women lived in proximity to each other and consumed drinking water from private wells which contained high levels of nitrate (19 - 26 mg/L nitrate-nitrogen). I am not aware of any published studies on nitrate in drinking water and the risk for spontaneous abortion in women. There have been some studies looking at source of water and spontaneous abortion, but these looked mainly at trihalomethanes."*
>
> *(Weyer, 2001)*

Gastric and other cancers: Shuval & Gruener (1977) refer to the possible carcinogenic, teratogenic and mutagenic properties of nitrosamines which can theoretically develop in food or in the human digestive tract if nitrates and nitrites are exposed to secondary and tertiary amines under certain conditions. No conclusions are drawn as to the real nature of the potential risks involved. In an earlier paper, Wolff & Wasserman (1972) reviewed 60 publications on the potential hazard of nitrate, nitrite and nitrosamines in the environment. They came to the conclusion that 'the extent of real danger is not yet known, but deliberate consideration of the available information would suggest that the hazard is not sufficiently great to cause alarm'.

After considering all available evidence, the WHO (1985) came to the conclusion that 'no convincing evidence of a relationship between gastric cancer and consumption of drinking-water containing nitrate levels up to 10 mg/L has emerged. Furthermore, no firm epidemiological evidence has been found linking gastric cancer and drinking-water containing higher levels of nitrate but a link cannot be ruled out due to the inadequacy of the data available.' However, in a study involving 16 541 older Iowa women (55 to 69 years of age), Weyer *et al*. (2001) found statistical evidence linking their bladder cancer risk to the nitrate level in the drinking water.

Hypertension and 'hotdog headache': In a study of 487 cases of hypertension in 18 communities of Weld County, Colorado, USA, it was found that the onset of hypertension was earlier amongst residents in communities with drinking water containing nitrate, compared to the control groups that had nitrate-free water (Malberg *et al*., 1978). The nitrate-N levels in the drinking water of the 9 communities with nitrate varied between 4.3 and 28.2 mg/L. The paper does not provide any information on the salinities of the various water supplies or other factors. However, it quotes Carmichael & Triben (1963) who found hypertension amongst workers in the explosives industry working with organic nitrates.

The 'hot-dog headache' has been described in the literature and has been related to nitrites used in the curing of meat to give it a uniform colour (Johnson & Goldfinger, 1982). The nitrites are also vaso-dilators, so that some people find that soon after eating these meat products, they develop flushing of the face and a headache. The hot-dog is the classical example, but other meat products including bacon, ham and salami can also cause these symptoms. A farmer in the Springbok Flats regularly complained about hot-dog headaches. The problem was solved when he started using nitrate-free water (Talma, 1991).

3.6 Livestock watering concerns

In the case of livestock, pregnant heifers, ewes and fully grown animals are all at risk. However, it would seem that chronic toxicity occurs only at higher nitrate levels. Accordingly, nitrate limits for stock-watering are set considerably higher than for human consumption. In Namibia the limit for stock-watering is set at 110 mg/L (DWA Namibia, 1977). In South Africa 90,3 mg/L is used as a guideline value for the watering of dairy cows (Baard, 1992).

According to Davison *et al*. (1964) cattle ingesting nitrates have a reduced life-span, inhibition of growth and increased incidences of abortion and related infertility. In their experiments milk production was similar for the control groups and the heifers fed various levels of nitrate. Stock losses due to nitrate poisoning have occurred in neighbouring Namibia (Anonymous, 1974, Tredoux, 1974). In these cases, the nitrate concentration was usually several hundred mg/L (as N). In a dolomitic area in the former Bophuthatswana the loss of some 140 heads of cattle was recorded in 1989 (Marais, 1991). The nitrate concentration was 691 mg/L (as N).

Kreitler (1975) reported the loss of *two herds of cattle* at individual wells with high nitrates in Runnels County, Texas, in the summer of 1969. It is noteworthy that the nitrate concentrations at several of the wells in that area varied significantly over a three-year period. In one case the nitrate-nitrogen concentration decreased from 506 to 280 mg/L and in another case from to 208 to 4.7 mg/L. Similar observations were made in Namibia in 1974 and in Botswana in October 2000. This underscores a serious problem related to nitrate concentrations in groundwater which may change significantly following heavy rainfall events, causing groundwater, which was perfectly safe beforehand, to become poisonous for infants and livestock. In Botswana approximately 200 heads of cattle died of nitrate poisoning in the Ghanzi area in October 2000. It is noteworthy that all the recorded instances of livestock losses concerned pregnant heifers.

In 1992, enquiries were made regarding the incidence of stock losses due to nitrate poisoning at the Office of the State Veterinarian, the Directorate of Animal Health, Onderstepoort and other Government offices (Tredoux, 1993). It was established that nitrate poisoning was not a controlled disease and no records were kept of such occurrences. The general perception amongst veterinarians was that nitrate poisoning due to the ingestion of high nitrate water occurred seldom. One veterinarian mentioned that he has witnessed nitrate poisoning of cattle after ingestion of turnips and that he saw this as a problem.

However, it would seem that detrimental effects could occur at lower nitrate concentrations, particularly affecting lactating cows. This was confirmed by a veterinarian at Onderstepoort (Myburgh, J, Onderstepoort, *pers. comm.,* 1999). A farmer in the Springbok Flats installed his own denitrification unit for stock-watering for protecting his dairy cows (Anonymous, 1985). He was reportedly reducing the nitrate concentration from 34.3 mg/L to 0.2 mg/L using molasses as a carbon substrate. It is important to note that livestock can adapt to relatively high nitrate levels but cannot tolerate a sudden increase in the total nitrate intake, either from the fodder or the drinking water (Myburgh, J, Onderstepoort, pers. comm., 2000).

Casey *et al*. (1998) reviewed the information on impact of water quality on livestock. According to the literature quoted, if the forage contains nitrate, the “problematic range” in the drinking water is from 445 to 1335 mg/L as NO_3 (which is 100 to 300 mg/L as N). If the nitrate in the water exceeds 1335 mg/L toxicity effects can be expected. Casey *et al*. (1998) carried out toxicological studies for a range of chemical constituents, including nitrate. At levels of 200 to 400 mg/L as NO_3 (which is equivalent to 45.2 to 90.3 mg/L) no significant adverse effects were noticed on the health of Dohne Merino sheep.

3.7 Irrigation impacts

Possibly one of the only advantages of mildly nitrogenous groundwater is that it can be applied fruitfully for the irrigation of certain crops during part of the growth cycle. In their discussion of nitrate in groundwater of Central Australia, Murray & Siebert (1962) suggested that the fixation of atmospheric nitrogen by legumes could account for the areas giving rise to moderately and highly nitrated waters. They continued: 'should it be proved, the possibility arises of producing such waters for irrigation purposes by the planting of selected Acacia species on catchment areas which provide sufficient waters of suitable quality'.

4 FIELD STUDIES AT SELECTED SITES

The initial purpose of selecting study sites was to carry out more detailed investigations of the soil, the groundwater, land-use, and other factors in order to identify those factors involved in nitrate accumulation in areas where this phenomenon occurs. At the same time, it was important to investigate densely populated rural areas in order to ensure that the local communities would gain from solutions that are found and implemented.

After the first year, the approach towards the project was reconsidered and revised with the approval of the Steering Committee. Once the costs involved in the field studies was determined, it was decided to limit the scope at each site, but it was planned to acquire information from as many other studies as possible to extend the available information and eventual database. This includes work done in neighbouring countries. In that way a wider range of environmental conditions will be taken into account which may provide the same or possibly a better outcome for the project and the nitrate strategy. This change in approach needed an adaptation in timing and the project was rescheduled to run until March 2003. The total budget of the project remained the same.

4.1 Study site selection

Study site selection, within the areas identified from the NGDB map, took take place in consultation and collaboration with the DWAF and RDP Offices in the relevant regions. Once the study areas and specific sites that may be affected by pollution were selected, attempts were made to obtain reports and recorded information on the groundwater resources in those areas.

The site selection criteria were the following

- nitrate should occur at significant concentrations
- there should be a significant water supply source
- it should be located in an area where nitrate accumulation is likely
- aquifer conditions should be known
- a sufficient number of boreholes should be available, or easily drilled
- a record of hydrochemical information, groundwater usage, etc should be available
- if possible, select areas with and without the likelihood of pollution
- the Provincial Government, RDP office, DWAF, and local authorities should agree on the selected site(s)
- the cooperation of the local community has to be secured

Accordingly the areas on the map were identified where high nitrate concentrations occurred and the sizes of the villages with the affected populations were assessed in order to decide where the high nitrates had a serious impact. This was facilitated by the fact that WSP had these data captured in electronic format. Table 4 lists the prospective study areas, which were delineated on the map. Based on the water supply information, these areas are most seriously affected by nitrate accumulation. The respective populations affected in each case are also indicated in the table.

In the selection of the field study areas the Springbok Flats, the irrigation areas around the Crocodile River, the area to the southeast of Beaufort West, the Richtersveld, and the high Kalahari nitrates were ignored, as these did not directly affect the water supply to a significant rural population. Investigations in those areas may, however, provide important clues regarding the factors responsible for the accumulation of nitrate in the subsurface.

As a first step, the area of Sinthumule-Kutama (at Makhado, formerly Louis Trichardt) and Marydale in the Northern Cape were selected for field study. Results of the preliminary investigation at each site, are given below. Depending on the needs of the strategy, more of the remaining sites may be visited, and the selected sites will be revisited.

Table 4: Groundwater nitrate study areas considered *(Data from WSP, DWAF via Paul du Plessis)*

Site/Area	Village/ Rural	Number of villages	Population	Ground-water dependence	Conform to RDP standards	Geology	Priority
Northern Province							
Sinthumule-Kutama	Village	19	67 266	100 %	0 %	Basalt/ Granite	High
Mokorong (near Ellisras)	Rural	-	60 000	100 %	1 %		High
Northwest Province							
Molopo	Rural	-	4 500	100 %	0 %		Medium
Morokweng	Villages	6	10 276	100 %	0 %		High
Madibeng	Rural	-	2 010	100 %	0 %		Medium
Northern Cape Province							
Rietfontein/ Mier	Villages	8	4 000	100 %	< 25 %	Kalahari	Medium
Marydale	Village	1	1 800	100 %	0 %	River alluvium	High
Leliefontein/ Kharkams	Villages/ rural	2 -	2 420 6 360	100 %	0 %	Namaqua-land granite/ gneiss	High

4.2 Sinthumule-Kutama

As a first step, the area of Sinthumule-Kutama (at Makhado, formerly Louis Trichardt) and Marydale in the Northern Cape were selected for field study. Results of the preliminary investigation at the site, are given below.

The Sinthumule-Kutama area comprises 19 separate villages with approximately 74 000 inhabitants and these villages are spread over 19 000 ha. The southern part of the area is underlain by granite and gneiss of the Basement Complex. The lithology is essentially a medium to coarse-grained, leucocratic granite becoming pegmatitic in places (WSM, 1999). Highly deformed, elongated lenses belonging to the Bandolierkop Complex are infolded into the basement. To the north, the Soutpansberg Group forms a major unconformity with the underlying Basement Complex. This Group comprises mostly basalt with minor intercalations of magnetite quartzite, shale and tuff. Numerous dolerite dykes have intruded into the Basement Complex and, to a lesser extent, the Soutpansberg Group (WSM, 1999).

The general groundwater flow direction in the area is from southeast to northwest. In the present sampling, only points in the western half of the area were sampled. Three production holes were selected for sampling and the remainder were wind pumps, hand pumps, and an open borehole. Of a total of 37 points visited, only 8 could be sampled. In all other cases, the hand pumps were out of order or the open boreholes had collapsed. The main reason is that water is supplied via a central distribution system and the hand pumps are not used anymore. The sampling was planned to obtain a profile from the southeast to the northwest across the area, i.e. in the direction of groundwater flow. In view of the many

pumps that were out of order, this was only partially successful. the results are presented in Table 5 together with earlier data. The layout of the area is shown in Figure 6.

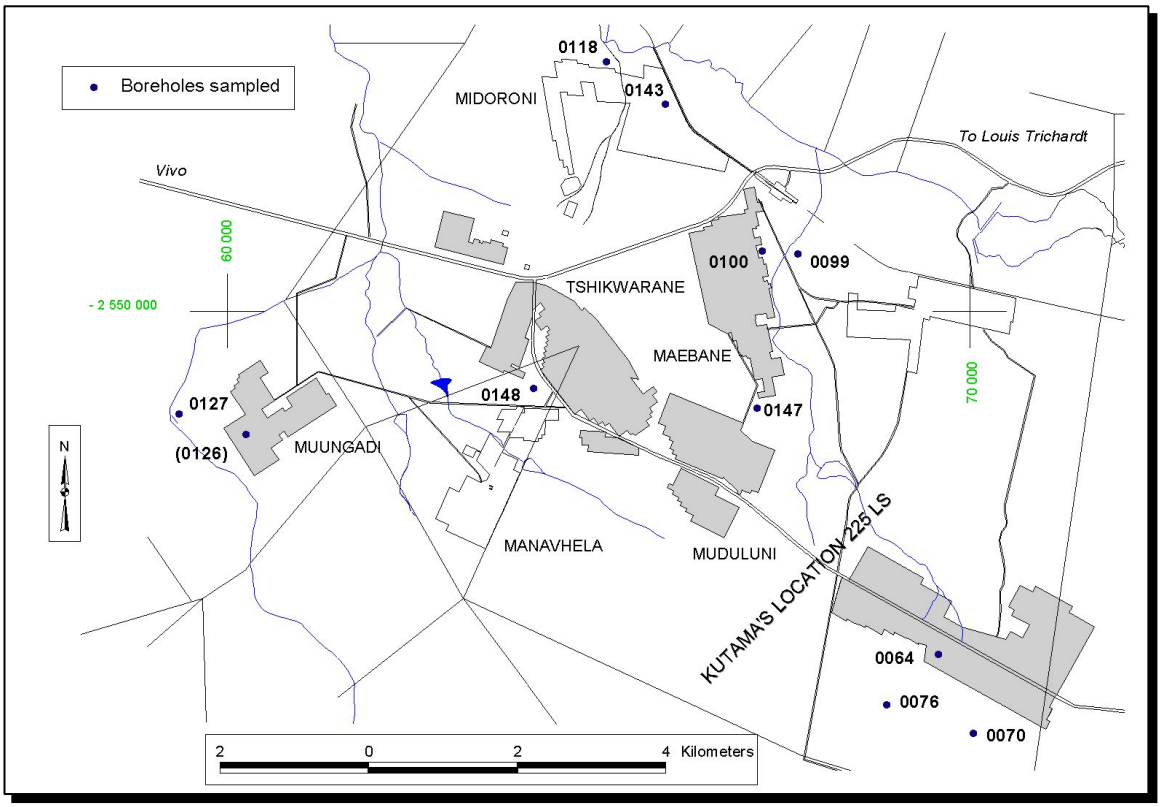


Figure 6: Borehole locations in Sinthumule-Kutama, at Makhado (formerly Louis Trichardt)

Production borehole G44251 and open borehole H19-0076 are both up-gradient of Madodonga village and both have a low nitrate concentration. The nitrate concentration at production borehole T3715, located further down gradient, and to the east of Maebane village, is also low. However, production borehole G44254, located to the north of Midoroni village, near the Dorps River, i.e. far down gradient, has a nitrate-N concentration of 25 mg/L. The ^{15}N isotope concentration indicates that this may be derived from faecal pollution. Although the borehole is 78 m deep, the main water strike was at only 12 m below surface. The three boreholes located inside villages, all have nitrate concentrations exceeding 20 mg/L.

