THE ASSESSMENT OF AMBIENT GROUNDWATER QUALITY

AT A NATIONAL SCALE IN THE REPUBLIC OF SOUTH AFRICA

Final report to the Water Research Commission

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EXECUTIVE SUMMARY

I INTRODUCTION

The Department of Water Affairs & Forestry have for many years been gathering groundwater quality data from around the country as part of ad-hoc groundwater resource investigations. However, little examination of the data has taken place, except for that depicted on the recently published Map of Groundwater Resources of South Africa (Vegter, 1995). The data gathering has intensified over the past few years as a result of the regional groundwater mapping programme and the establishment of a national groundwater quality monitoring network.

Additional value has to be added to data stored in databases. The differentiation between man-made and natural impacts on groundwater quality will in future have to be clarified. The benefitiation of the data and its presentation in the form of a groundwater quality atlas may affect various sectors thus enabling them to efficiently plan their activities as well as address important issues from a national health and environmental point of view. Water quality information is essential in the planning and management of groundwater resources – the results of this project will consequently provide valuable data for the Department of Water Affairs & Forestry's community water supply initiative.

II AIM AND OBJECTIVES

The purpose of this project was to provide intitial steps towards the national groundwater quality assessment and to update the knowledge on groundwater quality nationwide.

The research objectives for the project were defined as follows:

1. Re-evaluate the existing groundwater quality database both in terms of the availability of data and its structure

2. Outline a framework for an evaluation system to identify hydrochemical properties of groundwater resources at a national scale
3. Map and define spatial features of major hydrochemical parameters
4. Define the temporal component of groundwater chemistry
5. Identify main factors and issues that affect or indicate groundwater conditions and trends
6. Identify gaps in data collection and evaluation activities and provide recommendations to overcome these deficiencies

The main thrust of this project was to create the atlas of groundwater quality, not least as an extension of the first national hydrogeological undertaking – the map of groundwater resources (Vegter & others, 1995). By generating the atlas of groundwater quality, the visual information is created that is not apparent otherwise. The interpretation of the extracted information and seeking potential correlation with environmental and cultural factors would be the next natural step in expanding the national groundwater quality assessment project.

III APPROACH

The water quality database of the Department of Water Affairs & Forestry, QualDB, as the wealthiest source of the groundwater-quality data was utilized in this project. It contains over 55000 groundwater analyses (as of 1997), which are attributable to approximately 35000 boreholes. The distribution of points is very uneven reflecting different and isolated objectives of data-collection programmes. The analyses are comprised of major ions and a limited positional and sampling procedure data. Trace elements and organic data are rare and do not warrant an evaluation at a national scale.

The positional accuracy is uncertain although sample coordinates are mandatory. At a national scale however, the sample position accuracy is regarded as acceptable having in mind that broad regional trends are evaluated.

The probabilistic approach to the groundwater-quality assessment was chosen. This was done to overcome ambiguities from uneven data distribution and from inability to determine and separate the temporal components. A discretization approach was employed whereby the country was subdivided into units being a subpopulation of the lithological units. These units were identical to those utilized for the national hydrogeological map (Vegter, 1995). The data geographically attributed to a unit were aggregated using their log-transformed values and calculating basic statistical parameters. Each area unit was assigned a unique set of statistical values per each evaluated hydrochemical parameter. The units with similar statistical parameters were grouped using a classification scheme based on drinking water guidelines and mapped at the national scale using thematic mapping features of the Mapinfo GIS.

The probabilistic approach was given preference to contouring approaches derived from e.g. kriging, because the available dataset does not effectively allow for their nationwide application.

IV RESULTS

A set of maps at scale 1:10,000,000 was compiled using Access97 generated statistical summaries and Mapinfo GIS. All major water quality variables were mapped nationwide and are available on the CDROM attached to the report. The maps are in Adobe PDF format, which is widely used, cross-platform, with freely available viewer. The statistical summaries and maps are also available as Excel97 tables and Mapinfo formatted layers.

Although small-scale variations may be of importance for a local development of groundwater resources, the emphasis was placed on mapping broad, large-scale trends in groundwater quality.

IV.1 DATA QUALITY

Sets of maps were developed to depict the data itself, major groundwater quality parameters, a number of index parameters and derived maps. It is important to understand the quality of evaluated dataset and therefore the following maps were produced:

- Distribution of sampled sites countrywide
- Sampled site count per region
- Sample density expressed as km^2 per sample
- Sample cover for different time periods (pre-1970, 1970-1980, 1980-1990, 1990-1997)
- Sample ion balance error in three classes: more than 5%, more than 10% and more than 30%.

IV.2 MAJOR GROUNDWATER QUALITY PARAMETERS

The groundwater quality maps depict all major groundwater quality parameters as well as several derived and index parameters. All major ions were mapped nationwide.

These include calcium, magnesium, sodium, potassium, alkalinity, sulphate, chloride, nitrate nitrogen and fluoride. In addition, silica was also mapped.

IV.3 INDEX PARAMETERS

In addition to major ions other derived and index parameters include the following:

- Carbon dioxide activity expressed as log pCO_2 – to give an impression on how the carbonic acid may contribute to solute-forming processes in South African aquifers
- Chloro-alkaline distribution index (CAD) – to illustrate the dynamics of ion-exchange processes
- Saturation indices (calcite, dolomite, quartz)
- Total dissolved solids (TDS), TDS/EC correlation, TDS outliers (upper)

IV.4 HYDROCHEMICAL CLASSIFICATION

Piper diagram was considered as a classification system due to its wide use within the groundwater community. Four classes forming quadrangles of the Piper diagram were mapped as follows:

- (Ca, Mg) (HCO_3)
- (Na, K) (HCO_3)
- (Ca, Mg) (SO_4, Cl)
- (Na, K) (SO_4, Cl)

The presence of individual types was mapped as a fraction of total samples, worked out in per cent. The information can thus determine what is the probability of obtaining a hydrochemical type of concern for any region.

IV.5 DRINKING QUALITY PROSPECTS

A set of maps was generated to show compliance of groundwater for drinking water purpose. The classification was based on major ions, other parameters such as minor elements or bacteriological quality was not taken into account.

- Total hardness – to summarize the technological parameters of groundwater in various areas of the Republic
- Drinking water compliance – based on concentration of major ions
- Drinking water prospects – the probability of striking water of either drinking or acceptable water quality
- National monitoring results – selected representative results to illustrate the performance of national monitoring so far

IV.6 CAUTIONARY NOTES FOR DATA INTERPRETATION

Unstable parameters such as pH were mapped using the analytic value determined in the lab. This may differ from the in-situ conditions and therefore the results should be taken with caution. The same applies to alkalinity as it is the parameter closely associated with pH.

Several other ions may be affected by the standing time between sampling and the analysis. Large number of analyses have had their standing times in excess of three months. The redox sensitive parameters such as nitrate and sulphate may undergo significant changes during standing times, quite often mediated by bacterial activity.

No consideration was given to vertical variation of groundwater within the borehole – the available dataset does not really allow for such an examination. At a site-specific scale it may be of importance to examine vertical variations of groundwater quality when installing a groundwater abstraction system.

The data records do not reflect a snapshot of a single representative period. All available data had to be used in order to obtain acceptable coverage of the studied area. The temporal changes in groundwater quality could thus not be screened out in any acceptable way and units are compared using data records from different time periods. Most records fall into the 1970-1997 period, though. To visualize the spatial distribution of time intervals used for characterization of groundwater-quality trends a map was compiled. The map shows proportion of data records for the period 1990-1997 out of the total record count.

IV.7 TEMPORAL CONSIDERATIONS

Due to lack of historic long-term monitoring attempts very little exists to define and separate temporal components from spatial variations. An example from Springbok Flats is used to demonstrate the temporal variations in groundwater quality due to natural causes such as recharge. National groundwater-quality monitoring initiative is discussed and broadly evaluated as a means to obtain the information necessary to extract the temporal components nationwide.

The preliminary results were obtained from the national groundwater-quality monitoring, but the relatively short lifespan of national monitoring prevents from making authoritative statements as yet. Recommendations were made to adjust the network design to reflect manpower and budgetary constraints.

The factors contributing to groundwater quality are evaluated only from a broad angle. Much more work will be required to exactly identify and quantify impact of main factors. For example, rainfall seems to be a main controlling factor often overriding lithological controls. Another example, closely associated with the rainfall distribution is the availability of carbon dioxide, which is the main agent in hydrochemical dissolution of aquifer materials. The attribution of factors to groundwater chemistry should be the main thrust of the interpretive reporting that should follow this report.

Two fundamental activities have been discussed in this regard – the on-going data-collection as a product of the regional characterization and national groundwater-quality monitoring. While the former will in time fill in the gaps in the spatial distribution, the latter aims to cover the temporal dimension.

Other parameters have to be included into routine analyses such as more routine field measurements and redox indicators such as iron and manganese. Little is known about trace elements and organics, this should warrant focused initiatives to obtain the information on ambient levels of trace elements.

The more structured approach to bridging the gap in data-collection and evaluation activities is discussed in the section on reporting formats.

V RECOMMENDATIONS

The wealth of information transformed in the visual format will undoubtedly trigger other research initiatives. As this phase can be characterized as largely descriptive, the emphasis should be placed on the interpretation of the results achieved in this report.

For the first time the distribution of a number of hydrochemical parameters is presented nationwide. It will be necessary to try and distinguish the reasons for the spatial and temporal distribution of a number of parameters and try to use this knowledge in managing the water resources.

It will also be necessary to strengthen the link between two groundwater-data databases, the NGDB and QualDB. There is also a need for including other parameters into routine sampling such as iron and manganese. The field measurements of unstable parameters such as pH and alkalinity must be made more routinely and stored on the database.

The assessment of groundwater quality should be seen in broader hydrological perspective and the interaction between different parts of the hydrological cycle can be used to benefit of all hydrological agents and impactors.

The natural next phase will be to try and define or quantify existing causative relationships between groundwater quality and environmental factors. The description of major lithological units together with more detailed analysis of these units is recommended as the next step in the groundwater quality assessment programme.

The national monitoring programme, once fully implemented, will have to evaluated in terms of its representativeness and cost benefit analysis. This can be done by a more rigorous development of the reporting formats that should ideally streamline the flow of the groundwater-quality information. This can be done however only when statistically viable observation dataset is available, so it would be ideal to couple the monitoring analysis with lithological unit analysis.

Due to low pace of the implementation of national monitoring it is recommended that few adjustments be made to the monitoring strategy:

- Adopt a multi-tier strategy. The monitoring network will consist of several subnetworks with different frequencies and variable scopes. There is a potential for a scaled-down reference network, which will be sampled most often. The size of this network should not exceed 100 sites. The full network will be identical with the present design (once fully implemented) and may be sampled less frequently (every 1 or 2 years). Special networks will be designed to study certain groundwater quality phenomena or problem and will be more or less research-related.

- Adopt a cluster strategy. A sampling site may consist of more than one borehole. This is to avoid sampling failures when existing boreholes become unavailable. This however implies that a clear correlation must exist between boreholes forming a cluster.

- Re-evaluate the network design using spatial analysis available in this report. This is important from the representativeness point of view. Before the network was implemented no background information was readily available. The maps and statistical summaries generated by this study may be used to improve the network design and make it more representative.