When comparing the results from the latest sampling run with earlier results, most boreholes show relatively large variations and no particular trend can be identified. It is noteworthy that at the up-gradient production borehole at Madodonga village, G44251, which had its first water strike at a depth of 27 m, the nitrate concentration remained low. On the other hand it is of concern that the down-gradient production borehole at Midoroni, G44254, had a high nitrate concentration linked to a high ^{15}N isotope value which may be related to faecal and associated pollution.

Table 5 Hydrochemical data for groundwater at Sinthumule-Kutama *(Walton et al., 1993; WSM, 1999; this study)*

Borehole No	T3003		G44251				T3715		T3616			T3526	
Sample ID:	H19-0064		H19-0070		H19-0076		H19-0099		H19-0100			H19-0143	
Area	Madodonga		Madodonga		Madodonga		Maebane		Maebane			Midoroni	
Equipment	Windpump		Production		Handpump		Production		Handpump			Handpump	
Sampling Date:	960425	991203	951023	991203	981206	991203	960425	991203	960425	991203	~1990	960425	991203
Electrical Conductivity, mS/m	128	116	124	122	-	140	160	58	280	165		170	139
Potassium, mg/L		8.7	7.9	8.5		9.8	4	3		7.5			3
Sulphate, mg/L		26	49	23		29	99	18		49			34
Chloride, mg/L		63	144	121		174	286	42		148			120
Nitrate + nitrite as N mg/L	28.9	21.3	9	8.1	-	4.5	4.3	3.8	-	14.4	55.3	38.4	64
$\delta^{15}N$ ‰ AIR		11.1								9.9	22.2		13.7
Borehole No	G44254		Private		B73		T3207		T3735				
Sample ID:	H19-0118		(near H19-0126)		H19-0127		H19-0147		H19-0148				
Area	Midoroni		Zamekomst		Zamekomst		Mududuni		Mududuni				
Equipment	Production		Handpump		Handpump		Handpump		Handpump				
Sampling Date:	951129	991203	-	991203	960425	991203	960425	991203	960425	991203			
Electrical Conductivity, mS/m	112	136		138	72	58	175	175	182	176			
Potassium, mg/L	1.8	1.3		3.9		3.5		11		7.1			
Sulphate, mg/L	93	135		49		67		42		68			
Chloride, mg/L	188	198		117		13		212		178			
Nitrate + nitrite as N mg/L	22.1	25		37	16.3	<0.1	39.5	9.9	41.1	0.29			
$\delta^{15}N$ ‰ AIR		11.4											

4.3 Marydale

Marydale in the Northern Cape was also selected for field study. The town obtains its water from the shallow, unconfined alluvial aquifer along the ephemeral river to the south of the town (see Fig 7). The annual rainfall in this area is approximately 200 mm and the groundwater is slightly saline (with chloride in all boreholes sampled > 200 mg/L). The groundwater has a characteristically high nitrate and potassium concentration. Nitrate is generally close to the maximum allowable limit of 20 mg/L. Careful blending of water from different boreholes is required to ensure that the town supply does not exceed 20 mg/L. The hydrochemical data for Marydale are summarized in Table 6.

When comparing the 1996/7 analytical data with the recent results it is evident that the water quality varies considerably. This is, however, often the case in such a shallow, unconfined aquifer. Overall, the nitrate values have increased. The relatively high $\delta^{15}N$ values at Marydale are approaching levels which are typical for faecal pollution. Although sheep are grazing in the area, it is very unlikely that the groundwater is polluted and another explanation will have to be sought. The uniformity of the water quality over a large area also eliminates pollution as a source for the nitrate and other constituents such as potassium. Borehole Mar-1, which is located down-gradient of the other boreholes and the closest to the town, has a lower nitrate concentration and a higher $\delta^{15}N$ which would seem to indicate partial denitrification.

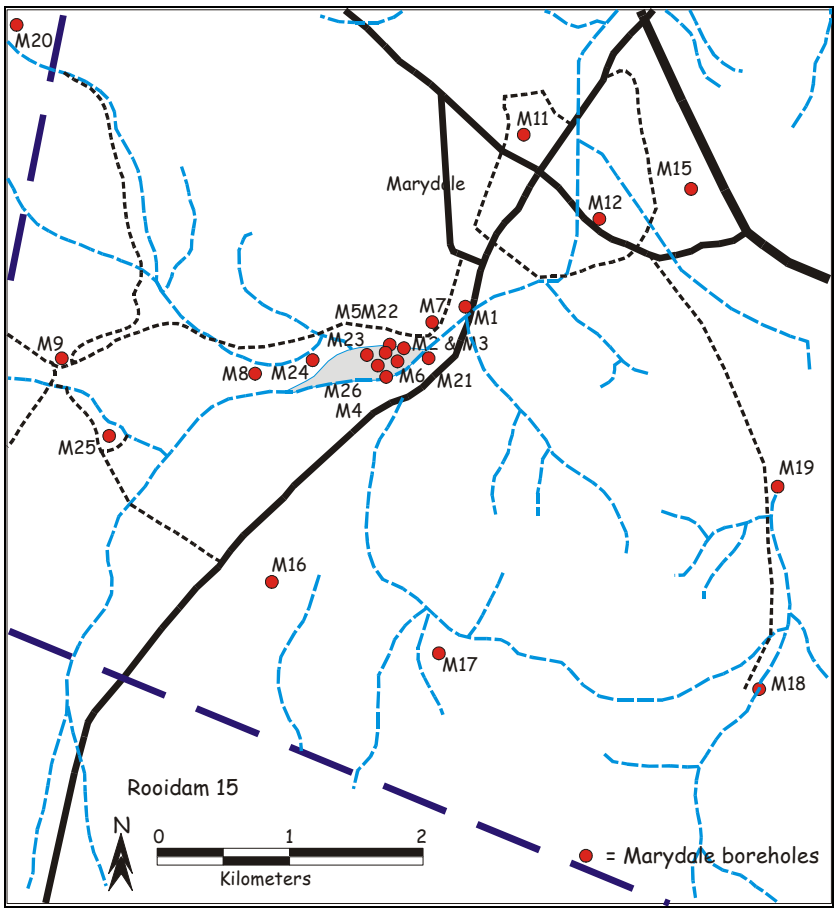


Figure 7: Layout of water supply boreholes at Marydale. In central area river flows in an east-northeasterly direction

Table 6: Hydrochemical and isotope data for town supply boreholes at Marydale *(Hoffman, 1997; this study)*

Borehole	**Mar-1**		**Mar-8**		**Mar-9**		**Mar-21**		**Mar-23**		**Mar-25**	
Date sampled	19961215	20000215	19961215	20000215	19961215	20000215	19970612	20000215	19971006	20000215	19971206	20000215
Conductivity	106	186	202	192	170	177	134	205	213	212	221	204
Potassium, mg/L	-	31	-	26	-	25	22	31	25	25	23	24
Sulphate as SO_4 mg/L	44	152	200	172	138	150	120	217	240	250	220	185
Chloride mg/L	198	255	318	258	246	226	140	252	295	273	337	294
Nitrate + nitrite as N, mg/L	3.4	13	4.5	19	11.2	25	11.9	19	18.6	20	24.9	25
□ ^{15}N ‰ AIR		12.4		10.6		10.6		10.8		10.3	(+10.0)*	9.9

*sampled 8 December 1998

4.4 Other sites visited

As part of a parallel study into the accumulation of nitrate in groundwater, samples were also collected in the Springbok Flats and analysed for nitrate and ^{15}N concentrations. The data are shown in Table 7. The typically high nitrate concentrations in the area (18 to 46 mg/L in this sampling) are mostly linked to moderate ^{15}N isotope values which indicate nitrification of organic soil nitrogen as the origin of these nitrates (Heaton, 1985). This is related to the tilling of the soil. However, pollution also occurs, e.g. at borehole Sf-52 which is situated some 30 m from the residence on the farm. This borehole has a nitrate concentration of 193 mg/L. This is high, also for polluted groundwater and it begs the question whether nitrate pollution is more severe in an area where natural accumulation of nitrate in groundwater prevails.

The soil and vegetation play a key role in the fixation of nitrogen and the accumulation of nitrate in the subsurface. For this reason the soil type and plant cover need to form part of the factors studied in regard to the accumulation process. Soil samples have been collected at certain places in the study areas, but this needs to be intensified for understanding the processes.

Hydrochemical profiles covering the electrical conductivity, pH, redox potential, dissolved oxygen, and temperature, were carried out in non-equipped boreholes. In the Springbok Flats area this clearly showed the difference in hydrochemical conditions in the basalt and the underlying sandstone. Further hydrochemical profiling is planned, both in polluted and unpolluted areas.

In 2001 a number of heads of cattle died on a farm northeast of Thabazimbi. This area was visited in December 2001 and the specific borehole sampled. The nitrate level was high but it was evident that the water in the drinking trough was considerably higher. This was also confirmed by Casey *et al*. (1998) and indicates a further important variable that reservoirs and roughs in nitrate prone areas need to be flushed if these have not been used for any length of time.

The village of nZawa, near Giyani was visited in December 2001. This village operates an ion exchange denitrification plant for town supply. When the production boreholes were visited, it was found that all of these are down gradient of the village at the bottom of the slopes. There is a distinct possibility that the nitrates are all derived from pollution by on-site sanitation systems.

Table 7: Hydrochemical and stable isotope data for boreholes in the Springbok Flats

Borehole	SF-5 Deeside Bh at house	SF-51 Hanover Bh S of barn	SF-52 Tuinplaas 30 m SSW house	SF-53 Tuinplaas Bh 1 in field	SF-59 Tuinplaas Bh 3 in field	SF-58 Tuinplaas Michau, open Bh	SF-56 Windpump at Bh M4
Date sampled	19991005	19991005	19991005	19991006	19991006	19991006	19991006
Nitrate-N, mg/L	37	26	193	18	21	46	23
^{15}N ‰ AIR	6.9	6.3	11.8	7	6.1	5.4	6.7

5 MAIN SOURCES OF GROUNDWATER NITRATE IN SOUTH AFRICA

The occurrence of nitrate in groundwater is a worldwide phenomenon and generally the concentrations have been increasing. For Southern Africa exact data on the trend of nitrate levels in groundwater are not generally available at this stage. However, the indications are that groundwater is becoming more and more polluted by nitrate. In neighbouring Botswana, this rising trend was already recorded some two decades ago and proposals were made for groundwater protection near villages. However, the abandoning of well fields, mainly because of nitrate pollution, is continuing and it is also occurring in South Africa.

Generally, the main inputs of nitrate to groundwater are derived from anthropogenic activities. Pollution sources are fertilizer application to land, sewage sludge application to soil, wastewater irrigation, on-site sanitation, deforestation, and mineralization and mobilization of natural soil nitrogen by tilling of the soil.

5.1 Field data interpretation and evaluation

Agriculture: In the highly-developed countries of the world, the high rate of fertilizer application is a major source of groundwater contamination by nitrate. Especially in Europe, strict measures are in place for limiting the nitrogen application rates and timing. Furthermore, groundwater protection zoning limits potentially polluting activities in the vicinity of production well fields.

In the developing countries, e.g. those in Southern Africa, fertilizer application rates are significantly lower than in Europe and elsewhere, and these have been shown not to make a significant contribution to nitrate in groundwater. The fertilizer application rates in South Africa are low enough not to cause leaching of nitrate to the groundwater. Furthermore, Vrba *et al*. (1985) indicated that the concentration of nitrates in groundwater does not depend only on the doses of inorganic fertilizers applied on the farm land. They cited factors such as the aquifer transmissivity in the vicinity of the borehole, redox conditions, thickness of the unsaturated zone, and the cyclical character of natural processes, which affected the actual concentration of nitrate found in the groundwater. The general absence of nitrogen fertilizer leaching in South Africa, was confirmed by a study of agricultural practices in South Africa (Conrad *et al*., 1999).

Rural areas are often surrounded by agriculture which may lead to a background nitrate value in the groundwater. The type of agriculture being practised will determine the levels (see Conrad, 1999). Any additional pollution from anthropogenic sources in the villages would then be superimposed on these background concentrations. This was clearly the case at Sinthumule-Kutama and at nZawa.