VI REFERENCES

Vegter JR, 1995: GROUNDWATER RESOURCES OF SOUTH AFRICA. *Two map sheets and explanatory brochure, Water Research Commission project TT74/95, Pretoria*

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THE ASSESSMENT OF AMBIENT GROUNDWATER QUALITY ON THE NATIONAL SCALE IN THE REPUBLIC OF SOUTH AFRICA

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1 INTRODUCTION

1.1 MOTIVATION

The Department of Water Affairs & Forestry recognizes its role as custodian of the nation's water resources. To sustain and improve water quality becomes be the core of the future water management. This is a step forward from the application of an effluent-standard-based approach practiced in the past. Water quality issues have become very important, especially with regards to the availability of water in rural or newly developed areas. The factors responsible for water quality deterioration are not only attributable to direct pollution sources (e.g. inappropriate disposal) – but over-abstraction and droughts often may be to the detriment of water quality.

The indications on changing groundwater quality have been brought about by site-specific studies. This makes up a crucial information need - to establish knowledge on ambient groundwater quality and to distinguish possible variations effected by natural factors from man-induced impacts.

The development of both the national groundwater quality assessment and monitoring programmes on a national scale was identified as an important tool for the responsible and effective formulation and implementation of the groundwater quality management. The periodic groundwater quality assessment and monitoring should be an integral part of the DWAF information system. Ideally, it has to provide both spatial and temporal components of the information requirements for management purposes. The recent achievements in the formulation of groundwater quality policy and strategy confirm the role of the national water quality data collection programmes.

The groundwater quality assessment (including monitoring) is linked to the development of the water quality guidelines and should "*furnish the* *scientific basis for deriving receiving water quality objectives*" (*DWAF, 1993*). The periodic assessment system is one of the tools that offer not only to establish whether those objectives have been met or not. It also provides a feedback mechanism for an improvement of guidelines so that they can optimally reflect South African conditions. Together with guidelines, the knowledge on spatial and temporal trends of groundwater quality nationwide allows for a quantification of the feasibility and success of water management and development decisions.

It is worth mentioning that the world community assistance towards the development of any activity requires as an important pre-requisite a sound regional account of available water resources. This project aims to contribute to understanding of groundwater quality, which may aid in accessing development funds from institutions such as World Bank.

It is important to realize that groundwater quality assessment (and monitoring specifically) presents a long-term goal with benefits more pronounced in the scope of years and decades to come. Therefore, a strong commitment is obligatory to maintain its goals.

1.2 OBJECTIVES

The purpose of this project was to give an account of achievements of the national initiatives regarding groundwater quality assessment and to update the knowledge on groundwater quality nationwide.

The research objectives for the project were defined as follows:

1. Re-evaluate the existing groundwater quality database both in terms of the availability of data and its structure
2. Outline a framework for an evaluation system to identify hydrochemical properties of groundwater resources at a national scale
3. Map and define spatial features of major hydrochemical parameters
4. Define the temporal component of groundwater chemistry

5. Identify main factors and issues that affect or indicate groundwater conditions and trends
6. Identify gaps in data collection and evaluation activities and provide recommendations to overcome these deficiencies

1.3 REPORT STRUCTURE

Formally, the report is organized as follows:

The motivation and research objectives are presented In **Chapter 1** together with the outline of the report. The previous work and historical background is presented in **Chapter 2**, while **Chapter 3** lists selected international experience. **Chapter 4** provides the evaluation of the data used for this project, the potential information users and lists data limitations. The approach adopted in the project is described in **Chapter 5.** The motivation for selected methods, their limitations and advantages are brought in this section. The actual results of the study are listed in **Chapter 6**. The spatial and temporal trends in groundwater quality on a national scale are illustrated in a groundwater quality atlas that is attached to the report on the CDROM. In **Chapter 7** main natural factors affecting groundwater quality countrywide are described. **Chapter 8** discusses the importance of reporting formats of the groundwater quality assessment as a long-term tool to manage groundwater resources in a sound scientific manner. **Chapter 9** evaluates the findings of this research project against the research objectives and summarizes the conclusions of the project and presents recommendations for a further expansion of the assessment project.

The report is complemented by the series of maps depicting groundwater quality parameters at a national scale. These are portrayed in colour in map sheets (A2 size), individual maps (black and white, size A4) and an electronic inventory of data and maps on CD.

2 PREVIOUS ATTEMPTS

Groundwater resources development has been accompanied by numerous local groundwater investigation studies within the Republic. More recently, the Department of Water Affairs & Forestry initiated a structured regional characterization program, which results in the production of geohydrological maps. These maps contain basic hydrochemical indicators.

Based on the approach the previous studies may be subdivided into the following two categories:

- Assessment studies
- Mapping projects

2.1 ASSESSMENT STUDIES

The well-known existing study on groundwater quality on a national scale is the one produced by Bond (1946). This pioneer work was compiled with the use of water for railway purposes in mind. It is based on a very limited number of hydrochemical parameters, which is the reflection of the status of the routine analytical chemistry at the time. The sampling conditions were not published. The work has a very good interpretive angle, its descriptive value is however outdated for today's uses and needs. The author made an attempt to seek the relationship between lithology and groundwater chemistry. Some of his conclusions appear to be no longer valid due to the progress in the science of hydrogeochemistry over time. The excellent point of this study was a quite detailed hydrochemical characterization of different lithological units.

The study was based on close to 600 sampling points, which at this point in time limits its wide application. This is to be compared with almost 40000 sites which the QualDB (Department of Water Affairs & Forestry's water quality database) has chemical analyses for at present.

The second, nation-wide attempt was conducted by van Noort & MacVicar (1958). This work was done for agricultural purposes and it was supposed to correlate geological formations and borehole waters. The dataset contained 1850 samples analyzed over the period of 1938-1957. The data was evaluated on a district basis (292 districts), but almost half of the districts was covered only by one sample.

The important aspect of this initiative was the fact that data aggregation was used to describe regional units (districts). Each district was therefore described by a single value (per each parameter), in this case arithmetic mean. On that basis, a series of simplified maps was produced with a very crude resolution. In addition, ANOVA (analysis of variance) was employed to distinguish whether there are definite statistical differences between four selected geological formations (Beaufort, Ecca, Dwyka, Old Grey Granite & Gneissoid Complex.

According to ANOVA all samples come from the same population, but authors expressed certain doubts about the sample accuracy. They attributed the bias in their statistical analysis to poor representativeness, cross-contamination of samples and poor positional data. Due to insufficient positional backing of their data the authors considered their effort as of marginal significance over the previous work of Bond (1946).

More recent pioneering ideas on defining ambient groundwater quality were expressed by Reynders (1987). This initiative was geared towards the development of the national monitoring programme. Both this initiative and the later one (Parsons, 1988) remained largely at the level of project proposals and were not fully pursued further. They implanted ideas towards a more structured approach to groundwater-resource evaluation and organization of groundwater-quality data-collecting activities.

Tredoux (?) addressed the special problem of nitrate contamination of groundwater in South Africa. In his study he mapped the occurrence of nitrate countrywide using a grid approach. 18827 sites were used to generate statistical summaries for each square (geographical) degree. The parameters used for the assessment were median and 90th percentile.

Bredenkamp and others (1991) attempted to relate groundwater quality to average annual rainfall distribution. Point maps were produced depicting EC, nitrate, fluoride, chloride and sulphate. The thrust of the study was to find correlation between rainfall and aforementioned parameters. This was found to be not straightforward and other factors such as thickness of overburden, geology have to be accounted for.

2.2 MAPPING APPROACHES

In order to utilize the wealth of data on the QualDB (DWAF water quality database) the Atomic Energy Corporation was approached to evaluate the spatial distribution of selected groundwater quality parameters (Levin & others, 1989). Their endeavor resulted in producing of maps of electrical conductivity (EC), nitrate, fluoride, chloride and sulphate. The maps however carried only a point information classified on the concentration ranges. A lot of work was devoted to data cleaning – out of original 33000 data points 19000 was excluded due to the stringent cleaning protocol that considered ionic balance, pH, sample position accuracy among others.

Beginning in early 1990s, the Department of Water Affairs initiated an ambitious aquifer characterization programme. This regional characterization programme is based on hydrogeological mapping and its results are being produced using numerous map formats. Recent visualization techniques, such as Geographic Information Systems (GIS) allow for the development of tailored-made maps putting relatively acceptable effort and time in service. They also allow to manipulate and evaluate (e.g. statistically) static map data in pre-determined and user-chosen area polygons. These polygons represent anything from simple quadrants to aquifer boundaries. That opened a challenging opportunity for an elaborate analysis of the data on a regional basis.

One of the first products of such an approach was the map of groundwater resources of the Republic of South Africa, which was published in 1995 (Vegter & others, 1995). The map contains groundwater quality component represented by two in-set maps:

- salinity map (depicting TDS ranges and fluoride and nitrate risk areas)
- hydrochemical types (based on Piper diagram)

Although based on a scattered and non-uniformly spaced data, the map gives an overview of trends and variation groundwater quality on the national scale.

The regional characterization programme is generating another important source of data. The advantages of the programme from the groundwater-quality assessment point of view are the following:

- relatively large dataset is created
- good and fairly uniform distribution of sampling points
- use of consistent sampling methods
- relatively short time-span within which the whole area is sampled
- other important hydrogeological features are investigated and evaluated at the same time

The regional characterization programme is presently generating the most important source of the groundwater quality information. An added benefit of above listed features is that the working objectives of the investigation are purely hydrogeological and the sampling is designed to study hydrogeological structures rather than, for example, meet the compliance requirements of certain management objectives.

The mapping programmes do not in general include an investigation of temporal components. The groundwater-quality monitoring should therefore be a complementary tool used to integrate spatial and temporal information. Department of Water Affairs & Forestry therefore initiated a national groundwater-quality monitoring programme, which started in 1993.

With the design and implementation of the monitoring programme it became clear that significant uncertainties existed in the knowledge on groundwater quality at a national scale. Although several measures were attempted to overcome these problems in the monitoring designs it became apparent that a more thorough and systematic evaluation of groundwater quality on the national scale is essential. While the regional characterization can in time bring the information for all mapped sheets, the level and detail of groundwater quality information carried in them is quite limited. As with the national map of groundwater resources only few parameters are portrayed and evaluated (most typically electrical conductivity, fluoride and nitrate). Alongside with the development of the national monitoring project it was very indispensable to investigate the spatial distribution of hydrochemical properties at a national scale. This was initiated in 1995, by the Department of Water Affairs & Forestry (Simonic, 1995).

3 INTERNATIONAL EXPERIENCE

Comparing attempts to map groundwater quality at a national scale elsewhere could give a useful insight on applicable methodologies and procedures. Ideally, a comparison with a country sharing similar natural and social setting would be most beneficial. Most published experience is however available from U.S.A. and European countries, with very little information from African countries or countries with semiarid climate, similar to South Africa.

3.1 NORTHERN AMERICA

The NAWQA (National Water Quality Assessment) program, funded by the U.S. Congress, was initiated in 1986 to achieve the following (Hirsch et al, 1988):

1. Provide a nationally consistent description of water quality conditions for a large part of the U.S. water resources
2. Define long-term trends (or lack of trends) in water quality
3. Identify, describe and explain, as possible, the major factors that affect observed water quality conditions and trends.

The program has been implemented through pilot projects, each addressing a major river basin or aquifer system. The project is not run to cover all major areas at the same time and therefore is of regional significance. The national program is therefore an attempt to characterize selected water systems, rather than provide a national summary. In addition, the NAWQA is not limited to groundwater, it is aimed at all fresh water resources. It is also not specific to ambient conditions. A team of investigators familiar with the region-specific conditions conducts each investigation. Individual reports are prepared for each investigation and no further level of reporting is pursued. Several pilot areas have been investigated, for example Hamilton and others (1987), Welch and others (1997).

The reports produced under NAWQA discuss major ion chemistry, but in contrast with South African conditions, considerable attention is given to minor constituents, radionuclides and synthetic organic compounds.

The NAWQA program in its focus can be matched with South African regional characterization. The differences include the following:

- NAWQA concentrates on water quality, the RSA characterization focus on groundwater quality is only limited to TDS (or EC), nitrate and fluoride
- NAWQA addresses a clearly defined aquifer system, the RSA characterization is organized through map sheets irrespective of the aquifer boundaries

Time factor is very important. The NAWQA program concentrates on a relatively detailed groundwater quality investigation within a generous time-span. The projects are phased-implementations with phase reports.

The attempt to provide a national summary of groundwater quality was provided in Groundwater Quality Atlas of the United States (Pettyjohn et al, 1979). The atlas provides basic groundwater quality information on state-by state basis. Only several parameters were mapped (TDS, hardness, Ca+Mg, Na+K, Cl, SO_4). The parameters were contoured for each state with quite a large contour interval.

Canada does not have a nationally driven groundwater quality program. There are however regional initiatives similar to NAWQA program in the U.S.A. As an example, a comprehensive overview of Alberta water quality is given in Pupp & others (1989).

3.2 EUROPE

The European scene is probably the most consistent in its approach, with very detailed and costly investigations taking place. This is no doubt the result of industrialization and socio-economical pressures experienced over relatively small space.

Although most of European countries have their own groundwater quality program (and a number of regional initiatives), the trend is towards creating international baselines that are a part of the environmental assessment on a global scale. Probably the most significant initiative is the IUGS/IAGC Global Geochemical Baselines Working Group.

3.2.1 IUGS/IAGC Global geochemical baselines

The groundwater quality forms only a part of a broad geochemical reference program. The research has been conducted since 1988 as part of the International Geochemical Mapping project [IGCP 259]. UNESCO approved the International Geological Correlation Project (IGCP). This project is an answer to a need for a consistent and internationally comparable geochemical dataset that could merge several national (European) and regional datasets describing geochemistry of the Earth's surface. All basic aspects of geochemical mapping are presented in the UNESCO publication (Darnley & others, 1995).

In 1994 the FOREGS Geochemistry Task Force was established in order to make an inventory of geochemical databases in European countries. The group identified 120 separate geochemical databases, but found that the materials collected, the sampling methods and analytical techniques varied widely (Plant et al, 1996).

During a series of international meetings, standardized methods for geochemical sampling were developed and agreed to by the representatives of more than 100 countries worldwide (Darnley et al, 1995). The methods were published in a Field Manual, which is specific for European conditions. The similar manual for tropical and arid climates was under preparation.

The project is based on the concept of a primary reference network (160x160 km grid) with at least 5 sampling sites each in 20x20 or 40x40 km subcells). The materials to be sampled are:

- 25 cm depth regolith

- Stream or lake sediment
- C horizon regolith
- Surface humus (if present)
- Water (groundwater) (if present)

It is important to note that each sample of each medium should be a composite of minimum of 5 subsamples.

On this basis several groundwater quality maps/atlases were recently generated in European countries (e.g. Rapant et al, 1995, Lahermo et al, 1990). These represent the most systematic approach available to date.

3.2.2 United Kingdom

Chilton et al (1995) described the UK perspective on the national groundwater quality assessment. They stressed that the assessment had to meet multiple objectives under limited financial constraints. A three-tiered strategy for England and Wales was proposed. A national network of 3000 sampled sites (1 sample per 25 km^2) was to provide knowledge on the spatial distribution of groundwater quality. Another subset was to be formed of 250 reference sites, to allow for trend observation and baseline provision. The third tier was to represent or address local issues or site-specific problems.

This framework was to be implemented under auspices of the National Rivers Authority (NRA). It was stressed that assessments of groundwater quality always involve simplifications. "*Choices have to be made concerning where, when and how to sample and what to analyze for, based on an appreciation of the way groundwater occurs in and moves through the aquifers under consideration and the way groundwater quality can change under the influence of natural processes and human impacts. These choices are inevitably not entirely scientific; available finance plays a major role in defining groundwater quality assessment programmes*" (Chilton and others, 1995).

Primary objectives of the UK national groundwater quality assessment were:

- Show **trends** of groundwater quality changes derived from natural causes, the impact of diffuse pollution sources and changes in hydraulic regime
- Provide background information on groundwater quality so that the impacts of future, as yet, undefined, human activities can be detected - **baseline for future issues**
- Provide a picture of the three-dimensional distribution of groundwater quality within aquifers – **spatial distribution**
- Provide **early warning** in recharge areas on aquifer outcrops of the impacts of diffuse sources of pollution
- Provide information to meet the requirements of the EC Nitrate Directive to identify and **monitor Nitrate** Vulnerable Zones

The assessment project was however in its design phase, the implementation results have yet to be compiled and evaluated.

3.3 OTHER COUNTRIES

Information from other African countries is especially significant for South Africa. The research initiatives in Africa are focused on Sahel region (e.g. Langenegger, 1987). Most of research there is process-related, studying the impact of desertification on groundwater quality and the environment as a whole.

Information on systematic mapping approaches at national scale could not be obtained from available sources. Most of studies are of local significance. Donor initiatives could sometimes span through regions. For example the Handpumps Project, executed under World Bank/UNDP auspices, provided opportunity to test groundwater quality in several Western African countries. The results were summarized by Langenegger (1987). Groundwater quality was presented in the form of frequency diagrams and was compliance oriented, using WHO drinking water guidelines.

In Botswana, groundwater quality was a part of the assessment of groundwater resources, implied in the Botswana National Water Master Plan. Groundwater quality was assessed using data from consultancy reports and various registers (Carlsson and others, 1993). The assessment was conducted for each major aquifer, using WHO drinking water guidelines as a classification tool. The results were generated using ARC/INFO GIS as a presentation tool. Water quality part, however, was embedded in groundwater extractability estimates and no detailed analysis was attempted.

4 SOURCES OF DATA

A relatively large amount of groundwater quality data currently exists in numerous reports and files in government and non-government organizations. Most of them are rather site-specific. The stored information is mostly of a spatial relevance only, because data have been acquired often from once-off surveys or from other investigations of a short duration. The quality of information is variable when taking into account various sampling methods and procedures, non-uniform analytic methods, inconsistency in availability of supporting data (e.g. borehole construction details) and different scopes of analyzed variables.

The distribution of sites at which the samples have been taken is of a scattered nature and is an expression of different priorities and objectives that were followed in the investigations. This is illustrated in *Figure 1,* which shows sampling sites that were considered for the recent compilation of the groundwater quality component of the national hydrogeological map. They represent the status quo of water quality sampling efforts for the period 1970-1997.

4.1 DATABASE OF DEPARTMENT OF WATER AFFAIRS & FORESTRY (QUALDB)

DWAF's water quality database (QualDB) is an entity separated from the borehole database (NGDB), which is the fact that has some important implications. In general it is very difficult if at all possible to relate water quality information with the borehole information. The unique identifiers for both databases are different, which makes linking of databases very difficult.

4.1.1 QualDB parameters

The water quality database (QualDB) stores information on main ions and, total dissolved solids (TDS), electrical conductivity (EC) and pH. It also allows storing of other elements, including trace elements, but their availability for a nation-wide study is very limited. The positional information typically contains geographic coordinates and their precision class, name of farm, number of the hydrological catchment and, sometimes, additional parameters such as the name of sampler or the project for which the sampling was done.

The QualDB has recently undergone significant changes and was renamed to WMS (Water Management System). The new system is intended to allow for easier data manipulation and includes data from various monitoring networks. It has to be stressed that neither QualDB nor WMS are specifically groundwater-related.

Minor constituents such as metals or organic contaminants were not typically sampled for in groundwater-related studies and therefore the database contains very little in this regard. The same applies to field measurements – parameters such as pH and EC were measured in laboratory. The only field parameter that was sometimes included with the sample was temperature. The measurements of field parameters are however mandatory for the national groundwater quality monitoring and in time allow for an evaluation of errors introduced into the database by not previously using the field parameters for routine sampling campaigns.

The parameters that are commonly available in QualDB include the following: calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), total alkalinity (TAL), sulphate (SO_4), chloride (Cl), nitrate-nitrogen (NO_3-N), fluoride (F), silica (SiO_2).

The less common parameters include ammonia-nitrogen (NH_4-N) and phosphate (PO_4-P). Almost all analyses include total dissolved solids (TDS), electrical conductivity (EC) and pH.

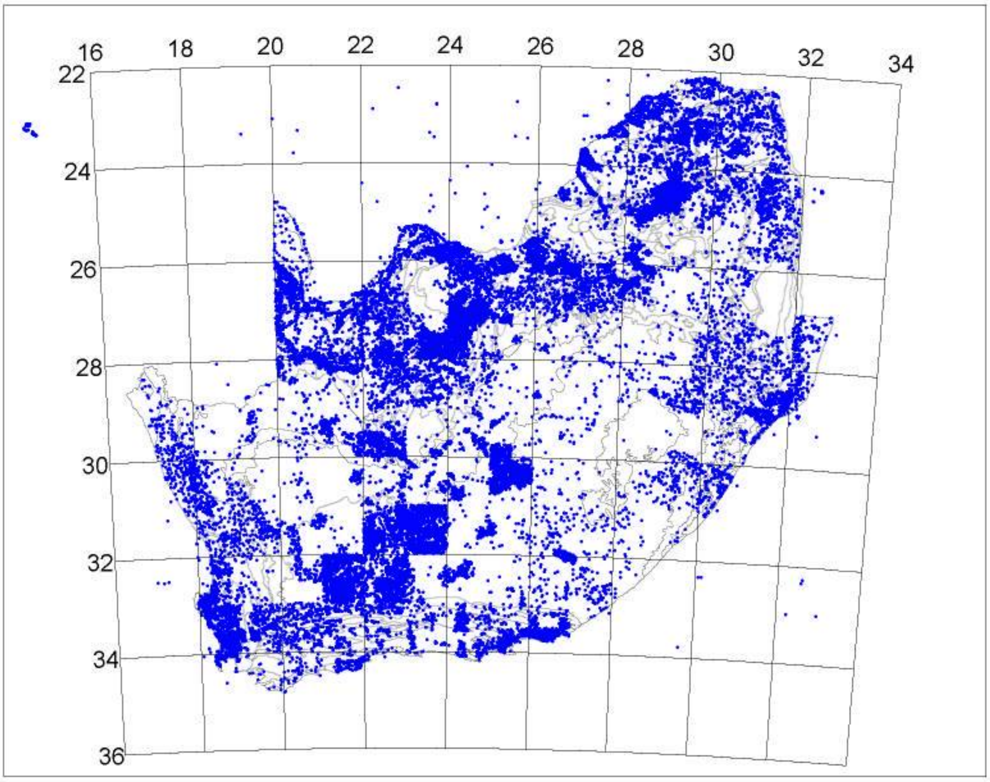

Figure 1: Sites with groundwater-quality information

4.1.2 Database structure considerations

The present storage and retrieval of groundwater quality data is not ideal. The centralized mainframe concept is not user-friendly and to extract the data a lengthy procedure is required. If one requires a non-routine query, an involvement of a programmer is necessary.