Land clearing/tilling: However, local studies have shown that already the process of tilling the soil leads to the nitrification of soil nitrogen and leaching into the subsurface. Pollution from diffuse sources is particularly problematic as it can affect an entire aquifer and can go unnoticed for decades, but once the effects appear, it may be necessary to abandon the aquifer (DWAF, 1991). A number of countries have proposed control measures for reducing nitrogen input to groundwater. Abroad, agricultural practices are considered to be the most important contributors and control measures mostly pertain to agricultural activities. In Czechoslovakia a system of protection zones around boreholes was introduced, limiting both agricultural activities and application rates for fertilizer, manure and wastes (Vrba *et al*., 1985). A similar system was proposed for the Netherlands (Van Beek, 1985). In the United States nitrate leaching under irrigation was identified as a serious problem. Both water management and nitrogen management are important in controlling nitrate leaching. Nitrate leaching can be reduced by applying only enough fertilizer to meet yield goals, correct timing of application, and the use of slow release fertilizers.

Feedlots: The main remaining concern regarding farming is the impact of livestock concentrations at watering points, and septic tanks with drainage systems near water supply boreholes. These point sources can yield high concentrations of nitrate and other pollutants (e.g. pathogens) in groundwater. Also in arid areas, such point sources have been confirmed by nitrogen isotope determinations (e.g. Heaton, 1984). Conrad *et al*. (1999) showed that intensive animal husbandry involved a certain risk of groundwater pollution. In all these agriculturally related activities nitrate was the main pollutant.

Irrigation is generally practised in areas where the rainfall is relatively low and has to be supplemented with irrigation water. In most cases, over-application of water for the purpose of leaching forms part of the management of the irrigation system. It is, therefore, to be expected that nitrate occurrences ascribed to percolate from irrigated lands will occur. It was noted that nitrate concentrations exceeding 20 mg/L were quite common in boreholes within the irrigated areas extending over 80 km along the Crocodile River in the Northern Province. The fact that the electrical conductivities of the water from these boreholes were also high, implied irrigation percolate as the source.

Wastewater treatment: The most important polluting practice was the (over)-application of sewage sludge to land. High levels of sewage sludge application have caused serious groundwater pollution (Tredoux, 1984; Conrad *et al*., 1999).

Nitrogen fixation is a natural process taking place over vast parts of the arid and semiarid zones followed by mineralization and leaching of nitrate from the soil horizon. At this stage, the factors controlling the process are still being debated. Intensive site investigations over a considerable length of time will be required to identify and quantify these factors. Such studies cannot be accommodated within this project's financial constraints and alternative approaches will have to be followed for arriving at meaningful conclusions and a workable nitrogen management strategy.

Similarly, denitrification occurs widely and provides considerable protection to aquifers. In this case ^{15}N isotope measurements can provide qualitative and sometimes quantitative indications of denitrification. This may provide answers also within the scope of this project and follow-up work will have to be done at the study sites. Additional isotope studies would include determining the abundance of ^{18}O in the nitrate ion (NO_3^-). Finally, the distribution of ^{15}N in plants in polluted areas needs to be compared with that of plants in other areas.

On-site sanitation: In vast parts of South Africa, on-site sanitation remains a viable or only option. Not all such practices lead to groundwater pollution, but in the wrong hydrogeological and environmental conditions, the effects on groundwater can be disastrous. On-site sanitation is a cost-effective approach and any nitrogen management strategy will have to contend with realistic on-site sanitation options. However, it also means that on-site sanitation needs to be planned with the particular hydrogeological scenario in mind. There is no general rule that can be applied everywhere. It is necessary to have a pragmatic approach in this regard, but where sensitive and sole source aquifer systems are at risk, alternative sanitation options have to be found. It should be noted that the occurrence of methaemoglobinaemia was mostly associated with private drinking water wells which were polluted by on-site sanitation, e.g. french drains associated with septic tanks. Abandoned well fields, often abandoned because of rising nitrate concentrations, bear witness to the nitrate threat to groundwater. In South Africa this has occurred e.g. at Sinthumule-Kutama that was visited in the course of this study. Also at nZawa, where an ion exchange plant was built for nitrate (and salt) removal, it was noted that the production boreholes were in the village while others were down gradient and, therefore, under threat of pollution by on-site sanitation. Many cases are known from neighbouring Botswana, e.g. that of Ramotswa (Staudt, 2003).

5.2 Nitrogenous pollution processes

For successful groundwater protection a strategy is needed consisting of a dual approach, i.e. legislation for pollution control and for reducing nitrogenous inputs to the environment, which is supported by an education and public awareness programme. In semiarid to arid regions, nitrate occurs extensively in groundwater in areas where anthropogenic influences can be excluded. This indicates that accumulation can take place under certain natural conditions. A full understanding of this process is required for designing the groundwater protection strategy.

Methaemoglobinaemia and nitrate poisoning of livestock are realities. Detailed information on its occurrence is sparse. Nevertheless, it is known that this only occurs at relatively high nitrate levels, and a review of the nitrate standard may be needed, but then taking due cognisance of the associated microbiological and other risks related to polluted water.

5.3 Describing accumulation of nitrate in groundwater

Considerable research has been carried out into the leaching of nitrate from agricultural soil. However, the natural accumulation has not been studied in great detail. It mostly happens in semiarid to arid areas and is a very long term process which runs over decades or centuries. Once the factors are better understood, mathematical modelling of the transport of nitrate through the unsaturated zone needs to be carried out in areas with longer term climatic records. In this regard the simulation package LEACHM could prove to be a suitable approach. This needs further exploration and development

NLEAP (Nitrate Leaching and Economic Analysis Package) was specifically developed for the agricultural application of nitrogen fertilizer (in the USA) Schaffer *et al*., 1991.

5.4 Controlling factors for the management of nitrogen sources

With regard to the management of anthropogenic groundwater nitrate in South Africa the main input process that needs to be controlled and managed is on-site sanitation.

Larger wastewater treatment systems also create a nitrate hazard due to sludge treatment (drying beds) and disposal to land, or through partly treated wastewater irrigation.

Agriculture is generally only important in the sense that it helps to create a background nitrate level upon which secondary nitrate pollution is superimposed. However, in certain irrigation areas, e.g. along the Crocodile River in the north-western part of the country, groundwater nitrate levels are elevated due to seepage from irrigation systems.

6 NITROGEN MANAGEMENT STRATEGY

Determining reliable groundwater nitrate trends is the first requirement for nitrate management. This in turn requires reliable analytical data extending over decades. There is a lack of consistent data sets for determining nitrate concentration trends. The degree to which the present National Groundwater Monitoring Programme fulfils this need will have to be established. In this regard an evaluation of the existing information collected in the National Groundwater Monitoring Programme may help to fill this gap. Following such an evaluation, the occurrence, or potential occurrence of nitrate may need to be added to the selection criteria for monitoring points in the National Groundwater Monitoring Programme. This will ensure that eventually, after another decade or more, reliable information will be available for evaluating nitrate trends in groundwater. Despite this lack of information, a first nitrogen management strategy should be developed to protect the groundwater resources. Once the trend data become available, the strategy can be adapted or refined to take the new information into account.

Permit systems are currently in place for controlling certain polluting activities, for example wastewater irrigation to land, establishment and operation of waste disposal facilities, and certain other activities. Guidelines are available for on-site sanitation but due to the site-specific nature of such practices, general control measures have not been introduced. Evidently, strict control measures are needed for manure and sludge application to land, feedlot operations, siting of cemeteries, and other pollution point sources

A nitrate management strategy for the region should be based on a dual approach that involves legislative control measures, as well as public information and education programs. Control measures are essential for reducing anthropogenic nitrogenous inputs to the environment that may affect groundwater quality. Such measures are also required for reducing groundwater nitrate levels in the rural areas and on farms that affect drinking water quality. Denitrification of drinking water supplies, aquifer restoration, blending of water sources, supply of bottled water for mothers and infants, and other measures are needed to reduce the risks of exposure of the population to excessive nitrate.

Details of the impacts of a variety of anthropogenic activities causing groundwater pollution are unknown and are ignored by local authorities, planners, developers and others. Nevertheless, the general features of the results of excessive nitrogen to groundwater are known. Parallel to the full introduction of control measures, an extensive public education and information program needs to be launched, particularly in the rural areas. Such a program is considered an important tool for the reduction of nitrogenous inputs, both with respect to diffuse sources as well as with the myriad of small point sources.

6.1 International approaches to nitrogen management

The international approaches mostly dealing with the management of agricultural impacts. This is generally the most important source of nitrate in groundwater in the temperate climates. The approaches include the introduction of slow release fertilizer additives, e.g. “N-serve” and “Didin” which are two of seven possible additives used in Germany (Rohmann & Sontheimer, 1985). In addition they also apply a levy system to agriculture for groundwater protection, called “water cents” (“Wasserpfennig”) in Germany.

In the Netherlands, 70 per cent of the water supply is derived from groundwater. First Van Duyvenboden and Loch (1983) and then Van Beek (1985) expressed concern about rising nitrate levels in the country and the ability of waterworks to comply with the drinking water limit of 11.3 mg/L for nitrate adopted in 1984. Peters & Boukes (1987) constructed a mathematical model to predict future nitrate trends. According to their model nitrate concentrations in the study area will only level off 25 years after the introduction of control

measures. This serves to illustrate the long term effects of nitrate pollution and the slow progress through the unsaturated zone.

As indicated by Van Beek (1985), the nitrate concentration in shallow groundwater in the Netherlands was increasing. As a result, the nitrate concentration in groundwater abstracted for public water supply was also increasing. In contrast, the guideline concentration of nitrate in drinking water in the Netherlands was lowered to 5.6 mg/L as N. The approach followed in the Netherlands is the establishment of protection zones around well fields (Van Beek, 1985).

6.2 Vulnerability mapping

Research Product 1:
Map(s) and database of sensitive, vulnerable and polluted areas

Target Groups:

Planners
Directorate Water Services Planning, DWAF
Water supply engineers and consultants

Aims:

Avoidance of areas with unacceptably high levels of these pollutants (either due to natural accumulation or pollution), for the siting of rural water-supply boreholes; identification of boreholes at risk.

Furthermore, the database can serve as basis for epidemiological studies on the effects of nitrate consumption by entire communities, and for (in-situ) denitrification studies.

Progress:

Limited progress was made with regard to the compilation of preliminary maps, but considerable work would be needed regarding the delineation of sensitive and vulnerable areas. There is a lack of consistent data sets for determining nitrate concentration trends. The degree to which the present National Groundwater Monitoring Programme fulfils this need will have to be established. In this regard the planned evaluation of the existing information collected in the National Groundwater Monitoring Programme may eventually help to fill this gap. This will ensure that eventually, after another decade or more, reliable information will be available for evaluating nitrate trends in groundwater. Once the trend data become available, the strategy can be adapted or refined to take the new information into account.

Managing the nitrate inputs to groundwater will entail identification and management of the nitrogen sources to the environment. The strategy will have to take into account priorities in terms of the aquifer classification based on aquifer type and importance, e.g. “sole source” aquifers (Parsons, 1995). The aquifer classification will, therefore, form a “base map” with various overlays dealing with the nitrate accumulation factors.

The potential nitrogen sources are discussed below (see Paragraph 6.5), but to a large extent the vulnerability of the aquifer will depend on the pollution type and source. The aquifer will be more easily affected by a pollutant from an intensive point source than from a diffuse source. On the other hand the total load derived from the diffuse source may be

significantly larger over the long term. This will require the development of a temporal and areal loading term which can modify the vulnerability.

The identification of vulnerable areas will have to be done by means of a nitrate pollution index, in some respects similar to the DRASTIC index (Aller *et al*., 1987). This may be especially useful for screening larger areas. The DRASTIC index considers the following factors:

- **D**epth to groundwater
- **R**echarge due to rainfall
- **A**quifer media
- **S**oil media
- **T**opography
- **I**mpact of the vadose zone
- **C**onductivity, i.e. hydraulic conductivity

Reynders & Lynch (1993) in several papers (Lynch *et al*., 1994 & 1997) applied the DRASTIC method to South African aquifers and produced a vulnerability map for the country. This was done by overlaying maps based on the components of the DRASTIC index. The hydraulic conductivity was, however, ignored as at that stage it was not deemed possible to obtain acceptable values for the hydraulic conductivity of the fractured aquifers in South Africa.

The first attempt at overlaying the existing groundwater nitrate data on the DRASTIC component maps, did not yield the desired result and an adaptation of the factors was considered essential. Using the DRASTIC index in its present form for determining the vulnerability of aquifers to nitrate pollution or accumulation will not work, as factors that may be of major importance, e.g. vegetation type and cover are not included. However, a revised index could be developed, once the nitrate accumulation factors are better understood. Furthermore, the soil organic nitrogen pool and the associated microorganisms play a crucial role both in intercepting and releasing nitrogen in its various forms. It is essential to take note of the bacterial processes each subject to its own set of environmental conditions. Whereas nitritifier bacteria facilitate most of the conversions, nitrite is converted to nitrate by nitratifier bacteria (see Figure 8, from Alleman & Preston, 2001).

Adapting the DRASTIC index for describing the vulnerability of aquifers to nitrate pollution will require that the important characteristics of the soil which play a role in the nitrogen cycle be taken into account. This could mean that the soil component may consist of a number of factors. The nitrogen cycle implies a vegetation input and, therefore, the vegetation type and cover are also needed for completing the picture. The nitrogen cycle is shown in Figure 9 (Hiscock, Lloyd & Lerner, 1991).