The accessibility of the database is therefore ripe for change, especially taking the IT revolution into account. The format of the database has to change to allow an on-line download for non-Department of Water Affairs & Forestry users. Another option is to implement a distributed (e.g. annual) approach customized for different users (e.g. CD with groundwater database, annual updates).

The mainframe database is very complex – it is almost impossible to perform queries for a person that does not work on the database full-time. A suggestion may be to develop an interface between the main-frame and an educated user that would "decode" the complex database structure. This is perhaps due to change with recent initiatives at Directorate: Geohydrology, with the implementation of an interactive on-line database (REGIS), based on ArcView interface.

4.2 OTHER SOURCES

Other sources of groundwater quality information were excluded from further consideration for several reasons. The previously computerized information from Bond (1946), as used for the Sheet 2 of the Vegter (1995) project cannot really improve the spatial coverage once the KwaZulu/Natal data became available. On the whole Bond published about 400 analytical results for the whole country, without accurate positional information. Gathering the data from the groundwater-consulting companies is not time-efficient, as the consultants could not afford spending their time transferring their data in useful formats. To access these sources perhaps a dedicated initiative is required by the combined effort of WRC and DWAF. The donor organizations will have to be rewarded for the data they submit, but must ensure the quality of data in return. A reward-based systm will have to be developed as a project on its own.

The value of the above sources for the current study would be questionable, because a lot of consulting companies are involved in groundwater pollution studies that do not reflect ambient groundwater conditions. The scope of determinands is quite often rather limited and various analytical techniques were used to analyze for the same determinand. This would jeopardize the consistency of the evaluated dataset.

Some of the data sources stored outside the Department of Water Affairs & Forestry were already uploaded in QualDB. The data from the Atomic Energy Corporation could be used as an example. The QualDB was therefore used as the sole source of groundwater-quality data for the present project.

4.3 ASSESSMENT EXPECTATIONS

4.3.1 Limitations of the national scale

At the national scale, it is not imaginable to cover all details - only broad, mostly regional changes can be evaluated. In case when a more detailed investigation is needed, the data-collection activities have to be adjusted above the scope of the national scale. The national scale cannot provide all answers, it can however provide clues which would not be available without both analysis and synthesis on a large scale.

The main reason for the limited detail is financial and manpower constraints. It is beyond the reach of any agency to provide all necessary groundwater quality information about every site in the country. At all times it is imperative to understand the iterative nature of collating and evaluating the groundwater quality information.

Because this is the first comprehensive evaluation of the groundwater-quality data at a national scale the emphasis is on descriptive rather than interpretive aspect of the assessment. The focus was on the visualization, to make numbers stored on the mainframe computer mean something that can be relatively easy to evaluate further. The visualization of data also allows for the easier detection of errors and enhance the definition of further data-collection needs.

The main thrust of this project was to create the atlas of groundwater quality, not least as an extension of the first national hydrogeological undertaking – the map of groundwater resources (Vegter & others, 1995). By generating the atlas of groundwater quality, visual information is created that is not extractable otherwise. The interpretation of the extracted information and seeking potential correlation with environmental and cultural factors would be the next natural step in expanding the national groundwater quality assessment project.

At this stage, little space is devoted to the interpretation of the portrayed groundwater quality trends. Yet using eyes trained in different hydrological and climatological phenomena, various apparent correlations come into consideration (e.g. rainfall distribution, and chlorinity of rainfall in coastal areas).

4.3.2 Information users

The following list of information users is by no means definite. The important thing is that the information users are a part of the iterative process of the assessment-objective formulation and its fulfillment. It should be possible in the future to incorporate the demands of information users seamlessly into the assessment objectives and activities.

The following list contains organizations and/or other entities that may benefit from or contribute to the national groundwater quality assessment project.

State departments and local authorities

Water boards

Other organisations:

- CSIR
- Soil & Irrigation Institute
- Water Research Commission
- Park Boards
- South African Agricultural Union
- Chamber of Mines
- Development Bank of South Africa
- Eskom
- World Bank

4.4 SUITABILITY OF DATA FOR ASSESSMENT AT A NATIONAL SCALE

4.4.1 Availability of groundwater-quality data

Some aspects of the QualDB data structure and range of variables determine their suitability for a further evaluation. For example, the fact that very little information on trace elements is stored in the database does not entitle one to make any statements about trace element trends in groundwater. Trace elements can however have a major impact on suitability of groundwater for drinking purposes.

Even constituents such as iron and manganese (and to a certain extent aluminum), which are fairly common in other water quality databases, were not historically analyzed for. This is a major limitation of the evaluation of the redox state of the aquifer systems and their potential contamination attenuation capacity.

Very little is known about organic constituents in South African aquifers. As these are introduced only through the man-induced activities, their evaluation is not strictly necessary, because of the emphasis on the ambient groundwater quality.

4.4.2 Consideration of ambient conditions

Having to evaluate a relatively large dataset (over 50000 analyses) the criterion of ambience is not strictly followed. The database (QualDB) does not contain flags indicating that particular analysis relates to a groundwater pollution problem. It is therefore not feasible to exclude all samples related to pollution problems or to quantify what is their proportion in the database. The data aggregation process (explained in section 5.4.1) hopefully reduces this source of bias to an acceptable degree.

4.4.3 Positional accuracy and representation

The positional information suffers from the low accuracy problem. It is known, for example, that close to 600 analyses are positioned outside the boundaries of the Republic. This means that at least almost one per cent of evaluated data have apparently wrong positional information. Hidden positional errors within the boundaries are difficult to determine. If the reason for the error is the misrepresentation of the longitude and latitude, it can impact on the accuracy of the results. If the reason for the positional errors is just the accuracy of coordinates (such as submitting coordinates read from the topographic map as opposed to surveyed or GPS-read ones), it should not have a great impact on the accuracy of the interpreted results of this study (because of the national scale of the evaluation).

The spatial representation of data over different parts of the Republic varies. Regions with a relatively high concentration of groundwater-quality sites are not as profuse as those with low occurrences. The assessment approach will have to take it into consideration.

5 ASSESSMENT APPROACH

5.1 INTRODUCTION

The considerations regarding the assessment of groundwater quality reflect the experience gathered at compiling the groundwater quality component of the national map of groundwater resources(Vegter, 1995).

The description of the spatial distribution of groundwater quality at a national scale requires an approach that can render regional groundwater quality patterns and trends. The national groundwater-quality assessment cannot be expected to answer questions related to more detailed scales. It might however be able to offer statistically probable ranges of spatial distribution of groundwater quality for the particular area.

Concentration ranges in the spatial domain are most often represented by contouring approaches. Two approaches appear to be most suitable for representing groundwater quality:

- Calculating lines (or areas) of equal concentrations for the whole space using geostatistical methods
- Calculating groundwater-quality statistical summaries for pre-defined spatial units and then represent different concentration ranges using a suitable classification system

5.2 GEOSTATISTICAL CONSIDERATION (VARIOGRAPHY)

The assessment of groundwater quality on the national or any other scale is very similar to a variance evaluation. The whole idea of assessment evolves around variability of groundwater quality in coordinates of interest, in our case in space and time. The secondary aquifers are similar to statistical entities, the different structural features, variable levels of weathering, variable recharge rates all contribute to the distribution of groundwater quality very much of the stochastic nature. In fact in most situations it would be very difficult to derive deterministic models for these aquifer systems.

It has been however shown a number of times that there is a regional continuity even in these systems. It is possible to define the spatial relationships by means of, for example, variogram modeling. In such a manner it is viable to determine the distances over which the sampling points are effectively associated and at the same time it is conceivable to evaluate the error in estimation of this association.

For a variogram assessment at a national scale data from all sampled sites will have to be taken into consideration and physical computation. This means that close to 40000 points would have to undergo a computation effort. Such a scale of computation was attempted using two software packages, GMS (Groundwater Modelling System) and Tricon (IGS), without obtaining a solution. The dataset of such a scale is apparently beyond capability of desktop software.

Alternatively it might be of some benefit to evaluate variograms related to several areas or regions within the country. The objective then is to find out whether the semivariogram parameters are more or less the same, or in other words, whether the variation in *range* parameter does not vary from place to place. If this is the case then it is possible to apply a contouring technique (such as kriging) over the whole country. If not, then the only way forward is to apply kriging with different parameters for different regions and then combine the results region by region. This alternative was not regarded as feasible due to obvious implications, such as time and resource constraints.

Atomic Energy Corporation (1990) conducted a detailed geostatistical analysis of Springbok Flats. The range of influence for different water quality parameters was: 58 km for fluoride, 48 km for nitrate, 45 km for chloride, 42 km for EC and 58 km for sodium adsorption ratio

(SAR). This is in contrast with other regions. For example, in the Limpopo area (Swartwater-Maastroom) our computed range for chloride was only about 2500 m.

In their study from the south-western Karoo, Atomic Energy Corporation (1991) reported yet other values of variogram range. This parameter changed when datasets with different number of sampled points were evaluated. For example, for a set with 120 and 75 samples the variogram range was 8000 and 7000 m, respectively.

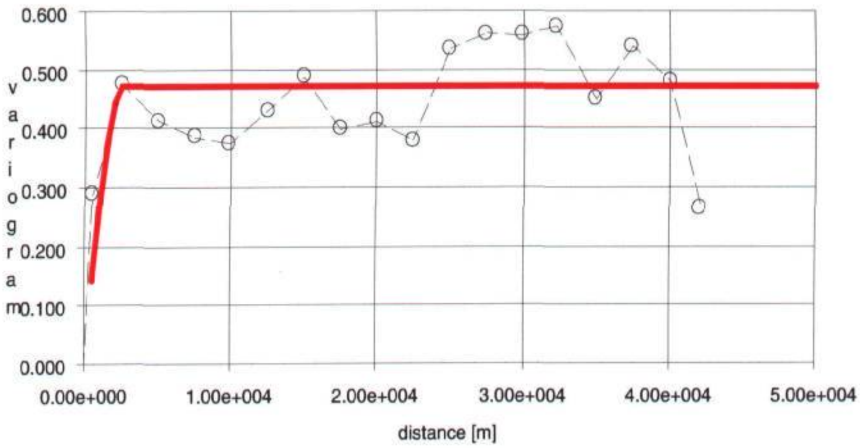

Figure 2: Semivariogram of chloride concentrations in Swartwater-Maastroom area

Using parameters from Swartwater-Maastroom area the map of krigged values can be produced (Figure 3).

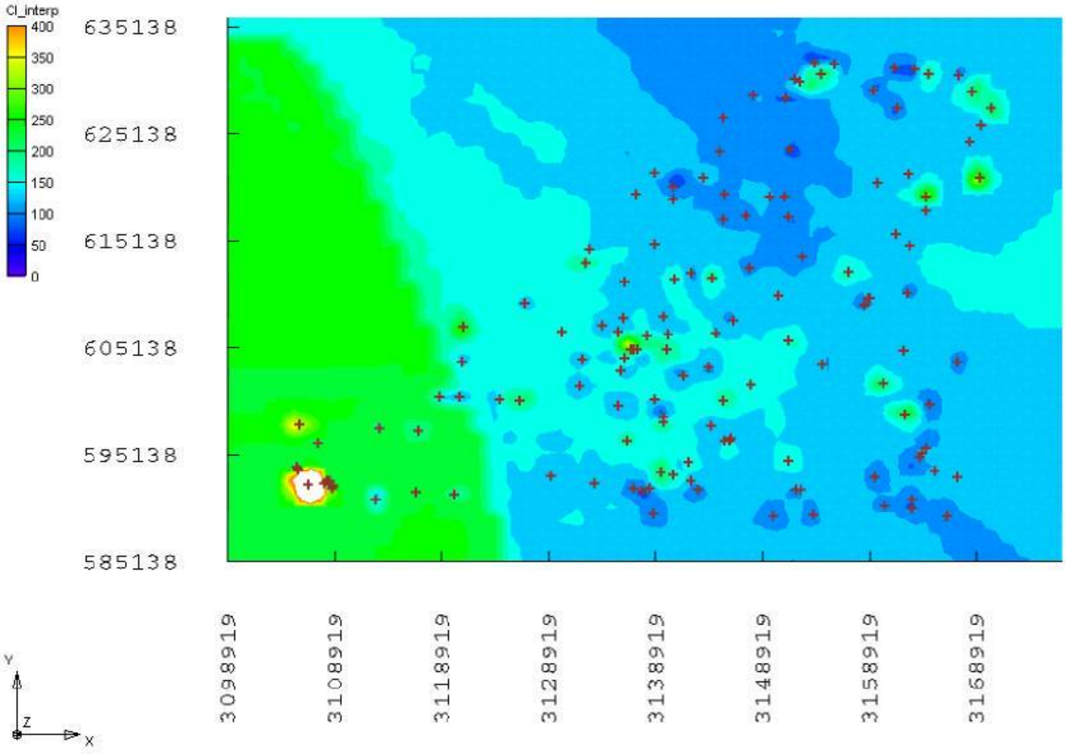

Figure 3: Krigged chloride concentrations in Swartwater-Maastroom area

While krigged values appear to present a realistic picture of groundwater chloride concentrations, the strength of the krigging method is in evaluating of uncertainty. The error of estimation can also be mapped providing an exact measure of data deficiency. The error specification is in Figure 4.

The error map shows that krigged estimates are only valid at a short distance from measured points. Most of the area is covered in pale hues suggesting high estimation error. This is a direct result of low semivariogram range. The randomness of chloride concentrations in the Swartwater-Maastroom area is probably a result of the aquifer system that does not show good hydraulic interconnection.

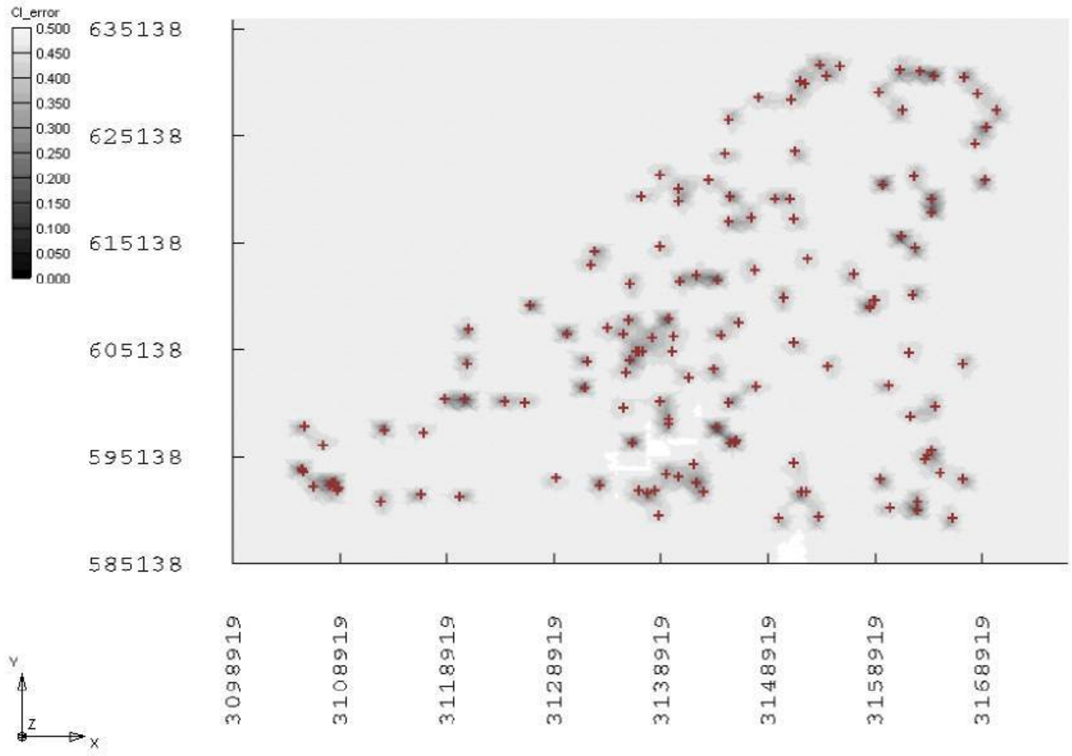

Figure 4: Error map of chloride concentrations

When compared with Springbok Flats where semivariogram ranges were about 50 km, the hydraulic system is likely to be well mixed. This suggests good groundwater flow communication over large distances. The difference between the two areas implies that a straightforward use of contouring over large areas of the country, as well as country-wide, will be charged with great error. Contouring groundwater quality using geostatistical techniques has to be accompanied by relatively low estimation errors in order to provide a credible picture.

In comparison with SW Karoo, this is yet another range different from the Swartwater-Maastrom area. The variability of variogram parameters is thus very high countrywide.

At a national scale the variogram approach and contouring associated with it seem not to be feasible. As shown on the previous examples, the variogram parameters vary from area to area and it is not possible to obtain universal parameters that would be acceptable for the country as a whole. The variogram approach is therefore more acceptable at a local or regional level.

Another problem with the application of variogram modeling is the fact that the national dataset is not homogeneous in temporal coordinates. With the existence of temporal variations the resulting variogram would have to be based on the dataset that was freed of the temporal variation.

5.3 AREA DISCRETIZATION

It seems logical that the approach that is based on areal units serving as elements of an overall areal system would be appropriate. Following such a reasoning, a (statistically) stratified sampling is employed where the entire population (national dataset) is subdivided into separate subpopulations. These subpopulations, in our case hydrogeological regions, are referred to as strata (in statistical sense).

The strictly catchment (hydrological) approach does not always fit consistently to hydrogeological concepts and conditions. In his regional hydrogeological classification Vegter (1991), already attempted to depict relevant regional features for the delineation of hydrogeologically specific regions. These were accepted as the basis for the spatial distribution. The strata in statistical sense are thus equal to such hydrogeological regions.

Other broad subdivision and various other levels of stratification could equally be considered (e.g. geological units such as Karoo, Table Mountain Group, or climatic regions, or various water uses, etc.). Such a statistical stratification can contribute to a higher accuracy of estimates of population parameters by weighting the influences of units.

5.4 PROBABILISTIC APPROACH

The groundwater-quality dataset was therefore evaluated statistically using the approach that was applied for mapping of Groundwater Resources of South Africa (Vegter, 1995). The lithological units were subdivided into smaller units applying their hydraulic properties on a regional basis. These units were taken from Vegter (1995) and are portrayed on Figure 5. Each of these units was typified by groundwater-quality analyses that fall into it geographically. This approach inherently assumes that:

- aquifers are defined by geological units
- units are homogenous in statistical sense

The maps generated using these polygons are thus consistent with the set of maps compiled by Vegter (1995).

5.4.1 Logarithmic transformation

The groundwater-quality information per unit was statistically aggregated. First of all groundwater-quality data were log-transformed, in order to make their distribution to follow the normal distribution. It is a well-known fact that water quality data is not normally distributed (e.g. Davis, 1973) and therefore lognormal transformation was necessary. The log-transformation resulted in better distribution. Some parameters such as alkalinity and pH were not transformed. Alkalinity tend to conform with normal distribution, while pH is already a log-transformed variable.

The log-transformed groundwater quality data were aggregated using arithmetic mean of the log-transformed data for all area units. The variation in data was portrayed as the range defined by standard deviation space. The standard deviation range was also determined from the log-transformed data.

5.4.2 Database manipulation and GIS pre-processing

A number of routines were assembled in the MS Access 97 environment to achieve this. Firstly, using the GIS every analysis was assigned to its respective regional unit. If at a sampled point more than one analysis was available, only the latest (most recent) analysis was used for further processing. This served to avoid the undesirable effect a sampled point could have on the unit dataset.

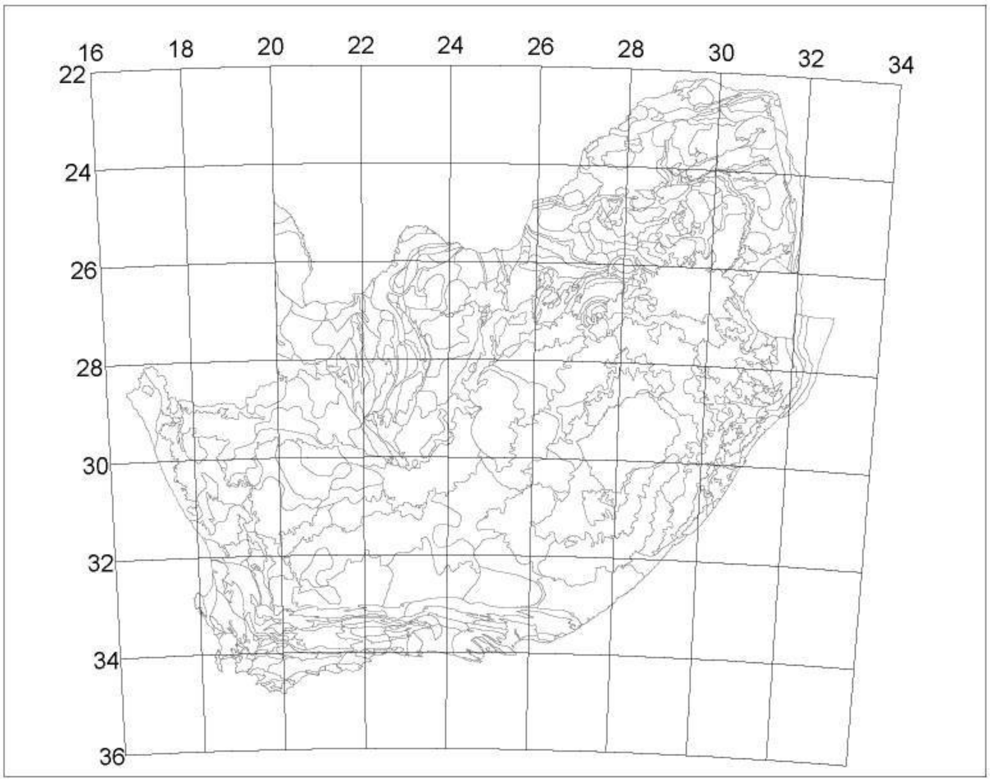

Figure 5: Area units used for the data aggregation

The number of sampled points per polygon varied a lot and is mapped countrywide. Very few polygons did not have any groundwater quality data.