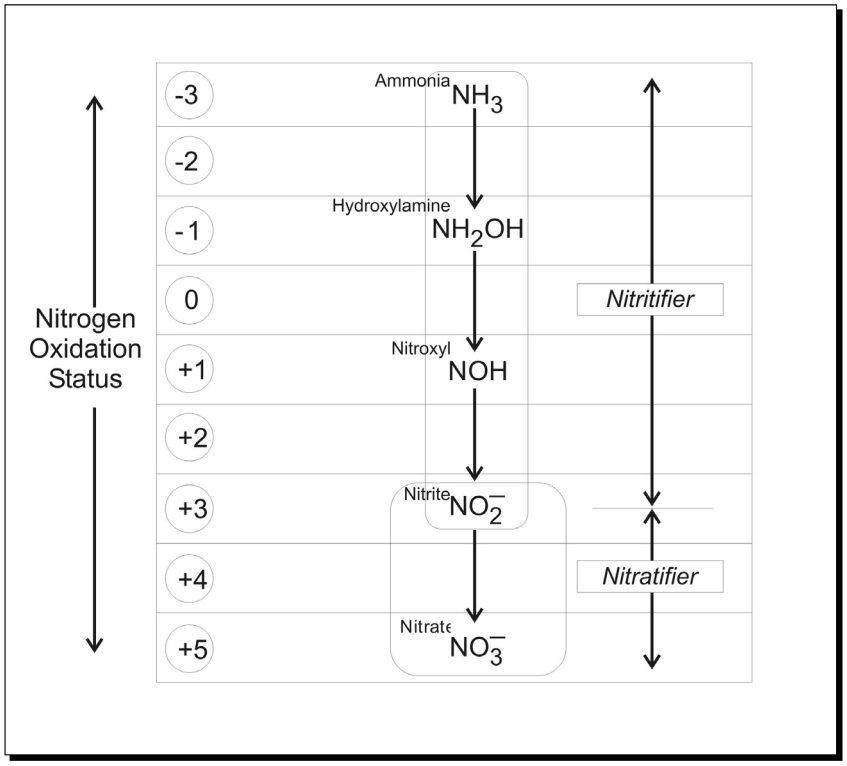


Figure 8: Bacterial conversions of the nitrogen compounds to different oxidation states *(Alleman & Preston, 2001)*

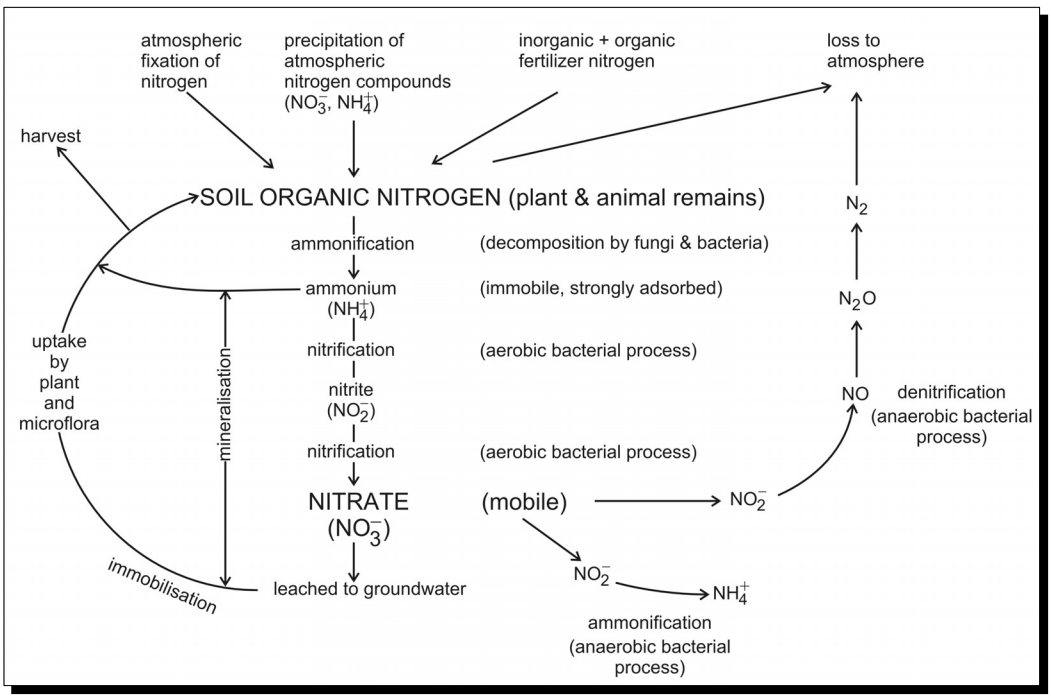


Figure 9: Nitrogen cycle in the soil zone *(Hiscock, Lloyd & Lerner, 1991)*

The soil characteristics of importance in determining the vulnerability of the aquifer listed below are adapted from Canter (1996):

- Soil texture is measured by the percentage of sand-, silt-, and clay sized articles present in representative soil samples. Clay is effective in removing pollutants because its pores are small and its particles have a high capacity for adsorption and ion exchange.

- Soil permeability is the measure of the rate at which water moves through soil. Large pores decrease the chance for pollutant attenuation, while smaller pores increase the potential for pollutant attenuation.

- Soil thickness is an important factor because the effectiveness of the soil in attenuating pollutants depends on the amount of contact time that transported pollutants has to with the mineral and organic constituents of the soil layers.

- Organic matter content of soil is an important factor because it increases the ability of soil to hold nutrients, water, and to adsorb organic materials. It is a valuable energy source for soil micro organisms that play an important part in the nitrogen conversions.

- The pH level of a soil is an important factor because the breakdown processes function better at a pH between 6 and 7.

- Sorption refers to the physical (absorption) or chemical (adsorption) attraction of individual molecules by soil particles. The rate of sorption will really depend on the contaminant and the properties of the soil material. It will also vary with the pH and the oxidation potential.

- Cation exchange capacity refers to the chemical exchange capability of soil. Clay and humus colloids, present in both weathering rocks and soils, contain negative electric charges at their particle surfaces; these charges are neutralised by electrostatically adsorbed cations, which are subject to relatively rapid exchange reactions with other salts (or pollutants) that may percolate through the soil or weathering rocks.

- The acid neutralisation capacity of soil or rock material is defined as the sum of cations minus the sum of strong acid anions, expressed as their potential to consume or produce protons above pH 3.

Some of these characteristics will be more important for the nitrogen cycle than others, and those should be awarded greater weight. It may also be difficult to determine all these characteristics for all soils, but it has to be attempted.

Ramolino (1988) developed a nitrate pollution index based on four factors for assessing the potential risk of groundwater contamination from nitrate applied as fertilizers in agricultural areas. He considered a set of 22 case studies for identifying the four factors. The four factors which he considered most important are:

- Nitrogen fertilization
- Net recharge (due to rainfall and irrigation)
- Soil texture
- Depth to water table

Such an index may for instance work in the irrigation areas, e.g. along the Crocodile River, where nitrate pollution is found in the groundwater from irrigation percolate. According to the literature and information from scientists abroad, agriculture is the main source of nitrate pollution, with on-site sanitation also playing an important role, mostly in rural settings.

For the semiarid and arid regions of Southern Africa the index will have to be adapted to provide for the phenomenon of natural accumulation of nitrate in groundwater. As with the DRASTIC factors a "vegetation factor" will have to be incorporated to provide for the role of vegetation in the nitrate accumulation.

The indications are that agriculture and fertilization may not be the main nitrogen source in the Southern African situation. On-site sanitation is an important pollution point source with respect to rural communities, but it is also very controllable. The strategy may also promote the use of urine and faeces separating latrines in view of their favourable nitrogen budget (e.g. Lagerstedt *et al*., 1994; Jacks *et al*., 1999). Such latrines have been tested by the University of the Western Cape at Vioolsdrif. Also, Mvula Trust is testing such units in the rural areas of the Eastern Cape in collaboration with Boutek of the CSIR.

The use of large trees to intercept nutrients, e.g. nitrate, should also be investigated as part of this strategy. In that respect ^{15}N isotope determinations of the vegetation could play an important role.

6.3 Priority protection areas

Priority protection areas need to be identified as not all aquifers can or have to be protected.

The selection of such areas will be based on:

a) The aquifer classification with the highest priority to the most valuable aquifers, e.g. "sole source" aquifers
b) Future (water resource) development areas
c) Vulnerable areas
   hydrogeologically, e.g. dolomites, etc
   land-use practices

6.4 On-site sanitation and groundwater protection policies

Based on the field studies, the evaluation of the local nitrogen inputs, reports from other areas, and experiences in other countries, "inappropriate" on-site sanitation is considered as the main factor in anthropogenic nitrate pollution in the Southern African rural community context. Sanitation points are often in (too) close proximity to the local water supply or the sanitation systems do not match the hydrogeological requirements for groundwater protection. Therefore, this practice needs special consideration. It should be noted that the impacts vary from place to place and from point to point and it will be virtually impossible to have a general policy in this regard. However, guidelines can be developed which will take care of the need to provide acceptable quality sanitation to all.

The subject of on-site sanitation and the associated risk of groundwater contamination has been widely debated. The fact that pollutants from on-site sanitation often reach the groundwater is not disputed in the literature. Stable isotope studies of oxygen and nitrogen have proven the existence of pollution plumes associated with septic tanks (Aravena, *et al*., 1993). The only question is what the extent of the pollution and the associated health risk would be. Fourie and Van Ryneveld (1995) carried out a review on the fate of contaminants associated with on-site sanitation. They concluded that contamination from on-site sanitation

is not a single entity, but has a number of components, which may be divided into two broad categories:

- microbiological contaminants: viruses, bacteria, protozoa and helminths and
- chemical contaminants: nitrogen and phosphorus, in the form of nitrate and phosphate respectively.

No reference is made to the presence of ammonia or an increase in salinity in the subsurface. The final conclusion is that the topic of greatest uncertainty was the pollution risk posed by elevated nitrate levels which could reach several hundred mg per litre of nitrate-nitrogen. No conclusion could be made as to the effectiveness of denitrification processes, particularly whether or not they occur to a significant degree in the unsaturated zone. Jackson (1998) questions the risks involved in groundwater pollution from on-site sanitation systems such as pit latrines and concludes that these may be exaggerated.

Groundwater protection policy: In view of the serious groundwater nitrate problems experienced in other countries timely control measures for reducing the nitrogen input are imperative. Already in 1991 DWAF published a document on water quality management policies and strategies listing nitrate as a groundwater quality problem to be addressed (DWAF, 1991).

The recent *Policy and Strategy for Groundwater Quality Management in South Africa* (DWAF, 2000) sets out the activities which, directly or indirectly, threaten groundwater resources and which the Department of Water Affairs and Forestry will seek to control by implementing “Source Directed Controls”. Diffuse sources of pollution, associated with urban and rural development, are listed among the “targeted activities” and are recognised to pose an ever- increasing threat to groundwater. Sanitation practices are highlighted as potential diffuse sources of pollution. Pit latrines, septic tanks and soakaways and leaking and overflowing sewers can pose a significant threat to groundwater supplies, particularly in areas with rapidly increasing density of residential development.

DWAF intends to control these sources by “raising awareness and encouraging better and improved practices”. The Department will promote the development and implementation of cleaner sanitation practices and discourage the use of pit latrines, septic tanks and soakaways in urban, peri-urban and high density rural settlement situations. DWAF also assumes responsibility for facilitating processes for the development of Best Practice guidelines which will serve to protect groundwater resources. The development of guidelines for sanitation for semi-rural and urban settlements, and remediation of contamination from leaking underground storage tanks have been singled out as priorities for groundwater protection (DWAF, 2000).

In view of protecting groundwater from potential impacts from sanitation systems, DWAF’s Directorate of Geohydrology and National Sanitation Co-ordination Office have produced a risk assessment protocol to guide practitioners involved in the installation or upgrading of sanitation systems (DWAF, 1997). This *Protocol to manage the potential of groundwater contamination from on-site sanitation* is based on the evaluation of existing groundwater resources and the risk of contamination of resources and suggests measures to reduce the contamination risk. Guiding principles are also given with respect to the level of investigation required, some minimum requirements and common sense rules relating to borehole positions and distances relative to sanitation systems (DWAF, 1997).

DWAF’s approach to pollution impacts from on-site sanitation is essentially to act in a persuasive or advisory capacity, but that the controls on users will be essentially self-

regulatory. The current priority is on service provision and, although risk-based approaches are recommended as a possible measure to counteract potential long-term impacts, there appears to be a general reluctance to introduce or enforce legal instruments that might hinder the delivery of sanitation services.

Management of non-point sources: A Water Quality Management discussion paper (DWAF, 1999) has been published to provide a framework for the implementation of source directed measures for managing non-point sources of water pollution under the National Water Act. The critical water quality concerns from non-point sources in this document mostly focus on streams and surface impoundments. In rough order of priority, these concerns are:

- *pathogens* in streams from under-serviced settlements and urban areas;
- *metals and toxins*, including pesticides;
- *salinisation* from irrigation;
- *eutrophication* from high nutrient loads in impoundments and
- *sedimentation* of rivers and impoundments, related to soil erosion.

Groundwater contamination and nitrates are not mentioned specifically on the priority list.

Since non-point sources are generally related to land-use practices, land-use management will be a central issue in controlling this type of pollution. DWAF's framework policy identifies commercial agriculture as a sector which contributes to non-point source pollution of water resources, but stresses that this sector is largely the mandate of the Department of Agriculture and care should be taken not to exceed the mandate for water management when developing controls. In irrigated areas, DWAF will have authority in controlling water abstraction and may use this as a means of driving non-point source management. Subsistence farming and livestock in traditional rural settlements will apparently be exempt from non-point source controls developed for the agricultural sector, while management requirements for emerging farmers will also be waived in the short term, in line with the need to redress past discrimination. Management of fertilizer application and irrigation scheduling are two proposed activities which may have an impact on nitrate pollution of groundwater, but it is not yet clear what these measures will entail.