The statistical analysis was achieved using a number of MS Access 97 queries.

The log pCO_2 values and saturation indices for calcite, dolomite and quartz were calculated using the WATEQ routines (Truesdell & Jones, 1973), reprogrammed into MS Access 97.

As a result of MS Access 97 query programming and manipulation a number of statistical summaries were generated, each for concerned parameter. The tables containing these summaries are available on CD in MS Access 97 and Excel97 formats.

5.4.3 Range classification

To obtain the spatial trends the units with similar statistical parameters were grouped together. The grouping was based on concentration ranges defined to mirror the guidelines for drinking water quality. The colour scheme representing drinking quality classes was used whenever appropriate.

The grouping was performed using a Mapinfo feature called "thematic mapping". Using SQL joins the statistical summaries generated in MS Access 97 table were mapped to the polygon map. This simple approach was applied to all parameters/variables of concern. The resulting maps are organized in "workspaces" (.wor files). All tables and workspaces are available on the CD. Using free Mapinfo Viewer (also on CD) one can view and print maps, or zoom into them or select only certain areas. Mapinfo table were also translated into shapefiles, for the benefit of ESRI GIS users.

The results mapped at a national scale (M=1:10,000,000) in a series of maps are also available in Adobe PDF format on the CDROM. This format enables cross-platform viewing and printing using a free viewer available on CD and on the Adobe web site (www.adobe.com).

Using underlying tables and statistical tables further customization is possible to answer the needs of potential users.

5.4.4 Bias/uncertainty assessment

The approach described above gives central values of solute concentrations that may be expected within certain area. Hence all anomalies are more or less smoothed out. This approach is charged with the following sources of uncertainty:

- Uncertainty from unspecified temporal variation
- Uncertainty resulting from different sampling methods
- Uncertainty from the uneven spatial distribution of sampled boreholes
- Uncertain information on the status of the sampled borehole – whether it reflects "ambient" or "polluted" conditions
- Uncertainty about vertical variations in groundwater quality along the borehole profile

5.4.5 Variability assessment

The presented maps do not give a complete picture on the groundwater quality as they provide only mean concentrations assigned to representative lithological units. No information is provided on how variable the concentrations for the particular units are. In order to provide the reader with an estimate on variability of assessed concentrations the following measure of variability is presented.

The standard deviations (SD) from selected log-transformed constituents (Ca, Mg, Na, TAL, SO_4, Cl) were normalized using the Lilliefors transformation (the transformation factor was the mean). The normalized SD were summed up and mapped. The variability expressed in such a way is directly proportional to the mean.

6 ANALYSIS OF AVAILABLE DATA

6.1 SPATIAL ANALYSIS

The results of evaluation are presented in a series of maps. The maps are at 1:10,000,000 scale. Statistical properties are thus presented in more understandable, visually appealing mode, in the from of a groundwater quality atlas.

6.1.1 Scale considerations

The spatial distribution of the groundwater-quality parameters was evaluated at a national scale. Although small-scale variations may be of importance for a local development of groundwater resources, the emphasis was placed on mapping broad, large-scale trends in ground-water quality.

6.1.2 Data quality descriptors

A set of maps was developed to map the data itself. It is important to understand the quality of evaluated dataset and therefore the following maps were produced:

- Distribution of sampled site countrywide
- Sampled site count per region
- Sample density expressed as km^2 per sample
- Sample cover for different time periods (pre-1970, 1970-1980, 1980-1990, 1990-1997)
- Sample ion balance error in three classes: more than 5%, more than 10% and more than 30%.

6.1.3 Major ions

The set of national maps was compiled using thematic features of the Mapinfo GIS. These maps depict all major groundwater quality parameters as well as several derived and index parameters. All major ions were mapped nationwide.

These include calcium, magnesium, sodium, potassium, alkalinity, sulphate, chloride, nitrate nitrogen and fluoride. In addition, silica was also mapped.

6.1.4 Derived and index parameters

In addition to major ions other derived and index parameters include the following:

- Carbon dioxide activity expressed as log pCO_2 – to give an impression on how the carbonic acid may contribute to solute-forming processes in South African aquifers
- Chloro-alkaline distribution index (CAD) – to illustrate the dynamics of ion-exchange processes
- Saturation indices (calcite, dolomite, quartz)
- Total dissolved solids (TDS), TDS/EC correlation, TDS outlier (upper) map

6.1.5 Water types

Piper diagram was considered as a classification system due to its wide use within the groundwater community. Four classes forming quadrangles of the Piper diagram were mapped as follows:

- (Ca, Mg) (HCO_3)
- (Na, K) (HCO_3)
- (Ca, Mg) (SO_4, Cl)
- (Na, K) (SO_4, Cl)

The presence of individual types was mapped as a fraction of total samples, worked out in per cent. The information can thus determine what is the probability of obtaining a hydrochemical type of concern for any region.

6.1.6 Drinking and technological compliance

A set of maps was generated to show compliance of groundwater for drinking water purpose. The classification was based on major ions, other parameters such as minor elements or bacteriological quality was not taken into account.

- Total hardness – to summarize the technological parameters of groundwater in various areas of the Republic
- Drinking water compliance – based on concentration of major ions
- Drinking water prospects – the probability of striking water of either drinking or acceptable water quality

6.1.7 Special considerations

Unstable parameters such as pH are mapped using the analytic value determined in the lab. This may differ from the in-situ conditions and therefore the results should be taken with caution. The same applies to alkalinity as it is the parameter closely associated with pH.

Several other ions may be affected by the standing time between sampling and the analysis. Large number of analyses have had their standing times in excess of three months. The redox sensitive parameters such as nitrate and sulphate may undergo significant changes during standing times, quite often mediated by bacterial activity.

No consideration was given to vertical variation of groundwater within the borehole – the available dataset does not really allow for such an examination. It goes without saying that it may be of importance to examine vertical variations of groundwater quality when installing a groundwater abstraction system under site-specific circumstances.

The data records do not reflect a snapshot of a single representative period. All available data had to be used in order to obtain acceptable coverage of the studied area. The temporal changes in groundwater quality could thus not be screened out in any acceptable way and units are compared using data records from different time periods. Most records fall into the 1970-1997 period, though. To visualize the spatial distribution of time intervals used for characterization of groundwater-quality trends a map was compiled. The map shows proportion of data records for the period 1990-1997 out of the total record count.

6.2 TEMPORAL ANALYSIS

Very little is available to make authoritative statements about temporal variation in South African aquifers. By temporal variations only naturally induced variations are understood as only the ambient groundwater quality is evaluated. The distinction between the ambient and man-induced variation id of course often a grey area – sufficient information is not always available to clearly distinguish between the two.

6.2.1 National Groundwater Quality Monitoring Programme

To assess the temporal variations nationwide is the aim of the national groundwater-quality monitoring presently run by Department of Water Affairs & Forestry (Geohydrology). The pilot scheme was started in 1993 (Southern Cape) and the monitoring network is presently being expanded to cover the whole country. The network currently consists of close to 300 monitoring boreholes.

Existing boreholes were used to establish the monitoring network. This represents some degree of uncertainty, because certain details of the sampled sites are not available or incomplete (e.g. geological log, borehole construction, etc.).

The period of monitoring is however too short for the large part of the network. It would be appropriate if a statistically valid set of observations was used. This is currently still not the case, a lot of sites have less than 5 observations, while it would be ideal to have at least 10 observations to start a meaningful evaluation of the network performance.

A map was compiled to show temporal variations expressed as cumulated standard deviation. This was done for boreholes, which have at least 5 observations. The resulting coverage is not sufficient to make statements about countrywide groundwater quality variations.

6.2.2 Case study: Springbok Flats

To illustrate the natural factors affecting temporal variations in groundwater quality a case from Springbok Flats will be used. Here, among extensive sampling activities, two sets of samples are available collected from the same boreholes during both sampling runs. The first set dates back to 1972 and another one was rendered in 1991. The time span is enough to consider slow, secular changes in water quality. The comparison of both sample sets by means of statistical tests gives an indication to suggest whether there is a (statistically) significant change in groundwater quality. Because the groundwater-quality samples are not drawn from normal populations the proof is sought using non-parametric tests. The Springbok Flats area is known for its irrigation practices, which could influence salinity levels. It is also known as an area with nitrate and fluoride problems. Having had the opportunity to use samples from the same boreholes for two periods, it is possible to assess any net change between sampling times without having to separate the spatial variations.

The following null hypothesis is tested - there was no significant net change in concentrations of water quality parameters. The alternative hypothesis is that there has been a significant change between sampling times under consideration. The fact that analyses were related to the same sampling points allowed for the use of matched tests and was another reason for the selection of non-parametric tests.

The results of the statistical analysis are presented in Table 1. If the considered significance level is 5%, then the change is significant for TDS, total alkalinity (TAL), pH, calcium, magnesium and sulphate. Sodium ion is the most rigid one, showing almost no net change with the highest levels of confidence. The same can be stated about chloride although its net mean values visually differ quite a lot. Surprisingly, the nitrate concentrations in the area show no significant change between two specified years. That may be a reason to suggest that variations in nitrate concentrations are attributed to seasonal changes rather than to a slow secular trend. However, all ions and electrical conductivity disclose net increase in concentrations although only some of them with the statistical significance. The net value of pH has decreased with the statistical significance.

It is interesting to note that parametric and non-parametric tests (Table 1-5) yield quite consistent results. Some values of the computed probability levels (p) balance around the evaluated threshold of 0.05 (e.g. Cl, EC) thus indicating a slow shift in concentrations towards the level of significance.

Table 1: Comparison of mean and standard deviation (SD) values of 1971 and 1991 samples (57 sites) at Springbok Flats. Computed t-test (paired) results show significant changes in TDS, TAL, pH, Ca, Mg and SO_4

	mean	**SD**	**mean**	**SD**
Year	1972	1972	1991	1991
EC	119.1	63.6	153.5	124.0
TDS	787	359	1142	749
pH	7.9	0.35	7.7	0.27
Ca	80	44	109	67
Mg	63	50	97	107
Na	79	74	86	87
TAL	253	96	323	117
SO4	38	40	70	92
Cl	160	198	275	445
NOx-N	21.09	21.55	23.96	21.40

It is noteworthy to observe significant increases in total alkalinity, calcium and magnesium and at the same time a significant decrease in pH. If variations due to analytic methods are excluded from consideration then a possible model for those phenomena could be the following:

Increased levels of alkalinity and TDS as well as decreased pH in 1991 as opposed to 1972 can reflect better recharge activities. Long-term rainfall figures expressed as cumulative rainfall departures[i] would indeed reveal that 1972 was at the low part of the rainfall cycle while 1991 was at its top. Better recharge conditions in 1991 would introduce more carbonic acid into the soil/aquifer system and enhance dissolution of calcium, magnesium and carbonate ions.

Table 2: Comparison of 1971 and 1991 sampling sets by means of Wilcoxon sign test (57 sampled sites) at Springbok Flats. Except for EC, Na and Cl the changes are statistically significant.