Confined animal facilities (feedlots, piggeries, dairies, chicken houses) are mentioned as a source of contamination from agriculture with a high priority for statutory non-point source control. The management of their impacts is, however, not addressed in any further detail in the framework document (DWAF, 1999). There may also be some debate over the classification of feedlots as a "non-point source". Mass commercial production of livestock is a scheduled activity under Section 21 of the Environmental Conservation Act (Regulation 1182, Government Gazette, 5 September 1997) and an environmental impact assessment is required for any new facility, which may provide an opportunity to implement nitrate pollution control measures.

Human settlements cause severe non-point source related water quality problems throughout the country. DWAF's framework document for non-point source management (DWAF, 1999) gives lower priority to traditional rural and residential small-holding settlements than other settlement types, including tourism resorts and recreational facilities. Local authorities have the mandate from managing municipal services and stormwater systems. DWAF may see it as appropriate, in cases where there are severe direct impacts on a water resource, to use statutory measures to control a particular element or activity, e.g. the sanitation or stormwater system.

The waste disposal sector is also addressed in DWAF's non-point source management strategy, although waste disposal activities would generally be considered as point sources of pollution. All waste disposal practices including collection, transport, handling and disposal

of waste, head the priority list of activities requiring short-term statutory authorisation (DWAF, 1999). Best management guidelines for this sector are available in the form of the Minimum Requirements (DWAF, 1998) and permitting of waste disposal sites is required in terms of Section 20 of the Environmental Conservation Act (Act 73 of 1989). Other types of waste disposal facilities, including sludge disposal from wastewater and water treatment plants and liquid effluent irrigation schemes, have not received as much attention as formal landfill sites, although efforts are being made to improve controls on these activities. Effluent irrigation and infiltration are regulated as controlled activities under Section 37 of the National Water Act (Act 36 of 1998) and General Authorisations (Regulation 1191, Government Gazette, 8 October 1999), while new sewage treatment plants require an environmental impact assessment under the Environmental Conservation Act (Act 73 of 1989). The minimum requirements for water monitoring at waste management facilities (DWAF, 1998) include sewage (sludge and unlined maturation ponds); wastewater irrigation; agriculture (feedlots and diffuse sources) and septic tanks and pit latrines as "waste environments", although these are only monitoring guidelines and not legally enforceable control measures.

Several guiding principles were recommended for adoption for non-point source control, based on the new legislation and past experience of water quality management in South Africa. Among these, those which may be relevant to the management of sanitation impacts are highlighted here. Non-point source management should:

- ❑ recognise the requirements of the Water Resources Classification system, which sets the levels of modification that would be considered acceptable.
- ❑ make provision for special cases where the Resource Quality Objectives are exceeded.
- ❑ recognise the distinctive technological and economic characteristics of different source types.
- ❑ include the pollution management hierarchy.
- ❑ balance development and protection.
- ❑ promote sustainability.
- ❑ promote self-regulation.

Economic instruments may be applied to change polluter behaviour or influence the adoption of voluntary or statutory management practices, such as applying differential rates for waste discharges. The National Water Act allows for penalties (including fines) to be prescribed for offences in terms of the regulation of water use, but these may be difficult to apply to non-point sources of pollution, where responsible individuals are difficult to identify. Catchment management agencies may also recover costs for clean-up where a directive has not been complied with, but this may also be problematic for non-point source pollution. The application of economic incentives is restricted by the fact that charges should only reflect the administrative costs and management benefits associated with the management practice, but cannot be of such a nature as to constitute a tax, levy or duty (Section 57(5)).

Environmental impacts of sanitation systems: Several reviews of the impact of on-site sanitation have been written (e.g. PDG, 1995; Fourie and van Ryneveld, 1994; Jackson, 1998), mostly from literature sources but few field studies have been conducted. Several reports cite the work of Lewis *et al*. (1980) in Botswana as the most significant contribution from Southern Africa.

All types of sanitation bring a degree of environmental impact. It is well-documented that on-site sanitation systems can have an impact on groundwater quality (Fourie and van Ryneveld, 1994; Wright, 1999; ARGOSS, 2001). With sewered systems, the impact is typically, but not exclusively, on surface water bodies, although some on-site systems can cause surface water pollution if sited on steep slopes (PDG, 1995). In terms of groundwater pollution, the two main issues are *microbiological* and *chemical* contamination, especially

nitrate and, to a lesser extent, *chloride*. In general, the risk of groundwater contamination from nitrate is considered high, whereas that from bacteria and viruses is low for a properly designed and constructed pit latrine (Wright, 1999). Poorly designed or operated on-site sanitation systems, especially those that use large volumes of water, can pose a greater threat to groundwater resources than areas with no sanitation systems or unimproved pit latrines. In some cases, potential nitrate pollution of groundwater has been (inappropriately) cited as a reason for installing more expensive water- borne sewerage schemes where “dry” on-site sanitation might have been more appropriate (Muller, 1989).

Palmer Development Group conducted a review of rural sanitation in South Africa (PDG, 1995). In the review, the following conclusions were drawn about the risk of groundwater pollution from on-site sanitation:

- The factor of primary importance is the extent to which groundwater is used. If water is brought in from outside the immediate vicinity of the settlement, groundwater contamination is seldom an issue.
- Pathogenic contamination is generally limited to the immediate vicinity of the pit or soakaway, while nitrates may travel fairly long distances and accumulate indefinitely.
- It is difficult to establish a general safe minimum lateral spacing between water supply and an on-site sanitation unit, because of the complexity of factors that control groundwater flow, e.g. permeability and hydraulic gradients. As a general principle, as much separation as possible should be maintained.
- The severity of the impact depends on the density of pits and soakaways and the extent of abstraction from boreholes and wells.
- The unsaturated zone is the most important line of defence against groundwater pollution. The risk of faecally contaminated groundwater is minimal if there is a continuous layer of relatively fine grained (<1 mm), unsaturated soil of more than 2 metres thick beneath the base of the latrine and the loading does not exceed 50 mm/day.
- Well sources can be protected by extending the casing of tube wells far below the water table.

Hydrogeological factors are of critical importance. Areas with a seasonally high water table or areas that are prone to flooding are most at risk of contamination from pit latrines. On-site sanitation systems are not expected to pose a significant pollution hazard in confined aquifer situations, provided that the disposal pit is not excavated through the confining layer, and provided that boreholes are conducted to a satisfactory standard so that they do not act as conduits of pollution to the confined aquifer (Xu and Braune, 1995).

There is some controversy over the severity of groundwater contamination impacts and it has been argued that the concerns about this risk may have been overstated and should not be used as an excuse to abandon on-site sanitation programmes (Foster, 1985; Jackson, 1997). There must be a trade-off between the positive benefits of public health arising from improved sanitation and the possible negative environmental impacts on the environment, and in particular groundwater quality (DWAF, 1997). Also, the nitrate threat should be considered together with the threat posed by microorganisms (including bacteria, viruses and parasites). The risk of methaemoglobinaemia increases significantly if the ingested water is microbiologically contaminated.

In conclusion it can be stated that much has been written (and rewritten), but little has been measured.

Nitrate pollution of groundwater: Nitrate pollution of groundwater is a major problem of on-site sanitation systems. The use of on-site sanitation systems will, almost inevitably, lead to increased concentrations of nitrate in underlying unconfined aquifers, except where the groundwater system is naturally anaerobic (Lewis *et al*., 1981). Nitrates may accumulate slowly in groundwater over several years.

Each person excretes in the region of 4 to 5 kg of nitrogen per year in the form of ammonium and complex organic compounds. Under aerobic conditions it can be expected that a significant percentage of this nitrogen will be rapidly oxidised to form nitrate (Lewis *et al*., 1981; ARGOSS, 2001).

The fate of nitrogen introduced into a pit latrine can be divided into Jacks *et al*. (1999):

- ammonia volatilisation
- denitrification
- residual nitrogen and
- deep leaching of nitrate.

Nitrate is a highly soluble and mobile anion. In a study of groundwater pollution impacts by nitrogen from pit latrines in two villages in Botswana, it was found that nitrogen losses by volatilisation of ammonia were negligible, while leaching of nitrate varied widely from about 1% to 50%. Denitrification accounted for 30 to 70% of the original nitrogen input, while 15 to 20% remained in the residues (Jacks *et al*., 1999).

Several factors may control the severity of nitrate contamination of groundwater from on-site sanitation, including:

- population density and dietary patterns, which determines the initial nitrogen loading
- availability of oxygen, which promotes oxidation of ammonium and organic nitrogen to nitrate
- physico-chemical conditions which enhance or inhibit microbial activity responsible for denitrification e.g. pH, temperature, salinity, moisture content
- physico-chemical conditions which enhance or inhibit volatilisation of ammonia e.g. pH and temperature
- dilution by local groundwater recharge and regional aquifer throughflow.

Case studies of nitrate pollution impacts on groundwater and potential mitigation measures in developing countries:

The United Nations Environment Programme supports an urban groundwater quality monitoring programme in six major African cities. The results have shown that groundwater contamination levels are rising rapidly and that urgent measures are needed to prevent groundwater supplies becoming unusable. Nitrate pollution was found to be a problem in all cases where nitrate concentrations were monitored and early warning bulletins have been posted (UNEP, 2001).

Dakar, Senegal: The quality of groundwater, used for urban supply has deteriorated since 1989, especially in the upstream suburban area where there is no proper sewerage system. Nitrate concentrations have risen and concentrations from 100 to 500 mg/L NO_3- have been reported for some boreholes in the city in mid-2001. Nitrate contamination appears to be spreading from the peri-urban areas.

Niamey, Niger: Chemical and bacteriological analysis of groundwater has shown that all aquifers (basement, continental, terminal and alluvial aquifers) below the city are

contaminated. Pollution increases are related to unplanned dumping sites, sewage disposal and urban runoff. Large volumes of drinking water are drawn from wells and boreholes in the suburban areas. Nitrate concentrations over 100 mg/L were found for 3 boreholes and over 200 mg/L for another 2 boreholes of the 10 boreholes reported.

Abidjan, Cote D'Ivoire: Boreholes used for water supply have shown an increase in salinity, ammonium and nitrate levels. Nitrate concentrations have increased steadily since 1999, exceeding the drinking water standard of 50 mg/L as NO_3- and concentrations >100 mg/L have been recorded. The pollution appears to be spreading northwards towards the recharge area. Progressive groundwater pollution is attributed to percolation of highly polluted surface water due to lack of an adequate sanitation system and an increase in waste production.

Ouagadougou, Burkina Faso: Groundwater in shallow wells have been found to have fluctuating levels of nitrate, sometimes exceeding the WHO 50 mg/L as NO_3^- limit, particularly in late summer. Deeper boreholes are less contaminated. The main sources of pollution are agricultural chemicals and fertilizers from the market gardens, wastewater runoff and industrial effluent.

Mukono District, Uganda: The predominantly rural (>90%) population of Uganda relies almost exclusively on groundwater for a potable water supply. Groundwater development has targeted two main aquifers in deeper fractured basement rocks and a shallow alluvial aquifer. The latter has been found to be more productive and more economical to exploit and intense shallow well development has taken place in the alluvial aquifer. Monitoring of water quality in the shallow wells of south-eastern Uganda has shown, however, that these often show levels of coliform bacteria and nitrate exceeding WHO guideline levels within months of installation. The source of the contamination was found to be human and livestock waste excreted in pit latrines, over land or in open-pit wells ("scoop wells"). Taylor and Howard (1995) have used a groundwater flow model to delineate wellhead protection areas (WHPAs), which are based on the same concept as a minimum separation distance (Xu and Braune, 1995), to protect shallow wells in Uganda. Although this should afford adequate protection against bacterial pollution, the authors do not give much attention to the fate of the nitrates, other than to acknowledge that it tends to behave conservatively, even though susceptible to denitrification processes. A protection zone or minimum distance can delay the time taken for nitrate contamination to reach a water supply well or borehole, but cannot prevent the pollution from eventually occurring.

Mochudi and Ramotswa, Botswana: Jacks *et al*. (1999) produced a tentative nitrogen budget for pit latrines in Eastern Botswana and discovered that up to 50% of the nitrogen input could be leached as nitrate with varying fractions from 30 to 70% being lost by denitrification before infiltration. To avoid excessive nitrate leaching, the authors suggested:

- promoting losses of ammonia, by increasing ventilation rates (e.g. by painting ventilation tubes black) or increasing the pH by addition of slaked lime.
- preventing leaching, by sealing the bottom and walls of the pit.
- separating urine for infiltration into nearby surface soils planted with fruit trees or other deep-rooted crops.

Yogyakarta, Indonesia: Nitrate concentrations in over 100 wells in the Kotagede subdistrict of the city of Yogyakarta, Java, Indonesia frequently exceed 50 mg/L NO_3-. Smith *et al*. (1999) found that the major source of the nitrate in groundwater is sewage tanks. Toilets in the village are attached to settling pits which act as a primitive septic tank system. The nitrate input is highly dependent on rainfall, resulting in a surge of nitrate into the groundwater at the start of each wet season. In the wet season, 65% of the samples exceeded 50 mg/L NO_3- and 13% were higher than 100 mg/L NO_3-, while only 50% of the samples were >50 mg/L

NO_3- in the dry season. Vegetation, particularly bamboo, may be a mitigating factor in nitrate contamination of groundwater in this case study. The authors recommend careful siting of toilet facilities and septic tanks in relation to water wells in villages.

Mitigation measures: DWAF's protocol to manage potential groundwater contamination from on-site sanitation proposes the following guiding principles to reduce contamination risks.