	Z	P
EC	13.25	0.185
TDS	4.503	0.000007
pH	4.923	0.0000008
Ca	2.539	0.011
Mg	2.697	0.007
Na	-0.134	0.894
TAL	4.677	0.000003
SO4	3.775	0.0002
Cl	1.589	0.112
NOx-N	2.649	0.008

Table 3: Comparison of 1971 and 1991 sampling sets by means of Wilcoxon rank test (57 sampled sites) at Springbok Flats. All parameters except for Na show significant changes.

	Z	p
EC	2.237	0.025
TDS	5.232	0.0000002
pH	4.101	0.00004
Ca	3.169	0.002
Mg	3.741	0.0002
Na	0.608	0.543
TAL	5.592	0.00000002
SO4	4.478	0.000007
Cl	2.089	0.037
NOx-N	2.066	0.039

Table 4: Comparison of 1971 and 1991 sampling sets by means of Mann-Whitney test (57 sampled sites) at Springbok Flats. Except for EC, Mg, Na, Cl and Nox-N the changes are statistically significant.

	Z	P
EC	0.918	0.359
TDS	2.927	0.003
pH	-3.035	0.002
Ca	2.664	0.008
Mg	1.627	0.104
Na	0.212	0.832
TAL	3.454	0.0006
SO4	2.055	0.040
Cl	1.451	0.147
NOx-N	1.04	0.298

Table 5: Comparison of 1971 and 1991 sampling sets by means of Kolmogorov-Smirnov test (57 sampled sites) at Springbok Flats. TDS, pH, Ca, TAL and SO4 changes are statistically significant.

	Z	p
EC	0.122	0.783
TDS	0.281	0.022
pH	0.316	0.007
Ca	0.263	0.039
Mg	0.193	0.239
Na	0.088	0.981
TAL	0.386	0.0004
SO4	0.263	0.039
Cl	0.158	0.476
NOx-N	0.158	0.476

More abundant activity of carbonic acid would also decrease the level of pH. Although some other processes could be involved, the above scenario could be an illustration of temporal changes of groundwater quality induced by natural factors.

6.2.3 Other studies

Other indications on groundwater-quality variations with time are available from the evaluation of the dolomite springs (Simonic, 1995, Bredenkamp & others, 1995). Dolomite springs as groundwater discharge representatives do show temporal variations in groundwater quality. However, some of the springs may be affected by the effluents from mining in the upper parts of the catchments.

6.3 FURTHER WORK CONSIDERATIONS

The set of groundwater-quality maps opens possibilities to evaluate the effects of various factors on groundwater quality and vice versa. Reviewing the maps one can immediately note the spatial patterns, which were already identified by Bond more than 50 years ago. At the same time index parameters allow to dig deeper into the groundwater-quality information and notice trends previously obscured or not apparent.

The rainfall availability seems to have an overriding effect on groundwater quality as opposed to lithological controls. Whether this is indeed so, it would be necessary to conduct a series of the statistical analyses combined with the GIS technology.

The national groundwater-quality monitoring project has covered a relatively short period of time so far. Only preliminary statements can therefore be made about the temporal components of groundwater-quality variations nationwide. Certain indications can be seen from the visualized results in the form of thematic maps. The statistical testing similar to one illustrated in the case of Springbok Flats will be required to separate the statistically significant variations.

The series of maps presented on the CDROM will hopefully aid not only planning or management decisions, but also to identify further research needs.

At this stage it is recommended that a detailed analysis of lithological units/aquifers be conducted – with Bond (1946) as a leading example. While the present study provided the spatial analysis of the country-wide groundwater data, the causative analysis should be done to further our efforts in groundwater quality assessment project.

7 FACTORS AFFECTING GROUNDWATER QUALITY

Numerous hydrogeochemical processes have major or minor effects on groundwater quality. The major hydrogeochemical processes are discussed in this section. The processes that occur in aquifers, the effect of these processes on the quality of groundwater will be briefly discussed.

7.1 AQUIFER CONDITIONS

South African aquifers are regarded secondary in their nature, reflecting the fact that bulk of their porosity is developed in fracture sets rather than in the rock matrix. Although the parent rock porosity may be small it can still influence forming of groundwater quality. The residence time in pores is likely to be higher and therefore the influence of the rock matrix on groundwater quality will be more substantial.

The two modes of groundwater flow in South African aquifers – relatively fast in fractures and relatively small in pores, may result in different groundwater resident times and hence variations in groundwater quality. These would obviously depend on mixing ratios between matrix resident water and fracture water. The matrix-resident water is affected by mineralogical composition of matrix, while fracture water may carry components from surface recharge. The major fracture zones may be leached and therefore the mineralization of passing groundwater might not be substantial.

Apart from mineralogical composition of the parent rock, other hydraulic and hydrological factors greatly influence groundwater quality. Abundance of dykes and sills within South African aquifers and presence of faults often control the mode of groundwater flow, availability of rainfall recharge and groundwater velocity and hence the residence time of water in the subsurface. Openness of groundwater systems is important in terms of availability of electron acceptors and carbon dioxide.

Mechanical processes close to the surface also influence the weathering patterns. Ice expansion, experienced on freezing of water, growth of the plant roots, animal holes etc. are activities that contribute to the development of the weathering process. Interestingly enough termite mounds were reported in Australia as being responsible for elevated nitrate concentrations on regional basis (Barnes & others, 1992).

Changes in dynamic equilibrium reflect themselves in changes in groundwater quality. The minerals become unstable and react in a way that thermodynamically allows for a development of a new thermodynamical equilibrium. Unless the equilibrium is held the concentration of constituents alters. These variations are responsible for groundwater quality changes in time.

Certain minerals and rocks are more vulnerable to the chemical reaction than the others – this is reflected morphologically having "harder" rocks forming elevations and "softer" rocks being eroded away. Large numbers of the boreholes in South Africa are constructed around dolerite dykes, either on a contact between the dyke and other rocks or directly in the dyke. Weathering of these extrusive rocks will therefore have definite impact on groundwater chemistry.

7.2 WEATHERING AND DECOMPOSITION

7.2.1 Aquifers in igneous rocks

Weathering applicable to igneous rocks is effected even in sedimentary environments, because of the presence of dolerite dykes. Tordiffe in describing weathering of main Karoo rock types gave an explanation of dolerite weathering in Karoo. The weathering sequence for igneous rocks goes from olivine and anorthite through augite, hornblende, biotite or albite and further through K-feldspar, muscovite towards quartz. Although the description was done for Karoo rocks, it can be applied countrywide whenever dolerite dykes are involved, because of similarity of the groundwater regimes.

The minerals that form dolerite are susceptible to chemical weathering. In this process quantities of calcium, magnesium and sodium are released into passing groundwater. Major anions are most probably not derived from the parent rock (with exception of fluoride).

7.2.2 Aquifers in sedimentary environments

South African sedimentary sequences are composed of sandstone/quartzite, mudstone and shale as main representatives of the sedimentary rock types. The special case represents dolostone aquifers, which are regarded as the most significant groundwater resources. Mudstone, however, is by far the most ubiquitous rock type, due to its presence in Karoo aquifers.

In addition to silicates the sedimentary sequences contain important groundwater chemistry minerals such as calcite and pyrite, largely in the form of incrustations between detrital grains. Calcite is a common secondary mineral in basin sediments of dry climates. The sandstones in particular contain K-feldspar in addition to quartz and also minor amounts of Na-plagioclase. The important fact is that the intergranular cement was mainly formed out of calcite, although silicified cement is not rare either.

Gypsum is also commonly found in arid soils. Gypsum is known to occur in the Karoo Basin resulting in groundwater in the western part of the Karoo containing substantial sulphate concentrations.

7.3 DISSOLUTION AND HYDROLYSIS

7.3.1 Carbonic acid and carbon dioxide

The most important solute-producing process is dissolution of minerals due to activity of carbonic acid. Weathering of the sedimentary sequence by the carbon dioxide is the most significant decomposition process in unconfined aquifers and in the recharge part of the confined aquifers

Most of South African aquifers have relatively poor soil cover, especially in the western part of the Republic. Although this encourages free flux of oxygen into the subsurface, the important weathering agent - carbon dioxide – may sometimes be in low supply. Both, the availability of carbon dioxide (and dissolved oxygen), together with distinctive climatic patterns are responsible for the groundwater quality differences between the rainfall-rich eastern part and the rainfall-deficient western part of the country. These differences also affect the hydraulic properties of the aquifer matrix. The decomposed residues as a result of soil-generated carbon-dioxide in the eastern part of the Karoo Basin provide material for a soil cover and may completely or partially fill in fracture sets in the parent rock.

Silicate weathering results in appreciable bicarbonate concentrations, which is typical for the eastern part of Republic. Weathering of plagioclase results in releasing cations such as calcium and sodium

When availability of carbon dioxide is greatly reduced, hydrolytic decomposition of silicates takes over. Major ions are removed, leaving clay minerals and amorphous iron oxides. The general rainfall conditions and residence times determine what type of clay mineral is formed. When considering rainfall patterns in South African conditions montmorillonite should be formed under relatively dry conditions (western parts) with kaolinite being formed in a wetter environment (eastern regions). These are however general trends, local occurrence of other clay minerals is common reflecting site-specific conditions.

7.4 ION EXCHANGE AND SORPTION

Ion exchange and sorption are processes that change proportions of ions in the solution. The better-known reaction is the exchange of calcium for sodium on the exchange sites of sodium rich minerals. This reaction depends on the concentrations of exchangeable ions in solution.

If availability of carbon dioxide is limited, hydrolysis of calcite (and silicates) occurs and the resulting hydroxyl ion may be involved in further reactions. In this way iron common in clay minerals may be leached out of them to form ferric hydroxide. This resulting mineral forms abundant coating on almost all rocks in arid and semi-arid zones.

Using exchange capacity of clay minerals allows for dissolution of more calcite than would otherwise dissolve. The process also mobilizes significant amount of sodium into solution. The factors can lead to excessively alkaline solutions as are those experienced at some coal mines in the northern part of the Karoo Basin.

7.5 EVAPORATION

South Africa experiences huge climatic contrasts over its territory. While eastern part can have over 1000 mm of rainfall per annum, the western sections are an order of magnitude drier. Rainfall availability and its seasonality thus have to impact on how groundwater mineralization is formed.

Recharge and evaporation patterns have a distinct influence on groundwater chemistry. Eastern and western parts of the Republic differ a lot in both the concentration and water types. The global climatic effects are very different from East to West. The regular and rich rainfall in the eastern part causes a continuous dilution, leaching and further transport of leached constituents keeping concentrations of constituents relatively low. Groundwater is undersaturated with respect to most minerals. Due to the dynamic discharge and availability of carbonic acid the dissolving minerals do not reach their solubility limits.

On the other hand erratic and insufficient rainfall combined with high evaporation rates in the West induces a continuous concentration of solutes because the flushing effect is negligible. Groundwater discharge is active through some pans rather than surface drainage. The combination of the long residence time and the effect of evaporation bring about high concentrations reported in the western half of the country.

High anion concentrations are quite often the result of rainfall-originated constituents. These were concentrated many times, with evaporated water leaving its salt contents behind.