- ❑ A hydrocensus should be undertaken of all water resources within a 2 km radius of the area being developed. (The size of the area may be increased or decreased, as long as a representative number of boreholes are assessed.
- ❑ The community should be involved in the hydrocensus and made aware of health impacts related to contamination of groundwater resources used for water supply purposes.
- ❑ No on-site sanitation system should be installed within 50 m of a water supply source (spring or borehole).
- ❑ No high loading sanitation system (e.g. schools or clinics) should be installed within 75 m of a groundwater supply source.
- ❑ All boreholes should be completed with a sanitary seal and appropriate wellhead construction aimed at preventing surface water from entering the borehole.
- ❑ No activity should be allowed within 30 m of a borehole, other than those associated with collecting groundwater.
- ❑ If appropriate and practical, new boreholes should be sited outside of villages and upgradient of potential sources of contamination.
- ❑ All failed or abandoned boreholes should be backfilled and sealed.
- ❑ All groundwater supply systems must have regular monitoring of water quality.

Minimum distances: The recommended minimum distances are conservative values that should protect groundwater from microbiological contamination in all hydrogeological settings. More detailed guidance on minimum distances is given by Xu and Braune (1995) for a range of unconfined aquifer types in South Africa. The concept of minimum distances is related to travel times which should allow the decay of organic contaminants and die-off of bacteria and viruses. Minimum separation distances should also attenuate conservative inorganic contaminants, such as nitrate, but cannot prevent their long-term encroachment. To protect against non-degradable species such as nitrate and chloride, a minimum separation distance would theoretically require a protected zone equivalent to the catchment area of the borehole concerned, which is seldom practical. Siting new boreholes some distance upstream of potential contaminant sources can address the nitrate problem to a large extent.

A minimum distance of 50 m separation between water supply points and sanitation is only practically feasible in low density settlements (substantially less than 100 people/ha) and for various social reasons, as well as user convenience, a minimum practicable separation will often be desired (Lewis *et al*., 1981).

Adapted sanitation technologies: About 95% of the nitrogen in human excreta is present in the urine, providing a possibility of mitigating nitrate impacts by using urine separating latrines, with near-surface percolation of the urine in the root zone of the vegetation or utilisation for crop growth. Since such latrines are used elsewhere in the world (e.g. Kerala, India), the problem with their introduction in Southern Africa is not technical, but one of social acceptability (Jacks *et al*., 1999). Urine diversion toilets are also not suitable for all hydrogeological environments. Small-scale local trials in coastal sands near Sodwana Bay found that nitrate was still problematic with the ions dispersing in all directions (L.M. Austin, Boutek, CSIR, *pers. comm.*, 2002).

6.5 Developing a South African nitrogen management strategy

Research Product 2:

Strategy for preventing, or at least decreasing, the accumulation of nitrate and associated pollutants, which is due to anthropogenic activities

Target Groups:

Planners;
Directorate Water Services Planning, DWAF
Groundwater Consultants

Aims:

Protection, relocation and redesign of production well fields;
redesigning boreholes to avoid nitrate- (and associated pollutant) bearing geological strata; proper siting of on-site sanitation systems.

Workshops will be designed to convey the information gained from the project and the strategy for preventing anthropogenic nitrate accumulation to the staff of the target groups

Progress:

For developing the nitrogen management strategy, a proper understanding is required of nitrogen sources and nitrate generation processes. ***Nitrogen sources*** in the environment include the following:

Anthropogenic related sources

- ❑ land application or disposal of waste materials
  - leachate from sanitary or industrial landfills
  - animal manures which may be concentrated in large commercial poultry, dairy, piggery, and cattle feed lots
  - land application of municipal or industrial sludge or liquid effluent, e.g. parks, golf courses, etc
  - disposal of household waste or commercial waste to land
  - on site sanitation, e.g. pit latrines, septic tanks, etc
  - cemeteries

- ❑ irrigated agriculture
  - enhanced leaching of nitrogen from excessive fertiliser application rates and inefficient irrigation rates
  - associated leaching of nitrogen from soils periodically subjected to leaching to remove salts so that the soils do not become saline and unproductive

- ❑ dryland agriculture
  - excessive fertiliser application
  - inefficient uptake of nitrogen by crops
  - mineralisation of soil nitrogen by tilling of the soil
  - nitrogen losses to the subsurface environment can occur as a function of fertiliser application rates, seasonal rainfall and temperature patterns, and tillage practices

- Acid rain

Natural sources

- natural biological nitrogen fixation, followed by mineralisation of the natural soil organic nitrogen
  - a full understanding is required as natural soil organic nitrogen is maintained by nitrogen fixation in the root zone
  - soil and subsurface permeability requirements
  - the significance of the C:N ratio in soils needs to be fully understood
  - climatic controls, semi-arid and arid vs. humid
  - vegetation types
  - the effect of climatic changes, particularly variations in precipitation, needs to be understood, recorded and a early warning system developed

- geological nitrogen which can be mobilised and leached to groundwater
  - reduced nitrogen species in the rock matrix can be oxidised and mobilised due to aeration caused by longer term changes in groundwater levels

- lightning discharge nitrogen inputs (area dependent)

The above list gives an indication of the diverse types of point and diffuse sources that will have to be managed in terms of any strategy to reduce the nitrogen input to the environment and specifically to groundwater.

Most of the control of the nitrogen input into the environment in developed countries is aimed at the farming fraternity. The reason is that farming practises are the main source of nitrogen leaching into the groundwater. An option for developing a local southern African strategy for managing and reducing the nitrate input to groundwater is to make use of the principles of the overseas strategies and to adapt it to our own circumstances.

On the other hand, most cases of methaemoglobinaemia in the United States of America have been linked to pollution from on-site sanitation. Also in Eastern Europe in countries such as Hungary and Romania, and in Africa, e.g. Botswana and Mozambique, inappropriate on-site sanitation has been shown to pose a threat to groundwater.

Dealing with the problem regarding groundwater containing an elevated nitrate concentration needs both an immediate and a longer term approach. This approach is set out in Diagrams 1 to 4 below. The problem of high nitrate drinking water needs to be assessed and addressed immediately, while in parallel, the causes of the high nitrate need to be identified and eliminated, by a medium term or a longer term strategy. Pamphlets for public distribution will need to be used in conjunction with the groundwater nitrate reduction strategy for dissemination of sufficient information in support of the required actions.

Although extensive scientific evidence is lacking for South Africa, the indications are that agricultural activities and the tilling of the soil constitute the most widespread diffuse source of nitrate pollution as it was identified in other parts of the world. In South Africa, this does not provide a high level of input but ensures a persistent nitrate presence in agricultural areas on which other contributions are superimposed. The highly variable rainfall worsens the situation in the case of fertilized dry land farming due to the associated unpredictable plant cover and fertilizer needs. Nitrogen isotope studies have provided proof that cultivation

of the soil leads to mineralization of soil organic nitrogen followed by leaching and accumulation in the groundwater even without any artificial nitrogen inputs. The situation in the Springbok Flats is ascribed to this phenomenon.

Point sources: Implementation of control measures to prevent pollution from point sources is feasible as such sources are easily identifiable and their effects measurable. For example, the water pollution threat posed by sanitary landfilling was recognised and a system of licensing of such sites introduced. Siting requires inter alia a full geohydrological investigation. Should the site comply with all requirements pollution free landfilling could be possible. Monitoring of groundwater quality remains essential for verification.

Diffuse sources: Pollution from such sources is particularly problematic as it can affect an entire aquifer and can go unnoticed for decades, but once the effects appear, it may be necessary to abandon the aquifer (DWAF, 1991). A number of countries have proposed control measures for reducing nitrogen input to groundwater. As agricultural practices are considered to be the most important contributor most control measures pertain to agricultural activities. In Czechoslovakia a system of protection zones around boreholes was introduced, limiting both agricultural activities and application rates for fertilizer, manure and wastes (Vrba *et al*., 1985). A similar system was proposed for the Netherlands (Van Beek, 1985). In the United States nitrate leaching under irrigation was identified as a serious problem. Ritter (1989) stated that both water management and nitrogen management are important in controlling nitrate leaching. Nitrate leaching can be reduced by applying only enough fertilizer to meet yield goals, timing of application and the use of slow release fertilizers.

Power & Schepers (1989) came to the conclusion that there are several courses of action for short-term solutions to problems of groundwater nitrates. As agriculture is widely recognised as one of the largest contributors, their short-term measures all include improved soil and crop management practices. However, they add that there are often additional costs from adoption of some of these practices. For this reason, financial incentives need to be provided to achieve the short-term goals. Best management practices listed by Power & Schepers (1989) include:

- irrigation scheduling
- fertilization based on calibrated soil tests
- conservation tillage
- acceptable cropping practices
- recommended manuring rates.

Agricultural engineers who play a major role as advisors to farmers and in planning farm layout and management, has a responsibility to alert farmers to the implications of their actions and management practices. They can play a large role in changing practices that increase nitrate pollution of groundwater in the interest of both the individual farmer and the groundwater user in general.

Control measures for reducing nitrogenous inputs to the environment are essential for protecting the groundwater resources. In view of the considerable delay (varying from years to decades) between the introduction of control measures and any decrease in groundwater nitrate levels it is a matter of extreme urgency to take action in this regard. Overseas experience provides valuable guidelines for developing workable local measures. This relates largely to fertilizer usage, manure and sludge application to land, feedlot operations, septic tank and pit latrine density, as well as control of other pollution sources. It has been proven that stable nitrogen isotope analysis can be used successfully to identify pollution sources. This technique can be used to confirm the effectiveness of any control measures adopted.

In view of the fact that the groundwater in many countries are already contaminated and that control measures will take many years (if not decades) to reduce these nitrate levels denitrification of drinking water is widely practised. In South Africa denitrification for potable use and/or stockwatering will be needed in areas where no alternative supplies are available.

Information programme: Even though groundwater in South Africa is no longer "private water", it is virtually impossible to introduce the extensive control measures needed for groundwater protection in the rural context, except where recognised point pollution sources are identified. Despite suggested control measures pollution from diffuse sources in South Africa remains practically uncontrolled. Such sources largely refer to agricultural activities and uncontrolled rural settlements. Protection of the groundwater resources is specifically of benefit to the local user but also to the country as a whole. Therefore, an information campaign bringing the detrimental effect and the hazards of nitrate pollution to the attention of farmers, owners of small-holdings and the public at large is essential for safeguarding the sparse groundwater resources. Such a campaign should complement any control measures introduced. Pollution prevention is the desired option providing the ultimate longer term cost-effective solution. The retrospective costly approach of drinking water treatment must be avoided as the whole water supply needs treatment to protect infants.

The preliminary strategy is set out in the following diagrams (see Diagram 1 to 4). The first step, i.e. the situation assessment, is set out in Diagram 1.

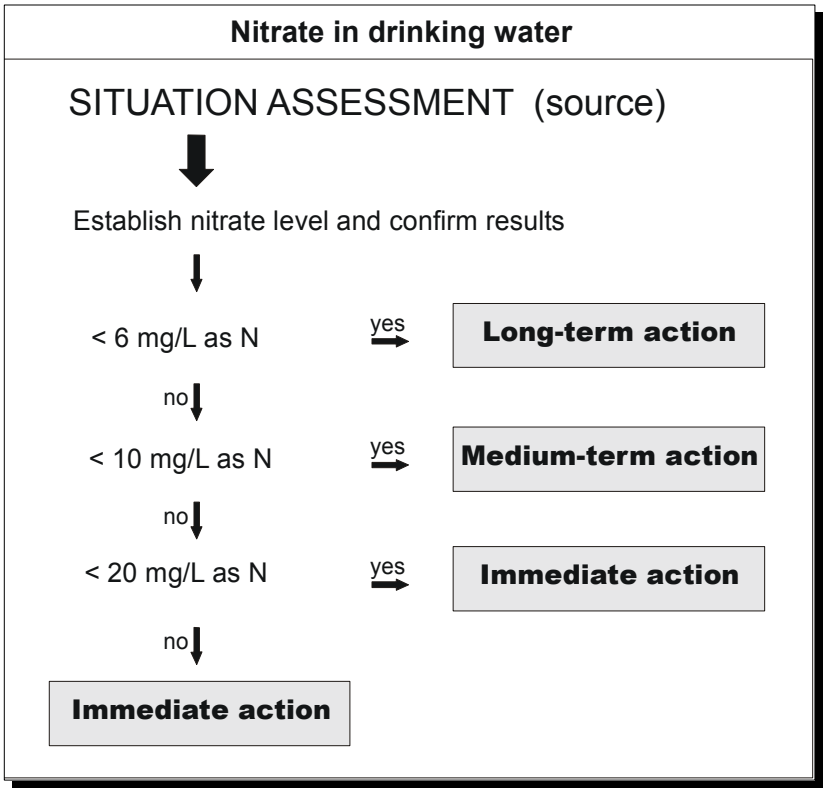


Diagram 1: Groundwater nitrate strategy: situation assessment

Based on the outcome of the assessment, immediate action, medium term action or longer term measures are needed to ensure the sustainability of the water supply. In all cases where the nitrate concentration in a drinking water supply exceeds 10 mg/L, immediate action is required. Such action would entail that the microbiological quality of the water be determined. If the nitrate exceeds 20 mg/L or if it is microbiological unfit, an alternative water resource must be found for members of the community that would be at risk (see Diagram 2).