The concentration effect is maximised by the lack of organic matter as the soil cover in these regions is poor. The insufficient amount of organic matter does not create favourable conditions for denitrification, elevated concentrations of nitrate can therefore occur. And as some minerals reach their solubility limits they tend to precipitate forming rejuvenated calcite and ferric incrustations.

7.6 OXIDATION AND REDUCTION

Chemical reduction and oxidation induced by various factors can lead to dissolution of oxides and hydro-oxides, oxidation of sulphides and conversion of nitrogen forms. A commonly described sequence involving the presence of sedimentary organic matter from a more oxidized to a more reduced state is:

- Consumption of dissolved oxygen
- Reduction of nitrate to nitrogen gas (denitrification)
- Dissolution of manganese
- Dissolution of iron
- Reduction of sulphate to sulphide
- Conversion of dissolved nitrogen gas to ammonia

These reactions can occur in the reverse sequence depending on the redox state of the aquifer system and how open or close the system is with respect to environmental impacts.

One of the well-known reactions to occur countrywide is oxidation of pyrite. When oxygen-enriched water reaches the horizons containing pyrite deposits, sulphate concentrations increase. If there is no sufficient buffering capacity present in the aquifer low pH acid water is produced that can mobilize an array of trace metals into solution. The pyrite oxidation is a number one environmental problem of the mining industry operating in Karoo and dolomite aquifers. Coal mining and gold mining offers a lot of examples of effluents bringing sulphate concentrations measured in thousands of mg/l.

Redox controlled reactions also influence the fate of nitrate in groundwater. The nitrification and denitrification rates are affected by existing redox conditions and more specifically the change in redox conditions. As these vary a lot over short distances it is quite often observed that nitrate concentrations do not follow any logical pattern and exhibit erratic behaviour.

8 ASSESSMENT PROGRAMME – FURTHER RECOMMENDATIONS

The national groundwater-quality assessment is not a once-off effort. Activities such as national monitoring and the on-going regional characterization programme require a periodic update of the groundwater-quality information. A selection of proper reporting formats is therefore vital to the on-going groundwater-quality assessment.

8.1 CURRENT STATUS

The assessment project concluded its initial phase. The first reported results could date to Vegter (1995) and the report under consideration aspires to be the first comprehensive account, on the updated spatial distribution of groundwater quality. National monitoring on the other hand is also in its implementation phase and it will require periodic assessment and reporting on its own. The regular reporting should start once the whole monitoring network has been fully implemented.

National monitoring does however not cover the whole country. This is a serious drawback as different areas cannot be evaluated against each other. The countrywide assessment of temporal changes is therefore not possible. A change in implementation is thus required and recommendation in this regard will be given below.

8.2 ASSESSMENT HIERARCHY LEVELS

It sounds logical that several levels of assessment are required. The reporting for the general public, for example, should be different from the reporting for regional offices of the DWAF. Different report formats will reflect specific requirements, level of knowledge as well as frequency of monitoring and the assessment update. In broad terms three levels of reporting are considered:

- basic
- advanced
- interpretive

8.3 BASIC REPORTING

The basic level reporting represents the most frequent and the most readier type. In most cases it will be just the presentation of the results with possibly simple graphs. It will however be sufficient for the clients that would utilize the results on a regular basis. These reports can be prepared after every sampling run.

The GIS technology seems to be the best vehicle to convey the message at all levels. It is possible to customize the GIS routine in such a way that the generation of basic reports will be a largely automatic routine.

With the onset of the on-line technology, the best medium to utilize for assessment results is Internet. This can be done much the same way as the results of other hydrological or meteorological networks.

The groundwater-quality part of the regional characterization sheets is also considered as a basic reporting format due to its limited amount of information. The groundwater-quality assessment has to updated every time a significant amount of new information is generated.

8.4 ADVANCED PROCESSING

The more advanced assessment will include statistical summaries and comparisons with a limited interpretation of the results. The graphs and plots will be more comprehensive and tailored to specific users. It is possible that a lot of reports can be made on request. The frequency of reporting may be reduced when compared to basic reporting.

This report is a special case of the advanced reporting. The spatial distribution is covered in it in the form of national maps. A detailed interpretation of the results is however not covered. A periodic update of the spatial distribution of groundwater-quality will fall into category of advanced processing. The frequency of assessment update will typically be more than 5 years.

National monitoring results may also be processed using advanced procedures. These will go beyond the scope of basic reporting. The typical procedures could include the evaluation of representativeness, decision-making procedures on expanding or reducing monitoring in certain areas etc.

8.5 INTERPRETIVE REPORTING

An in-depth interpretation of results will be given in these reports. They will also probably include projections of trends and recommendations for management options and actions. This category of reports will be done almost exclusively at clients' request. While the lower reporting levels more or less describe the status of groundwater quality, the goal of interpretative reporting will be to find relationships, correlations and other causative features that explain groundwater-quality trends. As such they can only be done by experienced specialists and could include using techniques such as hydrogeochemical modeling.

It would seem logical that such an interpretive report should follow the report under consideration.

8.6 REPORTING FREQUENCY

As was discussed earlier the frequency of reporting depends on a number of factors such as the level of reporting detail, client requirements, amount of interpretation involved etc. For any type of reporting it would be not reasonable to act on a more frequent basis than one year.

8.7 RECOMMENDATIONS FOR NATIONAL MONITORING

Due to low pace of the implementation of national monitoring it is recommended that few adjustments be made to the monitoring strategy:

- Adopt a multi-tier strategy. The monitoring network will consist of several subnetworks with different frequencies and variable scopes. There is a potential for a scaled-down reference network, which will be sampled most often. The size of this network should not exceed 100 sites. The full network will be identical with the present design (once fully implemented) and may be sampled less frequently (every 1 or 2 years). Special networks will be designed to study certain groundwater quality phenomena or problem and will be more or less research-related.

- Adopt a cluster strategy. A sampling site may consist of more than one borehole. This is to avoid sampling failures when existing boreholes become unavailable. This however implies that a clear correlation must exist between boreholes forming a cluster.

- Re-evaluate the network design using spatial analysis available in this report. This is important from the representativeness point of view. Before the network was implemented no background information was readily available. The maps and statistical summaries generated by this study may be used to improve the network design and make it more representative.

9 CONCLUSIONS AND RECOMMENDATIONS

The objectives of the national groundwater-quality assessment as set out in the Chapter 1 have been adequately met. In conclusions the relevant statements will be made in terms of these objectives. After concluding remarks suggestions for a further research will be made.

9.1 EVALUATION OF THE AVAILABLE DATABASE

The QualDB as the wealthiest source of the groundwater-quality data was considered for this project. While it contains over 55000 groundwater analyses, these are attributable to approximately 35000 points. The distribution of points is very uneven reflecting different and isolated objectives of data-collection programmes. The analyses are comprised of major ions and a limited positional and sampling procedure data. Trace elements and organic data almost do not exist and do not warrant an evaluation at a national scale.

The positional accuracy is uncertain although sample coordinates are mandatory. At a national scale however, the sample position accuracy is regarded as acceptable having in mind that broad regional trends are evaluated.

The mainframe database is very complex and intervention of programmers is required for custom queries. A good user-friendly interface is needed to address download requests of groundwater data users.

9.2 APPROACH FOR THE NATIONAL SCALE

The probabilistic approach to the groundwater-quality assessment was chosen in order to overcome ambiguities from uneven data distribution and from inability to determine and separate the temporal components. A unit approach was employed with unit being a subpopulation of the lithological units. The units were used identical to those utilized for the national hydrogeological maps (Vegter, 1995). The data geographically attributed to a unit were aggregated using their log-transformed values and calculating basic statistical parameters. Each area unit was assigned a unique set of statistical values per each evaluated hydrochemical parameter. The units with similar statistical parameters were joined using a classification scheme based on drinking water guidelines and mapped at the national scale using thematic mapping features of the Mapinfo GIS.

The probabilistic approach was given preference to contouring approaches derived from e.g. kriging, because the available dataset does not effectively allow for a nationwide application of non-probabilistic approaches.

9.3 SPATIAL DISTRIBUTION MAPS

All major water quality variables were mapped nationwide and are available on the CDROM attached to the report. The maps are in Adobe PDF format, which is widely used, cross-platform, with freely available viewer. In addition to major ions and summary parameters such as TDS, EC, and pH, other hydrochemical indicators were mapped including index parameters and derived parameters (e.g. log pCO_2).

Groundwater quality prospects have been mapped to show the areas with groundwater potential and to highlight groundwater quality problems.

Data quality issues were also mapped, including data distribution, temporal coverage, ion balance error etc.

9.4 TEMPORAL VARIATIONS

Due to lack of historic monitoring attempts very little exists to define and separate temporal components from spatial variations. An example from Springbok Flats is used to demonstrate the temporal variations in groundwater quality due to natural causes such as recharge. National groundwater-quality monitoring initiative is discussed and broadly evaluated as a means to obtain the information necessary to extract the temporal components nationwide.

Several maps depict the preliminary results obtained from the national groundwater-quality monitoring, but the relatively short life of national monitoring prevents from making authoritative statements as yet. Recommendations were made to adjust the network design to reflect manpower and budgetary constraints.

9.5 FACTORS CONTRIBUTING TO GROUNDWATER QUALITY

The factors contributing to groundwater quality are evaluated only from a broad angle. Much more work will be required to exactly identify and quantify impact of main factors. For example, rainfall seems to be a main controlling factor often overriding lithological controls. Another example, closely associated with the rainfall distribution is the availability of carbon dioxide, which is the main agent in hydrochemical dissolution of aquifer materials. The attribution of factors to groundwater chemistry should be the main thrust of the interpretive reporting that should follow this report.

9.6 GAPS IN DATA COLLECTING ACTIVITIES

Two fundamental activities have been discussed in this regard – the on-going data-collection as a product of the regional characterization and national groundwater-quality monitoring. While the former will in time fill in the gaps in the spatial distribution, the latter aims to cover the temporal dimension.

Other parameters have to be included into routine analyses such as more routine field measurements and redox indicators such as iron and manganese. Little is known about trace elements and organics, this should warrant focused initiatives to obtain the information on ambient levels of trace elements.

The more structured approach to bridging the gap in data-collection and evaluation activities is discussed in the section on reporting formats.

9.7 RECOMMENDATIONS

The wealth of information transformed in the visual format will undoubtedly trigger other research initiatives. As this phase can be characterized as largely descriptive, the emphasis should be placed on the interpretation of the results achieved in this report.

For the first time the distribution of a number of hydrochemical parameters is presented nationwide. It will be necessary to try and distinguish the reasons for the spatial and temporal distribution of a number of parameters and try to use this knowledge in managing the water resources.

It will also be necessary to strengthen the link between two groundwater-data databases, the NGDB and QualDB. There is also a need for including other parameters into routine sampling such as iron and manganese. The field measurements of unstable parameters such as pH and alkalinity must be made more routinely and stored on the database.

The assessment of groundwater quality should be seen in broader hydrological perspective and the interaction between different part s of the hydrological cycle can be used to benefit of all hydrological agents and impactors.

The national monitoring programme, once fully implemented, will have to evaluated in terms of its representativeness and cost benefit analysis. This can be done by a more rigorous development of the reporting formats that should ideally streamline the flow of the groundwater-quality information.

Once major factors contributing to groundwater mineralization are identified the process studies may be required to quantify their impacts.

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