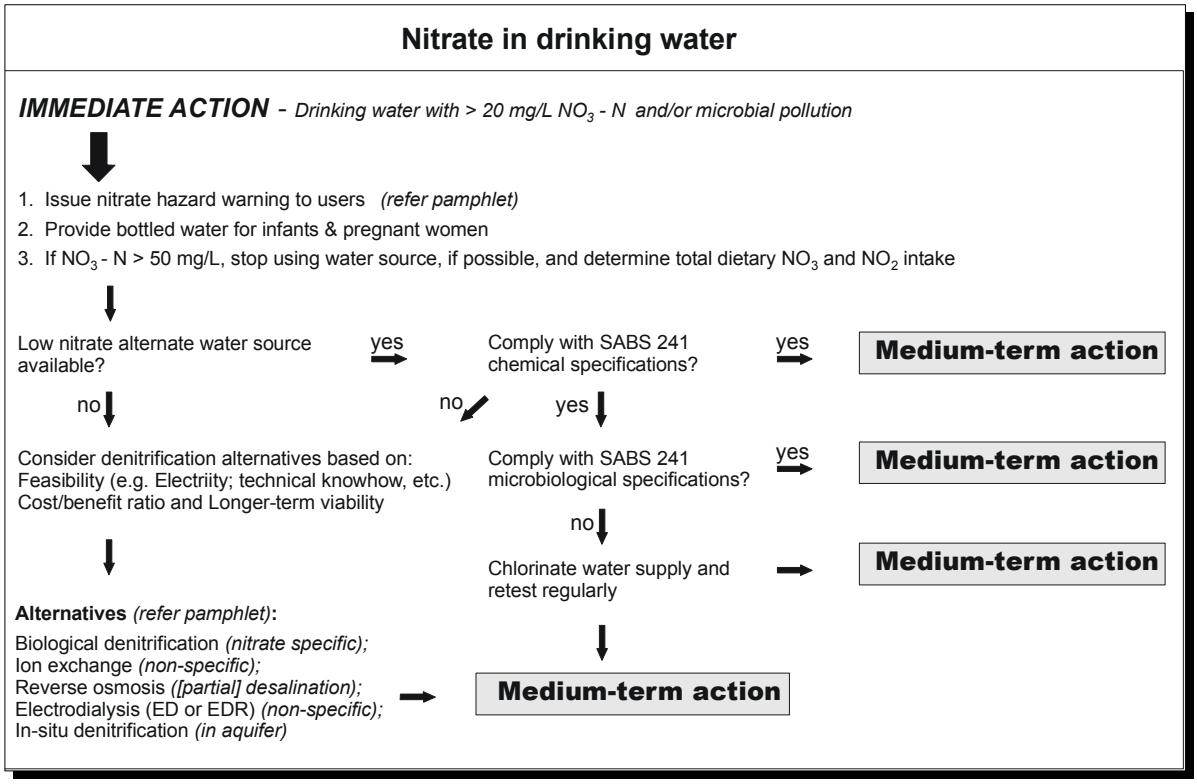


Diagram 2: Groundwater nitrate strategy: Immediate action situation

Once the immediate actions have been carried out, further steps may be needed, mostly in the medium-term. These are described in Diagram 3.

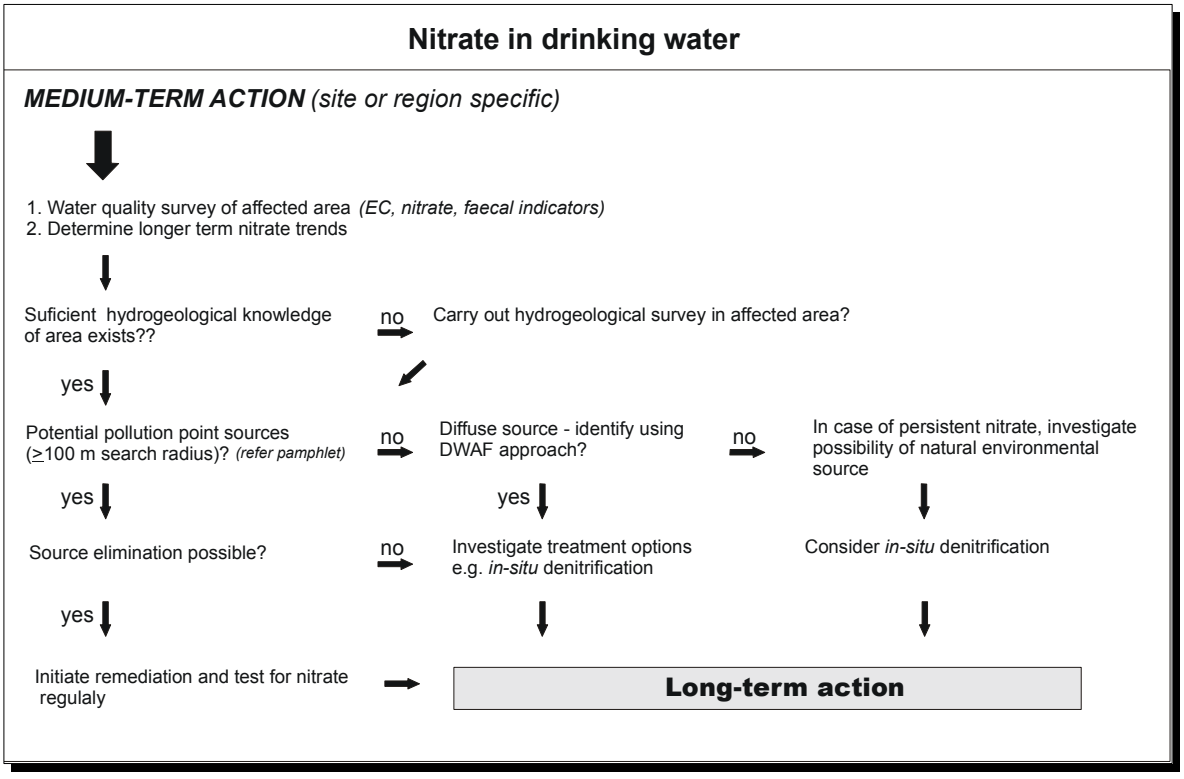


Diagram 3: Groundwater nitrate strategy: Medium-term requirements

In certain aquifers the nitrate concentration of groundwater varies considerably. In extreme cases, particularly after heavy rainfall events, the nitrate can suddenly reach such high levels that the groundwater becomes poisonous for cattle. This has been recorded in the USA, Namibia, Botswana and South Africa. Determining the longer term trends is an essential part of the strategy and forms part of the longer term actions described in Diagram 4.

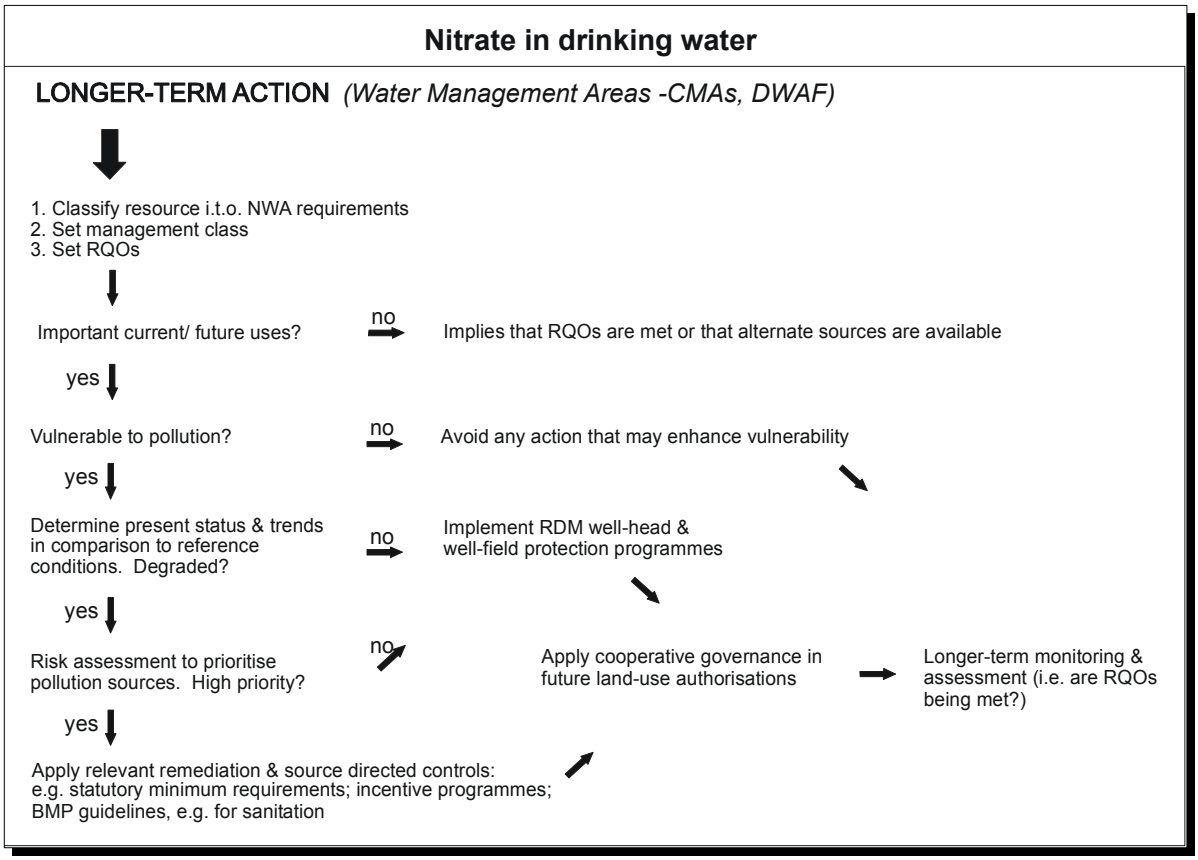


Diagram 4: Groundwater nitrate strategy: Longer-term protection measures

6.6 Public awareness campaign

Informing the public and particularly the farming community as well as farming related industries of the hazards of nitrate pollution is considered an important tool for voluntary reduction of nitrogenous inputs, both with respect to diffuse sources as well as the myriad of small point sources.

The compilation of guides, such as the one jointly published by the Water Research Commission and the Department of Agriculture for the handling of manure from animal feeding units (Funke *et al*., 1984) is considered to play a crucial role in environmental (and groundwater) protection. A similar guide, specifically for groundwater nitrate, is needed for the effective protection of groundwater resources.

Research Product 3:

Brochures for increasing public awareness of potential health risks and preventative strategies

Target Groups:

Chief Directorate Infrastructure Services and Macro Planning, DWAF
Chief Directorate Sanitation and Water Quality Management
NGOs
Rural Communities

Aims:

Based on the outcome of the research a brochure or pamphlet will be compiled indicating the health risks and ways and means to avoid them. It will also include information on the strategy to prevent the accumulation of nitrate. The brochures will be provided to WSP, NGOs and others to be used for increasing public awareness of the problem and for education.

The brochures (or pamphlets) will contain a brief description of the effects and symptoms of methaemoglobinaemia and nitrate poisoning of livestock. It will deal with the possible causes and the ways and means to overcome these, both with respect to water treatment and long- term sustainable solutions for eliminating the identified causes. It will also give references to DWAF's Directorate of Infrastructure Services and Macro Planning offices, NGOs and other consultants that can provide the necessary help.

7 CONCLUSIONS

7.1 Nitrate Sources

Nitrate in groundwater is derived from a wide range of sources that are generally well known although not all pollution pathways are necessarily fully understood. The sources can be grouped into two main categories:

- anthropogenic nitrogenous pollution, and
- natural nitrate accumulation, primarily in arid and semiarid regions.

In the highly-developed countries, the main anthropogenic source is agricultural nitrate, largely derived from excessive fertilizer and manure applications. Such sources are, however, controllable and particularly in Europe strict measures are in place for limiting the nitrogen fertilizer and manure application rates. The timing of such applications is also strictly controlled.

In South Africa the available data show that agricultural fertilizer application generally does not lead to any significant nitrate concentration in the groundwater. Such application may form a widespread diffuse source but it is of lesser importance. The low background concentration of nitrate found in groundwater in cultivated areas is largely derived from the soil organic nitrogen pool due to mineralization through tilling of the soil. This nitrogen source was confirmed by ^{15}N isotope analyses. The phenomenon of mobilization of soil organic nitrogen is clearly demonstrated in areas with highly productive soils, such as the black cotton soils overlying the basalts, e.g. in the Springbok Flats where groundwater nitrate levels are generally high although no fertilizers have been applied.

Point sources are generally associated with pollution activities, e.g. sewage sludge drying beds, land application of sludge, and irrigation of (partly) treated wastewater. At the large cities, high levels of sewage sludge application to land have caused serious groundwater pollution. In the rural areas and on farms local pollution can be caused by the high concentration of livestock near boreholes and by inappropriate on-site sanitation.

7.2 On-site sanitation

This nitrate source is discussed separately because the research results from South Africa, other southern African countries, and most developing nations show that on-site sanitation is the major source of groundwater nitrate in groundwater, apart from the naturally occurring groundwater nitrate in developing countries. In neighbouring Botswana, this rising trend was already recorded more than two decades ago and proposals were made for groundwater protection near villages. However, the abandoning of well fields, mainly because of nitrate pollution, is continuing and it is also occurring in South Africa. For large parts of southern Africa on-site sanitation remains the only viable option. Not all such practices lead to groundwater pollution, but where inappropriate hydrogeological and environmental conditions exist, the effects on groundwater can be disastrous. On-site sanitation is generally a cost-effective approach and any nitrogen management strategy has to contend with realistic on-site sanitation options. However, it also means that on-site sanitation needs to be planned with the particular hydrogeological scenario in mind. There is no general rule that can be applied everywhere. It is necessary to have a pragmatic approach in this regard, but where sensitive and sole source aquifer systems are at risk, alternative sanitation options have to be found. It should be noted that the occurrences of methaemoglobinaemia (also in developed countries such as the USA and Europe) were practically always associated with private drinking water wells that were polluted by on-site sanitation, e.g. french drains associated with septic tanks. Water supply and sanitation planning must be coordinated as many rural communities and towns are fully dependent on groundwater as sole source.

Nitrate pollution of groundwater from sanitation systems has tended to be overlooked or downplayed in many of the policies and strategies relating both to water supply and sanitation and to water quality management in South Africa. The reasons for this are varied, ranging from a historical focus on surface water in South Africa (where nitrate is rather an aesthetical and environmental problem than a potability concern) to the drive to supply sanitation services as fast as possible to fulfil the obligations in terms of the sanitation policy and to reach all members of the previously disadvantaged sectors of the population.

Doubts have been expressed about the true severity of the nitrate impacts from this source, but little data have been collected to disprove the extent of the impacts. In the short term, health impacts from pathogens are a far more pressing issue and most recommended mitigation measures revolve around providing sufficient separation between sanitation systems and water supply points to ensure that bacterial contamination cannot migrate to the point of groundwater abstraction. Little consideration appears to have been given to the long-term sustainability of this approach, which may delay the impacts, but ultimately will not prevent nitrate contamination of the water supply. An additional factor is the increase in the number of informal settlements at existing towns and elsewhere that could increase the groundwater pollution risk.

Directed research is needed into the impact of this source. Such research should take into account and confirm or modify the impact “models” that have been developed elsewhere also for local use. These models take into account the type, density and loading of systems, the thickness of the unsaturated zone, the nature of the soil and geological strata. Field measurements and / or tests should be carried out to provide actual data on the various parameters in different field conditions. Once such a “impact assessment model” has been developed for local use, it will assist to identify those situations where on-site sanitation is the correct solution and will also confirm the appropriate type of system.

Mitigation of impacts by appropriate measures, e.g. *in situ* denitrification provides alternatives where on-site sanitation was not the ideal but the only practical solution.

For any rural water supply project using groundwater in an area where on-site sanitation is practised groundwater quality monitoring at strategically selected points is essential.

7.3 Management strategy

Resource directed measures and user protection

A management strategy has been developed consisting of a situation assessment, immediate actions, medium and longer-term actions. The management and reduction of groundwater nitrate levels depend on an understanding of the nitrogen sources and the pollution and nitrification mechanisms. This also implies that the groundwater protection strategy has to rely on legislation for pollution control and proper infrastructure planning for reducing nitrogenous inputs to the environment.

With regard to natural nitrate accumulation, management options are limited and consist essentially of developing alternate low nitrate sources or implementing denitrification options.

Public awareness campaign and information dissemination

A public awareness and education programme forms an essential part of the groundwater protection strategy. This is a key component that will ensure the success of the legislative and pollution control approach for reducing nitrogenous inputs to the environment. The fact is that not all polluting activities in remote areas can be controlled by the authorities. For this reason, the public, including the farming community and other rural communities have to be

convinced to voluntarily take all necessary steps that will ensure a reduction in environmental nitrogen inputs, and particularly nitrate leaching to groundwater.

The distribution of flyers/brochures should be complemented with talks, lectures, workshops and other means of creating public awareness.

7.4 Health risks

Nitrate in groundwater involves various risks for human consumption. Mortalities as a result of methaemoglobinaemia is a reality. New information became available on earlier cases of methaemoglobinaemia, while spontaneous abortion may constitute a further risk related to nitrate in water. Microbiological pollution seems to aggravate the situation, increasing the risk of methaemoglobinaemia at lower nitrate concentrations and should be avoided.

The risks associated with nitrate ingestion have to be evaluated in terms of the total dietary intake of nitrate and nitrite. The intake of nitrate, and particularly nitrite from cured meat, has to be taken into account in this calculation.

At higher nitrate concentrations livestock is also at risk and nitrate poisoning of livestock has been recorded in southern Africa and elsewhere.

7.5 Naturally occurring nitrate

In the semiarid to arid parts of the Southern African subcontinent, and elsewhere in the world, there are large tracts of land extending over hundreds of kilometres, where groundwater has high nitrate concentrations. Not all of these are considered to be related to pollution, but rather to natural accumulation of nitrate in the groundwater. A full understanding of this process is required for designing a complete groundwater protection strategy. It is hoped that research projects undertaken in parallel (and also in Botswana and Namibia) will provide the necessary understanding of these accumulation processes.

7.6 Groundwater nitrate trends

In most countries around the world, nitrate occurs in groundwater and the latest information confirms that the concentrations as a result of pollution are still increasing in many countries. Reliable information on groundwater nitrate concentration trends is essential for developing and evaluating a successful nitrogen management strategy. This is a key issue that requires a long-term monitoring programme focussed on yielding reliable analytical information that is largely unavailable for South Africa. The national groundwater monitoring programme will need to be designed to provide reliable groundwater nitrate results for a countrywide nitrate database. Nitrate is generally an unstable constituent that may need to be preserved between sampling and analysis when the samples have to be stored for any length of time.

8 RECOMMENDATIONS

8.1 Protection strategy implementation

It is recommended that the preliminary groundwater protection strategy be implemented as soon as possible. Early implementation of the protection strategy is deemed essential as in the case of groundwater nitrate pollution, the alternative result is longer-term degeneration of groundwater quality. Implementation should commence in known problem areas.

8.2 Water quality monitoring

The monitoring of nitrate level trends in groundwater at strategic points, such as rural water supply schemes, is a key part of the groundwater protection strategy. It is essential for obtaining reliable information on short-, medium- and longer-term groundwater nitrate trends. This has to take place in parallel to the implementation of the protection strategy for evaluating progress and determining the need for further measures. At the same time the final drinking water should be diligently monitored for microbiological purity.

8.3 Risk assessment

A reassessment of risks should take place using an epidemiological risk assessment in areas affected by elevated nitrate concentrations in the drinking water supply. This should take into account the total nitrate and nitrite intake from food and water. The microbiological quality of the drinking water is a key factor and has to be taken into account in such a study.

8.4 Strategy revision

Evaluation of the success of the groundwater protection strategy, followed by revision and improvement of the policies and strategies, is required. This should be carried out in selected rural areas and using the information gained from the water quality monitoring programme.

8.5 Research needs

Based on the outcome of the initial protection strategy implementation, detailed research may be needed, particularly for understanding the pollution processes and the role of the unsaturated zone in groundwater protection. Monitoring of on-site sanitation processes should take place in all rural water supply projects using groundwater.

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APPENDIX A

Notes of discussion of research projects on nitrate in southern African groundwater: Gideon Tredoux and Peter Dillon

Appendix A

Notes of discussion of research projects on nitrate in southern African groundwater
Gideon Tredoux and Peter Dillon
CSIR Environmentek, Stellenbosch, 23 Nov 2000

The discussion firstly related to the WRC project K5/1058 entitled: "Nitrate and associated groundwater hazard quantification and strategies for protecting rural water supplies", and secondly to the successful proposal submitted by Gideon to the Department of Arts, Culture, Science and Technology Regional SADC S&T entitled "Developing control measures for the increasing nitrate hazard in groundwater in rural areas in Botswana, Namibia and South Africa".

In view of the limitations of the WRC project budget, it would seem to be very fortunate that DACST awarded the regional project at this stage, as it provides an opportunity for in-depth field studies using regional resources to the benefit of South Africa and the region as a whole. The notes below, therefore, refer to the WRC project, but also to the DACST project as they are considered to complement each other very well, and the literature and recommended approaches will benefit both of these.

The following thoughts are not necessarily new but aim to document the issues that may need to be addressed in the research projects.

Heterogeneity of: soils, N concentrations in soils, vegetation (N sources and sinks), and human and animal sources of waste are at scales that can be much smaller than the spatial scale at which wells are available to sample nitrate in groundwater. Therefore it may not ever be possible to deconvolve the relative importance of all these sources for any well or for any large collection of wells. All previous studies I have seen where the potential sources were identified for individual wells, could only account for at most about one third of the variance in nitrate concentrations in groundwater.

Similarly heterogeneity of subsurface sources of N , presence of calcretes, faults, attenuating factors such as sources of organic carbon, also suggest that it may not be possible to discriminate between sources on a broad scale, or to model and predict N concentrations in groundwater even at a local scale. However that is not to say that an attempt to understand these processes would be fruitless.

The approach suggested in the proposal is based on a full appreciation of these factors, and can have some valuable end points:

- a capacity to alert communities if their N is at concs that require eg bottled water for infants
- where high N concs are derived from wastes, a clearer view of the effects on groundwater may provide a driver for improved management of wastes and better protection of the groundwater resource
- where the N is considered to be derived from land management, tillage, irrigation, fertilisation, then process descriptions will be valuable for improved retention of N in soils and reduced leakage of N to aquifers
- where the N is derived from natural sources unaffected by land management, eg native legumes (such as acacias), termites, and shales, then techniques such as in situ denitrification which may be more easily controlled/managed than treatment plants on the surface, may be an appropriate solution.

The supporting data required, as well as the management responses, will depend on the source of nitrate, if known (see table).;

Sources of N	*Management response*	*Measurements required*
geological	in-situ denitrification	NH_4, NO_3, and N-15 on organic shales and clays
natural soil N - eg fixation by native legumes.	in-situ denitrification	N fixing species, amounts fixed, N15
mobilisation and/or additional mineralisation of N as a result of land use change, fertilisers, etc	improve land management practices	N in soils at start of recharge season. For N applications, priming effect on nitrification of soil organic N (develop model to show effects)
organic wastes - human, animal and vegetable	improve waste management practices	quantify sources and mineralisation rates if diffuse sources, generally will be point sources
unknown / combinations	better ability to discriminate and choose options In all cases bottled water for infant feeding if NO_3 high.	recognising confoundedness, make best guesses as to sources and potential solutions.

Peter promised to seek out and provide the following information to Gideon:

1. N study component of Glenn Harrington's PhD thesis (NO_3 and N-15, and any interpretation of sources of N)

2. Matthew Duthy paper on simulating denitrification

3. Pakrou and Dillon (2000) paper on type and depth of lysimeters for monitoring nitrate leaching

4. Pakrou and Dillon (2000) paper on key processes of N cycle in grazed leguminous pastures

5. Chris Barber paper or report on weights of evidence modelling (as alternative to DRASTIC for determining vulnerability classes) was about 1993/4?

6. Information on recently revised Australian drinking water quality guidelines (or web reference) showing NO_3-N limit had increased from 10 to 20 mg/L (and if possible references to justification).

7. Dillon *et al* (2000) Mingbool report giving recommendations for effluent irrigation management practices to reduce nitrate leaching to groundwater.

Also Peter to suggest to Graham Allison that he considers inviting Gideon to attend the workshop on making nitrate prognoses for Australian groundwater.

nitrate-Gideon-Tredoux23Nov00
P Dillon, 20 Dec 2000

APPENDIX B

World Health Organization: Water-related diseases: Methaemoglobinaemia



Water-related diseases

Methaemoglobinaemia

Methaemoglobinaemia caused by the decreased ability of blood to carry vital oxygen around the body. One of the most common causes is nitrate in drinking water. It is most important in bottle fed infants and water from wells in rural areas is of special concern. Controlling nitrate levels in drinking water sources to below around 50mg/litre is an effective preventive measure.

The disease and how it affects people

Methaemoglobinaemia is characterized by reduced ability of the blood to carry oxygen because of reduced levels of normal haemoglobin. It is uncommon. Infants are most often affected, and may seem healthy, but show signs of blueness around the mouth, hands, and feet, hence the common name “blue baby syndrome”. These children may also have trouble breathing as well as vomiting and diarrhoea. In extreme cases, there is marked lethargy, an increase in the production of saliva, loss of consciousness and seizures. Some cases may be fatal.

In the body nitrates are converted to nitrites. The nitrites react with haemoglobin in the red blood cells to form methaemoglobin, affecting the blood's ability to carry enough oxygen to the cells of the body. Bottle-fed infants less than three months of age are particularly at risk. The haemoglobin of infants is more susceptible and the condition is made worse by gastrointestinal infection. Older people may also be at risk because of decreased gastric acid secretion.

Malnutrition and infection seem to increase the risk of methaemoglobinaemia (McDonald and Kay, 1988). The general health of the infant as well as Vitamin C intake may determine whether or not the condition develops (Super et al, 1981).

Others at risk for developing methaemoglobinaemia include: adults with a hereditary predisposition, people with peptic ulcers or chronic gastritis, as well as dialysis patients.

The cause

The most common cause of methaemoglobinaemia is high levels of nitrates in drinking-water. High nitrate levels may be present in drinking-water due to the use of manure and fertilizers on agricultural land. The natural level of nitrites and nitrates from the environment is normally a few milligrams per litre, although high levels may occur naturally in some areas. Intense farming practice may increase this to more than 50 mg/litre (WHO 1998). Levels greater than 50 mg/litre, are known to have been associated with methaemoglobinaemia in bottle fed infants. Nitrate is also found in vegetables. Methaemoglobinaemia can also be a

side effect of some drugs (phenacetin and sulphonamides), although this is very rare with modern drugs.

Scope of the Problem

Methaemoglobinaemia is now rare in most of the industrialised countries due to control of nitrate contamination in water supplies, although occasional cases continue to be reported from rural areas. It is a risk in developing countries, for example where the drinking water is from shallow wells in farming areas.

There is no reliable estimate of the extent of the problem worldwide. WHO is presently collecting information in order to make such an estimate.

Interventions

Control of nitrate in drinking water is an effective preventive measure. WHO's Guideline Value for nitrate in drinking water is 50 mg /litre and for nitrite is 3 mg/litre. This is relatively readily achieved in centralised, piped, supplies, but is difficult in rural and small supplies.

The group at greatest risk is bottle fed infants. Breastfeeding protects babies from methaemoglobinaemia. Boiling water does not remove nitrate.

For severely affected individuals, medical treatment is possible.

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Prepared for World Water Day 2001. Reviewed by staff and experts from the Programme for Promotion of Chemical Safety (PCS), and the Water, Sanitation and Health unit (WSH), World Health Organization (WHO), Geneva.

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url1: http://www.who.int/water_sanitation_health/diseases/methaemoglob/en/

use: The 2-page fact sheet on Methaemoglobinaemia is intended for inclusion in a report to the RSA Water Research Commission (WRC) on a research project: "*Nitrate and associated hazard quantification and strategies for protecting rural water supplies" (WRC project K5/1058) as a WHO statement on the disease. The 2-page statement will be included as such with full acknowledgement to the WHO.

APPENDIX C:

Groundwater nitrate distribution map superimposed on the hydrogeological terrains map